Evaluation of the Physical Risk of Ship Grounding

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ABSTRACT

An investigation of the potential to formulate a model for the prediction of the physical risk of navigational groundings during transits of vessels into and out of ports was undertaken using historical data. A database that included information on the circumstances surrounding groundings in five U.S. ports (Boston, Houston/Galveston, New York/New Jersey, Tampa, and San Francisco) for the period between 1981 and 1995, was assembled and analyzed. Time series of the underlying grounding rates for the five ports of study were developed using U.S. Coast Guard casualty data and U.S. Army Corps of Engineers transit data. The grounding risk contributing potential of five parameters was examined to determine their usefulness as explanatory variables in the development of the physical risk model. These parameters are: wind speed, visibility, human factor, depth uncertainty and ship characteristics.

Even though the data acquired for the purpose was neither perfect nor complete, it was possible to extract useful information on historical groundings. The results suggest that wind speed and visibility conditions appear to be useful parameters in explaining the occurrence of groundings. In general, it was found that historical groundings are associated with higher average wind speed and lower average visibility than safe transits. Human factors are considered as one of the most risk contributing factors, responsible for 80% of maritime casualties. The information available were not adequate for a quantitative assessment of their grounding risk contributing potential. Additional information must be obtained. Uncertainty in hydrographic surveys, on which nautical charts are based, does not appear to contribute significantly to groundings in the particular set of study ports. Ship characteristics appear to provide another set of useful explanatory parameters. In general, barge trains were more likely to ground than other ships.

An approach is proposed towards the development of the mathematical model for the prediction of the probability of grounding (physical risk). The potential for mutual exploitation between the physical risk model and the International Safety Management Code is briefly discussed. Some conclusions and suggestions for the subsequent effort are presented.

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Vassilis Papakonstantinou
dedicates the present work to the
memory of his beloved father
Constantine (1916-1986).

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Chapter 1. Introduction

> "... The revolutionary idea that defines the boundary between modern times and the past is the mastery of risk: the notion that the future is more than a whim of the gods and that men and women are not passive before the nature. Until human beings discovered a way across that boundary, the future was a mirror of the past or the murky domain of oracles and soothsayers who held a monopoly over knowledge of anticipated events. ..."
>
> *"Against the Gods", P. L. Bernstein*

In the introduction of his recent book, P. L. Bernstein argues that the roots of the modern conception of risk trace back to the Hindu-Arabic numbering system [1]. The latter reached the Western World seven to eight hundred years ago, but it was not until the Renaissance, when serious studies on risk began. According to P. L. Bernstein, all began when in 1654, a French nobleman, the Chevalier de Méré, challenged the famed mathematician Blaise Pascal to solve a puzzle. The puzzle involved the division of stakes of an unfinished game of chance between two players, when one of them is ahead. Helped by another brilliant mathematician, Pierre de Fermat, they solved the puzzle that introduced for the first time the concept of decision making and future forecasting with the help of numbers [1].

Since that time the concept of risk has come a long way and new related concepts, such as risk analysis, risk assessment, risk management and risk communication have been developed. An article by Chauncey Starr [2] published in 1969 in Science Magazine titled "Social Benefit and Technological Risk" is considered a milestone in stimulating modern research on technological risk. The nuclear power industry was among the first to foster such studies and led the way for others to follow risk analysis methodologies like the so-called *Probabilistic Risk Assessment* (PRA). A landmark industrial risk assessment was the Reactor Safety Study of nuclear plants, an effort headed by Dr. Norman Rasmussen of MIT in the early 70s [2]. That and other subsequent efforts have led to a cultural change concerning our society's approach to risk. One of the many results was the so-called *Risk-Based Regulation* (RBS). The term refers to the process which attempts to prioritize risks and select risk reduction measures according to their risk reduction potential [3]. This process emerged as a result of the limited risk reducing resources that are available to our society, a shortage that can be mitigated only through a rationalized risk prioritization scheme.

Until the late 80s, the attitude of the maritime community towards marine casualties remained, in general, reactive. The main interest was restricted to what could be done after an accident had occurred in order to minimize its negative consequences. However, following a series of catastrophic accidents, especially the grounding of Exxon Valdez off the coast of Alaska, things started to change at an increasingly faster pace. Initially stringent regulating efforts like OPA 90 attempted to provide a solution to marine casualties by increasing the construction and operating standards of the ships along with the corresponding costs [28]. Other attempts followed towards quality assurance, like the *International Ship Managers Association's Code for Ship Management Standards*, the *ISO 9000 series* and the *International Safety Management Code* [57]. The latter attempts assumed a proactive approach towards marine safety but they may be difficult to enforce because of limited resources. These limitations in the available risk reducing resources existed before, but only recently came into the picture forcing the maritime community to reconsider its approach to marine safety. If limited resources are available, the optimization of their allocation requires, as mentioned earlier, the rationalized prioritization of risks. Thus, following the society wide paradigm, the maritime industry became increasingly interested in risk analysis and in particular risk mitigation techniques.

Among the research efforts initiated towards the investigation of such techniques was the one undertaken by researchers at the Massachusetts Institute of Technology, Ocean Engineering Department and the Marine Police Center of the Woods Hole Oceanographic Institution. The project began in the fall of 1995 and focused on the formulation of a *model for ship transit risk*. Transit risk manifests itself in different modes like groundings, collisions, etc. As an initial approach to the problem of transit risk modeling, the research focused on groundings that occur during ship transits into and out of ports. Groundings were selected as the subject of the initial effort because they account for one third of all commercial maritime casualties. The intention was to formulate a model for the prediction of the physical risk of grounding based on historical casualty data, expecting to take into consideration as many risk contributing factors as possible.

The present thesis presents the research effort of the first year of the project as well as the results obtained from this effort. The focus of the research during this period was on the collection and assimilation of data to support an improved understanding of the factors contributing to vessel groundings. Our main objective has been to investigate the relationship between factors such as environmental conditions and uncertainty in nautical chart depth data, and the historical grounding incidents. Our intention is to use these results for the development of a model for the estimation of the probability of grounding (physical risk).

The results obtained from the work performed over the past year are encouraging. They suggest that the historical data on the circumstances surrounding groundings in U.S. waters, while neither perfect nor complete, contain information useful in understanding the causes of groundings. In addition, our first year's work justifies further effort on the development of a model for the physical risk of grounding. Finally, our findings suggest areas for emphasis in the refinement of navigation tools.

Thesis Outline

The present introduction is followed by Chapter 2, where the necessary background information on the ship transit risk modeling project is provided. The project itself is described briefly in Chapter 3. A short discussion on risk analysis is presented in Chapter 4, succeeded by a review of relevant literature is provided in Chapter 5 to render a wider perspective on maritime safety issues. A short discussion on descriptive and inferential statistics, including risk modeling, is provided in Chapter 6. Chapter 7 begins with a detailed discussion on the physical risk of grounding. Subsequently the discussion goes on to a description of the available data source, the five factors that will be investigated as to their risk contributing potential, and a short discussion of the proposed grounding risk model. In Chapter 8 the process of data compilation is presented along with the tools employed for the purpose. The analysis of each individual factor in terms of its relation to the physical risk of grounding is presented in Chapter 9. Chapter 10 attempts to offer an insight on the potential relation between the International Safety Management Code and the transit risk model. The conclusions of the first year's work are presented in Chapter 11, accompanied by some recommendations concerning the following course of action.

Chapter 2. Project Background

The nation's ports and waterways are of significant economic importance. They are vital links in international, national, regional, and local inter-modal transportation and economic systems. The importance of the ports and waterways system is reflected in the flow of cargoes through the system and in the substantial national investment to support waterborne commerce. Every day, hundreds of tank ships and barges, and thousands of other vessels make their way into and out of the United States' ports and harbors. 99% of all U.S. foreign trade by weight (48% by value) and an increasing part of the nation's petroleum consumption are carried by marine transportation [4]. In 1988 the flow of cargoes through U.S. ports was 2.1 billion tons [5]. The annual waterway investments by the U.S. Army Corps of Engineers (ACE) alone exceed $1 billion [5]. The efficiency of this trade is directly affected by the condition of the ports and their waterways. Determining factors in safety, among others, are the accuracy of the nautical charts, waterway design, and the establishment of appropriate aids to navigation. Safety of vessel operations and properly constructed berths, basins and canals are also of importance.

Increase in trade has lead to, and will continue to lead to, an increase in traffic density and commercial ship size. According to Frankel [6], waterborne trade is expected to grow by a compound four percent, which will double channel traffic in about 18 years. Many existing ports and waterways do not adequately accommodate the most modern ships in terms of efficiency, safety, and cargo handling capabilities. Thus, there is interest nationwide in modernization of ports and waterways systems to accommodate modern ships and maintain competitive advantage in regional and international trades [5]. The safety of vessel operations in the waterways have been called to national attention by recent, well-publicized shipping disasters. Safety concerns are amplified by the large size of modern ships and barges transporting petroleum or other hazardous cargoes. Cargo volume has increased the scale of hazards to life, property and the environment that could result from just one catastrophic marine transportation accident. Therefore, waterway design, which has historically been largely an empirical process using large margins of safety, and the configuration of aids to navigation are becoming more complex and of ever increasing importance. At the same time, cost-sharing requirements of local project sponsors, and awareness of environmental impacts have increased pressure for more efficient waterway designs [5]. Hence, a rational methodology incorporating the efficacy of new technologies in the allocation of limited resources is needed.

A study of safety benefits of electronic charts (EC) conducted by the Marine Policy Center at the Woods Hole Oceanographic Institution (WHOI) suggested that we can expect more than 24,000 "EC-addressable" groundings, rammings and collisions involving commercial vessels in the U.S. waters between 1996 and 2010 in the absence of technological change, on average between four and five accidents each day [7]. EC-addressable accidents were in this analysis defined as accidents that may be avoided by using electronic charts or integrated navigation systems, and primarily included groundings, rammings and collisions caused by navigational error or human inattentiveness. Most of these accidents will be relatively harmless, but some may have severe consequences. The study estimated that average expected losses associated with these casualties would be more than $2 billion per year. Another disturbing issue is the fact that the average age of the world tanker fleet is increasing due to market forces. Structurally weakened old tankers are much more prone to experience large or catastrophic structural damage, if grounded, than newer vessels. According to Frankel [6], more than 88% of tanker accidents occur in port approaches and other navigational channels. Hence, there is much to gain from better management of the waterways. Recent studies have proposed the (re)establishment of vessel traffic services (VTS) to improve vessel transit safety [4, 8]. The benefit would be the prevention of human, environmental and economic loss incurred by vessel collisions, groundings, and rammings. VTS is a proactive approach where prevention of accidents is the principal objective, not just the reduction of the consequence of the accidents. However, as a result of several major disasters, such as the Exxon Valdez spill, U.S. and IMO regulations have moved radically towards the adoption of passive approaches such as outflow reduction or prevention solutions (OPA-90), while improved VTS and other preventative systems have received scant attention and even less financial and regulatory support [6]. This is a radically different approach from that taken to improve road and air safety.

Several recent groundings [4] have suggested that there may be a need to improve the way hydrographic data is collected and utilized. The fact that 50% of inshore surveys (depths less than 30m) supporting U.S. charts are over 50 years old and 60% less hydrographic survey ship time is available now than 15 years ago [9], indicates a potential problem affecting safe navigation. It is also known that there are over 20,000 reported but unsurveyed wrecks and obstructions, and that 500 new and uncharted features accumulate yearly. Furthermore, mariners can now position themselves to a much greater accuracy than that available to the agencies performing the older surveys. This means that mariners who misunderstand the limitations in the accuracy of their charts might be misled with hazardous consequences.

In recognition of the lack of rational methodologies to deal with ship transit risk, recent effort has focused on understanding transit risk in a quantifiable manner. Based on a review of risk assessment methods, e.g. the recent study by the Volpe National Transportation Center [4], we believe that a complete understanding of this risk has not yet been achieved. Additionally, we believe that while some progress has been made, a quantitative analysis using all readily available accident data has yet to be performed. Since the fall of 1995, the Department of Ocean Engineering and the Sea Grant College Program at MIT, and the Marine Policy Center (MPC) of the Woods Hole Oceanographic Institution (WHOI) have collaborated on a project on Formulation of a Model for Ship Transit Risk. The project was developed by MIT, in collaboration with MPC staff, as a three-year research activity. The project focuses on the development of a methodology for quantitative risk assessment as a comprehensive tool that explains the transit risk for a given waterway configuration, vessel type, and channel design. In particular, a risk model is being developed to predict the risk of groundings and associated economic damage, such as loss of cargo and environmental resources. This model could be used to evaluate changes in risk due to proposed changes in waterway configuration, and thereby inform resource allocation decisions to help achieve the most cost-effective reduction of risk.

This thesis is a part of the project and describes the findings from the first year of the project. The focus has been on getting an improved understanding of the factors contributing to vessel groundings.

Previous attempts to characterize risks associated with navigation hazards have focused on straightforward estimates of the probability of accidents [10] or considered only a subset of available accident data [4]. Other authors have attempted to find trends in historical accident data, such as the *Saturday effect* [11]. Stewart and Leschine [12] describe a variety of approaches to the assessment of oil spill risk. None of these earlier efforts attempted to construct a model of risk using a comprehensive sample of historical data and a discriminant analysis approach. This is the basis of our project. Several previous studies of navigation risk have used historical accident data to estimate simple unconditional probabilities of certain accidents -- that is, they have estimated the probability of a certain type of accident in a particular region, but they have not attempted to use historical data on the circumstances of each transit to explain the occurrence of the accident. For example, Dickins and Krajczar [10] examined the U.S. Coast Guard's CASMAIN casualty database to estimate the fraction of accidents (mainly groundings) that could be eliminated by the use of electronic chart navigation systems. Similarly, the Coast Guard's Port Needs Study [4] examined the probability of various accidents that might be prevented by vessel traffic service systems, but considered only a small subset of *VTS-addressable* accidents.

Attempts to find significant trends in the Coast Guard's CASMAIN casualty data have focused on simple distinctions such as the *Saturday effect* which are of little use to choices about infrastructure decisions. Statistical analyses of historical accident data from sources other than CASMAIN have attempted to estimate factors affecting, for example, the risk of wave damage incidents in cargo ships [13], or the severity of accidents involving oil tankers and barges [14]. These studies often made use of logistic regression models [15]. Our study is the first attempt to use the more general approach of discriminant analysis to estimate the probability of groundings as a function of a full range of explanatory parameters.

Groundings of commercial ships account for about one third of all commercial maritime accidents, including some of the worst in the United States' history, such as the Exxon Valdez. Many factors contribute to vessel groundings. Some of these factors are of particular concern to federal agencies charged with responsibility for certain aspects of the nation's marine transit routes. For example, the National Oceanic and Atmospheric Administration (NOAA) is responsible for the survey of U.S. waters and for the publication of nautical charts. The U.S. Coast Guard (USCG) and the U.S. Army Corps of Engineers (ACE) are responsible for navigation aids and for channel design and maintenance, respectively.

The Coast and Geodetic Survey of NOAA's National Ocean Service is exclusively mandated to produce the nautical charts for U.S. waters [16]. The nation's needs for these products and services have been the responsibility of NOAA and its predecessor agencies since the 1800s. At the present time, however, the nation's charting system is severely stressed. NOAA produces and maintains nearly 1000 nautical chart editions, over 400 bathymetric charts, nine coast pilots, and numerous miscellaneous supporting publications. About 1.4 million charts are printed and sold each year. The primary purpose of nautical charts is to help ensure safe navigation. All vessels over 1600 gross registered tons operating in U.S. waters must carry up-to-date charts published by NOAA or an equivalent recognized government authority. Nautical charts are an underpinning of commercial transport, as well as naval operations and the commercial fishing industry.

However, a nautical chart is only as good as the accuracy, reliability and currency of the data that form the basis of the chart. The National Research Council's Marine Board Committee on Nautical Charts and Information [16] recently drew attention to the backlog of nautical surveys, both for new areas that have never been charted and to update existing charts. In the report, the Committee found that NOAA does not presently have the resources to conduct all requested surveys over short periods of time. The resources available to NOAA's nautical charting programs over the last few years have decreased in constant dollars in relation to NOAA's overall budget. In addition, NOAA is faced with the need to satisfy an increasingly diverse user community and to adapt to rapid changes in technologies associated with its nautical charting mission. Therefore, a prioritization must take place. The Mapping and Charting Branch of NOAA's Coast and Geodetic Survey routinely receives requests for new charts. According to the report, each request is scored to determine its priority rank based on the importance of the requester, the chart adequacy of the area, marine use of the area, and area dynamics. As of August 1993, the backlog was approximately 1,000 requests. The report called for the development of improved means of prioritizing areas of hydrographic surveys. The old method was said to be subject to political influence and lacked ways to compare relative costs of alternative surveys. The Committee stated particularly that NOAA should establish a method for determining a benefit/cost ratio for each possible survey. This benefit cost ratio would then be used to prioritize the allocation of resources. It also stated the following:

> "The importance of maritime trade to the United States is well established. The benefits of investing an additional $20 million or $100 million annually in improvement and maintenance of nautical charts and information are not widely recognized. Studies of the value of nautical charting programs have provided interesting insights but have not convinced senior executive branch decision makers of the need for additional resources." [16]

The U.S. Army Corps of Engineers (ACE) is responsible for planning, designing, constructing and maintaining the nation's federal waterways. The Corps has been authorized to construct and maintain more than 14,000 miles of navigation channels and approximately 900 commercial navigation harbors. The corps spends more than $500 million annually on dredging the nation's channels and harbors [17]. Funds for dredging comprise over one third of the Corps annual operation and maintenance budget. More than 95% of the dredging is maintenance dredging of existing projects, with the remaining volume for new work, deepening or shore protection projects. Deepening and maintaining the nation's navigation channels by the ACE dredging program benefits the economy of the nation by providing waterways for commerce and recreation, which in turn support a variety of water related industries. Models of grounding risk can play a crucial role in the waterway design process, and ACE will benefit from the ship transit risk project's development of new models for both physical and economic aspects of this risk. In addition, ACE will benefit from the identification of new data collection requirements, both in the waterways and in simulation exercises, that will support improved decisions for waterway safety.

The Coast Guard is tasked by the Ports and Waterways Safety Act (33 USC 1221) with the responsibility of ensuring safe navigation. As such, it is responsible for implementing and maintaining appropriate aids to navigation, for the nationwide distribution of navigation safety information (in the form of notices to mariners), and for the management of navigation safety through such means as traffic separation schemes and possible vessel traffic services (VTS). The effective implementation of VTS and navigation aids requires close cooperation and common use of data between the Coast Guard, NOAA and ACE. According to a study by the Volpe National Transportation Systems Center [18] there was no officially stated, rigorous definition of risk assessment used by the Coast Guard at the time of the study (1994).

> "The term "risk assessment" is used by headquarters and district personnel not as a description of any routine, well-documented system of measurement and analysis but rather as an umbrella term for a variety of seemingly related activities, performed mostly at the district levels that are generally seen to have something to do with safety. This intuitive judgment substitutes for a definition of risk assessment."

Furthermore, the report explains that resource allocation appears to be driven more by political considerations than technical merit.

> "Coast Guard headquarters needs to select waterways projects for funding, in part, on the basis of risk reduction. Yet there is no risk-based resource allocation tool available to compare projects from the many districts in a consistent, objective and defensible manner."

Chapter 3. Short Description Of The Project

The "Transit Risk Project" focuses on the development of models for quantitative assessment of navigational risks entailed by vessels during transits into and out of ports. It is a three year long project that employs historical casualty data to build these models. Our thesis summarizes a good portion of the work performed over the first year of the project. The efforts during this period focused on the modeling of grounding risk at the port level, with special emphasis on the contribution of inaccuracies in navigation charts. Prof. N. M. Patrikalakis from the Design Laboratory of the Ocean Engineering Department at MIT and Dr. H. Kite-Powell from the Marine Policy Center at the Woods Hole Oceanographic Institution are the principal investigators of this project.

Most of the first year was spent collecting, evaluating, and analyzing data on groundings. Relevant data was acquired mainly from the digital archives of agencies such as U.S. Coast Guard, U.S. Army Corps of Engineers, and National Oceanographic and Atmospheric Administration. In addition the process included three on-site trips where formal and informal interviews with stakeholders took place, providing expert opinion, usually not captured in digital archives. The result of this effort was a data set that includes information on both casualties and safe transits, covering the 1981 to 1995 period, for the study areas: Boston, New York and New Jersey, Tampa, Houston/Galveston and San Francisco. These five U.S. ports were selected by the project advisory group on the basis of data availability for explanatory variables and to include a range of environmental and vessel traffic conditions. Two kinds of variables were primarily involved in the selection of the study areas. The first characterized the quality of information on charts while the second described the environmental conditions.

Based on U.S. Coast Guard casualty data and U.S. Army Corps of Engineers transit data, time series of grounding rates were constructed for each port. A number of parameters were examined to assess their contribution to the risk of grounding and thus their potential usefulness in the development of a port-level risk model. Vessel specific information, such as type and size, was found to have considerable effect on risk. Uncertainty in hydrographic surveys, on which nautical charts are based, does not appear to be a significant contributing factor. Wind speed and visibility conditions were found to be useful explanatory parameters. Other factors, such as operator's skill and complexity of the transit are still under investigation through some proxies developed in the absence of directly related data.

The results obtained from first year's efforts are encouraging. They suggest that sufficient data are available for the construction of a meaningful port-level model. Even though the accessible historical grounding data is not complete, the model is expected to provide some explanatory and predictive ability. A detailed description of the sources of information employed for this project follows later in section 7.2. Some recommendations for future data collection to improve the basis for modeling are also provided in section 7.3.

A separate model of economic risk has been developed also as part of the project. The objective of this model is to provide estimates of economic loss associated with the physical risk of grounding for a given region. Work previously performed by the U.S. Coast Guard and others [4] served as the basis for constructing an algorithm that calculates cost estimates for groundings as a function of relevant parameters, including vessel size, nature of cargo and nature of the transit area.

During the second year, the development of the port-level model will continue and a working prototype will be delivered. Meanwhile, the research group has started working on the construction of a larger-scale model of risk within a segment of a single waterway. This model is expected to incorporate results of the port-level analysis, but will mainly investigate local factors, such as specifics of channel design, navigational aids configuration, currents, etc. The economic model is expected to be refined as well, mainly by improving the characterization of internal cost and possibly by including new data for external environmental losses.

In the third year, the project focus is expected to shift to other types of casualties, such as collisions. Experience gained in building the grounding risk model will provide a basis for the development of other, related models.

Chapter 4. Short Discussion On Risk Analysis

The public awareness of technologically induced risks to human life and the environment has grown sharply in recent years while acceptability of accidents has shrunk. Several forces have altered people's perceptions of risks, like the intensified reporting of risks in the media and the growth of a complex, highly technological society. New technology, while having reduced risk substantially in some industries, has also made the systems more intricate and the risk less controllable. The focus is no longer only on safety of life, but also on protection of the environment and natural resources. A demand for higher standard has followed the increase of knowledge and the constantly improving average living-standard [19].

Risk analysis has emerged as one method to assess and manage risks to the society and the private sector due to environmental hazards and its damage to property. Risk analysis is an approach to risk control that includes both the identification of risks to the health and safety of individuals and organizations, and to the environment, and an estimation of the probability and severity of harm associated with them [20]. Risk analysis techniques have been used for many years to manage potential hazards in transportation, occupational safety and manufacturing, and for the development of technologies involving low probability, high consequence risks. These techniques have been described as comprised of three primary components: risk assessment, risk management and risk communication [21]. Risk assessment is the qualitative or quantitative evaluation of the environmental, health, operational or economic risks that may result from some process, activity or event. Operational risks may be assessed by using the frequency of an accident or failure and a measure of the magnitude of the hazardous operation. Risk management is the process of determining whether an identified risk is acceptable, and what action should be taken to mitigate or control that risk. Risk communication includes all purposeful exchanges of information about health, environmental or economic risks between interested parties. Traditionally, the scientific findings and policy judgments from risk assessment have not been mixed with the political, economic, and technical considerations of risk management. However, this separation is becoming more difficult as risk issues and technologies become more complex [22].

It is impossible to eliminate all risks from society. Risk management will always be a choice between different types of risks and a decision of acceptable risk level. There is a distinct difference between “risk” and “uncertainty” [23]. The notion of risk involves both uncertainty and some kind of loss or damage that might be sustained. Also it is of great value to differentiate between the notions of “risk” and “hazard”. Hazard is defined as "a source of danger”, while risk includes the likelihood of conversion of that source into actual occurrence of loss, injury, or some form of damage. For instance, the ocean can be said to be a hazard. The hazard will always exist, but we can safeguard against it by use of a “safe” ship which results in a small risk. If we know about the hazard we can take precautions, hence, the awareness of hazards will reduce the risk. Another property of risk is the relativity of risk. Risk is relative to the observer. If we consider two persons onboard a ship, and one of them knows that there is a hole in the bottom of the ship, this person will claim he is taking a large risk. The other person, unaware of the hole, will say that being onboard the ship is not very risky. To be able to communicate and compare risk fully, risk must be presented as a curve describing the cumulative frequency of maximum damage levels. By also including the probability of the frequency as lower and upper confidence levels, the uncertainty is incorporated as an intrinsic part of the risk curve. Any two rational observers given the same information must calculate the same risk curve and thus agree on the quantification of risk. Thus risk depends upon the evidence at hand, but other than that it is independent of the personality of the user [23]. Also, two alternative risks are not linearly comparable. Risk cannot be spoken of as acceptable or not acceptable in isolation, but only in combination with the costs and benefits that are attendant to that risk.

Knowledge of the uncertainty is important when assessing risk. Uncertainty is essentially the absence of information, information that may or may not be obtainable. Rowe [24] decomposes uncertainty into four cases:

- Temporal: Uncertainty in future and past states,
- Structural: Uncertainty due to complexity,
- Metrical: Uncertainty in measurement, and
- Translational: Uncertainty in explaining uncertain results.

All of these classes occur when investigating risk of ship grounding. Uncertainty in future states is probably the most familiar class of uncertainty. The likelihood of future outcomes is modeled with probability. Differences in the choice of the probability model used contribute to the uncertainty in expressing probability levels. Underlying all probability models based on historical data is the belief that the relationships and behaviors underlying historical events remain valid in the future. Past temporal uncertainty arises from one primary source: failure to measure past state conditions when they occurred in a manner that can be retrieved when needed; that is, failure to record history. Reconstruction of partially recorded or unrecorded history from secondary and other sources involves measurement uncertainty. If one has the complete set of historic information required for a given purpose, there is no past temporal uncertainty. When systems become too complex to deal with all parameters directly, simplification of one or more parameters is necessary, leading to structural uncertainty. The translational uncertainty is due to communication, interpretations and differences in perspectives. An important aspect of quantifying the uncertainty is that information on the major contributors to the uncertainty can be used to guide risk reduction efforts [25].

Risk analysis in the maritime environment is complicated by incomplete, inaccurate, and unavailable data. Safety trends are generally derived from analyses of casualty data. Although casualty data and accident investigations do not necessarily offer a complete picture, they are nevertheless initial and essential resources for assessing risk. They can be used to examine vessel performance, major safety trends, economic cost of casualties, and to a lesser degree, human performance [22]. They frequently provide the only useful safety data for certain ports and waterway systems. Public perception of risk in general is often unrealistic, in part because people lack direct experience with risks. Experts may view hazards as less risky than the public because experts often focus on statistical dimensions of risk, ignoring their emotional dimensions [22]. People respond to the hazards they perceive. If their perceptions are faulty, efforts at public and environmental protection are likely to be misdirected. For some hazards, extensive statistical data are readily available. For example, the frequency and severity of motor vehicles and air traffic accidents are well documented. In the United States there are annually about 50,000 auto fatalities and about 200 commercial airline fatalities. Yet it is clear that in our society there are many more people apprehensive about commercial air travel than about driving in automobiles. One of the reasons for this might be risk aversion for large consequence events.

Research shows that there are several other characteristics that lead people to feel differently about risks for which the product of frequency and consequence are the same. Litai, Lanning and Rasmussen [26] suggested using risk conversion factors (RCF) to compare some of the perceived differences in risks. Slovic, Fischoff and Lichtenstein [19] found that the greater the perceived risk, the greater the desired reduction. They also found that the public seemed willing to accept risks from voluntary activities such as skiing that were roughly a thousand times greater than it would tolerate from involuntarily imposed hazards providing the same level of benefit! Risk perception in the maritime world is no exception to this. The public has strong feelings about oil tanker spills and ferry accidents, while accidents happening onboard Ro/Ro vessels receive less attention.

Chapter 5. Literature Review

5.1 Tanker Spills, Prevention By Design

5.1.1 Introduction

The National Research Council's report "Tanker Spills, Prevention by Design" [28] provided helpful background information. The study was triggered by the grounding of *Exxon Valdez* in Prince William Sound, Alaska. Following a request by the U.S. Coast Guard, a committee was convened under the Marine Board to conduct a comprehensive review. This review focused on the safety, economic and environmental implications of alternative tank vessel designs and was expected to determine how these designs might affect the overall consequences of accidents.

To put things in perspective, the committee makes it clear from the very beginning that the improvement of tank vessel design is only one way to reduce the risk of oil pollution and its consequences. Many other factors influence the risk of accidents, such as the maintenance of the vessel or the operation practice. Further, the report acknowledges that the relative importance of the design in relation to these other factors is open to debate. However, the choice of alternative designs as the focus of the study can be partially attributed to OPA 90, and the concept of double hull equivalent designs.

In the study the term "risk" is defined in the following fashion: "The possibility of suffering harm from a hazard. A hazard is a source of risk and refers to a substance (e.g. crude oil), an event (e.g. an oil spill) that harms the environment, or a natural hazard (e.g. a hurricane)" [28]. Therefore, in the process of "contemplating alternative designs and operations of a tank vessel, one way to approach the definition of risk is to ask the following fundamental questions [28]:

- How can we define a possible tank vessel accident scenario?
- What is the likelihood or frequency of that scenario?
- What will be the magnitude of the resulting spillage in the given scenario?"

5.1.2 Background

Review of the historical records of accidents leads to the conclusion that there is no "typical" scenario that results in pollution. Accidental oil spills constitute 20% of the total pollution from maritime operations and accidents. These accidents may be collisions, groundings, structural failure, fires, explosions, or machinery failure. Even though no single cause has clearly dominated the historical records, there is some evidence of higher frequency in the case of grounding related accidental spills.

Market projections call for up to a 50% increase in U.S. imports of crude oil and petroleum products by the end of the 20th century and thus do not leave much space for optimism in terms of probable oil pollution. The problem becomes worse if one considers that more than 80% of the tankers calling on U.S. ports are foreign flag, and therefore the United States has limited control over their condition. U.S. flag carriers tend to be more expensive than other vessels of similar characteristics operated under foreign flags. They are mainly employed in the Alaska oil route which is subsidized by the U.S. government. Thus, because of the depletion of the Alaskan oil fields, the proportion of U.S. flag carriers is likely to decrease further [28].

According to the statistics compiled for the report, one five-hundredth of one percent of the total amount of oil moving through U.S. waters is spilled. The approximatelly 9,000 tons of crude oil and pertoleum products that are spilled into the sea annually can cause severe damage from enviromental, economic and social perspectives. "The large spills, that is spills of 30 tons or more, comprise less than 3% of the incidents; however, they are responsible for nearly 95% of the total accidental spillage in the U.S. waters" [28].

Following the *Exxon Valdez* accident, the Oil Pollution Act of 1990 (OPA 90) was passed on August 18, mandating double hulls for tankers traveling in U.S. waters. Nevertheless, in Title IV, Sec. 4115 of the Act, some space for double hull equivalent alternatives was provided. The section states "... the Secretary [of the Department of Transportation] shall determine, based on the recommendations of the National Academy of Sciences or other qualified organizations, whether other structural and operational tank vessel requirements will provide protection to the marine environment equal to or greater than that provided by double hulls ..."[28]. However, evaluating the equivalence of any two designs is not a trivial process. There are no generally accepted criteria to be used for the evaluation. The results of any such analysis of the performance of tank vessels depends on the assumptions and the particular accident scenario analyzed. Different designs may perform better in some situations and worse in others.

5.1.3 Approach And Findings

The report indicates that no single design among the ones reviewed is superior for all accident scenarios. Therefore the mandate for double hulls imposed by OPA 90 should be viewed as only an interim step to reducing oil spills. More work remains to be done [28].

Improvements in the design process of sea going vessels have resulted in the production of so called "efficient" structures. The main characteristic of these structures is reduced allowance for errors, unknowns and deterioration to a significant degree. Consequently what were once secondary concerns can become critical. Modern tank vessels are less robust than those built some decades ago. The committee believes that the structure standards set by the classification societies are no longer adequate. They "should be strengthened to ensure proper (1) protection against corrosion taking into consideration the fact that the surfaces that need protection in a double hull vessel are nearly three times as large as those in a single skin vessel; (2) dimensioning of the structural members; and (3) use of high-tensile steel" [28]. The timely implementation of these changes could be achieved by the coordinated action of the U.S. Coast Guard (USCG), the International Maritime Organization (IMO), and the classification societies. Additionally, these and possibly other internationally accredited organizations should start considering designs based on the possibility of accidents, a practice that is common in other industries [28].

"The paucity of data on tank vessel accidents and oil outflows, gaps in knowledge concerning vessel structural behavior during accidents, and uncertainties concerning the quantification of environmental benefits resulting from design improvements" [28] constitute another major problem. The information available was judged by the committee as inadequate to support a serious decision making process. The only alternative was to make any but the most primitive conclusions subject to conditional scenarios, assumptions and judgment ranging from the informed to the intuitive [28].

In spite of the scarcity of data, the committee was able to draw some conclusions. "The facts adequately supported the following:

- Double hull vessels in low energy (typically low-velocity) accidents should not pollute.
- Vessels that carry cargo in contact with a single skin are expected to cause some pollution in the accident that will result in cargo tank penetration. However, it is possible through certain design alternatives to minimize the amount of pollution, in a scenario specific manner.
- The data available shows that high-energy accidents nearly always result in pollution. The relative advantage of various design alternatives in reducing pollution from particular scenarios are highly dependent on the assumptions made in the scenarios.
- The endemic lack of data and knowledge could be addressed by a comprehensive research effort. Once that has happened it will shift the decision making process to a more factual basis, away from the only current alternative, the informed opinion.

Until the gaps in understanding are filled, all other findings, by the committee or any analyst, will be influenced by numerous variables including personal judgment" [28].

Based on the available data, the committee performed calculations on the "potential savings resulting from the full implementation of OPA 90 over the period of 25 years. According to these calculations it is expected that double hulls, in the absence of other risk reduction measures, could save about 3,000 to 5,000 tons of oil spillage per year in U.S. waters from collisions and groundings. The savings represent roughly half of the current average annual spillage from vessel accidents in U.S. waters. The added transport cost would be more than $700 million a year, or on the order of one cent per gallon transported" [28]. Based on cost-effectiveness, the double hull approach resulted in one of the best values among the designs evaluated by the committee.

It is should be noted that the above conclusions are valid on the assumption that the inner skin of the double hull is not breached in case of collision, or grounding. This assumption can be considered close to reality if sufficient space is provided between the inner and outer hulls. Additionally, the outer hull should be strong enough to absorb an adequate amount of the energy released during the accident and minimize the amount that will be transferred to the inner hull. The latter prompts for establishment of minimum thickness criteria for the outer plates. Until a scientifically supported answer is available, the minimum thickness should be no less than that of the outer plate of a single hull vessel. However, further research is also required to determine the spacing between the two hulls, so that all concerns will be satisfied, mainly related to salvage and personnel hazard [28].

"A total of seventeen design concepts, as well as three combination concepts, were evaluated by the committee" [28]. Fewer than half of them received a complete evaluation, in terms of technical considerations, outflow performance and cost. These designs were:

- Double bottom
- Double side
- Double hull
- Hydrostatic balanced loading (hydrostatic control)
- Smaller cargo tanks
- Intermediate oil-tight deck with double sides
- Double sides with hydrostatic control
- Double hull with hydrostatic control

The conclusion reached by the committee was that no one of the evaluated designs proved to be superior to a double hull for all accident scenarios. In general, the members of the committee agreed that different designs seem to perform better in some situations and worse in others, as mentioned earlier.

One of the committee's considerations was to add an operational feature, hydrostatic control, to various structural arrangements of new tank vessels. This feature uses the hydrostatic pressure developed within a shielded cargo tank to reduce or even prevent oil outflow in the case of bottom damage. The structural arrangements considered for this purpose were double hull, double sides, and conventional single hull designs. The conclusion of the effort was that none of the combinations was found to be as desirable as the double hull. The primary reasons that lead the committee not to support these alternatives were:

- "The effectiveness of hydrostatic control depends on the operator's strict adherence to the rules, and not on any permanent feature of the vessel's design and construction.
- Hydrostatic control does not provide complete protection against oil outflow, due to tidal variations or wave action following the grounding" [28].

Another approach that also employs a hydrostatic principle was considered as it exhibited some theoretical interest. The use of an intermediate oil-tight deck with double sides could result in less spillage, should a high-energy grounding or collision take place. Despite its apparent advantage over double hulls, the most important disadvantage of this approach is its increased operational complexity with respect to loading, unloading and preparation for docking. After weighing the pros and cons of the intermediate oil-tight deck with double sides design, the committee was split in two groups. One considered the design as practical and innovative, one that could be treated as equivalent to double hulls under OPA 90 requirements. The other group, after considering the gap between the theoretical concept and practical application, held the judgment that the implementation was not adequately proven. The second group suggested that further research should be performed before it can be treated as equivalent to double hulls in terms of OPA 90.

Any of the design options considered by the committee would add roughly one to two cents per gallon to the cost of oil transported, if fully implemented in U.S. waters. This might reflect a similar increase in the cost of gasoline and other products. Depending on the design that will be finally chosen in this hypothetical scenario, the amount of the total annual costs incurred will be somewhere between $340 million and roughly $2 billion [28].

The committee therefore suggested that other design alternatives should be proposed and investigated by the authorities in the course of future research. Finally, regardless of the designs that will be finally selected as the optimal solution, certain features should be standard on all new tank vessels. Towing fittings should be mounted on the bow and the stern of all tankers and barges. Such a feature will facilitate the towing of a vessel if that should be necessary after an accident or power failure. Moreover, all new tankers should have a reliable onboard system for transferring cargo from a damaged tank to another intact tank or another vessel. According to the committee, practical concepts have been developed for this purpose utilizing available equipment. It was also acknowledged that this feature may be less applicable to barges as they are unmanned. "IMO and the USCG should prohibit the placement of cargo piping in ballast tanks, to reduce the danger of fire and explosion due to hydrocarbon vapor leakage" [28]. Finally the committee admitted that the passive vacuum system, for use on fully loaded cargo vessels, deserves further research and development.

In general, there are fewer available options for providing pollution-resistant designs for barges. Barges are unmanned vessels; and the crew on board the attendant tug is limited. Therefore, the available personnel is not enough for dedicated presence and not skilled enough for introduction of operational control solutions, such as the hydrostatic balance loading [28]. At the same time, towed barges are less maneuverable than self-propelled ships and hence more damage prone. Therefore physical structural barriers for secondary containment, such as double hulls, double sides or double bottoms, are expected to be more reliable for barge applications. In this respect, the intermediate oil-tight deck might be a suitable solution for barges. But carefully controlled loading and discharge practice will be required.

As mentioned earlier, designs that incorporate large void spaces such as double bottoms, sides and hulls, have caused considerable controversy. In an effort to resolve this controversy, the committee attempted to provide some useful insight for the evaluation of related concerns. The increased risk of fire and explosion, possible vessel instability after an accident, perceived salvage difficulties, and the increased risk for personnel hazards were reviewed by the committee as the most important of these concerns.

Void spaces involve risk of fire and explosion because of the potential accumulation of hydrocarbon vapors. There is a possibility that such vapors can enter the void space through cracks or pits in the bulkheads of adjoining cargo tanks or through defects in the cargo piping system. However, there is no reliable evidence of an increased number of fires and explosions in existing double bottom or double hull ships. Despite the lack of reliable evidence, the risk cannot be ignored, and planned maintenance and thorough inspection of the void spaces are critical. This is most certainly true in the case of double hull crude oil carriers. Diligence will be needed to monitor corrosion from the cargo tank side as well as the ballast tank side, especially in horizontal surfaces [28].

Another problem of void spaces is that a potential damage may result in their flooding. This is important especially for double hull vessels. Should the flooding happen, instability problems may occur due to the additional and "misplaced" weight. The committee believes "that the criteria for evaluating the damage stability of double hull tank vessels should be tightened to assure that their damage stability approaches that of conventional single skin MARPOL tankers" [28].

Salvage concerns are only partially supported. These issues are related to the possibility of heeling or even sinkage of the loaded ship. However, the existence of void spaces may or may not be a problem, depending on whether the vessel remains firmly stranded following the initial grounding. After reviewing the available evidence, the committee reached the conclusion "that these concerns should not limit the use of properly designed double hull vessels" [28].

The increased risk of personnel hazards is not only related to the double hull vessels. It has been argued that some design features may increase the hazards to the crew during normal operation. However, there is insufficient evidence to judge the degree of personnel risk associated with various designs. The committee believes that these concerns do not represent unmanageable risks in any of the designs considered. Rather, they "constitute important factors that will demand continuing vigilance on the part of ship operators" [28].

Even though the double hull solution mandated by OPA 90 seems to point towards a promising direction, it should be viewed only as an intermediate step. In the meantime, since the phase out of single hull tank vessels trading to U.S. coastal ports is expected to be complete by 2015, some attention should be given to the improvement of pollution control measures for the fleet of existing tankers. As a starting point, serious consideration should be given to the requirement that all existing crude oil tankers should promptly meet the latest IMO provisions for pollution prevention for new tankers (MARPOL). Of these provisions, the segregated ballast tanks, crude oil washing and possibly protective location of ballast tanks, are considered to be the most significant. Furthermore the committee urged prompt evaluation of a multifaceted program to improve pollution control for existing vessels [28].

Another possibility is the introduction of hydrostatic control, which could be implemented immediately without structural overhaul. It was acknowledged, however, that additional research is needed to determine the optimal method of achieving hydrostatic control. Moreover, the design and condition of each vessel would have to be checked, and all the bulkheads should be inspected, to ensure sufficient strength to withstand the added liquid cargo sloshing. Also it should be pointed out that leakage from a hydrostatically loaded tank vessel following a grounding may be exacerbated by wave action, current, falling tide, or vessel's heel and trim. Implementation of this concept for the entire tank vessel fleet serving the United States would increase the number of vessels operating in U.S. waters. The increase would be the result of reduction of the available cargo space due to the use of the hydrostatic control. As a consequence, a potential increase of the number of accidents may be observed. Furthermore, the cost of this measure could be substantial and warrants further study. The passive vacuum system might be another alternative, depending on the results of further testing.

Retrofitting of double hulls in existing tank vessels should be considered as well. However, there is a chance that the combination of old and new structural members may result in difficulties. Retrofitting would be more expensive than hydrostatic control. Fewer technical difficulties may be entailed by replacing the entire ship forward of the machinery room, and shipyard time would be less. The committee, however, is concerned that the cost of this alternative may turn out to be much higher than retrofitting [28].

The potential costs and benefits of an extensive program for the enhancement of the safety of existing vessels against oil pollution are difficult to estimate. Yet such a program might expedite the construction of new vessels with double hulls. For instance, "the implementation of hydrostatic control on existing vessels would reduce cargo capacity on the order of 15 to 20%. If all existing vessel had been built at present costs, the limited data available to the committee indicated that reducing cargo capacity to accommodate hydrostatic loading (assuming that it is implemented immediately) would cost about $1.1 billion per year, while saving 3,700 to 4,300 tons of oil spilled annually. Existing vessels were built over many years at a wide range of costs, so the total cost could be considerably less than the dollar amount stated above. The actual impact on ship rates would be influenced by the relationship between vessel supply and demand. If the number of existing vessels was sufficient to meet the cargo capacity shortfall, then the cost would increase until new vessels were built" [28].

"This simplified model does not consider the additional person-hours that will be required to monitor and enforce the hydrostatic control, nor the increased vessel traffic that would result from carrying less cargo per vessel" [28]. Moreover, the benefits realized by such a program would be diminished as new vessels replace the existing fleet. In sum, the type of program that will address the issue of enhancing pollution control for existing ships needs further consideration because of its potential environmental benefits. Common ground to all the possible alternative forms of such a program should be to avoid encouraging retention of older vessels. Of course other measures, not design related, may turn out to provide the same benefits at a certain cost which may be more or less than the design based alternatives [7]. Approaches, such as crew training, electronic charts and vessel traffic systems were outside of the scope of this committee's study and therefore were not judged.

The closing chapter of the study discusses the need for further research. According to the committee, "the U.S. federal government, industry and academia should cooperate in a coordinated, substantive research effort that will be directed to:

- performing a comprehensive risk-assessment study that would lead to establishment of future risk-based design goals for tank vessels with attendant compliance guidance.
- accomplishing the basic research needs noted throughout the study.
- testing and evaluation of design concepts, including theoretical analysis, model tests, and field tests.
- advancing the capability to assess and value natural resource damages.
- achieving optimal pollution control by integrating use of design alternatives with operational considerations" [28].

The ideas introduced in the report aim to a "spill-free" tanker, a research interest of many foreign countries. Therefore, national research programs authorized under OPA 90 should be coordinated with those of foreign research centers, notably in Norway and Japan, and of course the effort of IMO. Such a comprehensive research effort is acknowledged by the committee as essential if important, far-reaching decisions concerning the future of oil transportation by tankers are to be made on the basis of fact, as contrasted to the present practice that is based on informed opinion.

5.2 Minding The Helm, Marine Navigation And Piloting

5.2.1 Introduction

Minding the Helm provides an overview of the marine transportation system and an essential foundation for understanding the role of government, pilot associations and pilot administrators, marine transportation companies, port authorities, and other organizations concerned with vessel operations [21]. The study was conducted by the Committee on

Advances in Navigation and Piloting, under the auspices of the Marine Board of the Commission on Engineering and Technical Systems of the National Research Council, for the U.S. Coast Guard (USCG). The USCG requested a comprehensive assessment of the state of practice of ship navigation and piloting, and recommendations to improve it. In requesting the study, the agency indicated that the examination should address waterways management, marine pilotage, application of navigational technologies, and the interaction of oceangoing ships with other commercial traffic in the nation's ports and waterways.

> "The committee was asked to (1) conduct a multidisciplinary assessment of the state of practice of ship navigation and piloting in the United States, with emphasis on navigation while entering and leaving ports; (2) identify advances in public policies, planning guidance, operational procedures, standards, training, and innovative technologies that have potential to improve safety and overall effectiveness of the marine navigation and piloting system; and (3) to make recommendations on research and development and on the role of government at all levels in advancing innovative applications of technology to improve ship navigation and piloting. The committee was to examine how changes in vessel systems, waterway systems, and human performance affect the basic navigation and piloting requirements in the port and on the vessel, to establish an improved technical basis for managing change in a competitive environment, and to improve navigation safety. Included in the scope of study were:
>
> - the changing character of vessel traffic (vessel types, vessel sizes, traffic density, port configuration and operation),
> - the changing state of practice of vessel navigation and piloting, including technology advances and their implications,
> - the changing roles of vessel's master, officers, and crew (bridge complement), marine pilots, and shore-based traffic safety personnel,
> - the effect of changes in technology on training, licensing, and performance,
> - how changes in technology affect administration of marine navigation and piloting,
> - the government role in oversight and operation of marine navigation and piloting system." [21]

The report acknowledges that public attention has opened a window for reasonable and positive changes in the marine navigation and piloting system, and that system improvements need to be carefully crafted and implemented to avoid unintended side effects. As a basis, "the study accepts and endorses the traditional concept that pilots are local experts in whom special trust and confidence are placed for the safe navigation of the vessels they serve. Those whom society officially recognized as pilots have a long history of dedicated and expert service to uphold. By long-standing maritime tradition, they are held to high standards of professional competence and official accountability" [21]. The Committee's recommendations expand on this fundamental view by prescribing a strategy for reducing operational and environmental risk and for improving safety performance, thereby enhancing public confidence in the marine navigation and piloting system and its pilotage component.

The report concludes that system organization, operation, and overall performance can be substantially improved to reduce operational risk by focusing more on the interactions among system components. "The marine navigation and piloting system is characterized by large disparities in its administration and standards of performance and by limitations in safety data that constrain informed oversight. The system is also characterized by considerable polarization over safety, economic, and jurisdictional issues that have prevented resolution of conflicts over marine pilotage and inhibited system-wide regulation of vessel traffic" [21]. In particular, specific improvements were recommended in system organization and integration, human systems, marine pilotage, waterways management, navigation and piloting technology, and marine research and development.

5.2.2 Background

The reason for conducting this study was to eliminate uncertainty and confusion about the quality of marine navigation and piloting. The background was that navigation and piloting had been mentioned as contributing factors to several recent, well publicized shipping disasters. Shiphandling, positioning, work practices, and communication in piloting waters had all been identified as key factors in these accidents. This called into question the professional qualifications of merchant mariners and marine pilots, and the effectiveness of marine navigation technology, shipboard navigation and piloting, and safety oversight. Also questioned were the programs and policies that led to equipment requirements, skill development programs, licensing regimes, and manning and pilotage laws. Safety concerns were accentuated by the large size of modern ships and barges transporting petroleum or other hazardous cargoes. Cargo volume had increased the scale of other hazards to life, property, and the environment that could result from just one catastrophic marine transportation accident. Based on this, "the National Transportation Safety Board continually called for revision of federal pilotage laws to place all pilots under Coast Guard discipline, a move opposed by the states and state-licensed pilots" [21]. At the same time, the federal government and several states had enacted laws greatly increasing the economic cost to polluters of oil pollution incidents.

According to the study, the development of a suitable program to improve safety, which includes the application of advanced technologies, was complicated by a lack of cohesion and wide variations within the marine navigation and piloting system. These variations occurred in terms of port, waterway, and river operating environments; vessel types, equipment, operating characteristics, loading, and manning; and professional qualifications. Interactions among these factors resulted in safety problems that defied a simple solution. Pinpointing opportunities for improving safety required careful consideration of risk, navigation and piloting practices, navigation technology, human systems, and public policy, as well as of the difficulty of providing the value and reliability of innovative practices and technologies in practical application. The system needed to be examined holistically, because a change in any aspect - training, manning, marine pilotage, systems maintenance, port and waterway operating environments, economics, government policies, and traditional approaches to navigation - could affect the performance of the entire marine navigation and piloting system and the value of innovative solutions and technologies to improve safety.

5.2.3 Approach and findings

> "The report focuses on the role of marine navigation and piloting in minimizing the number of accidents. It examines what can be done to reduce operational, economic, and environmental risks through improvements to navigation and piloting technology and practices in the nation's ports and waterways and their coastal approaches" [21].

The study recognizes that marine navigation and piloting involve complex, interdependent operations in a large sociotechnical system that encompasses waterways, vessels, navigation aids, and human operators. System elements are supported by an infrastructure for vessel and port management, pilotage, pilotage regulation, and professional development. The operating environment in which marine navigation occurs is characterized by extreme reliance on human performance, considerable diversity in geographic and hydrographic features, and great variability in operating conditions.

National and international authorities continually work to improve safety in marine transportation. The Committee agreed that improvements have been made in vessel design and construction, navigational aids, watch keeping guidelines, professional training, and marine traffic regulation. Some of these advances have been voluntarily implemented by some operating companies either to reduce perceived operational and environmental risks or to improve economic performance. However, "despite continuing efforts to improve operational safety, major shipping accidents involving all categories of commercial vessels have continued to occur, some with great spillage of oil. Most of these accidents were attributed to human causes rather than purely mechanical, environmental, or other causes. Public attention to safety in shipping has intensified, driven in part by major marine accidents resulting in oil pollution in ecologically sensitive areas" [21].

The Committee found that the marine navigation and piloting system was for the most part "safe", but that it could be made safer. The main arguments for this included (1) the potential consequences and costs of vessel accidents, (2) the accountability of carriers and mariners, and (3) the need to bring substandard ships up to acceptable operating conditions. It also believed that the marine navigation and piloting system could be enhanced substantially through specific improvements in marine pilotage and waterways management, as well as through maritime research and development, all of which would improve the safety performance of human systems. In particular, the Committee mentioned the need to address requirements and standards for pilotage of vessels, pilot development, and pilotage administration across the nation. Constructive changes in each of these areas, designed to reduce operational and environmental risk, would ensure full public confidence in pilotage. Strong action by federal and, in case of pilotage, state-level authorities would improve:

- the capability to determine and correct systemic problems underlying causal factors in marine accidents
- the organizational structure for interdependent decision making through measures that include application of vessel traffic services and other technological aids to marine traffic regulation
- the quality, integrity, and consistency of pilot development programs and associated marine licensing
- the accountability of pilotage systems and individual pilots, by closing gaps in official oversight and other measures, and
- the introduction and use of advanced navigation technologies.

The report recommended immediate action by all pilotage authorities to strengthen the existing federal and state pilotage requirements within their jurisdictions. It also recommended fundamental change in the federal and state pilotage systems that would ultimately lead to a single pilotage system, encompassing both federal and state elements, for each local pilotage region. Attention to human performance, new technology, and vessel traffic services (VTS) was viewed as fundamental to improving safety in marine navigation and piloting. The following sections provide a summary of the report's findings and recommendation.

Risk in the marine operating environment

Finding:

The committee found that marine safety authorities have failed to decide on what are acceptable levels of operational risk. Acceptable levels of risk are usually determined subjectively and vary widely among localities since risk factors are numerous and complex and their interactive effects are poorly understood. There are also substantial differences in operational risk and exposure among vessels, even within the same port and waterways complex, because of the complexity of the marine operating environment. Improved safety depends on understanding and effectively addressing these risk factors. Solutions that reduce risk in one operating environment may not achieve equivalent results in another. In fact, inappropriately applied solutions can increase risk. Consequently, system-wide remedies to problems identified in marine navigation and piloting need to look beyond intended effects in order to identify and address the broader array of effects that might also result from the proposed solution.

Recommendation:

> "Coast Guard should review and improve its capability to collect, analyze, and publish marine safety data on casualties, accidents, incidents, and near misses so that comprehensive safety performance data are available to guide improvements in marine navigation and piloting" [21].

Human systems

Finding:

The committee found human error to be a major causal factor in marine accidents. Hence, effective countermeasures must focus on areas in which human actions are paramount: navigation and piloting. By combining improvements in professional development, the organizational structure for decision making and technology, human performance can be improved. There is no systematic re-certification or professional monitoring that can detect or prevent substandard performance in pilotage. Deficiencies in pilot knowledge and skills are often identified only after a maritime casualty occurs. Official oversight of practical skill development is lacking in the federal marine licensing regime for masters, mates, and pilots. Although advanced navigation and vessel control technology may provide improved means to navigate and maneuver in pilot waters, training in using a new technology often lags behind its introduction aboard ships. There is a distinct potential for technology assisted marine accidents as navigators attempt to become familiar with advanced technologies on the job.

Recommendation:

> "Training programs should be developed concurrently with the introduction of new technology, and mariners should be trained in the use of this technology. Mariners should also be appraised of changes in roles, functions, and organizations that can result from introduction of this technology." [21]

Marine pilotage

Finding:

The study found effective piloting to be essential for navigational and environmental safety. A pilot provides expert knowledge about local operating conditions and local procedures in the pilotage area for which the pilot is licensed. There is an urgent need in pilotage for consistent application of high professional standards in every pilotage area as a defense against substantial variability in master and bridge team qualifications of foreign-flag ships.

Recommendation:

> "Nationally accepted professional and administrative standards and guidelines should be established without delay for all elements of existing pilotage systems. These elements include the professional development, licensing, and administration of pilots and pilotage with regard to pilot training, qualifications, pilotage boards, casualty investigation, discipline, and vessel pilotage requirements." [21]

Waterways Management

Finding:

There is evidence that the number of substandard foreign flag vessels (with respect to maintenance, bridge team composition and professional qualifications, and navigation and safety equipment) visiting U.S. ports is growing. These conditions increase the risk to life, property, and the environment. International efforts to counter substandard conditions rely on enforcement of international protocols by flag-states and port states. The United States has the option to enhance this effort by exercising its port state prerogatives strongly, including use of new port state authority for the inspection of crews that is being promulgated by the International Maritime Organization.

Recommendation:

> "The Coast Guard should continue to augment its effort to identify substandard vessels and take whatever action necessary to enforce compliance with applicable international guidelines and U.S. requirements" [21].

Navigation and piloting technology

Finding:

The study found innovations in navigation technology to hold significant potential for reducing operational risk and improving safety performance. Electronic charting systems are rapidly being introduced for marine use and will be an essential part of integrated bridge systems. Electronic charting systems have the potential to improve navigational safety and to significantly reduce operational risk through the accurate and instantaneous display of a vessel's position. The best available technical means for enhancing safety appears to be a combination of Differential Global Positioning System (DGPS) technology and electronic charting systems. This technology can provide instantaneous and accurate positions, steering guidance, automatic hazard warnings, and a permanent navigation record.

Recommendation:

> "The CG should strongly encourage the development and updating of international technical and performance criteria and corresponding national standards and criteria for advanced navigation systems. The introduction of electronic charting and precision navigation systems suitable as onboard aids to enhance navigation safety should occur as soon as practical, consistent with the application for which this technology is appropriate and with the development of the supporting infrastructure that is necessary to enable its effective use." [21]

Traditional Aids to Navigation

Finding:

Traditional aids to navigation will continue to play a central role in the future. The committee found that navigators continue to rely heavily on traditional short-range aids to navigation, principally buoys and ranges. The usefulness of these aids is compromised during heavy sea conditions and low visibility. The problem is being addressed by Coast Guard efforts to improve visibility of these aids and to advance the development and use of DGPS.

Recommendation:

> "The Coast Guard should maintain and enhance short-range aids to navigation that support traditional and evolving navigational technologies and should continue efforts to improve visual and electronic acquisition of buoys during unfavorable operating conditions. The feasibility of electronic ranges and distance measuring equipment for specialized local use should be examined." [21]

Minding the Helm provides a broad overview of the marine transportation system. The report contains a great deal of valuable information on the process of navigation and piloting. Chapters 1 and 4 of the report are especially important to our study of ship transit risk. Chapter 1 introduces issues in waterways management, marine pilotage, and navigation technology, and describes the marine navigation and piloting system. It also describes changes affecting marine transportation, the controversy over pilotage and safety performance, and the need for assessing navigation and piloting. Chapter 4 describes risk, risk-assessment methodologies, and risk assessment in marine transportation. It also characterizes and discusses risk and safety performance factors in piloting waters, the operating environment, and the complexity of vessel maneuvering behavior. The chapter provides a safety performance analysis and offers options for improving risk and safety assessment in marine transportation.

5.3 The Port Needs Study

5.3.1 Introduction

The purpose of the Port Needs Study was to document the costs and benefits of potential U.S. Coast Guard Vessel Traffic Services (VTS) in selected U.S. deep water ports on the Atlantic, Gulf and Pacific coasts [4]. The U.S. Department of Transportation Research and Special Programs Administrations (RSPA) Volpe National Transportation Systems Center (VNTSC) conducted the study for the U.S. Coast Guard, Office of Navigation Safety and Waterway Services, Special Projects Staff. The study was initiated at VNTSC in February 1990, prior to the passage of "The Oil Pollution Act of 1990", and was to evaluate the following:

- The nature, volume, and frequency of vessel traffic,
- The risks of collisions, spills, and damages associated with that traffic,
- The impact of installation, expansion, or improvement of a VTS system, and
- All other relevant costs and data.

The study was finished by August 1991 and satisfied all the relevant requirements of the Oil Pollution Act. The study is a comprehensive four volume report containing a considerable amount of valuable information on exposure to risk, operating environments, VTS technologies, VTS effectiveness, and costs and benefits. Coast Guard casualty records were used as the exclusive accident data set. Near miss and port incident data were not used. The general statistical method used by the Volpe Center was a multivariate regression model based on a similar methodology used in a Canadian study [29].

The report analyzed historical vessel casualties and their consequences, and potential future navigational risk in 23 study zones. It used a cost-benefit approach and measured *navigational risk* in terms of probabilities of vessel collisions, rammings, or groundings, and the human and environmental consequences and economic losses that attend vessel casualties. The 23 study zones encompassed 82 deep draft ports and their respective approaches. These ports loaded and unloaded over 80% of the U.S. total international and domestic cargo vessel tonnage at the time of the study. It was estimated that approximately 64% of the 1979-89 vessel casualties in U.S. waters that were potentially VTS addressable occurred within the 23 zones. The study examined each zone for waterway navigational characteristics and traffic patterns. It analyzed the historical VTS addressable vessel casualties and quantified significant navigational risk factors to enhance the estimation of future vessel casualties. A navigational risk model was developed and applied to estimate the potential future avoidable vessel casualties in each of the 23 zones. VTS benefits were defined as avoided vessel casualties and associated consequences, which were measured in physical units and assigned monetary values. VTS costs were defined as the initial federal investment for a state of the art VTS system in each study zone and its annual operating and maintenance costs (1996 - 2010).

5.3.2 Background

The Exxon Valdez spill in March of 1989 and three other vessel casualties involving crude oil just months later prompted Congress to task the U.S. Coast Guard to evaluate the need for VTS in several major U.S. ports and waterways. The PNS study was part of the response to that request and is based on four prior VTS studies. In particular, it builds on the foundation of the "Vessel Traffic Services" study performed by The Canadian Ministry of Supply and Services, Bureau of Management Consulting in 1988 [29]. The *Port Needs Study* was the first comprehensive study that estimated vessel casualties on the basis of a navigational risk model developed from regression analysis of aggregate historical casualties and related navigational risk factors. It included the most exhaustive analysis to date of the commercial and environmental impacts of hazardous commodity spills and, according to the authors, was the most comprehensive quantitative analysis to date performed in the subject area.

5.3.3 Approach

The study was completed the following way:

1. Study zones and sub-zones were defined,
2. Historical vessel casualties were analyzed,
3. Future vessel casualties were forecast,
4. Avoidable consequences in each study zone, associated physical losses, and the dollar values of those avoidable losses were estimated,

5. The cost of a state-of-the-art candidate VTS design for each study zone was estimated,
6. The benefits and costs among the 23 study zones were compared, and
7. The sensitivity of the relative benefits among the study zones to a range of uncertainty in key input variables was analyzed.

The study zones were selected based on historical accident rates and criteria consistent with IMO guidelines. These guidelines state that VTS is "particularly appropriate in the approaches to a port, in its access channels and in areas having one or more of the following characteristics: high traffic density, traffic carrying noxious or dangerous cargoes, navigational difficulties, narrow channels, and environmental sensitivity" [4]. Each study zone incorporated at least one major port, at least one major navigational challenge and at least one environmentally sensitive area. Since each specific waterway has its own unique navigational character, the study further subdivided each study zone into two or more sub-zones based upon a generic definition of sub-zone types. Each sub-zone type characterized the common navigational attributes of the waterways in the study zones. The approach allowed a comparison among study zones based upon a commonality of navigational characteristics of sub-zones contained within each zone. The classification of the sub-zones was based on the physical and hydrographic characteristics of the waterways in question with some attention given to traffic patterns, volume and type. The six sub-zone types were as follows:

1. Open approach,
2. Convergence,
3. Open harbor and bay,
4. Enclosed harbor
5. Constricted waterway, and
6. River.

Historical vessel casualties were analyzed to develop an understanding of the causes, circumstances and consequences of vessel casualties, and to aid in modeling navigation risk and estimating the reduction in casualties which would result from the operation of a VTS system. 36,000 vessel casualty records from the USCG central file were the primary data for the report. These records represented vessel casualties from within the 23 study zones for the period 1979 to 1989. Of these 36,000 casualties, 2,210 were selected as "VTS addressable". These were casualties that might have been prevented by a Coast Guard VTS system, involving the following situations:

- Open water collisions between two vessels caused by surprise, poor visibility, severe weather, or bridge team errors,
- Certain overtaking situations,
- Casualties at dredging operations or at similar work activities in a channel,
- Some casualties involving vessel at anchorage, and
- Collision when vessels enters a congested channel or waterway directly from the pier, dock, or anchorage.

Those vessel casualty records deemed not "VTS addressable" included those situations involving mechanical failures, fire or explosions, non-participating vessels (i.e. fishing boats, or those less than 20 meters in length), casualties outside VTS range of surveillance, groundings or collisions in close quarter situations such as docking, undocking, or maneuvering in a crowded anchorage, and incidents which occurred with insufficient warning or lead time. Six primary data sources were used in this study:

- USCG's Casualty Maintenance Database records (CASMAIN),
- USCG's Personnel Casualty Database (PCAS, linked to CASMAIN)
- USCG's Marine Pollution Retrieval System (MPRS),
- the pollution segment of USCG's Marine Safety Information System (MSIS),
- National Transportation Safety Board reports, and
- confirmation with Coast Guard offices in the study zones.

The study measured *navigational risk* as the probable number of "VTS addressable" vessel casualties per hundred thousand *future vessel transits*. Vessel transits were measured by vessel type and size moving within each of the 99 sub-zones. To forecast traffic for the period 1996 - 2010, the study applied growth rates to the base period vessel traffic patterns in proportion to the growth in tonnage of commodities shipped and received by the deep water ports. Consideration was given to changes in vessel sizes through the study period. Using the navigational risk measure, the report developed national average vessel casualty rates for "VTS addressable" vessel casualties, estimated by vessel type and casualty type. Historical casualty rates for the sub-zones with operating VTS services were adjusted upward to account for the "beneficial" effects of existing systems. These casualty rates were then aggregated across all sub-zones and divided by the appropriate vessel transits to develop *national average vessel casualty rates* by casualty type, vessel type, and vessel size. Vessel casualty probabilities for each of the 99 study sub-zones were developed by using the national average casualty rates, modified by sub-zone risk adjustment factors. These sub-zone adjustment factors were generated by multiple regression analysis of statistically significant navigational variables common to all sub-zones. Variables such as meteorological and hydrographic conditions, waterway configuration such as channel width and depth, and vessel traffic density in each of the sub-zones were explored to test the relative contribution of each variable to the overall navigational risk in that specific sub-zone. Sub-zone probabilities of casualties by casualty type, vessel type, and vessel size were then estimated by multiplying the national average vessel casualty rates by the sub-zone risk adjustment factors [22].

The benefit of VTS were measured as the *avoided consequences* associated with the avoided vessel casualties. To estimate the avoided vessel casualties for each study zone, the study applied VTS effectiveness factors to the projected vessel casualties under the NO-VTS case. The avoided consequences were then measured by subsequently applying conditional probabilities to the avoided vessel casualties. The benefits (avoided consequences) considered included:

- Vessel damage,

- Human deaths and injuries,
- Emergency response,
- Bridge damage
- Cargo damage and loss,
- Navigational aid damage,
- LNG and LPG explosions, and
- Hazardous commodity spills.

Hazardous commodity spills in turn were responsible for specific sub-categories of loss:

- Marine mammal and bird losses,
- Commercial fish species losses,
- Spill assessment costs,
- Spill cleanup costs,
- Recreation and tourism losses, and property value loss.

The total risk assessment process yielded the total expected number of avoided casualties by casualty type, vessel type and size, and the associated avoided losses by loss type, and their respective monetary values in each study sub-zone. Since the study involved a large number of individual input estimates, derived from data of varying scope and quality, and a number of imperfect assumptions, the sensitivity of the final results was tested to uncertainty in the key input variables.

5.3.4 Findings

The findings of the study were divided into a variety of topical areas as the list of benefits above, and aggregate findings summarizing best sites for maximized VTS cost-benefit ratios were presented.

Avoided vessel casualties. The candidate VTS designs for the 23 study zones were projected to avoid a total of 980 vessel casualties during the period 1996 - 2010. That represented a 29% decrease compared to vessel casualties projected without any VTS. The ports which would benefit the most from VTS presence with respect to avoided vessel casualties included New Orleans (375 casualties prevented, 56% involving barge tows), Port Arthur (75 prevented), New York (73) and Pudget Sound (60).

Avoided human injuries and deaths. If all 23 candidate VTS designs were implemented, a total of 138 injuries and 31 human fatalities were forecast to be avoided during the fifteen year period. New Orleans would benefit the most with 50 avoided deaths and injuries, followed by Puget Sound with 33 and New York with 14 avoided deaths and injuries.

Avoided hazardous commodity spills. A total of 100 hazardous commodity spills of all sizes were forecast to be avoided during the fifteen year period. This included bulk cargo spills from tankers and tank barges, and vessel fuel (bunker) spills from all vessel types involved in vessel casualties resulting in damage. In each of the top four zones, over 80%

of the spills were in the 10,000 to 750,000 gallon range. New Orleans was the overwhelming forecast beneficiary of the VTS implementation in this category with 40 of the 100 avoided spills. Candidate VTS designs in New York, Houston/Galveston and Puget Sound each were forecast to avoid eight hazardous commodity spills.

Avoided dollar losses of all consequences. The fifteen year total avoided vessel casualty consequences attributed to the 23 candidate VTS designs was forecast to be $1.98b (not discounted). 83% of the total was forecast to result from seven ports: New Orleans, Port Arthur, Houston/Galveston, Mobile, Los Angeles/Long Beach, New York, and Corpus Christi. Furthermore, losses associated with hazardous commodity spills were responsible for between 74% and 92% of the total avoidable dollar losses. In Los Angeles/Long Beach, property value losses associated with spills reaching shore predominated, while in Houston/Galveston and Mobile, commercial fish species losses and clean-up costs predominated.

In summary, the 23 study zones were divided into three groups in terms of their relative life cycle net benefits (1993 discounted value of avoided losses minus the discounted annual stream of VTS investments and operation and maintenance costs):

Positive Net benefit:
- New Orleans
- Port Arthur
- Houston/Galveston
- Mobile
- Los Angeles/Long Beach
- Corpus Christi
- Boston

Sensitive Net benefit (either positive or negative over the range of uncertainty tested):
- New York
- Tampa
- Portland, OR.
- Philadelphia/Delaware Bay
- Chesapeake North/Baltimore
- Providence
- Long Island Sound
- Puget Sound

The remaining zones retained their negative net benefit status over the full range of uncertainty tested.

The report has special value for our project not only for its serious treatment of risk analysis and attention to statistical significance, but also because the wealth of data contained in the appendices to the report. However, the results themselves are of limited utility to our project. The application of a generic model to multiple ports using spare, inaccurate data has produced results that can be "dangerous" to use directly in other studies. The incompleteness of the data and the generalized approach to risk analysis combine to limit the report's usefulness. In addition, the study only involves the "VTS addressable" groundings, which are know to be only a little part of all groundings since VTS is more effective in avoiding collisions than it is in avoiding groundings. This further limits the use of the results in our study.

The interesting part of the study to our project is the risk assessment model. In volume 1, section 5, and in volume 3, section 3, a detailed treatment of the algorithms and procedures used for forecasting vessel casualties and their consequences is provided, including treatments of risk estimation, risk variables, and risk variable coefficients used in the multiple linear and non-linear regression analyses. The risk analysis model is also described. This is valuable detailed information that is useful in normalizing the study's analyses, results, and conclusions across other related studies.

The risk estimation process involved the development of national average probabilities by casualty type, vessel type and size, followed by sub-zone specific adjustments to represent the navigational characteristics of the sub-zone. The process was used to compensate for the absence of casualty observations in several of the cells of the multidimensional analysis matrix. The sub-zone specific adjustment estimates were derived by incorporating into the model, via regression analyses, a number of the risk variables which characterized the unique navigational risk and explained the historical casualties in each of the 99 sub-zones. In particular, the contributing factors to vessel casualty events and the future navigational hazards of the waterways in the study zones were analyzed. The major navigational risk variables for which data were available and used in the study covered the following:

- Frequency of reduced visibility,
- Prevailing wind conditions,
- Adverse currents,
- Waterway configuration,
- Vessel route alignment
- Channel width and depth
- Vessel traffic volume in channel, and
- Density of other local traffic.

5.4 Articles By M. E. Paté-Cornell

Prof. Paté-Cornell has conducted extensive studies on risk management for industrial facilities. In this section, we review her most recent articles. Her approach to risk management is based on a Probabilistic Risk Analysis (PRA) framework to identify possible risk reduction measures. PRA is founded on a quantitative definition of risk, which views a risk analysis as a set of scenarios whose consequences and frequencies are quantified probabilistically. The structure of the scenarios is facilitated by dividing the analysis into three models: the facility/plant, its immediate consequence, and the final "result" [25]. The facility model transforms initiating events into damage states. The consequence model uses the damage states as input to develop the frequencies of occurrence of different accident/release categories, while the 'result' model translates the consequences into off-site effects such as health and property damage. PRA is very effective as a risk management tool to show how and where to allocate resources to reduce the public and financial risk. By using this technique, it is possible to focus on the risk contributors to identify specific failures and associated causes. To be most useful as a risk management tool, a study must quantify the uncertainty in the results, and hence, point out the major contributor to the uncertainty, which again can be used to guide risk reduction efforts.

Quantitative safety goals for risk management of industrial facilities

The paper [30] discusses the issues, constraints and conflicts involved in risk management for industrial facilities and proposes a global and explicit approach to numerical safety goals. According to Paté-Cornell, the first step in setting priorities among safety measures is to conduct a probabilistic risk analysis, which should not be limited to technical parameters, but should also include organizational factors. The article acknowledges that the use of numerical safety goals is part of a more general strategy of risk management that involves both technical, organizational, ethical, social, legal and economic factors.

The overall objective in the management of the risks involved in the operation of hazardous industrial facilities is to achieve a satisfactory level of technical safety through good management and sound engineering practice. It is noted in the article that the legal philosophy of risk regulation in the United States has evolved towards attempts to balance costs and benefits of risk regulation. However, many companies are still reluctant to employ risk analysis because they believe they will be penalized in court if accidents happen due to problems that were deemed minor by the risk analysis and therefore not fixed.

Since different risk reduction measures generally compete for existing resources, these measures need to be prioritized. A good way to assess the relative contribution of different factors to the overall risk, according to Paté-Cornell, is by use of PRA. Once PRA results have been obtained, the question of numerical safety goals arises. It is worth noting that risk acceptance does not rely on risk magnitude alone, but on many characteristics of the risk such as controllability and voluntariness. The study suggests that several dimensions of safety objectives must be considered:

1. the probability of catastrophic failure of a facility,
2. the individual risk to each worker of the facility,
3. the individual risk for each member of the public off-site,
4. the economics of safety measures,
5. the time horizon (old versus new facilities), and
6. the overall societal risk (which depends on the number of people at risk).

Regulatory agencies and government authorities in the United States have for a long time been looking for a consensus about safety goals that would allow them to streamline the decision making process. This article proposes a global safety strategy for industrial risk management. An important issue to avoid is a "numbers game" that applies strict criteria and seems to distract both industry and regulators from fundamental safety issues. The strategy can be summarized as follows:

1. Requirements and traditions of the profession should be satisfied.
2. The annual probability of catastrophic failure should be less than a specified threshold e.g. 10^{-4} per year.
3. No worker should be exposed to an individual risk greater than 10^{-3} to 10^{-4} per year in his workplace.
4. No member of the public off-site should be exposed to an individual risk greater than a threshold of 10^{-5} to 10^{-6} per year.
5. Risk reduction measures should be adopted if it costs less than a certain amount to eliminate a certain risk.
6. Beyond this, all industries should expect to be on their own as they may not be fully protected by only complying with regulatory requirements.

This proposed format involves minimum individual safety requirements (risk upper bounds) for the workers and for the public, minimum values under which the risks are below concern, and in between, a range of risks where cost-benefit analysis dictates the adoption of further safety measures.

Learning from the Piper Alpha accident

In three papers [31, 32, 33], Paté-Cornell describes a risk assessment methodology which utilizes a post-mortem analysis of accidents to analyze an interconnected web of factors which led to an accident. In particular, a PRA framework is used to identify the accident sequence of the 1988 Piper Alpha accident. The framework is extended to include the human decisions and actions that have influenced the occurrences of failure events and their organizational roots. A wide spectrum of possible risk reduction measures is identified, and an explicit PRA model is developed to assess the benefits of some of these safety measures. The articles show how PRA can be used to assess, for example, the cost-effectiveness of safety measures designed to decrease the probability of severe fire damage onboard platforms similar to Piper Alpha.

The Paté-Cornell articles provide us with extensive insight into probabilistic risk analysis. In particular, the articles focus on the many important issues that must be considered when performing risk analysis. Even though the articles are valuable to us on a theoretical level, they provide little data that can be directly used in our project. However, as Paté-Cornell explains, the methodology is generalizable to many other industries and industrial processes. Examples of how the technique can be used in the shipping sector are provided in Amrozowicz' theses [34, 35], reviewed later in this chapter.

5.5 Decision Support To Masters, Mates, Watch, And Pilots: The Piloting Expert System

In 1986, Rensselaer Polytechnic Institute (RPI) initiated a research project under the auspices of the U.S. Department of Transportation to develop a prototype Piloting Expert System (PES). The objective of this initiative, headed by Prof. Grabowski, was to assess whether the emerging fields of artificial intelligence and expert systems could be effectively implemented for this type of application. In 1988, the prototype was ready and the field test results were promising [36].

The system was intended to "provide decision support in the three following forms:

- Training of junior ships' pilots by senior pilots: an efficient form of piloting knowledge distribution within the pilot community.
- Training of ship junior deck officers by senior masters: an efficient way of transferring expertise in the essentials of good piloting and ship-handling.
- On-line reminder and assistant for watch-standing officers and off-line simulation and contingency planning functionality" [36].

The impetus for introducing expert systems in the navigation of ships comes in part from extended studies performed over the years in a number of maritime casualties. According to Prof. Grabowski's information, the majority of maritime accidents occur inside or near the approach of harbors, and approximately eighty percent of them are attributable to human error. Therefore, the focus of this research effort was to develop a system that would allow the human operator to perform better and thus reduce the risk of maritime accidents. Such a decision aid was expected to "support the cognitive tasks of piloting by:

- representing all the types of knowledge necessary for piloting: local, transit-specific and ship-handling knowledge,
- supporting the appropriate levels of cognitive skills, and
- providing recommendations in order to assist in the basic tasks of: track-keeping, maneuvering and practicing good seamanship" [36].

The development of the knowledge base required three types of piloting knowledge. Local, transit-specific and ship-handling knowledge for piloting in the harbor of New York was provided by the Sandy Hook pilots. The initial knowledge base was then refined through a series of knowledge acquisition experiments where the New York pilots reviewed and edited the prototype expert system. The problem facing the navigators can be described generally as "situation assessment" [36]. This means that a human or mechanical device collects new data about a decision situation and reasons about its implications. The reasoning within the PES was implemented by moving "forward" from top to bottom through the structure of hierarchies [36].

The RPI research team worked to develop a user friendly, stand-alone application, with graphic capabilities. The input was provided by the user via mouse and pull down menus. There was no external connection to shipboard sensors, and thus the track-keeping capabilities of PES were limited. Based on input such as visibility, traffic condition, etc., the system provided the user with two types of recommendations. General ship-handling knowledge was provided in transit specific manner and was usually static ("recommended course 347 for 1.94 miles; half ahead"). The other type had the form of dynamic recommendations about maneuvering, collision avoidance and the practice of "good seamanship" generally ("If visibility closes reduce speed to minimum required to maintain way").

After completing the prototype, an evaluation was conducted to assess its contribution to the performance of inexperienced decision makers. The evaluation took place at the Computer Aided Operations Research Facility, a ship simulator located at the U.S. Merchant Marine Academy at Kings Point, New York. Fourth year cadets participated as subjects of the experiment, divided into three member watch-standing crews. "The performance of each team on the bridge was assessed using two sets of measurements, watch team performance and vessel (track-keeping)" [36].

The results clearly indicated that the performance of the watch team improved after the introduction of the Piloting Expert System. However, the effect of PES on vessel performance was not statistically significant. The usefulness of the Piloting Expert System was considered encouraging. Nevertheless, the author acknowledged that it is difficult to obtain accurate measurements of performance and that caution should be exercised when interpreting the results. She encouraged additional research to ascertain the degree of dependency between the motor, perceptual and cognitive skills used in task performance or problem solving in general, in ship piloting in particular [36].

5.6 The Need For A Probabilistic Risk Assessment Of The Oil Tanker Industry And A Qualitative Assessment Of Oil Tanker Groundings

Different from our approach to modeling grounding risk is the one followed by Michael D. Amrozowicz in his master's thesis [35]. Being particularly interested in the oil tanker industry, he argues the need for a total system approach towards risk and risk management based on *Probabilistic Risk Assessment* (PRA). This is a tool used in safety studies for the nuclear power industry. It provides a formal process for determining the full range of possible adverse occurrences, the values to be assigned to their probabilities and the expected cost of any undesirable event.

The underlying risk in the case of the oil tanker industry is related mainly to the oil spillage following an accident. Oil spills have both short and long term effects on the environment. The former, even though they can be remarkably harmful to the surrounding ecosystem, are quire well understood. Our understanding, however, is limited in the case of the long term environmental impact. Amrozowicz argues that "regardless of their consequences, oil spills are preventable man-induced perturbations of the environment which stress the ecosystem unnecessarily" [35].

Given that is difficult to eliminate oil spills completely, society's effort must concentrate on minimizing their effects. National and international regulatory bodies, working together with oil companies and tanker owners, have made significant steps to minimize the amount of oil pollution from tanker accidents. So far, however, the efforts have been reactive. A proactive approach may be necessary in order to realize greater benefits. For such an approach to be possible, all the elements of pollution prevention must be thoroughly understood by the parties involved.

Amrozowicz identifies a "need for a regulatory structure capable of efficiently addressing pollution prevention and mitigation, while minimizing any unnecessary economic burdens and innovation impediments" [35]. He argues that a technology-based standard may not provide an adequate solution, and suggests the implementation of a technology-based strategy. The mission statement of this strategy will be to reduce the waterborne oil transportation associated risks by expanding the technological options available. Breaking the boundary conditions imposed on safety by a mandated technology, such a strategy will encourage safety developments. The first step is to identify the components of waterborne oil transportation with the greatest risk reducing potential. Then, "the problem of oil pollution could be addressed through one or all of the following:

- An appropriate combination of efficient engineering systems and equipment.
- Efficient system and procedures management.
- A practical understanding of people and human factors" [35].

From a traditional point of view the formal risk analysis is divided into two part:

- "Risk assessment: The process of seeking to identify hazards and calculate their expected adverse effects.
- Risk management: The process of seeking a way to structure decision making for the definition of acceptable risks and the measures that society is expected to employ against unacceptable levels of risk" [35].

Society demands that risk should not exceed a certain level. The criteria employed to set the marginal levels are usually based on the per unit of risk cost and the consequences. Amrozowicz claims that "an integrated approach to risk assessment and risk management should be undertaken to determine and manage tanker industry related risks. Once risk management options have been identified, they can be prioritized not only in terms of risk, but also in terms of their risk reduction potential. Regulators then will be in a position to systematically influence the risk levels according to the societal demand while minimizing the regulatory burden placed upon the ship owners. This way, it may be possible to develop a framework which will address a wholesale solution rather than discrete problems" [35].

A modified version of the probabilistic risk assessment approaches used in the nuclear industry is proposed by Amrozowicz for the purpose of risk management in the oil tanker industry. The outcome will be the understanding of the economic and environmental impacts of an oil spill. The general form of the mathematical model (Figure 6) proposed by Amrozowicz for the calculation of the probability, *P(impact)*, of oil pollution that will produce adverse economic and environmental consequences has the following form [35]:

$$P(impact) = P(damage\_extent) \times P(outflow / damage\_extent) \times P(impact / outflow)$$

where:

- $P(damage\_extent)$: probability of ship's damage and its extent.
- $P(outflow / damage\_extent)$: the probability that oil will flow to the environment given the damage and its extent.
- $P(impact / outflow)$: the probability of impact on the environment given that oil is released to the environment.

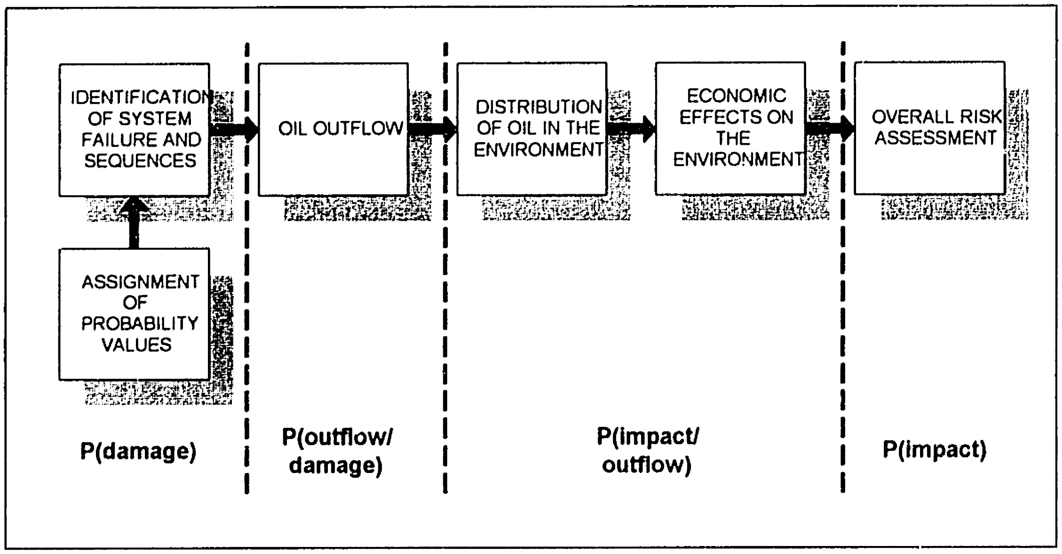


Figure 1 - Illustration of the proposed model.

Complex systems such as tankers have multiple failure modes with physical and operational interactions. The analysis of such systems in terms of safety is best performed using fault trees. These are graphical representations of how the failure of basic components of a system can lead to a pre-determined failure state. The concept of fault trees was first introduced in the aerospace industry but since has been implemented extensively in probabilistic risk assessment studies performed in the nuclear power industry.

A common feature of complex man-made systems is human failure. In general, it can be manifested in one of the two following forms:

- "Active failures resulting from almost instantly observable effects.

- Latent failures not immediately noticeable" [35].

Active failures are usually associated with direct and responsive operations and can be recognized immediately. Latent failures may lie dormant within the system for a long time; they become evident only when they are combined with other factors. There are numerous schemes to characterize and classify human failures and their causality. Human failure may occur in any phase of the design, construction and operation of a complex system. On the other hand, accidents are distinguished based on the factors to which they are attributed. There are two such types of factors: environment and human related. Accidents due to environmental factors are those unavoidable environmental events that exceed the reasonable demands of the structure during its lifetime. Accidents resulting form human error can be differentiated into those caused by design, construction, and operation. Focusing on operational accidents, "the elements of human failure are influenced by the synergistic effects of (1) individuals, (2) hardware, (3) organizations, (4) environment, and (5) procedures. The amount of interdependence reflects the amount of coupling that exists within the system. In a tightly coupled system each area cannot be addressed in isolation" [35].

Studies of the role of human failure in engineered structures have shown that human failures are inevitable, but many of them can be prevented through the appropriate management and use of technology. The latter can take the form of specific programs aiming to reduce the probability and/or the effects of human failures. Such programs may focus on:

1. "Qualification and training of personnel resulting in licensing.
2. Procedures related to normal and emergency operation as well as maintenance and emergency preparations.
3. Technical specifications.
4. Human-Machine interface in both the bridge and the propulsion control room.
5. Organization and management" [35].

Very important processes in terms of safe operation of any ship are the planning, piloting and navigation through narrow channels and waterways. These processes are prone to human failure and deserve a closer look and understanding if proper assessment of the risks during tanker operation is the goal. The causality of human failure to order the proper course requires special attention in order to evaluate how errors are introduced in the ship piloting and navigation process. It should be acknowledged that maneuvering a ship to a proper course involves constant comparison of the actual position to the desired position, and this may lead to information overload of the persons involved [35, 36]. Amrozowicz argues that "both piloting and navigation can be seen as a feedback control system with the human pilot an essential part of the control loop. In the open ocean with little or no traffic, the navigation system is tolerant of errors" [35]. In that situation is it possible to have an inaccurate control loop with no serious ramifications. However, as the ship approaches narrow and restricted channels with high density traffic, the error tolerance of the system decreases significantly and the amount of information to be processed by the controller increases sharply. That makes the concepts involved in these three processes, planning, piloting and navigation, very important in the development of the fault trees through which Amrozowicz seeks to model tanker risks.

In the last two chapters of his thesis, Amrozowicz presents the process of developing an actual fault tree for the modeling of risk in tanker related accidents, and applies the results in a qualitative validation. The first step taken towards the modeling of the risks is to identify the possible states of system failure and the corresponding consequences. In the case of tanker related incidents, the major classes of accidents resulting in pollution are: collisions, groundings, fires and explosions, and structure and hull failure. The effort of developing an actual fault tree is focused on groundings. Level by level all possible causes that may lead to real incident are identified. Finally, the validation of the developed fault tree is achieved in a qualitative manner through the study of certain accidents: "Torrey Canyon" (1967), "Transhuron" (1974), "Amoco Cadiz" (1977), "Exxon Valdez" (1989) and "Braer" (1993).

In his conclusions, Amrozowicz urges the maritime community to invest in probabilistic risk assessment and proceed to more comprehensive applications of it in other types of accidents. He argues that "PRA will efficiently assist policy makers to achieve the desired detailed understanding of accident causes and allow them to take the required measures for risk management" [35]. Amrozowicz continued his research in a second thesis "The Quantitative Risk of Oil Tanker Groundings (Amrozowicz, M. D., 1996)" [34].

5.7 The Quantitative Risk Of Oil Tanker Groundings

5.7.1 Introduction

The focus of this thesis is on the prevention of tanker spills from groundings through identification of factors that increase the probability of groundings [34]. Tankers are the largest contributor by vessel type to worldwide oil spill volume; and the grounding of tankers represents a significant failure state contributing to the total accidental oil outflow of tankers. A systematic approach was undertaken to gain insight into the factors that contribute to the grounding event. The thesis states that a closer look at human error, to which 80% of marine accidents have been attributed, revealed that many accidents attributed to human error are system errors. The study acknowledged that a probabilistic risk assessment (PRA) provides a formal process of determining the full range of possible adverse occurrences, probabilities and expected costs for any undesirable event, and that PRA can be used to identify those areas that offer the greatest risk-reducing potential. It therefore used the first level of a proposed three-level risk model to determine the probability of a tanker grounding. The approach utilized fault trees and event trees and incorporated the Technique for Human Error Rate Prediction (THERP) data to quantify individual errors. The THERP analysis provided a tool for understanding the tasks that the mariner performs. From the task analysis, the high-leverage factors were identified. The study recognized that effective reductions in the individual error rate had to encompass a total systems approach, since individual errors are a subset of human failures, which are a subset of system failures. The approach used in the thesis builds on a sound and simplistic methodology which has been proven to work well in the nuclear industry. However, because of the limited resources available and the many assumptions made, the validity of the absolute value of the probability of grounding can be questioned. Nonetheless, the approach definitely serves to give relative values that can be compared, and indicates areas for improvement. The specific areas for improvements that were recognized lied within the domain of sub-systems, organization and procedures. In particular, integrated electronic chart systems were believed to offer significant potential for reducing piloting and planning errors, while the ISM code was mentioned as a framework that could enhance safety within the maritime industry by providing incentives and improved performance.

5.7.2 Background

Tankers are the largest contributor by vessel type to worldwide oil spill volume. According to the National Research Council [28], tanker *groundings* cause a significant part of these oil spills. From 1981 to 1990, groundings represented 45% of the major spill volume in U.S. waters. Globally, groundings represented 20% of all the tanker losses between 1987 and 1991. It is clear that groundings present a significant spill classification to investigate in order to understand how to minimize oil pollution. Further motivation for the thesis was explained as follows:

> "The magnitude of oil outflow is a function of many unpredictable circumstances. There can be groundings that are preceded by marked and profound blunders, yet, the degree of oil spilled may be negligible. So while limiting oil outflow motivates the investigation of groundings, the scope is much broader and concerns itself with the nature of the events leading to vessel's grounding. A formal risk analysis is an important step toward prevention. The ultimate goal is to understand the nature of the errors that lead to a grounding. Once understood, the proper policy and technology can be implemented to reduce groundings and serve to make the maritime industry safer in all respects." [34]

5.7.3 Approach

The thesis covered the following issues:

- the nature of the problem,
- the risk assessment methodology used to investigate the problem,
- human failure analysis,
- the methodology required to quantify the human related failure probabilities,
- failure sequence development and the rationale behind it, and
- determination of the probability of grounding and ways to reduce it.

The study explained the high level of tanker groundings by the increasing number of poorly managed and sub-standard vessels. Buzz words mentioned were, among others: Volatile markets, oversupply, flag of convenience, increasing average age of tankers, commercial pressure, and low wage personnel. As positive developments were mentioned the formation of The International Association of Classification Societies and increasing port state control.

The study was based on Probabilistic Risk Assessment (PRA). PRA is a technique for identifying, characterizing, quantifying and evaluating hazards. The report shows how the risk assessment methodology that is firmly established in the nuclear industry can be applied to the maritime industry. Fault trees were used as a framework for quantitative evaluations, while event trees were used to display the results of a task analysis. A fault tree for tanker groundings developed in an earlier study [35] was the basis for the evaluation.

Human errors are significant in the progression of events leading to a tanker grounding. The report states that human error should be recognized as a system failure, and that it should be broken down into two sets: 1) Human failure and 2) individual errors. This results in a new representation of the 80% of maritime accidents attributed to "human error":

1. *40 percent are individual errors:* component failures where the operator is the component that failed. (Errors whose adverse consequence may lie dormant within the system for a long time and only become evident when they combine with other factors to breach the system's defenses.)
2. *5 to 10 percent are system failures:* accidents that are an integral characteristic of the system; the interactive complexity and tight coupling of the maritime system inevitably will produce an accident.
3. *30 to 35 percent human failures:* errors resulting from a complex and tightly coupled system which requires long hours, has misplaced priorities, and skewed incentives. (Errors whose effects are felt almost immediately.)

To predict human reliability, the study used the Technique for Human Error Rate Prediction (THERP). This technique breaks the system down into its constituent elements, assigns reliability estimates, and then computes the aggregated result. The THERP analysis consists of the following steps:

1. Define system failures of interest.
2. List and analyze the related human operations (task analysis).
3. Estimate the relevant error probabilities.
4. Estimate the effects of individual errors on the system failure events.
5. Recommend changes to the system and recalculate the system failure probabilities.

Both failure sequences for powered grounding and drift grounding were developed in detail. The fundamental failures resulting in powered groundings were found to lie in the processes of planning and piloting. To get a drift grounding, several conditions had to be present: unsafe wind/current, assistant failure, anchor failure, and loss of steering or propulsion. The probability of grounding in the powered grounding mode of failure was dominated by the piloting process. This was confirmed by the CASMAIN database, which attributed only 15 cases of 716 tanker groundings to either steering failure, or propulsion failure. The analysis seemed to overestimate the probability of powered grounding based upon statistical data.

5.7.4 Findings

In order to determine those events that offered the largest potential for improving the failure probabilities, a sensitivity analysis was conducted. The high-leverage events that had potential for affecting the probability of powered grounding were:

Passage planning:

- Captain's verification of planned route.
- Checking of publications for changes in waterway.
- Proper determination of voyage way-points.

Piloting:

- The actual course deviates from the planned track, and this difference error of direction is detected by on-board instruments.
- Properly taking a fix of location.
- Detecting the difference error from the plotted fix.

As mentioned above, the validity of the absolute value of the probability of grounding can be questioned because of the limited resources available and the many assumptions made. Nonetheless, the approach serves to give relative values that can be compared, and indicates areas for improvement. The study has value to our project since it broadens the understanding of the relation between groundings and human failures. However, there is not much information in this thesis that can be used directly in our work.

5.8 Oil Tanker Environmental Index

During the spring term of 1996 we attended "Marine Safety", a project based class offered by the MIT Department of Ocean Engineering. In 1996 the class focused on the development of a "ship environmental index". It is a concept introduced by Norway as a potential solution that will reduce the risk of oil pollution resulting from the operation of tanker vessels. The proposal for the development of this concept was submitted at the 37th session (fall 1996) of the IMO Marine Environmental Protection Committee (MEPC) as agenda item 21. The underlying idea is to develop a scientifically-based system that will assist the evaluation of the overall potential for pollution from specific ships entering a given waterway. This system is expected to incorporate different environmental accounts in order to quantify all types of operational and accidental pollution associated with a ship.

For the purpose of the index, the term environmental account refers to the vessel operating factors that effect the risk of pollution. The resulting index value assigned to each ship evaluated under the scheme is to be based on a properly weighted consideration of all these separate accounts. The objective, as foreseen by Norway, is to introduce this system as a more flexible criterion for regulatory compliance or as a basis for building economic incentives for the owners in terms of reduced port fees, taxes and insurance premiums. The complete project was expected to be submitted by Norway to the 38th session (to be arranged) of MEPC for appraisal by other members countries.

The United States are represented in MEPC by a U.S. Coast Guard delegation. The purpose of this semester-long project was to develop a possible framework for the establishment of an international environmental index for oil tankers in order to assist the U.S. delegation in their evaluation of the Norwegian proposal. The project was undertaken by the students under the supervision of Prof. Brown and Prof. Marcus in the context of the "Marine Safety" class. The original group of students was divided in two separate teams. One of these teams was responsible for the evaluation of the potential of a given ship to produce an oil spill while entering a specific waterway. The other team took over the assessment of the potential oil spill effects on the environment surrounding the waterway. The probability values produced for each system, ship and waterway, by the corresponding team would be combined to produce the overall oil pollution probability. Based on the process it would then be possible to provide some measure of the relative risk by applying the index to compare various ship and waterway combinations.

In order to ensure that maritime industry views were appropriately captured in the report, one student, acting outside these two teams, was assigned to identify representatives of the industry stakeholders. That goal was achieved using a questionnaire sent out to a certain number of industry participants. The survey served two complementary purposes. The first was to ensure that the project considered concerns on a wide spectrum of issues related to the development of the index, some of which may not have been published because the idea of an index is new. The second was to model the position of the various players with respect to their areas of involvement in the maritime industry. The selection of these representatives was based on their role within the industry. In particular, three general categories of stakeholders were represented in the final report: owners, operators and charterers; regulators; and academia. A fourth category asked to provide their views, environmentalists, was not captured properly because of their delayed response. One important observation based on the survey results was the fact that the views of group members seemed to be consistent within each stakeholder group. There is a lot of common ground between the views of the different groups, but there is a lot of disagreement as well. The major point raised was that the current system of international tanker operation does not offer any benefits to offset the high cost incurred by the owners if they decide to implement any of the myriad of alternative tanker risk reduction techniques.

The ship team examined the effect of ship design and operations on the probability of having an accident. Four different types of oil spill causes were identified: collision, grounding, fire and structural failure. A fault tree approach based on the related work by

Amrozowicz [35] was employed to determine the significant parameters that could potentially lead to an oil spill. Separate work was originally to be performed within each of the four categories. That was not possible within the context of this project class, due to the bounded resources employed and the accompanying time restrictions. Therefore the fault approach was applied only in the case of groundings, and was followed by a detailed analysis of the fundamental inputs leading to an oil spill. These inputs were separated into two categories, human and management related. The distinction of input between human and management in the context of the project attempts to capture the difference between managerial failure (tactical decisions with strategic intent) and execution failure along with the different factors that effect each category. The work accomplished by the ship team focused on five distinct areas, as follows:

1. Probability of a tanker groundings.
2. Determination of the ship damage extent
3. Human factors.
4. Tanker system.
5. Ship management.

The waterway team tried to identify the features of a given port that influence the probabilities and the effects of an oil spill. These features were divided in three different areas, which were explored in depth both in terms of individual features and of interactions among them. The areas identified and investigated by the waterway team were as follows:

- Characteristics affecting the probability of an oil spill through interaction with the ship.
- Human and natural factors influencing spill mitigation capability.
- Features determining the ultimate economic and ecological damage from the oil spill.

The paradigm of the fault tree was followed by the waterway team. The areas of concentration of the waterway team were the following:

1. Waterway risk assessment.
2. Spill contingency plan and its impact on spill consequence.
3. Mitigation of tanker spills.
4. Gauging the ecological harm.
5. Economic costs of oil spills.

The result of this effort was the development of two metrics, one for the economic impact and the other for the ecological impact. Both were obtained using similar methodologies. In the process of developing these metrics, the most serious problem was the conversion of the ecological impact into economic terms. The main difficulty relates to the different weights these two measures may be assigned in the context of different cultures, in different ports. Therefore the final decision for the ultimate combination of the two metrics was left in the hands of the end user. The equations for the calculation of these two metrics are given below:

Total Economic Impact ($I_{ECONOMIC}$)

$$I_{ECONOMIC} = \left(k_1 \times P_{ship} + k_2 \times P_{waterway}\right) \times \left(0.75/CPF\right) \times \left(1 + (MF - 1)/10\right) \times MDF$$

Total Ecological Impact ($I_{ECOLOGICAL}$)

$$I_{ECOLOGICAL} = \left(k_1 \times P_{ship} + k_2 \times P_{waterway}\right) \times \left(0.75/CPF\right) \times \left(1 + (MF - 1)/10\right) \times EDF$$

In the above equations, *CPF* is the *Contingency Planning Factor* that measures and quantifies the effects of the mitigation efforts after the oil spill has occurred. *CPF* is calculated based on the preplanning and response capability of the port in question. The values of *CPF* range from a high of 1.0 corresponding to a port of above average planning and response capabilities to a low of 0.25 for compliance with the minimum requirements.

Another factor with strong influence on the success of the mitigation effort is the natural conditions observed in the port when the accident occurred. Therefore the effect of winds, currents, and temperature on the mitigation process is captured in the above equations through the so called "*Mitigability*" *Factor* (*MF*). The values of this factor range from 1.0 corresponding to the ideal port up to 3.0 that represents the worst case port. These values result on a total effect ranging between 1.0, for no effect, and 1.2 that represents a 20% increase of the impact.

MDF and *EDF* are the *Monetary* and *Ecological Damage Factors*, respectively, that have been introduced in order to capture the relative impacts for a given port in the two equations above. They have been developed as a method of comparison of the economic and ecological damages for different port areas based on their characteristics as identified by the waterway team. Finally, k_1 and k_2 are the weighting factors for ship and waterway specific probabilities, respectively.

The metrics developed in the course of this project by no means are to be considered absolute. On the contrary, they should be viewed as a first rough approximation of what the final measures are expected to be. Both the metrics and their development process may be revised significantly in the future, as additional and more meaningful data are obtained. For the moment, their sole purpose is to provide some measure of quantification and differentiation between different port and ship scenarios to be used as a starting point for further investigation.

Chapter 6. Theoretical Background

6.1 Short Discussion Of Statistics

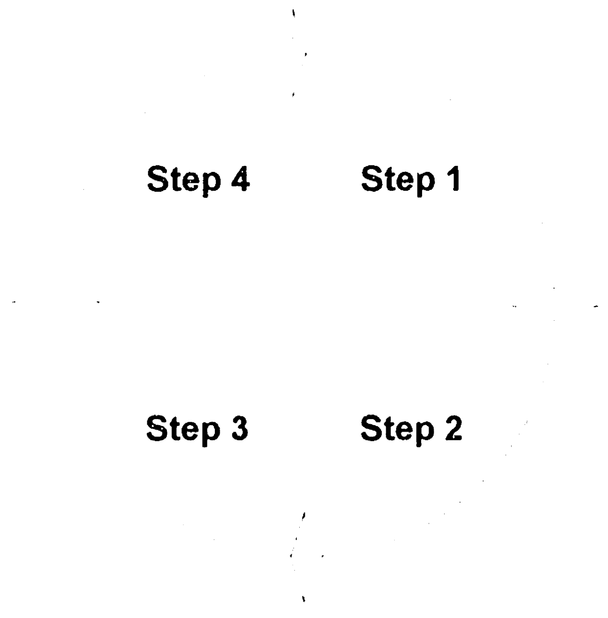
6.1.1 Processes, Process Analysis and Process Control

Navigating a ship is a process, a sequence of steps taken in order to achieve a specific goal. The goal of navigation is to reach the destination port, and the steps are maneuvers performed by the ship under the command of her master or pilot. Navigation, like any other process, produces results, the most important of them being whether the ship makes it safely to her destination. However, humans are seldom interested in simply noting the results of a process [27]. Of higher importance to them is the *quality* of the results. For instance, a successful trip form New York to Boston may be a matter of hours or months. The result in both cases is the same; the ship safely unloaded her cargo at the destination port. However, the shorter trip certainly encompasses higher quality.

To assess the efficiency of navigation in terms of cost, cargo quality as delivered, etc., the measurement of certain characteristics of the process is required. A need to obtain relevant data arises. The number of different types of data necessary to provide adequate insight into a process depends strongly on its complexity. It should be expected that simple processes such as coffee brewing will necessitate only a few types of data, maybe fewer than ten. On the other hand, more than fifty different data types may be necessary for highly complex processes, such as running nuclear reactors, flying airplanes or navigating ships. Finally, it should be noted that the results of a single process are expected to vary when the conditions of the surrounding environment change [27].

During the progression of a process, input is provided at the beginning of a given step. That input undergoes a certain transformation and results in the output of the step. This output provides, in total or partially, the input of the following step, and so forth until the process concludes.

Scientists seek to model the individual steps comprising a process as well as their interconnecting relationships. The purpose of studying each step is to understand the fundamental causes that are responsible for the variation of the process results. The entire set of activities carried out in order to achieve that understanding is called process analysis [27].



Step 1: What could be the most important accomplishment of this team? What changes might be desirable? What data are available? Are the observations needed? If yes, plan a change or test. Decide how to use the observations.

Step 2: Carry our the change or test decided upon, preferably on small scale.

Step 3: Observe the effects of the change or test.

Step 4: Study the results. What did we learn? What can we predict?

Step 5: Repeate Step 1, with knowledge accumulated.

Step 6: Repeate Step 2, and onward.

Figure 2 - Deming's Wheel (PDCA).

The higher the understanding of a process, in terms of its details, the more precisely it can be modeled, yielding more accurate predictions about its future behavior. The ability to tell how the process will behave in the future is fundamental to exercising process control. There are two kinds of process control. The first, process regulation, applies to processes with results already close enough to desirable and seeks to maintain the "environmental" conditions that are responsible for the particular results. The second, process or quality improvement, is necessary when the process results are not the desired results. The ability to understand the causality of each step in its sequence within the process makes it possible to alter some of the responsible conditions and get closer to the desirable results [27].

The application of these concepts, process analysis and process control, in ship navigation is very difficult because of its complexity. Many factors influence its outcome, and it is hard to identify each of them. Even more difficult is understanding the synergism among the factors and how it affects the process results [27]. However difficult the application of process analysis and control in navigation might be, it should be considered important as well. Every day, ships get larger and their cargo becomes more valuable. If the result of navigation is anything but safe unloading of the cargo at the destination port, the economic and environmental burden to the society may be unpredictable [21, 28]. It is essential to identify the factors influencing the efficiency of the navigation process, understand their causality and synergism, and use them in our favor.

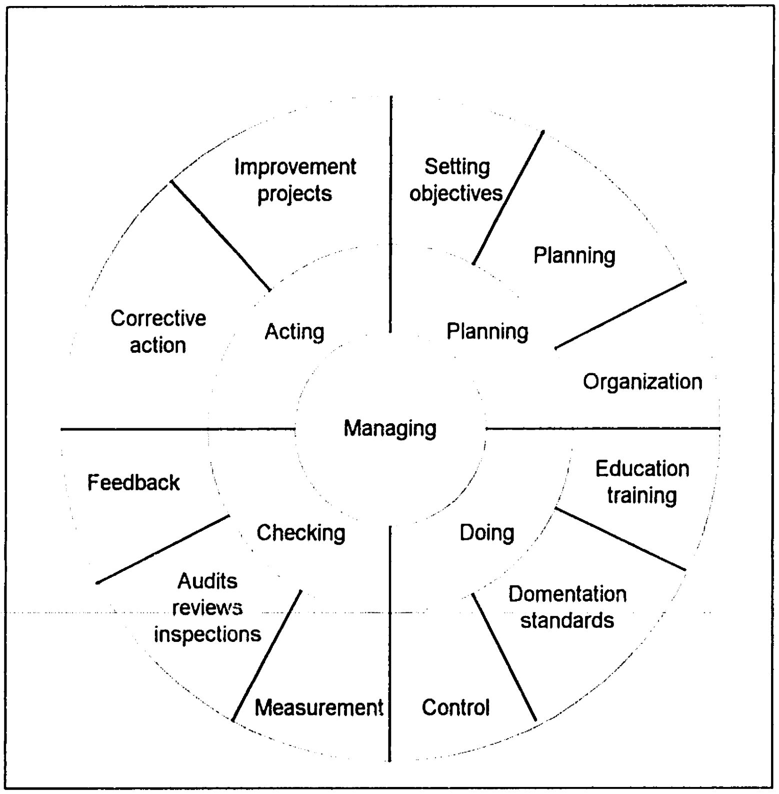


Figure 3 - Organization of R&D at AT&T.

"Deming's wheel" (Figure 2) provides a coherent graphical representation of the steps involved in the concept of process improvement developed by Walter A. Shewhart, that was further elaborated and popularized by Edward W. Deming [27]. The underlying idea can be summarized in the following statement: "Process improvement is not a "one-shot" proposition but rather cycle after cycle of painstaking planning, experience, checking, setting new standards, looking for new ways to improve, and so on" [27]. According to PDCA (Planning, Doing, Checking, Acting), an alternative term used for "Deming's wheel", planning (P) is the starting point. At this point the situation at hand is evaluated, the goals are set and the procedures for testing, experimenting or surveying are developed. The materialization of these plans follows during the "doing" phase (D). The results realized are then compared against the previous behavior of the process over the subsequent "checking" step (C) in order to assess the magnitude of change. Finally the loop concludes with acting (A), where study on the implications of the materialization of the plans is performed. After some conclusions have been drawn the loop starts all over again, using the output of the previous cycle as input. The goal this time, as in any subsequent loop, is to improve the process further based on the lessons learned. An enhanced version of the wheel is presented in the diagram in Figure 3 that illustrates the organization of research and development at AT&T [27].

Essential to the concept of process improvement is the idea of "listening". The latter starts by collecting data relevant to the process and subsequently taking appropriate action based on the information gathered. In analyzing the process of ship navigation, a variety of data can be collected. The database should include information on physical characteristics of the ship, onboard equipment, crew, cargo, environment, navigational aids, external assistance, if any, and waterway characteristics. However, the quantity of data gathered is not the issue. What matters most is the quality of the information because of its strong effect on the quality of the corresponding decisions. Our ability to collect large quantities of information is far ahead of our ability to gather trustworthy data [27]. Hence, we should not concentrate our efforts only on improving our data analysis skills, but also our ability to evaluate the trustworthiness of the data.

Efficient acquisition, analysis and presentation of data involves extended use of statistical tools because scientific methods rely heavily on data for the development and testing of theories. This is evident if we think of the scientific equivalent of the PDCA wheel. The four steps are: observation, hypothesis, deduction and experimental verification. The use of statistics is important during all these steps, but the first and fourth steps make the greatest use of them. They should be thought as "diagnostic" tools. They assist the researcher in identifying exceptional values in the collected data, providing a hint on what might have gone "wrong" with the process. The term "wrong" means that something unusual occurred that resulted in a noticeable change in the process behavior, either beneficial or detrimental.

There are three different schemes for the collection of data. The simplest is observation, where all the outcomes generated by the process under investigation are recorded in a systematic fashion. Sample surveying is another method for collecting information on a sample of process characteristics drawn from a wider universe of all the characteristics of the given process that are available for measurement. The benefit of this approach is that it allows the collection of the information required for the analysis of the process at the minimum cost. Both of these methods involve passive listening, as opposed to the third scheme, experiments, that is an active approach. The researcher studies the effects of changing some variables of either the process itself or the surrounding environment, assuming that the latter is partially under his control. Although an experiment provides more accurate information than the other two schemes, it is not always feasible to perform one, because of either practical or economic limitations [27]. One can brew a cup of coffee many times trying to figure out ways to improve the taste. However, one can not run a real ship up and down a waterway in order to come up with improvements to the navigation process. It is not economical to perform such an experiment, and it may be dangerous. Therefore, our study of the navigation process was based on data sets of historical safe passages and accidents. More information about the development of the data sets is available in section 8.3.

Our approach to the study of navigation practice was longitudinal. We studied the evolution of the process over time as we tried to identify the factors influencing the risk of grounding. We compared corresponding sets of data obtained with different time frames and documented the variations observed. Based on these observations we evaluated the changes in the process behavior over time. Among other tools, data plots were employed to assist our effort. Most frequently we used sequential plots that provide a clear insight on the evolution of process characteristics over time. This is feasible by displaying time on the horizontal axis with values of the corresponding characteristics on the vertical axis. An example of a sequential plot is provided in Figure 4, that illustrates the change of quantity A, visibility for example, over twelve months. Sequential plots have also been used to illustrate the evolution of differences and percentage changes of these values during different time periods.

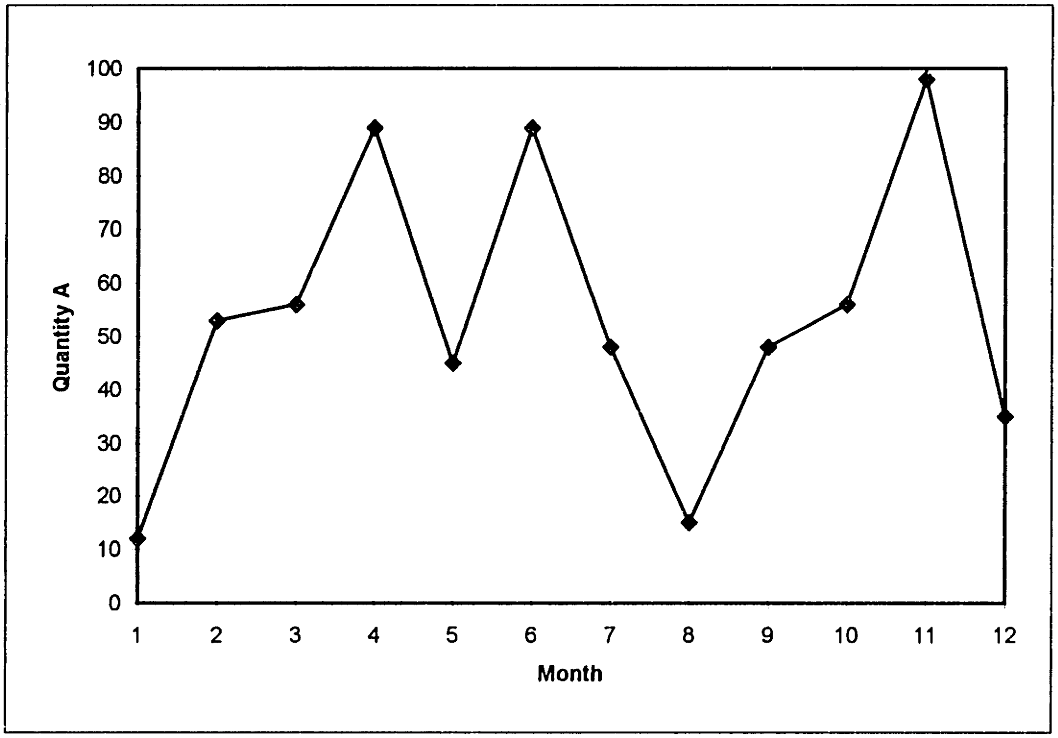


Figure 4 - Example of sequential plot.

Distribution plots, particularly histograms, were also employed extensively throughout the study. These types of graphs provide an insight on cross-sectional aspects of the data. For instance, we use distribution plots when there is no time dimension of data values for a given characteristic or when we seek evidence for the influence of certain factor over the process. The relation between visibility conditions and the risk of grounding was studied using plots like the one provided in Figure 5. In these plots the vertical axis represents

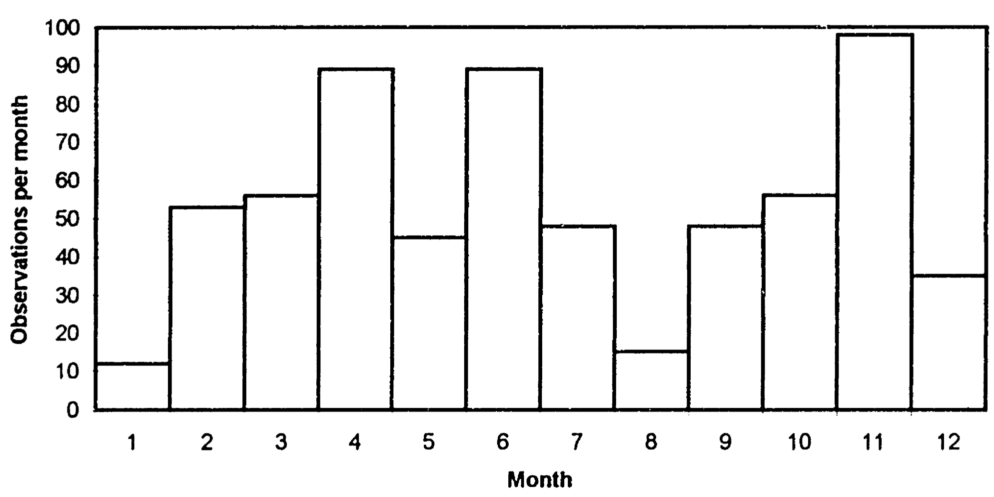


Figure 5 - Example of frequency plots.

usually observations or frequencies and not individual values. One way to build a typical frequency histogram is to group the data into a number of value classes and report the frequency of values falling into each class on the graph. It is usual for these types of plots to have the frequency values displayed on the vertical axis and the midpoints of the corresponding value classes displayed on the horizontal. Other types of histograms, like relative frequency histograms and density histograms, were employed as needed.

6.1.2 Important Statistical Concepts

Besides the use of data plots, descriptive statistics were employed for the purpose of our analysis. There are two kinds of statistics, those based on ordered values and those based on moments. In the first category we have the median, the range, and the symmetry and skewness of data. The median is defined as the middle value of an ordered data set; it is as close as possible to the value of the midpoint of the ordered series. Thus half the data in the set are below while the other half of the data are above the median value. Assume we have a series of n data values $y_1, y_2, y_3, \ldots, y_n$ where y_i represents the value of the i^{th} observation, and define $m=(n+1)/2$ if n is odd and $m=n/2$ if n is even. Then the median can be expressed as follows:

$$Median = \begin{cases} y_{(m)} \\ \dfrac{y_{(m)} + y_{(m+1)}}{2} \end{cases} \qquad (6.1)$$

where the upper part on the right side of the equation holds for odd values of n and the lower for even values of n. An important attribute of the median is the lack of influence on its value by the extreme observations of the data set.

The range is another important number that describes the spread, dispersion or variability of the data set around the middle. Following the notation introduced earlier, the definition of the range is as follows:

$$Range = y_{(n)} - y_{(1)} \qquad (6.2)$$

where $y_{(n)}$ is the largest value in the data set and $y_{(1)}$ the smallest.

A distribution is said to be symmetric when the left and right sides of the plot are mirror images of each other. Every detail observed on the left can also be observed on the right side of the distribution at the same distance from its middle. In any other case where the values are stretched towards the one or the other end, the distribution is asymmetric and said to be skewed. Perfectly symmetrical distributions are rarely found in real data [27].

Mean value is the most common of the statistics based on moments. In this same category we also have the standard deviation, and the coefficient of skewness. Using the notation introduced earlier in this chapter, we can define mean value as follows:

$$\bar{y} = \frac{1}{n} \cdot \sum_i y_i \qquad (6.3)$$

Standard deviation is the most common measure of the dispersion or variability of data values around the mean. Again using the above notation, the mathematical definition of standard deviation is as follows:

$$s = \sqrt{\frac{\sum_i \left(y_i - \bar{y}\right)^2}{n-1}} \qquad (6.4)$$

Finally, a numerical measure of lack of symmetry may be provided in terms of the coefficient of skewness. The mathematical formula to calculate the coefficient has the following form:

$$\kappa = \frac{1}{n-1} \cdot \sum_i \left[\frac{y_i - \bar{y}}{s}\right]^3 \qquad (6.5)$$

As mentioned earlier, the ultimate goal of studying a process is the development of a model, hopefully as accurate as possible, that will allow prediction of future process behavior. Essential to this goal is the identification of the important variables affecting process results and the relationships among them. To investigate the relationship among any two metrics, we start by developing scatter plots of their corresponding values. Figure 6 presents an example of such a scatter plot. These plots provide a first approach to understanding the relationship among the two variables. For a descriptive measure of their inter-relation, we utilize the product-moment correlation coefficient. This coefficient measures the linearity observed in the relationship between the two metrics (*x* and *y*). Keeping the same notations, the coefficient can be expressed as:

$$r = \frac{1}{n-1} \cdot \sum_i \left[\left(\frac{x_i - \bar{x}}{s_x} \right) \cdot \left(\frac{y_i - \bar{y}}{s_y} \right) \right] \qquad (6.6)$$

where s_x and s_y are the standard deviations of *x* and *y* correspondingly. Some of the most important properties of this coefficient are [27]:

- $r \in [-1,+1]$
- $r = +1$ implies a perfect linear positive correlation between the variables. $r = -1$ implies a perfect linear negative correlation between the variables.
- $r = 0$ indicates that there is no linear component in the relation between the variables.

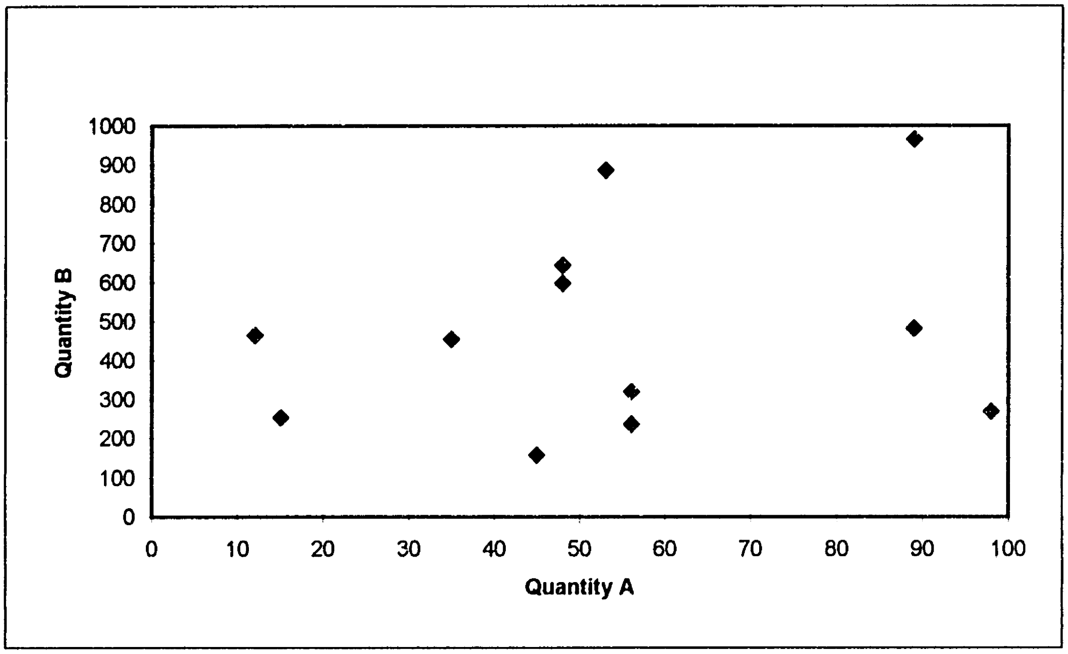


Figure 6 - Example of scatter plot.

Correlation coefficients and other moment based statistics are very sensitive to the presence of outliers - points separated widely from the main body of data. It is relatively easy to identify outliers using scatter-plots. Their explanation can be as simple as typing errors, or complicated features of the process that did not receive adequate attention. Outliers deserve special attention because if they are not the result of typos, measurement or gross instrument malfunction, they can provide useful hints about the process.

Much of the data required for the study of navigation risks comes in time series. Good examples are visibility conditions, wind speed and tide level measurements. They result as a sequence of value recordings of a given characteristic of the process taken consistently at fixed time intervals. Whenever such data is available for a process, it is possible to gain some insight about its future behavior, using time series analysis. For the purpose of our study, clues about future development of waterway traffic or environmental conditions can be obtained by implementing auto-correlation. The latter represent a form of time series analysis were information can be extracted by examining the relationship between a series and its own past history [27]. It is done by constructing pairs of the quantity values separated by a fixed time interval, and looking for a strong correlation between them. For instance, consider a time series of monthly measurements of visibility conditions, obtained for a number of years. Each pair will be composed of two monthly values that are a year apart, or any other desired time interval. If there is a strong correlation between the past and the present, we can assume that this will continue to some degree in the future. Thus we can infer the value of visibility that is likely to be observed during a given month using the corresponding values of that same month over the previous years.

Predictive statements like the one above are conditional as well, because they are based on the assumption that the observed behavior will continue in the future [27]. There are many possible ways to produce predictive statements given a set of data. For instance, the time interval may be a month, two months or a year, as in the short discussion above. All these prediction rules are associated with an error, the deviation between prediction and actual value. Calculating the errors of any two rules applied to the available provides a basis for comparing their relative performance. For example, we can examine the pairs of monthly measurements of visibility conditions using the one year interval rule. We denote by a_i the actual value, by p_i the predicted value and by pe_i the prediction error corresponding to month i. The prediction error then equals:

$$pe_i = a_i - p_i \quad (6.7)$$

We can obtain a population of n prediction errors, for which mean and standard deviation values can be computed. It is then possible to calculate the root mean square prediction error (PMSPE) based on the following formula:

$$RMSPE = \sqrt{\overline{pe}^2 + s_{pe}^2} \qquad (6.8)$$

Repeating this process with rules using other intervals, we can calculate the corresponding RMSPE values. The rule with the smallest RMSPE is expected to produce the most accurate predictions.

6.2 Discussion Of Risk Modeling

6.2.1 About the nature and scope of Bayesian statistics

In the previous section we presented a brief discussion on the branch of statistics that is known as descriptive statistics. This major branch represents a body of techniques providing the means for effectively organizing, summarizing and communicating large amounts of data. The statistics employed for the analysis of the different potential risk contributing factors that will be presented in chapter 9 are descriptive.

The other two major branches of statistics are the following: inferential statistics and statistical decision making theory. The term "inferential statistics" refers to the body of methods employed for arriving at conclusions that extend beyond the immediate data [53]. Such methods are useful, for example, in answering questions of the following type: "what can be inferred about the taste preferences of any given population based on limited information regarding the taste preferences of a small subset of that population?". In general, in situations where limited data is available, inferential statistics provide the means for drawing conclusions or making predictions. Sometimes, however, conclusions or predictions are not the end of the story. There are cases where the decision maker needs to choose among a number of alternative actions based on the information at hand. Such a situation may arise by extending the previous example about the prediction of the taste preferences of a given population. Assume that the marketing department of a food company considers a number of alternative products to be introduced in a given market. Further, assume that because of production constrains not all products can be introduced. The marketing department has to choose the product that best fits the market preferences in order to maximized the return on the investment involved in the development of the selected product. Under such circumstances, statistical decision theory can provide the means for choosing the best alternative based on the limited information about the taste preferences of a small subsection of the market.

Whether inference must be drawn or actions must be chosen based on limited information, uncertainty is the common denominator. When uncertainty is accompanied by some kind of sustainable loss or damage, risk becomes an issue, as discussed in chapter 4. To reduce the amount of uncertainty and possibly risk involved in any inferential or decision making problem, the Bayesian approach to statistics attempts to utilize all available information. The underlying characteristic of this approach is its ability to combine legacy data with newly acquired information. The formal mechanism employed for this combination is known as Bayes' Theorem and involves the use of probabilities to represent the uncertain quantity. As new information is made available these probabilities are revised accordingly to incorporate the newly acquired knowledge. Uncertainty, either inferential or decision making, stems from not having the complete set of information necessary to draw the right conclusions or choose the right action. By constantly incorporating new information, the Bayesian approach brings the statistician one step closer to that complete set of information. This way the amount of inferential and decision making uncertainty can be reduced, providing the means for more efficient risk management, assuming that risk is involved.

In their book "Bayesian Theory", J.M. Bernardo and A.F.M. Smith [55] provide the following answer to the question about the scope and nature of Bayesian statistics:

> "Bayesian statistics offer a rationalist theory of personalistic beliefs in contexts of uncertainty, with the central aim of characterizing how an individual

> should act in order to avoid certain kinds of undesirable behavioral inconsistencies. The theory establishes that expected utility maximization provides the basis for rational decision making and that Bayes' theorem provides the key to the ways in which beliefs should fit together in the light of changing evidence. The goal, in effect, is to establish rules and procedures for individuals concerned with disciplined uncertainty accounting. The theory is not descriptive, in the sense of claiming to model actual behavior. Rather, it is prescriptive, in the sense of saying "if you wish to avoid the possibility of these consequences you must act in the following way"."

6.2.2 Important concepts on probability

As implied earlier, the concept of uncertainty is very important in the context of statistical inference and decision. De Finetti [55] argues that uncertainty is the only relevant thing and implies that it can be perceived as the extent of our own knowledge and ignorance. Assuming that probability is the mathematical language of uncertainty [53], we need to spend some time discussing a few important concepts involved in the theory of probability. The following discussion goes beyond the one presented in section 6.2. Section 6.2 focused on concepts important in descriptive statistics, while the current will concentrate mainly on inferential statistics issues.

By definition, uncertainty becomes an issue when the *true situation* is not known for certain. However, if a problem is well-defined, it should be possible, even under uncertain conditions, to predict a variety of possible outcomes. An "event", in the context of statistics, is any set or class of such potential outcomes. There are two kinds of events: elementary and compound. An event is said to be elementary if it cannot be decomposed into a number of "smaller" events, as opposed to the compound event that is a collection of elementary events. For example, assuming that one is interested in the number of groundings in the port Boston during any given month, the event "exactly two groundings" is an elementary, while the event "two or more groundings" is a compound one. The set of all elementary events of a given uncertain situation is called the sample space or event space. Coming back to the previous example, the sample or event space is defined as the set of all possible numbers of groundings that may occur in any given month. Theoretically, this event space can be represented by zero and the positive integers. In practice, however, no more that a given small number of groundings are likely to occur within any given month.

Following the definition of the event space, the next thing to consider are the probabilities associated with the different events of which this event space is composed. Probabilities can be developed in the form of an abstract mathematical system, based on certain fundamental axioms. Robert L. Winkler [53] provides the following informal version of these axioms of probability:

1. The probability of an event E, denoted as $P(E)$, can assume only nonnegative values.
2. Assuming that the event space (the set of all possible events) is denoted with S, then the probability of S, written as $P(S)$, is equal to one.

3. Assuming that two events E_1 and E_2 are mutually exclusive (they cannot both occur), the probability that at least one of these two events will occur is equal to the sum of their individual probabilities $P(E_1)$ and $P(E_2)$.

Figure 7 illustrates these axioms using a Venn diagram that represents probability with area. The outside rectangle represents the entire event space S while the inside geometric figures, circles in this case, represent any two possible events E_1 and E_2. The first axiom is illustrated by the fact that the area of each circles representing any possible event cannot be negative. The second axiom states that the area of the outside rectangle is equal to one. The final axiom reflects the fact that if any two non-overlapping figures are considered then the total area is equal to the sum of their individual areas.

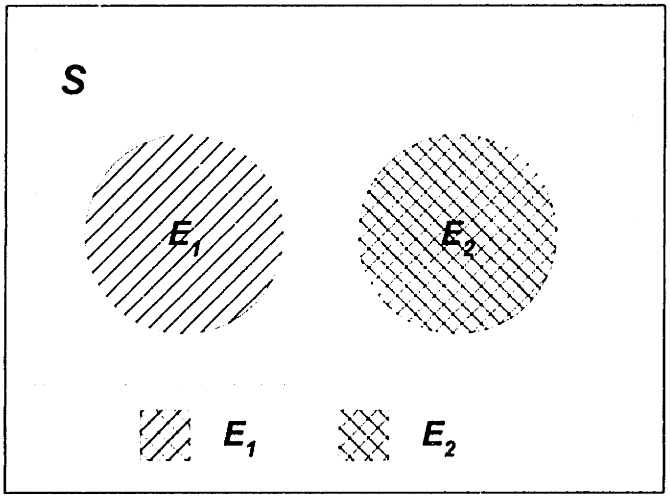


Figure 7 - Event space and probabilities.

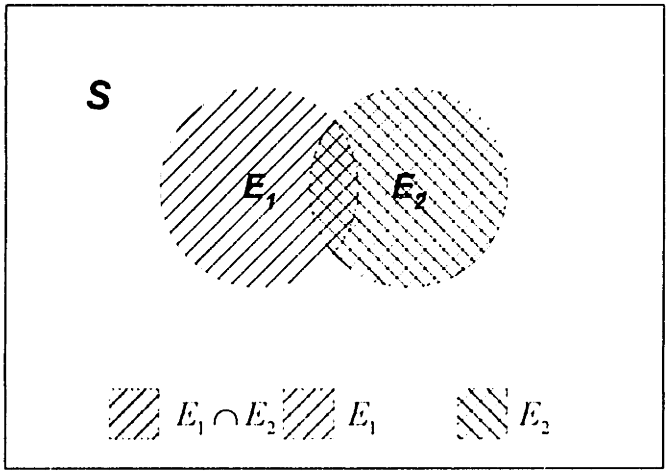


Figure 8 - Intersection of events.

Before continue it will be helpful to provide three fundamental definitions of set theory terminology in order to facilitate better communication. First, the event "*E_1 or E_2* (or both) will occur" is called the union; the event "*E_1 and E_2* will occur" is called the intersection; and third the event "E does *not occur*" is called the complement of E and is denoted by a tilde E. These three definitions are illustrated in Figures 7, 8 and 9 respectively.

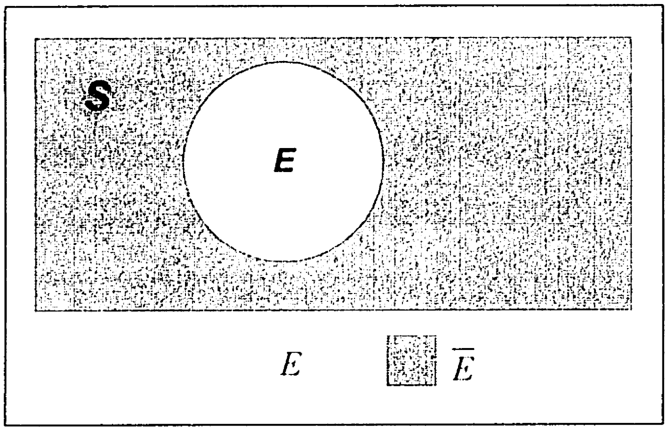


Figure 9 - An event and its complement.

Following the above stated basic axioms of the theory of probability, many theorems useful for calculating actual probability values can be deduced. The most interesting of these elementary rules of probability, in terms of the present discussion, are the following:

- The probability of any event is a number between zero and one, inclusive:
$$0 \leq P(E) \leq 1 \quad (6.9)$$
- The probability of the complement of an event is equal to:
$$P(\overline{E}) = 1 - P(E) \quad (6.10)$$
- The probability of the intersection of two events is equal to:
$$P(E_1 \cup E_2) = P(E_1) + P(E_2) - P(E_1 \cap E_2) \quad (6.11)$$

Probabilities so far have been presented as an abstract mathematical system where, given certain probabilities, others can be computed using the rules of probability theory, some of which have been presented above. However, there are more ways to interpret probability: classical, logical, frequency (or statistical) and subjective. In the preface of his two-volume "Theory of Probability", De Finetti attempts to present the essence of the first three different views [55]. The relevant extract is provided below:

> "... The main points of view that have been put forward are as follows.
> The classical view, based on physical considerations of symmetry, in which one should be obliged to give the same probability to such "symmetric" cases. But which symmetry? And in any case, why? The original sentence becomes meaningful if reversed: the symmetry is probabilistically significant, in someone's opinion, if it leads him to assign the same probabilities to such events.
>
> The logical view is similar, but much more superficial and irresponsible inasmuch as it is based on similarities or symmetries which no longer derive from

> the facts and their actual properties, but merely from the sentences which describe them, and from their formal structure or language.
>
> The frequentist (or statistical) view presupposes that one accepts the classical view, in that it considers an event as a class of individual events, the latter being "trials" of the former. The individual events not only have to be "equally probable", but also "stochastically independent" ... (these notions when applied to individual events are virtually impossible to define or explain in terms of the frequentist interpretation). In this case, also, it is straightforward, by means of the subjective approach, to obtain, under the appropriate conditions, in a perfectly valid manner, the result aimed at (but unattainable) in the statistical formulation. It suffices to make use of the notion of exchangeability. The result, which acts as a bridge connecting the new approach with the old, has often been referred to by the objectivists as "de Finetti's representation theorem".
>
> It follows that all the three proposed definitions of "objective" probability, although useless per se, turn out to be useful and good as good as valid auxiliary devices when included as such in the subjectivist theory. ..."

The subjective interpretation regards probability as a measure of degree of belief, or as the quantified judgment of a particular individual. De Finetti clearly states this subjectivity by arguing that "the actual fact of whether or not the events considered are in some way determined, or known by other people, and so on, is of no consequence". In a sense, subjective probability was developed to facilitate discussions about probability when the frequency viewpoint does not apply [56]. The latter is true for the case of assigning probabilities to events of non-repetitive nature. It may be possible using the frequency approach to determine the probability of getting a head on a coin toss. It is expected that over a long series of tosses, heads will be observed about fifty percent of the time. The same approach may be followed for determining the probability of drawing a red ball from a box containing a mix of forty red and sixty blue balls, where the ball is replaced in the box before the next drawing. It is reasonable to expect that after a long series of drawings a red ball should come up about forty percent of the time while a blue should come up about sixty percent of the time. The assessment of probability in both situations is based on an important theorem of probability theory known as "the law of large numbers". This theorem states that if an experiment is repeated many times under identical conditions, the probability of the occurrence of any event is likely to be close to the relative frequency with which that event had occurred throughout the experiment. Using formal notation the above can be stated as follows:

$$P\left[\left|\frac{r}{n} - P(E)\right| \geq \varepsilon\right] \rightarrow 0 \text{ as } n \rightarrow \infty \qquad (6.12)$$

where n denotes the number of experiment repetitions, r denotes the number of occurrences of the event E, $P(E)$ denotes the probability of that event E and ε is any arbitrarily small positive number. In the long run the relative frequency of the event E will get closer and closer to the probability $P(E)$.

However, when trying to assign probability to an event such as a vessel grounding, it is not possible to set up an experiment that in the long run will provide a good indication of the grounding probability. Even if there were not social or economical constraints in setting up such experiments, the problem would still be there. Such events are unique and the exact conditions under which they occur are very difficult, if possible, to duplicate. There may be certain information available regarding past occurrences in similar situations, but it is unlikely that such information could be useful in developing observation frequencies for the entire set of identical conditions. For example, many vessel groundings may occur throughout any given year but each one will occur under a different set of conditions. As discussed later, there are some factors that have been identified as having an influence on vessel groundings: wind speed, visibility, vessel type, and crew. It may be possible to develop a frequency distribution of groundings under given wind speed conditions, another for given visibility conditions and so on. However, it will be difficult, if possible at all, to develop a frequency distribution of groundings for a given combination of all these and possible other influential factors.

The question "how can we determine subjective probability?" remains unanswered. The process that needs to be followed is not as theoretically straightforward as the calculation of frequency probability. In general, subjective probability can be determined by retrospection. The simplest way of determining subjective probability is through the comparison of the probable events to obtain an estimate of their relative likelihood. In this respect, a given event E can be compared, for example, with its compliment. If E is thought to be three times as likely to occur as its compliment, then it is possible to calculate the subjective probabilities using the formula:

$$P(E) = \frac{a}{a+b} \qquad (6.13)$$

where a are the odds in favor of the event and b the odds in favor of its complement. Thus, for the specific example the subjective probability of the event E is equal to:

$$P(E) = \frac{3}{3+1} = \frac{3}{4}$$

Another way for determining subjective probability is the construction and use of hypothetical bets. The goal of such betting scenarios is the determination of the probability $P(E)$ through the imaginary involvement in a gamble where z will be lost if the event E occurs, while $(1\text{-}z)$ will be gained if the complement of the event E occurs $(0 \leq z \leq 1)$. A proper value of z must be selected in order to have a fair gamble. The "fairness" of the gambling game is achieved by setting the following utility function equal to zero [56]:

$$Expected\_Utility = U(-z) \cdot P(E) + U(1-z) \cdot (1-P(E)) = 0 \qquad (6.14)$$

The previous equation can be solved for $P(E)$ yielding:

$$P(E) = \frac{U(1-z)}{[U(1-z) - U(-z)]} \qquad (6.15)$$

where U is the utility function that provides a quantification of the decision maker's preference or value pattern. For small values of z the utility function can be considered approximately linear, and thus the subjective probability of the event E takes the following approximate form:

$$P(E) \cong 1 - z \qquad (6.16)$$

Both these approaches provide strong evidence for the use of subjective probability in the process of uncertainty quantification. However, they are not considered valuable as operational devices for determining subjective probability. There are other processes more suitable for this task; these will be presented later on.

6.2.3 The decision problem and Bayes' Theorem

J.M. Bernardo and A.F.M. Smith [55] define the decision problem as any situation in which choices are to be made among alternative courses of action with uncertain consequences. The structure of any decision problem is determined by three basic events:

(i) a set $\{a_i, i \in I\}$ of available actions, one of which is to be selected;
(ii) for each action a_i, a set $\{E_j, j \in J\}$ of uncertain events, describing the uncertain outcomes of taking action a_i;
(iii) corresponding to each set $\{E_j, j \in J\}$, a set of consequences $\{c_j, j \in J\}$.

The structure of the decision problem presented above can be thought of in the following way. Assume that from the set of available alternative actions, an action a_i is chosen. Then one and only one of the uncertain events E_j, $j \in J$, will occur and will lead to its corresponding consequence a_i. According to J.M. Bernardo and A.F.M. Smith [55], each set of events $\{E_j, j \cdot J\}$ forms a partition (an exclusive and exhaustive decomposition) of the total set of probable events. In Figure 10, decision trees are employed to represent the decision problem schematically.

A rational individual is expected to select one of the alternative actions a_i based on the information currently available concerning the decision problem at hand. That selection can provide some insight about that individual's perception of the state of uncertainty expected to result from his choice. The decision maker forms a partition $\{E_j, j \in J\}$ of the total set of relevant possible events according to the information available at any given point in time. Any additional information might change the perception of uncertainty and therefore lead to modification of the partition $\{E_j, j \in J\}$ and possibly the selection of the alternative action a_i. It is important to understand that Figure 10 captures the structure of the decision problem as perceived by a particular individual at a specific point in time.

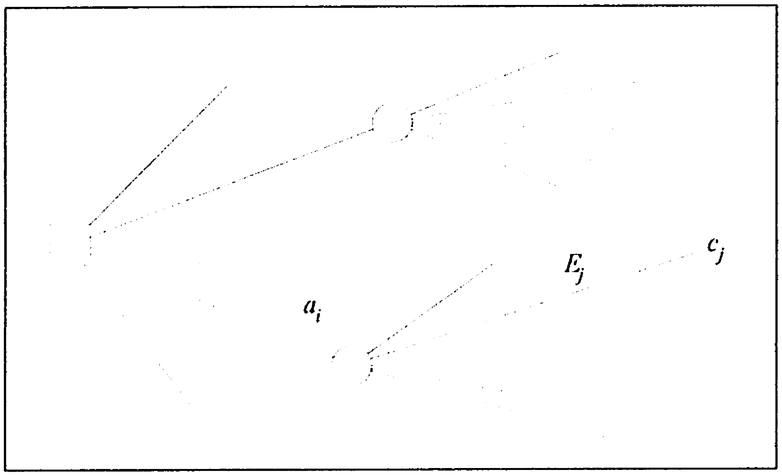


Figure 10 - Decision tree.

Thus the preference of the uncertain scenario that results from the choice of one among alternative actions depends on the attitude towards the consequences involved and the assessment of the uncertainties attached to the corresponding events [55]. Earlier in this section three elements employed for representing the structure of a decision problem were discussed. However, these elements do not capture the idea of preference introduced above. Therefore, a forth element of the decision problem might be necessary to fulfill the task:

(iv) The relation $\leq$, which expresses the individual decision-maker's preferences between pairs of available actions, so that $a_1 \leq a_2$ signifies that a_1 is not preferred to a_2.

Assume at this point that a partition of uncertain events $\{H_j, j \in J\}$ corresponds to an exclusive and exhaustive set of hypotheses (events) about some aspects of the world. Further, assume that an event D corresponds to a relevant piece of evidence, or data that is available to the decision maker. On the basis of these assumptions we have the following definitions [55]:

(i) $P(H_j), j \in J$, are called the prior probabilities of the $H_j, j \in J$;
(ii) $P(D \mid H_j), j \in J$, are called the likelihoods of the $H_j, j \in J$, given D;
(iii) $P(H_j \mid D), j \in J$, are called the posterior probabilities of the $H_j, j \in J$;
(iv) $P(D)$, is called the predictive probability of D implied by the likelihoods and the prior probabilities.

Using these definitions Bayes' Theorem is stated as follows [55]:

For any finite partition $\{H_j, j \in J\}$ of Ω and $D > \varnothing$,

$$P(H_i|D) = \frac{P(D|H_i) \cdot P(H_i)}{P(D)} \qquad (6.17)$$

In the above mathematical expression $P(H_j|D)$ is the posterior probability of a single event H_i belonging to any finite partition $\{H_j, j \in J\}$ of the certain event Ω. The predictive probability $P(D)$ can be calculated using the following formula [55]:

$$P(D) = \sum_{j \in J} P(D|H_j) \cdot P(H_j) \qquad (6.18)$$

and characterizes the way in which the initial beliefs concerning the hypotheses $P(H_j)$, $j \in J$, are modified by the acquisition of data D, into a revised set of beliefs $P(H_j|D)$, $j \in J$.

Equation 6.17 presented Bayes' Theorem in terms of a discrete probability model, where the uncertain quantities correspond to discrete random variables. For example, consider the operation of an engine. In this case the uncertain event, the engine's operation, can be represented as a binary variable that assumes one of the two discrete values: working properly or malfunctioning. There are cases, however, where the uncertain quantities can be represented by continuous random variables. A good example to illustrate that case is the temperature within an engine, which conceptually can assume an infinite number of values. For such problems where continuous probability models are involved, Bayes' Theorem can be stated in the following form [53]:

$$f(\theta|y) = \frac{f(\theta) \cdot f(y|\theta)}{\int_{-\infty}^{\infty} f(\theta) \cdot f(y|\theta) \cdot d\theta} \qquad (6.19)$$

In the equation above, the densities $f(\theta|y)$ and $f(\theta)$ represent the posterior and prior distribution, respectively, of the uncertain quantity θ, while $f(y|\theta)$ represent the likelihood function. Generally speaking these are mathematical functions for calculating posterior and prior probabilities as well as likelihoods for certain values of the continuous variables θ and y. The probability density function of any variable x must always satisfy the two basic axioms of probability theory that were discussed in the beginning of the chapter:

$$f(x) \geq 0 \text{ for all } x \text{ and } \int_{-\infty}^{\infty} f(x) \cdot dx = 1 \qquad (6.20)$$

The denominator of equation (6.19) represents the marginal density $f(y)$ that is not generally known but can be calculated from the following formula:

$$f(y) = \int_{-\infty}^{\infty} f(\theta) \cdot f(y|\theta) \cdot d\theta \qquad (6.21)$$

The application of Bayes' Theorem for the calculation of posterior probabilities is simple once certain information is available. Posterior probabilities are essentially conditional probabilities of the occurrence of the uncertain event given that some experimental evidence concerning the situation has been acquired. The decision maker first has to select the uncertain quantities of interest and then assess their prior probability distributions and likelihoods. The difficulty in developing Bayesian models lies in the process of assessing prior probability distributions and likelihoods, that is discussed in the following subsection.

6.2.4 Prior probabilities and likelihoods

The prior probabilities should reflect the prior information that is available to the decision maker concerning the uncertain quantities. They consist of a set of values of the uncertain quantity, together with the corresponding probability of observing any of these values. This prior information usually has the form of expert knowledge or sampling results. However, no matter what form the prior information may have, the ultimate assessment of prior probabilities relies on the subjective choice of the decision maker. Thus, it can be assumed that the prior probabilities are subjective probabilities.

If prior information is available only in the form of expert knowledge, then the assessment of prior probabilities most likely will be performed through comparison of the possible alternatives or the use of imaginary bets. Both these approaches were presented earlier. However, their value as operational devices may be questionable because they lack an acceptable level of formality. More systematic approaches may be considered for assessing prior probabilities if the available prior information has the form of sample results. In such cases prior probabilities can be selected to represent the observed relative frequencies. For example, lets consider a manufacturing line that produces mechanical shafts. The shafts coming out of that line can be either A, B or C grade. Members of the first category are premium quality products supplied to first tier car manufacturers. Second grade shafts have some defects but are usable and cover the needs of second tier car manufacturers. Shafts characterized as C are not usable and need to be scrapped. If there is no quality control process in the manufacturing line then the only people who can provide some information on the probability of having a shaft of certain grade are the machinists. Presumably their experience is such that they can be engaged in a comparison of the three probable outcomes or an imaginary game. The goal from such an engagement will be the assessment of the prior probability for each grade. In this case prior information is available only in the form of expert knowledge that complicates the probability assessing process. If there is some kind of quality control and product sampling then, after a given period of time, an adequate set of sampling results may be available. In such cases it will be possible to construct relative frequencies of each grade as observed in the sampling process and assign them as prior probabilities of the corresponding product grades. These probabilities will provide a good starting point for the purpose of Bayesian analysis and can be revised later on to capture any available expert knowledge.

The assessment of prior probabilities based on sampling results is a relatively simple process. The first thing to be done is the construction of histograms to represent these results. If the uncertain quantity can be represented by a discrete variable then each one of the histogram bars will depict the observed frequency of that particular value. If the uncertain quantity needs to be represented by a continuous variable, then things are more complicated. The statistician must divide the range from which the variable assumes values into smaller intervals and find the frequency of observations falling in each of them. These frequencies will be presented in the histograms as bars of corresponding intervals. Figure 11 illustrates the concept of frequency histograms. In the case of continuous probability models, one can fit a smooth curve to develop the prior probability density function $f(\theta)$.

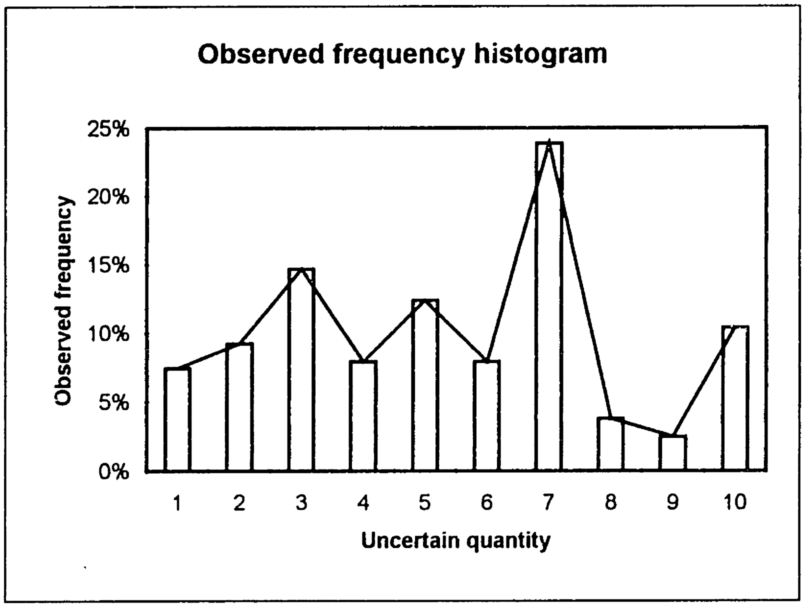


Figure 11 - Sample histogram.

Following the assessment of prior probability, distribution likelihoods need to be determined. Using the notation introduced earlier, likelihoods can be interpreted as the probabilities of observing an information D given a particular event or hypothesis H_j, $j \in J$. The determination of likelihoods depends on the problem at hand more the assessment of prior probability. Thus, it will be discussed in section 7.5 in the context of the grounding risk.

Note that there are occasions where the process under investigation may be regarded as a Bernoulli, Poisson, Normal, or any other standard process. In such cases both the prior probabilities and likelihoods can be approximated by corresponding standard probability distributions. The output of these models then can be introduced to Bayes' Theorem for the determination of the posterior distribution. Such approximations will not be employed in the modeling of grounding risk because enough data is available for the application of more direct methods like those discussed in the following subsection.

Chapter 7. Physical Risk Of Ship Grounding

7.1 Definition And Discussion Of The Physical Risk Of Ship Grounding

7.1.1 Definition

The risk of ship grounding can be divided into two main components: physical risk and economic risk. Physical risk is the risk of an incident occurring, e.g. the probability of a ship going aground under particular environmental or loading conditions. Economic risk is the resulting risk of economic loss (broadly defined), given that a physical incident has occurred, e.g. the loss associated with a tanker going aground in a particular setting. One measure of total risk exposure is the product of the two components.

7.1.2 Factors affecting the physical risk of grounding

The probability of an adverse event occurring during ship transit depends on numerous and complex variables and their interactive effects. To determine what must be done to improve marine safety, the effect of all risk factors must be understood and effectively addressed.

Marine safety authorities acknowledge that most of these factors are poorly understood, and that they have not been able to establish guidelines for what level of risk is acceptable for use in planning waterway improvements [18]. Most operational risk assessments that have actually been conducted are related to operating company liability and insurance, and are not available to safety authorities for performing marine safety assessments [21]. Consequently, acceptable levels of risk are determined subjectively and vary widely among localities. Considering the complexity of the marine operating environment and the substantial differences in operational risk and exposure among vessels, even within the same port and waterways complex, this might not be that negative. However, directing attention at subsystems and results of accidents, rather than at the overall system, too often causes the symptoms of the problems to be addressed instead of the roots of the problems themselves. The result of this approach is symptom-based safety improvement measures and ineffective allocation of resources. On the other hand, making broad assumptions about similarities between localities might cause problems as well. Solutions that reduce risk in one operating environment may not achieve equivalent results in another. In fact, inappropriately applied solutions might make the system more complex, increasing the risk of an accident.

On a practical level, risk in vessel operations is determined on a case-by-case basis, typically during the course of operations, by the pilot or the master. Mariners think in terms of threats to vessel safety from traffic and environmental conditions. To protect themselves, they must constantly identify, assess, and respond to actual or potential threats and conduct operations to reduce exposure. Their performance reflects, among others, their accumulated experience, and the planning and risk reduction measures of their operating companies. However, according to the National Research Council's study "Minding the Helm" [21], there is a general lack of understanding, even within the marine industry, of the nature and variability of risk factors that are present in port, waterway and river operating environments.

Marine transportation has over the past several decades changed in both form and character. Marine traffic has become more dense and diverse, and ships and barges have become bigger and more unwieldy. Rapid development in technology, competition and public concern has been accompanied by increases in operating costs and in the costs of marine accidents. With these changes there has been a shift in risk and in the relative importance of risk factors. For instance, improvements in navigation channels to ensure adequate margins of safety for maneuvering lag years behind the changes in vessel design and operating characteristics [5]. At the same time, modern ship propulsion systems have sacrificed maneuverability in favor of fuel economy [21].

Measured in terms of marine casualties, the operational safety of ships has improved overall. But with the increasing age of commercial fleets and the continuing low profit margins in the industry, it is questionable how long this trend will continue. In addition, the risk in marine transportation has not been reduced as much as casualty statistics might suggest. While the probability of an accident may have decreased, the actual cost of the average accident has increased, counteracting the decrease in the total risk of an accident. (Risk is the product of probability and consequence.) In particular, during the 1980s the marine industry appears to have failed to recognize the significant change in cost of accidents due to the limited number of high consequence accidents [21].

Change is needed to meet the new challenges of public expectations. Determining how to reduce operational risk without creating unwarranted economic burdens on operating companies and public resources is a substantial challenge. Several new navigation systems have been developed recently that potentially could be employed to reduce the probability of accidents (and improve operational efficiency). These technological developments can provide dramatic improvements in position fixing, steering, information display, and hazard avoidance [21]. However, as mentioned earlier, inappropriately applied solutions can lead to increased risk. Therefore, to best employ these new technologies, their effect on waterway risk and the total navigation system must be investigated.

The objective of our Ship Transit Risk Project is to develop a procedure for estimating the risk of grounding during a ship's transit of a particular region (such as a port approach). The modeling approach employed for the purpose is based on historical casualty data and is discussed later in section 7.5. The grounding probability calculated from accident incidence data represents a state of knowledge based on past occurrences recorded in the accident database. Therefore, the probabilistic risk is an estimate of actual risk and testable against continuing experience. The probability model, being strongly data driven, can appropriately address the risk significance of combinations of different risk factors and can also address cross-waterway problems [39]. The results are useful for examining the effects of operational changes and for deciding if a new technology should be introduced. (The risk analysis identifies the major contributor to the risk of grounding. This knowledge can be used to guide risk reduction efforts.)

The explanatory variables must be found among the factors that affect the physical risk of grounding. These factors have been identified in several earlier studies (Port Needs Study [4]; Minding the Helm [21]; the Waterways Management Research & Planning Project [18]; Screening for Environmental Risk, Washington State Office of Marine Safety [40]; and Tanker Environmental Risk [37]). For our purpose[1], the waterway risk factors can be divided into four main groups: *human factors, physical waterway characteristics, vessel characteristics, and accident specific factors.*

The human factors group covers the human part of the vessel system from crew to vessel management procedures. Issues incorporated in this group are suitability, qualifications, and proficiency of crew members and support system personnel. In addition, the category covers work environment on-board, decision patterns, maintenance demands, vessel manning standards and quality, experience and procedures of the ship management company.

The physical waterway characteristics group covers the factors that define the "static" waterway. These factors are due to the nature of the area and to systems developed by humans over a long time. The factors are independent of what kind of ship the risk model is being employed for, and are not easily manipulated or altered on a short term basis. Examples of such factors are *environmental conditions* (weather, currents, tide, etc.), *waterway geometry and configuration* (width, depth, turns, obstructions, etc.), *traffic densities* (transits per route mile, ship scheduling, etc.), *navigation aids and support systems* (man made, natural, chart quality, notice to mariners, etc.), and *route characteristics* (route length, duration, etc.).

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[1] Note that we are <u>not</u> studying drift groundings, steering failure groundings and intentional groundings.

The physical attributes of the vessel are covered by the vessel characteristics group. Grounding risk in ports, port approaches and waterways varies according to vessel types, sizes, maneuverability and on-board navigation aids. These factors are specific to the type of ship, but also vary according to loading condition.

The last group, accident specific factors, covers the waterway functions which are established to prevent accidents from happening. These functions interact with the ship entering the waterway, and some of the factors in the group are therefore undetermined until we know to what extent the ship will use the functions. The factors in this group include the information about the extent to which the ship interacts with vessel traffic service, if the ship had a pilot on-board, and if the ship was escorted by tugs.

A list of potential factors that affect risk of grounding is given in Appendix A. It must be noted that this list is explanatory and in no way exhaustive. In theory, it is possible to come up with hundreds of factors that may affect the risk of grounding. A significant part of the research conducted by the Ship Transit Risk Group has focused on developing non-dimensional explanatory variables as indicators for the most important factors thought to affect the risk of grounding. While the historical data on circumstances surrounding groundings are neither perfect nor complete, they contain information useful to understanding why groundings occur, and therefore justify the development of a physical risk model. While it would have been beneficial to have information about the many factors that were not recorded in the historical databases, we recognize that data must be collected in a cost-effective way. Risk modeling will always involve imperfect information; the important issue is therefore to recognize the most relevant factors. In the following sections, we will describe which explanatory variables can be created from the historical data and discuss what other data we believe would be beneficial and cost-effective to gather in the future.

7.2 Available Data Sources

As outlined in the previous section, we focused our effort initially on the identification of factors with potential to affect the probability of grounding. Our selection was based on theoretical speculations, resulting from our understanding of the grounding process. Subsequently, we shifted our focus to the collection of data that would be used in the analysis of factors and in modeling their actual contribution to risk. Two kinds of historical data were required for our analysis: information on accidents and information on safe transits. Accident related information was needed for two reasons. First, it was expected to narrow our selection of potential factors to those adequately supported by historical data, and second, to provide insight on the process of grounding. Safe transit information was needed to verify the actual contribution of risk affecting factors and provide the means of prioritizing them according to their importance. The latter is important given that society has limited resources for reducing risk [41].

To develop our database we obtained information from three different government agencies. The U.S. Coast Guard (USCG) investigates the cause of marine casualties and records related information, and provided historical accident data. The U.S. Army Corps of Engineers (ACE), through its Waterborne Commerce Statistics Center, monitors the transit of vessels through waterways, and provided the number of safe passages. Two centers of the National Oceanic and Atmospheric Administration (NOAA), the National Climatic Data Center (NCDC) and the National Geophysical Data Center (NGDC), provided weather information and waterway depth surveys, respectively.

7.2.1 U.S. Coast Guard

Among others duties, the USCG is responsible for the investigation of marine casualties. Since 1981, the USCG has maintained summaries of the causes and circumstances of investigated marine casualties. A computer database called CASMAIN served that purpose from 1981 until 1992. This was the first structured approach undertaken by USCG to collect and statistically analyze data on all serious marine casualties. The project of developing the database was established under the Marine Investigation Division. The result was a relatively flat record structure. In this kind of data structure different incidents are represented by different entries. For each particular entry multiple fields hold different information, for instance the location of the accident, the wind speed and visibility conditions during the accident, etc. These data were gathered mainly by Investigation Officers assigned to investigate and determine the cause of accidents. We are not certain of the exact database structure because we received only a file containing the type of data relevant to our project. Our interest was limited to grounding cases within the five ports mentioned earlier.

In 1992, the USCG introduced a new database, the Marine Investigations Module (MINMOD), to replace the outdated CASMAIN. This was part of a broader system called the Marine Safety Information System (MSIS) which, according to USCG [42], set a milestone in the way marine casualty investigations were reported. The following attributes of MINMOD were considered revolutionary:

- This system first introduced detailed taxonomies for reporting human factor causes. Taxonomies are the tools employed to render accident data into a meaningful set of codes, which could support statistical analysis.
- It included a chain of events analysis of accident causes.
- It introduced an organizational change. Each Investigation Officer (IO) was responsible for entering the casualty data directly into the database. This practice was expected to reduce the number of typing errors when clerks transferred data from paper forms into the system, a major problem of the previous system.

MINMOD was structured as a relational database and was expected to provide more efficient data management. (More information on relational databases will be provided in section 8.2.) We received a copy of MINMOD tables including project related data, which was far more detailed that what was made available to us earlier. However, because

CASMAIN did not provide similar information, we were forced to "ignore" a lot of interesting details. The remaining data were consolidated into a new database covering the period between 1981 and 1995, that was built using Access for Windows 95. Due to problems resulting from the system migration that occurred in 1991, the information concerning the maritime casualties for 1991 are incomplete.

7.2.2 U.S. Army Corps of Engineers - Waterborne Commerce Statistics Center

The Waterborne Commerce Statistics Center (WCSC) operates under the authority of the Rivers and Harbors Act of 1922. Its mission is to collect, process, distribute, and archive vessel trip and cargo data (http://www.wrc-ndc.usace.army.mil/ndc/wcscmiss.htm). Vessel operating companies are obliged under Federal law to inform the center of their domestic waterborne commercial movements. WCSC monitors the movements of the following types of vessels: dry cargo ships and tankers, barges (loaded and empty), fishing vessels, towboats (with or without tow), tugboats, crew-boats and supply boats to offshore locations, and newly constructed vessels from the shipyard to the point of delivery. The data gathered by WCSC is used primarily by the Army Corps of Engineers, or other government agencies. Organizations outside the government and the general public can be provided only with summary statistics that do not reveal the movements of individual companies.

The Quality Control, Products and Services Office, of the Waterborne Commerce Statistics Center provided information on the number of vessel trips by vessel type and draft (in feet). We acquired information only for the five ports of interest. The 1985-1994 data was available in digital format, and received as ASCII (American Standard Code for Information Interchange) files. Hard copies of the *Waterborne Commerce of the United States* publication were provided for the previous period 1981-1984 because no digital records were available prior to 1985.

7.2.3 National Climate Data Center

The National Climate Data Center (NCDC) provides data management and data synthesis services, including data and information dissemination and publication. They are responsible for supporting scientific and technical programs involving remotely sensed and in situ retrospective meteorological and climatological data (http://www.ncdc.noaa.gov). Using data acquisition devices located at airports, the National Weather Service (NWS) (http://www.nws.noaa.gov), also part of NOAA, collects hourly values of certain meteorological and climatological quantities. These values are kept in archives maintained by NCDC. The data gathered is available either off-line, via compact disks and other digital storage media, or on-line, through NCDC's web page (http://www.ncdc.noaa.gov). In both cases, the user can identify the desired quantities, reference locations and time frame, through simple point and click queries. Our search was limited to wind speed and visibility values for the five ports of interest between 1981 and 1995. The results of a particular query can be obtained either as a hard or a digital copy. Because of the particular time frame we were interested in, the CD-ROM version was employed for the acquisition of values between 1981 and 1990, and the on-line request service with off-line delivery for the remaining period. The results came in ASCII file format and were incorporated in our database using customized Access queries and filters.

7.2.4 National Geophysical Data Center

The National Geophysical Data Center (NGDC) manages environmental data in the fields of marine geology and geophysics, paleoclimatology, solar-terrestrial physics, solid earth geophysics and glaciology (snow and ice) (http://www.ngdc.noaa.gov). Part of their effort is the assimilation, storage and retrieval of geophysical data. For that reason they have developed an interactive database management system called GEODAS (GEOphysical DAta System). This system presently handles three types of data: marine track-line geophysical data; hydrographic (bathymetric) survey data; and aeromagnetic survey data. The GEODAS includes database searching software that allows queries based on geographic area, year of survey, institution, platform, cruise, or geographical characteristic. Our interest was limited to hydrographic survey data for the five ports of interest, to be used with Hydrostat, an application discussed below in subsection 8.6.4. These same data are used for the development of the nautical charts employed by mariners in transiting U.S. waterways. The data are available either via a CD-ROM that includes PC-compatible search and retrieval software, or via anonymous FTP (ftp.ngdc.noaa.gov).

7.3 Additional Useful Data

Our work has revealed considerable potential for the development of a grounding risk model, as a risk management tool. The data that were available to our team, through the sources previously described, introduced a certain level of explanatory capability to our risk model. However, we feel that we could have developed a more *accurate* model, if it was possible to acquire additional data that would have allowed further analysis of certain issues like human factors. The information we wished to have, which will be useful for future attempts to model risk, can be divided into four categories: human factors, environment, vessel and accident specific information. Not all of the data mentioned below would have improved the mathematical accuracy of the risk model, as some of them are qualitative in nature. Instead, this information would have enhanced our understanding of the process and helped identify other issues lying in the background, not visible under the present circumstances.

7.3.1 Human factors information

A variety of research has been conducted to determine the relationship between human factors and maritime accidents. The results indicate that approximately eighty percent of these accidents are due to human error [36, 42]. Unfortunately, the data we acquired from the U.S. Coast Guard concerning historical accidents, included little, if any, information on human factors. Therefore, we were compelled to develop a proxy for human factors effects in our model. We decided to use vessel's flag as an appropriate proxy. The reasoning that supported our selection is provided later in section 9.3.

Amrozowicz argues [35] that human failure manifests itself in two different ways: active and latent. In the first case the results of failure are almost immediately noticeable; in the second it usually takes some time. In terms of the operating process in the maritime industry, active failures tend to be more common for onboard crew members than they are for shore based management teams. The reverse seems to be true for latent failure. The fact that crew members are more involved in the everyday operation of the vessel than the management team serves as a reasonable explanation for the previous observation. Crew members are more concerned with the short term implementation of the medium to long term planning performed by shore-based management.

In this respect, future models of grounding risk would benefit from the availability of more information concerning the competency of onboard crew, as well as the professionalism of the management team. Training of officers and the level of authority delegated to them are particularly important issues, as well as regulation concerning the onboard behavior of crew members, such as alcohol and drug use or watch-keeping standards. Also important issues are the operator's familiarity with the waterway, as well as the presence of assisting pilots. Such issues affect substantially not only the risk of grounding (officers training, regulations), but as well the severity of the results once an accident has occurred (delegation of authority for immediate response). On the management team side, it would be important to know the location of headquarters as that affects communications with the vessel and the response time to accidents. One may argue that given the state of today's telecommunications the latter might be irrelevant. However, there are many issues involved in the process of efficiently responding to an accident that are not easily addressable over the telephone line. Other information would include hiring patterns for crew members and officers, mix of the fleet under their management, experience as operators, and any type of certification such as ISO 9000 or the recently established International Safety Management Code (ISM). More detailed discussion on the relation between ISM and the physical risk model is provided in section 10.2.

The above list of information concerning human factors is not exhaustive. We acknowledge that additional data may be required, or found to be more beneficial in future modeling attempts. However, it should also be understood that there are two important problems in the data acquisition process. First, is difficult to gather complete and accurate information on issues like those listed above. A study conducted by the U.S. Coast Guard in August 1994 indicated that "investigation officers do not feel confident of their abilities to identify and report human factor causes of accidents" [42]. Similarly, vessel owners and managers concerned with potential liability are likely to be reluctant to provide accurate information on such issues. Second, even if certain agencies find a way to gather the information, there may be liability associated with the release of such information to third parties like our research team. The liability problem is similar to releasing clinical information of a patient for the purpose of a study on AIDS or cancer. A potential solution to these and other similar problems is expected to be the world wide implementation of ISM, given some conditions that are discussed later in section 10.2.

7.3.2 Environmental information

Two of the six factors we have analyzed for contribution to grounding risk are environmental. Even though one can argue that our current data set provided substantial coverage of environmental issues, we feel that additional and more accurate information would have been valuable (see section 8.5). A future attempt would benefit from having available accurate water current data and tidal level measurements. Both of them may be as important as wind speed and visibility information. Water currents affect the maneuverability of the vessel and tidal levels affect the available navigable water.

7.3.3 Vessel information

Even though our data set included some information about vessel characteristics, only size was consistently recorded. Loading conditions and especially trim and draft values were not included, even though it is understood that they greatly affect the risk of grounding. The reason for not recording such vital and relatively easy to measure information is not clear to us. However, we firmly believe that the acquisition scheme needs to be adapted so that these data are made available for future modeling efforts. It is difficult to assess the importance of chart accuracy without knowing the vessel's draft. It will not make a difference if the charts uncertainty is a meter when we know that the distance between the keel of the vessel and the bottom is more than ten meters. On the other hand, chart accuracy would be vital if the clearance under the keel were only a meter or so.

It would be equally useful to know whether the ship had special navigation equipment like a Global Positioning System (GPS) receiver or electronic chart. Further it would be useful to have an idea of the familiarity the bridge crew had with this equipment. The presence of such equipment, fully utilized by the bridge crew, might affect the importance of other potential explanatory variables, making visibility conditions, for instance, not as relevant.

Finally it would be nice to have some idea about the vessel's classification society, maintenance patterns and prior history. Such information will not add much to the model's accuracy, but will enhance our understanding of the accident causes from a qualitative perspective. For instance, knowing the vessel's classification society might provide useful information of the maintenance standards under which the vessel operates. Similar deductions might be possible through the other kinds of information proposed above.

7.3.4 Accident specific information

In the present context, the term "accident specific information" refers to issues that do not belong explicitly into one of the above categories, but are of interest because of their influence on grounding risk. The presence of pilots and assisting tugs is considered to be of primary importance. Our data set provided some indication concerning both issues, but recording of relevant information is far from consistent. The majority of the accident records were missing the corresponding field or provided incomplete information. For instance, in many cases the presence of tug boats was indicated in the record; however, we do not know their number or their configuration. Thus we were not able to assess their contribution to the maneuverability of the vessel. We believe it would be enlightening to have information on the certification of pilots for the entire study period, as well as the exact number and configuration of tug boats, in addition to an indication of their presence.

Another potentially important factor is the vessel's sailing direction. Knowing whether the vessel is sailing inbound, towards port terminals, or outbound to the open sea, will allow researchers to better utilize information such as wind or water current direction. It might be even possible to investigate the relation, if any, between accidents and crew conditions. For instance, if accidents tend to be more frequent for inbound vessels, then fatigue resulting from a long voyage might be partially responsible for increased risk of grounding.

Finally, communications between the vessel and the management office prior to the accident might reveal potential risk increasing factors. We do not suggest that a future version of the U.S. Coast Guard database should hold audio files with the recorded messages. Nevertheless, we believe that it would be useful to have a qualitative description of the pressure induced to the bridge crew by the shore-based managing team, if any. Such pressure, to make it, for instance, on time to the next port regardless of the present state of the sea, might result in navigational errors due to stress with unpredictable consequences.

7.4 Factors To Be Analyzed

To be able to identify which explanatory variables can be constructed from historical data, we performed a thorough examination of the historical data sources described above. This section provides a brief overview of the factors and indicators of factors that are sufficiently supported by the existing historical data to be included in the vector of explanatory variables. Further explanation of our understanding of these factors, why they might contribute to the likelihood of grounding, and the results of our investigation will be provided in chapter 9.

As mentioned earlier, the task of identifying relevant factors from historical data has occupied most of the project's analytical effort over the past year. While we want to include as many factors as possible in the risk model, we also need to set certain criteria for a factor to be included. First of all, the factor must be sufficiently supported by existing data. By this we mean: information concerning the factor must have been consistently recorded in the accident database; the information must exist for a statistically significant number of accidents; and we must know something about the status of this factor during the safe transits. These criteria enable us to understand the correlation between the factor in the accident mode and in the safe transit mode. The accident records we had access to varied in quality. For some accidents, the records provided detailed information, while for others, fields were missing or provided incomplete information. Although vague conclusions could have been drawn from this inconsistent data, we chose not to speculate about it. However, we hope that further data gathering during the second year of the project will fill some of the gaps and provide us the opportunity to identify more explanatory variables. Another criterion we set for a factor to be included in our analysis was that the factor had to be thought to affect the risk of grounding, or be an indicator/proxy for other factors thought to affect the risk. The following paragraphs briefly describe the factors we identified and some preliminary results concerning the inclusion of these factors in the vector of explanatory variables.

Human factors: Flag

Other things equal, more highly skilled or seasoned operators, and those with better local knowledge, may be expected to experience a lower risk of grounding. The only proxy for this factor that can be readily constructed from historical data is the flag of the vessel. Results from the first year work suggest that this factor is relevant to the determination of grounding probability.

Environmental conditions: Wind and visibility

Other things equal, a transit through an area characterized by poor visibility and strong currents, for example, may be expected to involve a greater risk of grounding than a transit through an area with unlimited visibility and no currents. Two indicators tested to date, wind speed and visibility, show markedly different distributions during grounding events than over the course of the year as a whole, particularly in the Houston/Galveston and Tampa Bay study areas.

Navigation aids and support systems: Chart quality/depth uncertainty

Other things equal, a transit through an area for which perfect charts are available may be expected to involve less risk of grounding than a transit through an uncharted or poorly charted region. Analysis of uncertainty in charted depth using "Hydrostat" software [43] and locations of historical groundings implies that operators' uncertainty about topography have not contributed to the incidence of historical groundings in U.S. ports in recent decades.

Vessel characteristics: Type and size

Other things equal, a more maneuverable vessel may be expected to have a lower probability of grounding than a less maneuverable vessel. The difficulty of obtaining meaningful summary measures of maneuverability suggests that the analysis may have to rely on proxies such as vessel type and size.

7.5 Modeling The Physical Risk Of Grounding

The general hypothesis employed for the development of the physical risk model is that the probability of grounding on a particular transit depends on a set of explanatory variables. The following is a formal description of the proposed model:

> Let G denote the event that a transit results in a grounding, and S the event that a transit is completed safely. Also let
>
> $$X = (X_1, X_2, \ldots, X_P)$$
>
> denote the vector of the explanatory variables. These variables may be categorical (including binary) or continuous. The model attempts to estimate the conditional (posterior) probability of the event G given a specific set of values
>
> $$x = (x_1, x_2, \ldots, x_P)$$
>
> of the explanatory variable vector X. By Bayes' Theorem, this posterior probability can be calculated by the formula:
>
> $$P(G|x_1, x_2, \ldots, x_P) = \frac{L(x_1, x_2, \ldots, x_P|G) \cdot P(G)}{L(x_1, x_2, \ldots, x_P|G) \cdot P(G) + L(x_1, x_2, \ldots, x_P|S) \cdot (1 - P(G))}$$
>
> or for short:
>
> $$P(G|x) = \frac{l(x|G) \cdot P(G)}{l(x|G) \cdot P(G) + l(x|S) \cdot (1 - P(G))}$$
>
> where $P(G)$ is the unconditional (prior) probability of the event G, and
>
> $$L(x_1, x_2, \ldots, x_P|G) \text{ and } L(x_1, x_2, \ldots, x_P|S)$$
>
> are respectively the likelihood of the specific set of values x given a grounding (event G) and a safe transit (event S).

The implementation of the proposed model requires the following two steps. First, it is necessary to define a set of explanatory variables that discriminate between the events G and S [38]. Second, it requires the estimation of the unconditional (prior) probability of grounding $P(G)$ and the likelihoods $L(x|G)$ and $L(x|S)$. Candidate explanatory variables represent the attributes of the transit with a potential to contribute to the risk of grounding. For each chosen attribute, explanatory variables x_i must be extracted from the historical data as numerical or categorical indicators.

We have already discussed the selection of explanatory variables earlier in chapter 7.4. Having decided, to a certain degree, the candidate explanatory variables, the following step is the estimation of their likelihoods and the prior probability of grounding. The estimation of these parameters will be based on the USCG casualty data, the NOAA/NCDC weather data and the ACE/WCSC transit data.

As discussed in the section 6.2.4, in the absence of other prior information, observed frequencies can serve as a good approximation to the prior probability of the uncertain quantities. Thus, it was decided that for this initial approach to the physical risk model, observed frequency would be a proxy of the prior probability of grounding $P(G)$. The frequency of groundings is defined as the number of groundings per year. For that purpose annual grounding figures will be divided by annual transit figures and then the average of the resulting estimates will be averaged for the entire study period. Annual grounding and transit figures will be provided in section 8.4.

The process of estimating likelihoods is a little more complicated. Unlike the uncertain quantity that can be represented by a discrete variable, binary in particular, not all the explanatory variables are discrete. Some of them, such as wind speed and visibility, are better described as continuous, while others, such as vessel's type, are better described as discrete. Whether the explanatory variables are discrete or continuous, the estimation of their likelihoods will follow the same pattern. As discussed earlier, the likelihood $L(x_i|G)$ can be thought of as the probability of observing the value x_i of the explanatory variable X_i given that a grounding (event G) has occurred. The interpretation and estimation process of $L(x_i|S)$ are similar. Thus, the estimation of the likelihood $L(x_i|G)$ can be done by developing the observed frequencies of the variable x for all the grounding incidents. These frequencies can be calculated using the histogram approach discussed in the previous subsection for the assessment of prior probabilities. If necessary, especially in the case of continuous variables, the probability density function can be calculated by fitting a smooth curve between the resulting pairs of values (or value intervals) and corresponding observation frequencies.

However, in the model described earlier, the calculation requires the joint likelihood $L(x_1,x_2,\ldots,x_P|G)$ and not the individual $L(x_i|G)$. If the explanatory variables can be considered independent then the joint likelihood $L(x_1,x_2,\ldots,x_P|G)$ can be calculated from the individual likelihoods $L(x_i|G)$ using the following attribute of independent probabilities:

$$L(x_1,x_2,\ldots,x_P|G)=\prod_{i=1}^{P}L(x_i|G)$$

It may be reasonable to assume independence between certain explanatory variables, like vessel type and wind speed, but not for others, like wind speed and visibility. For such cases and in general to avoid unnecessary assumptions of the previous type, it is better to estimate likelihoods simultaneously. The latter process can be described as follows. For the sake of simplicity, assume that we have two explanatory variables x_1, and x_2 that are continuous in their respective domains $D_1=\{x_{1,min}, x_{1,max}\}$ and $D_2=\{x_{2,min}, x_{2,max}\}$. We divide each domain in smaller adjacent intervals $d_{1,i}$ and $d_{2,i}$ so that:

$$D_1 = \bigcap_i d_{1,i}, \; D_2 = \bigcap_i d_{2,i}$$

$$\text{and } \bigcup_i d_{1,i} = \varnothing, \; \bigcup_i d_{2,i} = \varnothing$$

Assume also for simplicity that the scheme followed for dividing the domains D_1 and D_2 results in ten intervals in each case. Then we have to estimate the observation frequencies for every combination the intervals $d_{1,i}$ and $d_{2,i}$. The result of this process for the case of two explanatory variables will be a probability surface. This surface will assign a probability value to each pair of values of the two explanatory variables. The process can be easily extended in the case of more than two explanatory variables as in the case of modeling the physical risk of grounding.

Having developed a prior probability distribution for groundings and the joint likelihood distribution of the explanatory variables, it is easy to apply Bayes' Theorem to calculate the posterior probability distribution of groundings.

Chapter 8. Data Compilation

8.1 Description Of The Input

As mentioned earlier in chapter 7.2, the data used for the analysis of grounding risk was drawn from the historical databases of three U.S. government agencies. The U.S. Coast Guard (USCG), National Oceanic and Atmospheric Administration (NOAA) and U.S. Army Corps of Engineers (ACE) provided data on accidents, environmental conditions, and safe transits, respectively. In addition to the structured input received from these agencies, unstructured input in the form of local expert knowledge was acquired through visits by team members at three of the ports. The latter form of input was underutilized during the first stage of the project that focused on the development of the port-level model of risk. It is expected, though, to be more valuable during the following stage when localized analysis of risk will be performed.

8.1.1 USCG Historical Accident Data

The input received from USCG concerning the historical accidents came in two different parts. The first part covered the period between 1981 and 1990. It consisted of data drawn from CASMAIN, the original casualty reporting system employed by USCG. The second part covered the period between 1992 and 1995 following the database migration that occurred in 1991. The data included in the latter part came out of the successive casualty reporting system, called MINMOD.

The difference between these two parts goes beyond the different time frames they cover. Each one represented the different design philosophy embodied in the corresponding accident reporting system; flat versus relational database models. The first part came in the form of a single table that aggregated all the information that was available on a particular accident and was deemed important enough to be included in the database. The second part came in a more sophisticated form comprised of several interrelated information tables. In this case, a more rational conception of the different entities involved in an accident was employed to group together the data that was available.

Table 1 provides a brief description of the different data groups included in the CASMAIN file. Table 2 provides a brief description of the different data tables we acquired from MINMOD. A detailed description of the fields included in each of these tables was omitted for conciseness. We feel that the length of such a description would be disproportional to the rendered insight.

Table 1 - Brief description of the CASMAIN fields.

Data fields group	Description
Event	Information concerning the incident; case number, date, period of day, latitude and longitude, number of vessels involved, number of vessels damaged.
Vessel	Information concerning the vessel(s) involved in the accident; identification number, name, flag, year built, service, primary physical characteristics, propulsion system characteristics, vessel condition, vessel use, operator, classification society, previous vessel names, vessel inspection verification, date of inspection, Marine Safety Office responsible for certification.
Weather	Information concerning the environmental conditions; wind speed and direction, visibility, sea conditions, weather conditions.
Investigation	Information concerning the investigation that followed and the findings; office responsible for the report, day report entered database, type of report, nature and cause of the accident (multiple levels), determination of vessel's seaworthiness.
Pilot and tugs	Information concerning the presence of pilot on board the vessel and assisting tugs; name of the pilot company, assisting tug configuration.

The input from both these data sources was provided in fixed-width text file format. These files had the data arranged in rows corresponding to different entity entries and fixed-width columns corresponding to the different data fields that were available for each entry. Fixed-width format allocates a certain number of character positions for data entry in each field. For example, if the vessel name field in the CASMAIN table had a width of ten then the information entered in this field could be up to ten characters long. An alternative to the fixed-width file format is the delimited text format, were different fields are separated by commas, spaces, tabs, semicolons or other characters. The environmental data acquired from NOAA came in delimited text format.

The entries in both CASMAIN and MINMOD were not restricted only to grounding incidents. All kinds of accidents were included, and groundings represented a good percentage of the total cases. Since our work was focused only on groundings, all the other entries needed to be removed. The process of manipulating the original data to keep only those deemed useful for the development of the grounding risk model is outlined in the section 8.3.

Table 2 - Brief description of the MINMOD tables.

Table Name	**Important types of information included**
Marine Casualty and Pollution Master Record (CIRT)	Information concerning particular incident; Marine Safety Information System (MSIS) case number, date, time, location, latitude and longitude, type of the reporting source, date investigator endorsed report, incident type (whether grounding, collision, explosion, etc.), casualty class (major, serious, public, etc.), environmental impact mode.
Vessel Supplement Record (CIVT)	Information concerning the vessel(s) involved in particular incidents; MSIS case number, identification number, name, flag, type of service, status (towed, moored anchored, underway), position of the tow configuration, evaluation of seaworthiness.
Facility Supplement Record (CIFT)	Information concerning the facilities involved in particular incident, if any; MSIS case number, facility name, type, status.
Marine Casualty Event File (CEVT)	Information concerning the nature of particular incident; MSIS case number, sequence of events, nature of incident (fire, capsize, flooding, grounding accidental, grounding intentional, personnel casualty, etc.).
Marine Casualty Causal Factor File (CCFT)	Information concerning the cause of particular event; MISI case number, event chain, cause of the event, details of cause category, causal party, first causal event, second causal event.
Marine Casualty Collision and Grounding File (CCGT)	Information concerning particular incidents involving grounding or collision; MSIS case number, vessel/facility identification number, speed at time of casualty, location where impact occurred, double bottom or double hull.
Vessel Casualty Structural Failure File (CSFT)	Information concerning particular incidents involving structural failure; MSIS case number, classification of failure mode, type of failure mode, structural failure pattern type.
Marine Pollution Substance File (CPDT)	Information concerning potential pollution substances involved in particular incident; MSIS case number, CHEM ID code (based on CHRIS code), single character indicating substance type (C=chemical, P=petroleum based products, G=garbage, N=natural substances, etc.), quantity of potential substance spilled, quantity of substance recovered, units of measure, substance name.
Personnel Injury and Death File (CPCT)	Information concerning particular incidents involving personnel injury or death; MSIS case number, involved party identification number, name, date of birth and position, party missing or died indicator, type of accident, result of injury, body part injured, accident location, type of equipment involved, time of party involved in the industry, time of party involved with company, time of party involved in present position.
Fire and Explosion File (CFET)	Information concerning particular incidents involving fire or explosion; MSIS case number, vessel identification number, fire location, source of ignition, source of fuel, presence of smoke detectors.
Weather Supplement (CWXT)	Information concerning weather conditions during particular incidents; MSIS case number, vessel/facility identification number, wind speed, visibility, sea state.

An important observation concerning MINMOD is that all tables include the "MSIS Case Number" field The table "Marine Casualty and Pollution Master Record" represents each of these incidents as a single entry. That particular field serves as the "primary key" of that table. The "primary key" is a field or a combination of fields whose value or values uniquely define each record in a table. In the case of the "Marine Casualty and Pollution Master Record" table, the value stored in the "MSIS Case Number" field uniquely defines each accident in the database. The "MSIS Case Number" field in the other tables serves as a "foreign key". A "foreign key" in one table is a field or a combination of fields that relate to the "primary key" of another table, defining unique relationships between these two tables.

Table 3 - Description of fields in NCDC weather data.

Extraterrestrial horizontal radiation	Amount of solar radiation in Wh/m^2 horizontal surface at the top to the atmosphere during the 60 minutes preceding the hour indicated.
Extraterrestrial direct normal radiation	Amount of solar radiation in Wh/m^2 received on a surface normal to the sun at the top of the atmosphere during the 60 minutes preceding the hour indicated.
Global horizontal radiation	Total amount of direct and diffuse solar radiation in Wh/m^2 on a horizontal surface during the 60 minutes preceding the hour indicated. (9999=missing data)
Direct normal radiation	Amount of solar radiation in Wh/m^2 received from the sky (excluding solar disk) on a horizontal surface during the 60 minutes preceding the hour indicated. (9999=missing data)
Total sky-cover	Amount of sky dome (in tenths) covered by clouds. (99=missing data)
Opaque sky-cover	Amount of sky dome (in tenths) covered by clouds that prevent observing the sky or higher cloud layers. (99=missing data)
Dry bulb temperature	Dry bulb temperature in degrees Celsius. (9999=missing data)
Dew point temperature	Dew point temperature in degrees Celsius. (9999=missing data)
Relative humidity	Relative humidity in percent.(999=missing data)
Station pressure	Station pressure in millibars. (9999=missing data)
Wind direction	Wind direction in degrees (N=0° or 360°, E=90°, S=180°, W=270°). (999=missing data)
Wind speed	Wind speed in m/s.(9999 or 99.0=missing data)
Visibility	Horizontal visibility in kilometers.(777.7=unlimited visibility, 99999=missing data)
Ceiling height	Ceiling height in meters.(777.7=unlimited ceiling height, 999999= missing data)
Present weather	Present weather conditions denoted by 9 indicators.
Precipitable water	Precipitable water in millimeters.(9999=missing data)
Broadband aerosol optical depth	Broadband aerosol optical depth on the day indicated.(99999 = missing data)
Snow depth	Snow depth in centimeters on the day indicated. (9999=missing data)
Days since last snow fall	Number of days since last snowfall.(88=88 or more days, 999=missing data)
Hourly precipitation	In inches and hundredths for each hour that precipitation was reported.

8.1.2 NOAA Historical Environmental Data

NOAA provided our research group with input on environmental conditions; weather conditions (wind speed and visibility) and waterway depth surveys. The weather data were drawn from the National Climatic Data Center (NCDC) database and the depth surveys were provided by the National Geophysical Data Center (NGDC). As mentioned earlier, the historical environmental data received from both these centers came in the form of delimited text files. In this format the different entries in the file are arranged as separate rows and the data available for each entry are separated by delimiters; commas, spaces, tabs, semicolons, etc.

Wind and Visibility

The wind speed and visibility hourly values came in two parts. The first covered the period between 1981 and 1991 and was available on CD-ROM that included a search engine. Operating that engine through a simple interface, we were able to specify the atmospheric quantities we were interested in, as well as the desired period of time, and locations of wind speed and visibility measurements. The result came in separate ASCII files, one for each of the measurement locations closest to the ports of interest. Wind speed and visibility data for the period 1992 to 1995 were not yet available on CD-ROM, therefore, the second part came in diskettes. These diskettes included output from NCDC databases in compressed ASCII files. The queries that were employed by the NCDC personnel to develop these output files were provided by our team and matched those used in drawing data from the CD-ROM. Table 3 provides a short description of the weather data that are recorded hourly by NWS and archived by NCDC.

Depth Measurements

The hydrographic survey data was provided on CD-ROM that included the GEODAS (GEOphysical Data System) search engine. The search engine enabled us to download the National Ocean Service (NOS) hydrographic surveys we were interested in by specifying area in latitude/longitude, year range of surveys and/or NGDC survey number. The search engine also contained a plotting function so that we easily could see on a map which areas the surveys covered, see Figure 12.

NGDCs Hydrographic Survey Database includes surveys by NOS, providing the most accurate and extensive digital bathymetric data available for the coastal waters of the continental United States, Alaska, Hawaii and Puerto Rico/Virgin Islands. We were only interested, at this stage, in the newest hydrographic survey data for the five ports mentioned earlier (Boston, New York/New Jersey, Tampa, Houston/Galveston, and San Francisco). Each survey we downloaded comprised one Header record and multiple Data records. The Header record documents both the content and the structure of the subsequent Data records, containing that part of the data that remains invariant throughout the survey. Table 4 provides an example of this data.

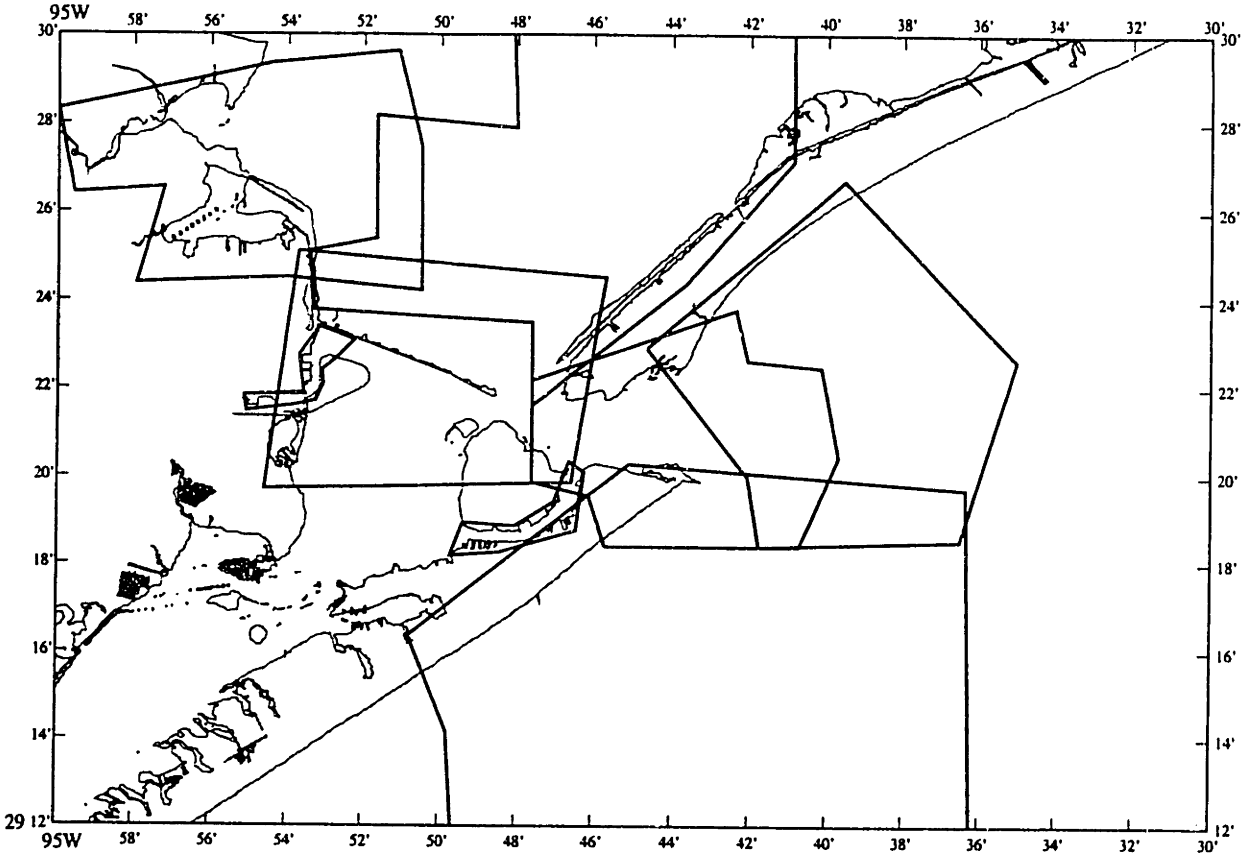


Figure 12 - Plot of a GEODAS search covering the Houston/Galveston area.

The Data records present hydrographic data with corresponding positions. Documentation that varies within the survey is included with these data records. The hydrographic survey data is stored in the HYD93 exchange format and each ASCII data file contains a series of 37-character Data records for a particular survey operation. Table 5 is a detailed description of the Data records.

Table 4 - Header record information describing the hydrographic survey.

Source institution	Organization which collected the data
Survey year	Start and end year of survey work
Quality of survey description	e.g. "Adequate" or "complete"
Position determination	Method of determining horizontal position (e.g. GPS system)
Horizontal datum of records	e.g. North American Datum 1983
Vertical datum of records	e.g. Mean Lower Low Water
Average tide range	in meters for survey area
Sounding method	e.g. digital echo sounder
Data processing methodology	e.g. digitized smooth sheets

Table 5 - Description of the Data record for a hydrographic survey.

Character Numbers	Type	Description
1-8	Character	Survey identifier (e.g. NGDC number)
9-17	Real	Latitude x 1,000,000 (+ = North; – = South)
18-27	Real	Longitude x 1,000,000 (+ = East; – = West)
28-33	Real	Depth value x 10 in meters
34	Integer	Value type code (defines depth type)
35-37	Integer	Cartographic code (describes type of record)

To be able to use the survey data as input for the Hydrostat program (described in section 8.6) we first decoded the Data records into plain latitude, longitude and depth records using a simple FORTRAN program and then transformed the geographic coordinates into rectangular coordinates. This transformation was done by using a geodetic-to-Universal Transverse Mercator (UTM) coordinate conversion program provided to us by the Canadian Hydrographic Service (CHS). A geodetic-to-UTM transform is one that relates UTM coordinates to a geodetic latitude-longitude coordinate-system using a reference spheroid to define the shape of the earth. Hence, the Transverse Mercator projection represents ellipsoidal positions (latitude and longitude) as grid coordinates (easting and northing) on a cylindrical surface.

8.1.3 ACE Safe Transits Data

The Waterborne Commerce Statistics Center provided annual summaries of the waterborne commerce statistics for the years 1981 to 1994. These statistics were developed using data on safe transits of vessels through each of the study ports. The data were developed by counting the number of vessels passing through the different waterways of any particular port and were grouped in three ways: vessel direction (inbound or outbound), vessel type (dry bulk or tanker, self-propelled or towed, etc.) and vessel draft (in feet). Table 6 provides a short description of the codes used for the distinction of vessels according to type and movement direction.

Table 6 - Field codes used for the distinction of vessels in ACE database.

Code name	Description
USDRY	Upbound / Inbound trips of self-propelled dry cargo vessels.
USTANK	Upbound / Inbound trips of self-propelled tanker vessels.
USTOW	Upbound / Inbound trips of towboats / tugboats.
UNDRY	Upbound / Inbound trips of no-self-propelled dry cargo (barges) vessels.
UNTANK	Upbound / Inbound trips of no-self-propelled tank (barges) vessels.
USDRY	Downbound / Outbound trips of self-propelled dry cargo vessels.
DSTANK	Downbound / Outbound trips of self-propelled tanker vessels.
DSTOW	Downbound / Outbound trips of towboats / tugboats.
DNDRY	Downbound / Outbound trips of no-self-propelled dry cargo (barges) vessels.
DNTANK	Downbound / Outbound trips of no-self-propelled tank (barges) vessels.

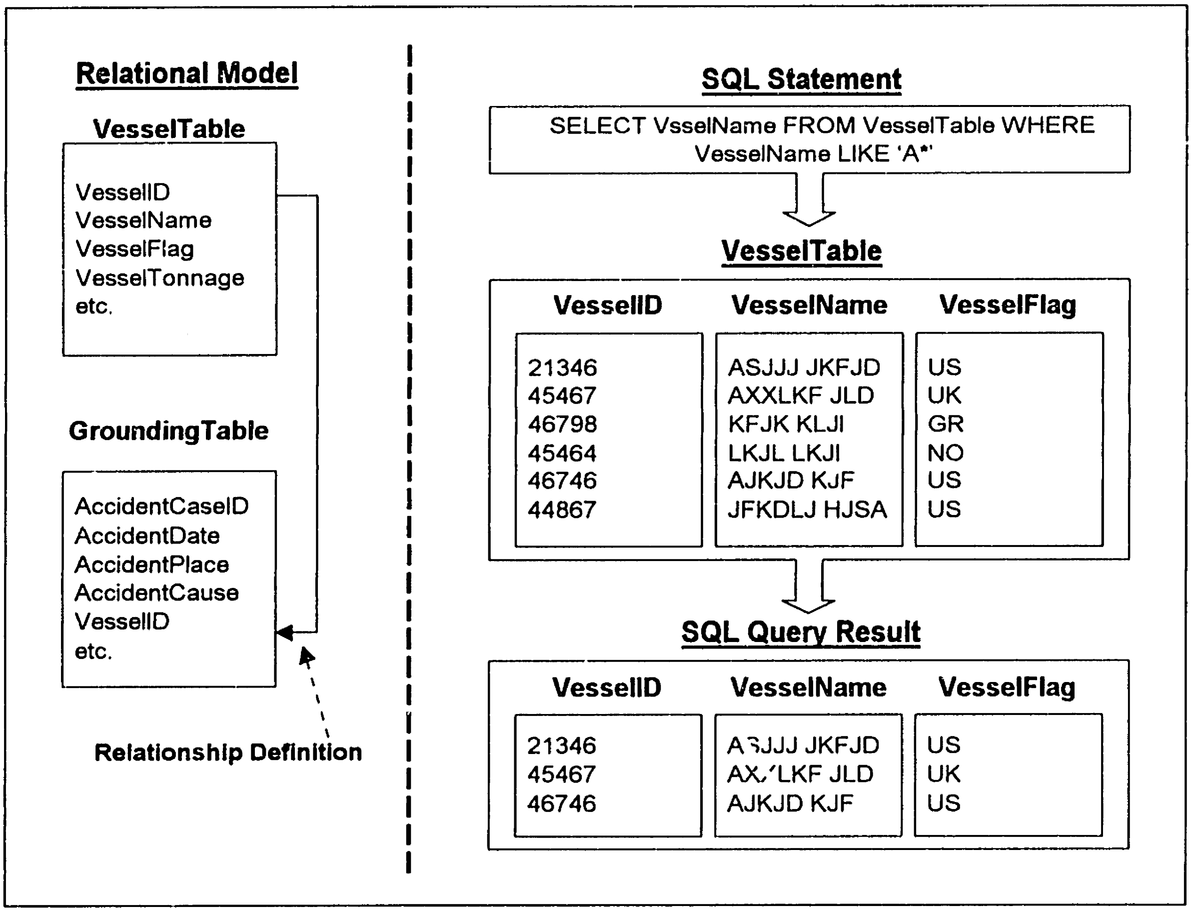
The data was obtained in two parts. Two computer diskettes arrived including data for the calendar years 1985 to 1994 using fixed-width text files. Data was arranged in rows corresponding to the different waterways of each port that were involved in the vessel counting process. Information for the calendar years 1981 to 1984 was not available in digital format. Instead WCSC provided a copy of the Trips and Drafts of Vessels tables from the Waterborne Commerce of the United States publication.

8.2 Microsoft Access For Windows 95

8.2.1 Selecting Application Development Platform

The diversity of the data sources we expected to utilize for the development of the grounding risk model seemed to be a serious problem from the beginning of the project. The diversity stemmed from the fact that three agencies, USCG, NOAA and ACE, were expected to provide information using different data formats. Therefore it was not possible to build our research effort on any of the data managing applications these agencies had developed to support their own functions. The only alternative was to develop our own application, in which we would be able to import and consolidate the acquired data. More than one option was available for the development tools we could utilize to build such an application: a data management system, a spreadsheet, or a combination of statistical software and programming language.

The most important attribute of the development platform was its inherent ability to manage data using the relational database model. This is based on set theory and predicated logic, and was conceived in 1969 by E.F. Codd, then a researcher at IBM [44]. Briefly, a relational database represents different classes of entities - real world objects or events - using unordered tables. Any two such tables are associated with each other through relationships representing real world links between the corresponding entities. For instance, vessels involved in groundings belong to one class of entities, while the groundings themselves belong to another. A relational database will hold information on each of these entities using two separate tables, one for vessels and a second for groundings. Each row of these tables holds particular attributes concerning one member of the corresponding class of entities. For example, the vessel table may include data such as vessel's identification number, draft, length, breadth, name, etc. Likewise, the grounding table may include an official case number, incident date and place, cause, number of vessels involved, etc. These two entities have a real world link; each grounding involves at least one vessel. A simple way to represent this link in the database model is to include the vessel's identification number in the corresponding entry of the grounding table. Then, using Structured Query Language (SQL) statements, it is possible to extract the desired information in a meaningful form. The following is a simple SQL statement example: SELECT VesselName FROM VesselTable WHERE VesselName LIKE 'A*'. According to this statement, the relational database will return all the entries from the vessel table that satisfy the following condition: the name of the vessel starts with the letter "A". Figure 13 provides a simple illustration of the relational model and a corresponding SQL statement.



```
SELECT VsselName FROM VesselTable WHERE
VesselName LIKE 'A*'
```

VesselID	VesselName	VesselFlag
21346	ASJJJ JKFJD	US
45467	AXXLKF JLD	UK
46798	KFJK KLJI	GR
45464	LKJL LKJI	NO
46746	AJKJD KJF	US
44867	JFKDLJ HJSA	US

VesselID	VesselName	VesselFlag
21346	ASJJJ JKFJD	US
45467	AXXLKF JLD	UK
46746	AJKJD KJF	US

Figure 13 - The relational database model and a sample SQL statement.

The benefits realized by the introduction and implementation of the relational model are numerous compared with the alternative of a flat database model. Here are the most important of them [44]:

- More efficient data entry, updates and deletions.
- More efficient data retrieval, summarization and reporting.
- More predictable behavior of the database due to better formulation.
- Easier and more efficient changes of the database schema.

The alternative to a relational model is a flat database with a single table holding all available information relevant to the incident itself, the vessel involved, etc. We did not find that alternative appealing, because of its low efficiency in terms of data manipulation. Furthermore, a flat database provides limited capabilities for future expansion of the data model. Initially we were expected to concentrate on two entities, the grounding itself and the vessels involved, because of limited data. However, we anticipated having more data in the future and needed to develop an application that could easily incorporate that data, once it became available, independent of the data format.

Two other attributes of the prospective development platform were deemed to be important as well. In order to avoid the use of more than one software tool during the course of the project, we thought it would be convenient if the selected platform had build-in statistical functions and some programming capabilities. The entire project was based on the statistical analysis of historical data to identify potential risk contributing factors that would be useful in a model for grounding risk. If the development platform did not provide statistical functions, we would have to export the data, analyze it using other software, and import back the analysis results. That process is time consuming and involves a lot of software compatibility problems, all of which could be easily avoided. Also, the development of the grounding risk model was expected to require certain computer programming effort. If the platform provided programming capabilities, we could save ourselves a lot of time trying to transfer data between different software tools and resolving compatibility issues.

Another long term objective of our project was a provision for the availability of the grounding risk model over the Internet. According to that provision, the prospective users would have to be able to remotely access and execute the risk model through a World Wide Web (WWW) interface. The objective was to develop a client/server application using the Internet as the networking medium. The application server side, set up initially in one of our computers, would include the HTTP (Hyper Text Transfer Protocol) [45] server and the risk model with its historical database. The HTTP server would be running in the foreground, serving as middle-ware between the end user and the risk model. The latter would be running in the background. On the client side of the application, a standard HTML (HyperText Markup Language) [45] browser would be acting as the user interface. Under this scenario, another attribute of the software development platform was deemed to be essential in terms of our final choice. We were looking for easy WWW connectivity, for platforms that supported standard data gateway protocols to HTTP servers leaving only customization to be performed by the application developers.

Reviewing the alternatives mentioned in the beginning, it seemed that a relational database management system (RDBMS) was most suitable for the development of our application. First, this platform certainly supported the relational database model. Second, the availability of build-in statistical functions was about to become a standard for that particular class of applications. Third, many commercial RDBMS software packages provided adequate programming capabilities beyond a version of SQL (Structured Query Language), which was almost mandatory. Finally, due to the rapid expansion of the Internet, many RDBMS providers were either supporting or planning to support the kind of WWW connectivity we were looking for. After a quick market research, the runner-up RDBMS were: Access (Microsoft Corp.), Approach (Lotus Corp.), Paradox (Borland International Inc.), Visual Basic (Microsoft Corp.), Powerbuilder (Powersoft Corp.), and Delphi (Borland International Inc.). The last three were more powerful than the others; however, that came at the cost of higher programming effort, which was not desirable.

Among the remaining three, Microsoft's solution prevailed. Access won several awards as the best product in the desktop database category for the year 1995. Computer specialized press called Access the "holy grail" of database vendors [46]. It was the only product providing both ease of use for beginners and considerable power for demanding developers. As reported by PC Magazine: "it had always straddled the line between end users and developers" [47]. Furthermore, it was the only desktop database that was a member of a larger database family that included Microsoft Visual FoxPro and Microsoft SQL Server. We considered that, along with Microsoft's reputation, to be a sound guarantee for the future in terms of application upgrade availability and compatibility with emerging Internet standards.

Access was considered powerful enough to support our application development requirements for the initial stage of the project. Because we anticipated having more historical data in the near future, which would allow further refinement of our risk model, it was expected that Access would not be adequate to support our model beyond a certain point of maturity. At that point, we could easily migrate to one of the more powerful development platforms available from Microsoft, like the SQL Server, with the least possible effort, because Access and the other Microsoft family members share a lot of common technology. Furthermore, we were about to select a tool for developing an application intended to become available on the World Wide Web. At that time, the World Wide Web was on the verge of big changes; new players kept flocking into the software industry, pushing hard on Internet based technologies. However, given Microsoft's leadership in the software industry, we could rest assured that Access and other Microsoft products would support emerging Internet technology.

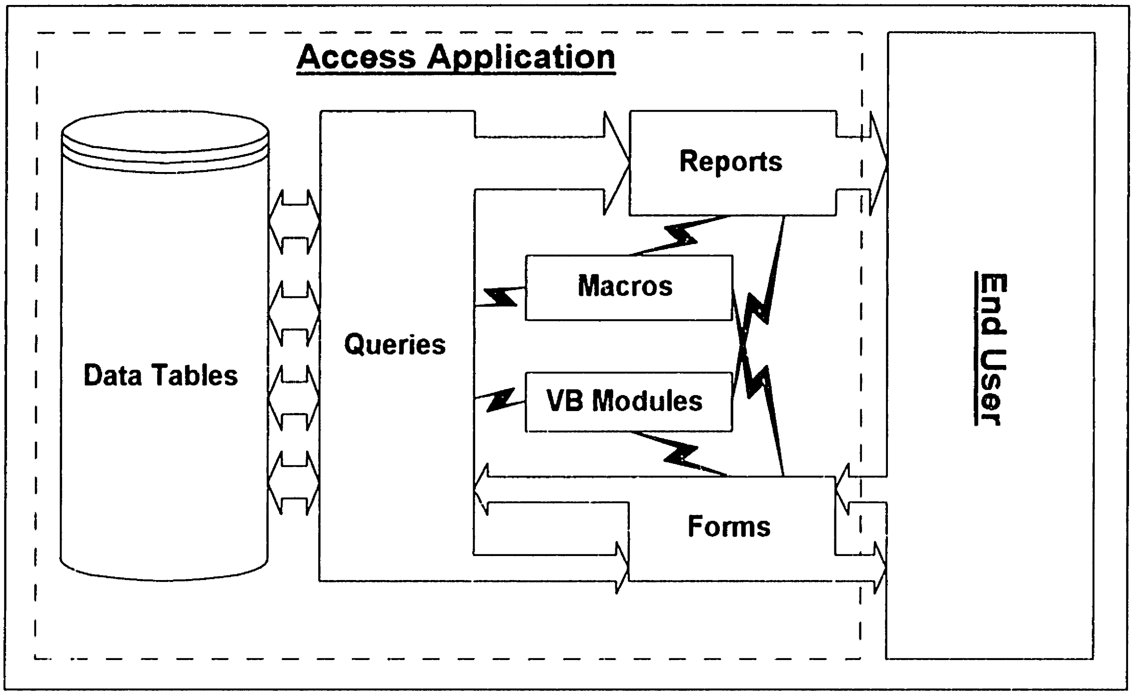


Figure 14 - Access Application Model

8.2.2 Access Operation Basics

Figure 14 illustrates the general model that is employed when developing applications with Access. Every application is a collection of different objects and events. The term *object* in the context of Access refers to tables, queries, forms, reports, macros and modules, as well as the things they contain, like data fields, indexes, and controls. All these objects exist in the database explorer, Access's main window. Figure 15 provides a snapshot of the database explorer for a particular example: NOAA Weather Information 81-90. The term *event* refers to the change in the state of objects that occurs when actions are performed by a user, a program or the computer. For example, an event would occur as the result of pushing a button using the mouse.

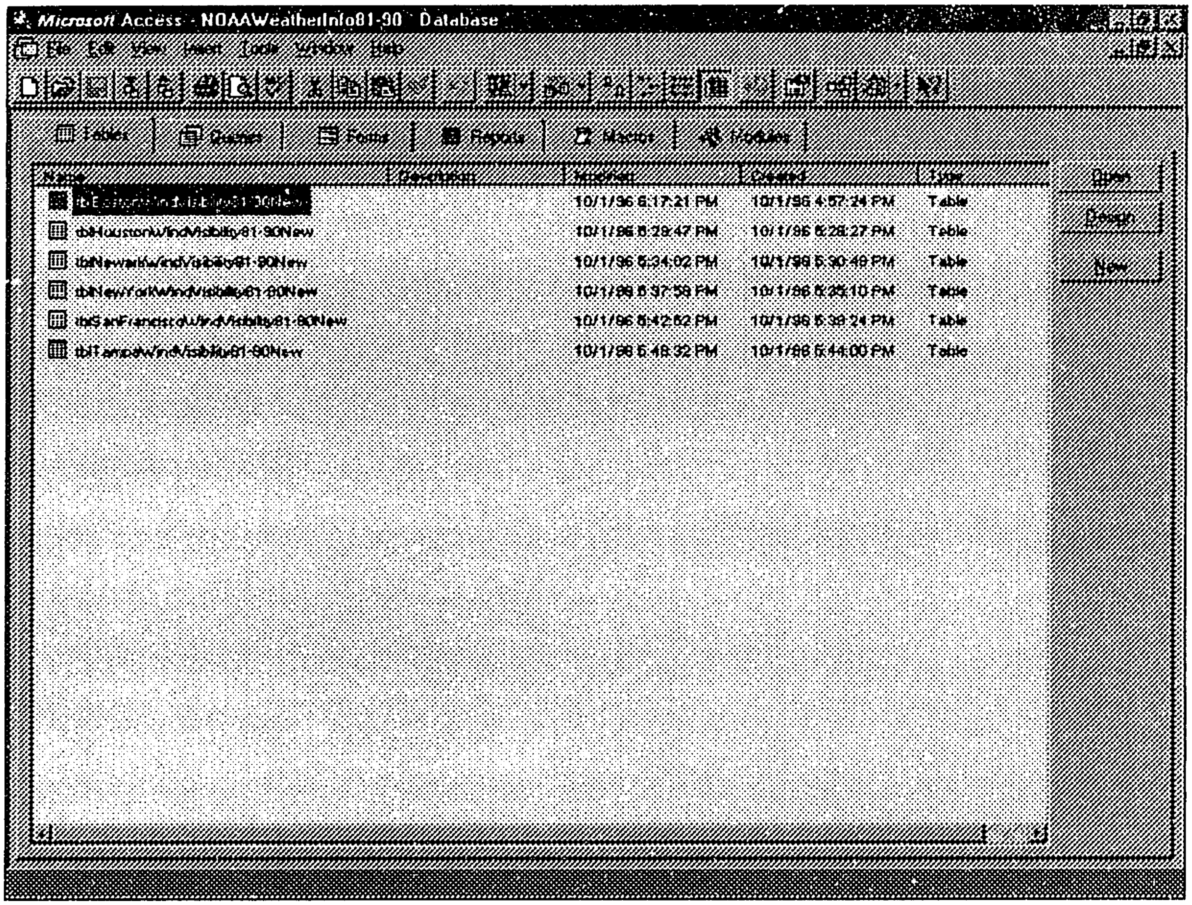


Figure 15 - Access 95: a snap shot of the main window.

To build an application using Access, one needs to take some fundamental decisions about the application design and then follow a series of basic steps. The most important decision concerns the entities that will be represented through the relational model and the information recorded for each of these entities. Once the decisions are made, the corresponding database tables can be designed. Each table must be designed to hold information about a particular entity, to avoid duplication of data and make data management more efficient. Access provides special table wizards and templates for fast results. Caution must be exercised at the entity identification and table design stage because the efficiency of the entire application depends heavily on these decisions. For example, in our applications we have selected vessels to be one class of entities and groundings to be another. The vessel table was then designed to hold information like vessel name, identification number, tonnage, flag, etc. A serious design flaw would have been, for example, to include the investigator's name in the same table. Then, we would have to enter the same piece information many times, because the same investigator might have been involved in many accidents. Multiple entries of the same information are generally prone to typing errors, which in turn can lead to serious problems when performing data queries.

Table design is followed by the development of queries. Access supports a subset of the ANSI SQL standards. One can built queries either directly by writing SQL statements, or indirectly through the Query by Example (QBE) model. Queries are used for viewing, modifying and analyzing the data that is stored in tables. The most important kinds of query types available in Access are the following [44]:

- *Select queries*: The most common type of queries, used to retrieve data from one or more tables and display the results in a data-sheet. They can be used to group records and calculate sums, counts, averages, and other types of totals.
- *Crosstab queries*: They are used to display summarized values (sums, counts, and averages) from one field in a table and group them by one set of facts listed down the left side of the datasheet and another set of facts listed across the top of the datasheet.
- *Action queries*: They are used for making changes to many records in just one operation. There are four types of action queries: make-table, delete, append, and update.
- *Parameter queries*: They are used when on-the-fly data manipulation is required. They are based on predefined searching criteria without specific values. The values to be used for a specific run must be provided by the user through a dialog box prompting for information.

Even though a perfectly functional Access application can be developed using only tables and queries, the utilization of forms, reports, and macros can make such an application more ergonomic and certainly more elegant. Forms can be used for a variety of purposes. We can create data-entry forms to type information in the database tables, switchboards to navigate through the different parts of an application, or dialog boxes to prompt for user defined information for the execution of data queries. Reports provide the most effective way of presenting large quantities of data to the user, either on the computer monitor or through the printer. Even though the end user can interact directly with tables and queries, it is more efficient if this interaction is accomplished through forms and reports. Therefore, both forms and reports are usually associated with either tables or queries.

In order to improve further the human-application interaction, macros can be utilized. They provide the ability to automate common tasks that include a series of sequential and standardized actions, like those involved in printing the results of a query. Macros offer a simple way to take care of certain details such as opening and closing forms, showing and hiding toolbars, and running reports. They render the ability to tie together different database objects. In general, macros are easy to use because they don't involve complex syntax. They should be used for: custom menu bars; running other macros or procedure from a button on a toolbar; and carrying out an action or series of actions when a database first opens.

Macros can provide adequate automation to an application developed using Access, within some limits. When the maturity of the application goes beyond a certain point, and more complicated tasks need to be performed, then *Visual Basic for Applications* (VBA) modules will provide a better solution. The risk modeling application is a good example. Macros will be used to perform simple operations like opening and closing menus, or customizing simple forms. However, in order to build the mathematical model of risk, we would have to utilize VBA modules. This was one of the essential criteria that led us choose Microsoft Access as our development tool. VBA is a version of Microsoft's Visual Basic programming language, and thus renders much of the power and flexibility offered by Visual Basic. It also provides a cross-product, shared application development language. The current versions of Microsoft Excel, Access, Visual Basic, and Project share the same language engine.

In general, VBA modules consist mainly of procedures. A procedure contains a series of statements and methods that perform an operation or calculate a value. Statements are systematically complete units used to express one specific kind of operation, definition or declaration. Methods are statements that operate on specific objects. The following is an example of an event procedure we have used to open the visibility files we acquired from NOAA (see subsection 8.1.2) and append them to the TampaVisibility91-95Original table, based on certain specifications (Visibility Import Specification):

```
Public Function OpenFiles()
DoCmd.TransferText acImportDelim, _
"Visibility Import Specification", _
"TampaVisibility91-95Original", "D:\windtemp\hvl2842a.prn"
End Sub
```

Visual Basic offers two kinds of procedures: sub procedures and function procedures. Sub procedures, like statements, perform one operation or series of operations without returning a value. Function procedures return a value, such as the result of a calculation. Visual Basic provides many built-in procedures in addition to those that can be developed by the user. Table 7 illustrates a simple array manipulation module that contains one declaration and three procedures [44]. The first and the second procedures are sub type procedures, while the third is a function.

The versatility rendered by combining VB modules and macros was heavily exploited during the development of the data sets, a process described in section 8.3. Extended use of both modules and macros is expected during the model development stage that will follow in the second year of the project.

Table 7 - VBA example: an array manipulation module.

```
Declaration
'
' From Microsoft Access 95 Developer's Handbook
' by Litwin, Getz, Gilbert, and Reddick. (Sybex)
' Copyright 1995. All Rights Reserved.
'
Option Compare Database
Option Explicit
```

```
Sub Procedure
Sub ArrayFunc()
    ' Use the Array() function to create an array.
    ShowValues Array(1, 2, 3, 4, 5)
End Sub
```

```
Sub Procedure
Sub ShowValues(varValues As Variant)
    ' If you get an array, list all the values.
    ' Otherwise, just list the single value.
    Dim varValue As Variant

    If IsArray(varValues) Then
        For Each varValue In varValues
            Debug.Print varValue
        Next varValue
    Else
        Debug.Print varValues
    End If
End Sub
```

```
Function Procefure
Function VarArrays()
    Dim avarValues(1 To 20) As Integer
    Dim varArray As Variant
    Dim intI As Integer
    Dim varValue As Variant

    For intI = LBound(avarValues) To UBound(avarValues)
       avarValues(intI) = intI * intI
    Next intI

    ' Now assign the array to a variant, and print out its values.
    varArray = avarValues()
    ShowValues varArray
End Function
```

8.3 Developing Data Sets

The development of the data sets used in the analysis of grounding risk turned out to be a four step process based on Microsoft Access. During the first step the historical accident data were processed. The goal was to combine the two original data sets into a single Access file for the entire period of interest that would include only data fields common in

CASMAIN and MINMOD. The second step involved processing of the environmental data received from NOAA. The objective was to combine the two parts that came with different data structures into a single file. Following the compilation of the accident data, a problem was observed concerning the wind speed and visibility values reported in the USCG database. These values were consistently higher than those reported by NOAA for corresponding dates. During the third step the environmental values reported by NOAA were introduced to the corresponding entries of the accident database to address a potential problem stemming from the observed inconsistency. Finally, the fourth step involved the development of the safe transit data set from the text files provided by ACE. A detailed description of these steps is provided below.

8.3.1 First step: processing of accident data

The development of the accident database used in the analysis of grounding risk was divided in two stages. The first stage focused on CASMAIN and the second on MINMOD. Both of them involved importing the original text files into Access and manipulating the resulting tables to produce a data set including only grounding incidents. The final products, the tables including only grounding entries from each source, were then combined into a single file that served as the basis for building our analysis.

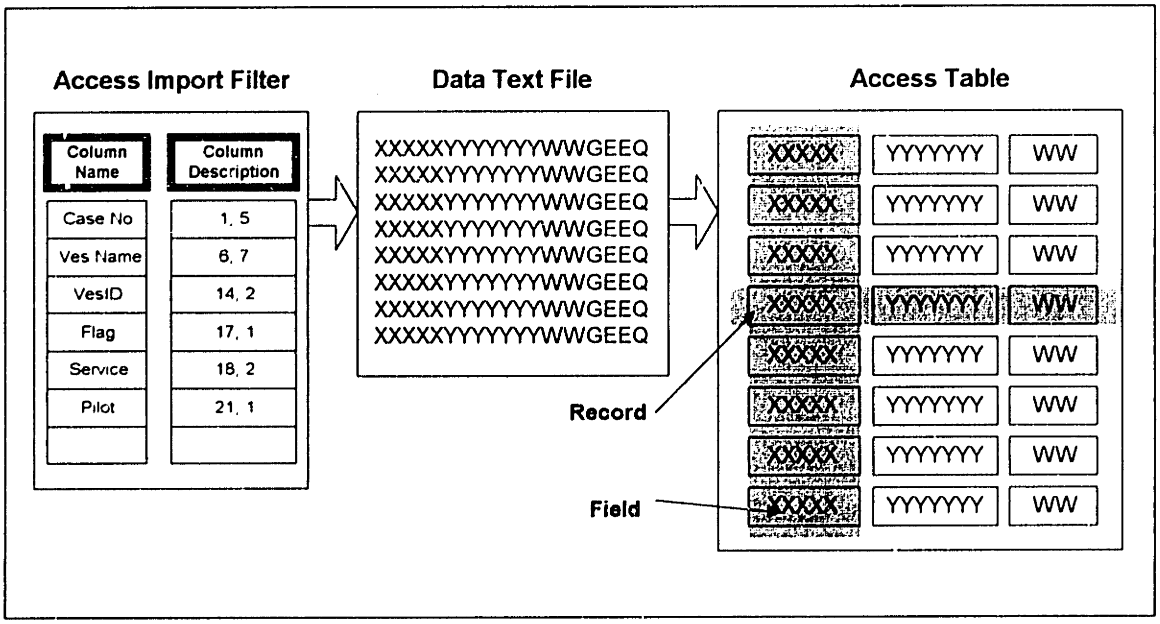


Figure 16 - Text file import filters.

During the first stage the CASMAIN data table was imported into Microsoft Access. That was made possible through the use of customized filters for fixed-width text files. These filters require a description of the columns included in the text file. That description must be provided in the form of the first character of the column and its length. In return the filter creates a table where records correspond to text file rows and fields to text file columns. Figure 16 illustrates this process. The result of this process was an Access table that included all the data provided in the text file arranged in rows and columns. Rows corresponded to different incidents and columns to different fields holding information relevant to each entry. This table was given the name "tblCASMAIN". This name complies with Microsoft's recommendation according to which all Access objects must be given a name with a prefix providing an indication of object's type: "tbl" for tables, "qry" for queries, "frm" for forms, etc. [44].

Following the importation of the CASMAIN text files into Access, two kinds of entries had to be removed from the data set: non-grounding incidents and groundings located outside the five ports of interest. Both these tasks were made possible through action queries, specifically delete queries. Written in SQL, these queries find the entries matching specific criteria defined by the user and delete the entire record from the table. The general syntax of delete queries is provided in Table 8.

Table 8- Syntax of DELETE queries.

Syntax	
`DELETE field-list FROM table-expression WHERE criteria`	
Part	**Description**
field-list	The name of the field or fields to be retrieved along with any field-name aliases, selection predicates.
table-expression	The name of the table or tables from which data is retrieved.
Criteria	An expression that records must satisfy to be included in the query results.

The query used to remove the non-grounding entries from the data set had the following form:

```
DELETE [tblCASMAIN].*, [tblCASMAIN].NATURE1
FROM [tblCASMAIN]
WHERE ((Not ([tblCASMAIN].NATURE1)="GRNDGA"));
```

According to the above SQL statement, all "tblCASMAIN" records with "NATURE1" field entries different from "GRNDGA" will be deleted from the data set. The field "NATURE1" holds the code identifying the nature of the accidents reported in CASMAIN. The particular entry code "GRNDGA" corresponds to accidental groundings. Some of the accident nature codes supported by CASMAIN are: GRNDGI (intentional grounding with damage), EXPCGN (cargo explosion with no fire), FIRMCS (fire in machinery space), FIRELC (fire due to electrical problems), FLDING (flooding without sinking), etc. The result of the previous query was a modified version of "tblCASMAIN" that focused on accidental grounding incidents covering the period between 1981 and 1990.

Intentional groundings are associated with efforts to avoid other more hazardous situations. Under such conditions the individuals involved are expected to have adequate understanding of the alternatives and the associated risks. Grounding is then a matter of "educated" choice that is not affected by unknown factors as in the case of accidental groundings. Therefore, it was decided that intentional groundings would not be included in the analysis of grounding risk.

Likewise, the query used to eliminate groundings that occurred outside the boundaries of the five ports of interest had the following form:

```
DELETE [tblCASMAIN].*, [tblCASMAIN].PORT
FROM [tblCASMAIN]
WHERE ((Not ([tblCASMAIN].PORT)="BOSTON" Or "HOUSTON" Or "NEWYORK"
Or "SANFRAN" Or "TAMPA" ));
```

Following the above SQL statement, Access is expected to delete all the "tblCASMAIN" records with "PORT" field entries other than the codes corresponding to the five ports of interest: Boston, Houston, New York, San Francisco, and Tampa.

The resulting table "tblCASMAIN" included data only for vessel grounding incidents that occurred within the boundaries of the ports of interest. The table was almost ready to be used for the analysis of grounding risk. What remained to be done was the update the grounding records with environmental (wind speed and visibility) values according to the data received from NOAA. That was deemed necessary for two reasons. First, the USCG data was incomplete and many records were provided without wind speed and visibility values. Second, as mentioned earlier, during a primitive compilation of CASMAIN data it was observed that the values in these two fields - wind speed and visibility - were markedly higher than the corresponding measurements received from NOAA. One possible explanation of these inconsistency could be, for example, that winds over the water tend to be higher than winds over land, even adjacent to the water. A second explanation could be the fact that UCSG reported values were compared with corresponding daily averages computed by the hourly measurements collected from NOAA in some location distant from the accident location. Taking into consideration during the analysis the NOAA daily values of wind speed and visibility was expected to provide a better insight on the effects these two factors may have on the probability of vessel grounding.

The second stage of the accident data set development focused on MINMOD. In general the processes involved in this stage were similar to the corresponding processes of the previous stage. The only difference was the higher level of complexity that MINMOD possessed compared to CASMAIN, due to its relational character. As a result of this higher complexity the second stage required greater effort, and it turned out to be more time consuming especially for data manipulation.

The process followed to import the original data tables into Access format was simple and was based on customized data acquisition filters similar to those used for CASMAIN. Since several tables were provided by USCG, different filters had to be developed to accommodate the transition of each table from one format to another. Following the naming recommendation mentioned earlier, the resulting Access tables were given names corresponding to their original name including the "tbl" prefix, e.g. tblMarineCasualtyAndPollutionMasterRecord.

Following the importation of the original tables into Access, data manipulation had to be performed in order to produce a data set appropriate for the analysis of grounding risk. This process began with the definition of the relationships among the tables. In order to establish a relationship between any two tables, primary and foreign keys had to be determined. A primary key is a field or a collection of fields in one table that uniquely identify the entire record. Including this primary key into another table creates the foreign key of this second table. Using the primary and foreign keys, a relationship can be established between these two tables. According to the relationship, all the fields in the second table are related to those in the first table with corresponding values of the two fields serving as foreign and primary key respectively. A relationship can be one-to-one, one-to-many, or many-to-many. In one-to-one relationships, records from the first table have only one corresponding record in the second table. This is not a usual type of relationship and is employed primarily to subdivide big tables to smaller, easier to manipulate data subsets. A more common type is the one-to-many relationship. In this case one record from the first table may have multiple corresponding records in the second table. An example is the relationship between accident cases and vessels, each case may involve multiple vessels. Finally, when tables are associated through a many-to-many type of relationship, a record in first table can have many matching records in second, and vice versa. This is only possible by defining a third table (called a junction table) whose primary key consists of at least two fields - the foreign keys of both the other tables. For example, the grounding table and the vessel table may have a many-to-many relationship that is defined by creating two one-to-many relationships to a third junction table.

The relationships defined among the MINMOD tables were "one-to-many" with the Marine Casualty and Pollution Master Record usually on the "one" side. The tables on the "many" side were: Vessel Supplement Record, Marine Casualty Event File, Marine Casualty Causal Factor File, and Marine Casualty Collision and Grounding File. Table relationships in Access can be defined using the relationship window. This window is illustrated in Figure 17 for the case of "Northwind" database, a sample application provided with Access. All the relationships presented are one-to-many where the "one" side is identified by the presence of "1" and the "many" side by the presence of "∞".

The Weather Supplement table was not used because of two reasons. The majority of the grounding cases received from USCG did not have a matching record in this table. Further, the inconsistency observed among the values of wind speed and visibility reported by USCG investigating officers and corresponding NOAA daily averages was an important issue in MINMOD as well. Therefore it was decided to use the latter values instead of the Weather Supplement table included. That process is outlined in the following step for both CASMAIN and MINMOD.

Following the definition of table relationships, unnecessary data had to be removed from the data. Non-grounding and intentional groundings had to be discarded on the basis explained earlier for CASMAIN. In addition, the grounding incidents located outside the boundaries of the five ports of interest had to be filtered out. The process was a little more complex in the case of MINMOD because of the existence of multiple interconnected tables. Queries had to be applied usually on two tables at the same time to delete the records matching the criteria.

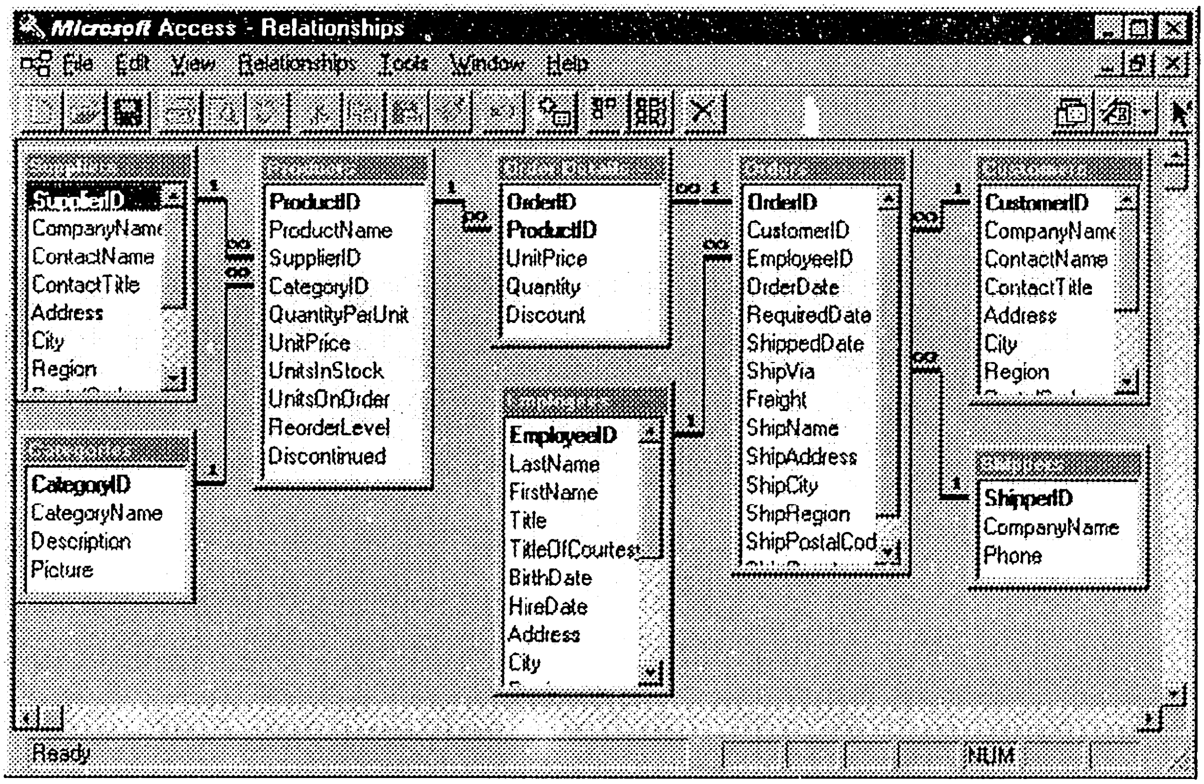


Figure 17 - View of the relationship window for a sample application.

In MINMOD the primary nature of any particular accident is defined in the field "NATURE" of the "Marine Casualty and Pollution Master Record" table using codes like: FIRE, CAPSIZE, SINKING, FLOODING, COLLISION, EXPLOSION, GROUNDING, etc. Further explanation of the accident nature is possible through the use of the "TYPE" field of the "Marine Casualty Event File" table. There were certain cases where the code "EXPLOSION" was found in the "NATURE" field of the first table while the code "GROUNDING ACC" was residing in the "TYPE" field of the second table. Therefore, the process of removing all but the accidental grounding records had to take into consideration both these fields. The query employed to achieve this goal had the following form:

```
DELETE DISTINCTROW tblMarineCasualtyAndPollutionMasterRecord.*,
tblMarineCasualtyEventFile.*,
tblMarineCasualtyAndPollutionMasterRecord.NATURE,
tblMarineCasualtyEventFile.TYPE
FROM tblMarineCasualtyAndPollutionMasterRecord INNER JOIN
tblMarineCasualtyEventFile ON
tblMarineCasualtyAndPollutionMasterRecord.MSISCAS =
tblMarineCasualtyEventFile.MSISCAS
WHERE (Not (tblMarineCasualtyAndPollutionMasterRecord.NATURE =
"GROUNDING"))OR (Not (tblMarineCasualtyEventFile.TYPE)=
"GROUNDING ACC"));
```

According to the above SQL statement, Access will delete all records from the tables “tblMarineCasualtyAndPollutionMasterRecord” and “tblMarineCasualtyEventFile” that satisfy either of the criteria defined in the “WHERE” portion of the statement: “NATURE” not equal to “GROUNDING” or “TYPE” not equal to “GROUNDING ACC”. In this query the portion “INNER JOIN” represents the relationship between the two tables that is defined through the value of the “MSISCAS” field - the MSIS case number discussed earlier. The resulting table included only accidental grounding entries.

Following the removal of the non-accidental groundings, the entries corresponding to incidents located outside the five ports of interest had to be removed from the data set as well. The process of achieving that goal was a little more complicated in the case of MINMOD because there was not “PORT” field in any of the tables strictly defining the port in which the incident occurred. To circumvent the problem, queries based on longitude and latitude values had to be developed. Using the port maps by NOAA, minimum and maximum values of longitude and latitude were defined for each of the ports of interest. The query employed for discarding the entries corresponding to all the ports but those of interest, from the table “tblMarineCasualtyAndPollutionMasterRecord”, had the following form:

```
DELETE [tblMarineCasualtyAndPollutionMasterRecord].*,
[tblMarineCasualtyAndPollutionMasterRecord].LATITUDE,
[tblMarineCasualtyAndPollutionMasterRecord].LONGITUDE
FROM [tblMarineCasualtyAndPollutionMasterRecord]
WHERE ((([tblMarineCasualtyAndPollutionMasterRecord].LATITUDE)<MINLT
Or ([tblMarineCasualtyAndPollutionMasterRecord].LATITUDE)>MAXLT)
And (([tblMarineCasualtyAndPollutionMasterRecord].LONGITUDE<MINLN
Or ([tblMarineCasualtyAndPollutionMasterRecord].LONGITUDE)>MAXLN));
```

The above SQL statement deletes all the entries of the above mentioned table that have latitude and longitude values outside the minimum and maximum values defined for each port. The above query was executed five times, one for each of the ports. The tables resulting from each run were then combined to produce one data set that includes only entries that occurred in the ports of interest. This task was performed using the following table appending query, which inserted the five tables produced through the previous process into the “tblMarineCasualtyAndPollutionMasterRecordFinal” table.

```
INSERT INTO tblMarineCasualtyAndPollutionMasterRecordFinal
SELECT DISTINCTROW tblMarineCasualtyAndPollutionMasterRecordPort.*
FROM tblMarineCasualtyAndPollutionMasterRecordPort;
```

The resulting table “tblMarineCasualtyAndPollutionMasterRecordFinal” included only accidental groundings that occurred within one of the ports of interest. In order to make the following analysis more efficient, all the unrelated records had to be discarded from the other tables as well. The query used to achieve this goal had the following form:

```
DELETE DISTINCTROW [OtherTables].*
FROM OtherTables  LEFT JOIN
tblMarineCasualtyAndPollutionMasterRecordFinal ON
[OtherTables].[ MSISCAS] =
```

```
[tblMarineCasualtyAndPollutionMasterRecordFinal].[MSISCAS]
WHERE ([tblMarineCasualtyAndPollutionMasterRecordFinal].[ MSISCAS]
Is Null);
```

This query was executed many times, one for each of the other tables in the set that was related to "tblMarineCasualtyAndPollutionMasterRecordFinal". All the records found in these other tables for which the "MSISCAS" field in the master record table was null were deleted.

8.3.2 Second step: processing of environmental data

The process involved in the manipulation of the environmental data using Access was simple compared to the accident data compilation described above. Two parts of delimited text files were provided that had to be combined into a unique Access table. The first part came out of the CD-ROM and had the data arranged in a sequential format. Each line in these text files corresponded to one particular observation, including all the necessary information, year, month, day, hour and values, separated by commas. All the text files that were produced from the data on the CD-ROM were imported into Access using simple delimited text file filters. The only extra work required was to create a date field, to consolidate all the separate year, month and day values of each observation into the regular date format (DDMMYY). That task was completed using the following query:

```
SELECT DISTINCTROW [tblPortEnironmentalRecord91-95]![Month] & "/" &
[tblPortEnironmentalRecord91-95]![Day] & "/" &
[tblPortEnironmentalRecord91-95]![Year] AS MMDDYY1,
[tblPortEnironmentalRecord91-95].*
INTO tblPortEnironmentalRecord91-95Final
FROM [tblPortEnironmentalRecord91-95];
```

The above query created a new field as a combination of the month, day and year values in the MMDDYY format and resulted in table: "tblPortEnironmentalRecord91-95Final". The new table included all the fields of the old table "tblPortEnironmentalRecord91-95" plus the combined MMDDYY field.

The environmental data covering the period 1991 to 1995 that came directly from NCDC was a little more complex in terms of internal structure. Processing this part turned out to be more time consuming. We had to output the Access tables into Excel format, use Visual Basic for Applications in Excel to perform certain alterations in the way data was outlined, and finally import the Excel files into Access to resume the process of developing the environmental data set. All these became necessary because the data were not arranged sequentially in the text files received from NCDC. Instead, the text file was divided in sections, each for one day. Following a section header stating the date corresponding to a particular day, the environmental values were arranged in twenty four lines. Each line included the time of the observation and the value measured. The data outline used for these files is illustrated in Figure 18.

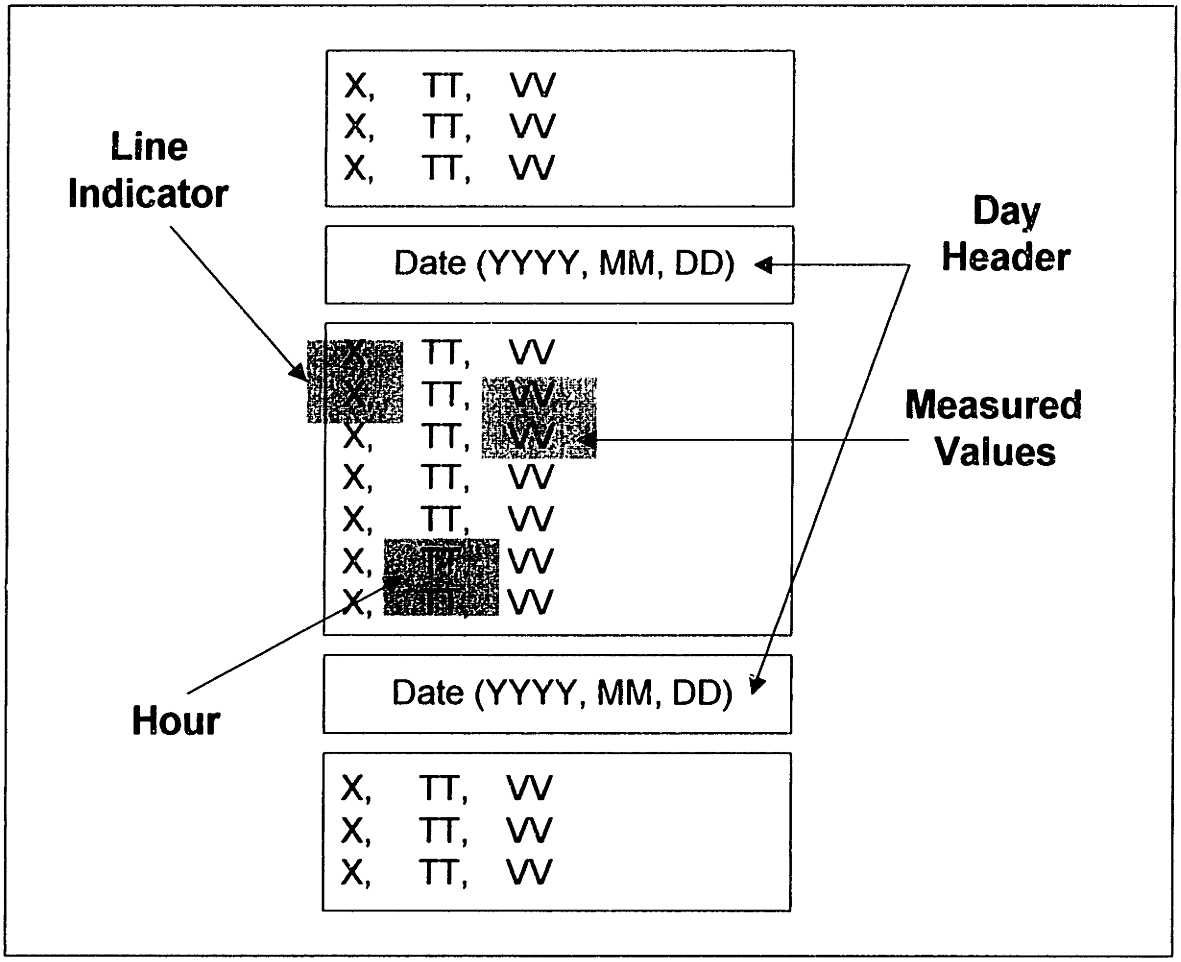
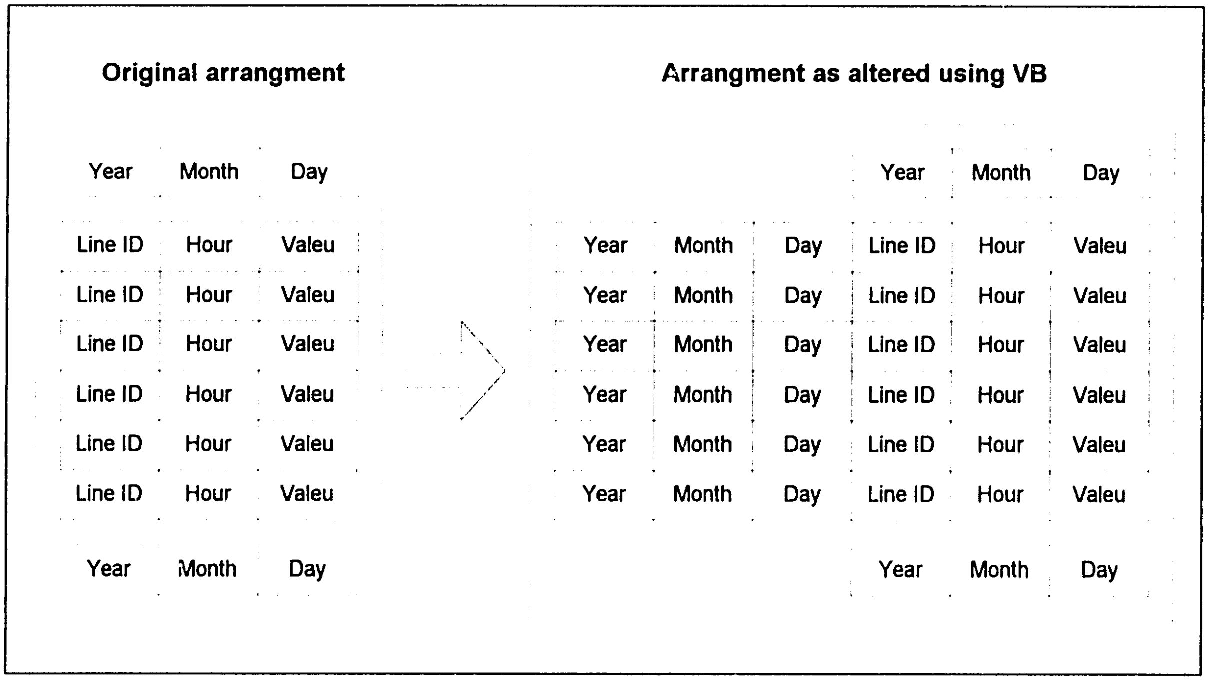


Figure 18 - Arrangement of data in the NCDC text files.

Because more than three hundred text files were provided, it was not efficient to import all of them manually, thus macros were designed for the job. Each macro focused on one of the five different ports. All of them employed user defined file import specifications to open and append the corresponding text files into five different Access tables, one for each of the ports. As an example, part of the macro used to import the visibility data for Tampa is provided below.

```
Public Function OpenFiles()
DoCmd.TransferText acImportDelim, "Visibility", _
"tblTampaVisibility91-95Original", "TampaTextFileToBeImportedA"
..............................................................
End Function
```

"Visibility" is the user defined import specification file employed in the case of visibility data. A similar file was defined for wind speed data. Five macros were used to perform the task. Each included a number of code lines like those provided in the example, equal to the number of text files provided by NCDC for a particular port. The second pair of lines opened "TampaTextFileToBeImportedA", and so forth. The result of each macro was a table in Access format containing all the data for a particular port. For instance the table for Tampa was given the name "tblTampaVisibility91-95Original".



Original arrangment

Year	Month	Day
Line ID	Hour	Valeu
Line ID	Hour	Valeu
Line ID	Hour	Valeu
Line ID	Hour	Valeu
Line ID	Hour	Valeu
Line ID	Hour	Valeu
Year	Month	Day

Arrangment as altered using VB

			Year	Month	Day
Year	Month	Day	Line ID	Hour	Valeu
Year	Month	Day	Line ID	Hour	Valeu
Year	Month	Day	Line ID	Hour	Valeu
Year	Month	Day	Line ID	Hour	Valeu
Year	Month	Day	Line ID	Hour	Valeu
Year	Month	Day	Line ID	Hour	Valeu
			Year	Month	Day

Figure 19 - Data arrangement in NCDC files before and after alterations.

After creating the corresponding tables, we had to alter the way their data was structured. The change was necessary to match the outline used in the part of environmental data previously described. It was possible to perform the process within Access. However, it was less time consuming to export the tables in Excel, make the changes and import the results into Access afterward. That was an exception to the rule set earlier concerning the use of multiple software tools.

The table on the left side of Figure 19 illustrates the original arrangement of wind speed and visibility data in the corresponding files received from NCDC. The altered arrangement of the data is illustrated in the right side of the same picture. In this latter version, all rows include the corresponding date (MM/DD/YY) as in the 1991 to 1995 data. This arrangement is efficient in terms of data manipulation and analysis. The Visual Basic code used to perform these changes is provided below.

```
Sub TransformDate()
    Dim counter, j As Integer
    For counter = 1 To 16000 Step 25
        Set RefYear = Worksheets("ExcelFileName").Cells(counter, 6)
        Set RefMonth = Worksheets("ExcelFileName").Cells(counter, 7)
        Set RefDate = Worksheets("ExcelFileName").Cells(counter, 8)
        For j = 1 To 24
Worksheets("ExcelFileName").Cells(counter + j, 3).Value = "1" & Re-
fYear.Value
Worksheets("ExcelFileName").Cells(counter + j, 4).Value = RefMonth.Value
```

```
Worksheets("ExcelFileName").Cells(counter + j, 5).Value = RefDate.Value
        Next
    Next counter
End Sub
```

The above module starts by defining two integer variables that will serve as counters for the iterative process that follows. The data layout is such that day headers repeat every twenty five lines starting at the beginning of the table. The lines in between correspond to the twenty four hourly measurements of the day. Starting at the beginning of the table, the module finds the day header and assigns respectively the year, month and day values to three variables: "RefYear", "RefMonth", and "RefDay". Then the nested loop iterates over the following twenty four lines. Each run results in setting the values of three corresponding cells respectively equal to the "RefYear", "RefMonth", and "RefDay" variables. When the inner loop is done with a particular day, the outer loop takes over and moves to the following day. This way the outer loop runs through the entire table that has 16,000 rows. The number of rows in each file was close to 40,000; however, because of Excel limitations these files had to be broken down in smaller blocks and reassembled after the compilation was over. The first two columns of each row are reserved. Cell (counter, 1) holds a record identification number used for the process of reassembling the files. Cell (counter, 2) holds a value between "1" and "10" depending on the type of the data recorded in the particular row. This was a row identification scheme that was included in the original files received from NCDC. Both these columns were removed, along with the day header lines, using simple delete queries once the Excel tables were imported into Access.

The two parts of environmental data that were available for each port had to be combined in a single table for the years 1981-1995. Prior to this combination, the wind speed and visibility values had to be converted to the same measuring units. That was necessary because the data acquired from CD-ROM measured wind speed in meters per second while the data that came directly from NCDC used miles per hour. Likewise, in the first set visibility was measured in kilometers as opposed to the second where miles were used. It was decided then to use meters per second (m/s) for measuring wind speed and kilometers for measuring visibility. Therefore, the wind speed and visibility values of the 1991 to 1995 data set had to be converted to the right units. This unit conversion was made possible through the use of two simple action queries, one for wind speed and one for visibility values. The following query is provided as an example.

```
SELECT 0.447*[tblBoston]![WindSpeedMPH] AS [WindSpeedMPS]
FROM Boston;
```

This query receives the wind speed value in miles per hour "WindSpeedMPH", multiplies it by the conversion constant which in this case is equal to 0.447, and stores the resulting meters per second value in the "WindSpeedMPS" field. Both fields in this sample case belong to a table that was given the name "tblBoston". Similar SQL statements were used for converting the wind speed and visibility values of all the other ports. The resulting tables for each port were then combined using appending queries like the ones discussed earlier.

8.3.3 Third step: combining environmental with accident data

The objective of this third step was to blend wind speed and visibility values recorded by NOAA into the historical accident database. As explained earlier, that was deemed necessary to address potential problems stemming from the inconsistencies observed in the corresponding values reported by USCG. This objective was accomplished by means of action queries. These queries fulfilled two tasks: calculating daily average from the hourly measurements and joining accident records with the corresponding environmental records.

Most of the records in the historical accident database did not include the time of the accident. Therefore, only daily averages of wind speed and visibility values could be used to update the historical accident records. The calculation of the daily averages was performed using action queries like the one provided below:

```
SELECT [tblBostonHourlyObs].MMDDYY,
Avg([tblBostonHourlyObs].Wind) AS AvgOfWind,
Avg([tblBostonHourlyObs].Visibility) AS AvgOfVisibility
INTO tblBostonDailyAverages
FROM [tblBostonHourlyObs]
GROUP BY [tblBostonHourlyObs].MMDDYY;
```

For the purpose of this example it is assumed that each row in "tblBostonHourlyObs" consist of four fields. The first field includes the date using the "MMDDYY" format, the second includes the time of observation and the last two the corresponding hourly values of wind speed and visibility. The above query groups the observations by date and calculates the corresponding daily values through the built-in statistical function for averages "Avg". The results of this operation, saved respectively as AvgOfWind and AvgOfVisibility, are then appended to a new table that also includes the date field. This table is created on the fly by the above query and is given the name "tblBostonDailyAverages". Each row of this table starts with the date and is followed by the daily wind speed and visibility values.

The date field "MMDDYY" in the latter table is assigned to serve as primary key. A relationship is then established between the average value and grounding tables. This is a one-to-many relationship with the grounding table on the "one" side and the average value table on the "many" side. Multiple grounding incidents may occur on the same day in one or more ports. The date field "MMDDYY" in the grounding table serves as the foreign key in this relationship.

Having the above relationship in place, one query needs to be designed that will append daily values of wind speed and visibility to corresponding records of the grounding table. It was decided that the daily values calculated based on the data from NOAA will not replace those reported by USCG. Instead the query is expected to create two new fields in the grounding table for appending these daily wind speed and visibility values. It was also expected that the designed query will have to satisfy the port constraints between the grounding records and the environmental values. The following SQL code was employed for the task:

```
SELECT DISTINCTROW [tblGroundingOriginal].*,
tblBostonDailyAverages.AvgOfWind,
tblBostonDailyAverages.AvgOfVisibility INTO tblGroundingBostonFinal
FROM tblBostonDailyAverages INNER JOIN [tblGroundingOriginal] ON
tblBostonDailyAverages.MMDDYY=[tblGroundingOriginal].MMDDYY;
WHERE ((([tblGroundingOriginal].PORT)="BOSTON"));
```

This query combines the fields from "tblGroundingOriginal" with the daily averages of wind speed and visibility fields from "tblBostonDailyAverages" into a new table created on the fly: "tblGroundingBostonFinal". To perform this task the relationship defined earlier, inner join between "tblGroundingOriginal" and "tblBostonDailyAverages", is employed by the query to extract only those records satisfying the criterion set in the last line: only groundings that occurred in the port of Boston. Similar queries are employed for the other ports. Finally the resulting tables for each port that include daily values are combined to form the final grounding table that will be used in the subsequent analysis of grounding risk.

8.3.4 Fourth step: processing safe transits data

This final step of the data set developing process focused on the Waterborne Commerce Statistics annual summaries received from ACE. As mentioned earlier, safe transit statistics were available for all the study years except 1995. To circumvent this deficiency and proceed with the analysis of grounding risk it was decided to use the 1994 statistics as a proxy for the 1995 situation.

As explained earlier in section 8.1, safe transit data was obtained for each major waterway of the study ports. In general, ports may have multiple waterways available for entrance or exit of vessels, and a single vessel may use several waterways in making a single transit. Thus, there is a chance of double counting if data from all waterways in a given port are considered when estimating the number of safe transits for that particular port. To avoid that problem it was agreed to consider only one waterway in each study port for counting safe transits. The name and code of the waterways selected are provided in Table 9. It is acknowledged that the approach proposed for counting safe transits will lead to underestimation of actual vessel movements, especially for New York and Houston. Unfortunately, no other simple alternative was available for building more accurate time series of transits for the ports of interest.

Table 9 - Waterways employed for counting safe vessel transits.

Port	Waterway Code
Port of Boston	0149
New York and New Jersey Channels	0388
Tampa Harbor	2021
Houston Ship Channel	2012
San Francisco Bay Entrance	4320

The ACE input was provided in two parts. The first part came in digital format and included statistics for the years 1985 to 1994. This portion of the data was imported into Access using customized text file import filters and compiled using action queries to calculate totals. The latter were similar to the queries used in daily averages calculations for the environmental data. A sample of the corresponding SQL statements employed for calculating total annual transits of each port is provided below:

```
SELECT DISTINCTROW [tblVesselSafeTrips].YR,
[tblVesselSafeTrips].WTWY_ID,
[tblVesselSafeTrips].WTWY_NAME,
Sum([tblVesselSafeTrips].USDRY) AS SumOfUSDRY,
Sum([tblVesselSafeTrips].USTANK) AS SumOfUSTANK,
Sum([tblVesselSafeTrips].USTOW) AS SumOfUSTOW,
Sum([tblVesselSafeTrips].UNDRY) AS SumOfUNDRY,
Sum([tblVesselSafeTrips].UNTANK) AS SumOfUNTANK,
Sum([tblVesselSafeTrips].DSDRY) AS SumOfDSDRY,
Sum([tblVesselSafeTrips].DSTANK) AS SumOfDSTANK,
Sum([tblVesselSafeTrips].DSTOW) AS SumOfDSTOW,
Sum([tblVesselSafeTrips].DNDRY) AS SumOfDNDRY,
Sum([tblVesselSafeTrips].DNTANK) AS SumOfDNTANK
FROM [tblVesselSafeTrips]
GROUP BY [tblVesselSafeTrips].YR,
[tblVesselSafeTrips].WTWY_ID, [tblVesselSafeTrips].WTWY_NAME;
```

The query above groups data in "tblVesselSafeTrips" by year and waterway using the statement "GROUP BY" and the following fields: year (YR), waterway identification number (WTWY_ID), and waterway name (WTWY_NAME). Subsequently it calculates the total number of safe transits for every year and waterway combination in each of the ten vessel categories identified in the ACE database of safe transits. The calculation of totals in each vessel category is accomplished by ten statements of the following form:

```
Sum([tblVesselSafeTrips].DATAFIELD) AS SumOfDATAFIELD,
```

The results of the "SUM" function, one of the built-in functions provided by Access, are then saved in a new field that is given the name "SumOfDATAFIELD".

The second part of the input that included statistics for the years 1981 to 1984 was not available in digital format. Instead copies of the Trips and Drafts of Vessels tables from the Waterborne Commerce of the United States publication were provided. The safe transit totals manually obtained from these tables were imported into Access and tabulated using a format similar to that employed for the 1985-1994 data. Finally these two sets of data are consolidated in a single table to be used in the subsequent analysis of grounding risk.

8.4 Some General Trends

8.4.1 Groundings

As mentioned earlier in section 7.2 the grounding data used for the purpose of the present project was constructed using the casualty data provided from USCG in the form of CASMAIN (1981-1990) and MINMOD (1992-1995) databases. Because of the database migration that occurred in 1991 and resulted in the replacement of CASMAIN with MINMOD, the casualty data for 1991 is incomplete.

The analysis presented in this thesis focused, as explained earlier, only on accidental grounding resulting from navigational misconduct. Intentional groundings, as well those resulting from mechanical or other failures, where ignored during this initial attempt to model the physical risk of grounding. Other kinds of casualties, such as collisions, explosions, etc. will be studied in future risk models that will draw upon the present work on groundings.

The USCG casualty data were broken down into two major vessel type categories. The first included only ships and the second included only barge trains. The process followed for the above separation was simple. On the original data set we run a query to select all the entries that included barges. In the first portion of the data, period 1981 to 1990, the distinction between barges and all other vessels was made based on propulsion plant information. All records holding "NA" in the "PROP" field were assumed to be barges because in the CASMAIN data directory that indicator stands for "not self-propelled". The distinction of barges in the second portion of casualty data, period 1992 to 1995, was made more straightforward by the "SERVICE" field. After obtaining the results of the "select only barges" query, a second query was applied. Using the results of the first query, the second tried to match and select all the records of the original data set that were entered under the same case number. The result of this latter query was to obtain all the cases involving barges and probably some other vessels. After a manual inspection it was observed that the results of the latter query included entries corresponding to tow/tug boats, as well as few other types, in addition to barges. In general, our inspection indicated that the majority of the cases involving barges included one tow/tug boat. A smaller portion of cases included more than one tow/tug boat. In the light of these observation it was assumed, for simplicity, that each case involved only one barge train. During the same inspection it was also observed that barge trains in Boston, New York and Tampa included, on average, one barge. In Houston the average number of barges per train were two and a half, and finally in San Francisco one and a half. For simplicity we have assumed for the purpose of our analysis that all barge trains in corresponding ports include the average number of barges. These assumption may be revised in the remaining part of the project after a more detailed analysis. The records that were not included in the latter query were assumed to fall in the ships category. In addition, a third query was applied on the results of the second in order to get all the records involving other vessels besides barges and tow/tug boats. The records selected from this process were removed from the barge trains category and added to the ships category.

During refinements of the modeling process, the ships involved in groundings will be divided in two sub-categories according to an approximation of their designed draft. The reason for using an approximation of the designed draft for this sub-categorization is that the casualty data acquired from USCG does not include actual values. The approximation will be calculated using the registered length and tonnage of the ship, provided in the casualty data sets, and a crude assumption about the relation between these three quantities: length, tonnage and draft. All vessels will also be further divided in two sub-categories according to the nature of their cargo: liquid and dry.

Table 10 summarizes the grounding data in the form of number of incidents, ships and barge trains separately, in each one of the study ports per year for the entire period of study. Another comprehensive illustration of the casualty data is provided in Figures 20 and 21 in the form of seasonal trends for each study port. Figure 20 corresponds to ship groundings while Figure 21 depicts the situations involving barge trains. These plots were constructed from the average number of incidents for each of the twelve months of the typical year. To develop these seasonal trends, we had to work in the following fashion. Following the division of the grounding cases between ships and barge trains, we counted the number of accidents per month per port for the entire period of fifteen years. Then we estimated the number of groundings for the typical month by averaging the counts by month. To smooth the distribution of these results we applied a five point moving average process before calculating the average for each of the twelve months of the year. A moving average provides trend information that a simple average of all historic data would mask. The moving average is based on the formula:

$$F_{(t)} = \frac{1}{N} \cdot \sum_{j=1}^{N} A_{\left(t+j-\frac{N+1}{2}\right)}$$

where N is the number of periods to include in the moving average, A_j is the actual value at time j and F_j is the moving average at time j. The result of this process were then employed in the calculation of the average values of grounding incidents for each of the twelve months of the year, from which the seasonal trends were constructed.

Observing these two figures one can conclude that the seasonal trends of groundings are most significant in the Port of Houston. The seasonal trends in the other ports are not as significant for the purpose of this initial approach. Probable explanations of these seasonal fluctuations of grounding incidents may be the corresponding fluctuations of the environmental conditions and/or seasonal fluctuation in traffic volume. Evidence for the seasonal fluctuation of the environmental conditions are provided later on in sections 9.1 and 9.2. Unfortunately, no data became available to our team so far that would be helpful in the construction of the corresponding seasonal fluctuation of the traffic volume in each study port. Such data is expected to arrive during the course of the second year and then we will be able to refine the analysis of the seasonal fluctuations of grounding incidents.

Table 10 - Summary of groundings for the period 1981 to 1995.

*Barge Train Annual Groundings**

Year	Boston	Houston	New York	San Francisco	Tampa
1981	0	15	0	1	7
1982	1	16	1	2	6
1983	1	12	2	1	2
1984	1	10	2	1	8
1985	3	1	9	1	15
1986	1	1	14	1	9
1987	0	3	8	1	3
1988	2	8	10	1	4
1989	1	4	16	2	2
1990	0	5	2	0	4
1991	0	0	0	0	1
1992	0	8	3	0	5
1993	0	10	3	0	5
1994	0	20	7	0	4
1995	0	11	0	0	1
Total	***10***	***123***	***77***	***11***	***76***

** These numbers incorporate the tow/barge factor discussed in the transits subsection 8.4.2.*

Ship Annual Groundings

Year	Boston	Houston	New York	San Francisco	Tampa
1981	3	22	3	2	4
1982	7	17	3	8	6
1983	2	47	5	7	6
1984	3	22	8	3	11
1985	8	11	18	11	14
1986	3	9	13	7	12
1987	1	14	8	11	8
1988	5	35	15	6	17
1989	3	22	19	12	14
1990	3	11	3	2	6
1991	0	3	2	1	0
1992	3	31	10	3	7
1993	4	21	8	5	6
1994	2	29	4	7	8
1995	2	23	3	7	7
Total	***49***	***317***	***122***	***92***	***126***

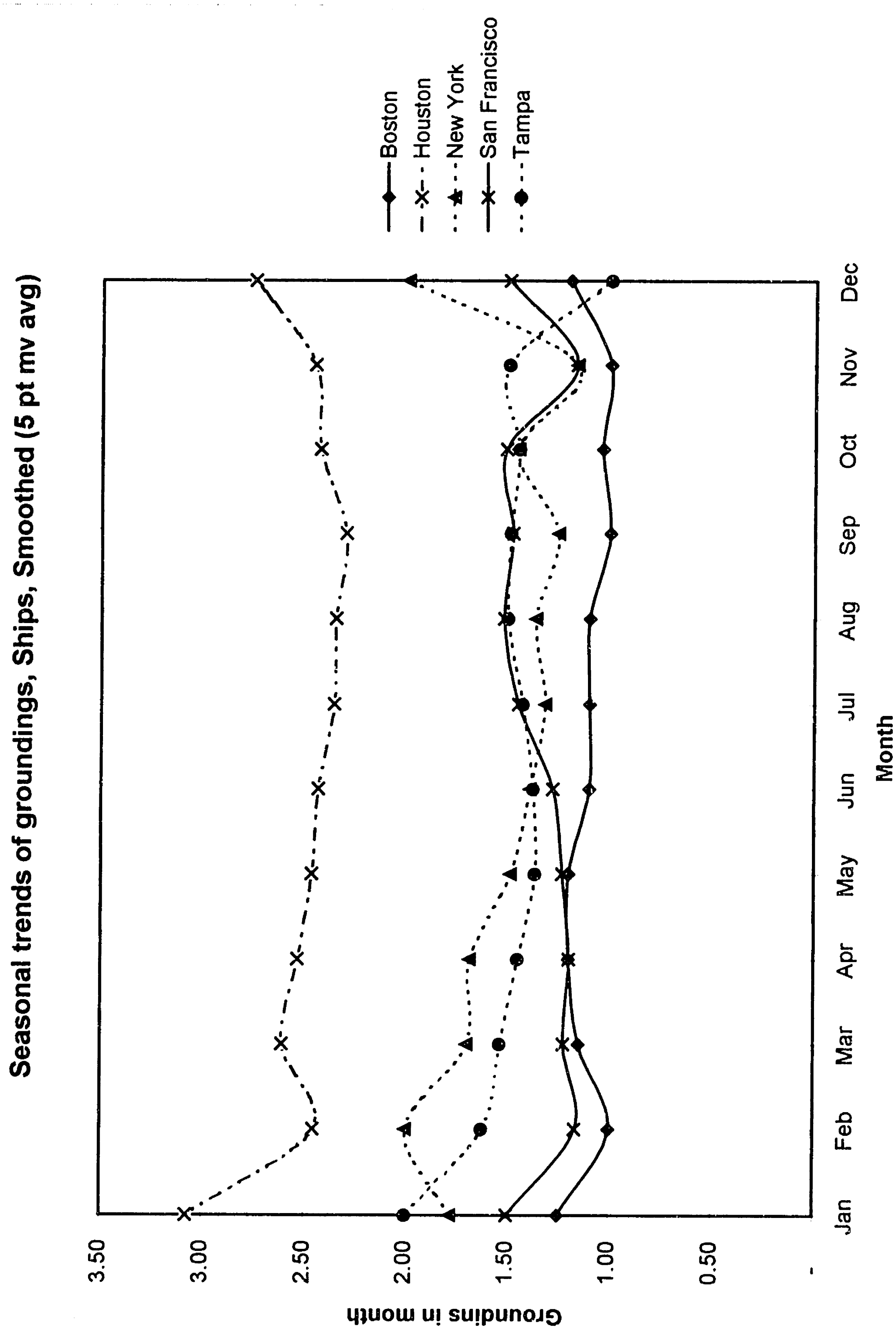


Figure 20 - Seasonal trends of ship groundings.

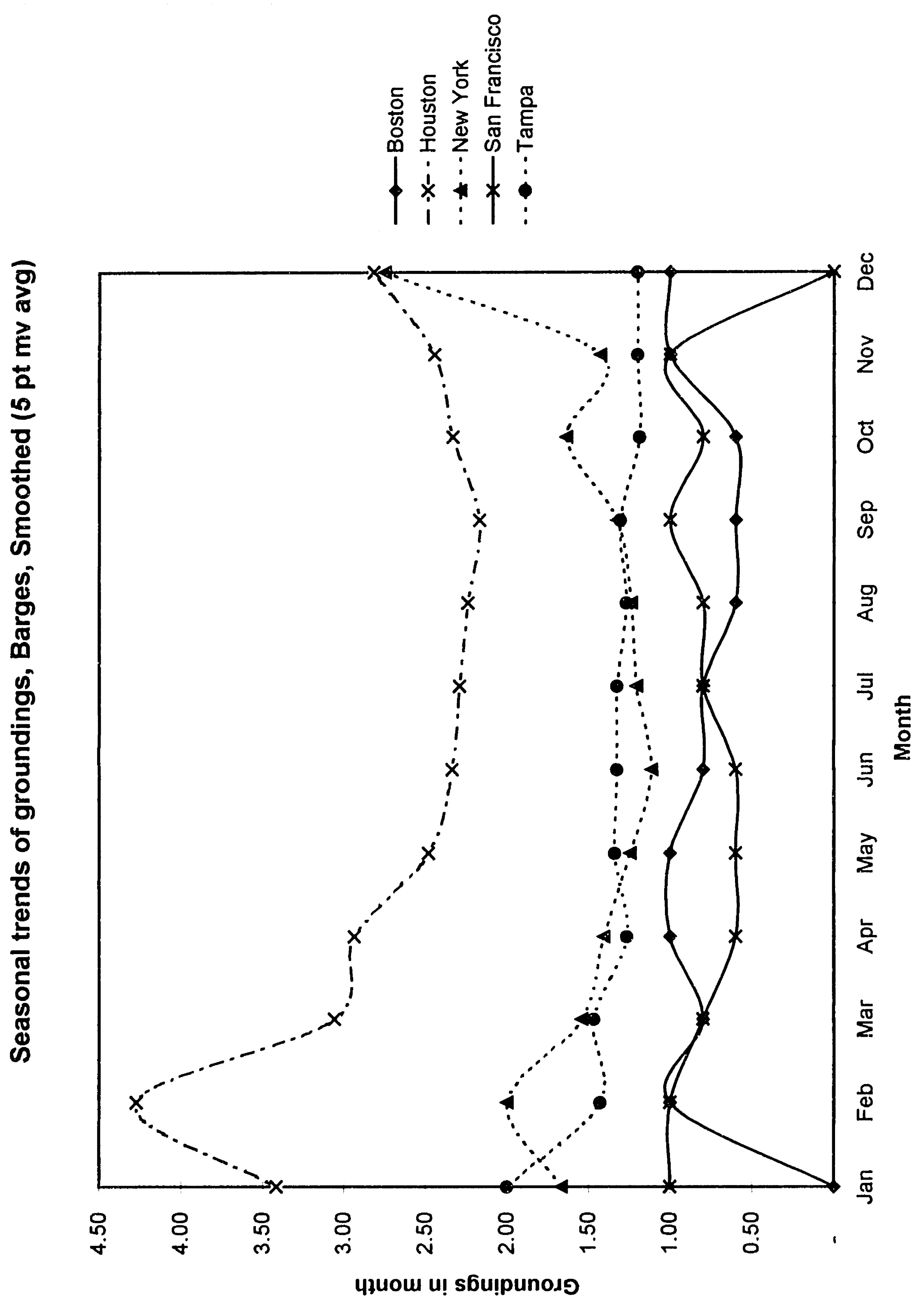


Figure 21 - Seasonal trends of barge groundings.

8.4.2 Transits

The ACE's Waterborne Commerce Statistics Center (WCSC) provided transit annual statistics for the period 1981-1994, as discussed in section 7.2. The 1995 statistics were not available on time, thus, for simplicity we have assumed them to be the same as 1994. The availability of nothing but annual transit statistics introduced certain limitations in our analysis of grounding risk. As mentioned earlier, monthly transit distributions would be required to develop seasonal trends of traffic volume in each study port. It is expected that such statistics will arrive shortly after the completion of the present thesis covering the period 1992 to 1994. Using them, we will be in a position to further investigate the seasonal fluctuations of groundings discussed in the subsection above. The transit counting process was described earlier in subsection 8.3.4.

Following the reconstruction of the barge train annual statistics, we calculated the average annual transits for each of the study ports, distinguishing between ships and barge trains. The only explicit adjustment that was made in the original WCSC transit data was to remove a large number of very small passenger vessels (local passenger ferries) that was included in the small dry vessel and passenger category for the port of Boston. This adjustment was performed by excluding the entries in the dry cargo passenger category that corresponded to vessels with draft less than 18 feet from the total number of transits that were provided in hard copy for the years 1981 to 1984. Then using the average ratio between the remaining vessels and the total before the adjustment, the totals for the following years 1985 to 1994 were adjusted. Figures 22-26 illustrate the annual transit numbers for each study port and the entire study period, separately for ships and barge trains.

8.4.3 Grounding Rates

In the context of the risk modeling project, the term grounding rate is defined as the result of the division of groundings by the transits. Both figures refer to the same port and the same period of time, which in this case is a year. As discussed earlier, simple averages of all historic data tend to mask actual trends. For that reason a five point moving average process was applied in the raw data that resulted from the division of groundings by the corresponding transits. The results of this smoothing process are illustrated in Figures 27 and 28 for the case of ships and barge trains respectively and each of the study ports. As discussed in section 6.2.1, these annual grounding rates form the basis for calculating the unconditional (prior) probability of grounding. The unconditional probability of grounding is a major input for the model of physical risk of grounding to be developed.

Before closing the discussion about grounding rates, one thing needs to be mentioned. When comparing grounding rates across different ports caution is in order, because of the following two reasons: (1) local USCG officers may employ different reporting criteria from one port to another, and (2) the process we employed in the development of annual transits may have underestimated, as mentioned in the previous subsection, actual traffic volumes to varying degrees in different ports. The first problem might result in an apparent reduction of the actual groundings, while the second might have artificially inflated the actual grounding rates.

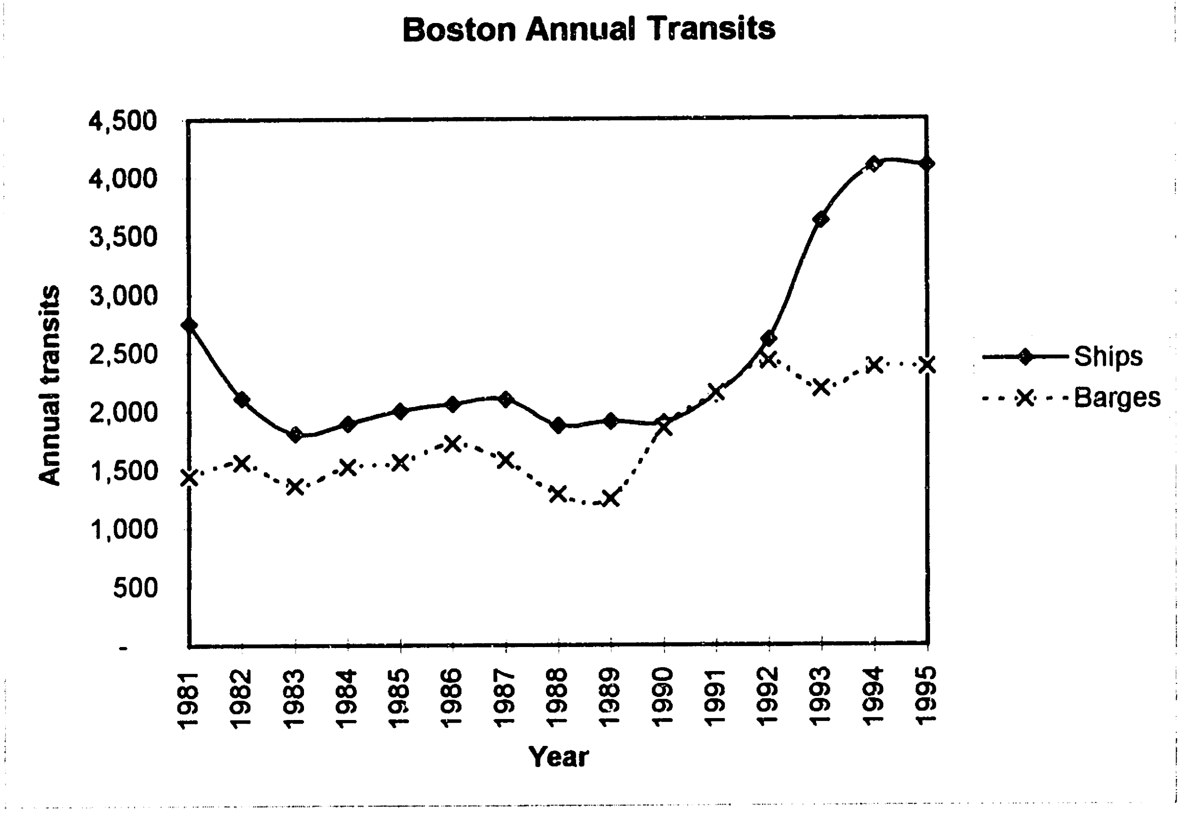


Figure 22 - Annual transits in the port of Boston.

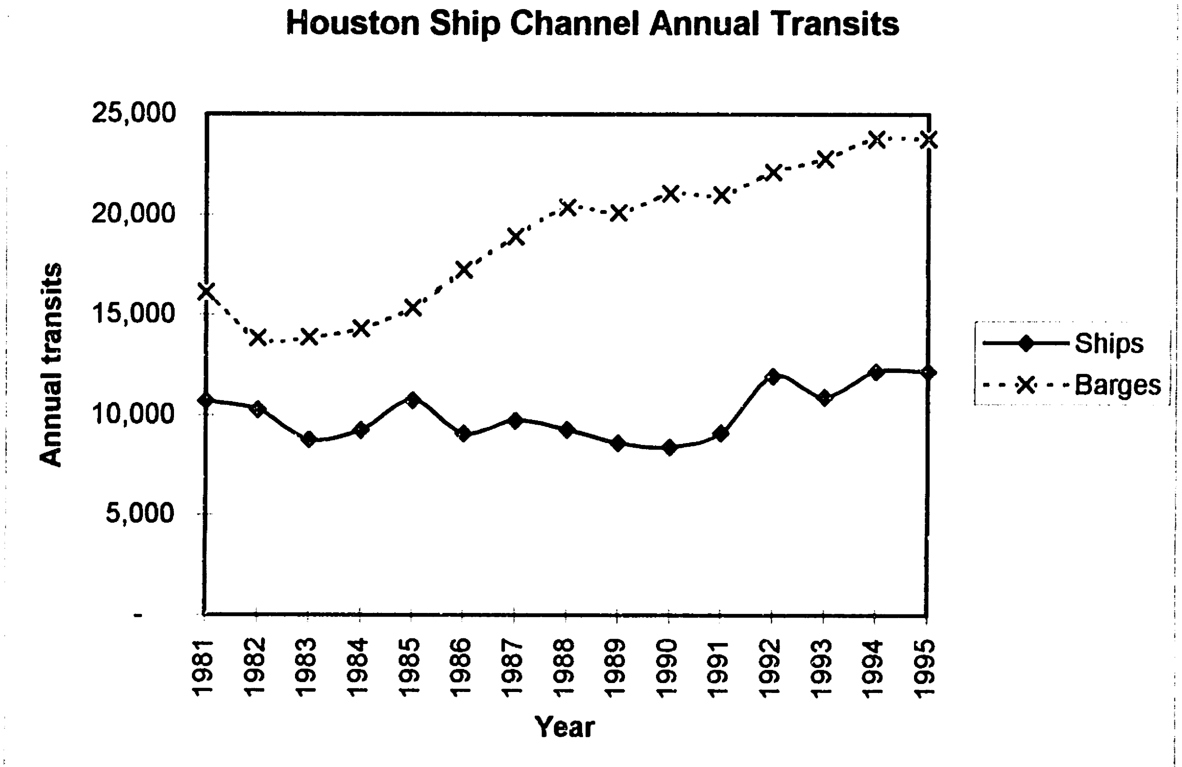


Figure 23 - Annual transits in the port of Houston.

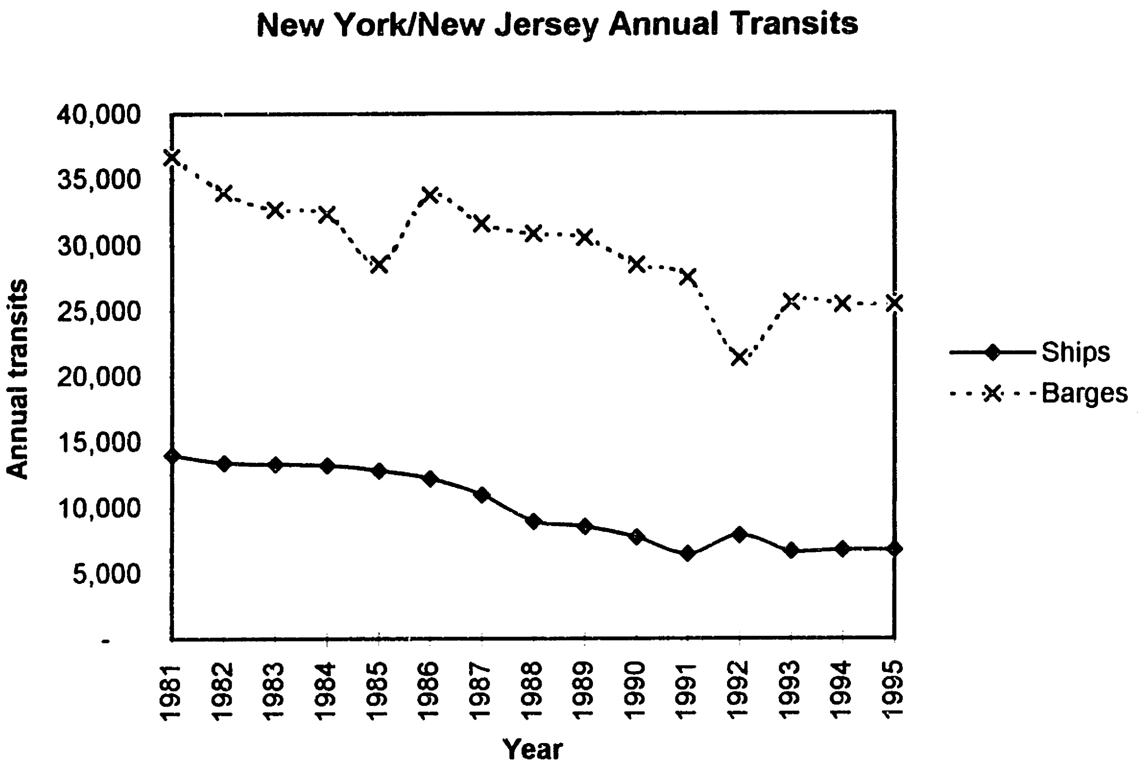


Figure 24 - Annual transits in the port of New York / New Jersey.

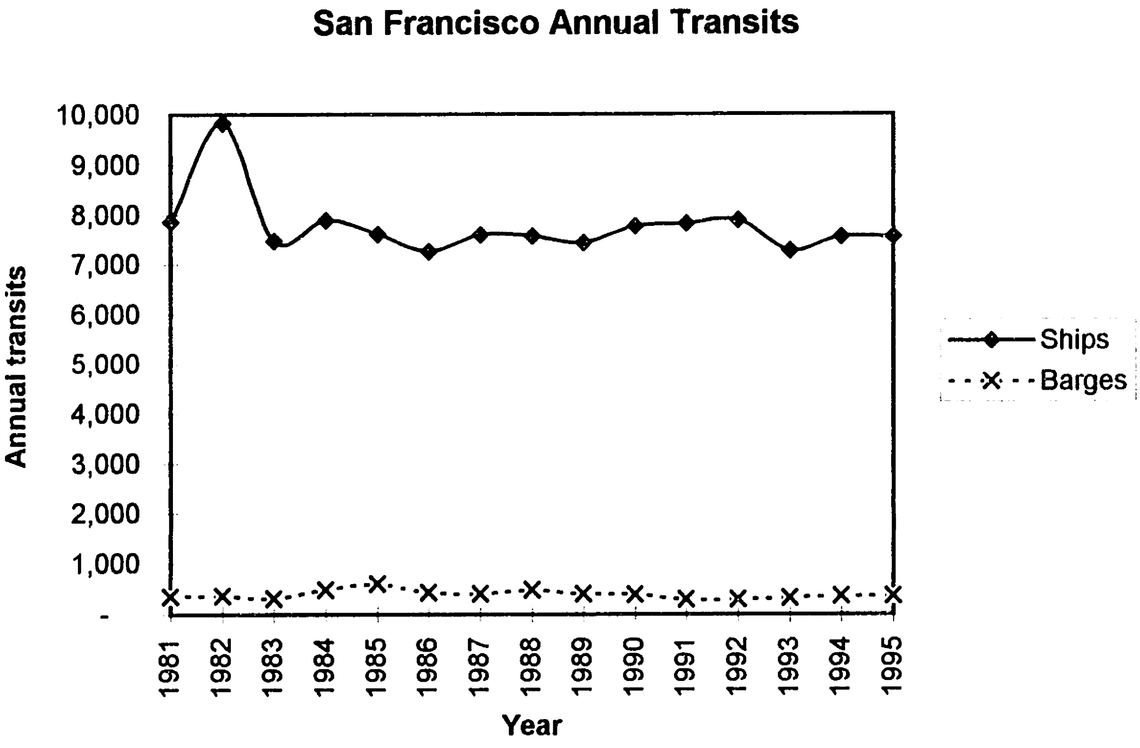


Figure 25 - Annual transits in the port of San Francisco.

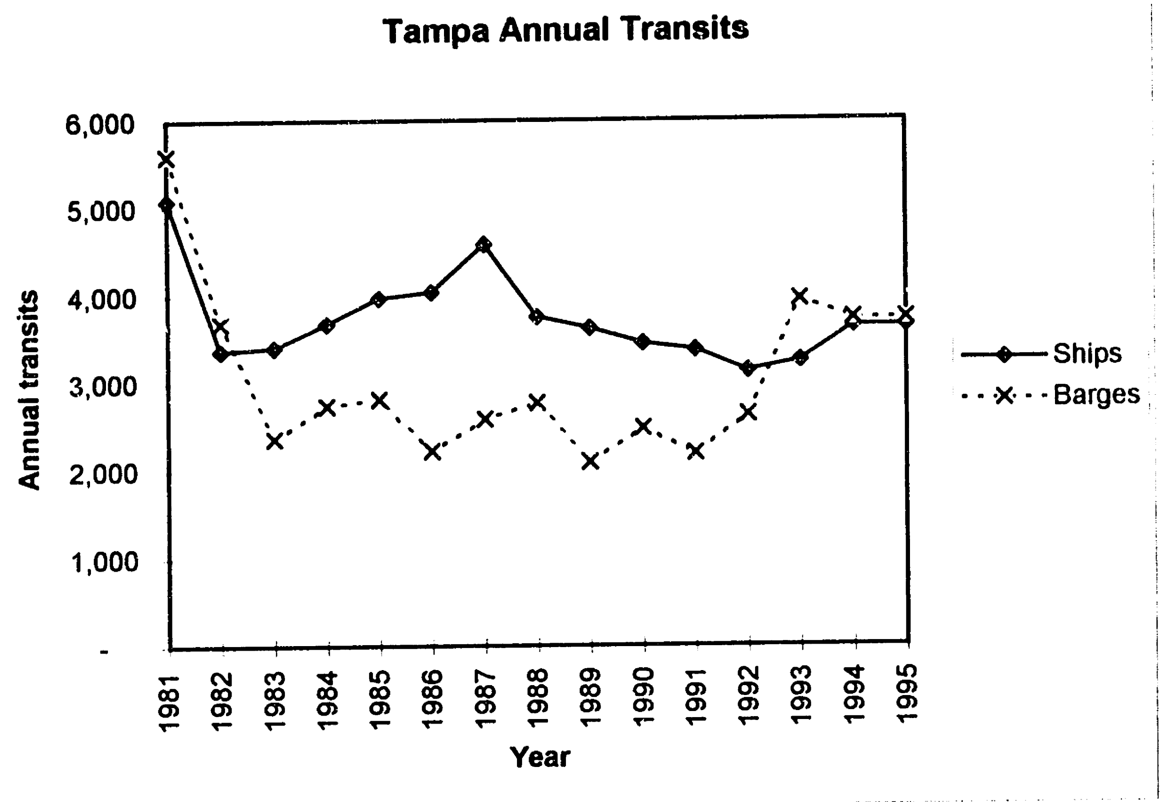


Figure 26 - Annual transits in the port of Tampa.

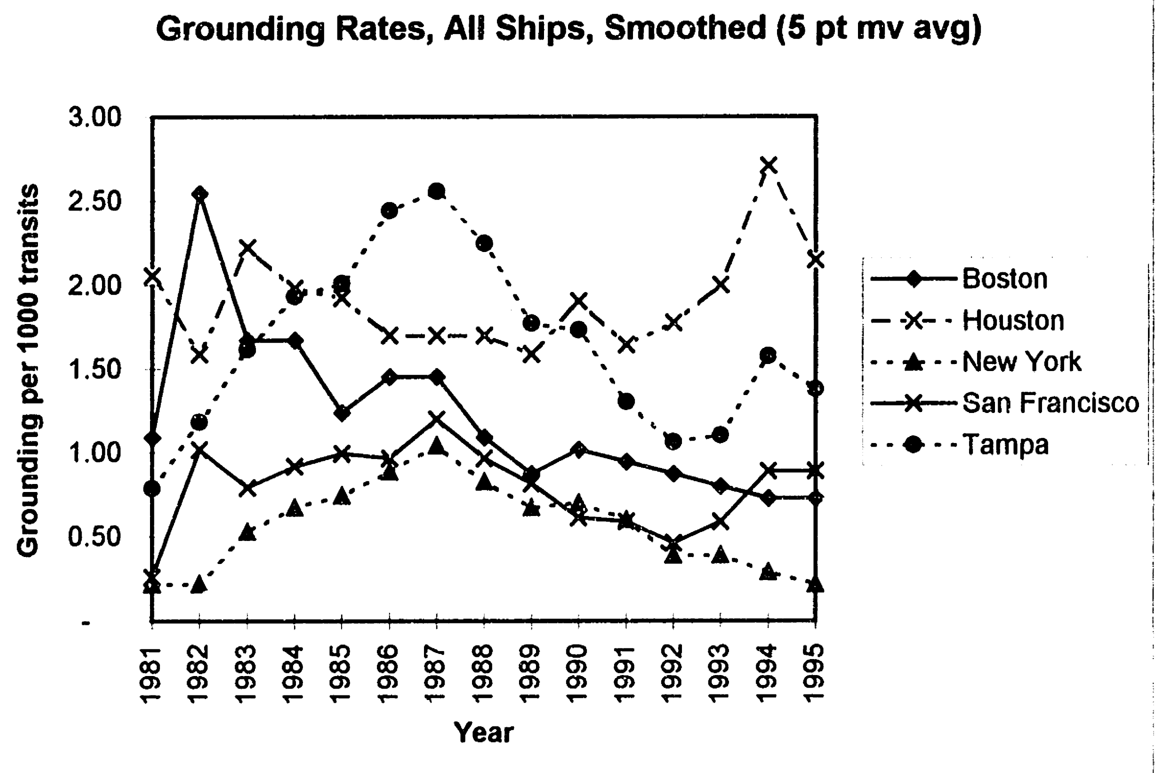


Figure 27 - Annual grounding rates for ships.

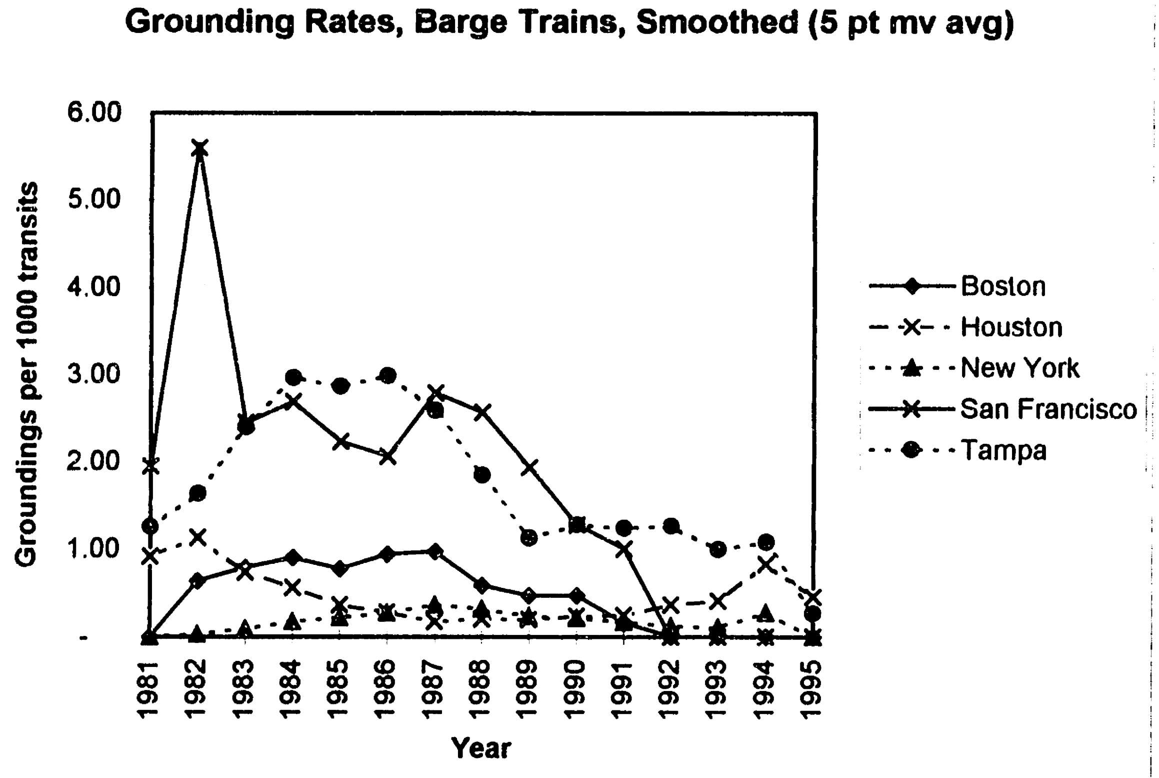


Figure 28 - Annual grounding rates for barge trains.

8.5 General Issues On Data

Throughout the course of the first year, certain deficiencies and limitations have been identified in the historical data sets provided by USCG, NOAA and ACE. A brief description of these deficiencies and limitation is provided below.

8.5.1 Historical Accident Database (USCG)

The historical accident databases maintained by USCG, originally CASMAIN and thereafter MINMOD as part of MSIS, are the most comprehensive source of information available for merchant marine casualties in U.S. waters. Nevertheless, these databases were sometimes troublesome to work with, especially CASMAIN, because of missing data, duplicate entries, and inaccuracies.

CASMAIN was developed using non-relational database technology, as explained earlier. Non-relational models are inefficient, especially when used to manipulate enormous amounts of data, like marine casualties. Their inefficiency is not related only to data manipulation, when running queries to extract certain pieces of information. Non-relational databases are also inefficient in terms of data entering because they lack mechanisms that can minimized mistyped, duplicated or omitted information.

The successor, MINMOD, was closer to the relational approach, but still certain deficiencies were evident. Most of these deficiencies were primarily attributable to inadequately normalized data structure. In the context of database development, normalization is the process for simplifying the database design to achieve optimum structure. This process is based on the so-called "normalization theory" that provides the designer with the concept of normal forms to assist him in achieving the optimal structure (see section 8.2) [44]. Normal forms are a linear progression of rules applied during the development process with each higher normal form achieving a better, more efficient design. The second normal form dictates that each of the database tables should store data relating to only one "thing" or "entity". Unfortunately, "Marine Casualty And Pollution Master Record", the main table in the MINMOD structure, was not designed in full compliance with that normal form. This table holds information on mainly two entities: the casualty itself and the investigation that followed. A simpler structure, compliant with the second normal form, would have incorporated two tables instead of one. Each of these tables would be holding information on one of the two entities. As a result of this complex form, data manipulation was not as efficient as it could be in a truly relational model.

Among other, these deficiencies in the data structure were partially responsible for the following problems: missing data, duplicate entries, and mistyped information. These problems were evident in both databases, but CASMAIN seemed to suffer more, probably because it employed an older data model. Missing data seems to be the most common and far more obvious problem. Many of the tables received had entire columns almost empty of information. These columns were as good as if they did not exist at all in terms of added value, while they introduced considerably increased data manipulation time. In certain cases the data missing were essential for successfully analyzing grounding risk; for example, 18% of the CASMAIN grounding entries had no latitude or longitude information at all. Duplicate entries were frequent as well and were manifested in two forms: actual duplicate records and duplicated query results. The first form was due to erroneous data entry that lead to identical records. The second form seemed to be the consequence of falsely defined relationships among different entities as well as minor variations in the contents of certain fields that gave the impression of different records. The latter type was not as common as the first, but it was more troublesome to eliminate. Mistyped information was the last of the three problems mentioned above and the most comprehensive example was casualty locations that plotted outside water on adjacent dry land.

Accident locations suffered from another problem that did not seem to be the result of false data entry. As mentioned earlier, casualty locations were reported using latitude and longitude values. These values were supposed to be recorded to tenths of minutes. However, our analysis indicated that the accuracy of the reported values was far lower in certain data entries. The inconsistencies observed in the accuracy of latitude and longitude values are crucial, especially in the analysis of the bathymetry uncertainty.

When USCG migrated from CASMAIN to MINMOD in 1992, a huge amount of legacy data was developed corresponding to ten years of merchant marine casualty information. This legacy data is essential to efforts like the one undertaken by our team. However, the form in which this data was delivered was not practical, especially for the data consolidation stage where the two historical casualty sets had to be combined into a single continuous table. To facilitate similar efforts, USCG should develop some middle-ware that will provide the means for easy accommodation of the legacy data into the new structure.

Missing data were not only the result of omissions during the data entry process of information already acquired. The data sets provided by USCG were missing completely several kinds of data; it seems that they were not recorded at all, even though they are of certain interest in the study of accidents. For instance, vessel's draft and trim values at the time of grounding were not reported despite their apparent importance in reconstructing actual water depth and below the keel clearance. These latter values are necessary in analyzing the accuracy of depth information provided by charts as discussed in section 9.4. Another example of missing information is that those concerning the presence of escort tugboats and pilots. Both kinds of information were partially recorded in CASMAIN but completely removed from MINMOD.

Further improvement of data quality in the historical casualty database maintained by USCG can be achieved by adopting a consistent set of criteria to govern the incident monitoring process. The criteria concern mostly the categorization of casualty nature and cause, and the reporting of environmental values. In many cases it was not clear why the primary nature of an accident was identified as accidental grounding and the cause as explosion or vise versa. Our impression is that each investigator uses his or her own understanding of the accident's nature and cause without necessarily conforming to some set of organization-wide criteria. The same is true about the reported environmental values.

Many of the above mentioned problems are expected to be resolved following a study conducted by the Research and Development Center of USCG [42]. This study investigates different aspects of the casualty database implementation, especially in the area of human interface. The results of this study were certain recommendations addressing certain issues such as the development of organization-wide casualty investigation and reporting criteria.

8.5.2 Environmental Database (NOAA)

The hourly averaged data on wind speed and visibility obtained from NOAA allowed the performance of a fairly detailed time-analysis. However, caution is required in interpreting the results of such analysis because these values do not necessarily reflect the wind speed and visibility conditions prevailing in the accident area. These environmental quantities are measured at a nearby airport which may or may not be close enough to each particular accident location. Measured over dry land, these wind speed and visibility data can not be expected to accurately represent these quantities over the water.

The analysis of the environmental effects on grounding risk was further limited due to insufficient information on historical water level and currents. These data were not reported with the same level of detail and consistency as wind speed and visibility, therefore it was not possible to reconstruct the water level and current conditions during groundings. This problem is expected to be resolved as real-time oceanographic data acquisition systems become operational in U.S. ports. Such a system is already in service in Tampa (PORTS).

8.5.3 Safe Transit Database (ACE)

The safe transits data acquired from the Waterborne Commerce Statistics Center of ACE were useful but introduced several limitations to our analysis. The fact that only annual summaries of transits were provided did not allow a detailed seasonal analysis of the traffic patterns in each of the study ports and their effect on grounding rates. Rough approximations are also required in the analysis of traffic by vessel type because the database included both dry cargo and passenger vessels in a single category. The breakdown of transits by specific waterways was useful. However, since no aggregated traffic statistics were provided for each port, the compilation of the available data towards the development of a composite port region entailed the danger of double counting transits. Finally, barge movements are reported on an individual vessel basis, and there is no completely accurate way to determine the number of safe barge train movements.

8.5.4 Data that would improve the model's accuracy

To summarize the above discussion we can mention four types of data that could be gathered to improve the model's accuracy:

More accurate data about current included factors

More accurate data about current included factors can reduce the "variance" of the predicted posterior probability. An example of this is the accuracy of the grounding locations in "Hydrostat area". Although we did not recommend including the depth uncertainty as an explanatory variable, more accurate data would increase the data set and provide us with further evidence for not including this factor. Another example is information about the seasonal fluctuations of vessel traffic. If we knew the monthly traffic numbers we would be able to answer questions such as: Are higher monthly average wind speeds related to higher monthly average concentration of groundings? and, What are the seasonal grounding rates?

Data about other factors

The most obvious way to improve the accuracy is to gather more data about other potential risk contributing factors. Unfortunately, we lacked a lot of historical data that would have been nice to have, such as:

- information on human factors (e.g. competency and experience of the crew),
- information on environmental conditions (e.g. currents and tide levels),
- information on vessel characteristics (e.g. maneuverability), and
- accident specific information (use of pilot, tugs and VTS).

It is here worth reminding that only having this kind of information for the transits that ended as groundings is not enough. We also need information on these factors during the safe transits to be able to improve the model.

Data for a longer time frame

Data for a longer time frame would make us independent of natural variations. Things may vary for no particular reason and introduce "white noise" into our statistics. However, since there is a limit for how long data has been gathered, we have here no other option than to "wait and see".

Data for other ports

Data for other ports are a good option for improving the accuracy of the model. With the experience of data collection and analysis from the current study areas, extending the study should be simple. Looking at other ports may provide a good validation of the current model.

Some of the information mentioned above are expected to be acquired during the second year of the project.

8.6 Investigating Nautical Charts' Depth Uncertainty Using Hydrostat

8.6.1 Introduction

A nautical chart is a graphic portrayal of the marine environment. It represents the culmination of a process that begins with hydrographic surveys at sea and ends with dissemination of a chart to users. The chart shows the shoreline, the water-depths, the general character and configuration of the sea bottom, the location of hazardous and man-made aids to navigation, the rise and fall of tides, and the characteristics of the Earth's magnetism [48]. The primary purpose of nautical charts is to help ensure safe navigation, especially for commercial shipping.

Maneuvering large commercial ships safely through coastal waters and harbors requires great skill, years of experience and, just as important, accurate charts. A ship's master uses nautical charts to plot a vessel's course and determine its current position, as well as check water depth, obstructions, and the location of shipping channels. In "shallow" water, all mariners need to know about the sea floor topography and about the obstructions that exists there to get safely and efficient from one point to another. How accurately the topography must be known and what constitutes an obstruction depends on the mission and characteristics of the particular vessel and on the mariner's perspective towards safety and efficiency [16]. Safe navigation occurs when a navigator evaluates and balances the risk involved in any planned course. Consistently taking a high level of navigational risk will eventually result in an accident and economic loss, while truly minimizing navigational risk on the other hand implies a thoroughness that limits the profitability of the voyage. The objective of a commercial cargo carrier is to transport the cargo with maximum profit.

This means taking the shortest (or quickest) and most economical safe route with a vessel loaded as full as possible. Because there is economy of scale in ship size, shipping companies are employing larger and larger ships with deeper and deeper drafts to transport cargo in and out of U.S. ports. However, the waterways into many U.S. harbor facilities are not as deep as the commercial shippers would like. While it is most economical to utilize the ships' full capacity all the way to their destinations, channels cannot always accommodate the ships' drafts. The trend has been to push the draft to the absolute limit. Vessels are commonly taken up channels at high tide with only inches of clearance between the keel and the harbor bottom [16].

Large commercial shipping vessels generally keep well to sea, following customary traffic lanes, when transiting between ports. In the vicinity of a port, they transit the approaches and harbors in the marked channels. However, situations such as mechanical failure, operator error, storms, and emergency maneuvers sometimes require the vessel to deviate from the regular traffic patterns. Smaller vessels such as tugs with barges often transit harbors outside marked channels. In open waters they usually travel as close to the geodesic as possible between ports. In coastal waters substantially deeper than the ship's draft it is sufficient for the master only to have a general idea of the bottom topography. When getting closer to port and upon reaching shallower waters, for instance twice the draft of the ship, the master needs an extremely accurate depiction of the bottom, including topography and artificial obstructions, to navigate safely. Charts and other information products are no better than the information they display. Therefore the accuracy, reliability and currency of the data that form the basis of the charts are central to providing accurate and reliable nautical charts [49]. Present charts are based in part on hydrographic surveys dating back to the days of the lead line. In comparison with today's needs and capabilities, older surveys collect sparse data. In addition to this, some charts based on relatively recent surveys quickly become outdated due to the changes, both man-made and natural, that occur.

Historically, the navigators' knowledge of their own position was uncertain enough that they were very cautious of approaching charted hazards. The charts, and their underlying surveys, had generally far greater accuracy, and were constructed with much better instruments than those available to the average mariner. During the last 15 years we have experienced a shift in the technology available to navigators. Global Positioning Systems (GPS) and Electronic Chart (EC) products are becoming increasingly useful and affordable. Today, GPS users can position themselves with more accuracy than most of the surveyors were able to, when they collected the data on which most navigation charts are based. This may have eroded some of the safety margin that was previously incorporated into the charts [50].

Sea floor terrain has always been difficult to survey. It is very costly to acquire sufficiently dense depth soundings to fully define the shape of the sea bottom. Traditionally[2], hydrographic surveys were conducted using vertical depth sounders. Depth measurements

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[2] Vertical depth sounders have been employed in hydrographic surveys since the 1930's.

(bathymetry) were taken every 10 to 30 meters along parallel lines for instance 50 to 300 meters apart. To construct the nautical charts, the sea floor which lies between the discrete hydrographic sounding profiles must be interpolated from the sparse data. In areas with rough bottom topography, this can result in very large depth errors in the chart models used by navigators. One of the best known groundings claimed to have been caused by poor chart quality is the recent grounding of the Queen Elisabeth II. The vessel grounded on a shoal that had gone unsampled between the hydrographic survey profiles and consequently was not correctly contoured on the chart [50]. Today, surveys are often conducted with multibeam depth sounders that covers 100% of the survey area. However, these are extremely expensive surveys and due to the current budget restrictions it is expected that most charts will still be based on sparse surveys for another decade.

According to "Minding the Helm" [21], the need for better bathymetry around shipping routes is a prime concern to maintain safe and efficient commercial transportation. Likewise, in a survey of "chart users" needs conducted by NOAA [16] it was revealed that more detailed and accurate bathymetry was requested by all user communities. There is no question that masters take risks when navigating in and out of ports. The question is whether inadequate charts contribute significantly to the risk of groundings involving deep draft, large tonnage vessels or other commercial vessels, and result in human casualties, property damage or substantial environmental damage.

A deficient chart can result in a vessel grounding by incorrectly depicting water deeper than it actually is, by omitting obstructions, or by misrepresenting navigational aids. Our objective has been to examine the possibility that the depth uncertainty in paper charts based on older hydrographic surveys have made a contribution to the incidence of groundings in U.S. ports.

8.6.2 Depth uncertainty in charts

There are three main error sources when charts are designed from survey data [43]:

- Instrumental errors,
- Interpolation errors, and
- Design errors.

Instrumental errors are the uncertainty of each data point that has been measured during the survey. They are inherent to the survey equipment used to measure soundings. These errors can easily be quantified based on the characteristics of the technology that was employed for the survey. The bathymetric instrumental errors are of two types; positioning errors and depth measurement errors. Positioning errors are controlled by the surveyor by observing multiple lines of position in order to over-determine the vessels location. Depth measurement errors are the acoustic errors, calibration errors, etc., in each observed point. The size of these errors vary widely from survey to survey. Especially for old surveys it is often hard to know the correct size of these errors. However, since most surveys are collected in accordance with the International Hydrographic Organization's (IHO's) guidelines, a possible error range can be established. IHO sets data quality standards that assures the survey to be "sufficiently accurate for navigational purposes" [43]. Although instrumental errors are subject to a host of variables and the complexity of bathymetry is constantly changing from place to place, the instrumental errors can be approximated to be constant over the survey without making too large a mistake.

Interpolation errors are bathymetric uncertainties that exist in the unsounded zones between measured soundings. They are inherent to the density of the soundings (the survey line spacing) with respect to the complexity of the sea floor, and are the least controllable error for chart design. As the chart designers move away from the survey lines, they are forced to interpolate depths based on nearby soundings. Nearby may be anywhere from a few meters to hundred meters or more. When continuous contour lines are drawn based on the interpolated depths, the chart is "contaminated" by interpolation errors. Hence, interpolation errors vary continuously and are unique to every location on a chart, and they are therefore at least as important as the instrumental errors.

The third error source, design errors, are document related processing and compilation errors. These errors are linked to a particular graphical interpretation of a sparse historical data set. They are usually safety biased errors due to the subjective nature of the many data reduction steps that go into compiling a navigation document. For instance, when drawing contour lines based on surrounding measured depths, an expert cartographer will intentionally make graphical errors to bias the contour lines towards the shallowest interpretation. The design errors vary from location to location, but are controlled by quality standards and are usually small compared to instrumental and interpolation errors.

In addition to the three sources of chart errors mentioned above, there is also uncertainty caused by the dynamic nature of the sea floor. As time passes by, the seabed shifts and the quality of the survey data deteriorate. Except in rivers and river inlets, these changes are small from year to year unless made by humans. For instance, in a descriptive report of a hydrographic survey covering the lower bay of New York harbor (survey H-9820) conducted in 1979 [51], a comparison to an older survey conducted in 1934 (survey H-5735) is described as follows:

> "Prior hydrographic survey H-5735 (1934) covers approximately one-sixth of the present survey in the southeastern portion. Major differences in hydrography exists between the present and prior surveys. Most of the major differences are attributed to dredging for fill material which show areas deeper by as much as 60 feet on the present survey. In most areas not dredged there is reasonable agreement between present and prior sounding with differences ranging generally ±2 to 4 feet. Features in undredged areas such as shoals and troughs existing on the prior survey generally still exist on the present survey in similar structure and depths with some differences in shape, size, and placement" [51].

8.6.3 Interpolation error as a proxy for depth uncertainty

To examine the possibility that the depth uncertainty in paper charts based on older hydrographic surveys have made a contribution to the incidence of groundings in U.S. waters, we have used the interpolation error as a proxy for depth uncertainty. We have analyzed hydrographic data for interpolation errors using a program called Hydrostat and combined the results with grounding locations data to check for correlation between cartographic uncertainty due to interpolation errors and historical groundings. Why we think the interpolation error is a good proxy for the depth uncertainty is explained as follows: Instrument errors and interpolation errors dominate design errors which are comparatively small and safety biased. They also dominate the uncertainty due to the natural changes in the seabed that have occurred since the most recent survey were conducted. Since we are looking not for the absolute value of the uncertainty, but for the differences in uncertainty internally in each survey, it makes the most sense to study the interpolation error that varies across the survey. Instrument errors are caused by the equipment applied when conducting the survey and are approximately constant over the survey. If the surveyed depths are far apart then, depending on the topography of the sea floor, the interpolation errors can be much greater than the instrumental errors in the measurements themselves. In fact, "experience has shown that interpolation errors are usually greater than instrumental errors" [43]. What this means is that our results measure whether it is more likely for a ship to run aground at places where the depth uncertainty is high compared to the rest of the survey, and hence, not if it is more likely for a ship to run aground at places where the survey quality is poor compared to other surveys. We are investigating if the inconsistencies in depth uncertainty internally within each survey is a factor that contributes to groundings.

8.6.4 Hydrostat

Hydrostat [43, 50, 52, 61] is a hydrographic data processing program that was developed by Geostat Systems International Inc. under contract with the Canadian Hydrographic Service [52]. The program computes the depth in the unsounded zones between measured soundings using a geostatistical depth interpolation algorithm which also predicts the depth estimation errors inherent to each point on the interpolated bathymetric model [50]. In this way the software provides a standard algorithm for statistically describing the spatial errors inherent to bathymetric data.

The true uncertainty of any bathymetric representation is continually varying and unique to every location on a chart. This is evident since the complexity of the bathymetry being sampled is unique at each charted location. Hydrostat evaluates the interpolation errors and combines them with the instrumental errors into a single spatial uncertainty for every point within the zone covered by a bathymetric data set. The instrumental errors must be analyzed first so that the uncertainty of the observed data can be propagated into the interpolation error estimates. The density of the points where total vertical error estimates can be computed is arbitrary and independent of the density of the survey points. However, when using Hydrostat it is most practical to compute them onto a grid having two or three times the density of the observations so as to adequately resolve the growth of uncertainty between the surveyed points.

The products of the Hydrostat computation are two specific features; a bathymetric surface and a stochastic surface. The bathymetric surface is the terrain model interpolated from the observed sounding profiles and is strictly a function of water depth. The stochastic surface is composed of the vertical error estimates for every point on the bathymetric surface. This surface is a function of both seabed texture and data sampling density. We have used the Hydrostat program without specifying any instrumental errors, and hence our resulting stochastic surface shows only the interpolated errors of the depth estimates.

Background for development

Hydrostat, originally a part of "IHOstat", was developed as a quality control tool for hydrographers. The International Hydrographic Organization considers having good error estimates for hydrographic data as very important, and the organization has therefore set up an official IHO data quality standard Special Publication 44 (SP44). The standard SP44 is a series of guidelines for obtaining hydrographic data of sufficient quality for production of nautical charts [43]. Much of the document, however, consist of fairly subjective survey guidelines adequate for gathering data to be used in traditional scale-dependent hydrographic documents, but inadequate for collecting data to be used in scale-independent Electronic Charts (EC). The IHO guidelines are therefore currently being updated. As part of this revision process, a Working Group was formed (1989) and tasked with developing ways and means to assess digital bathymetric data in a manner that would complement the capabilities of the Electronic Chart. One of their recommendations was to create a public domain computer program which could analyze and qualify the digital bathymetry. This project was named "IHOstat" and was meant to be the basis for establishing a quality standard for digital hydrography. The Hydrostat program grew out of and is a result of the "IHOstat" project [43].

There are several reasons why a tool such as Hydrostat is needed. One of the possible uses of Hydrostat is as a quality control tool for hydrographers while they are performing a hydrographic survey. "The program, when fully developed, will be able to render survey procedures more efficient by permitting survey observations to be refined until a desired level of data confidence is achieved" [43]. This way the "software package" will aid hydrographers in determining an optimal sounding pattern and survey line spacing which produces a permissible level of interpolation error. It is also envisioned that Hydrostat will provide EC users with statistically valid error estimates for the data being viewed on the chart [43]. In order to navigate safely, a navigator should be aware of both the real-time vessel position uncertainty and the map model uncertainty throughout the time of the voyage. An Electronic Chart system is simply a real time computer program which graphically integrates digital map information with observed vessel positions. The first generation of EC's only display images of traditional paper charts that have been converted into a computer display format. Hence, the accuracy of the bathymetric model portrayed in the Electronic Chart is really unknown and unstated. As we know, the spatial real uncertainty of bathymetric models varies from place to place. If the user of an Electronic Chart misinterprets the bathymetric model to be as modern as the highly accurate Differential Global Positioning System (DGPS) vessel positioning system, he runs the risk of getting into an accident [43]. Otherwise, if he is aware that there exists uncertainties in the model, he has little information available except his experience to chose a safe yet economically efficient course through the waterways. Acknowledging that survey errors are no longer negligible compared to other uncertainties facing navigators, Hydrostat will provide statistically valid error estimates to navigators [43]. It is expected that by integrating knowledge of vessel position and depth uncertainty into an EC/DGPS navigation system, the system will provide far more utility and safety for the commercial shipping community compared to traditional paper charts.

Interpolation of depths and estimation of interpolation errors

To interpolate the bathymetric surface based on the nearby depth soundings, Hydrostat employs a classical grid interpolation algorithm called *kriging*. The kriging algorithm in Hydrostat is essentially a least-square depth interpolator which uses the *variogram* as a weighting function. The variogram is the principal analysis tool in the field of statistics known as "geostatistics". It is a useful indicator of bottom roughness and is computed from a population of the surveyed depths.

> "A variogram graphs the variability of all possible depth differences in the data sample against the horizontal distance separating each pair of soundings used to compute the differences. This relationship provides a statistical basis for predicting the uncertainty of an interpolated depth at any given distance from measured sounding" [50].

The easiest way to interpolate the depth in between of the depth soundings would have been to assume a linearly varying bottom. With this presumption of a linear slope between the depth samples, the new interpolated depth could simply be found by taking an inverse distance weighted average of the two closest measured depths. However, since the bottom is rarely perfectly smooth, higher order statistical models have to be used to find the most probable depth and the size of the interpolation error in between the soundings. When the bathymetry is not perfectly straight and smooth, the interpolated values will become somewhat uncertain. The uncertainty grows larger as the topography grows rougher and as the distance between the interpolated depth and the observed values used to interpolate it increases.

Hydrostat computes variograms within small local regions throughout the data set. In this way the program recognizes the changing bottom roughness that occurs across the survey. The local variograms are again used to interpolate depths in their local regions.

> "At each desired grid location, kriging uses the local variogram model to assign an appropriate weight to each sounding in the neighborhood of the grid point as it is used to interpolate the depth. The farther away a sounding is

> from the grid node, the less its statistical weight will be in the least-squares interpolation. Conversely, if the grid node being interpolated is exactly coincident with a measured depth then that sounding's weight will be 100% and the grid node takes on its exact value (i.e. kriging "honors" the data). By fully exploiting variograms, kriging permits the spatial variability of the sea floor to be use to control the gridding process. The stochastic nature of kriging permits the [Hydrostat] algorithm to interpolate a grid of depths from the survey data and also to estimate a standard deviation for each of those depth estimates." [50]

The fact that the kriging algorithm honors the observed data points is very desirable in hydrography where observed values must be preserved. If a grid point is interpolated at the exact location of a measured sounding then its estimate of the interpolated error will be zero. As mentioned above, the predicted interpolation error within any local area is directly related to the sounding line spacing chosen for the hydrographic survey. Since hydrographic surveys usually are conducted with fairly constant line spacing over large areas, it means that we will find the largest interpolation errors where the local sea floor morphology is rough.

Hydrostat assures the statistical validity of the computed interpolation errors using an automatic process to "calibrate" the predicted errors. The procedure involves randomly selecting 25% of the data points to act as calibration points, then kriging depth estimates for each of these measurement locations using the remaining data. The difference between the surveyed and interpolated depths are then "real" interpolation errors. The standard deviation of these real errors is then compared to the average of the predicted interpolation errors for the same points. If a bias exists between the real and the predicted errors, these two measures will be unequal and there ratio is used to calibrate the local variogram models prior to proceeding with the actual kriging process. By correcting the variograms, the average predicted error will adjust accordingly and the bias will be eliminated.

The final products of Hydrostat are the bathymetric surface, the depths interpolated from the hydrographic survey data, and the stochastic surface, the depth interpolation error estimates. The computed value of the stochastic surface represents the estimated standard deviation of the corresponding depth estimate on the bathymetric surface. A further explanation of the variogram models and kriging is given in Appendix B.

Running Hydrostat

After having transformed the hydrographic survey file from geographical coordinates into rectangular coordinates, it can be read into Hydrostat. Hydrostat runs on Windows 95 and provides a user friendly interface. However, before the soundings can be read into Hydrostat by use of a simple read command, the format of the file containing the soundings must be specified under the "Edit project parameters" menu. Under this menu it is also possible to specify the "General settings": project name, and percentage of soundings displayed on the screen; and the "Soundings classification grid settings": the cell size, number of cells in each direction, and coordinate of origin or grid registration point (bottom left corner of grid). All this information about how Hydrostat should handle a survey file can be collected in a control file for later use. Once having read the soundings file successfully and classified the grid, the *variograms* can be calculated. The results of the variogram calculations can be displayed graphically in the viewer window as variogram ellipses (see Appendix B for an explanation of the meaning of these ellipses). Furthermore, the program can continue with the *cross-validation* and the final *kriging* calculations. In addition to displaying the soundings and the variogram ellipses, Hydrostat can also display the interpolated depths (the bathymetric surface) and the depth estimation errors inherent to each grid point (the stochastic surface). An example of the hydrographic survey is provided in Figure 29, followed by an example of a bathymetric surface in Figure 30. Finally, for our purpose, the interpolated depths and interpolation errors can be saved to a grid-file together with their respective grid coordinates. This file is later used in our investigation of the depth uncertainty (see section 9.4).

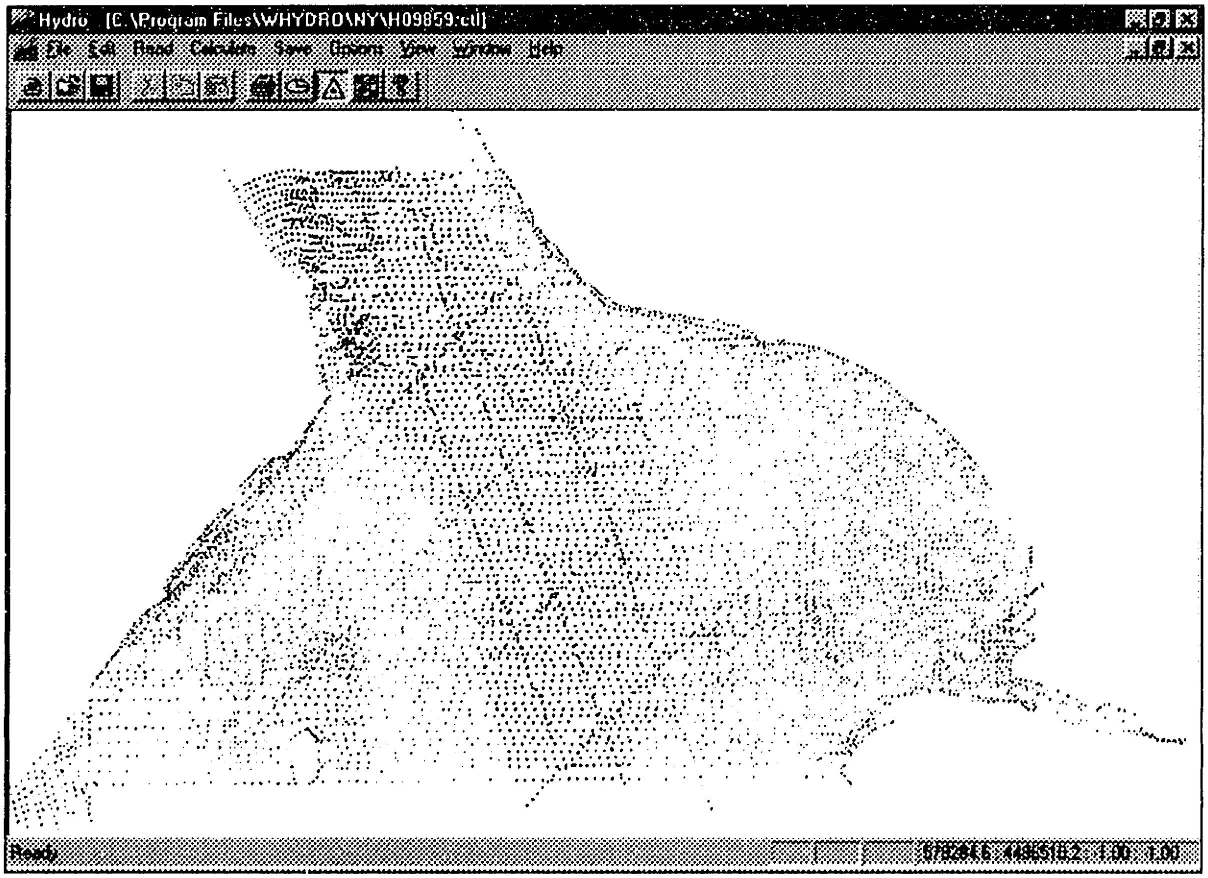


Figure 29 - Screen plot of hydrographic survey.

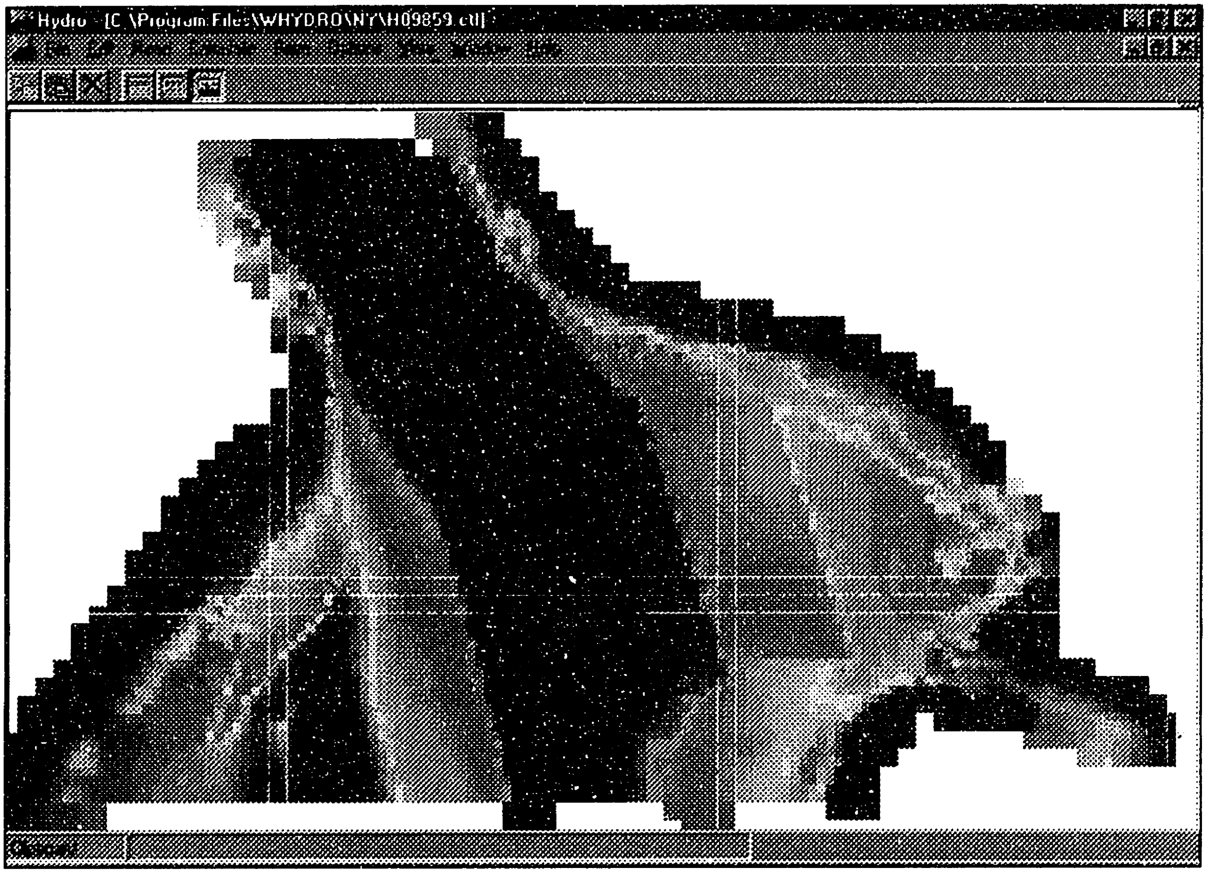


Figure 30 - Screen plot of bathymetric surface.

Chapter 9. Analysis Of Individual Factors

9.1 Wind Speed

Assuming other things are equal, unfavorable environmental conditions may be expected to involve higher grounding risk for a vessel in transit through a particular waterway compared to the same transit under favorable environmental conditions. During the initial stage of the project, this assumption was tested for two environmental variables, in particular wind speed and visibility. It is expected that other environmental variables, such as water currents and tide levels, will be investigated in the course of the following stage, once adequate data becomes available. In the present section the analysis will concentrate on wind speed. The analysis of the other environmental variable, visibility, will be discussed in the following section.

As mentioned earlier in section 7.2, wind speed data was acquired from two separate sources: USCG and NOAA. The casualty database provided by USCG included wind speed values corresponding to grounding incidents, as these were reported by the investigating officers. Unfortunately these data were not complete. NOAA's National Climatic Data Center (NCDC) provided hourly average wind speed values covering the entire period of study. These data proved to be very useful, although they need to be treated very cautiously. These data were acquired using sensors located at airports nearby the study ports. Therefore, they should not be expected to reflect the actual wind speed conditions prevailing at the site of the incident.

One initial concern was to develop an idea of the seasonal fluctuations of wind speed. That is useful for a qualitative test of the initial assumption that high wind speed conditions increase grounding risk. This test can be performed in two ways that are not, however, equally reliable. First, the less reliable way is to develop seasonal trends of wind speed and compare them with the seasonal distribution of groundings on the basis of the following question: "are higher monthly average wind speeds related to higher monthly average concentration of groundings?". Such seasonal grounding distribution graphs were developed in section 8.4. The answer must be treated cautiously because it does not take into account the seasonal fluctuation of vessel traffic. The second way to test the initial assumption does not suffer from the previous limitation. This time the seasonal trends of wind speed will be compared against the seasonal distribution of grounding rates. Grounding rates, as discussed earlier, are defined as the ratio between the grounding incidents and safe transits of any given period. Unfortunately, the safe transit data acquired from the ACE's Waterborne Commerce Statistics Center included only annual statistics. Thus, we were not able, during the first year of the project, to develop seasonal distributions of grounding rates. Because of lacking monthly transit statistics, we have assumed that the annual data provided were uniformly distributed throughout the year.

The process employed to develop the seasonal wind speed distributions was the following. First, the daily average was developed by averaging the corresponding hourly values for each individual day. Averaging these daily averages resulted in the wind speed value of each of the twelve months. The results of the process that was followed for each of the study ports are illustrated in Figure 31 at the end of this section. Worthwhile mentioning in this figure is the fact that the seasonal trends in San Francisco are reversed. The latter means that during the period April to September, where the wind speed in all four other ports is lower than the rest of the year, in San Francisco it is higher.

Following the development of the above seasonal distribution of wind speed, mean daily values were calculated for the so called "grounding" and "safe" days for all five ports of the study. The term "grounding day" refers to individual days when groundings occurred, while all the rest were characterized "safe days". Table 11 provides the calculated values. In this table, in addition to "safe days" we included what we call the "safe dates". This a subset of the "safe days" that corresponds to days that coincide in month and date with grounding days of each particular port. The latter approach reduces the influence of seasonal weather effects on the daily mean wind speed of "safe days". These effects become evident by the differences between the daily means computed for "safe days" and 'safe dates", respectively. In ports with little seasonal fluctuation these difference are small while those corresponding to ports with more significant seasonal effects are larger.

The analysis of wind speed conditions on grounding days was based both on NOAA and USCG values. In both cases the mean daily values of wind speed conditions corresponding to grounding days were calculated. The results are all provided in Table 11. It is clear that the mean daily values of wind speed are higher in the case of USCG reported data than those corresponding to NCDC average daily values. There are two possible explanations for these differences. First, probably the wind speed over water tends to be higher than the wind speed over dry land where the NCDC data was recorded (sensors located at airports nearby each of the study ports). Second, the NCDC values used in the process are daily averages and not individual values corresponding to the time of the incident. It is expected that during the course of the second year the analysis will be refined to take into account the time of the day that each grounding occurred. Data concerning the time of grounding are partially available in the USCG data.

Regardless of the analytical approach or the data source employed for the calculation of mean daily wind speed values, it is apparent that the values corresponding to grounding days are higher than those of safe days. This observation suggests that wind speed is a grounding risk contributing factor. Therefore, it should be employed as an explanatory variable in the model of the physical risk that will be discussed in section 7.5.

To illustrate further the differences between the grounding and safe days, cumulative distribution graphs of wind speed for each port are provided in Figures A5-A9, in Appendix C. In addition to what has been discussed so far the provided cumulative distribution graphs take into consideration the difference in vessel types. Thus, for each port we provide one cumulative distribution graph for all vessels, a second for ships only and a third for barge trains only. In each graph three plots are included: safe days (NOAA), grounding days (NOAA) and grounding days (USCG). These plots illustrate the percentage of days that were observed to have mean daily wind speed above a series of given values. These latter values were arbitrarily chosen at steps of 0.05 m/s from 0 to 30 m/s. The step of increment was selected to be small to increase the smoothness of the resulting plots. The higher "tail" in most of these cumulative plots towards the upper end of the wind speed range in the case of grounding days illustrates the association between groundings and higher wind speeds. This association becomes far more evident from the plots that were developed using the USCG wind speed data.

The analysis of wind speed presented above did not take into consideration port closures at times when winds were very high and vessel transit deemed not to be safe. Additional information is expected during the second year that will allow appropriate truncation on the right side of the safe distribution to reflect such situations. In addition, when such information arrive, it might be appropriate to consider different high wind cutoff values for ships and barge trains. Both these refinements are expected only to amplify existing differences between the mean daily wind speed distributions of safe and grounding days.

Table 11 - Mean daily wind speed values (m/s).

	Boston	**Houston**	**New York**	**San Fran.**	**Tampa**
Safe Days	7.33	4.77	6.59	6.58	4.44
Safe Dates	7.32	4.76	6.79	6.79	4.46
Grnd. Days (USCG)	9.19	7.96	7.73	6.89	6.61
Grnd. Days (NOAA)	7.05	5.23	6.32	6.51	4.47

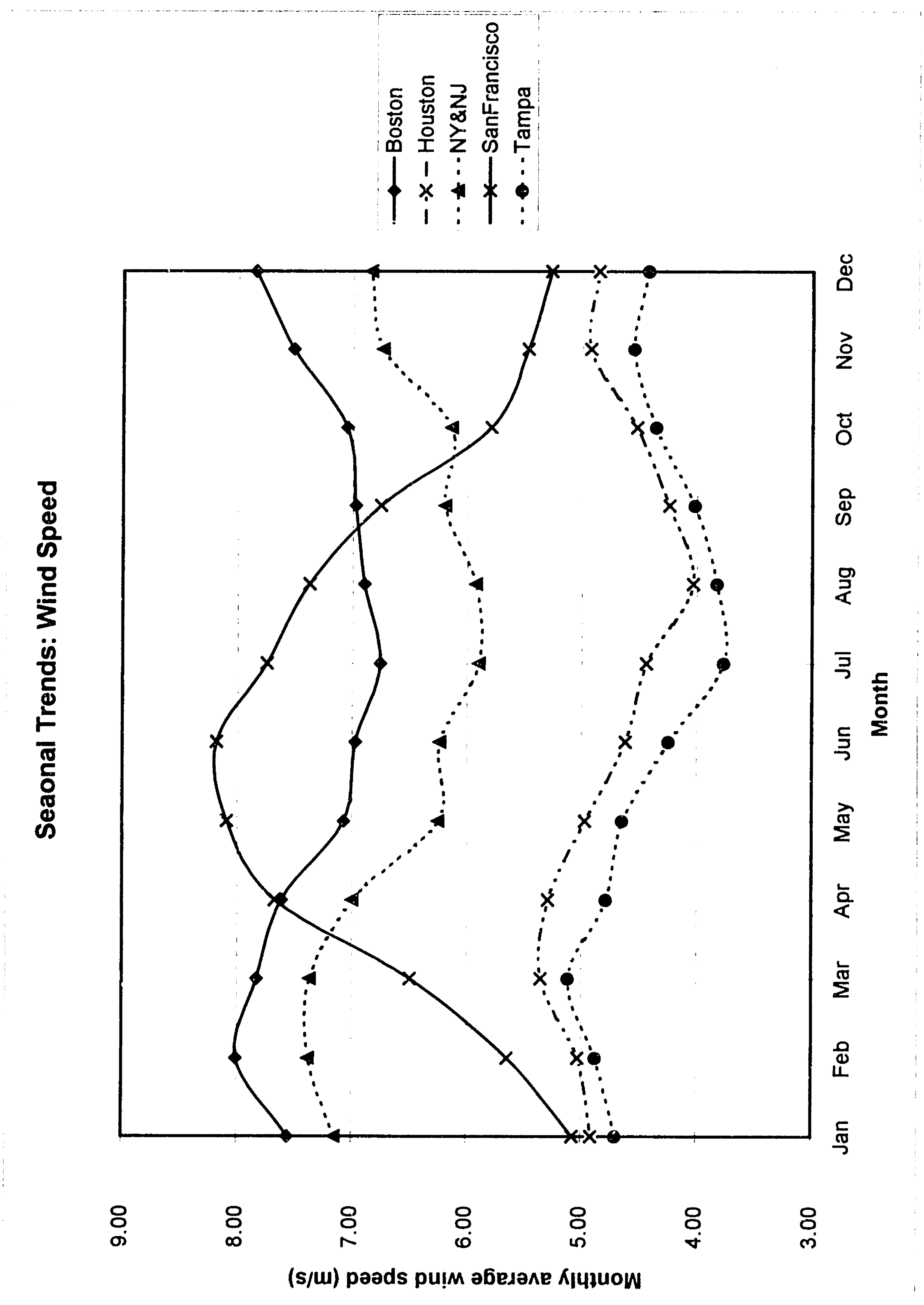


Figure 31 - Seasonal distribution of wind speed.

9.2 Visibility

Visibility is the second environmental factors that was investigated in terms of its potential grounding risk contributing effects. Again, assuming other things are equal, unfavorable visibility conditions may be expected to involve higher grounding risk for a vessel in transit through a particular waterway compared to the same transit under favorable visibility conditions. As in the case of wind speed, the analysis of visibility was based on the data provided by NOAA and USCG.

The USCG casualty database included visibility values corresponding to grounding incidents, as these were reported by the investigating officers. Again these data were not complete. NOAA's National Climatic Data Center (NCDC) provided hourly average horizontal visibility values covering the entire period of study. These data were also acquired using sensors located at airports nearby the study ports. Therefore, caution in their treatment must be applied as in the case of the wind speed data provided by NOAA/NCDC.

Our concern about seasonal fluctuations of visibility led once again to the development of corresponding plots, one for each port. The process followed in the development of these plots was similar to the one employed in the case of wind speed. The results for each of the study ports are illustrated in Figure 32 at the end of this section. As mentioned in the case of wind speed seasonal fluctuations, the seasonal trends of visibility in San Francisco are reversed compared with the other four ports. This phenomenon, however, is not as evident in the case of visibility, mostly due to a less significant fluctuation of visibility in the other study ports.

The development of seasonal distribution of visibility was followed again by the calculation of its mean daily values for the so called "grounding" and "safe" days for all five ports of the study. The terms "grounding day" and "safe day" are defined as in the case of wind speed. The resulting mean daily values of visibility are provided in Table 12, at the end of this section. The concept of "safe dates" is employed in the analysis of visibility as well for the same reasons. This approach reduces the influence of seasonal weather effects on the daily mean wind speed of "safe days". These effects become evident by the differences between the daily means computed for "safe days" and 'safe dates", respectively, in the case of ports with more significant seasonal visibility, for example San Francisco.

The analysis of visibility conditions on grounding days followed a pattern similar to the one used for analyzing wind speed effects. The mean daily values of visibility conditions corresponding to grounding days were calculated for both USCG and NOAA/NCDC data. The results are provided in Table 12, at the end of this section. The observation made for wind speed values holds in the case of visibility as well. It is apparent that the mean daily values of visibility are distinctly lower in the case of USCG reported data. The explanation for the observed difference is similar to that provided in the case of wind speed. First, it is probable that visibility over water tends to be lower than the visibility over dry land. Second, the values calculated using NOAA/NCDC data are daily averages, not the visibility corresponding to the time of the incident. These data are also expected to be refined during the second year so that the analysis will to take into account the time of the day that each grounding occurred.

The conclusions concerning the grounding risk contributing nature of visibility that were drawn based on the analysis presented above are similar to those for wind speed. Again, regardless of the analytical approach or the data source employed for the calculation of mean daily visibility values, it is apparent that the values corresponding to grounding days are higher than those of safe days. Our observation suggests that visibility is a grounding risk contributing factor and should be employed as an explanatory variable in the model of physical risk discussed in section 7.5.

Cumulative distribution graphs of visibility for each port are provided in Figures A10-A14, in Appendix C, for the visual illustration of the previous observation. Following the paradigm of the wind speed analysis, for each port we provide three different cumulative distribution graphs. The first represents the situation if all vessels are considered, while the second and the third show the results if ships and barge trains, respectively, are taken into account separately. Again every graph includes three plots, each one corresponding to: safe days (NOAA), grounding days (NOAA) and grounding days (USCG). These plots illustrate the percentage of days that were observed to have mean daily visibility below a series of given values. These values were arbitrarily chosen at steps of 0.05 km from 0 to 50 km. As in the case of wind speed, the incremental step was selected to be small to increase the smoothness of the resulting plots. The higher "tail" in most of these cumulative plots towards the lower end of the visibility range for grounding days is indicative of the association between groundings and lower visibility conditions. This association becomes far more evident from the plots that were developed using the visibility values reported by USCG.

As with wind speed, our visibility analysis did not take into consideration port closures at times when visibility was very poor and vessel transit deemed not to be safe. The necessary information is expected along with the corresponding information for wind speed. Again once such information becomes available, it might be appropriate to consider different high visibility cutoff values for ships and barge trains. Both these refinements, however, are expected once again only to amplify existing differences between safe and grounding days.

Table 12 - Mean daily visibility values (km).

	Boston	Houston	New York	San Fran.	Tampa
Safe Days	18.87	17.82	19.64	23.23	18.56
Safe Dates	18.97	17.76	19.71	23.86	18.56
Grnd. Days (USCG)	10.01	9.33	12.74	12.41	12.47
Grnd. Days (NOAA)	18.50	17.64	19.00	23.53	18.01

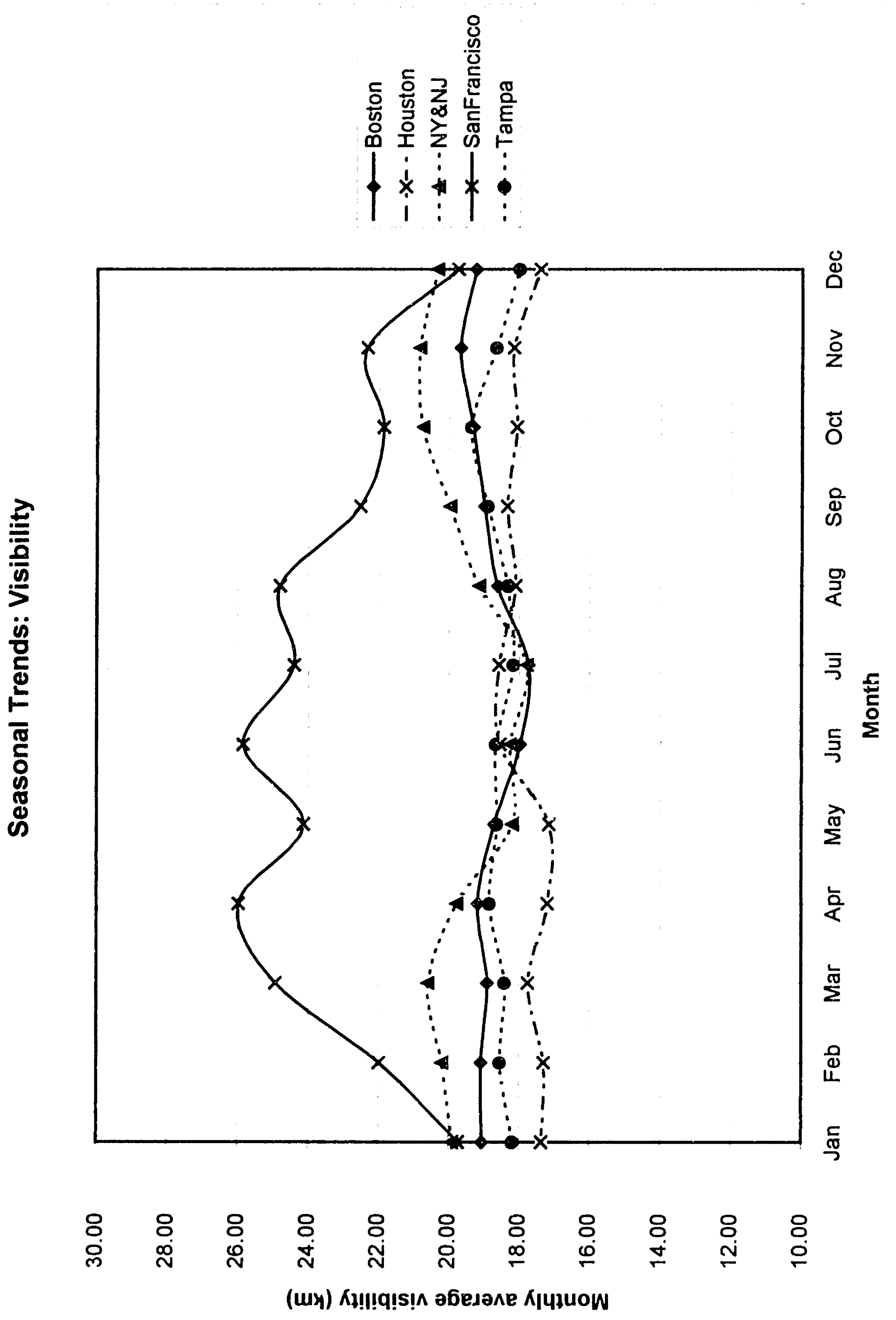


Figure 32 - Seasonal distribution of visibility.

9.3 Human Factors

Humans are widely considered to be the most risk contributing constituent in industrial activity of all kinds including maritime. Numerous studies have identified the human element as the underlying cause of 60% to 80% of all maritime casualties [36, 42]. The present thesis attempted to address the issue by performing statistical analysis on relevant data extracted from the USCG historical accident database. Unfortunately this database did not provide adequate information on human factors to support a comprehensive analysis. The alternative employed was to study human factors through the use of proxies. The only proxy that could be readily constructed from the available historical data was the vessel's flag. Another useful proxy could be the presence of a pilot during the transit. The USCG casualty data included information about the registry of each vessel involved in a grounding. However, the use of pilots during the transits was not completely documented and additional data are required before this proxy can be employed to draw valid conclusions. We expect to receive such data from local marine exchanges during following stages of the risk project.

Other things being equal, more competent vessel operators may be expected to experience lower risk of grounding. In general, the term "vessel operators" refers both to on-board personnel and the shore-based management team. However, when using flag as proxy for human factors, caution must be exercised when drawing conclusions concerning the competence of vessel's crew and managers. The rationale mandating that caution is presented below.

Many vessel registries mandate the employment of their nationals *only* in ships under their authority. For such registries, flag can be considered a valid proxy for both crew and management team. Usually such registries belong to countries with expensive crews that are trying to "subsidize" local maritime labor. The high cost of crews can be attributed to high skills, to high standards of living, or unions. Therefore, for such registries, generalizations based on the flag concerning crew and management competency are relatively safe. However, things are not as simple in the case of the so called "flags of convenience". Such registries provide vessel managers with the opportunity to use multinational crews. Even the managers themselves are not nationals of the same country as the registry used for their vessels. In general it may be expected that such registries impose lower operating standards on the ships under their authority, including crew and management competency. This assumption, however, should not be generalized because there are other reasons for selecting a particular registry, taxation being a very important one. Therefore, not all the crews under a flag of convenience should be characterized as less competent and certainly that is not de facto true for their managers. That being said, the distribution of groundings by flag should be viewed as a potential indication of the way operator competency may contribute to grounding risk and not as the explanatory variable itself.

A second potential assumption concerning human factors and the use of vessel's flag as their proxy is the following. Other things being equal, operators with better local knowledge may be expected to experience lower grounding risk. In this respect it may be anticipated that operators of U.S.-flagged vessels have better knowledge of U.S. ports and thus encounter lower risk. However, a study conducted by the Transportation Safety Board of Canada [54] (TSB) provides evidence that things may not be as simple. According to the study findings, there was an indication that among pilot assisted transits through Canadian waterways, those conducted by foreign flagged vessels involved lower accident risk. This situation runs counter to the assumption stated earlier, regarding the relation between local knowledge and the risk of grounding. A potential explanation of this seeming paradox is the level of teamwork between the pilot and the vessel officers. TSB conclusions indicate that vessel masters and officers without prior knowledge of the waterway facilitated more the function of the pilot in such a way that the overall safety of the vessel was enhanced. These masters and officers seem to be uncertain of their capabilities to safely navigate through the unfamiliar waterway and thus try to shift the burden to the local pilot. On the other hand, vessel masters and officers with knowledge of the waterway seem to act in ways that make the pilots function less efficiently, thus making the process of navigation more prone to accidents.

The verification or rejection of the previous assumptions required the overall registry distribution of vessels calling on the study ports. In addition, the verification of the second assumption and the validation of the Canadian results required a similar study for the U.S. ports. Unfortunately, the database provided by the Waterborne Commerce Statistics Center did not include registry information and to date no study of U.S. ports similar to the Canadian study has appeared to our knowledge. To circumvent the problem and acquire registry distribution information for safe transits, we had to contact local marine exchanges and port authorities. The results of this effort are presented in Tables 13 and 14, where the overall safe transit flag distribution is contrasted with the overall grounding flag distribution for the case of two ports: Tampa and San Francisco. Figures 33 and 34 provide a comprehensive illustration of the same results. All acquired data and the relevant analysis of human factors using flag as a proxy concerns only ships; tugboats/towboats and barges calling in U.S. ports are almost without exception registered under the U.S. flag. Data on the remaining three ports were pending and expected to be received during the course of the second year.

Table 15 summarizes the percentages of U.S. flagged vessels participating in transits and groundings for the five ports and the entire period of study. Figures 35 provides a comprehensive illustration of the same percentages. The difference in grounding rates between U.S. and non-U.S. flagged vessels in Tampa seems to provide an important signal. Even if U.S. flagged vessels are only a small fraction of the overall traffic, they represent a high percentage of grounded vessels. However, further exploration is required before this factor can be endorsed as useful in the development of the risk model. More detailed information must be acquired on other issues like the vessel size distribution or the breakdown of non-U.S. flag-ships. The first kind of information is necessary to investigate other possible explanations of the higher number of U.S. casualties besides the suggested operator's competency. The second kind of information is necessary to investigate the issue of human factors in terms of operator's competence in a more detailed and global fashion.

As suggested in the beginning, data concerning the presence of pilots on the vessel during the transit could provide useful insights on human factors. Unfortunately, the database acquired from USCG included such information only through 1990. Therefore, it was not possible to make a valid comparison in a way similar to the one presented above. It is expected that local marine exchanges will be able to furnish useful information to complete the database in this respect. Such information may allow certain useful conclusions about the effects of pilot presence, including a possible validation of the Canadian results in the case of U.S. ports.

Human factors analysis suffers a lot from incomplete data. As opposed to other potential explanatory variables where incomplete data results from not recording all necessary information, human factors data are difficult obtain. The USCG records far more information on human factors than that provided in both CASMAIN and MINMOD, but they were reluctant to make them public because of liability issues. That is a serious drawback in the analysis of grounding risk given that human factors are such an important risk contributing constituent. It is expected that during the course of the second and third year of this project, some of these restrictions may be lifted partially, providing necessary data to allow more detailed analysis of human factor contribution to grounding risk.

Table 13 - Ships' registry distribution for safe transits and grounding in Tampa.

	All ship transits			**Ship groundings**		
Year	**U.S.**	**non-U.S.**	**%U.S.**	**U.S.**	**non-U.S.**	**%U.S.**
1981	-	-		3	1	75
1982	289	1421	17	6	0	100
1983	267	1411	16	3	3	50
1984	287	1458	16	4	7	36
1985	263	1650	14	8	6	57
1986	203	1596	11	10	2	83
1987	332	1781	16	8	0	100
1988	333	1597	17	7	10	71
1989	345	1486	19	11	3	79
1990	328	1311	20	3	3	50
1991	276	1313	17	0	0	-
1992	259	1282	17	3	4	43
1993	242	1296	16	4	2	67
1994	241	1461	14	4	4	50
1995	350	1257	22	7	0	100
Total	**4015**	**20320**	**16**	**81**	**45**	**65**

Table 14 - Ships' registry distribution for safe transits and grounding in San Francisco.

	All ship transits			Ship groundings		
Year	**U.S.**	**non-U.S.**	**%U.S.**	**U.S.**	**non-U.S.**	**%U.S.**
1981	2184	1597	58	2	0	100
1982	2077	1361	60	6	2	75
1983	2356	1265	65	3	4	43
1984	2644	1135	70	0	3	0
1985	2557	1129	69	8	3	73
1986	2549	1120	69	1	6	14
1987	2591	1071	71	11	0	100
1988	2551	1120	69	3	3	50
1989	2490	1144	69	6	6	50
1990	2531	1130	69	1	1	50
1991	2449	1222	67	0	1	0
1992	2375	1269	65	0	3	0
1993	2293	1191	66	5	0	100
1994	2375	1127	68	4	3	57
1995	2200	977	69	4	3	57
Total	**36222**	**17858**	**67**	**54**	**38**	**59**

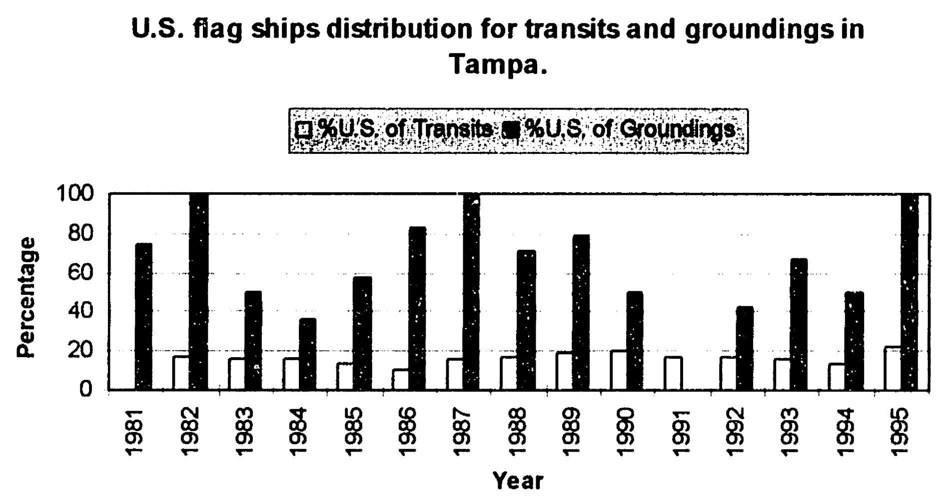


Figure 33 - Tampa distribution of US flag vessels.

Table 15 - US flag vessels as percentages in study ports.

Port of study	U.S. percentage of safe transits	U.S. percentage of groundings
Boston	NA	85
Houston	NA	81
New York / New Jersey	NA	74
San Francisco	67	59
Tampa	16	65

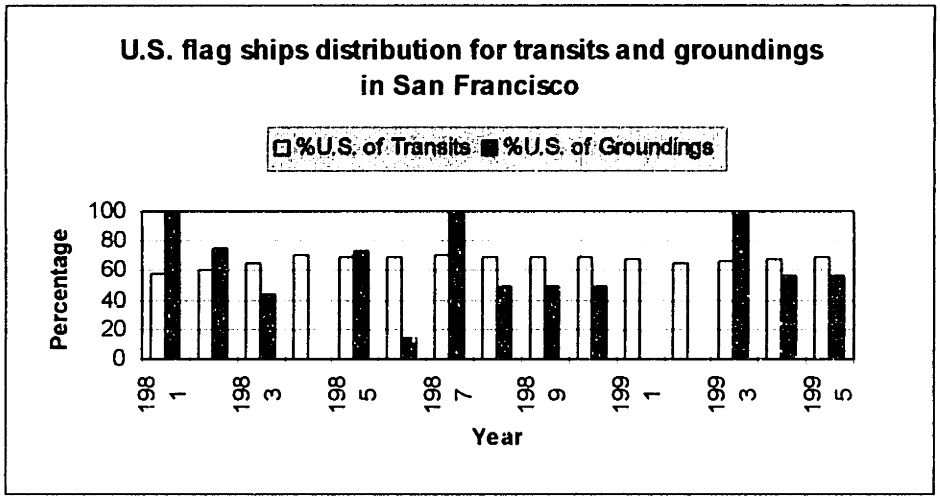


Figure 34 - San Francisco distribution of US flag vessels.

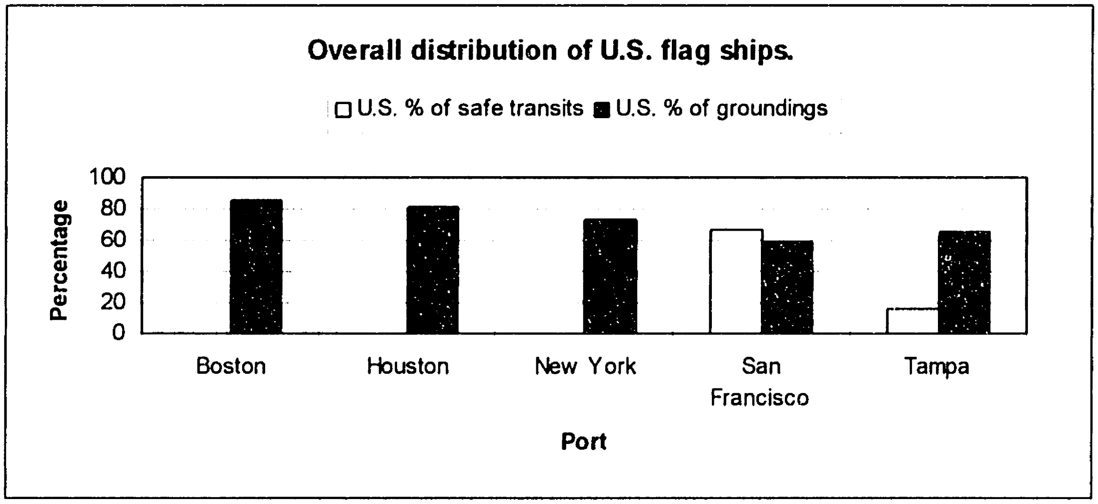


Figure 35 - Overall distribution of US flag vessels.

9.4 Depth Uncertainty

9.4.1 Introduction

Other things equal, a transit through an area for which perfect charts are available may be expected to involve less risk of grounding than a transit through an uncharted or poorly charted region. Historically, navigators' knowledge of their own position was uncertain enough that they were very cautious of approaching charted hazards. Today the situation is changed. GPS users are able to position themselves with more accuracy than what is the basic position accuracy for the details on the chart. This development may have eroded some of the safety margin that was previously incorporated into the chart [43]. The question is whether the uncertainty in a nautical chart is an explanatory variable for ship groundings. Do depth uncertainty errors contribute to the likelihood of accidents? To get knowledge of this we have analyzed hydrographic data for interpolation errors using Hydrostat and combined the results with grounding locations data to check for correlation between cartographic uncertainty due to interpolation errors and historical groundings. The results of this investigation are presented below for all of the five areas.

Sequence of investigation

The analysis proceeded as follows:

1. All the groundings that occurred in the study area during the investigation period were extracted from the United States Coast Guard's accident databases by using a query.
2. All grounding locations were plotted on nautical charts and validated. Groundings that we were able to analyze with Hydrostat were collected.
3. Surveys covering the areas where the groundings had happened were found and downloaded from CD-ROM. These surveys were subsequently translated into rectangular coordinate format.
4. The surveys were run through the Hydrostat program. Interpolated depths and interpolation errors were saved to files.
5. The interpolation errors and depths where the groundings occurred were extracted from the files and compared to the overall distribution of depths and errors.

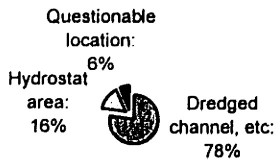
Validation of groundings

All together, within the five study areas, we found about 1,000 groundings that had entries for location (see Table 16). All of these groundings were plotted on nautical charts. Hydrostat assumes the sea floor to be isotropic (the variability observed along sounding profiles is the same variability we would encounter in other directions) or anisotropic (that the depth variation is similar in each direction within the local area) and the variation in depth variation to be normally distributed. Hence, it only makes sense to investigate groundings which happened on natural bottom conditions with Hydrostat. The depth uncertainty around man-made channels or harbor areas are small in practice, but will be artificially high when investigated by Hydrostat. Therefore, groundings that happened in and around dredged channels or harbor areas, clearly due to misinterpretation of aids to navigation or other similar causes rather than due to bathymetric uncertainty, were not part of the investigation.

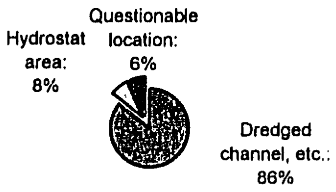
Of the 994 groundings with valid location entry, 775 happened around dredged channels, harbor areas or in rivers, and 63 had an obviously faulty entry for location (they plotted within very shallow areas or on dry land). This left us with 136 groundings located within "Hydrostat area".

Table 16 - Grounding location information.

[illegible]	Boston	Houston/Galveston	San Francisco	Tampa	New York	[illegible]
Minimum latitude, (deg.min):	42.14	29.05	37.20	27.30	40.25	
Maximum latitude:	42.30	29.50	38.10	28.05	40.50	
Minimum longitude:	70.46	94.25	121.40	82.20	73.48	
Maximum longitude:	71.06	95.12	122.50	83.02	74.20	
Groundings 1981 -1990						
Number of accidents in area:	47	391	73	156	156	823
No location:	1	144	2	8	1	156
Valid accidents:	46	247	71	148	155	667
of which were located in:						
Dredged channel, etc:	14	209	39	127	126	515
Hydrostat area:	27	26	21	21	15	110
Questionable location:	5	12	11	0	14	42
Groundings 1992 - 1995						
Number of accidents in area:	11	211	23	43	39	327
No location:	0	0	0	0	0	0
Valid accidents:	11	211	23	43	39	327
of which were located in:						
Dredged channel, etc.:	5	192	13	38	32	280
Hydrostat area:	5	10	5	5	1	26
Questionable location:	1	9	5		6	21



Grounding locations 1981 - 1990



Grounding locations 1992 - 1995

Unfortunately, not all of these 110 groundings were reported to sufficient accuracy to be useful for our analysis. In theory, the location of the groundings were given in the USCG databases to an accuracy of ±0.1 minutes latitude/longitude, or ±150 to 200 meters in the areas we were examining. However, many of the accident locations were reported without the last decimal, which resulted in an accuracy of ±1,500 to 2,000 meters and made them worthless to our study (see Table 17). For the groundings found in the CASMAIN database (1981-90) we could only trust, statistically, the groundings given with both the latitude and longitude decimal unequal to zero, while for the 1992-95 groundings we discarded the groundings that had both the minute latitude and the minute longitude decimal equal to zero. Hence, the basis for our evaluation was reduced to 71 groundings, or 7% of the original number of groundings with valid location entry. Although we would have preferred to have more data available, this is still a statistically useful sample.

Surveys

The 71 sample groundings were located within 17 surveys. The surveys were easy to locate and download thanks to the GEODAS search engine. However, these 17 surveys differed greatly in age, quality and density of data. The oldest survey used was a survey covering the approaches to Boston harbor dating back to the year 1940, while the newest was a survey from the San Francisco Bay taken as late as in 1989. We of course made sure to only use surveys taken prior to the time the actual grounding took place.

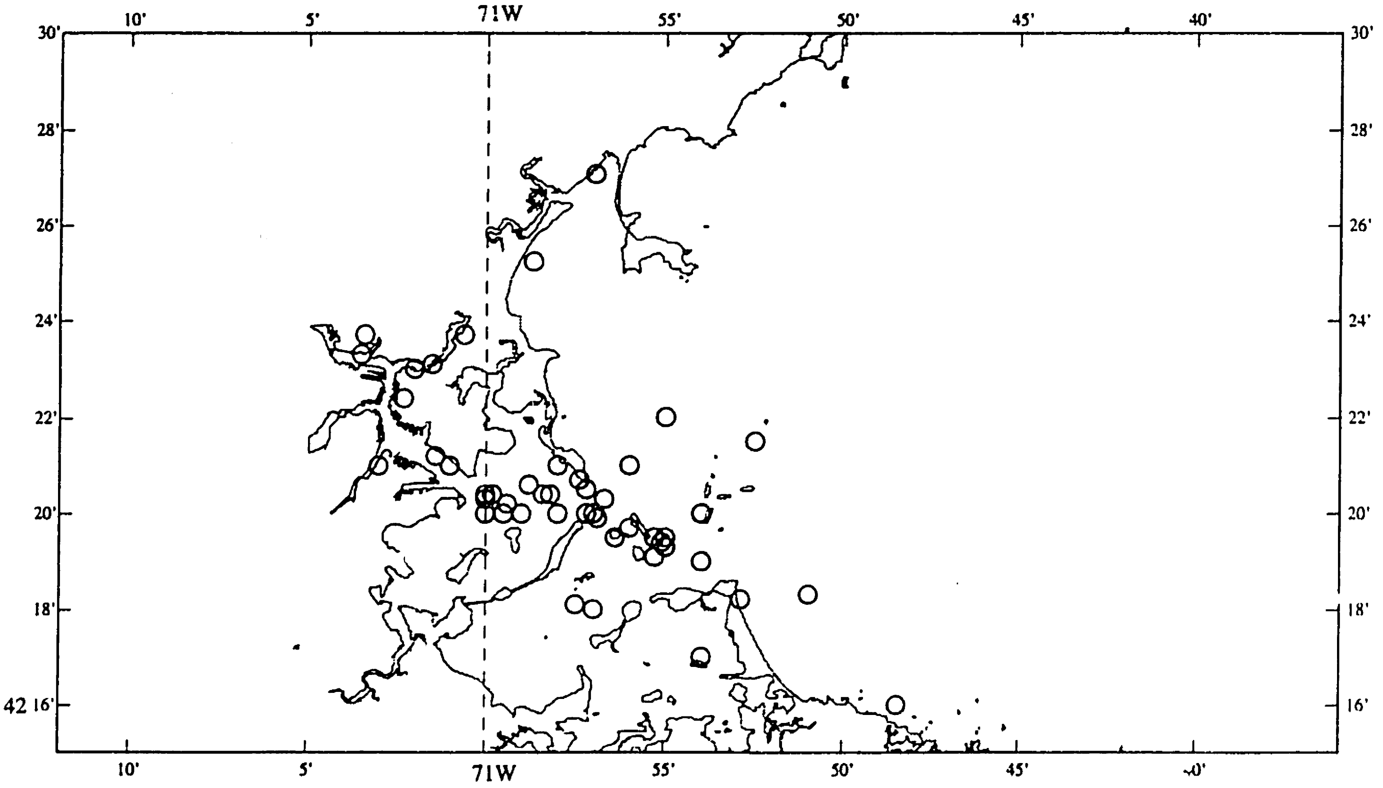


Figure 36 - All groundings in Boston

Table 17 - Accuracy of grounding locations.

Groundings 1981-90						
[illegible]	Boston	Houston/Galveston	San Francisco	Tampa	[illegible]	[illegible]
Number of groundings located within "Hydrostat" area:	27	26	21	21	15	110
of which has:						
both minute latitude and minute longitude decimal equal to zero:	11	6	10	3	4	34
only minute latitude decimal equal to zero:	3	1	4	4	0	12
only minute longitude decimal equal to zero:	4	4	1	0	5	14
Groundings with sufficient accuracy:	**9**	**15**	**6**	**14**	**6**	**50**
Groundings with insufficient accuracy:	18	11	15	7	9	60
Groundings 1992-95						
[illegible]	Boston	Houston/Galveston	San Francisco	Tampa	[illegible]	[illegible]
Number of groundings located within "Hydrostat" area:	5	10	5	5	1	26
of which has:						
both minute latitude and minute longitude decimal equal to zero:	0	0	1	4	0	5
only minute latitude decimal equal to zero:	0	1	0	0	0	1
only minute longitude decimal equal to zero:	1	1	0	0	1	3
						0
Groundings with sufficient accuracy:	**5**	**10**	**4**	**1**	**1**	**21**
Groundings with insufficient accuracy:	0	0	1	4	0	5
In Total:						
[illegible]	Boston	Houston/Galveston	San Francisco	Tampa	[illegible]	[illegible]
Number of accidents located within "Hydrostat" area:	32	36	26	26	16	136
of which has:						
Groundings with sufficient accuracy:	**14**	**25**	**10**	**15**	[illegible]	**71**
Groundings with insufficient accuracy:	**18**	**11**	**16**	**11**	**9**	**65**

Comparison for correlation

Once the Hydrostat bathymetric and stochastic surfaces were produced, we were able to extract the interpolated errors and generate grounding location error distributions and overall chart/survey error distributions. The interpolated error where the grounding occurred was taken to be the maximum error within the ±0.1 minute latitude/longitude (±150-200 meters) area of the position entry. Likewise, the depth of the grounding was taken to be the average depth within the same area. The point distributions and the overall distributions were then compared to check for correlation between cartographic uncertainty due to interpolation errors and historical groundings. A correlation would be indicated by a concentration of the point-errors on the high side of the general error distribution.

9.4.2 Results

Boston

Only 14 of the 57 valid groundings in the Boston area were located in the right kind of region and had good enough location accuracy to be evaluated by Hydrostat. Figure 36 shows all the groundings (except some of the most questionable groundings) and Figure 37 shows the groundings investigated and the surveys they are located within. The surveys H09134, H07066 and H06643 are from year 1970, 1945 and 1940, respectively. The port area of Boston has a rocky bottom and many of the ship channels are naturally deep channels. However, closest to the port itself, where most of the groundings have occurred, the channels are dredged.

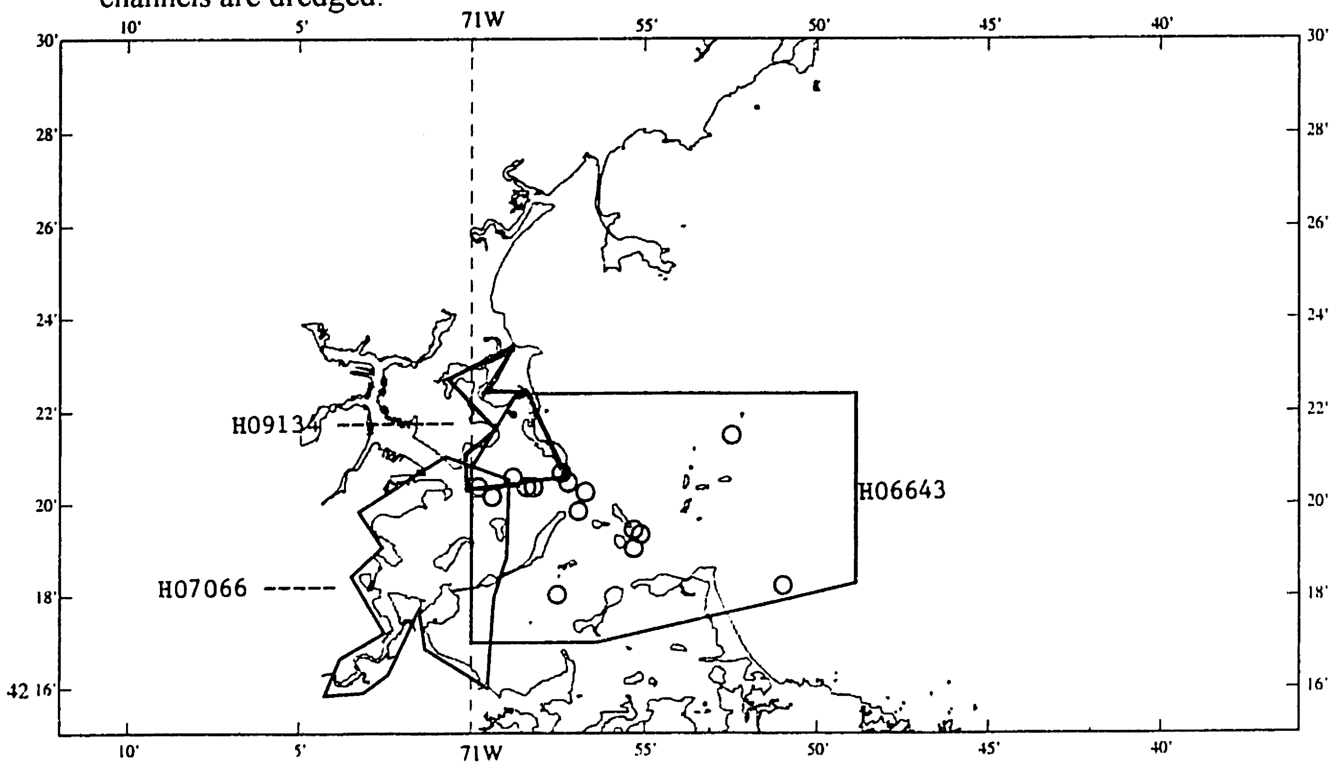


Figure 37 - Groundings in Boston investigated with Hydrostat.

Figure 38 shows a depth contour plot of survey H07066 and the location of the groundings located within this survey. The plot is produced from the interpolated depths calculated by Hydrostat. Figure 39 shows depth error, depth curves and grounding locations for the same survey. The interpolation depth and error comparisons for the three surveys follows in the next 6 figures. Figure 40 shows the overall distribution of estimated depths for survey H07066 and depth where groundings occurred, while Figure 41 shows the overall distribution of interpolated errors of estimated depth and maximum interpolated errors of depth estimate where groundings occurred for the same survey. From these error comparisons it might look like there is a correlation between the groundings and the error. However, to get the right comparison, it is important that we compare the interpolation error where the groundings occurred with an area representative of the area the ships transit. This area is equal to the ship-lane areas of the respective surveys. Hence, in Figures 46-51 the grounding location depths and errors are compared to the ship-lane area distributions. Clearly we get a different picture of the correlation. These graphs show no sign of a concentration of the point-errors on the high side of the general error distribution. There is no evidence that "open-water" groundings tend to happen in high uncertainty areas.

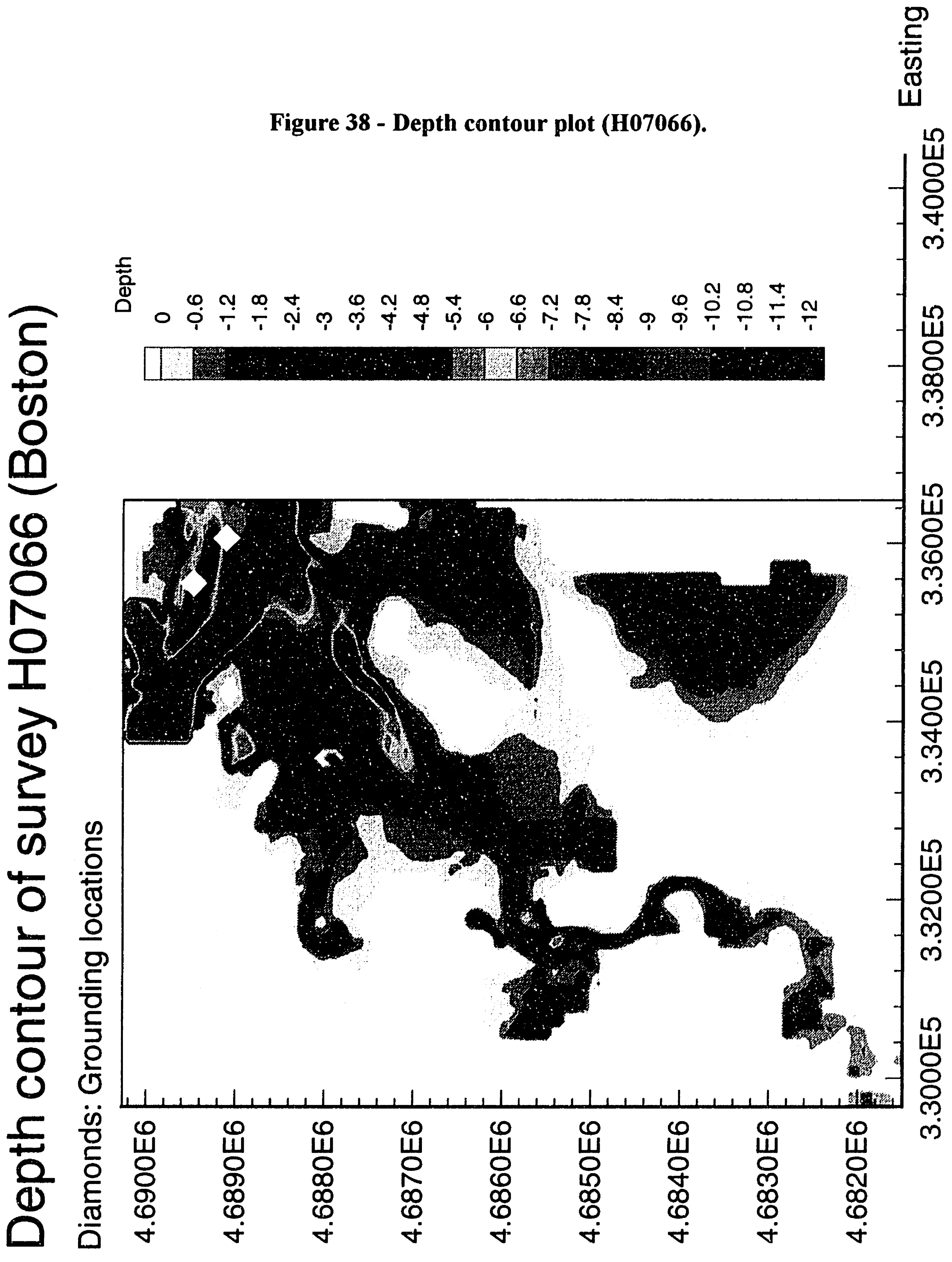


Figure 38 - Depth contour plot (H07066).

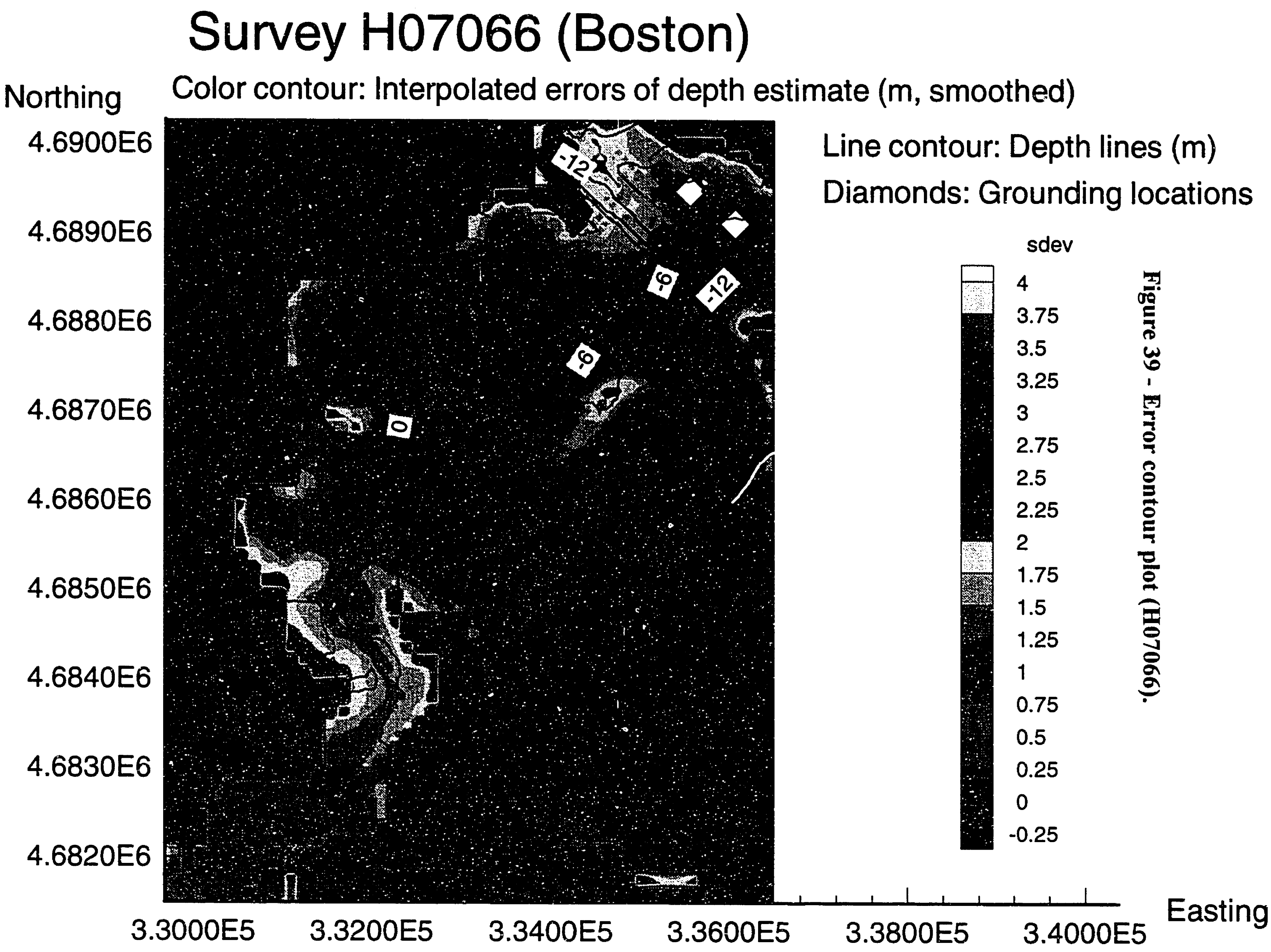


Figure 39 - Error contour plot (H07066).

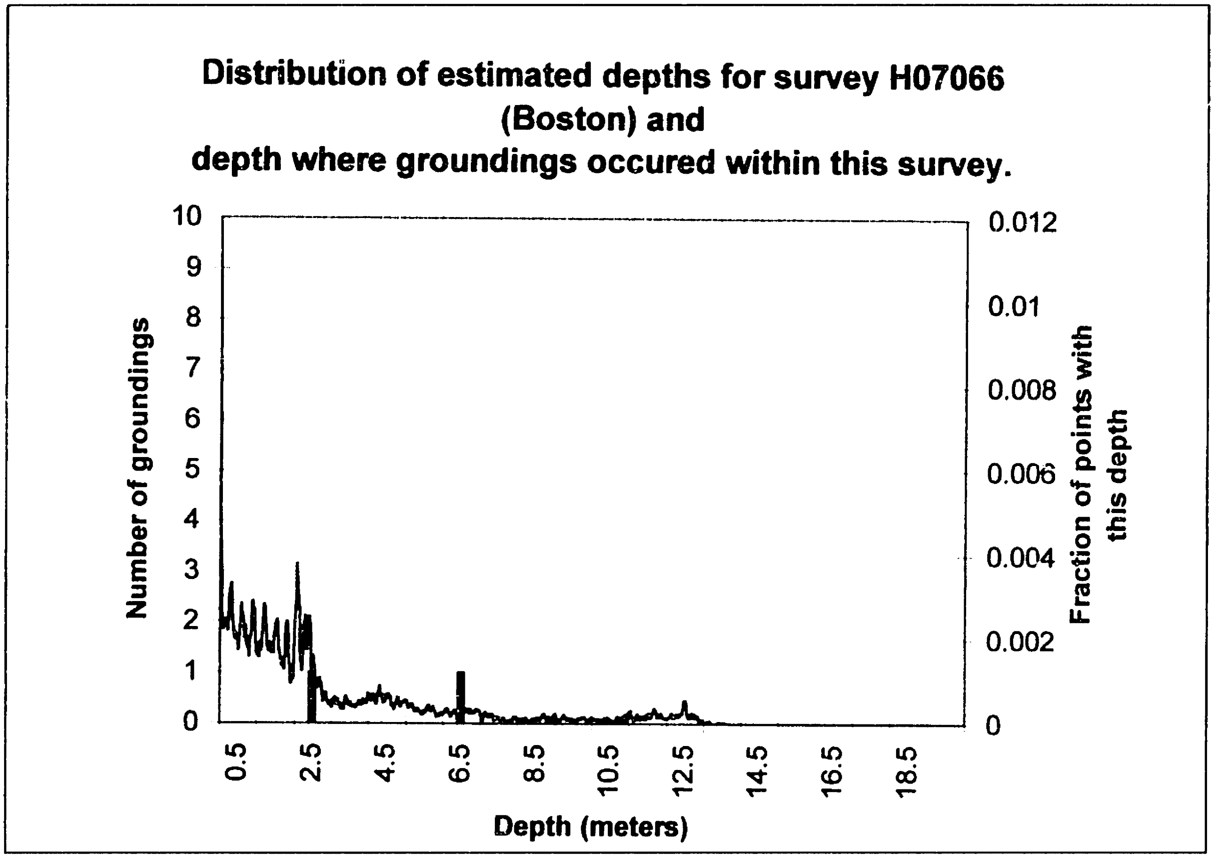
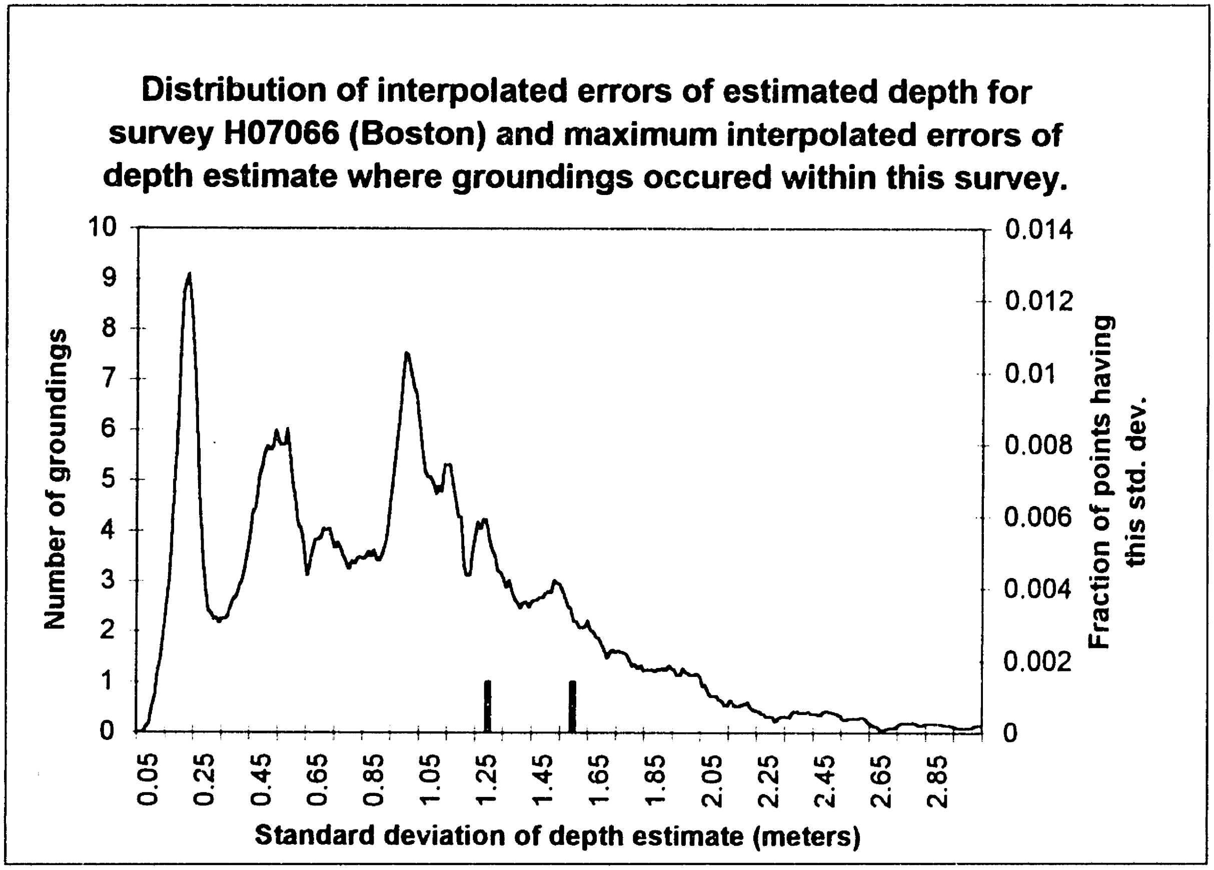


Figure 40, 41 - Depth and error comparison, survey H07066.



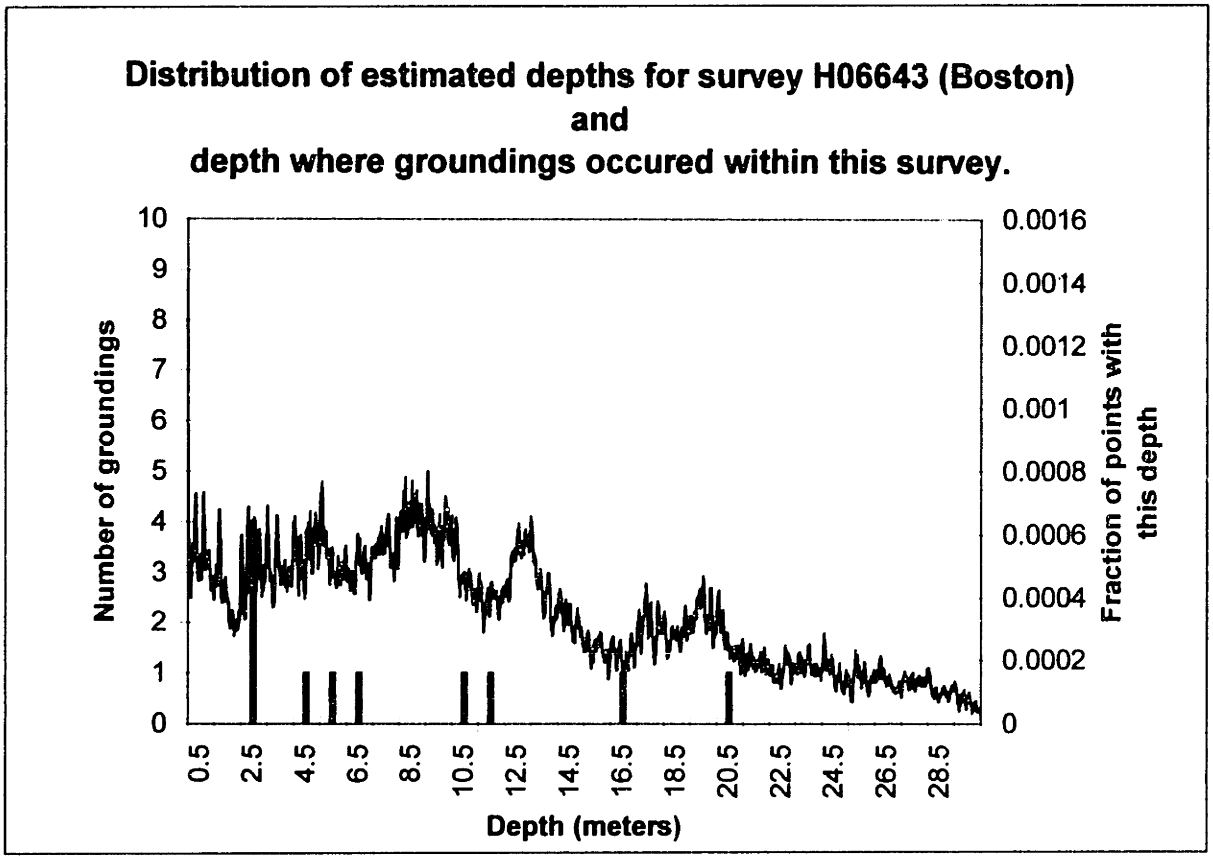
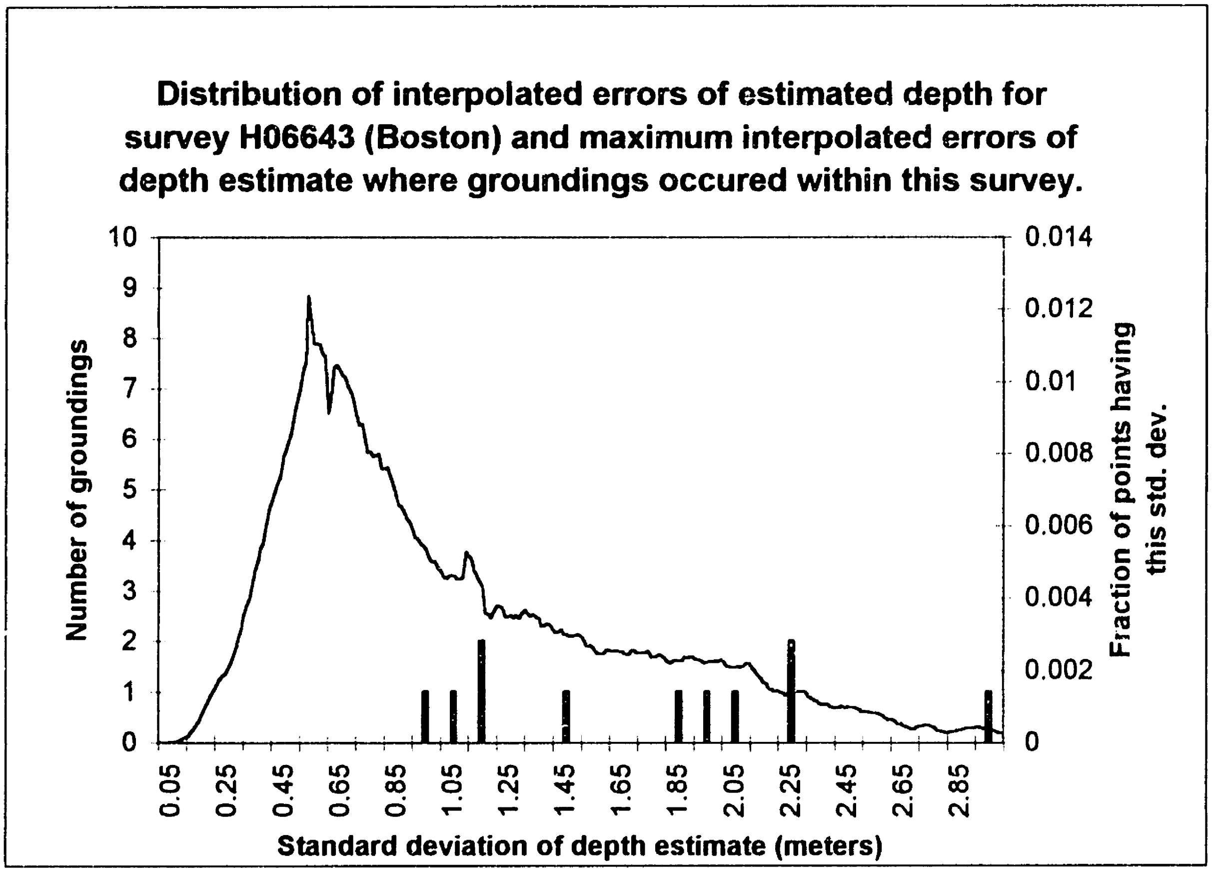


Figure 42, 43 - Depth and error comparison, survey H06643.



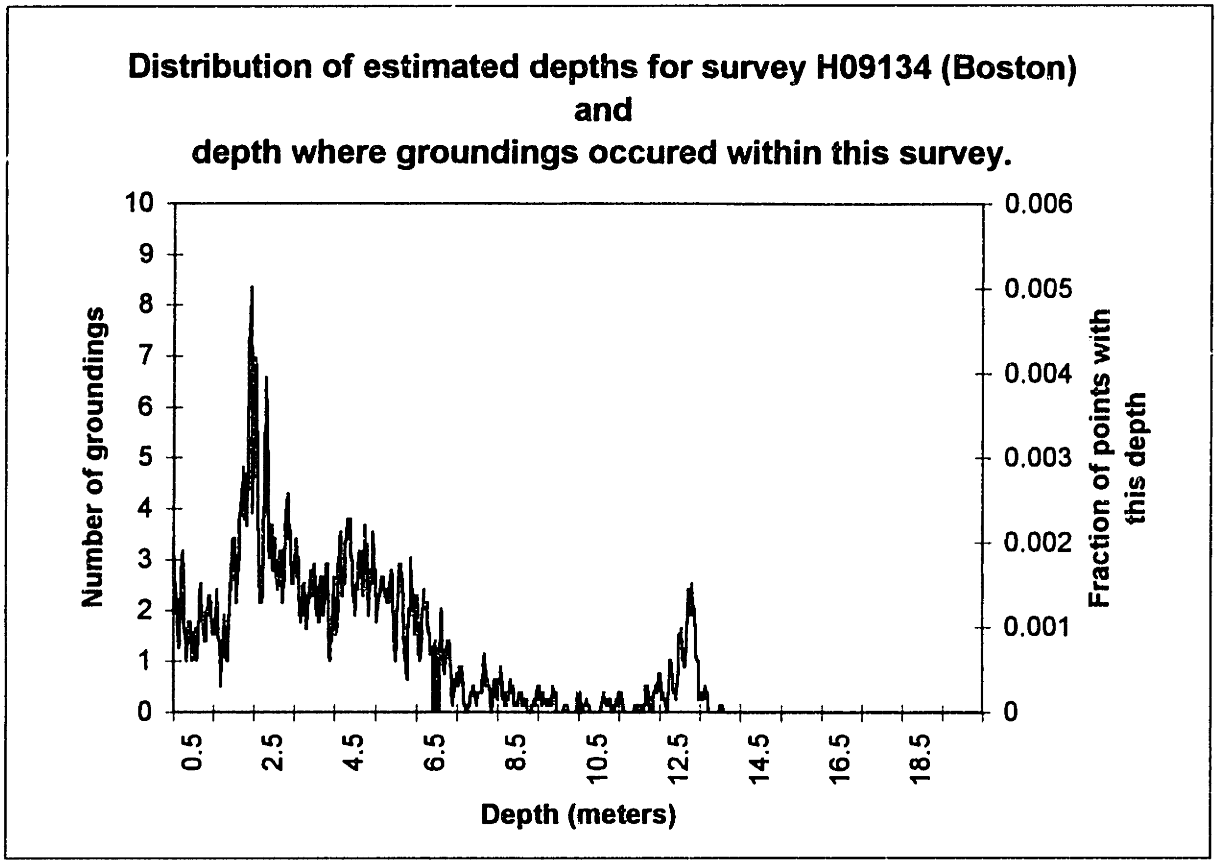
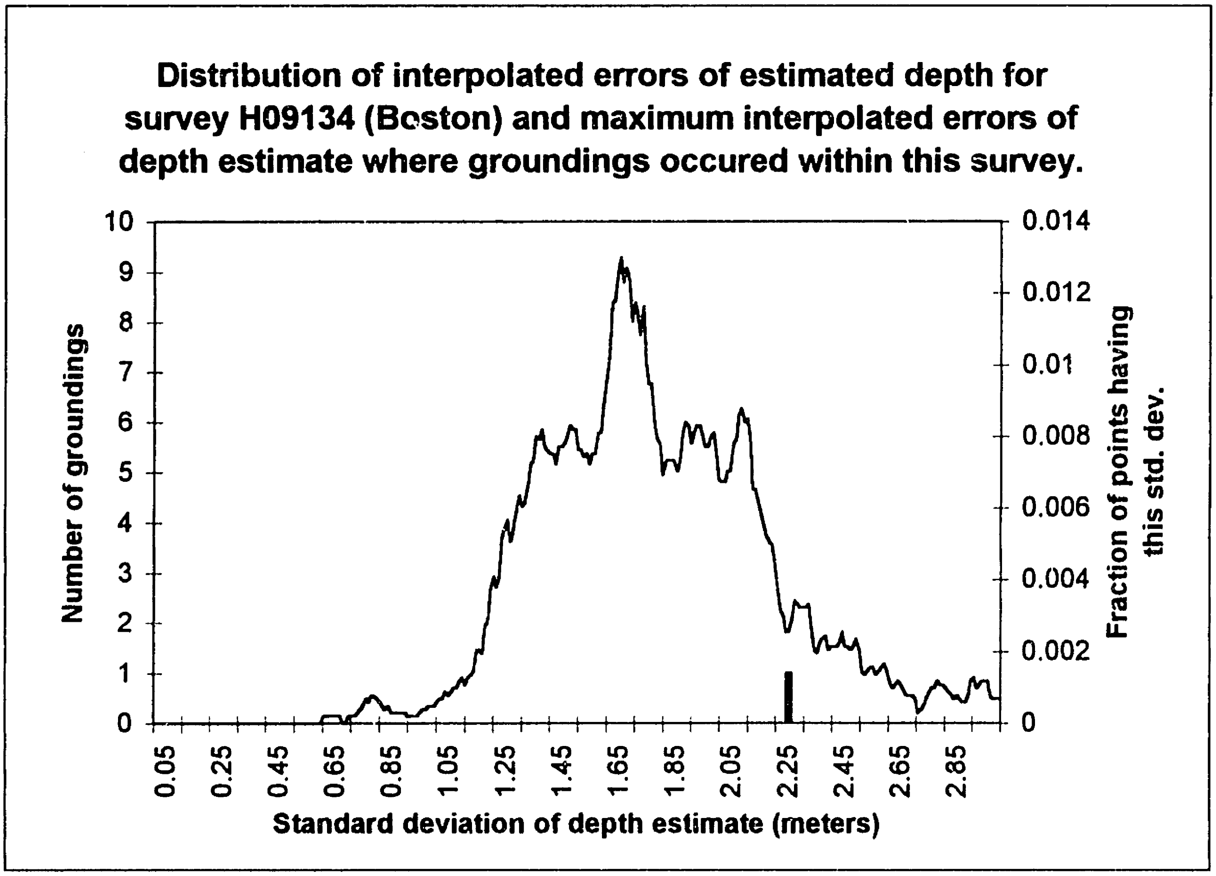

Distribution of estimated depths for survey H09134 (Boston) and depth where groundings occured within this survey.

Figure 44, 45 - Depth and error comparison, survey H09134.


Distribution of interpolated errors of estimated depth for survey H09134 (Boston) and maximum interpolated errors of depth estimate where groundings occured within this survey.

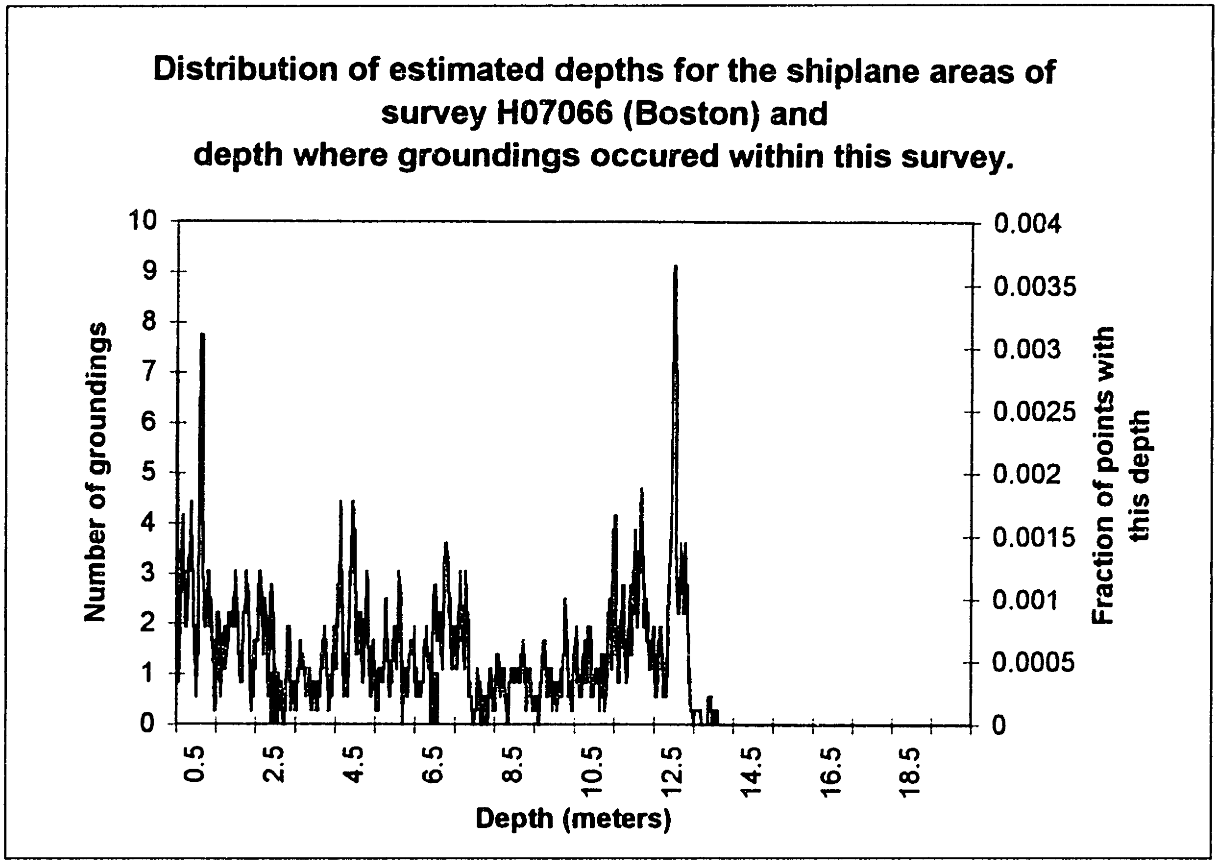
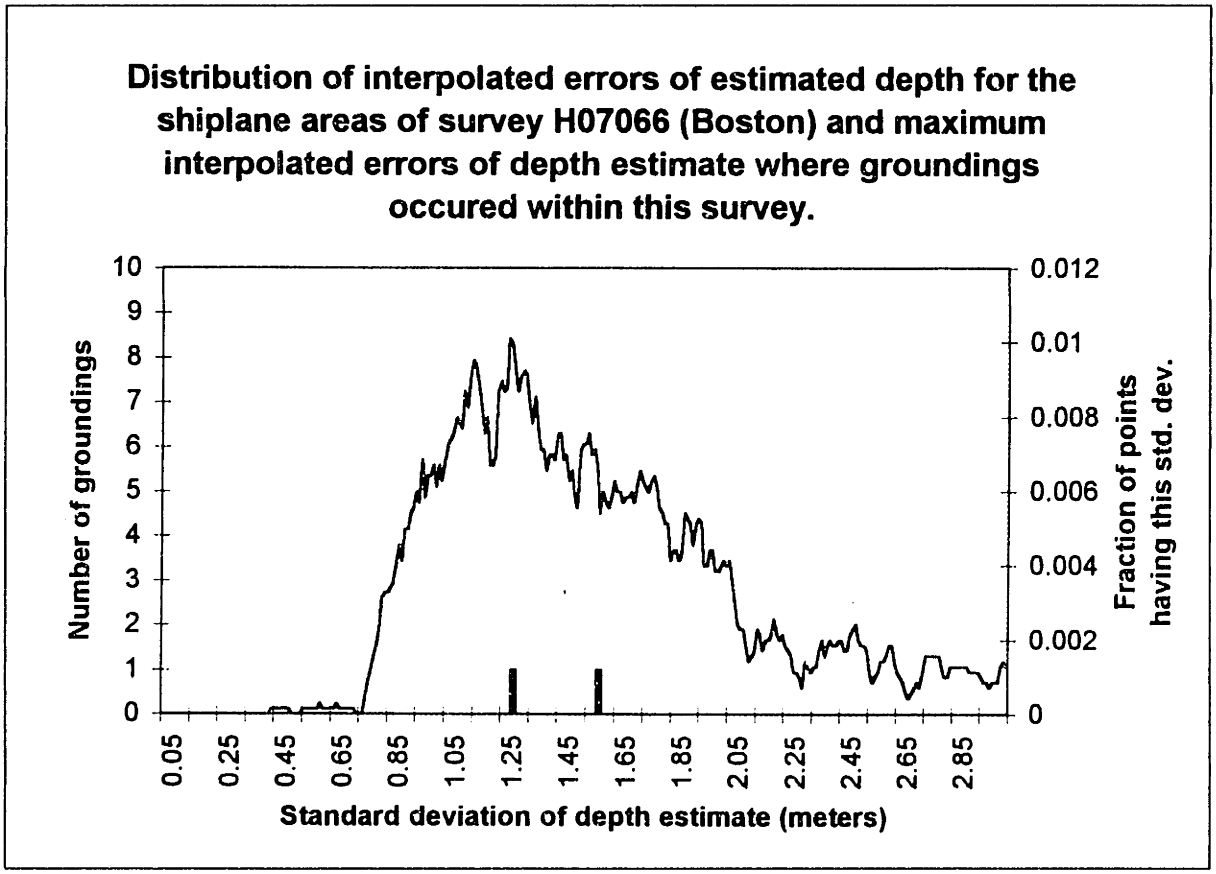
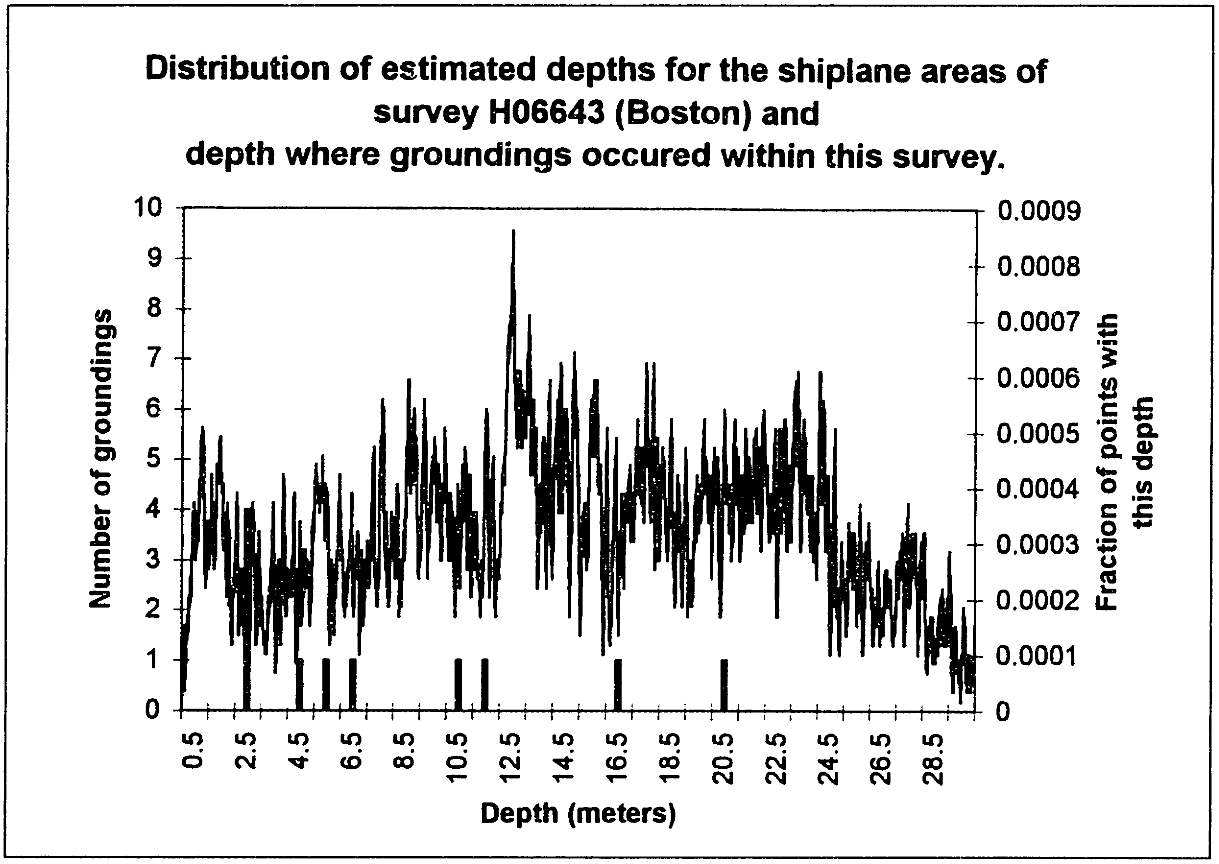

Distribution of estimated depths for the shiplane areas of survey H07066 (Boston) and depth where groundings occured within this survey.

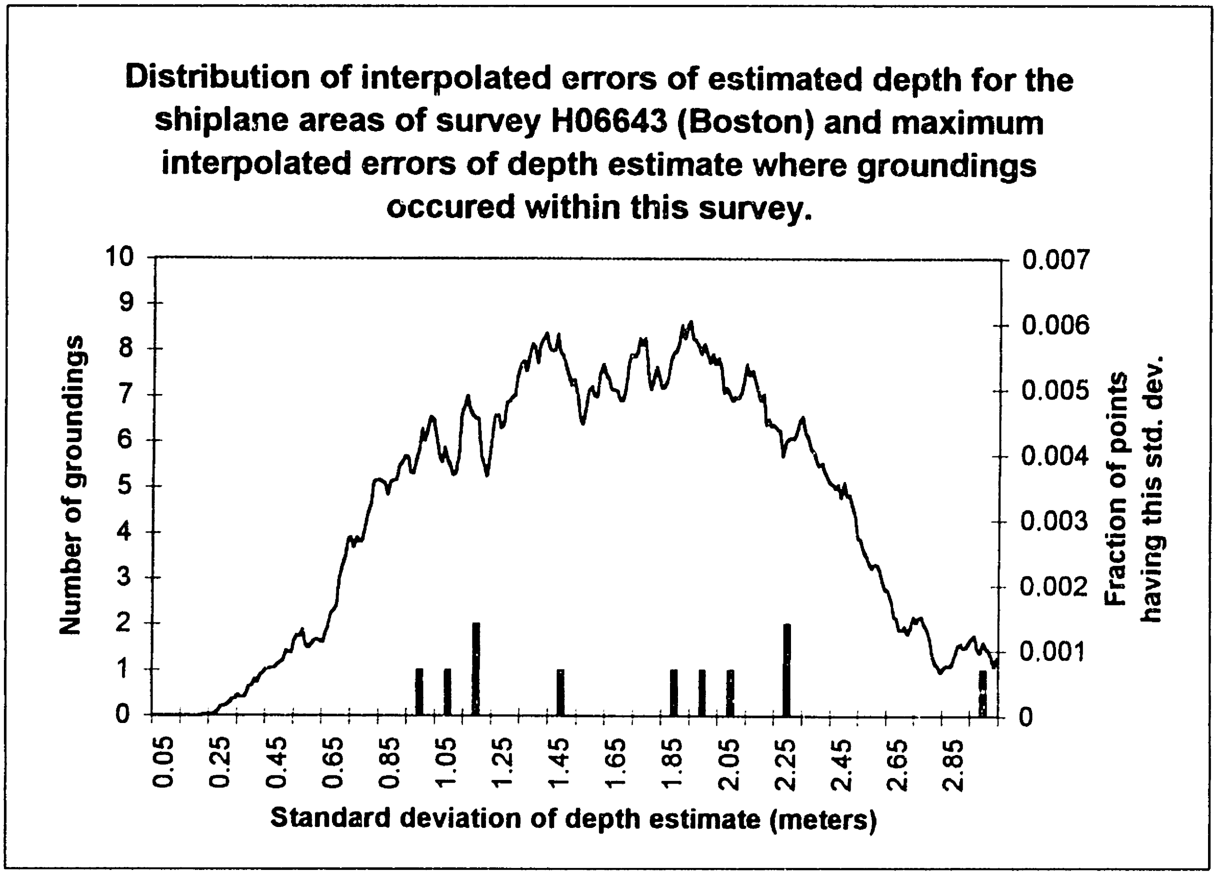
Figure 46, 47 - Depth and error comparison, survey H07066 (shiplane area).


Distribution of interpolated errors of estimated depth for the shiplane areas of survey H07066 (Boston) and maximum interpolated errors of depth estimate where groundings occured within this survey.



Distribution of estimated depths for the shiplane areas of survey H06643 (Boston) and depth where groundings occured within this survey.

Figure 48, 49 - Depth and error comparison, survey H06643 (shiplane area).



Distribution of interpolated errors of estimated depth for the shiplane areas of survey H06643 (Boston) and maximum interpolated errors of depth estimate where groundings occured within this survey.

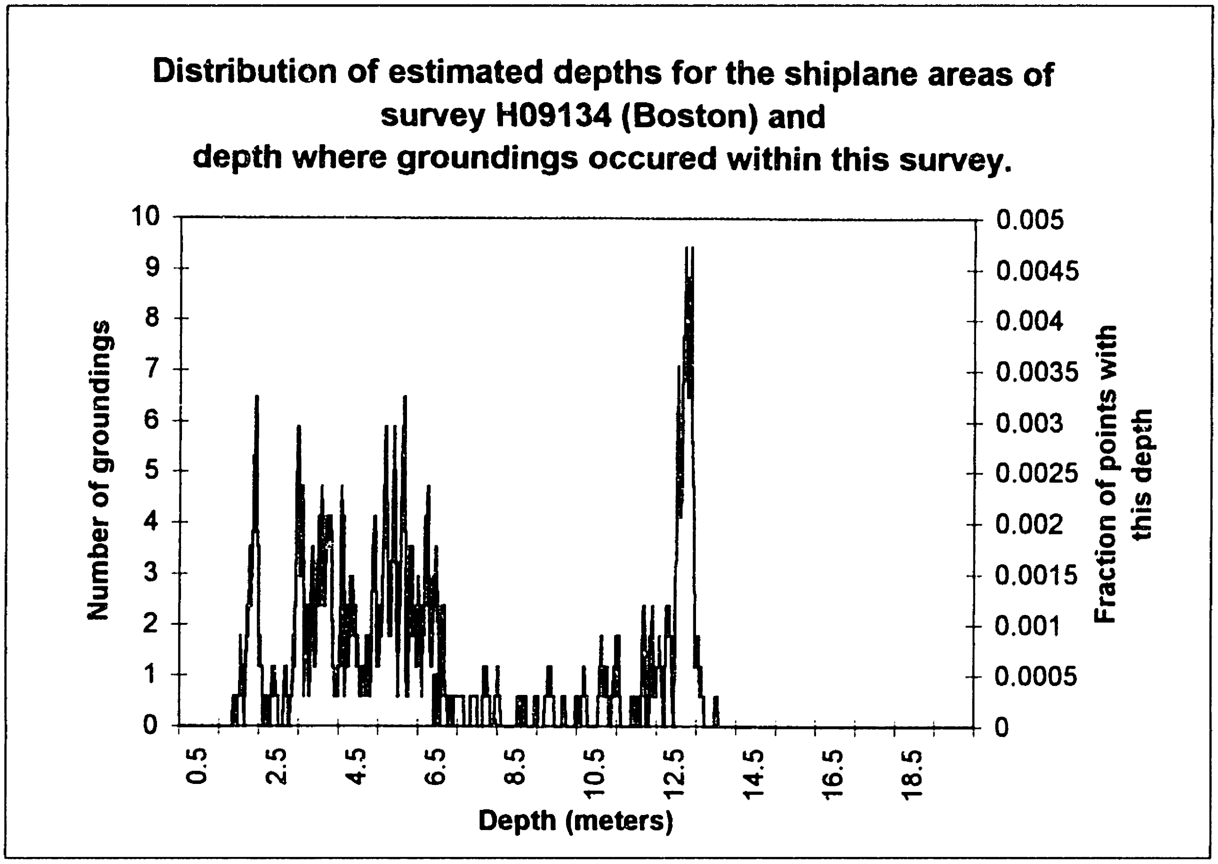
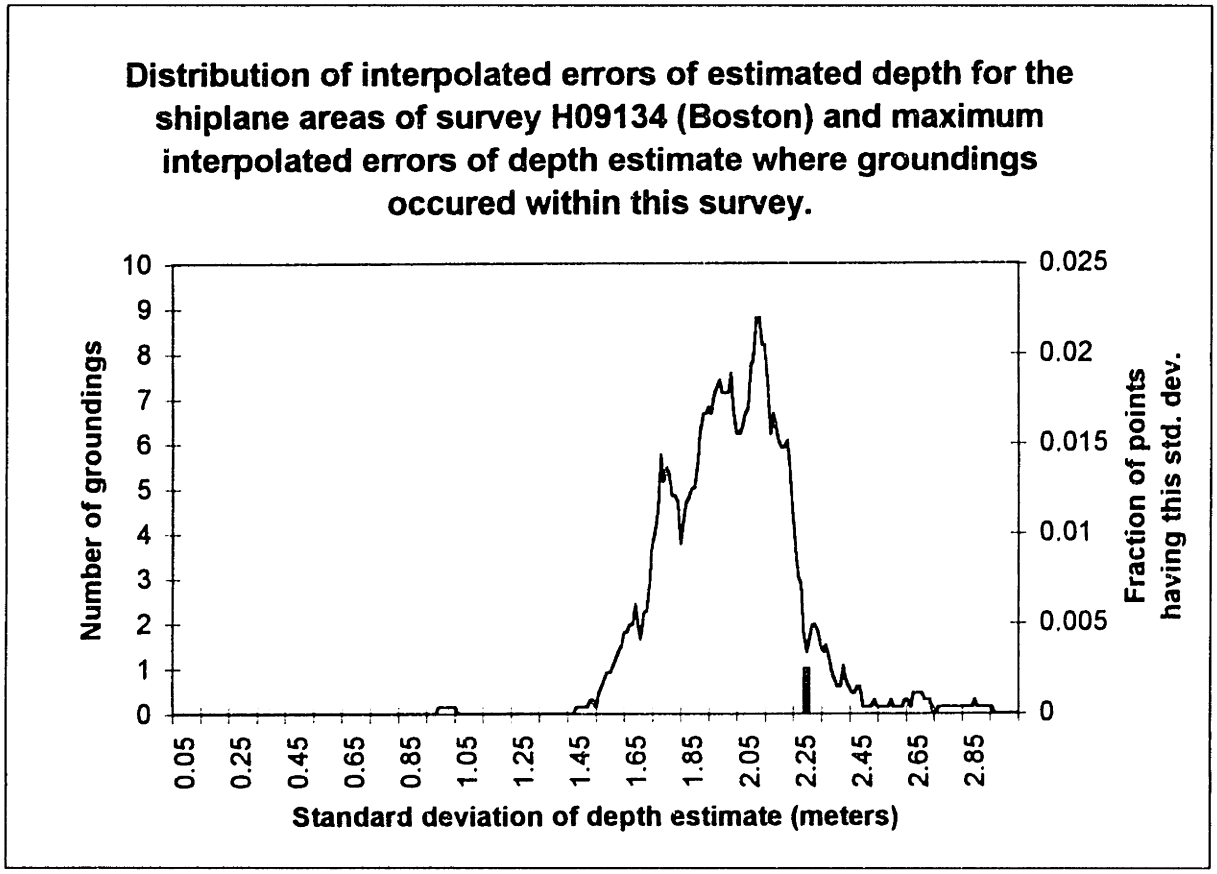


Figure 50, 51 - Depth and error comparison, survey H09134 (shiplane area).



Houston/Galveston

25 of 458 groundings around the Houston Ship Channel have been investigated. The low percentage of investigated groundings is due to the fact that most parts of this channel are dredged. The Houston/Galveston area consists of large areas with sandy, flat bottom, and most of Galveston Bay is very shallow and not suited for commercial shipping. Figure 52 shows all the groundings in the Houston/Galveston area. It is not hard to see where the dredged channels are located. All of the investigated groundings have happened in the entrance of the channel (Figure 53). The surveys covering these accidents (H08747, H08748 and H08751) are all from the years 1962 to 1965. A similar analysis as the one done for Boston is shown in Figures 54-59. Also in this area we have compared the groundings to there ship-lane areas. No correlation is evident.

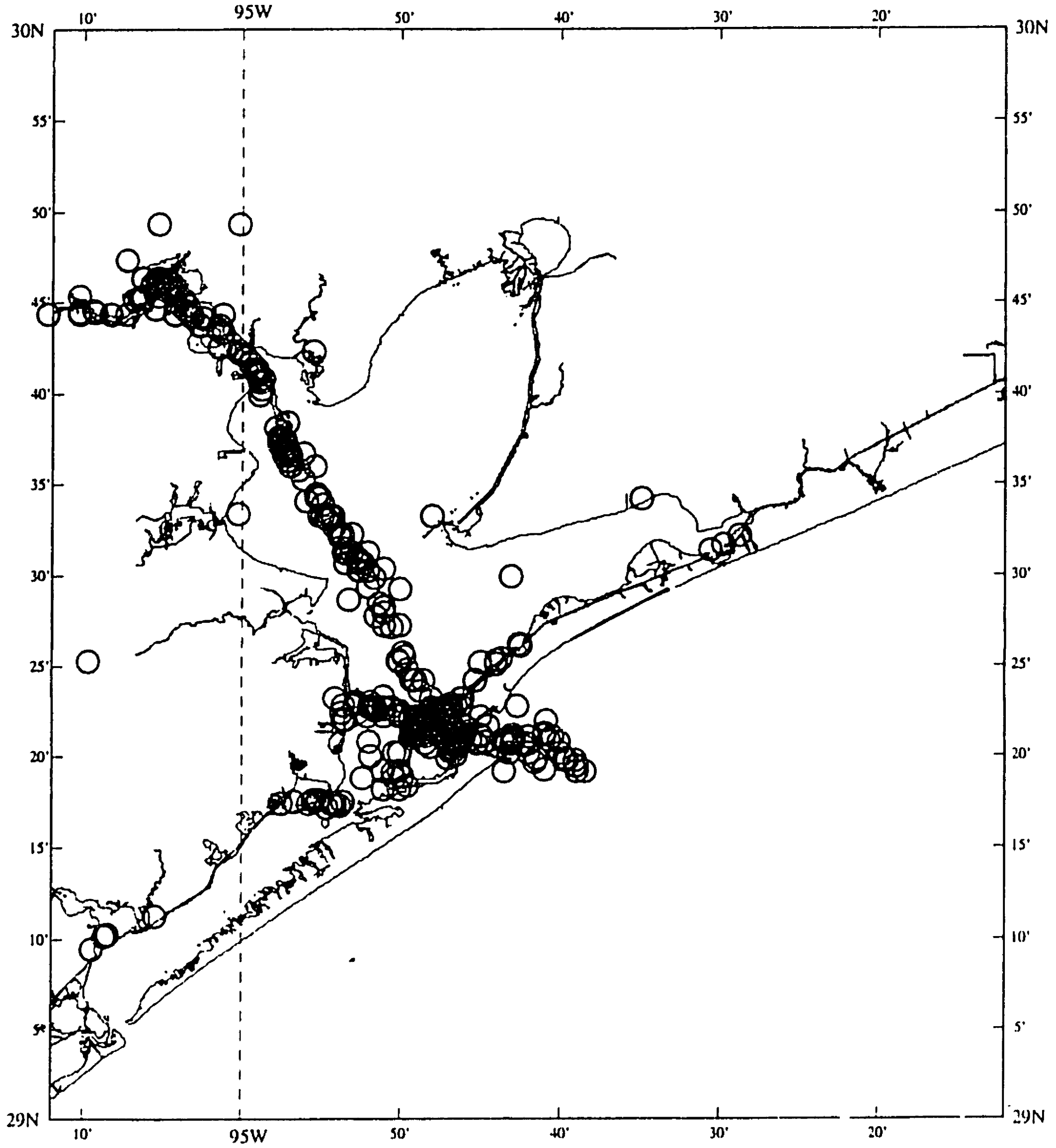


Figure 52. All groundings in Houston/Galveston.

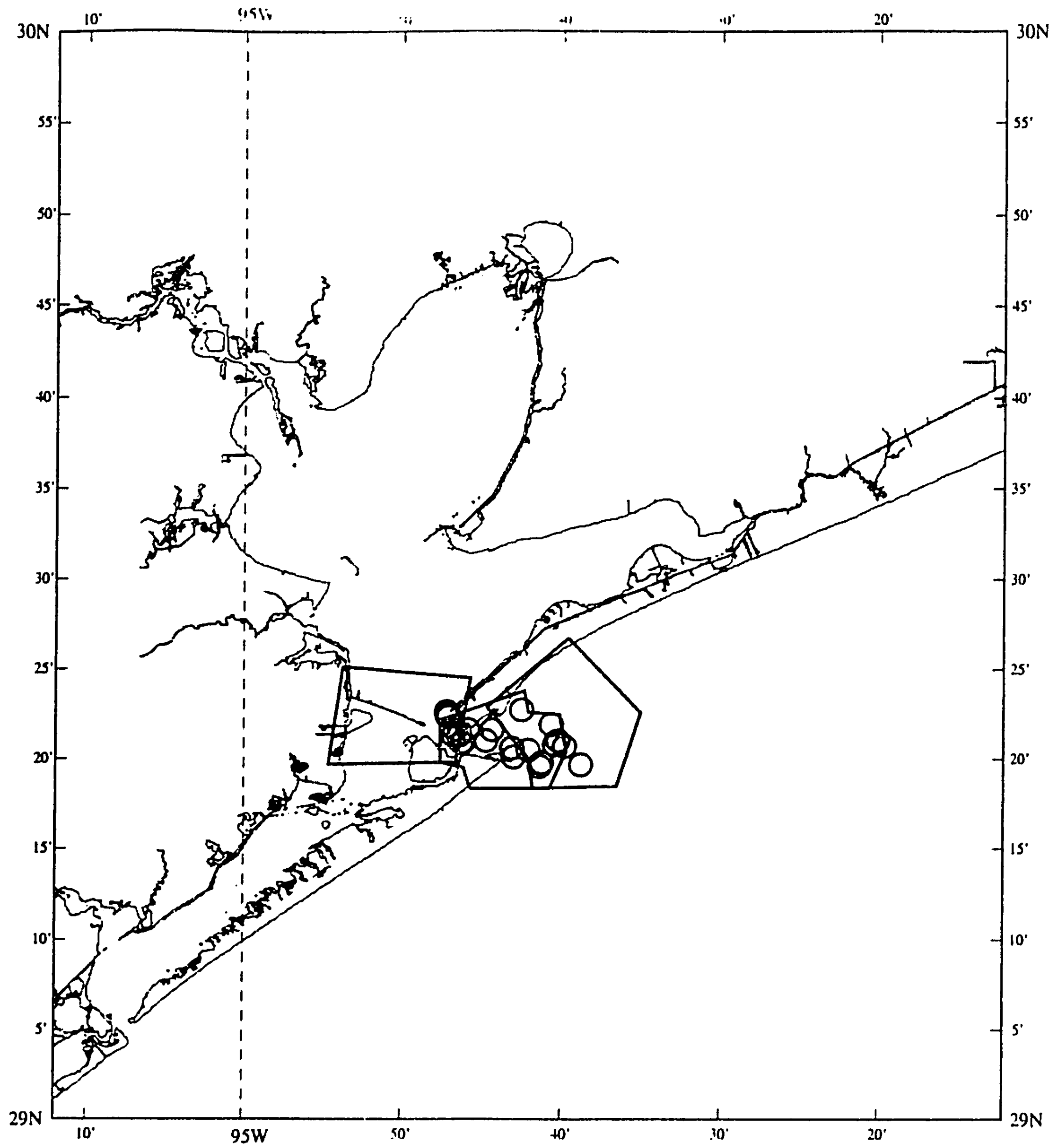


Figure 53. Groundings in Houston/Galveston investigated with Hydrostat.

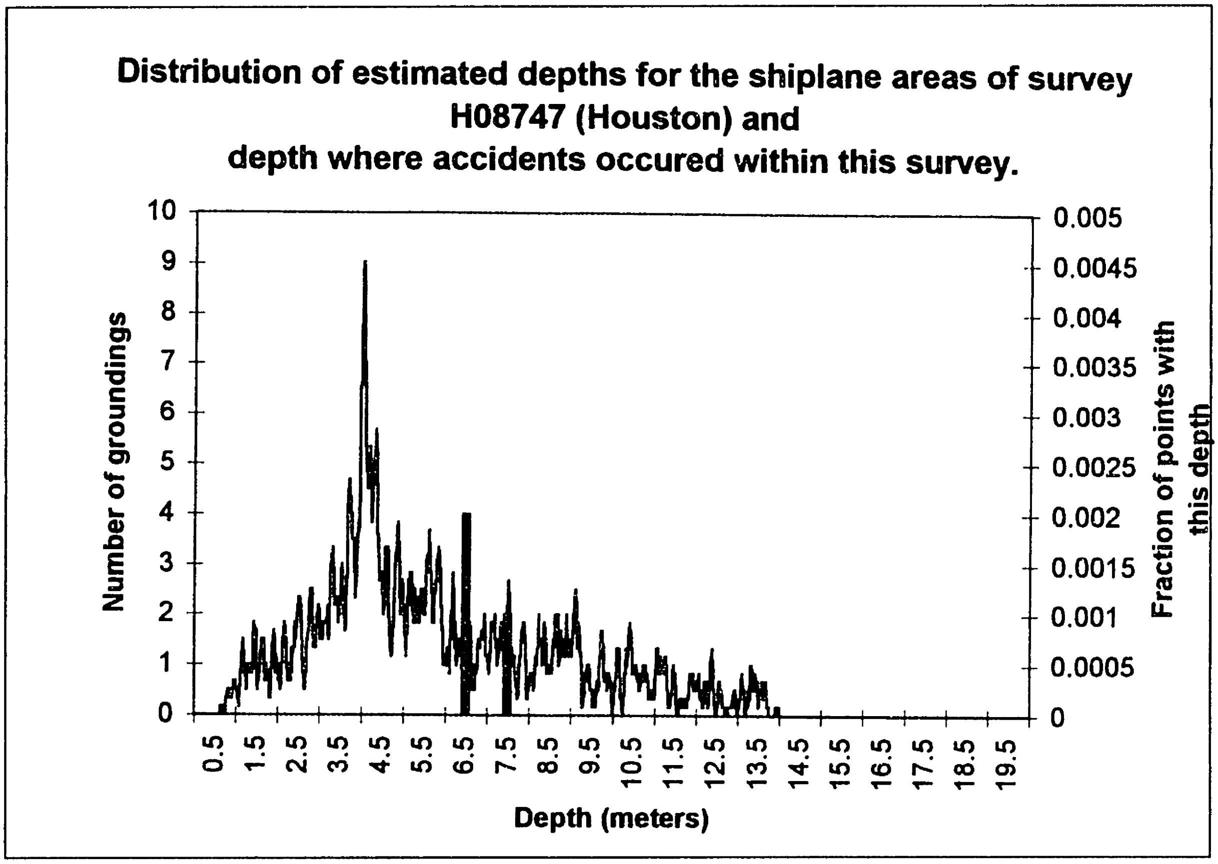
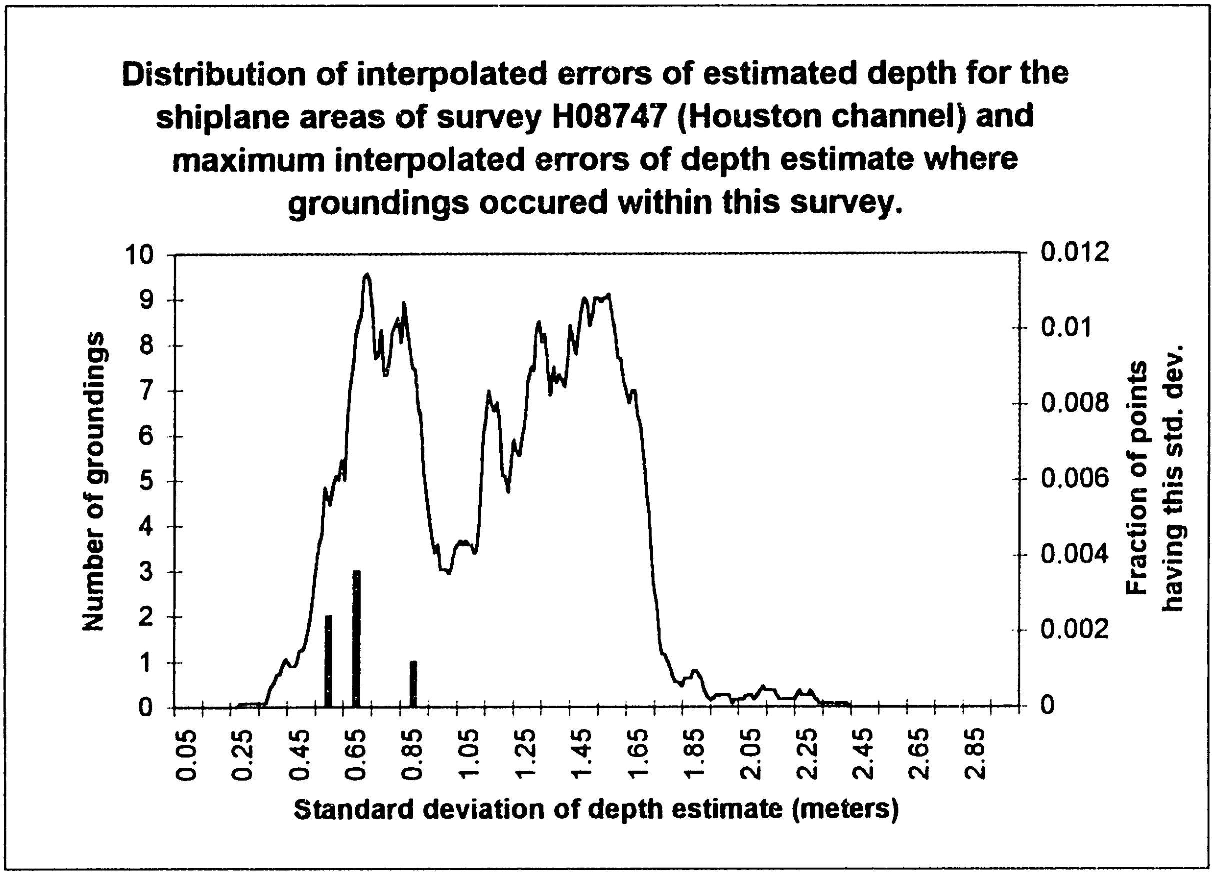


Figure 54, 55 - Depth and error comparison, survey H08747.



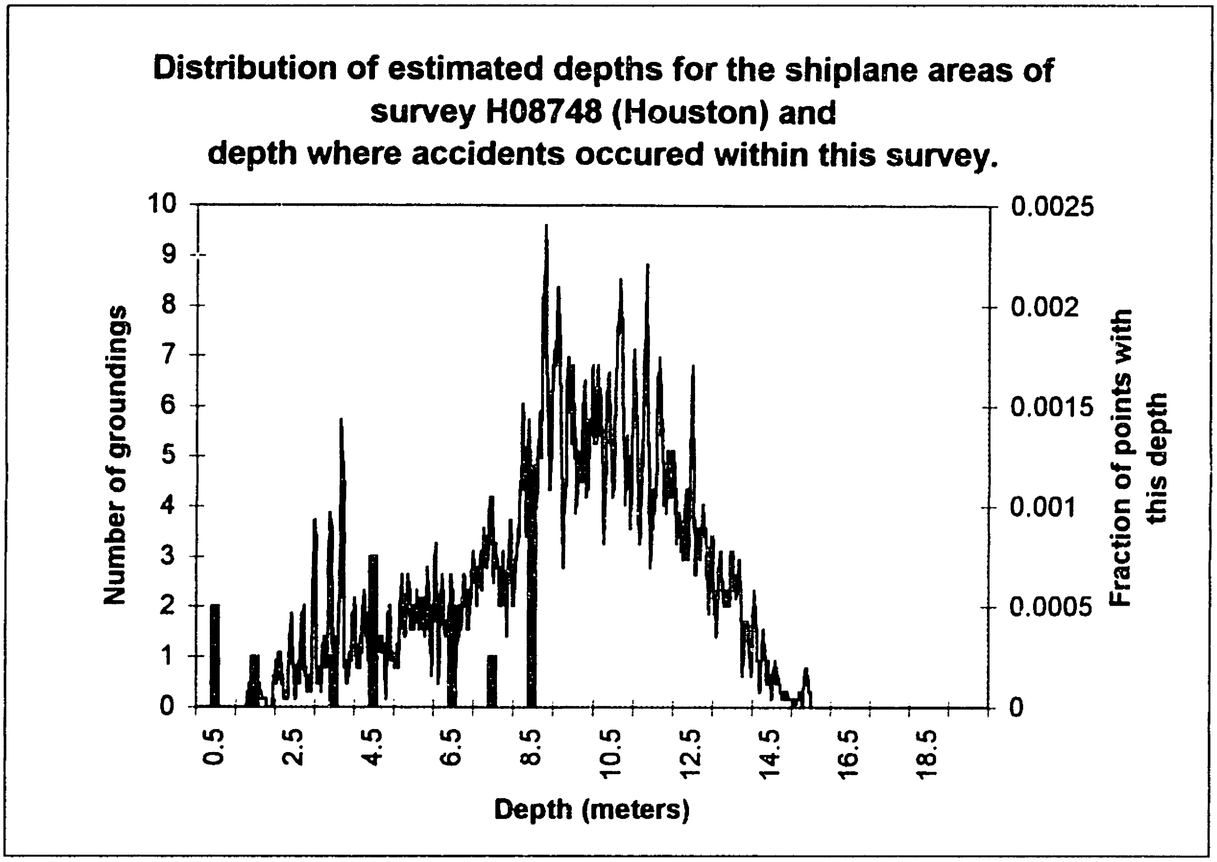
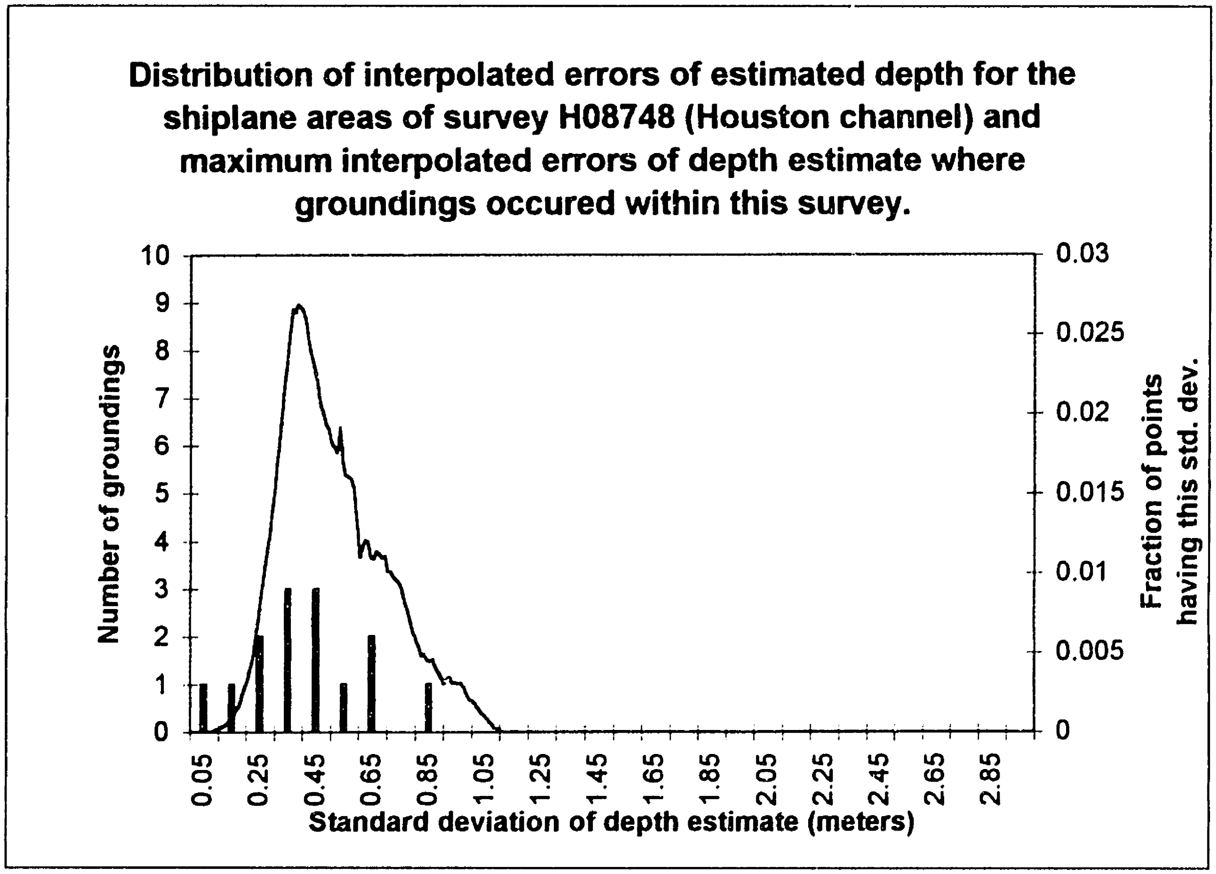
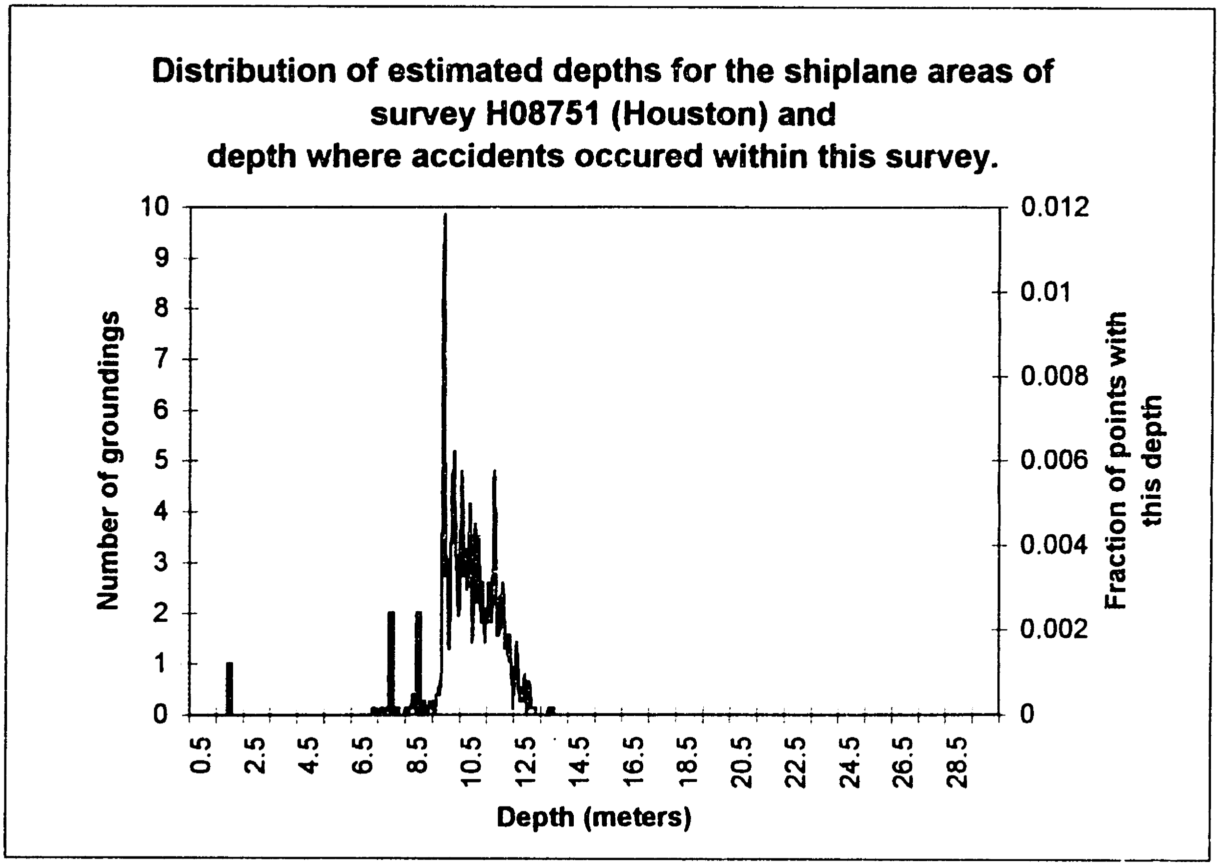


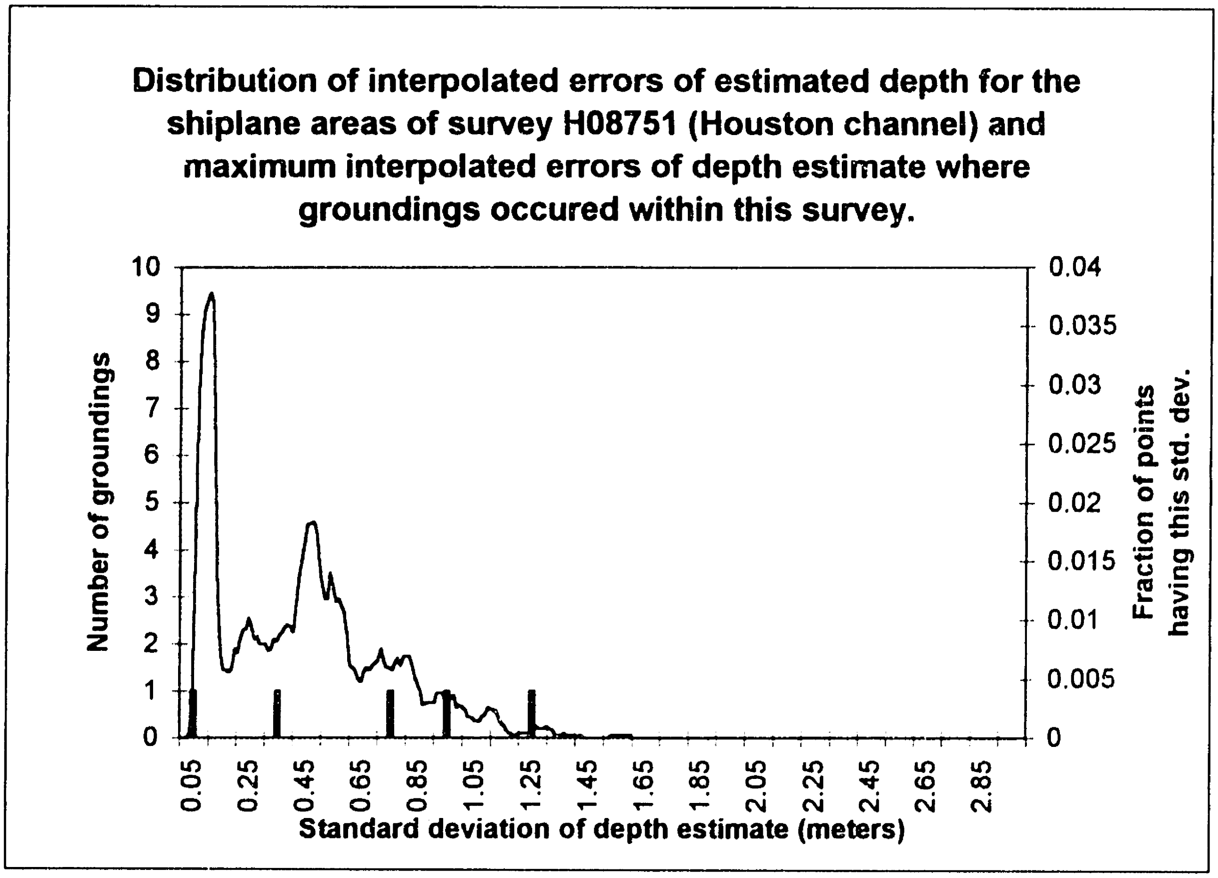
Figure 56, 57 - Depth and error comparison, survey H08748.





Distribution of estimated depths for the shiplane areas of survey H08751 (Houston) and depth where accidents occured within this survey.

Figure 58, 59 - Depth and error comparison, survey H08751.



Distribution of interpolated errors of estimated depth for the shiplane areas of survey H08751 (Houston channel) and maximum interpolated errors of depth estimate where groundings occured within this survey.

New York/New Jersey

Figure 60 shows the 194 groundings located in the New York/New Jersey area. It is especially dense with groundings in the Kill van Kull channel. The whole New York/New Jersey port area is dredged to allow for the huge number of ships visiting the port to actually pass through there. Hence, only 7 groundings, located within surveys H09820 (1979) and H09859 (1979), have been investigated (Figure 61). This analysis, as the previous two, shows no sign of any correlation between cartographic uncertainty and historical groundings.

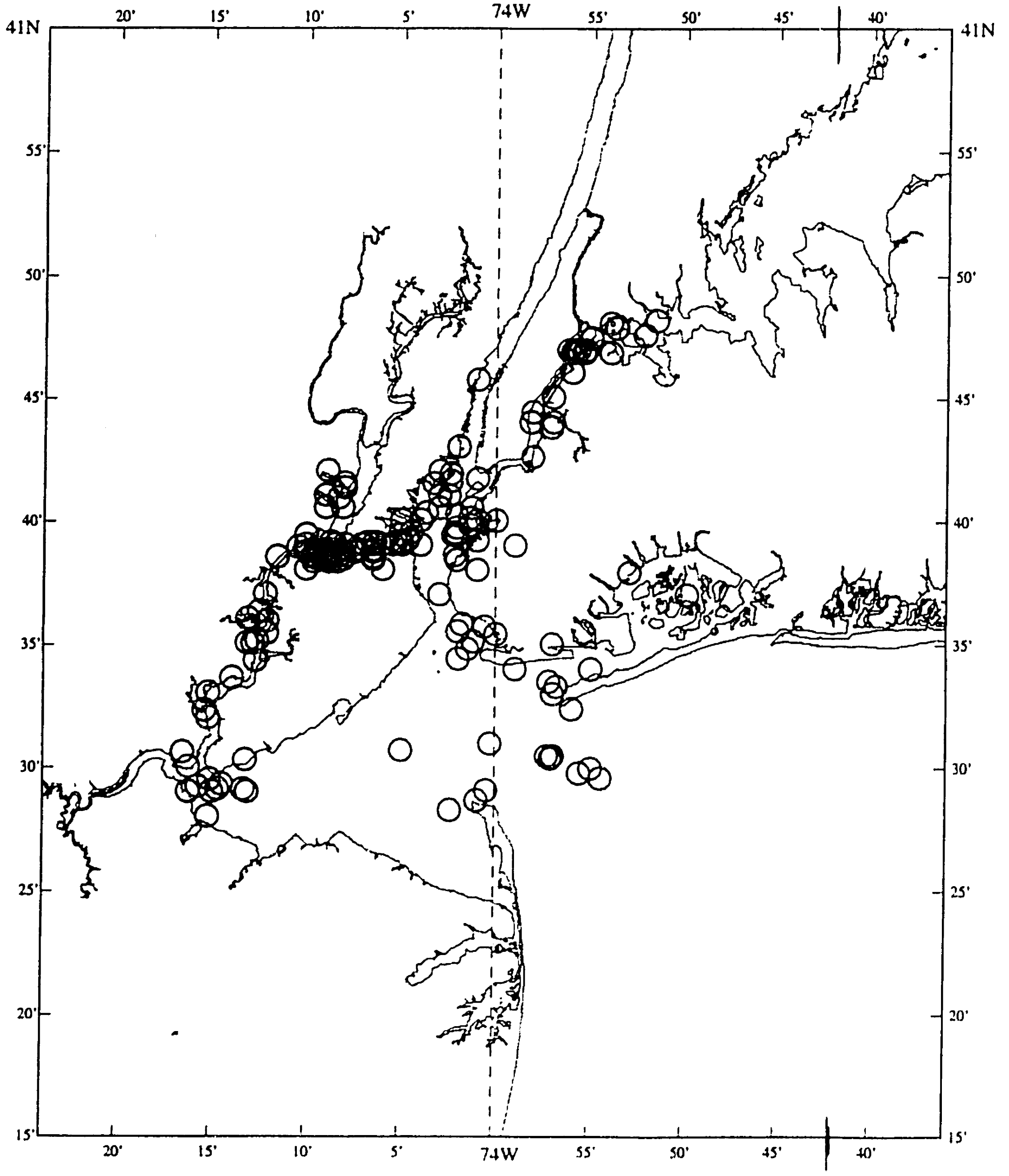


Figure 60. All groundings in New York/New Jersey.

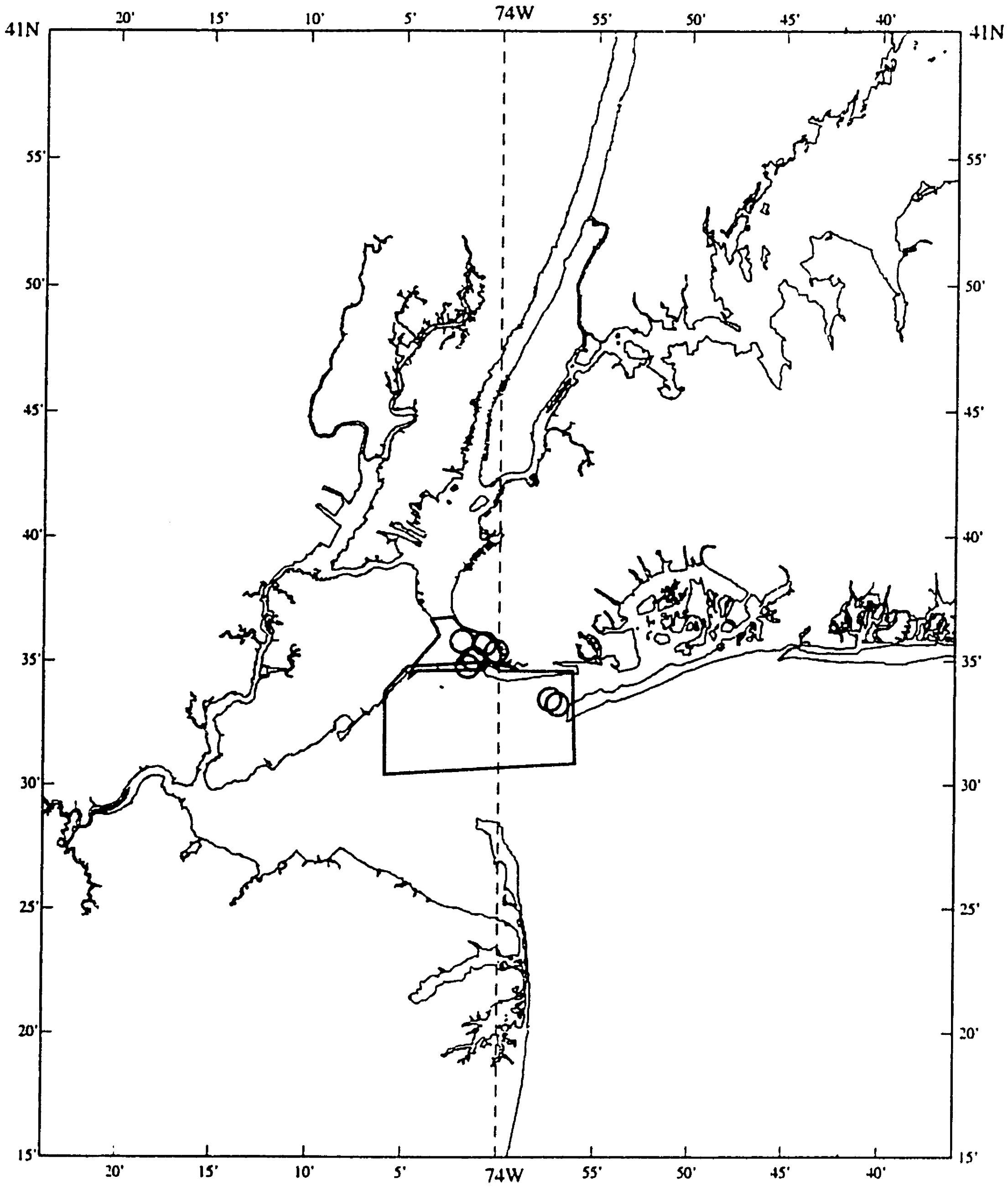


Figure 61. Groundings in New York/New Jersey investigated with Hydrostat.

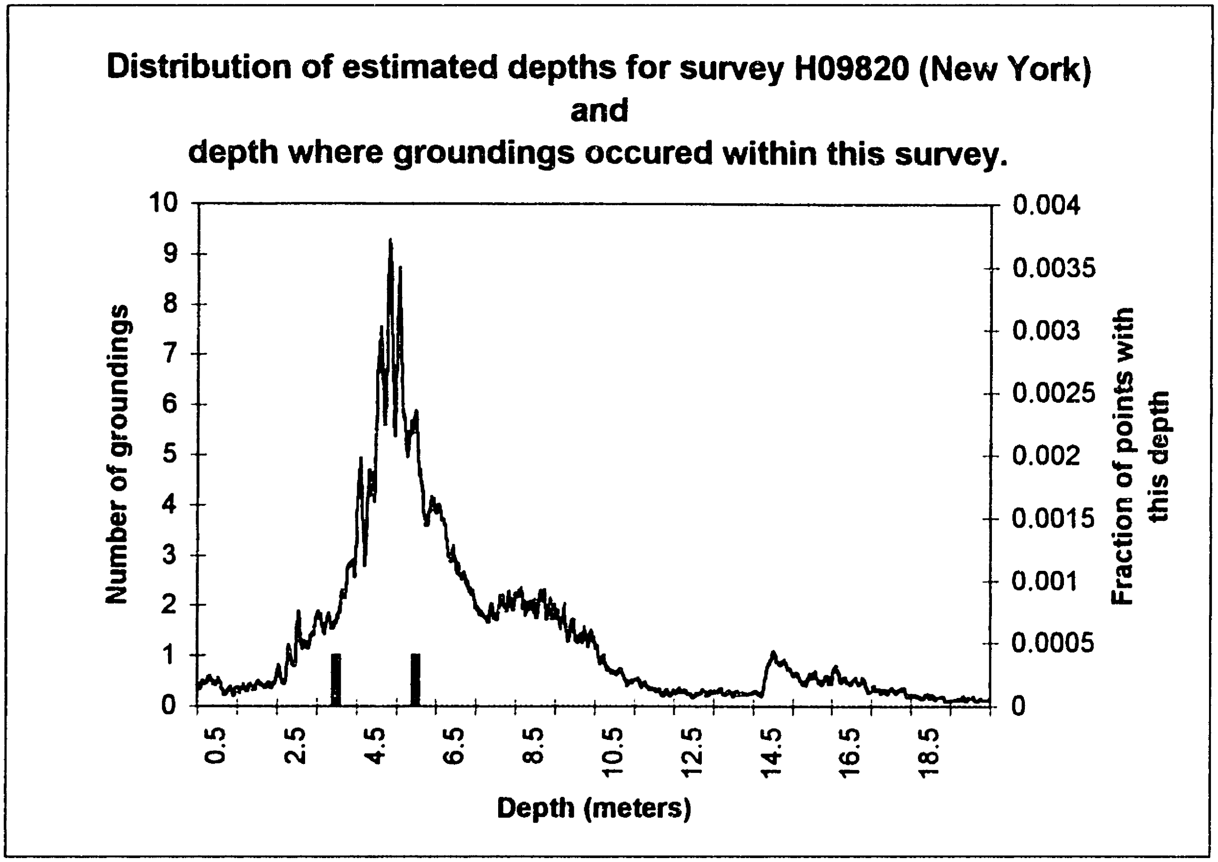
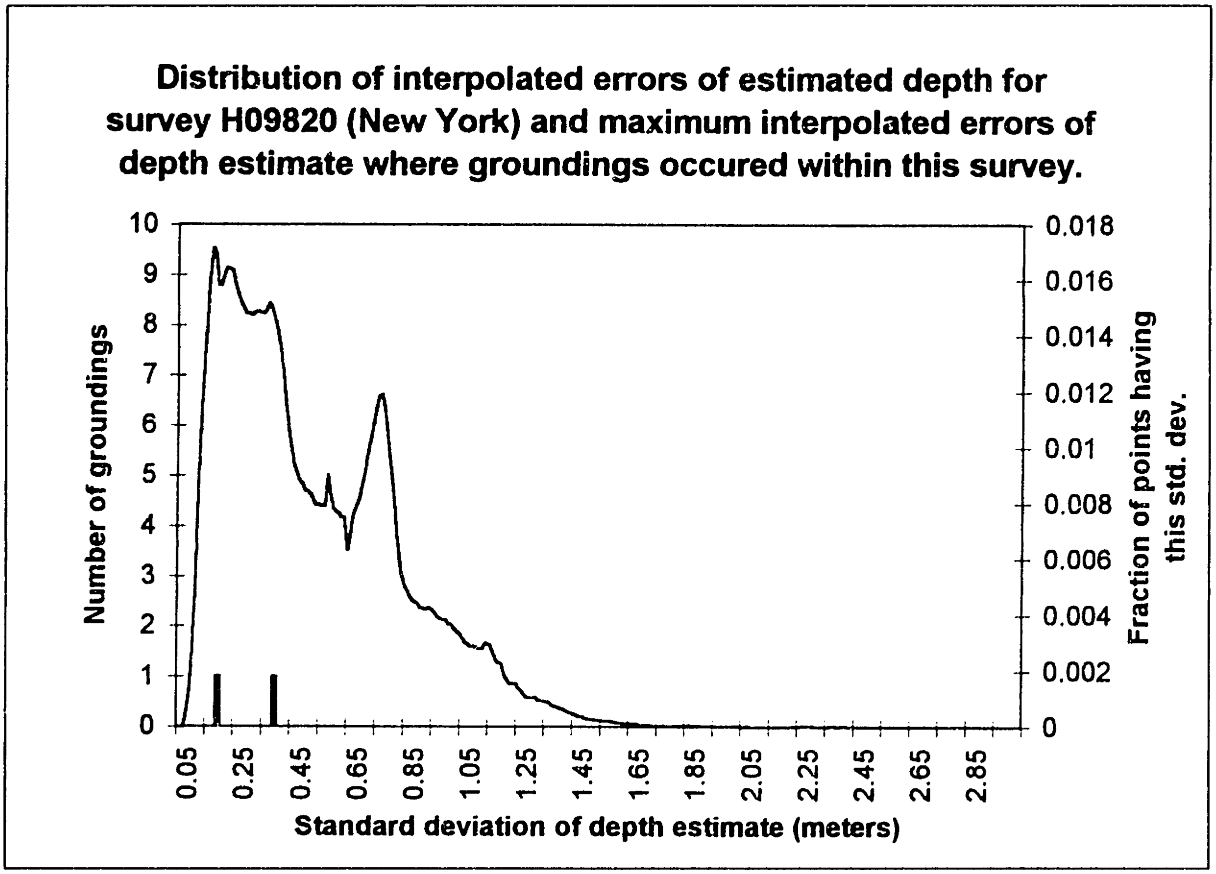


Figure 62, 63 - Depth and error comparison, survey H09820.



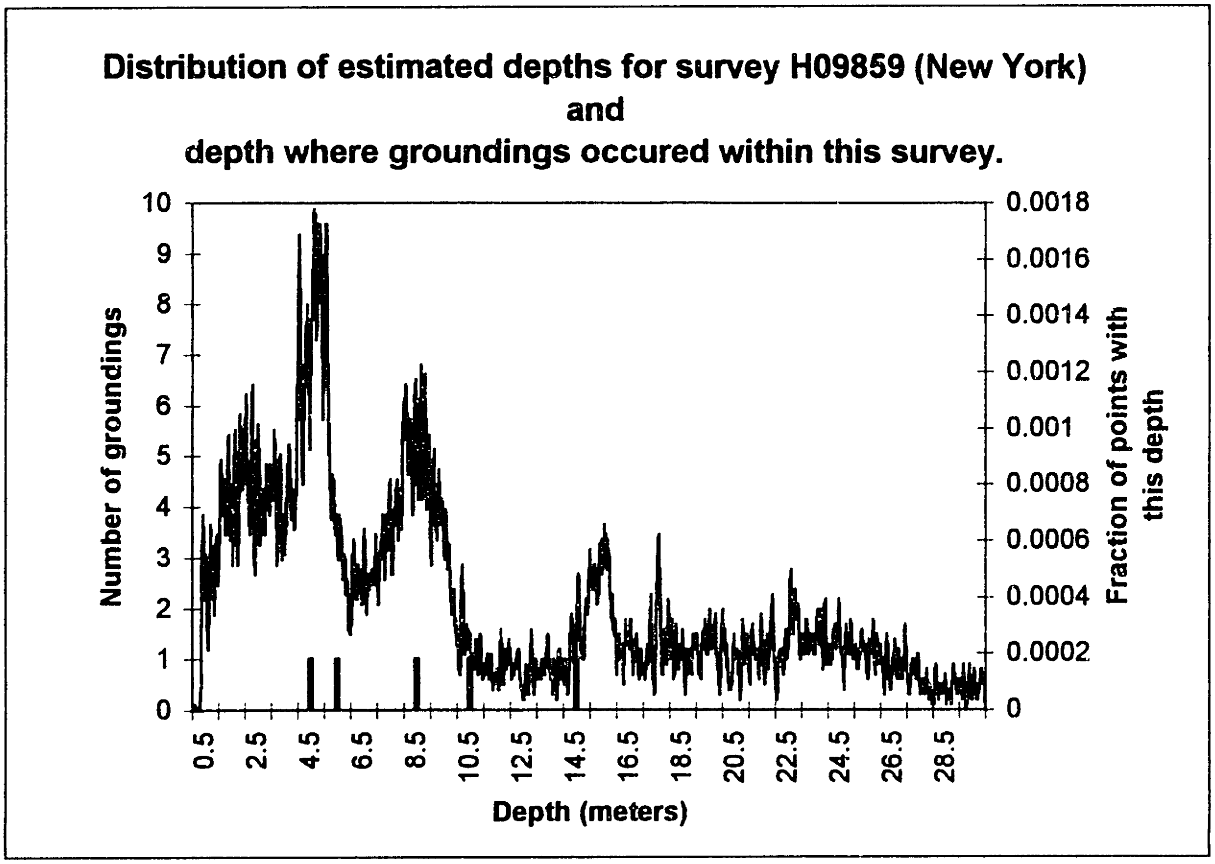
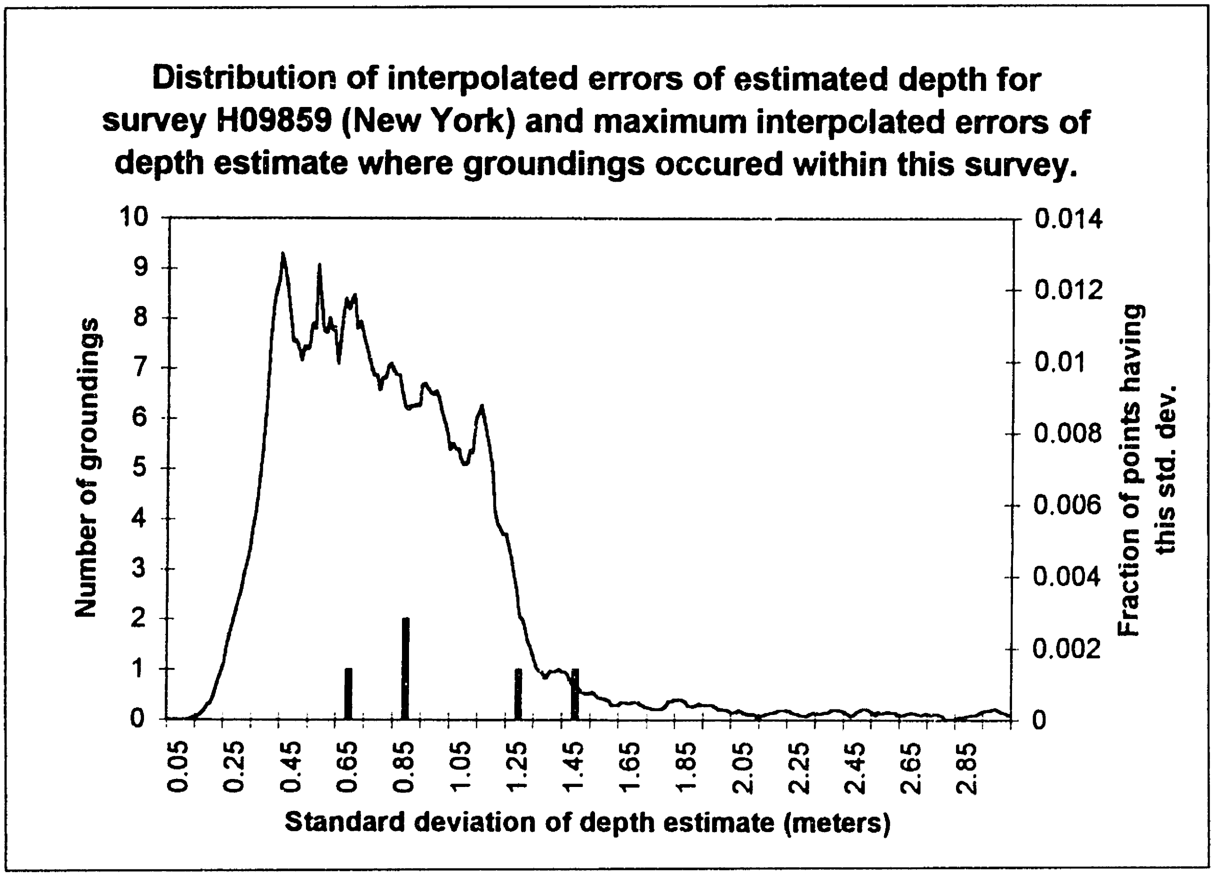


Figure 64, 65 - Depth and error comparison, survey H09859.



San Francisco

The 94 groundings in the San Francisco Bay area are equally distributed over a large area. Hence, all together 7 surveys were needed to investigate 10 groundings. The surveys were: H07785 (1965), H09794 (1979), H09811 (1979), H09844 (1981), H10223 (1987), H10283 (1989) and H10306 (1989). The groundings attributed to each survey happened after the respective surveys were conducted. The results are presented in Figures 68-81. Once again there is no evidence of any correlation.

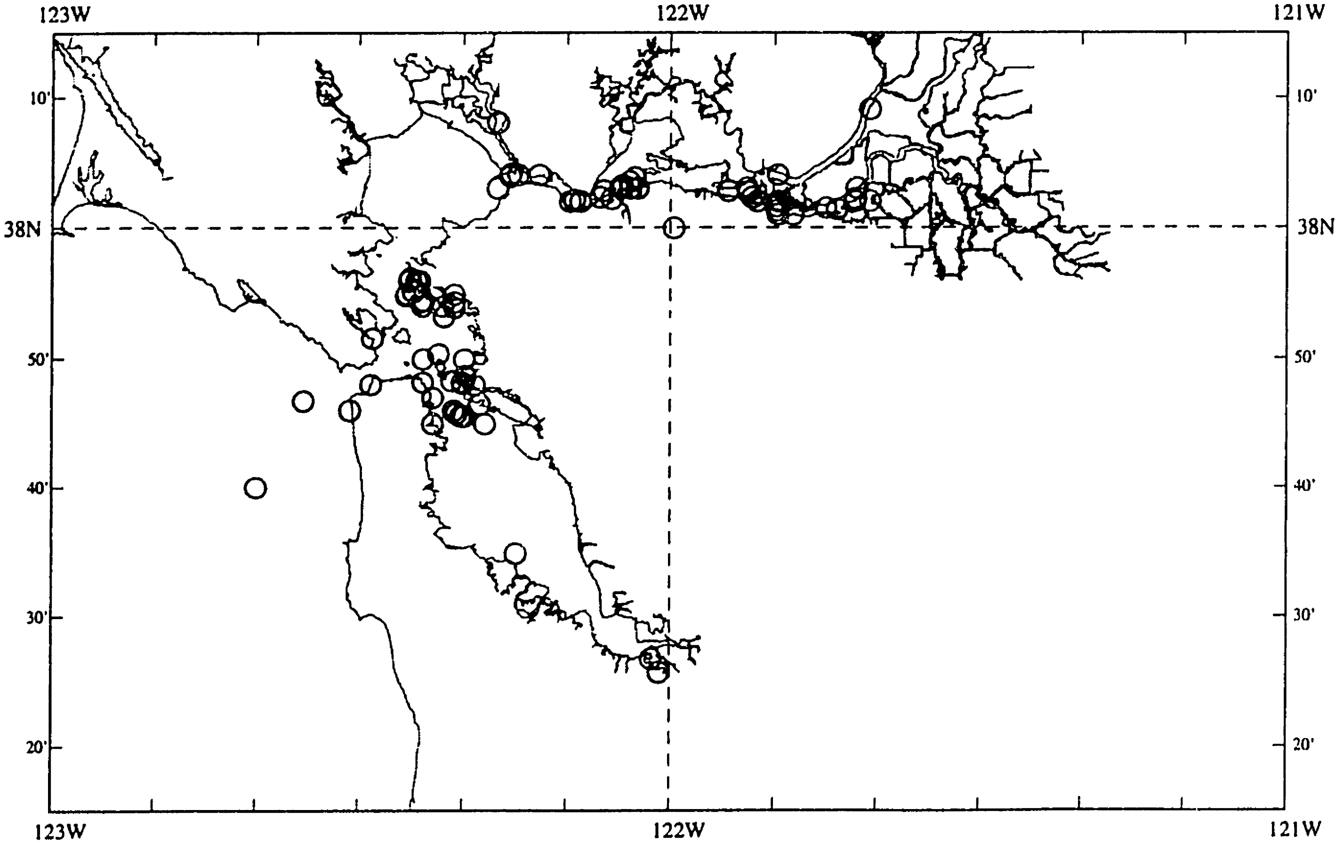


Figure 66. All groundings in San Francisco.

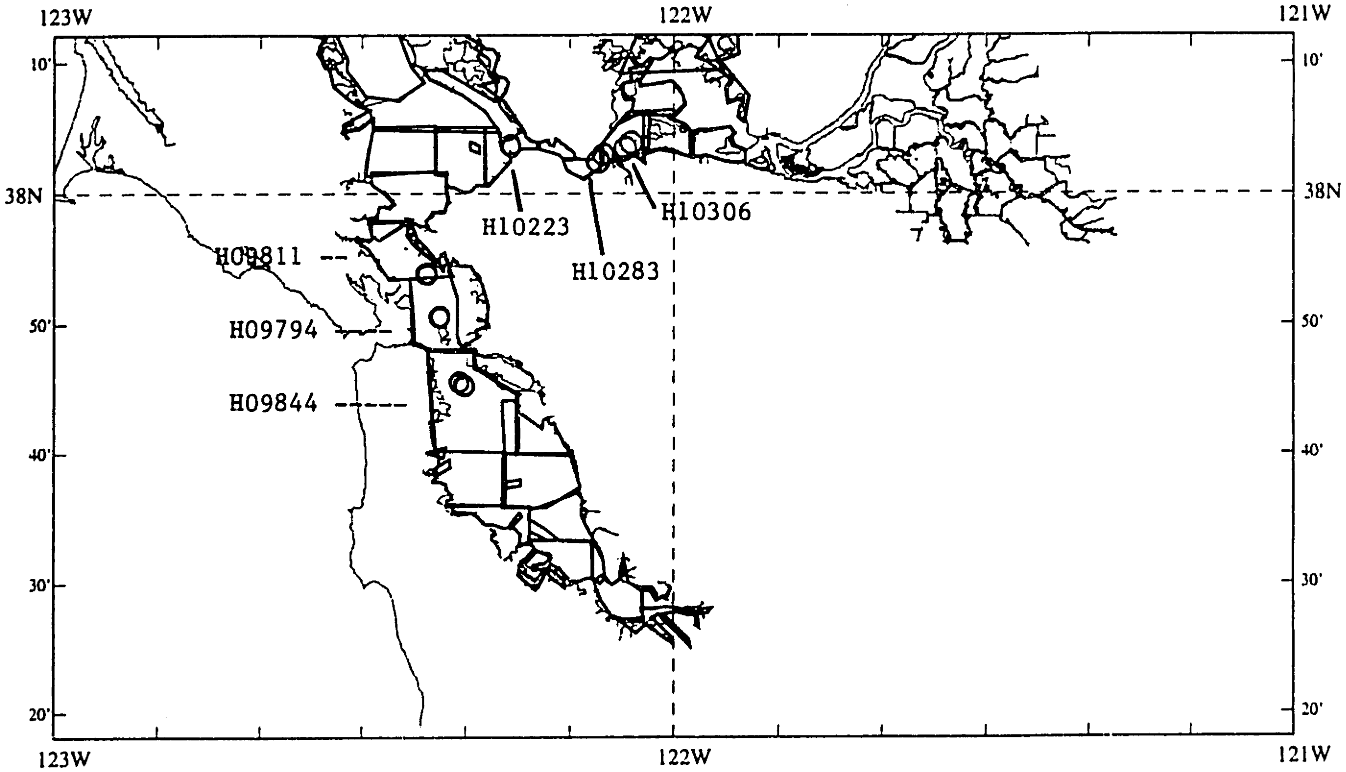


Figure 67. Groundings in San Francisco investigated with Hydrostat.

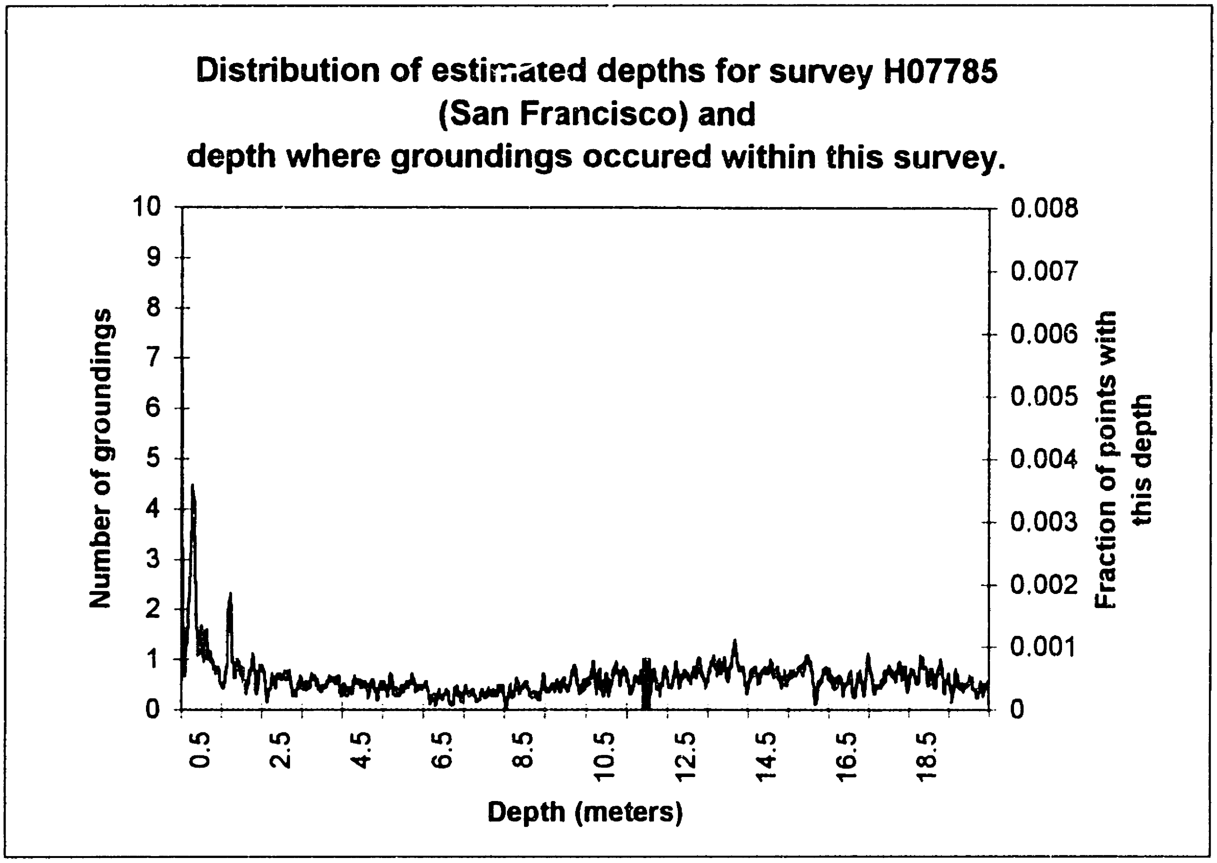
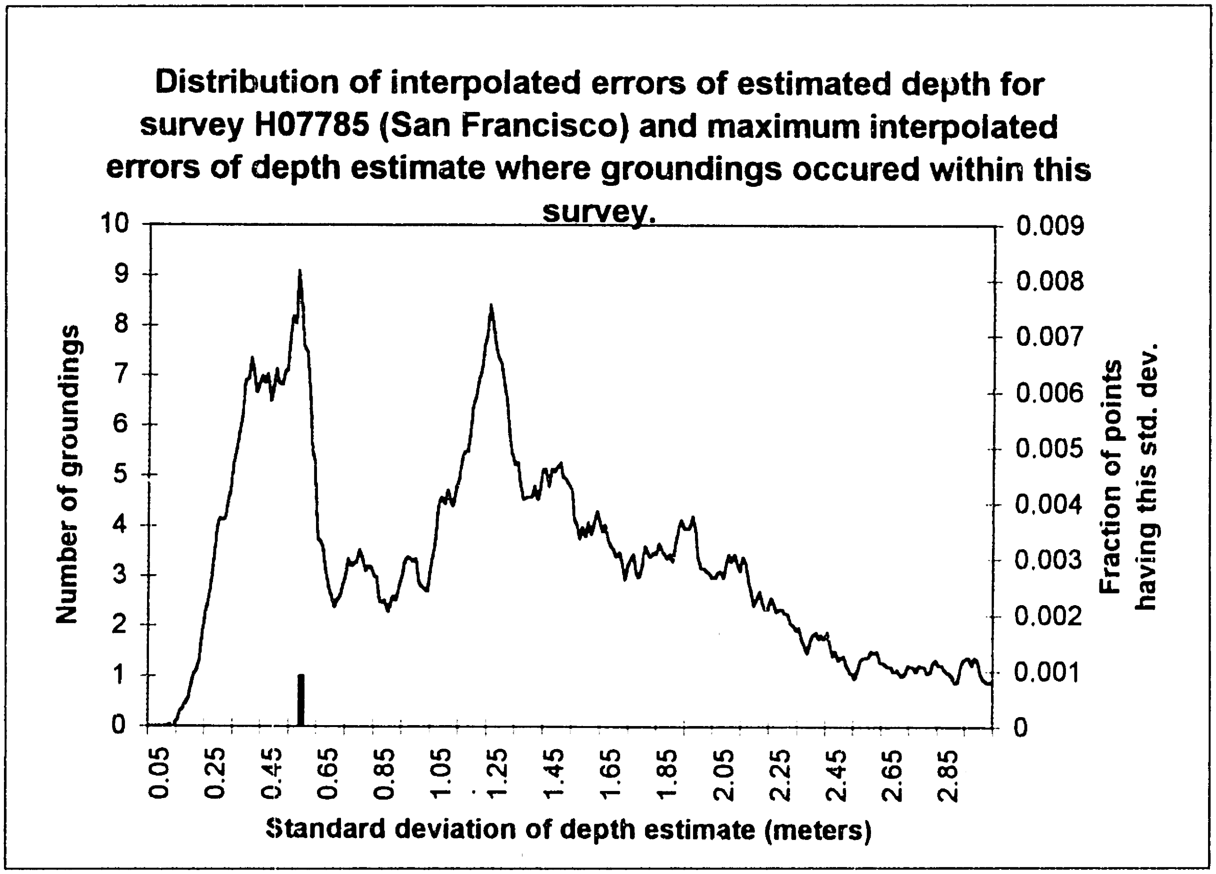


Figure 68, 69 - Depth and error comparison, survey H07785.



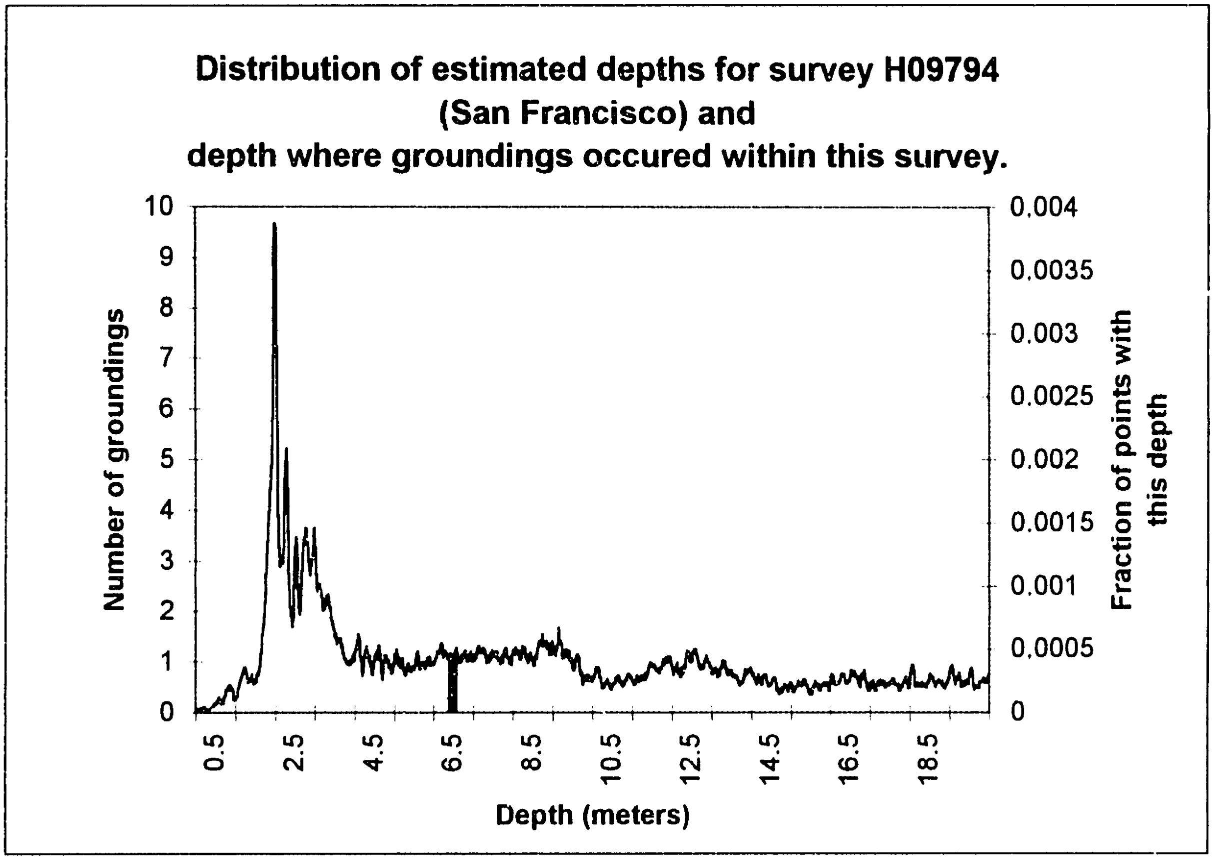
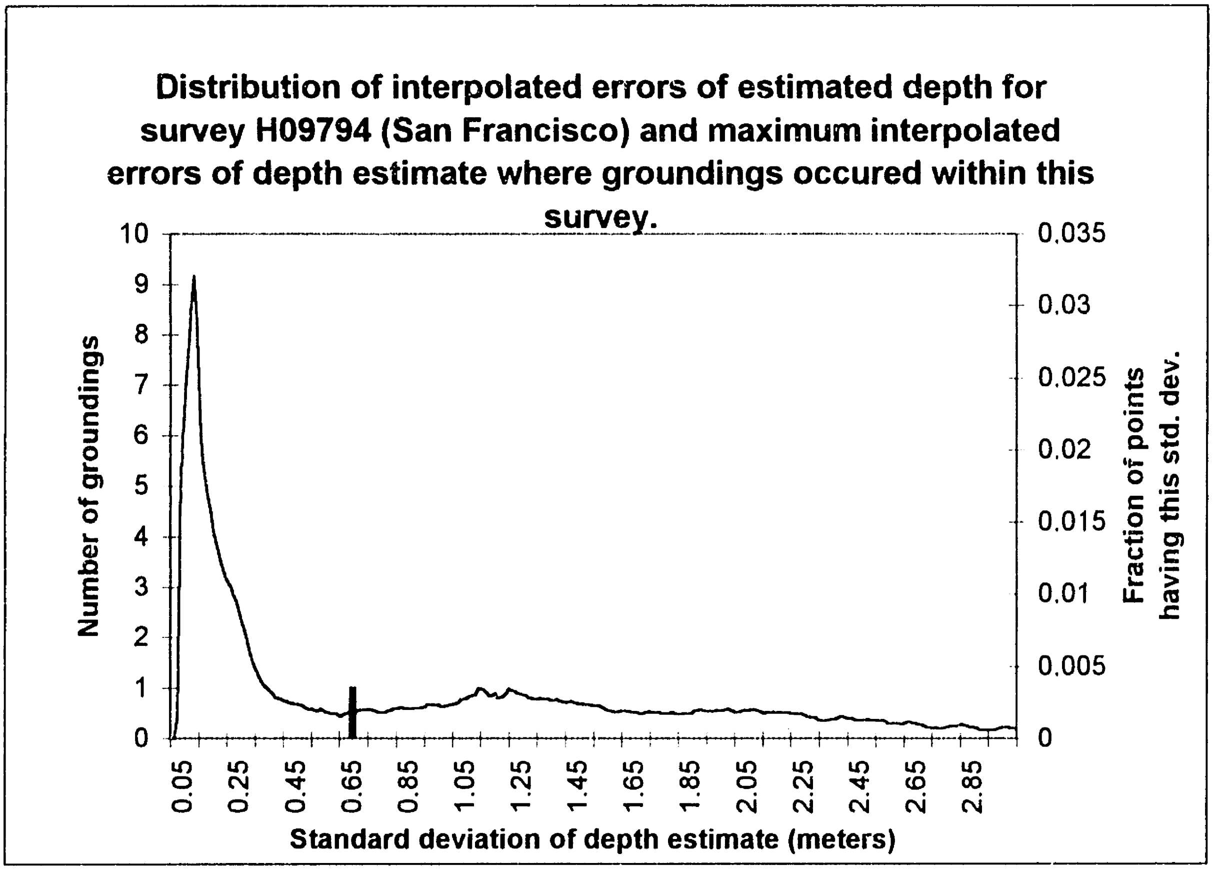


Figure 70, 71 - Depth and error comparison, survey H09794.



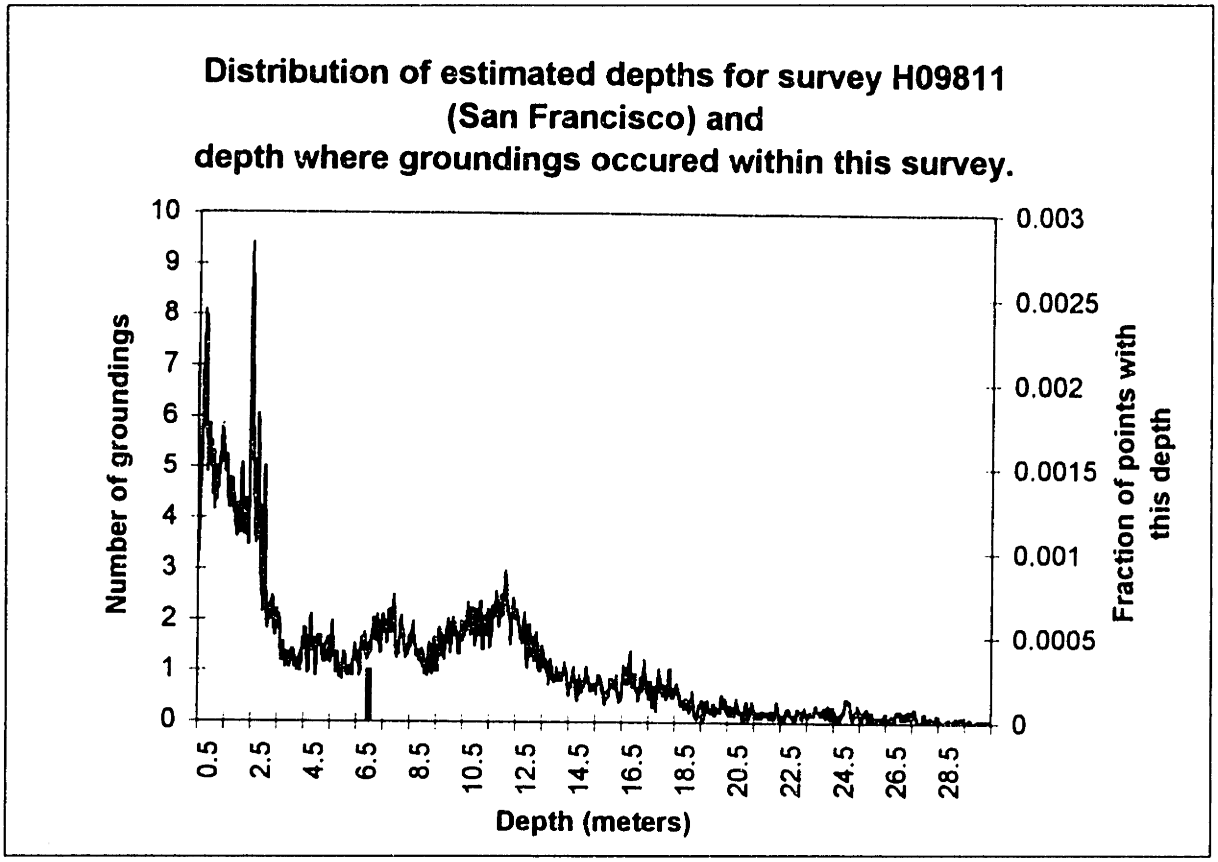
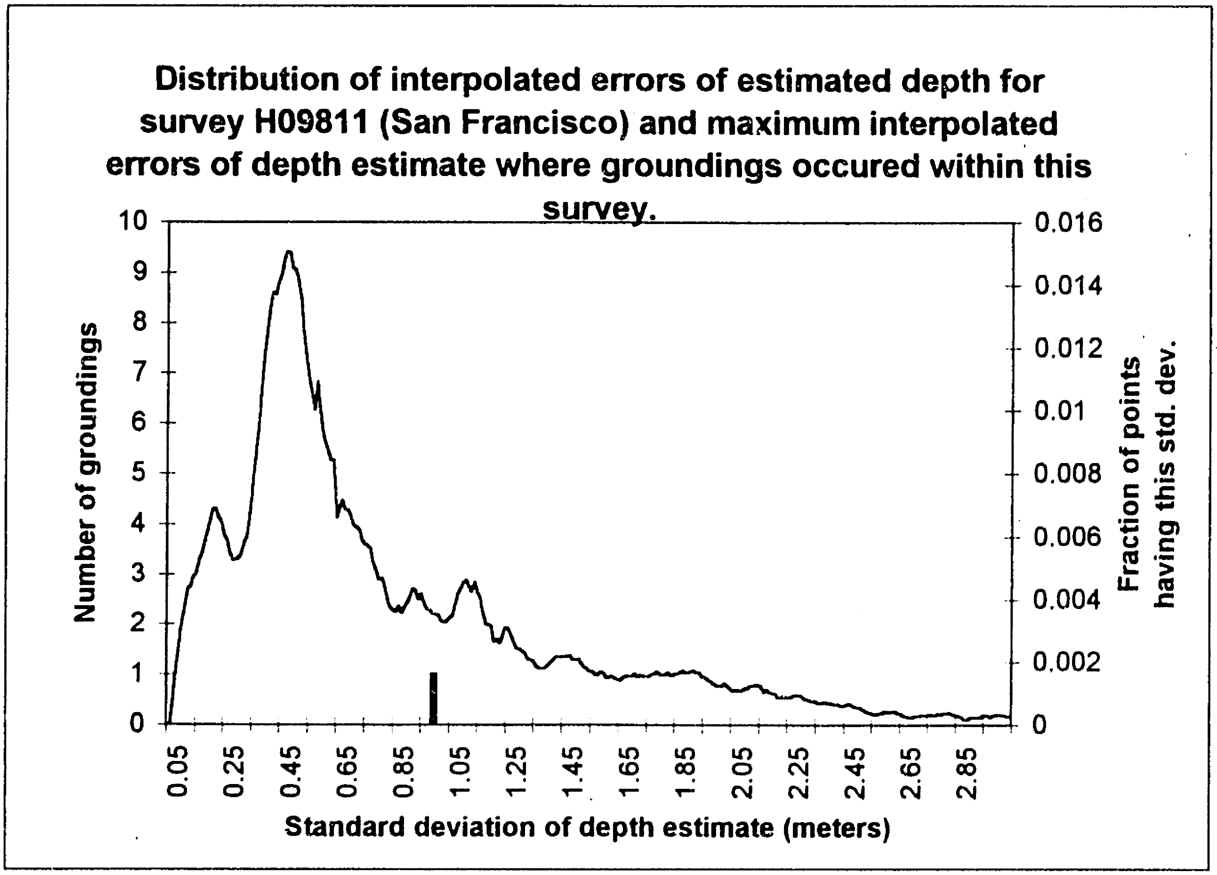


Figure 72, 73 - Depth and error comparison, survey H09811.



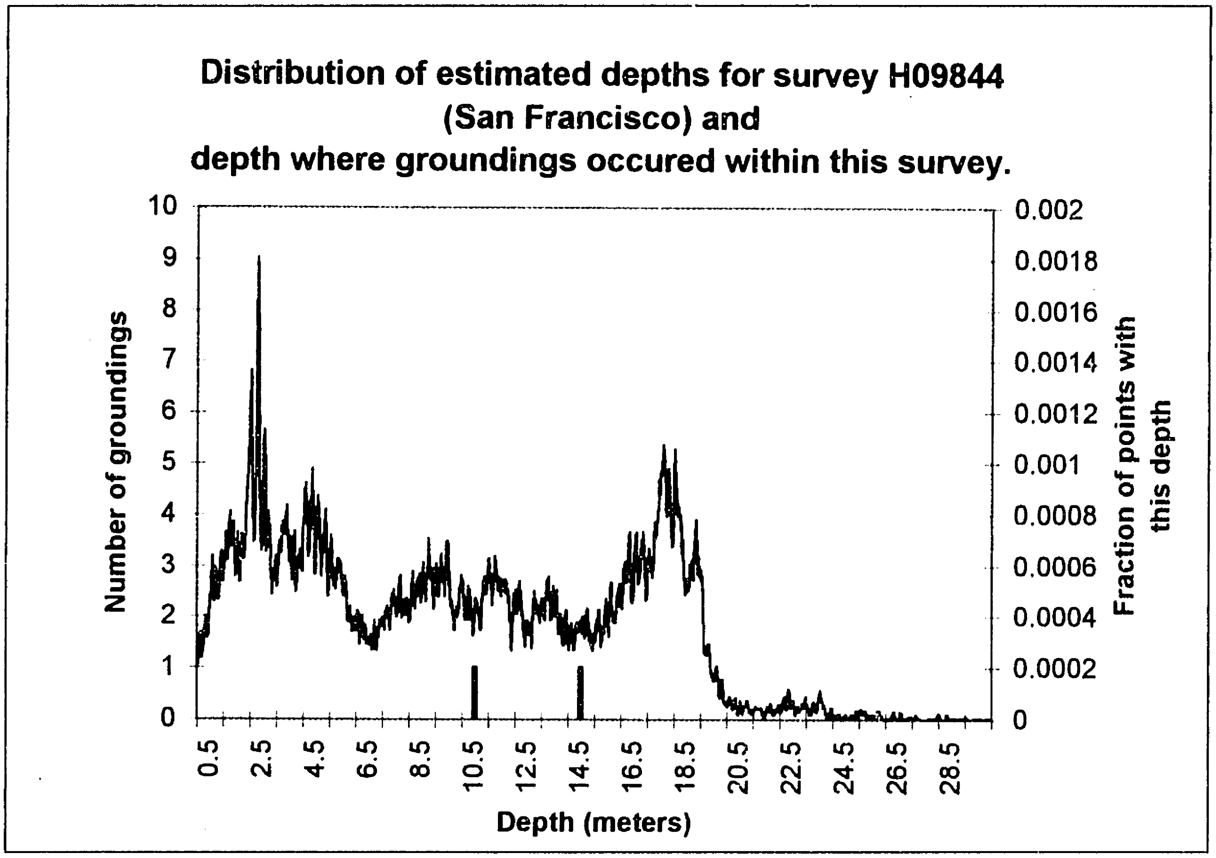
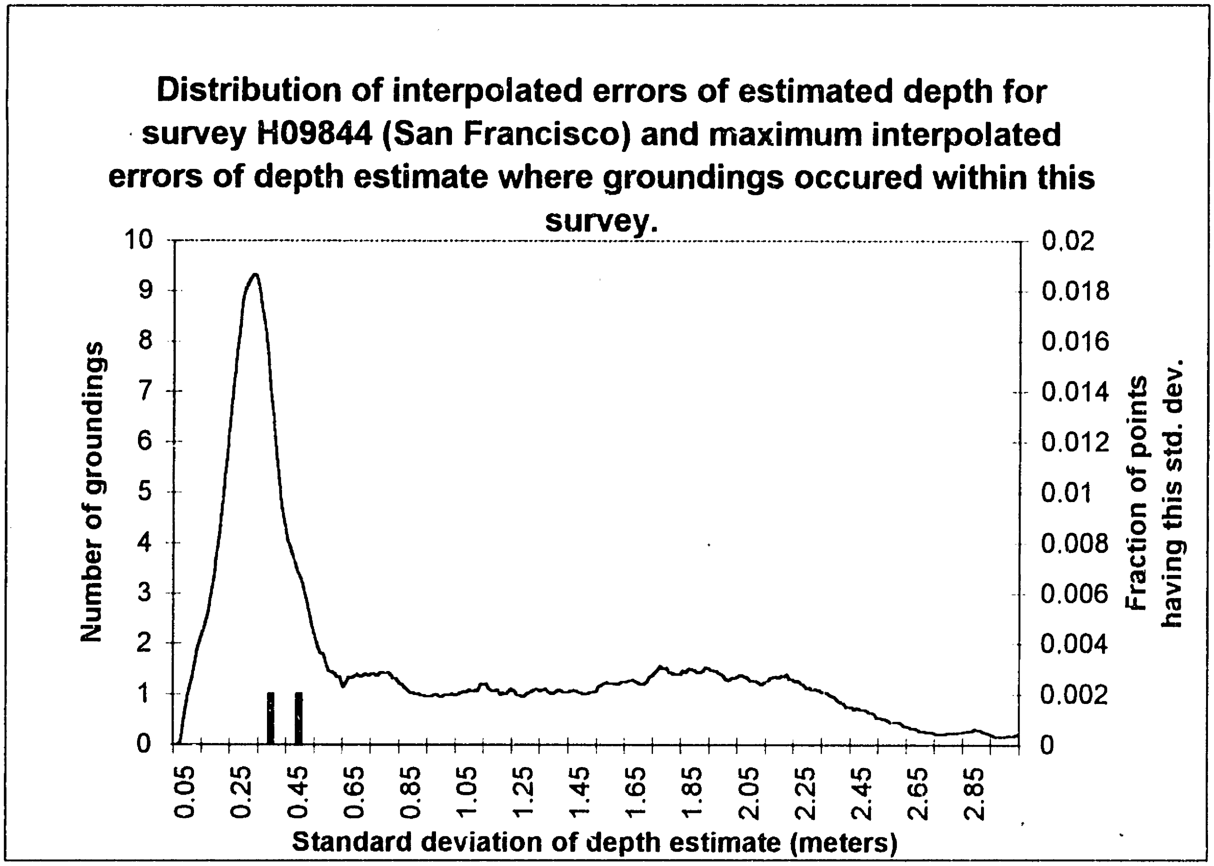


Figure 74, 75 - Depth and error comparison, survey H09844.



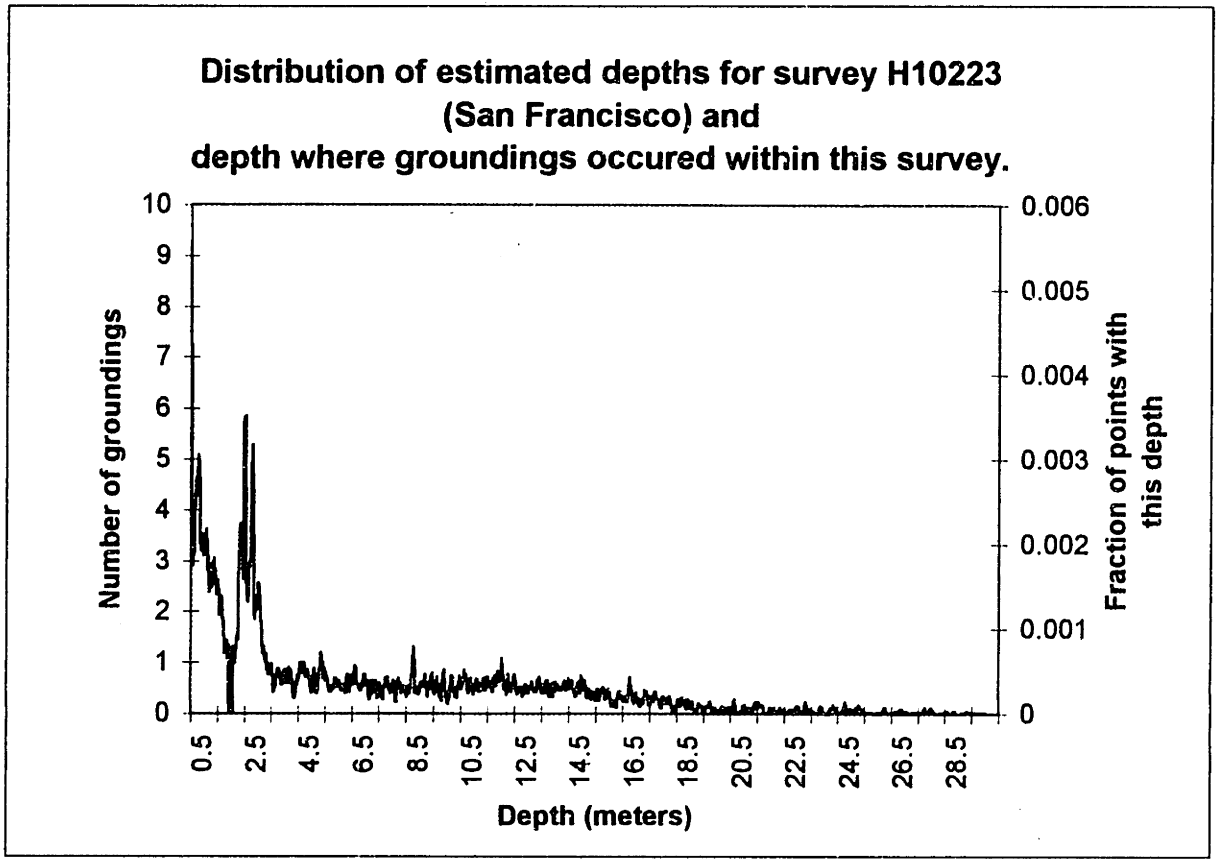
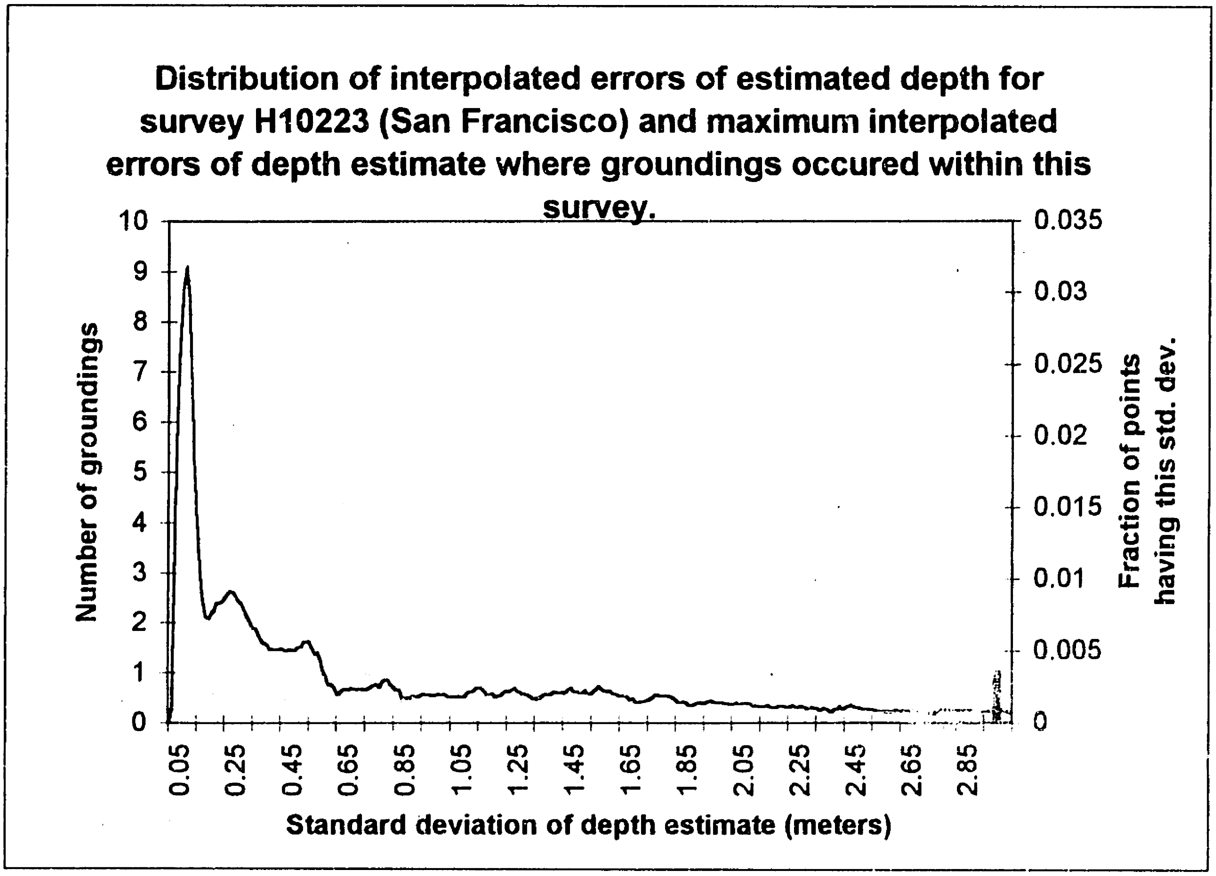


Figure 76, 77 - Depth and error comparison, survey H10223.



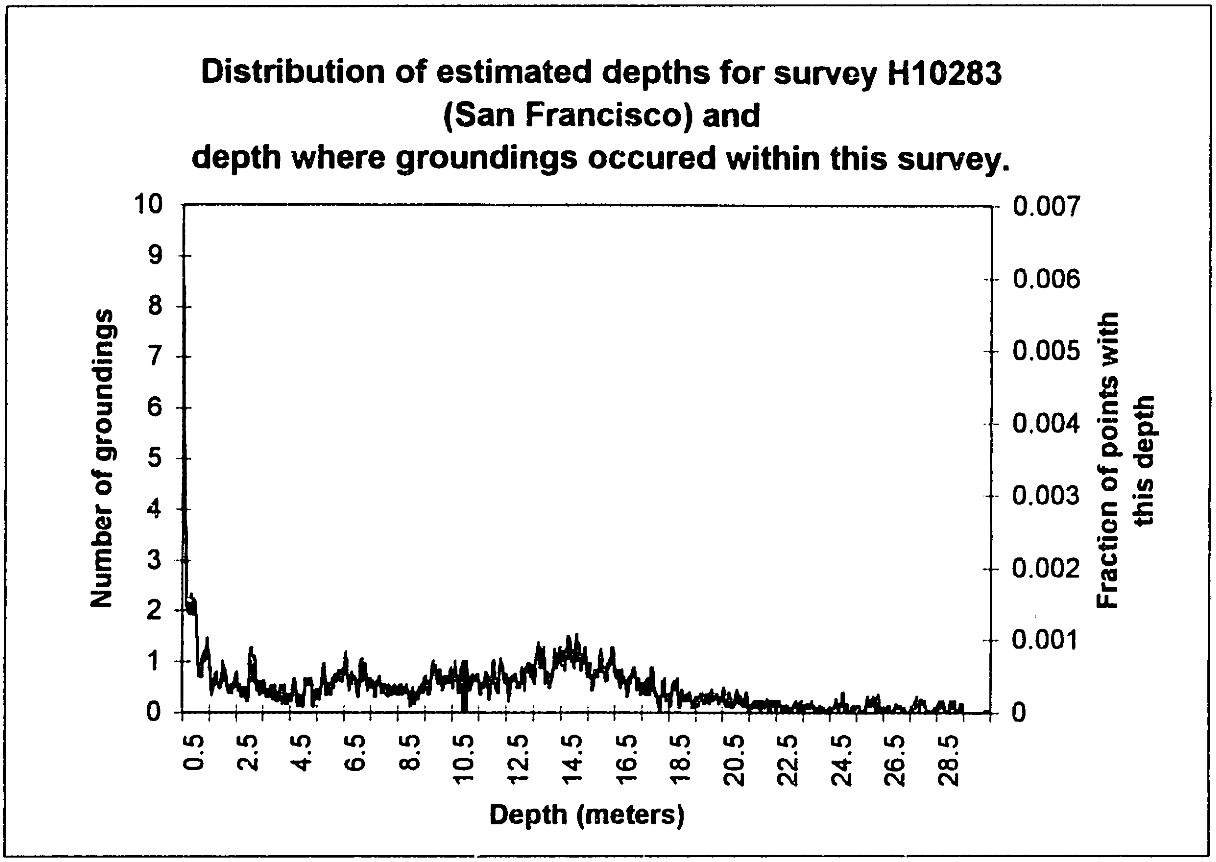
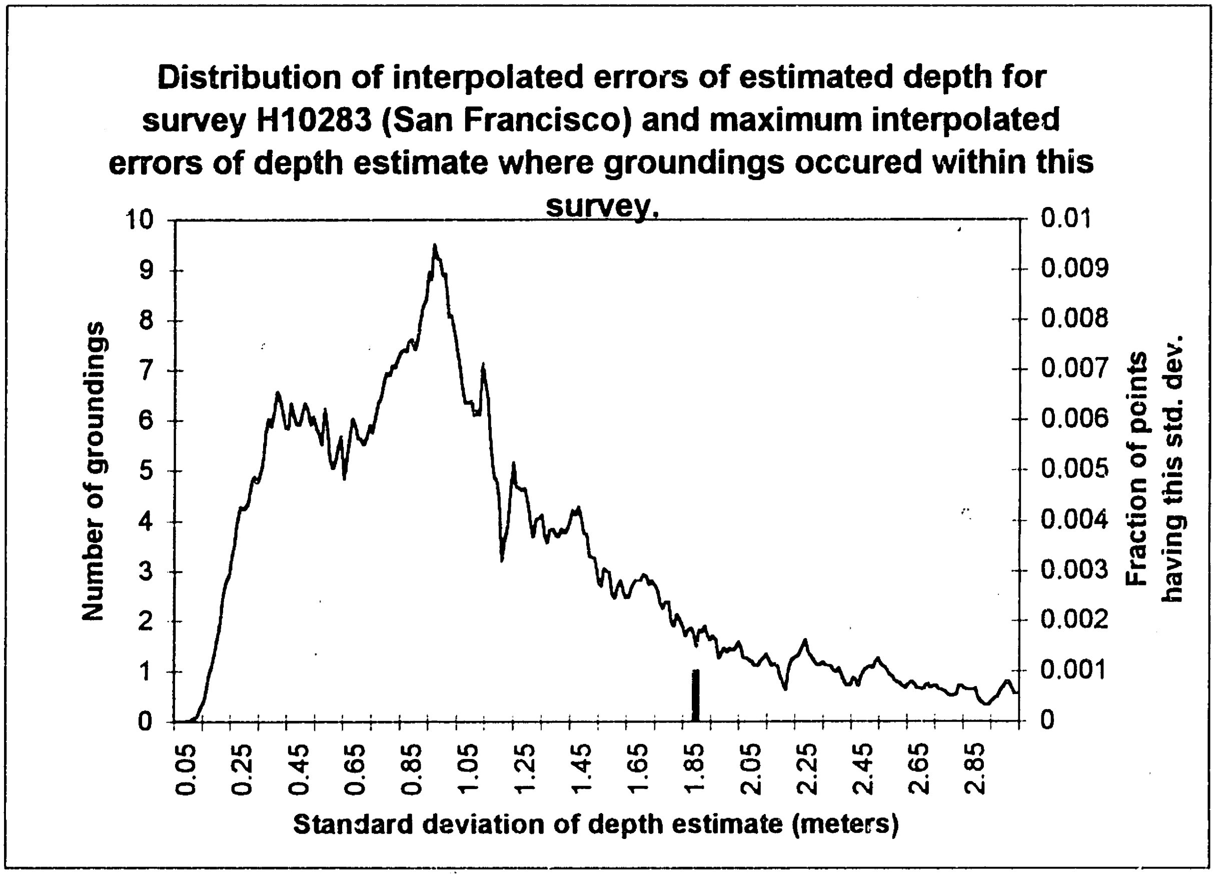
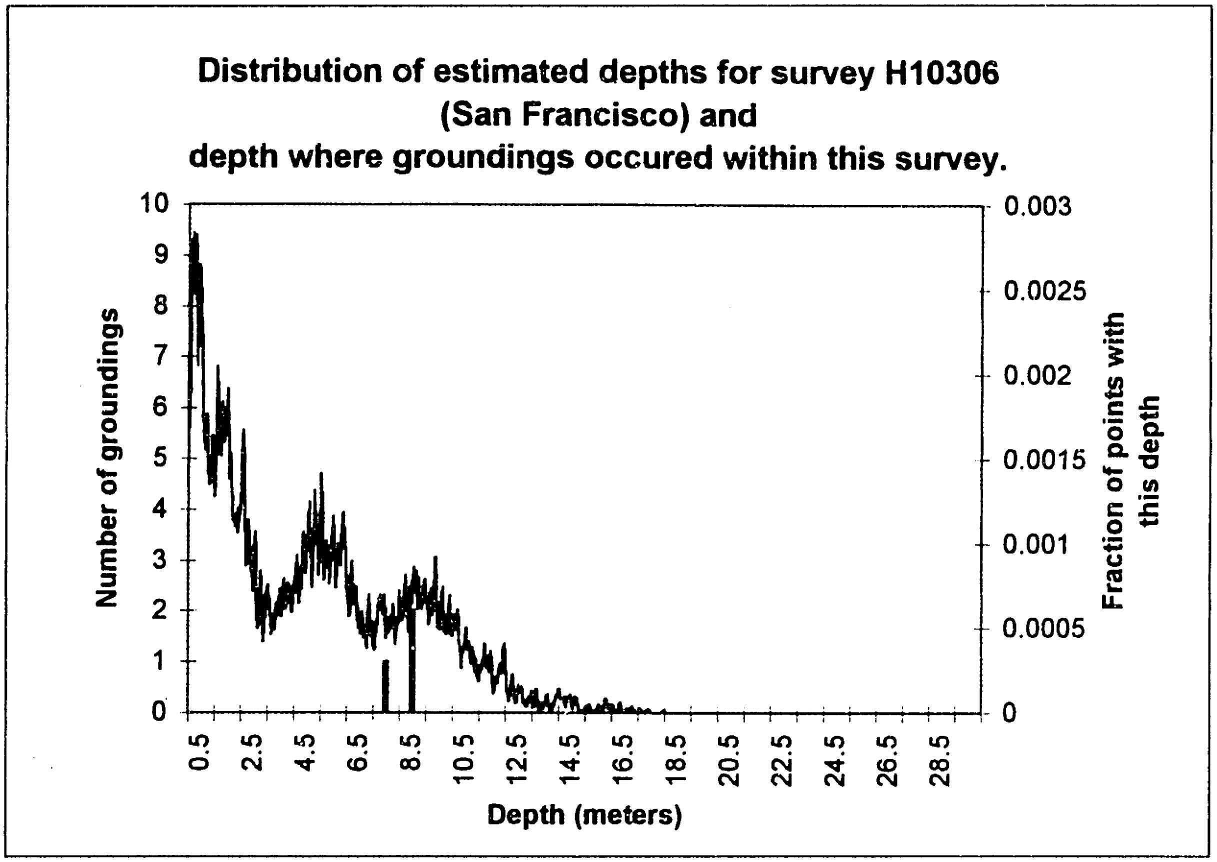


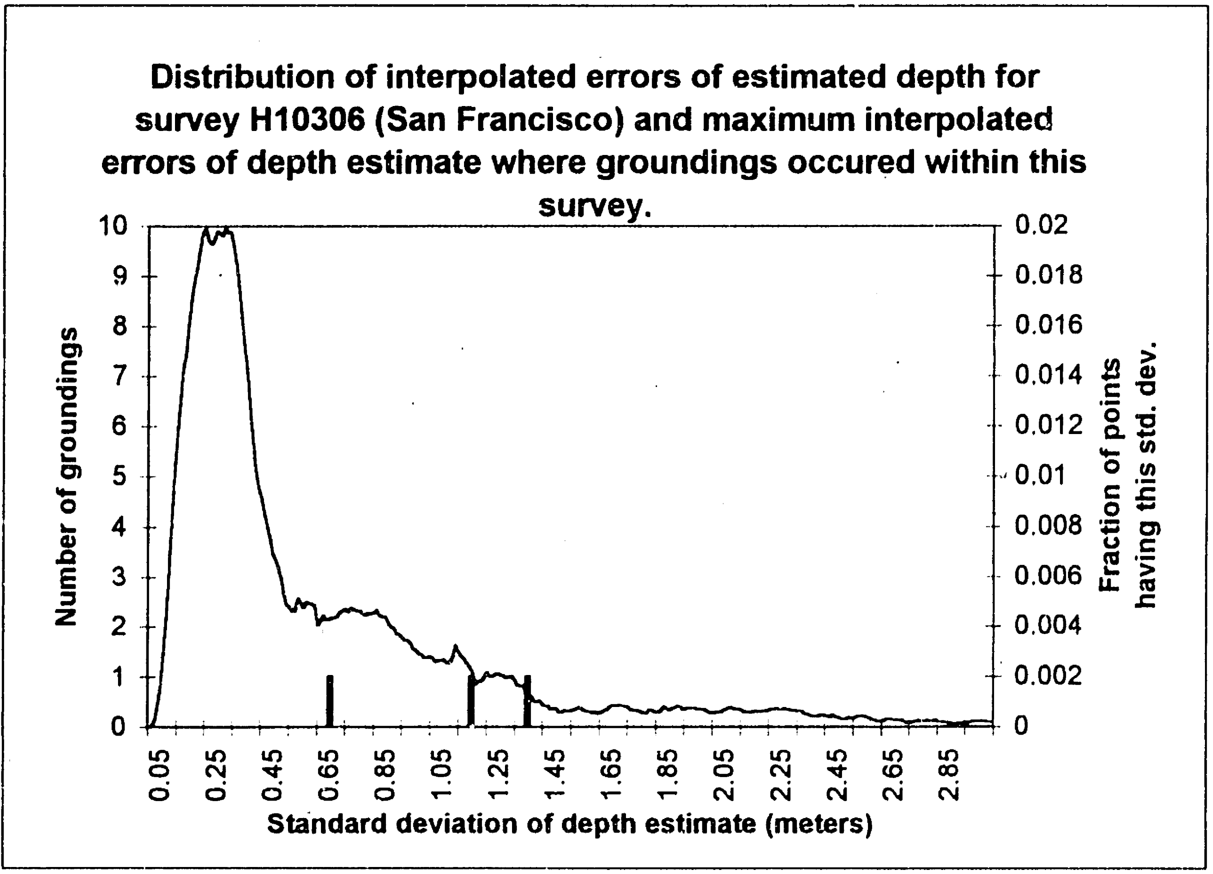
Figure 78, 79 - Depth and error comparison, survey H10283.





Distribution of estimated depths for survey H10306 (San Francisco) and depth where groundings occured within this survey.

Figure 80, 81 - Depth and error comparison, survey H10306.



Distribution of interpolated errors of estimated depth for survey H10306 (San Francisco) and maximum interpolated errors of depth estimate where groundings occured within this survey.

Tampa

The last port is Tampa. Here we found that 15 out of 64 groundings could be investigated. Tampa Bay is a shallow bay with lots of dredged channels. Thus, all the investigated groundings are found in the entrance of the bay. The two surveys covering these accidents were H08427 (1958) and H09338 (1975). The results here are not as clear as in the previous four ports. Actually there seems to be a small skewness towards the higher values. However, since we are comparing maximum point-errors within the grounding area with overall distribution, a small skewness is expected. The skewness evident on the graphs are also not very strong. Statistically there is no evidence of correlation.

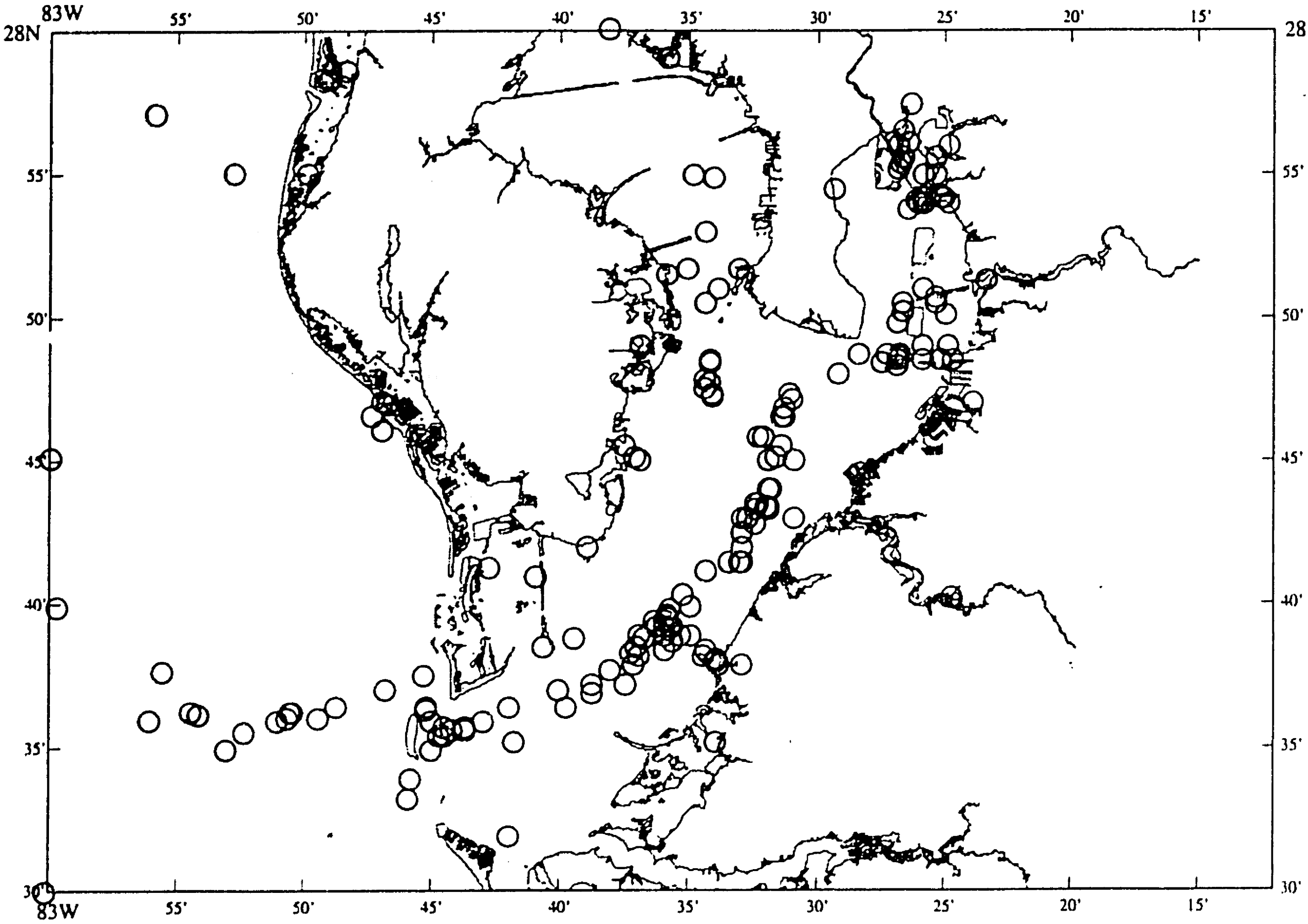


Figure 82. All groundings in Tampa.

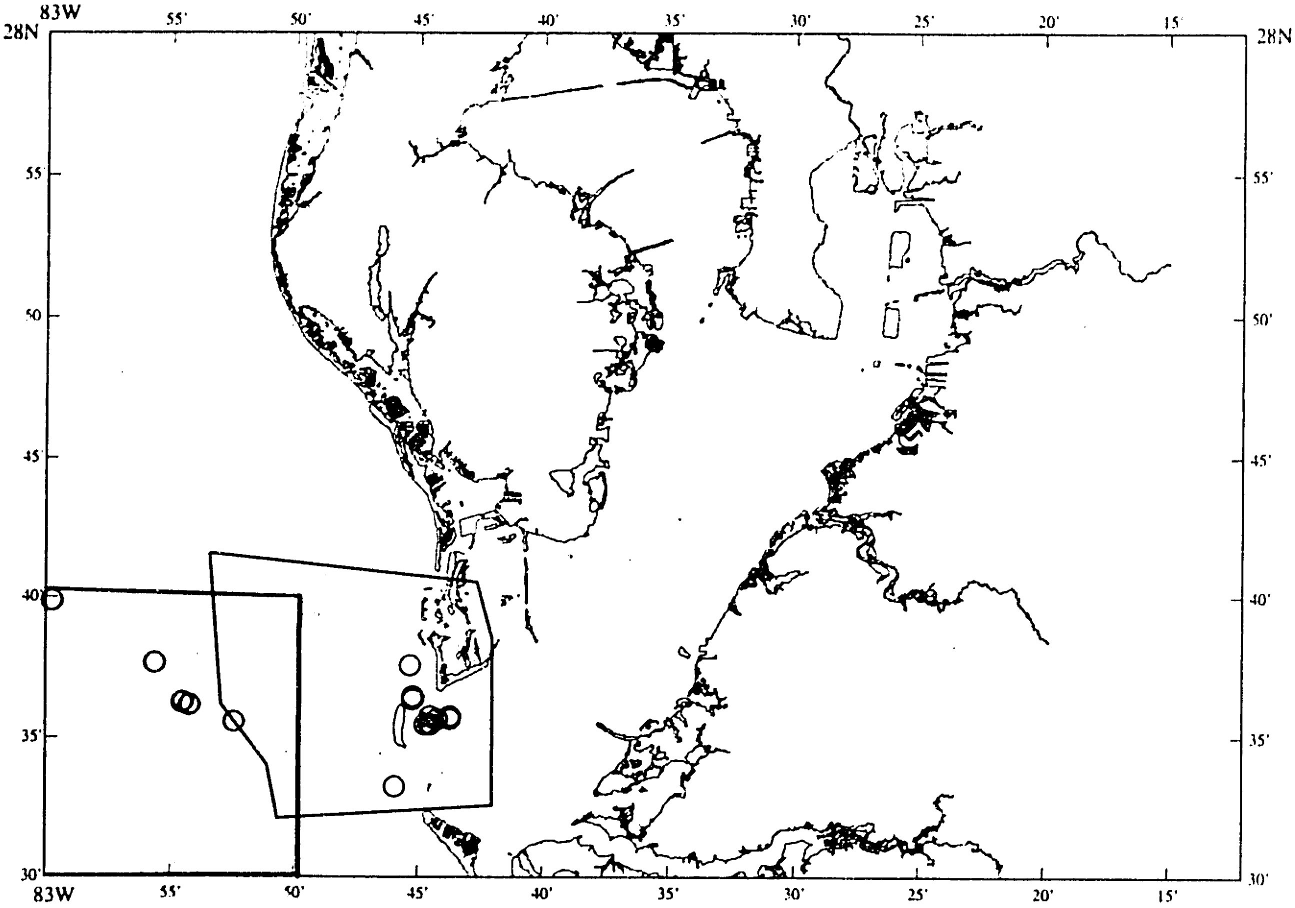


Figure 83. Groundings in Tampa investigated with Hydrostat

9.4.3 Conclusion

We have examined 71 groundings within five different major ports to see if there is any sign of correlation between cartographic uncertainty due to interpolation errors and historical groundings. The findings are quite clear. There is no evidence suggesting that operators' uncertainty about topography has made any contribution to the incidence of historical groundings in U.S. ports in recent decades. However, one thing must be noted. Our analysis has focused on differences within each survey and not compared different surveys and areas with each other. Hence, our examination suggests that it is <u>not</u> more likely for a ship to run aground at places where the depth uncertainty is high compared to the rest of the survey.

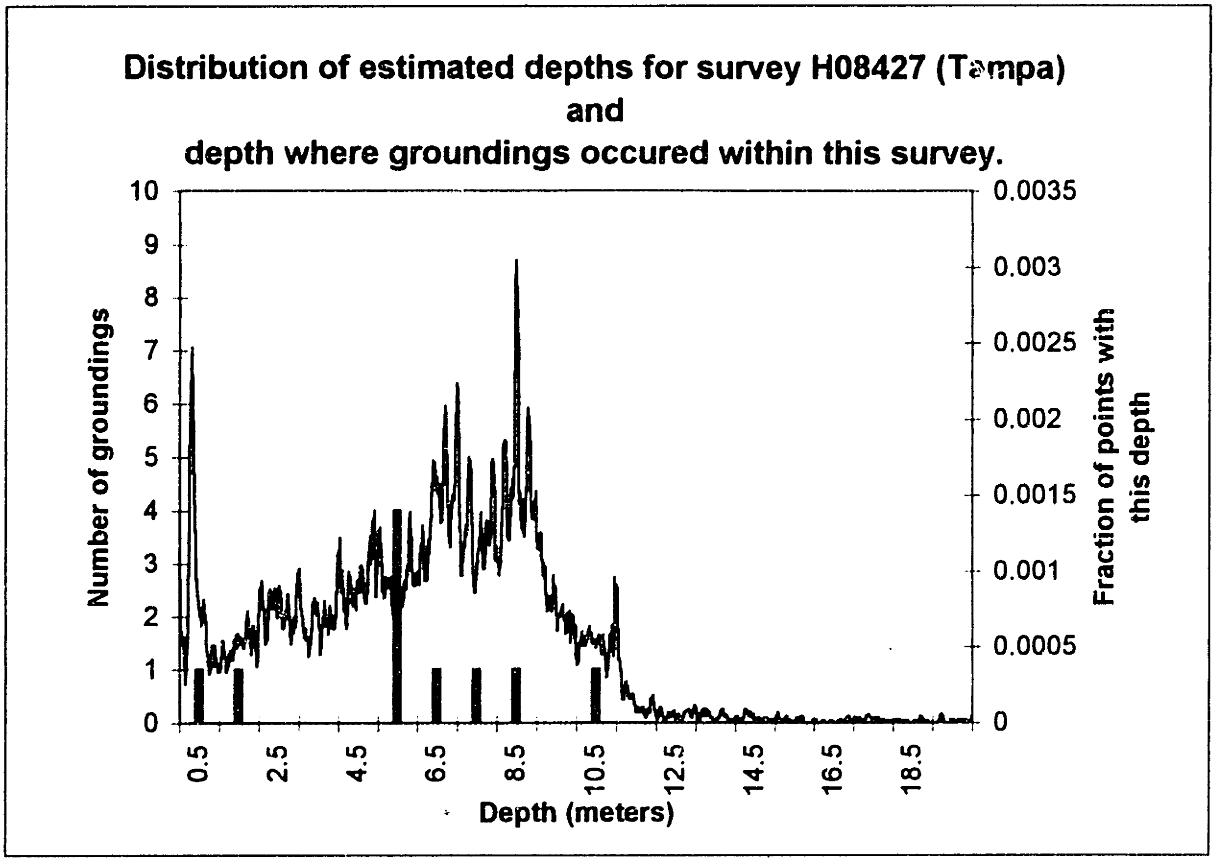
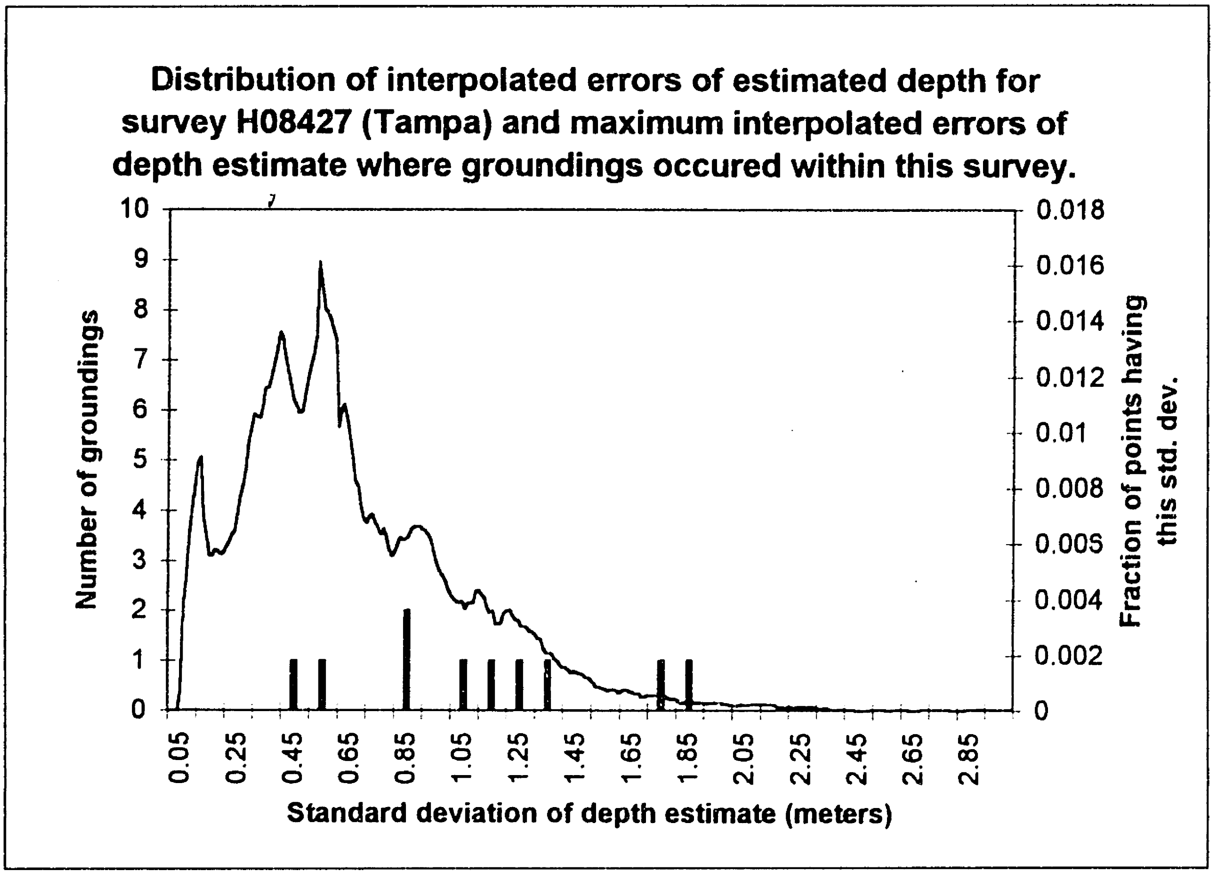


Figure 84, 85 - Depth and error comparison, survey H08427.



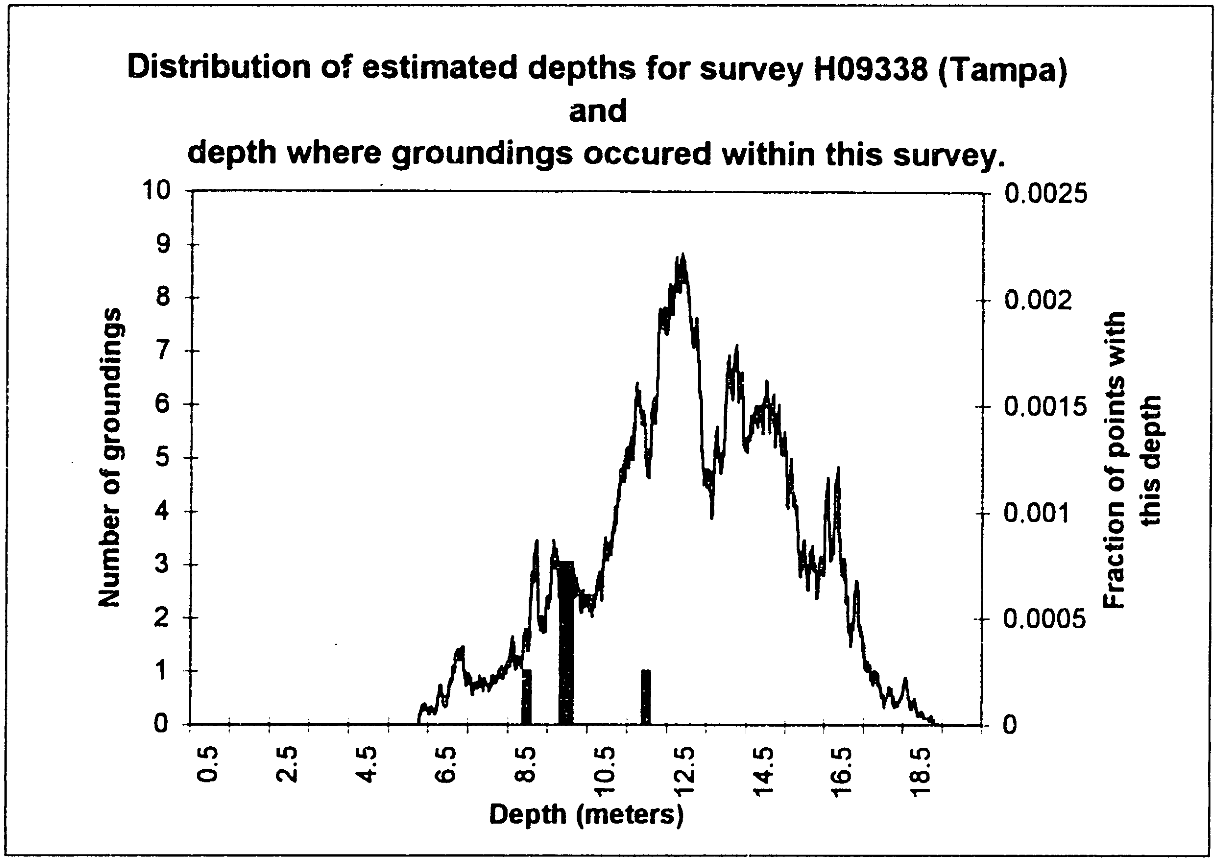
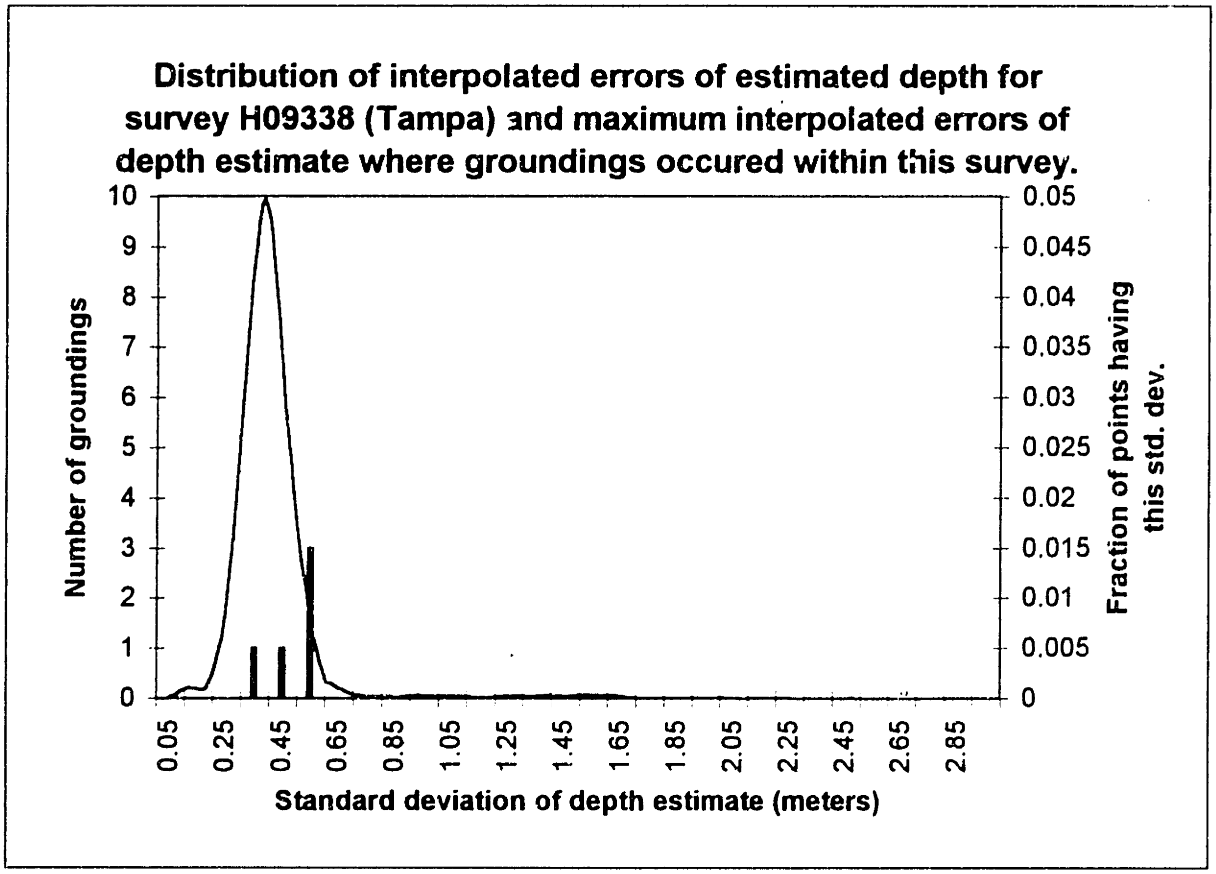


Figure 86, 87 - Depth and error comparison, survey H09338.



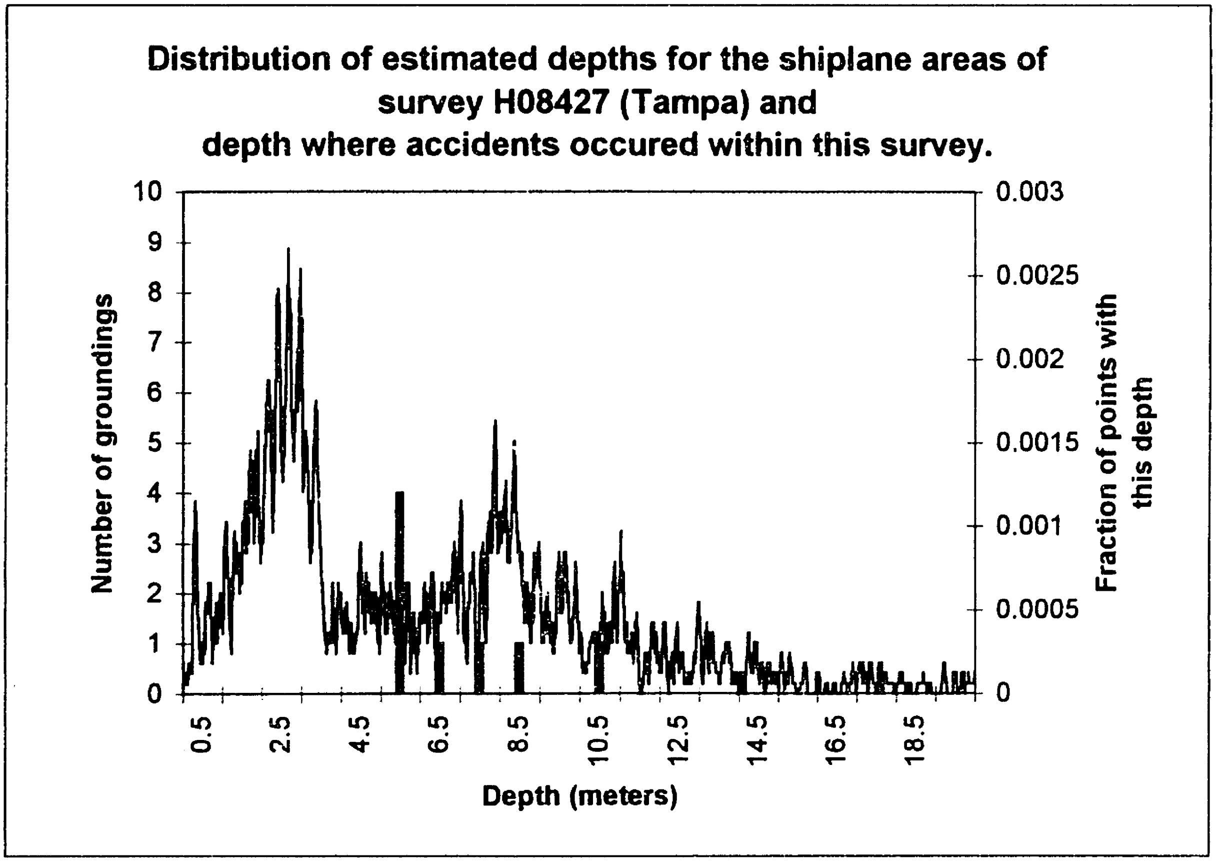
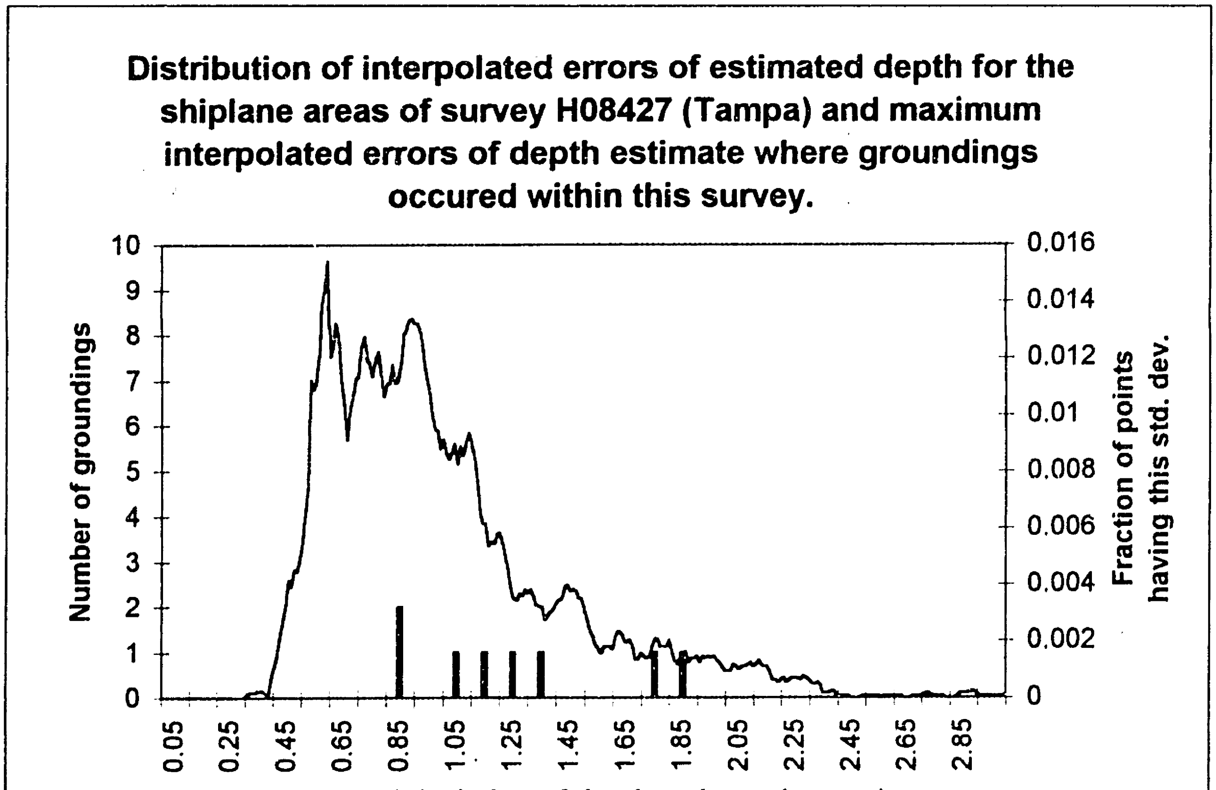


Figure 88, 89 - Depth and error comparison, survey H08427.



9.5 Vessel Characteristics

Assuming other things are equal, vessels considered to be more maneuverable may be expected to experience lower grounding risk during transits through a certain waterway than other less maneuverable. Measuring maneuverability for any vessel is a complicated process that requires a lot of vessel specific data. Unfortunately, such data were not available at the initial stage of the project; thus, it was not possible to obtain meaningful summary measures of maneuverability. Therefore, our analysis had to rely on proxies for maneuverability. The casualty data provided enough information for the following to be considered as proxies: vessel type, vessel size, and presence/use of tugs during the transit. In the initial stage of the project only vessel type was tested as a possible explanatory variable. Work on the other two is expected to be finished shortly after the completion of the present thesis.

As discussed earlier in section 8.4, the USCG casualty data set records were divided in two broad categories: ships and barge trains. Based on that distinction, we calculated the number of ship and barge train grounding per year for each port. Dividing these number by the corresponding annual ship and barge train transits, we obtained annual grounding rates for ships and barge trains. Averaging these annual rates over the entire period of study, 1981 to 1995, we were able to obtain the typical grounding rates for each one of the study ports (Table 18).

Table 18 - Average of groundings per 1000 transits for the study period 1981-1995.

	Boston	*Houston*	*New York*	*San Francisco*	*Tampa*
Ships	1.21	1.91	0.56	0.80	1.65
Barge Trains	0.45	0.47	0.17	1.77	1.72

The results included in the table above suggest that in Boston, Houston and New York barge trains experience lower risk of grounding that all the other vessels. The reverse is suggested for the remaining two ports. These observations need to be investigated further. In the case of San Francisco and Tampa, they are consistent with the general expectation concerning the relative maneuverability of the two vessels types: barge trains are, in general, likely to be less maneuverable than all the other vessels. However, the reverse results acquired from the other three ports might indicate that there are other external factors affecting the maneuverability of the two types of vessels not captured in our analysis.

Preliminary study of our data concerning the effects of ship size (barges trains not included) showed that large ships are consistently more likely to ground than small ships. These findings are also consistent with our expectation about ships' maneuverability but need to be refined further. The distinction between large and small ships is based on an approximation of the ship's design draft. The latter was calculated using ships' registered length and tonnage (available in the casualty data) and some crude assumptions about the relation of these three quantities (draft, length and tonnage)..

In three of the ports, barge trains experience higher risk of grounding, and in the remaining two, ships experience higher risk of grounding. However, except in Tampa, the differences in the grounding rates between ships and barge trains are considerable. The latter means than in both cases, the type of vessel affects the probability of grounding, although in a different way. Therefore, it would be reasonable to assume that vessel type will be useful as an explanatory variable in the modeling of the physical risk of grounding. Also the preliminary results on vessel size suggest that larger ships are, in general, more likely to ground than small ships. Hence, it would also be reasonable to assume that ship size will be useful as an explanatory variable in our modeling effort.

Chapter 10. Ship Transit Risk And International Safety Management Code

10.1 What Is The International Safety Management Code

W.N. von Zharen and W. Duncan provide the following definition of the International Safety Management (ISM) Code [57]: "The International Safety Management Code for the Safe Operation of Ships and Pollution Prevention, also known as the "International Safety Management Code" is a document addressing shipboard and shore-based management for the safe operation of ships and the prevention of marine pollution". The ISM Code was adopted by the International Maritime Organization (IMO) as Resolution A.741(18) on November 4, 1993. Following the Safety Of Life At Sea (SOLAS) Conference in May 1994, the ISM Code applies to ships regardless of the date of construction, as follows:

- Passenger ships including passenger high-speed craft, not later than 1 July 1998.
- Oil tankers, chemical tankers, gas carries, bulk carriers and cargo high-speed craft of 500 gross tonnage and upwards, not later than 1 July 1998.
- Other cargo ships and mobile offshore drilling units of 500 gross tonnage and upwards, not later than 1 July 2002.

The objectives of the code as stated in the original text of the Resolution A.741(18), has the following form:

1. The objectives of the Code are to ensure safety at sea, prevention of human injury or loss of life, and avoidance of damage to the environment, in particular, to the marine environment, and to property.
2. Safety management objectives of the Company should, inter alia:
    - 2.1. provide for safe practices in ship operation and a safe working environment;
    - 2.2. establish safeguards against all identified risks; and
    - 2.3. continuously improve safety management skills of personnel ashore and aboard ships, including preparing for emergencies related both to safety and environmental protection.
3. The safety management system should ensure:
    - 3.1. compliance with mandatory rules and regulations; and
    - 3.2. that applicable codes, guidelines and standards recommended by the Organization, Administrations, Classification societies and maritime industry organization are taken into account.

The process followed towards the award of the "Document of compliance" for the managing company and the "Safety Management Certificate" for each of the ships under management usually comprises multiple steps. The exact number of these steps as well their nature depends heavily on the organization responsible for awarding the ISM compliance documentation. In Resolution A. 741 (18), IMO has provided some form of guidelines concerning the certification process composed of the following twelve points:

1. Safety and environmental protection policy
2. Company responsibility and authority
3. Designated person(s)
4. Master's responsibility and authority
5. Resources and personnel
6. Development of plans for shipboard operations
7. Emergency preparedness
8. Reports and analysis of non-conformities, accidents and hazardous occurrences
9. Maintenance of the ship and equipment
10. Documentation
11. Company verification, review and evaluation
12. Certification, verification and control

10.2 ISM And Ship Transit Risk Modeling

Although not clearly stated in the context of the present thesis, it is expected that the modeling of the ship transit risk will provide a useful tool to support decision making processes related to maritime safety. The model will provide the decision maker with a quantitative perception of transit risk, giving him the chance to optimize the allocation of his risk mitigating resources using such things as utility functions and decision trees.

Therefore, one may argue that the transit risk model can be considered as a proactive approach to marine safety. Actually, given that the model attempts to capture all the potential risk contributing factors, one may take the argument further talking about a *total approach to maritime safety*. The latter term can be defined as:

$$\textit{Total Safety Approach} = \textit{Technical} + \textit{Organization} + \textit{Personnel}$$

and is considered to be one of the recent buzz words of the maritime community [58].

Although the discussion is section 10.1 was kept short, it is easy to understand that ISM fosters the same kind of proactive approach to maritime safety. It is long due legislation expected to be the forerunner of a new era in the shipping industry [59, 60]. In this respect, ISM and the ship transit model may have to benefit from each other more than the eye can catch. We believe that there is potential for mutual exploitation in such relationship, that needs to be further investigated. Given the restriction of the present thesis as to the subject of discussion we will not go into detail, however, a simple example of this potential will be provided. Earlier the basic guidelines of IMO concerning the application of ISM were presented. Among others, point 8 calls for the development of a system capable of reporting and analyzing non-conformities, accidents and hazardous occurrences. It should be clear that an extension of the present effort on the modeling of the physical risk of grounding may serve the purpose perfectly. ISM will provide a more complete world wide database for the study of transit risk and marine safety, while the experience of building the risk model will assist in designing the database and data acquisition process.

Chapter 11. Conclusion

This thesis has focused on the development of a methodology for quantitative risk assessment as a comprehensive tool to predict the physical risk of navigational groundings during transit into and out of port. The work presented in the thesis has been done as part of a MIT/WHOI project on "Formulation of a Model for Ship Transit Risk".

In particular, we have tried to get an improved understanding of the specific factors contributing to vessel groundings. The statistical model itself is a Bayesian technique that uses likelihood and prior probabilities to calculate the posterior probability of grounding given a set of explanatory variables. These explanatory variables must be found among the factors that affect the physical risk of grounding. Therefore, to determine which factors are meaningful "contributing factors" to the risk of grounding, we have examined a variety of parameters based on a comprehensive sample of historical data. The historical data contained information on both groundings and safe transits, between 1981 and 1995, for the five chosen study areas (Boston, New York/New Jersey, Tampa, Houston/Galveston, and San Francisco) and were acquired from different sources within USCG, ACE and NOAA.

The results obtained from this effort are encouraging. Although the accessible data on historical groundings and safe transits are far from complete, we find that sufficient information is available for the construction of a port-level model. Two environmental factors found to have considerable effect on risk are wind speed and visibility. Historical groundings are associated with higher average wind speeds and lower average visibility than safe transits. On the other hand, uncertainty in hydrographic surveys, on which nautical charts are based, does not appear to contribute significantly to groundings in the ports we have studied. In fact, by plotting each grounding location on navigational charts it was found that most groundings occur near dredged channels, suggesting that the major practical problems of harbor navigation reside in the proper planning and execution of maneuvers in confined spaces. It was difficult to obtain meaningful summary measures of maneuverability. However, by using vessel size and type as proxies, we found that barge trains are more likely to ground than ships, and that larger ships are consistently more likely to ground than small ships. Both these findings are consistent with our expectations about maneuverability and also imply that proxies can usefully be employed in developing the physical risk model. When analyzing human factors, we encountered limitations and deficiencies in the historical data. Unfortunately, the only proxy for operator skill that could be readily constructed from the data was the flag of the vessel. This proxy is relevant only to ships and embodies many variables beyond operator skill, hence, it requires further exploration before it can be endorsed fully for the development of the physical risk model.

The findings described in this thesis are the results of the first year work of the "Formulation of a Model for Ship Transit Risk" project. Further work is recommended to include a more detailed examination of groundings in particular local channel segments, and an extended search for data from alternative sources to fill the gaps in the current historical data set, thereby supporting the findings of additional "contributing factors".

Appendices

Appendix A: List Of Potential Factors That Affect Risk

The following presents a summary of factors discussed in the Port Needs Study [4], Minding the Helm [21], the Waterways Management Research & Planning Project [18], Screening for Environmental Risk [40] and Tanker Environmental Risk [37]. For our purpose, the waterway risk factors can be divided into four main groups:

- Human factors,
- Physical Waterway Characteristics,
- Vessel Characteristics, and
- Accident specific factors.

The human systems group covers the human part of the vessel system from crew to vessel management procedures. The physical waterway characteristics group covers the factors that defines the "static" waterway. These factors are due to the nature of the area and to systems developed by humans over a long time. The factors are independent of what kind of ship the risk model is being employed for, and are not easily manipulated or altered on a short term basis. The physical attributes of the vessel are covered by the third group. These factors are fairly specific to the type of ship, but vary according to loading condition. The last group, accident specific factors, covers the management systems which are established to prevent accidents from happening. These systems interact with the ship entering the waterway, and some of the factors in the group are undetermined until we know to what extent the ship will use the systems. The factors in each group can be subdivided into the following categories:

Human factors

- Vessel crew qualifications
- Vessel management

Vessel characteristics

- Type
- Size
- Maneuverability
- On-board navigation aids

Physical waterway characteristics

- Environmental conditions
- Waterway geometry and configuration
- Traffic volume/densities
- Navigation aids and support systems
- Route characteristics

Accident specific factors

- Escort vessels
- Pilotage
- Waterway management/traffic systems

The following section lists the factors included in each category:

Human factors:

Vessel crew qualifications

It is extremely important that the vessel crew are able to operate safely given adequate shipboard equipment. An experienced and alert bridge crew with even minimal equipment is far safer than a confused bridge crew using the most advanced bridge information system. Upon equipment failure due to the hostile marine environment, it will be basic seamanship which allows continued safe operation. The IMO's Standards of Training, certification and Watch-keeping for seafarers set minimum requirements for what can be recognized as basic seamanship [37]. Some of the factors concerning the crew factors are:

- Crew size
- Environmental conditions (overtime, fatigue, etc.)
- Maintenance demands
- Level of local knowledge
- Vessel manning standards
- Training and experience

Vessel management

The management of a vessel has the overall responsibility and represent a crucial element in ensuring safe and environmental friendly transits. IMO are promoting and enhancing safety through their newly proposed International Safety Management Code (ISM Code). In addition to this, the major classification societies are insuring safe behavior through their Safety Management Certificates. Factors that matter include:

- Procedures
- Proficiency in rules and regulations
- Company standards
- Support system personnel

Physical waterway characteristics:

Environmental conditions

The fast changing marine environment has always been the seafarers worst enemy. Fog limiting the visibility or currents worsening the maneuverability of the ship are only two of the many factors that might increase the risk of a grounding. Unfortunately little can be done to change adverse weather, but it helps knowing how different environmental conditions affect the waterway system. Factors include:

- Current
- Visibility
- Wind speed
- Sea state
- Season (winter, spring, etc.)
- Time of day (light or dark)
- Tides
- River stage

Waterway geometry and configuration

The unique navigational character of each waterway might contribute to groundings. The Port Needs Study [4] looked at the following factors when investigating the need for VTS in different study zones:

- *Minimum width*: Minimum channel/waterway width along the route in meters.
- *Average width*: Average channel/waterway width along the route in meters.
- *Minimum depth*: Minimum channel/waterway depth along the route in meters.
- *Average number of turns per route mile*: Number of course changes along the route.
- *Sum of delta headings*: Total degrees of delta values of course changes with no regard of direction along the route.
- *Average delta headings per mile*: Average degrees of course change along the route.
- *Number of obstructions per mile*: Total number of bridges, anchorage's, crossing lanes and other obstructions along the route.
- *Bottom conditions/variability of depth*: Mud, sand/gravel or rock/coral

Route characteristics

- *Depth*

  The depth is a basic factor since there is a greater chance of a grounding if the waterway is shallow. If the whole area is deeper than the ship's draft, then it is impossible to run on ground.
- *Route length*

  The route length is included since the traffic volume factors and waterway configuration factors are normalized by a standard length (per route mile).
- *Duration of the transit*

  If the ship is exposed longer to the hazards than normal, the probability of a grounding will increase.

Traffic volume/densities

The denser the traffic is in a waterway, the greater the chance is that a ship must deviate from its planned track. This is particularly the case in confined waterways where meeting, crossing and overtaking agreements between vessels need to be worked out well in advance of actual encounters. The Port Needs Study recognized among other the following factors:

- All transits divided per route mile.
- Ferry miles per square-mile.
- Other vessels (fishing boats, recreational boats etc.) per route mile.
- Ship scheduling.

Navigation aids and support systems

When navigating a waterway it is extremely important to have up-to-date support systems and reliable navigation aids. One of *Minding the Helm*'s major findings was that traditional aids to navigation will continue to play a central role in the future, particularly for pilots. Some of the issues/factors related to navigation aids and support systems are:

- Man made (lighted buoys, etc.)
- Status of man-made aids to navigation
- Chart defined or user defined
- Natural (ability to radar navigate, etc.)
- Chart quality
- Age of bottom sounding data
- Notice to mariners

Vessel characteristics:

Type and size

The type and the size of the vessel are definitely factors that affect the risk level. In Houston Ship Channel it is recognized that barges are more often involved in groundings than regular vessels. The mix of tankers, cargo ships and tugs/barges also contribute to groundings, especially under poor weather conditions in the channel [4].

Type

- Passenger
- Dry cargo
- Tanker
- Dry cargo barge tows
- Tanker barge tows
- Tug/tow boats

Size

- Displacement
- Height
- Length
- Beam
- Loaded draft

Maneuverability

The maneuverability of a ship is an obvious factor connected to the risk of grounding. Particularly during meeting situations in restricted shallow waters with small under-keel clearances it is important to be able to maneuver freely. Maneuverability can be specified by the following factors:

- Steering
- Propulsion
- Maneuvering speed
- Turning diameter
- Redundancy of systems

On-board navigation aids

Having on-board navigation aids are crucial to navigate safely. The level of automation and sophistication might contribute both positively, if handled correctly, or negatively, if used incorrectly, to the navigation risk. Some issues are:

- Sophistication of equipment
- DGPS
- Radar
- ECDIS, etc.
- Aids to navigation dependence

Accident specific factors:

Escort vessels

- *Use of tugs*: The use of tugs increases the maneuverability of the ship and is in most instances mandatory for tankers.
- *Reliability of tugs*: The quality and strength of the tugs might be factors reducing the likelihood of accidents.

- *Availability of tugs*: If the traffic volume is unusually high or in the case of emergency, having extra tugs available might be critical.

Pilotage

- *Use of pilot*: The pilot has expert knowledge about the local operating conditions, limitations posed by other traffic and procedures for operating vessels in the local pilotage area.
- *Type of pilot*

  > "Traditionally, these services are provided by independent, locally based pilots because most ship's captains, while possibly very knowledgeable about the maneuvering of their vessels, lack detailed knowledge about local operating conditions. The pilot normally maneuvers the vessel and is subject only to the overriding command authority of the captain. However, for U.S. flag ships traveling between U.S. ports, the captain or a mate may serve as pilot if licensed by the Coast Guard to do so. In general, federal pilotage rules govern U.S. merchant vessels traveling between the nation's ports, while each state governs the piloting of merchant ships in foreign trade while those ships are in state waters. Each state may set its own standards for licensing and regulating pilots that operate in state ports. In many cases states rely on professional standards set by pilot groups." [21]
- *Availability of pilots*: It is important to have pilots available when needed.
- *Experience of pilot*: The experience of the pilot is a critical factor determining his performance. The license is of little value if the pilot is not maintaining his/her knowledge by regular training. It is also important that pilots are up-to-date with new technologies.

Waterway management/traffic systems

Vessel traffic services are interactive, shore-based communications systems, usually augmented with surveillance equipment (radar) for acquisition of position and traffic flow data, that provide information and navigation support services to improve navigation safety and traffic efficiency. The NRC report, Minding the helm [21], defined VTS functions as consisting of five more or less progressive categories of activities or services:

- General information services, (simple)
- Navigation advisory services
- Traffic direction management, (medium)
- Shore based pilotage
- Traffic control, (extensive)

Collectively, all five functions or services would constitute a generic model of a full-mission, comprehensive system for regulation of marine traffic. In practice, a VTS may provide one or a combination of the first three services and functions. Some of these services are provided to all categories of vessels, while others may be vessel- or scenario-dependent. The Coast Guards VTS operations are limited to the first three elements by agency policy.

Comment:
With all these risk factors listed, we might perceive the marine transportation system to be risky. However, the marine accident record indicates that high consequence accidents rarely occur in the marine system. Apparent reasons for this was explained in "Minding the Helm" as follows:

- The slow speed at which most action occurs, usually - but not always - provides time for human operators to recognize and recover from mistakes.
- The operating environment usually does not lead immediately to catastrophic results such as total loss of vessel.
- The nautical rules of the road provide adequate procedures for preventing collisions or groundings in interactions between two vessels.

Appendix B: Hydrostat, Variogram Models And Kriging.

Introduction

The Hydrostat program produces two maps of hydrographic data: a bathymetric surface that interpolates actual depth measurements; and a related stochastic surface that models the vertical error estimate for all points on the bathymetric surface [61].

The interpolation of depth measurements between observed soundings is performed by *Kriging* [52], which in turn is based on the concept of variograms [43]. A variogram relates the expected depth variation at a given location to the distance from that location to a point of known depth. Kriging is a weighted linear interpolation function whose weights are determined by a variogram. To compute the depth interpolation at a given location, the weight assigned to a actual depth sounding is proportional to the depth variation associated with the distance between the given location and the depth sounding.

The Variogram

A variogram is a function that relates the variance of differences (of function values) to distance. The variogram represent the similarity or rather the dissimilarity which exists between the depth at one point and the depth some distance away. The error of estimation is again a function of the similarity which can be expected between the depths. This expected variation can also be expressed as spatial correlation. In the Hydrostat program variograms relate the average squared depth differences to average positional distances between soundings. Casey [62] defines the variogram as

$$2\gamma(h) \quad = Var\left[d(i) - d(i+h)\right]$$

where $d(i)$ and $d(i+h)$ are depths at two points i and $i+h$, h meters apart. Expanding this equation one can derive another common form for the variogram

$$\begin{aligned} 2\gamma(h) &= Var[d(i) - d(i+h)] \\ &= Var[d(i)] + Var[d(i+h)] - 2 \cdot Cov[d(i), d(i+h)] \\ &= 2 \cdot Var[d(i)] - 2 \cdot Cov[d(i), d(i+h)] \\ &= E[d(i) \cdot d(i)] + E[d(i+h) \cdot d(i+h)] - 2 \cdot E[d(i) \cdot d(i+h)] \\ &= E[d(i) - d(i+h)]^2 . \end{aligned}$$

Hence, the variance of any two soundings separated by a distance of *h* can be expressed as

$$2\gamma(h) = E[d(i) - d(i+h)]^2 .$$

This form of the variogram is measuring the average difference (squared) between any two sample points a distance *h* apart. In practice we can estimate the variogram by the formula:

$$2\gamma(h) = \frac{1}{N(h)} \cdot \sum_{i=1}^{N(h)} [d(i) - d(i+h)]^2$$

where *N(h)* is the number of pairs of sample points separated by a distance of *h*.

David [63] explains that the most natural way to compare two values, say two depths *d(i)* and *d(i+h)*, is to consider their difference. Since differences and absolute values are difficult in calculus, the easiest way is to consider the squared differences. This way he derives the following type of variogram:

$$2\gamma(\vec{h}) = Ave[d(i) - d(i+\vec{h})]^2 = E[d(i) - d(i+\vec{h})]^2$$

This variogram is a function of a vector, in other words, a function of distance and the orientation of that distance, and it expresses how depths differ in average according to the distance in that direction. Variograms are usually estimated in a number of different directions. The purpose is to see if the variation is the same in the different directions. If no significant differences are seen then the bottom is considered isotropic. Otherwise, the bottom is considered anisotropic. Special methods for kriging have been developed to handle anisotropic cases which involve parameterizing the variograms as a function of direction.

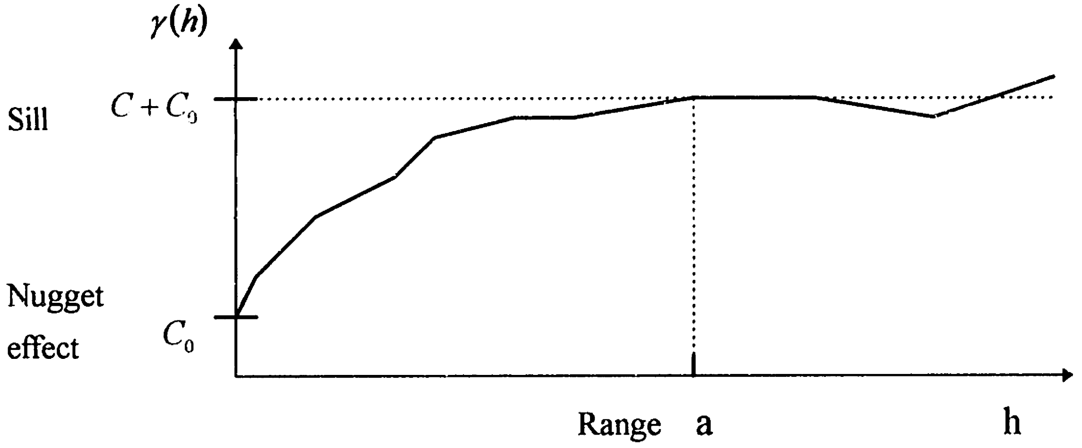


Figure A1 - Variogram.

Figure A1 shows a variogram. Special names have been given to the three parameters C_0, $C+C_0$ and a. If the variogram rises and then levels off or stabilizes about a value $C+C_0$, it is said to have reached a *sill*. This value is equal to the variance of the process under study. The value a of h where the sill is reached is called the *range*, the distance beyond which "samples" are independent of each other. If $C_0=\gamma(0)$ is greater than 0, it is called the nugget effect and is in fact the variance of a random noise that is added to the correlated process (the sampling error, e.g. instrumental error). The variogram gives indications about the continuity of the variable under study. The continuity is reflected by the rate of growth of γ(h) for small values of h. In hydrography we usually obtain variograms with gentle, regular growth, while in geology we might find unregular or totally flat variograms, indicating rapid changes over a very short distance or independence between two samples.

Because it is, in practice difficult to find enough sample points which are separated by exactly the same distance h, the soundings are collected into groups G_k on the basis of their relative positional distances:

$$G_k = \left\{ \left(x_i, x_j\right) \middle| h_k < \left\| l_i, l_j \right\| \le h_{k+1}, \mathit{for}\ 1 \le i, j \le n \right\}, \quad \mathit{for}\ 1 \le k \le m$$

where $h_1 = 0$ and $h_{m+1} = h_{max}$, the maximum positional distance between two soundings in x [64]. The number of sample points in group G_k is $N(G_k)$. The average positional distance $\bar{h}_k$ and average squared depth difference $\bar{d}_k$ of G_k are:

$$\bar{h}_k = \frac{1}{N(G_k)} \sum \left\| l_s, l_t \right\|, \quad \text{and}$$

$$\bar{d}_k = \frac{1}{N(G_k)} \sum \left(d_s - d_t\right)^2,$$

where x_s , $x_t \in G_k$. Hence, "vectors" that end in the same group are classified into one class and variogram value is estimated separately for each class. The set of all pairs ($\bar{h}_k$, $\bar{d}_k$), for $1 \leq k \leq m$, trace out the variogram function.

The observed variogram is generally modeled by an analytic variogram. The notion of nugget, sill and range are reflected in the mathematical models used as theoretical variograms. The two most popular models for variograms without sills are the spherical model [65]:

$$\gamma(h) = \begin{cases} C\left(\frac{3h}{2a} - \frac{h^3}{2a^3}\right) + C_0 & \textit{for } h \leq a \\ C + C_0 & \textit{for } h > a \end{cases}$$

and the exponential model:

$$\gamma(h) = C\left[1 - \exp\left(\frac{-h}{a}\right)\right] + C_0.$$

Variogram modeling in Hydrostat

In Hydrostat the variogram relates the distance between measurements sites to the variability of all the depth pairs separated by that distance. The variogram is a simple *XY* graph with average distance between observations along the *X* axis and the average squared difference between measured values along the *Y* axis. The variogram has the desired property of relating the depth uncertainty of an interpolated point to its distance away from any of the observations. The relationship provides a statistical basis for predicting the uncertainty of an interpolated depth at any given distance from a measured sounding. Hydrostat relies heavily on variograms and computes them in the following way (see Figure A2 and A3):

1. A data sampling window onto the survey area is established.
2. 1D-variograms are computed in 8 directions of the sample (N, NW, W, SW, S, SE, E, NE).
3. The distance between all soundings in each direction are computed and groups of all possible sounding pairs are formed according to distance (e.g. all pairs from 0-10 meters apart, pairs from 10-20 meters apart, ... etc.)
4. Within each distance group, the average squared difference in depth among the member pairs is computed (the groups variability) as well as the average distance between the sounding pairs in the group.
5. The average squared depth differences are then plotted against the average distance between the soundings to form the variogram which characterizes the spatial variability of the data within the window.

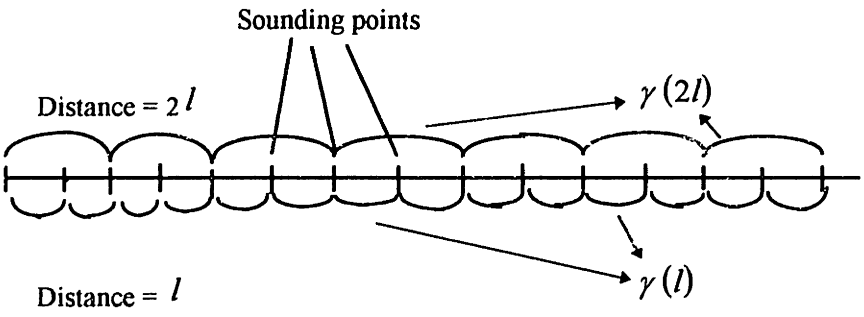
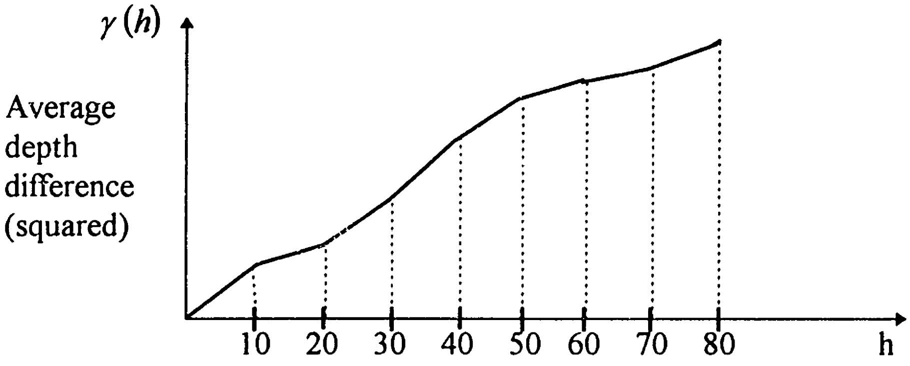


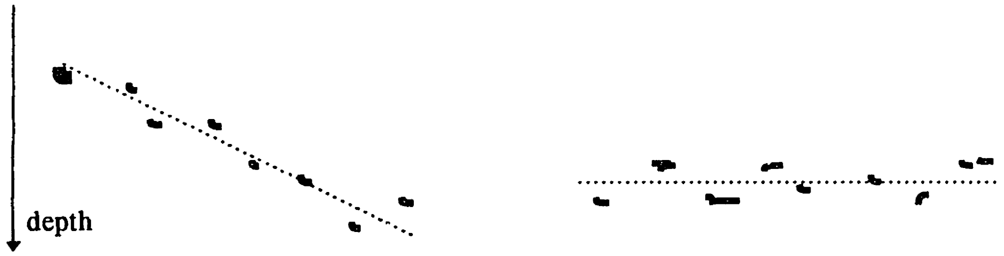
Figure A2 - Computation of a variogram using pairs of samples a given distance apart.



Variogram characteristic of windowed soundings

Figure A3 - Variogram from depth soundings, e.g. taken 10 meters apart.

The final variogram is dependent on the bottom topography in the following way: rough terrain results in a steep graph, while smooth terrain results in a flat graph. There is one constraint on the variogram worth noting in this relation. Because the variograms are based on the vertical distance between soundings, the variogram of a linear set of measurements with non-zero, non-infinite slope will display exaggerated variation. To prevent this, Hydrostat de-trends the raw hydrographic data by subtracting a linear regression line from the soundings before computing the variograms (see Figure A4).



Raw soundings

De-trended soundings

Figure A4. Raw and de-trended soundings

To model the resulting observed variogram, Hydrostat uses a power variogram model which is appropriate for variograms without sills:

$$\gamma(h) = \alpha \cdot h^{\beta} + C_0 \quad \left[m^2\right] \quad \mathit{for} \quad 0 < \beta < 2.$$

The variables α and β are determined by a least-squares fit. When $\beta = 1$ the variogram is linear. The rate of increase of differences is controlled by the slope α. The most usual case in hydrography is that the rate of increase of differences is decreasing with distance, that is $\beta < 1$. The model fitting is restricted to the part of the experimental variogram which is monotonously growing. The analytical variogram model is required for the actual interpolation process, the kriging process. It also permits compact storage of the large number of local variograms that are needed to define the varying geostatistics of a digital bathymetric data set.

One provision for obtaining a realistic variogram model is that there needs to be enough soundings in the sample window. This ensures that the variogram curve will be defined by enough depth comparisons to have statistical significance. If too few soundings are used in its computation, then the graph of the experimental variogram will be too noisy for reliable modeling. This points to a weakness in the Hydrostat process: it requires dense data samples in order to serve as a usable predictor of localized terrain variability. Fortunately, hydrographers generally collect data continuously along sounding profiles so this does not pose a major problem provided raw, un-decimated sounding data is input to Hydrostat.

Since the objective is to produce a map showing the interpolated depths and how interpolation errors vary over the ocean floor, variograms must be computed for many small zones so as to resolve these variations. Hydrostat thus impose a cell structure over the data and variogram models are computed for the data in each cell. The cell size is as small as possible while maintaining a statistically significant sample. The variogram is a function of direction. To describe the possible anisotropy, Hydrostat calculates variograms in eight different directions. The variogram model in each cell is then parametrized as a function of direction. The anisotropy can be interpreted by saying that a given distance in one direction is equivalent to the same distance in another direction multiplied by an anisotropy factor *k*. For instance if the anisotropy factor is 3 then ten meters in one direction is equivalent to thirty meters in the other direction as far as depth variation is concerned.

Kriging

Kriging is a method of weighted interpolation that minimizes the variance of the estimation error by using a variogram to construct optimal weights. Like any other estimate, a kriged estimate is a weighted combination of the sample values around the point to be estimated. Other linear unbiased estimators exist, such as polygons, triangles, inverse distance methods, but kriging is the minimum variance estimator.

Kriging is the process of estimating the value of a spatially distributed variable from adjacent values while considering the interdependence expressed in the variogram. The kriging process involves the construction of a weighted moving average equation which is used to estimate the true value of a regionalized variable at specific locations. This equation is designed to minimize the effect of the relatively high variance of the sample values by including knowledge of the covariance between the estimated point and other sample points within the range. The emphasis is on the weights as data points further away from the point being estimated will exert a smaller influence on the estimated value than do closer points.

The depth d_0 at location l_0 can be interpolated from the observed soundings d_i at location l_i, for $1 \leq i \leq n$ as follows [64]:

$$d_0 = \sum_{i=1}^{n} u_i d_i = u_1 d_1 + u_2 d_2 + \dots\dots\dots + u_n d_n$$

For a given interpolation point l_0, kriging assigns a weight u_i to each observed depth sounding d_i in proportion to the expected depth variation for the positional distance between the interpolated point l_0 and the actual sounding l_i. The aim of the process is to minimize the estimation variance. This is achieved through the correct choice of the weighting coefficients. These weighting coefficients must sum up to unity to make the interpolation unbiased (the value which is computed should on average be equal to the real value). The problem is thus to find those weights u_i which minimize the estimation variance, or the variance of the interpolation error at l_0 under the condition that $\sum u_i = 1$. The estimation variance is expressed as

$$\sigma_e^2 = Var\left(d_0\right) - 2\sum_{i=1}^{n} u_i\, Cov\left(d_0, d_i\right) + \sum_{i=1}^{n}\sum_{j=1}^{n} u_i u_j\, Cov\left(d_i, d_j\right)$$

The variance and covariances on the right hand side of the equation can easily be computed from the variogram model. The solution to the minimization problem is found by using the Lagrange multiplier technique to minimize the variance under the constraint that the error has a zero average. One thus find the weights u_i and the estimation variance (and the stochastic surface). This technique is called Ordinary Kriging (OK). The mathematics of Ordinary Kriging are complex and outside the intent of this thesis appendix. Therefore for further insight on the theory of kriging we recommend David [63, 66].

Kriging in Hydrostat

Kriging is generally used in hydrography as a method for automated contouring since it interpolates an arbitrarily dense grid of depth values. Contour lines can then be drawn between grid points of equal value to produce the contour-map. The kriging algorithm in Hydrostat is essentially a least-squares depth interpolator which uses the variogram as a weighting function. Hence, the variograms are the fundamental device used for predicting interpolation errors. The variogram is a useful geostatistical indicator of bottom roughness which is computed from a population of surveyed depths. Variograms are, as mentioned above, computed within small local regions throughout the data set. This creates a "map" of changing bottom roughness which then is used to interpolation of the overall bathymetric model. At each desired grid location, kriging uses the local variogram model (a directional function of the 8 1D-variograms) to assign an appropriate weight to each sounding in the neighborhood of the grid point as it is used to interpolate that depth. (A variogram model is assigned to each cell of the grid.) The farther away a sounding is from the grid node, the less its statistical weight will be in the least-squares interpolation. Conversely, if the grid node being interpolated is exactly coincident with a measured depth then that sounding's weight will be 100% and the grid node takes on its exact value. (Kriging "honors" the data.) The stochastic nature of kriging permits the Hydrostat algorithm to interpolate a grid of depths from the survey data and also to estimate a standard deviation for each of those depth estimates.

> "Kriging forms a linear combination of depth values from nearby survey lines to interpolate the depth estimates for each grid point. The weights used in the linear combination are derived directly from the variogram. This property permits unique error estimates to be made for each of the interpolated depth values. Hydrostat also introduces, if wanted, the previously estimated instrumental error into the kriging equations and propagates them into the total error estimate for each interpolated point." [43]

In fact, kriging with vertically uncertain data is equivalent to having a large nugget effect when modeling variograms, while in kriging with uncertain position the locations of the depth soundings are represented by probability functions. Thus, the kriging algorithm in Hydrostat computes both the bathymetric and stochastic surfaces for any set of depth observations.

Calibration of the variogram models

> "Hydrostat assures the statistical validity of the computed stochastic surface using an automatic process to "calibrate" the predicted interpolation errors. The procedure involves extracting a subset of the surveyed soundings to act as

> calibration points, then using the remaining soundings to interpolate depths at their exact locations. The differences between the surveyed and interpolated depths (the real interpolation errors) are then compared to the predicted interpolation errors for those points." [50]

In a statistically significant sample, the standard deviation of the measured (real) errors shall be equal to the average of the predicted errors. Biases are the result of faulty assumptions in the algorithm regarding:

1. the anisotropy of the terrain,
2. the trend model used to compute the experimental variograms, and
3. the analytical models used to characterize the experimental variograms.

Whatever the origin, the composite of these biases has to be dealt with if the stochastic surface is to have statistical validity. Hydrostat does this in the following way:

> "A bias ratio (C) is computed by random selecting 25% of the data points, then kriging depth estimates for each of these measurement locations using the remaining data. The observed depth misclosures and predicted errors are accumulated and used to compute:
>
> $$C = \frac{\textit{Standard deviation of observed misclosures}}{\textit{Average of predicted errors}}$$
>
> This ratio is an index of how statistically valid the error predictions are with respect to the observed interpolation errors. If the correction factor is significantly different than 1.0 it indicates a bias condition. Once computed, this ratio can be used to adjust the slope coefficient, α, in all the variogram models previously computed for the data set, $\gamma(h) = \alpha h^{\beta} + C_0$. By correcting the slope of all the variograms, the average predicted error will adjust accordingly. The cross-validate procedure thus calibrates the variograms, forcing the interpolation error estimates to conform statistically to the actual predictability observed in the data." [43]

(The calibration is performed before the final interpolation of grid-points are done.)

Appendix C: Cumulative Distributions Of Wind Speed And Visibility

The cumulative distribution plots of wind speed and visibility for the five study ports are provided in the following pages.

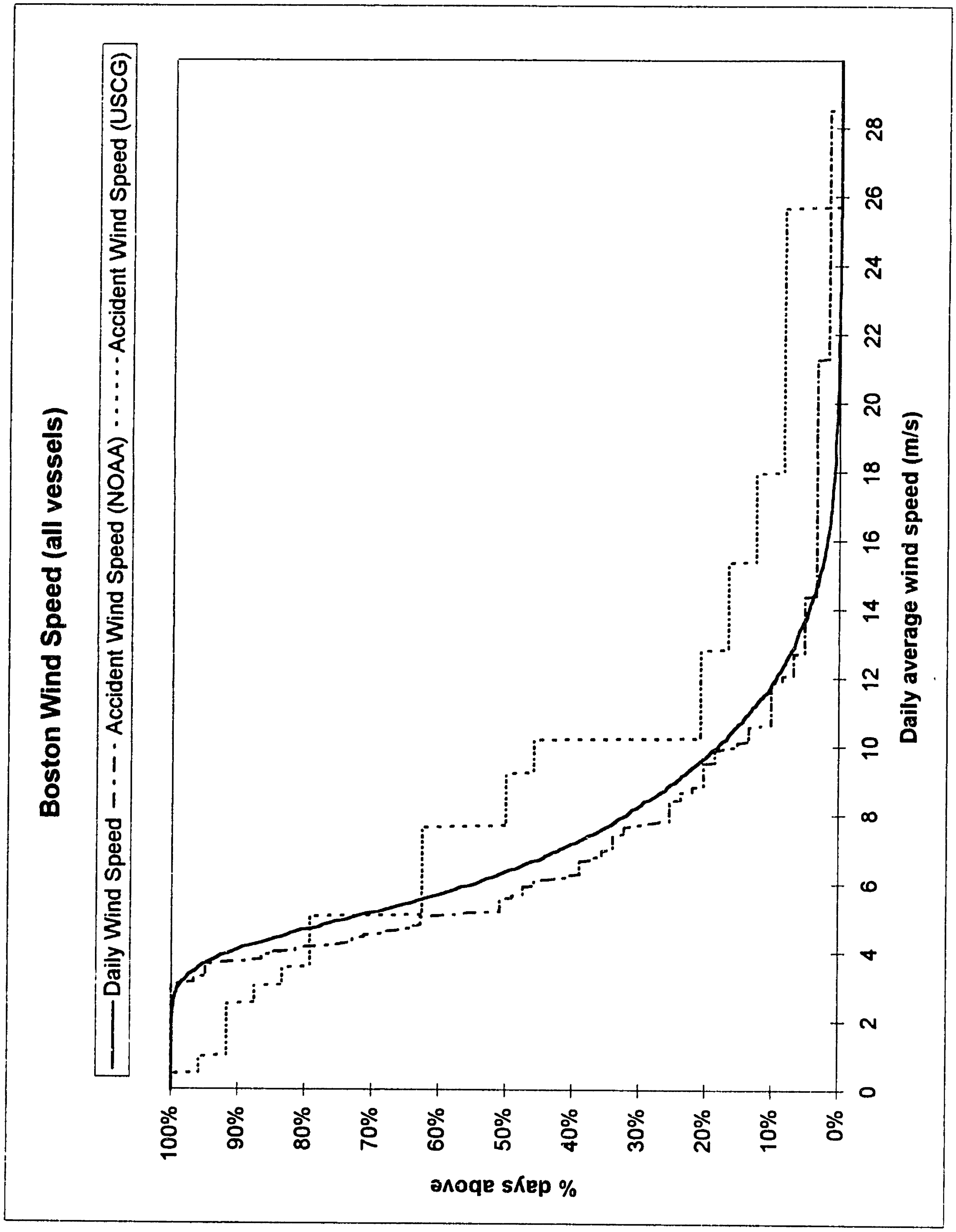


Figure A5 - Cumulative distribution of wind speed in Boston (all vessels).

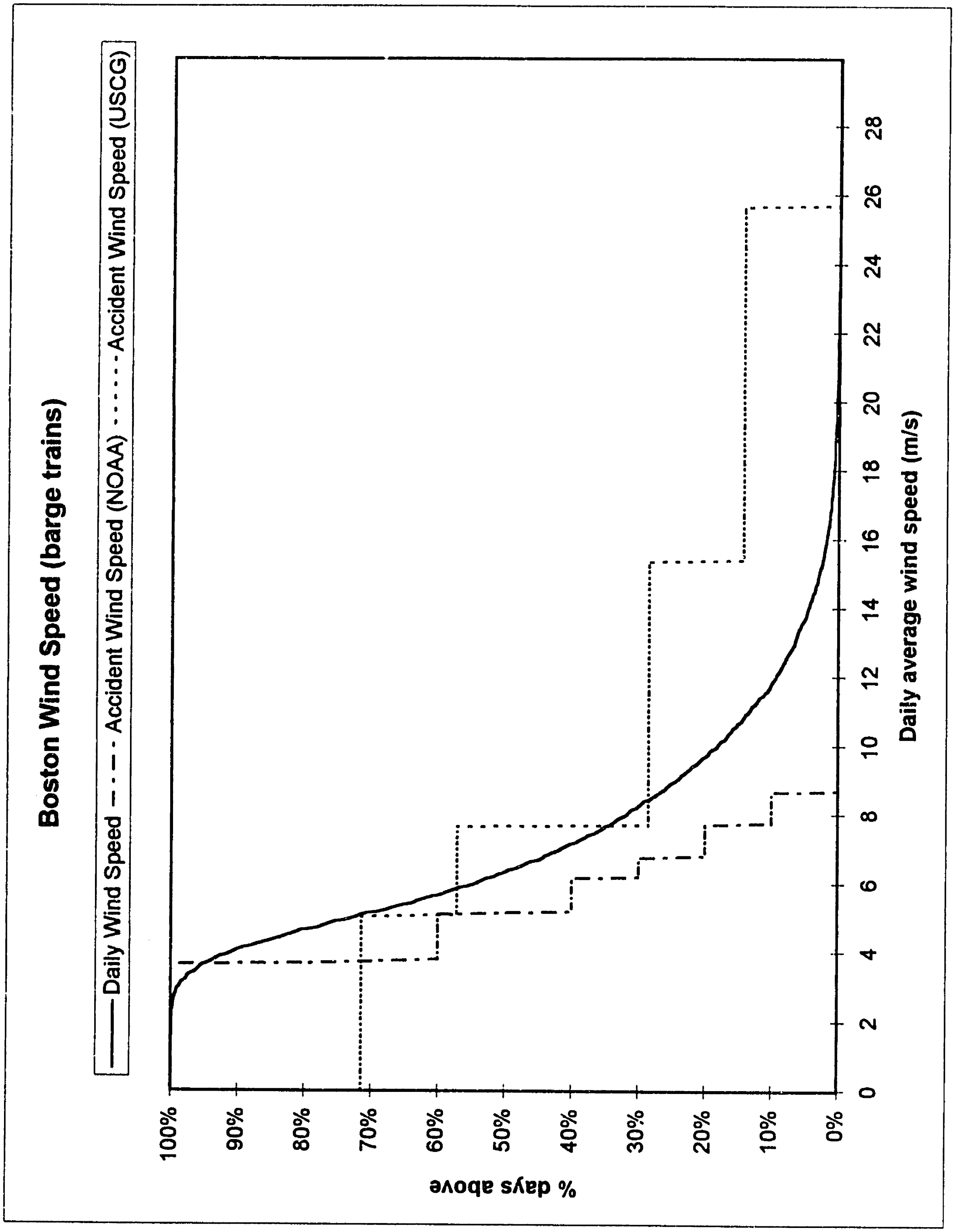


Figure A6- Cumulative distribution of wind speed in Boston (barge trains).

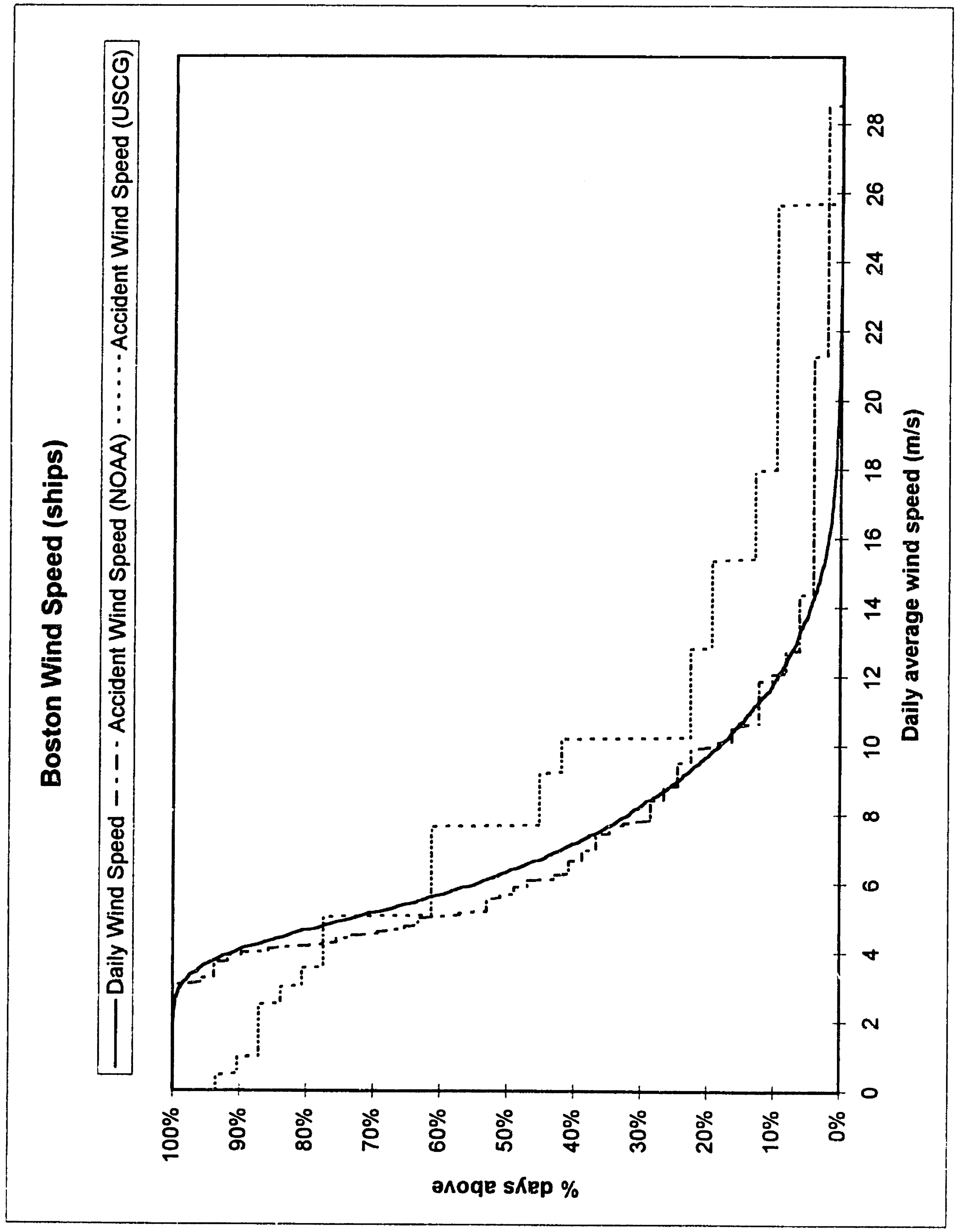


Figure A7- Cumulative distribution of wind speed in Boston (ships).

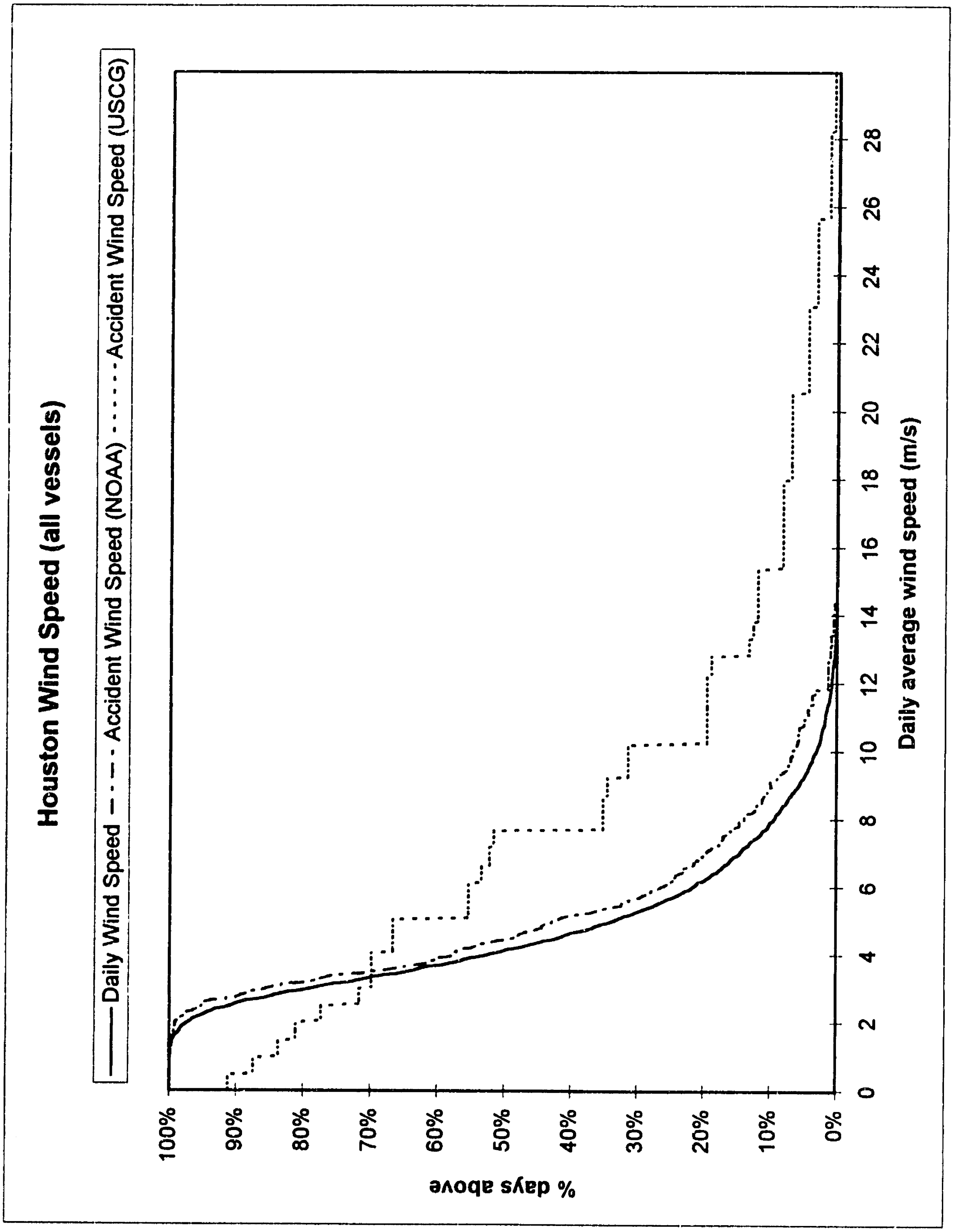


Figure A8 - Cumulative distribution of wind speed in Houston (all vessels).

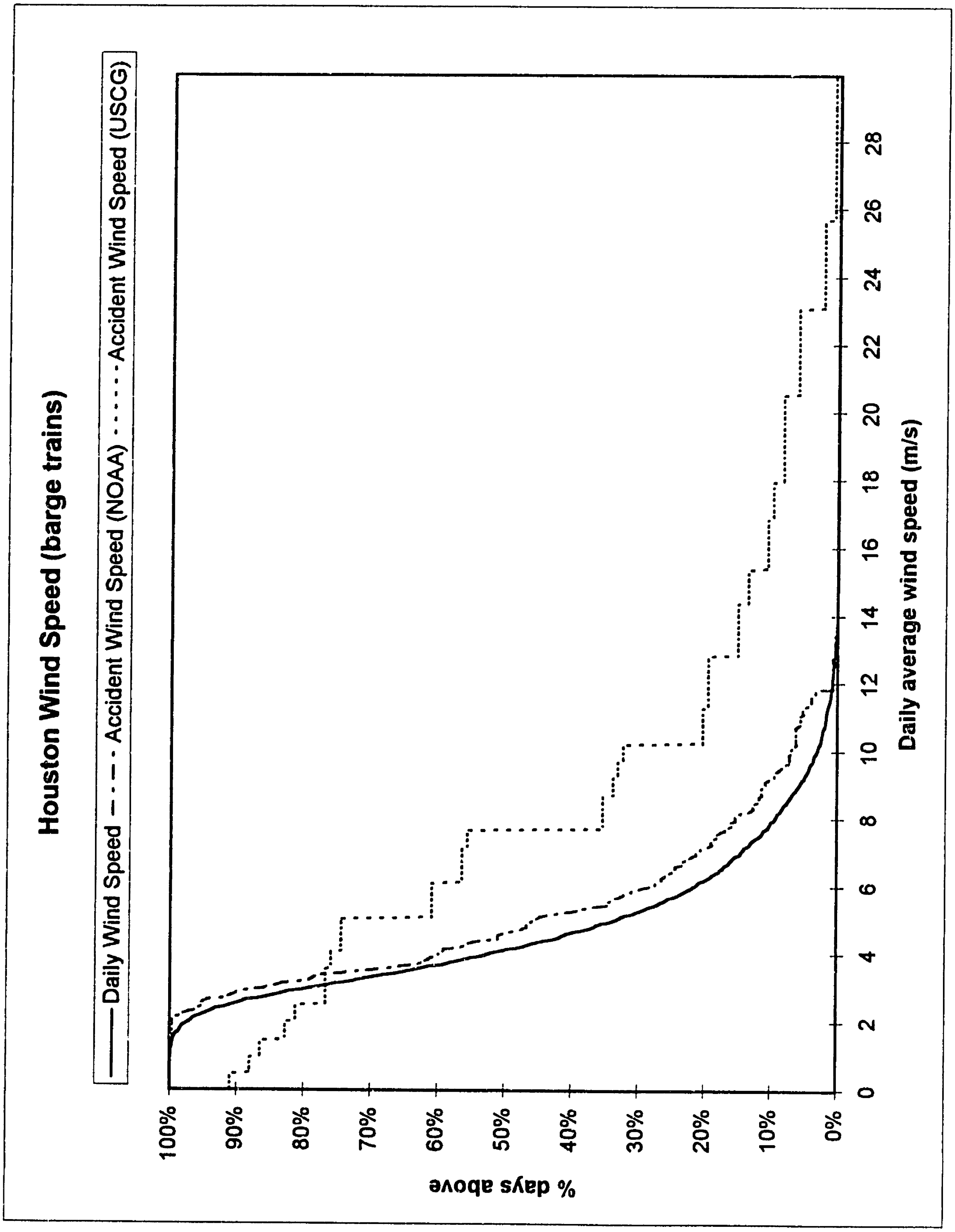


Figure A9 - Cumulative distribution of wind speed in Houston (barge trains).

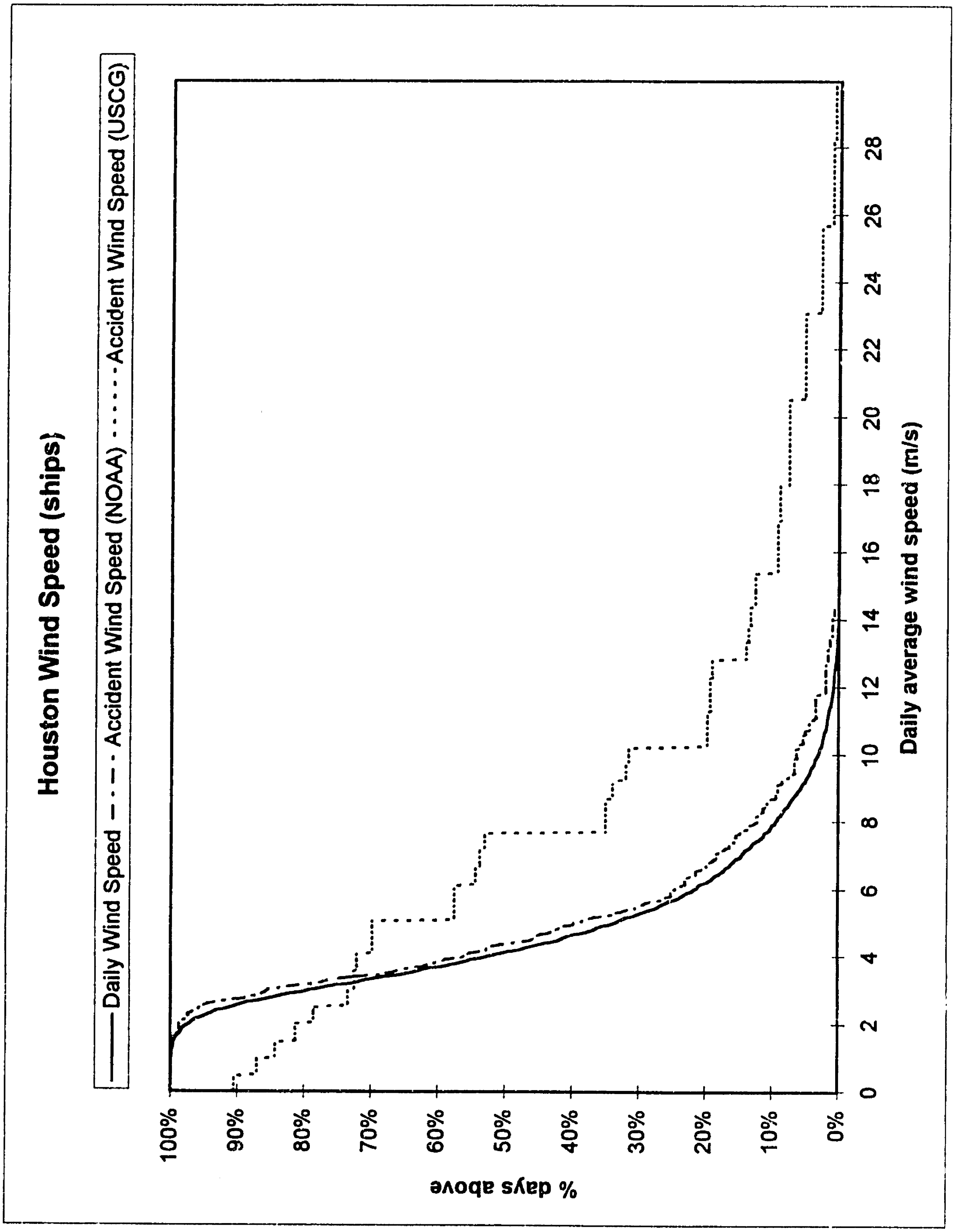


Figure A10 - Cumulative distribution of wind speed in Houston (ships).

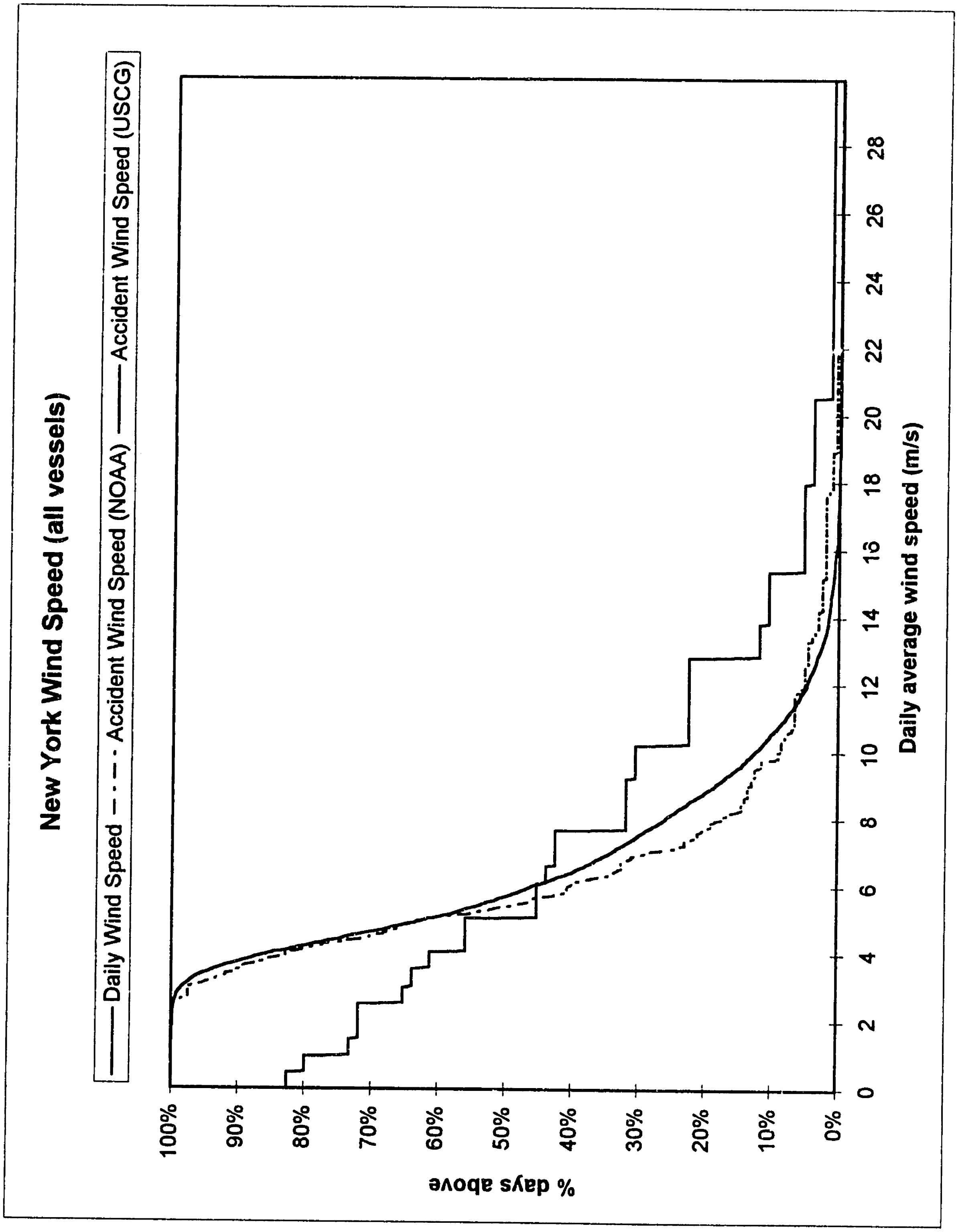


Figure A11 - Cumulative distribution of wind speed in New York (all vessels).

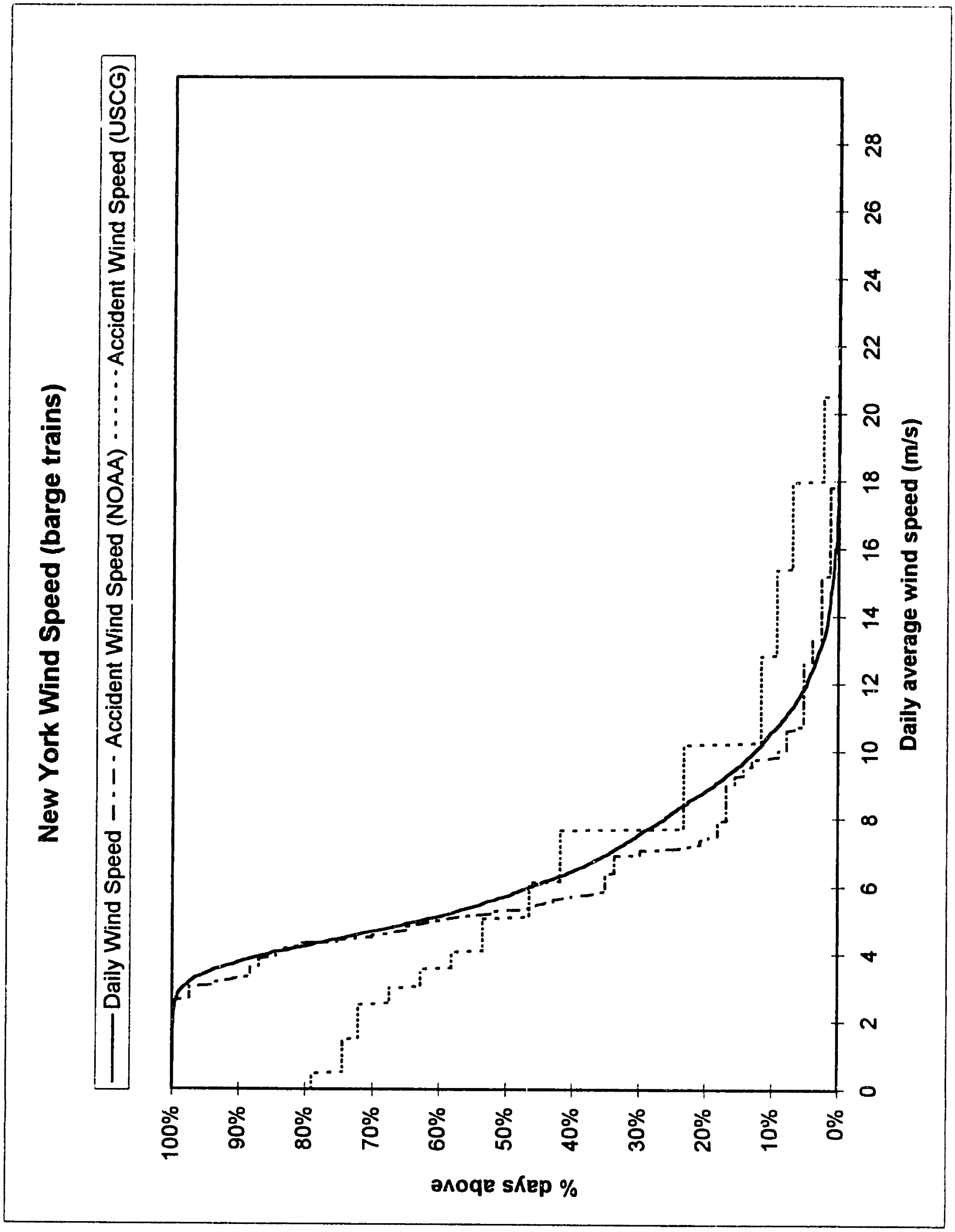


Figure A12 - Cumulative distribution of wind speed in New York (barge trains).

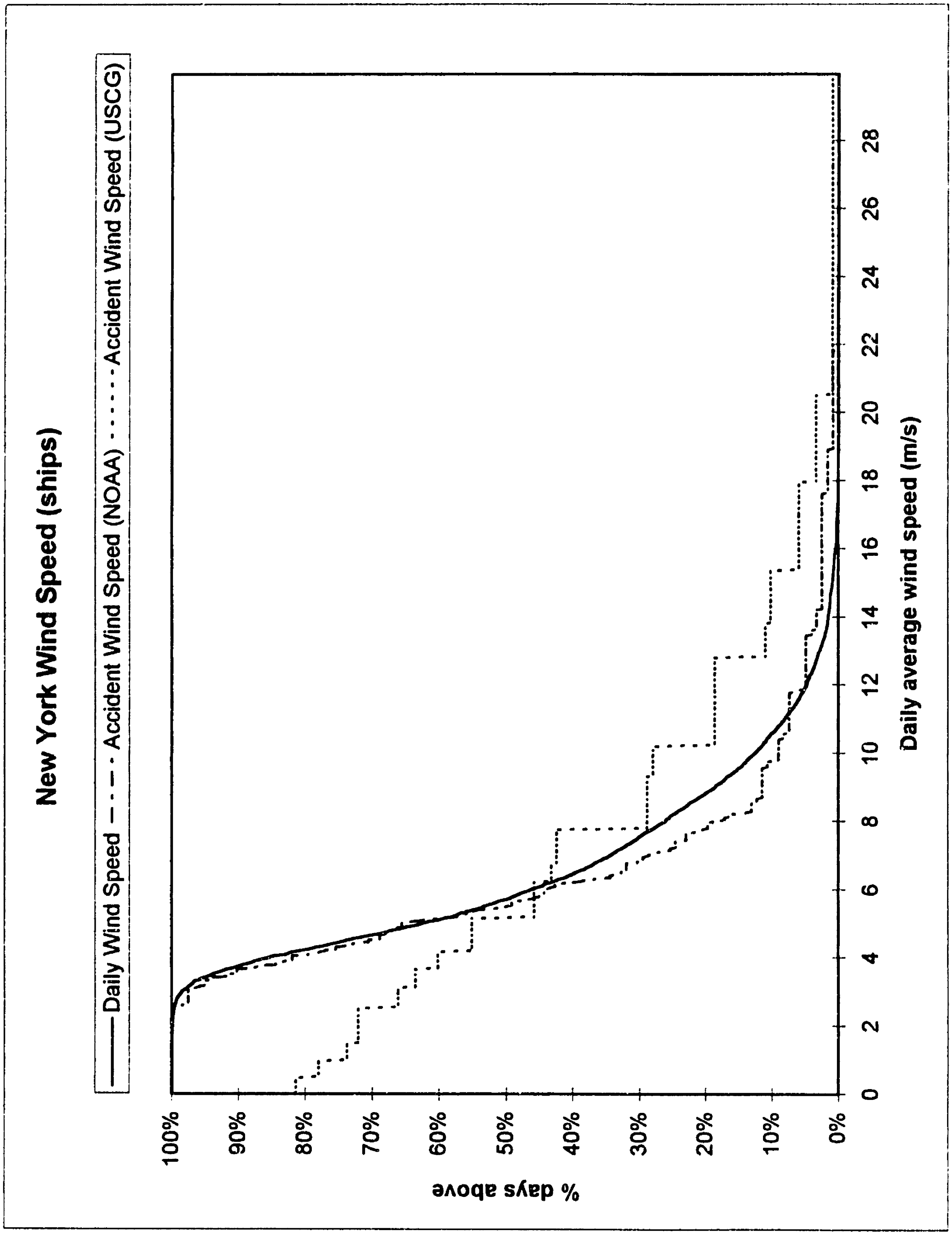


Figure A13 - Cumulative distribution of wind speed in New York (ships).

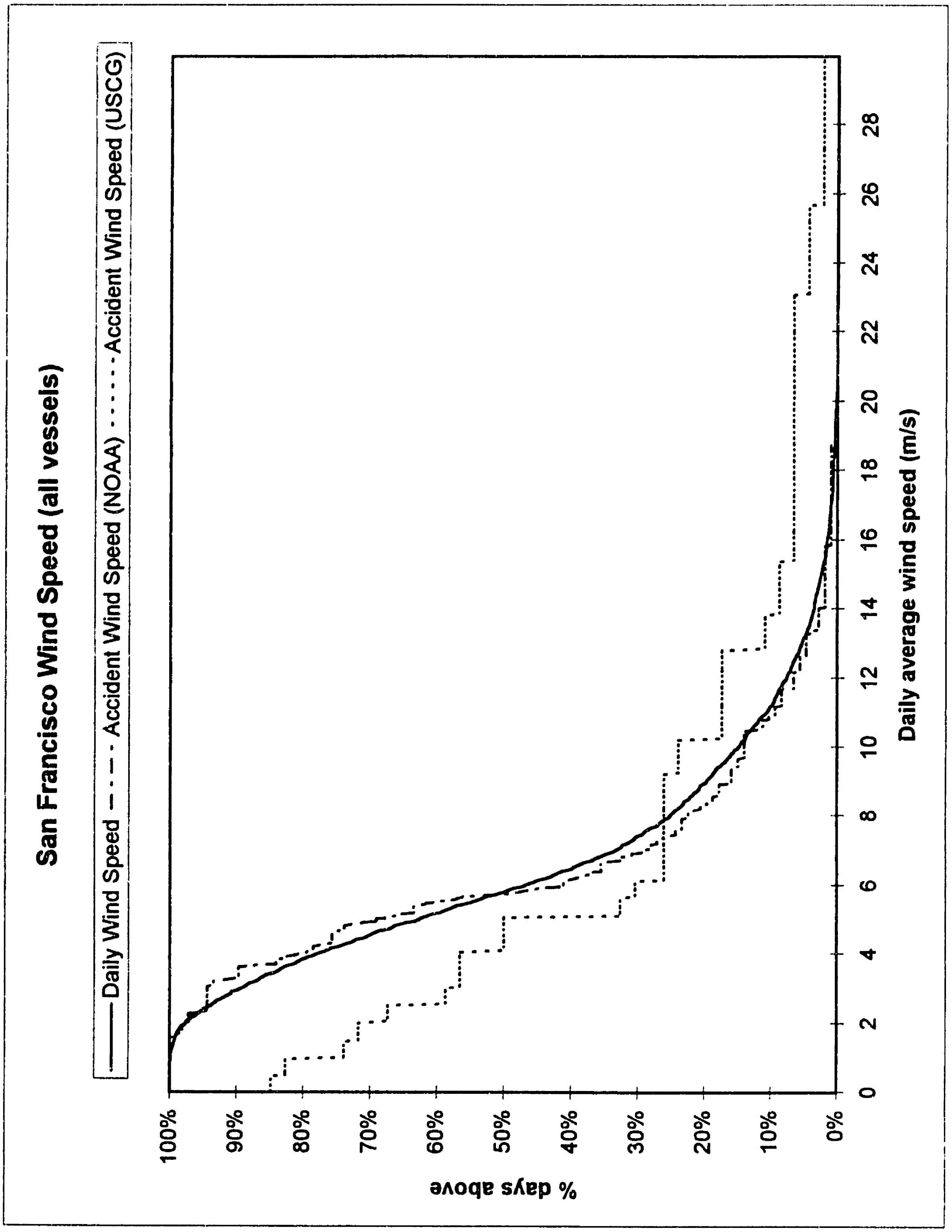


Figure A14 - Cumulative distribution of wind speed in San Francisco (all vessels).

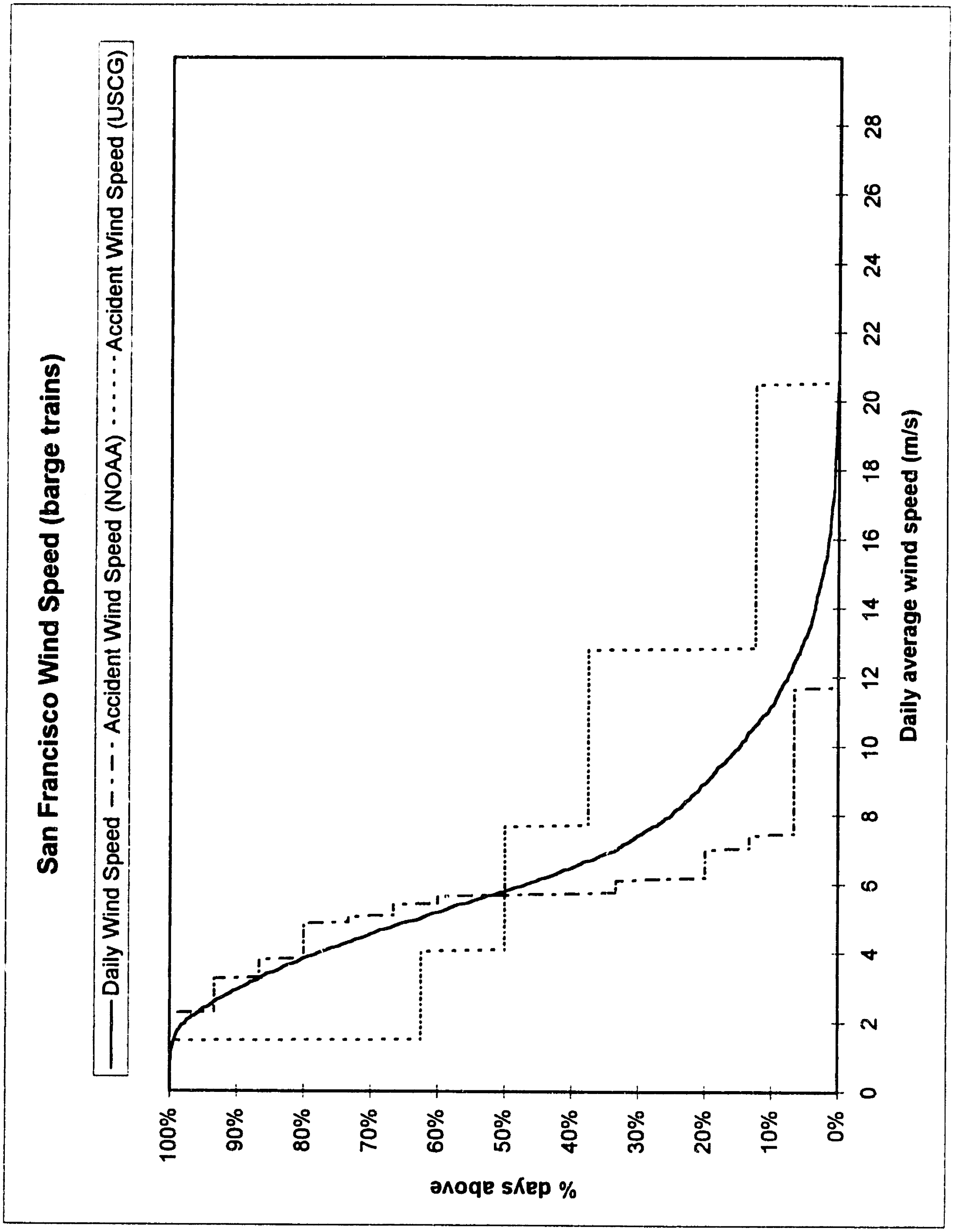


Figure A15 - Cumulative distribution of wind speed in San Francisco (barge trains).

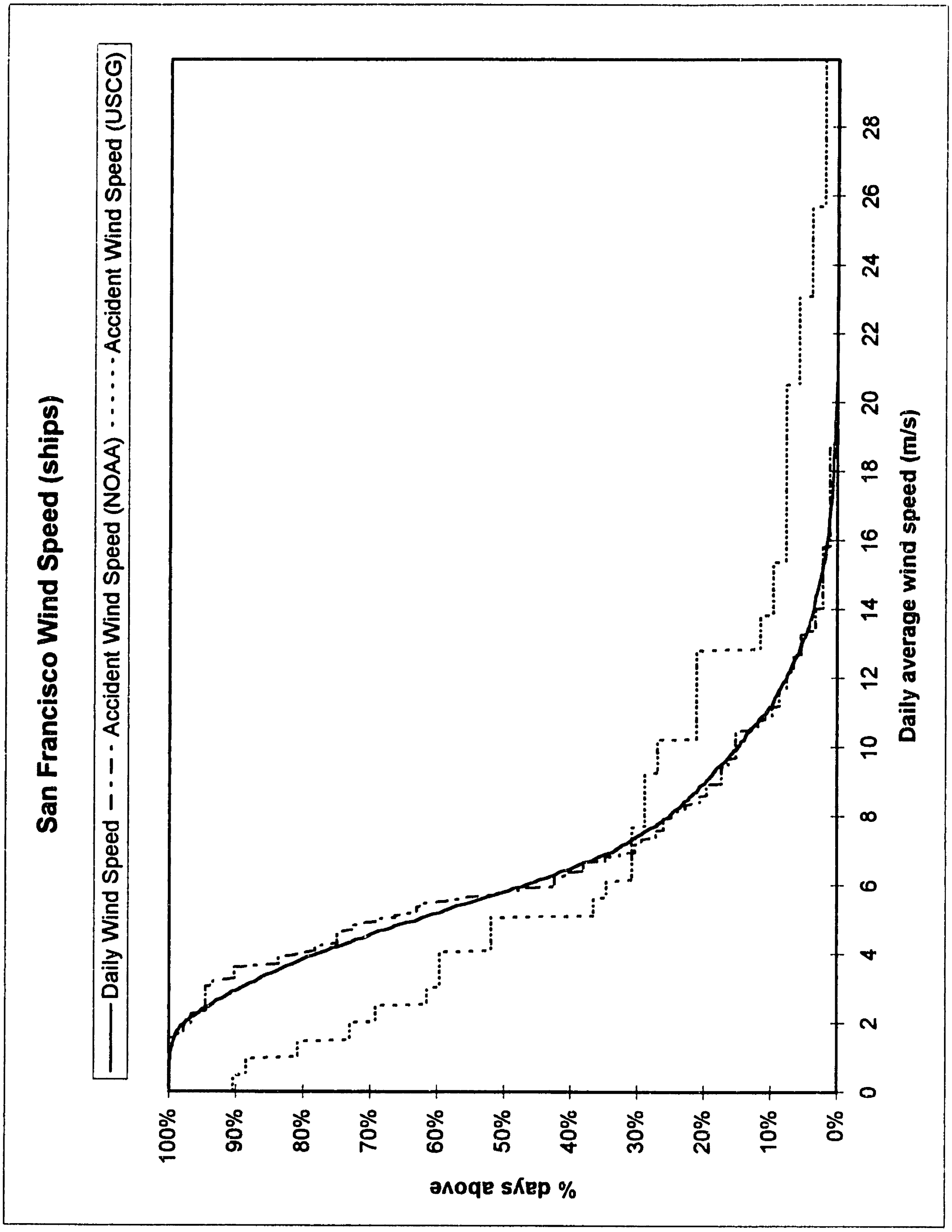


Figure A16 - Cumulative distribution of wind speed in San Francisco (ships).

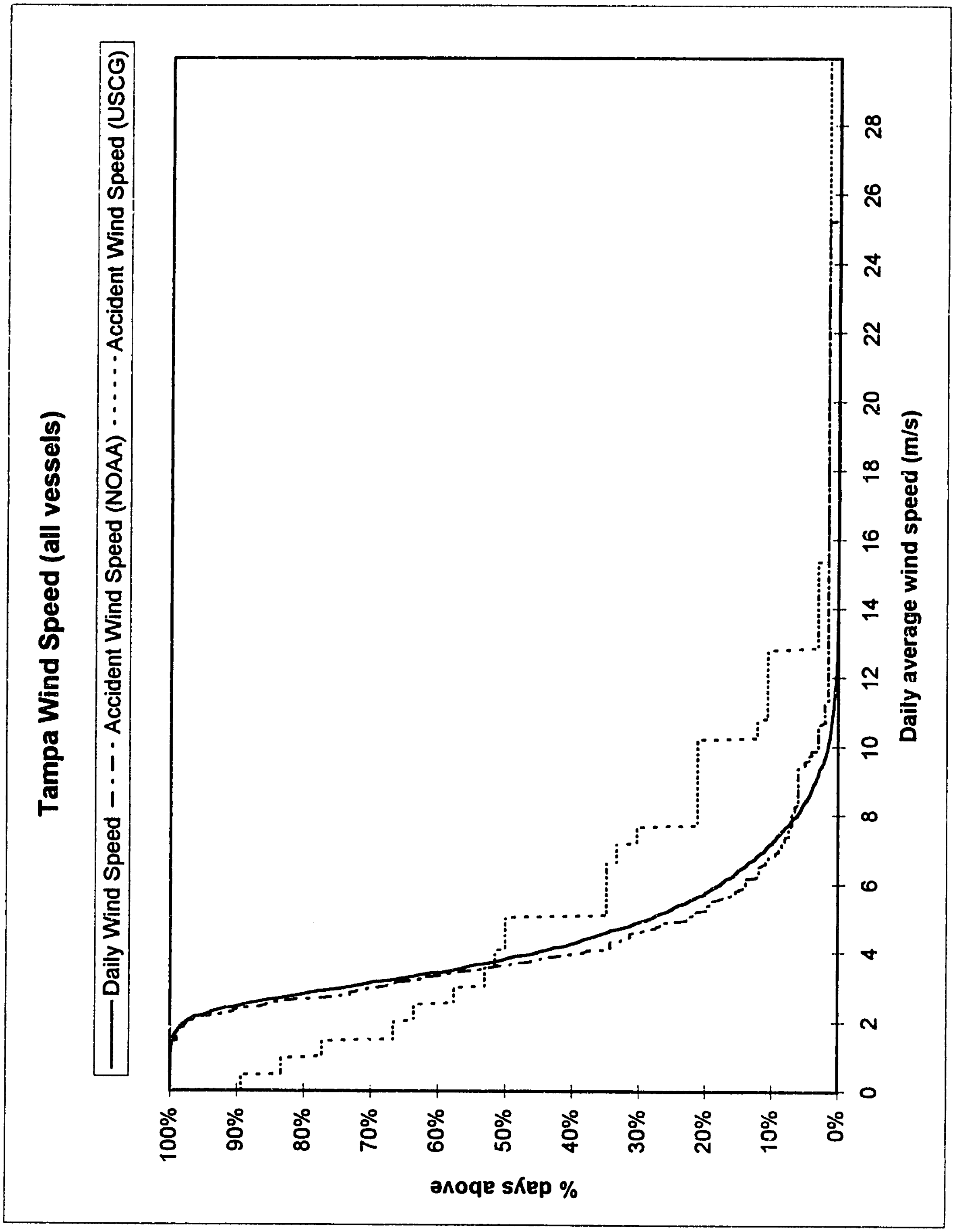


Figure A17 - Cumulative distributions of wind speed in Tampa (all vessels).

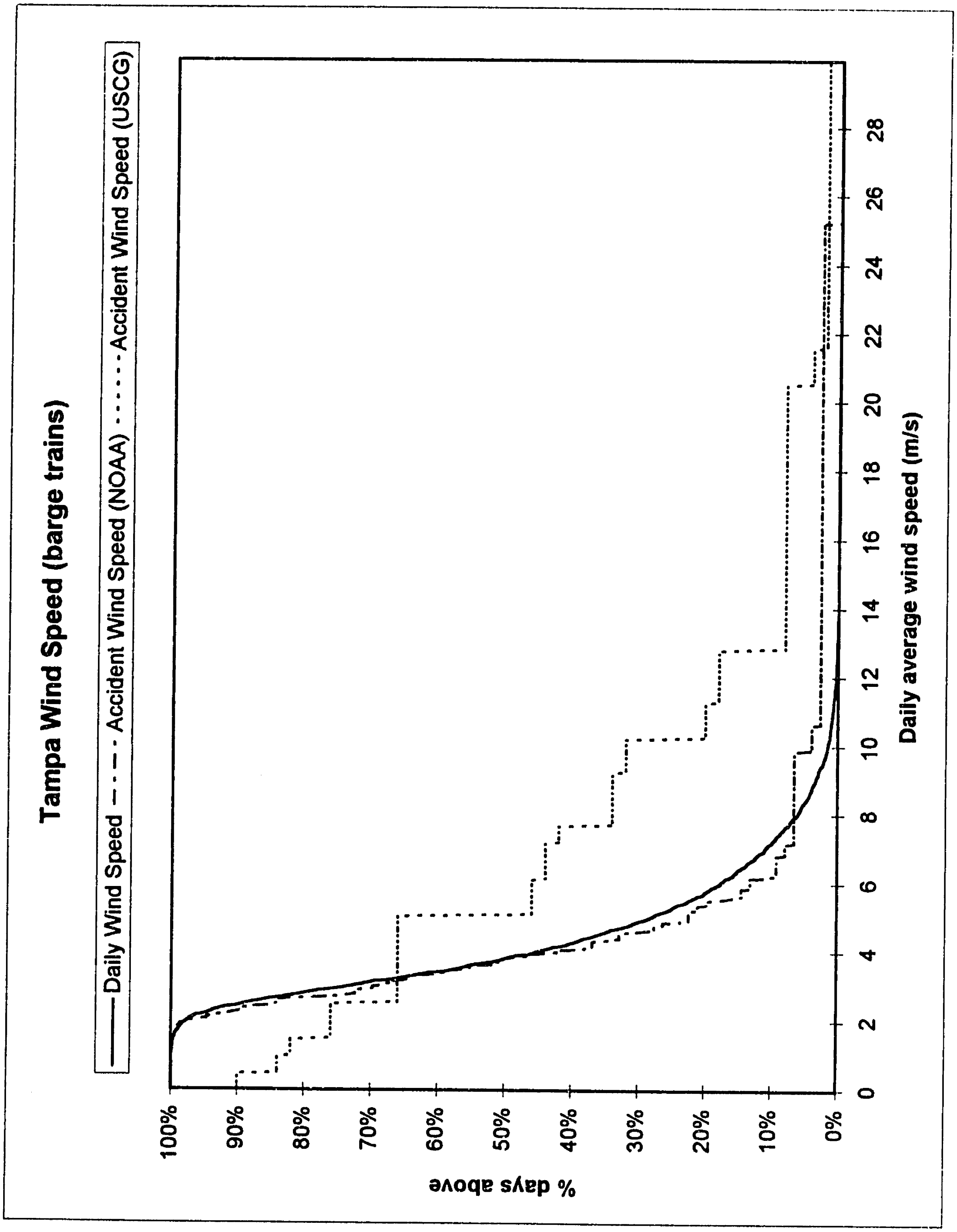


Figure A18 - Cumulative distributions of wind speed in Tampa (barge trains).

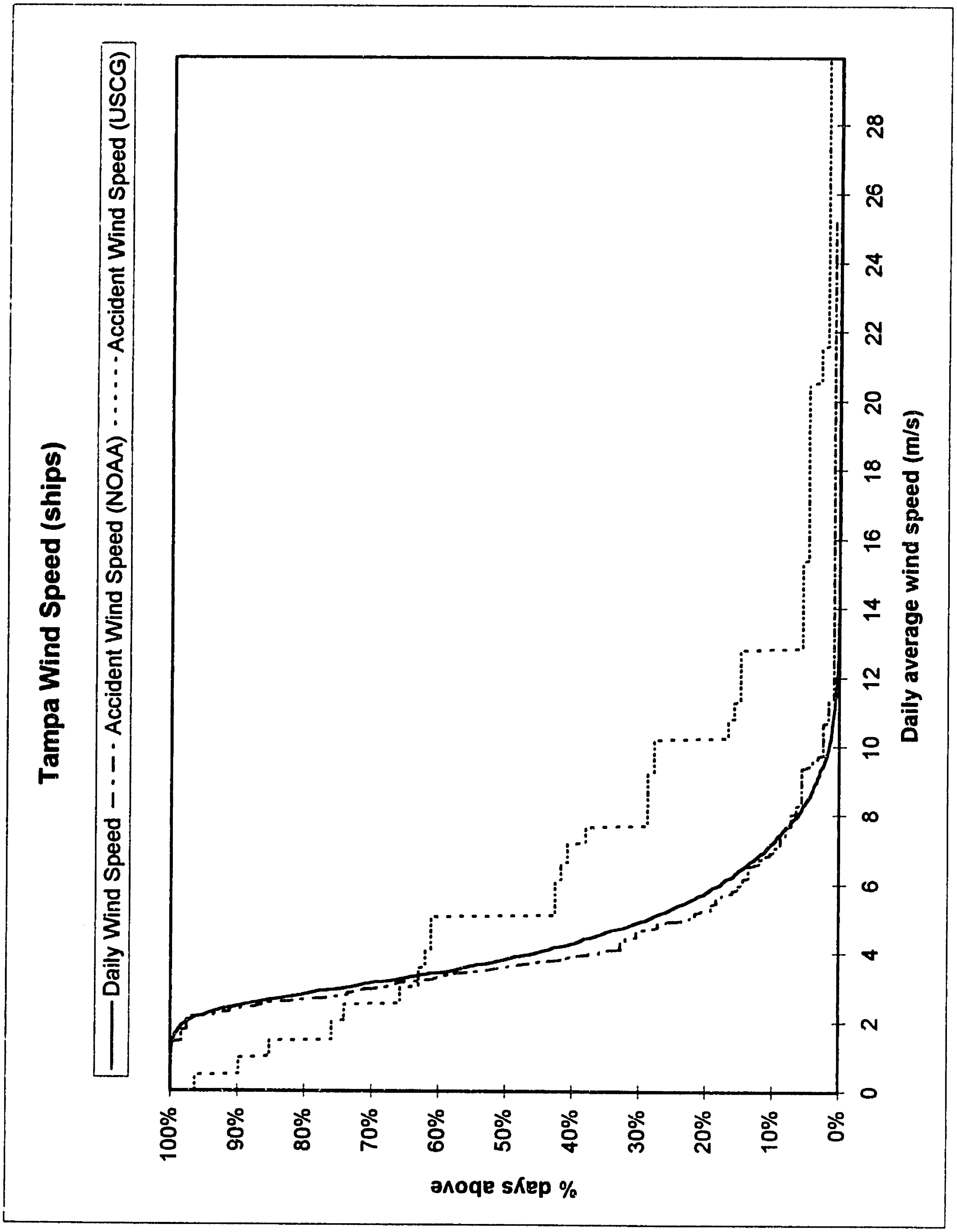


Figure A19 - Cumulative distributions of wind speed in Tampa (ships).

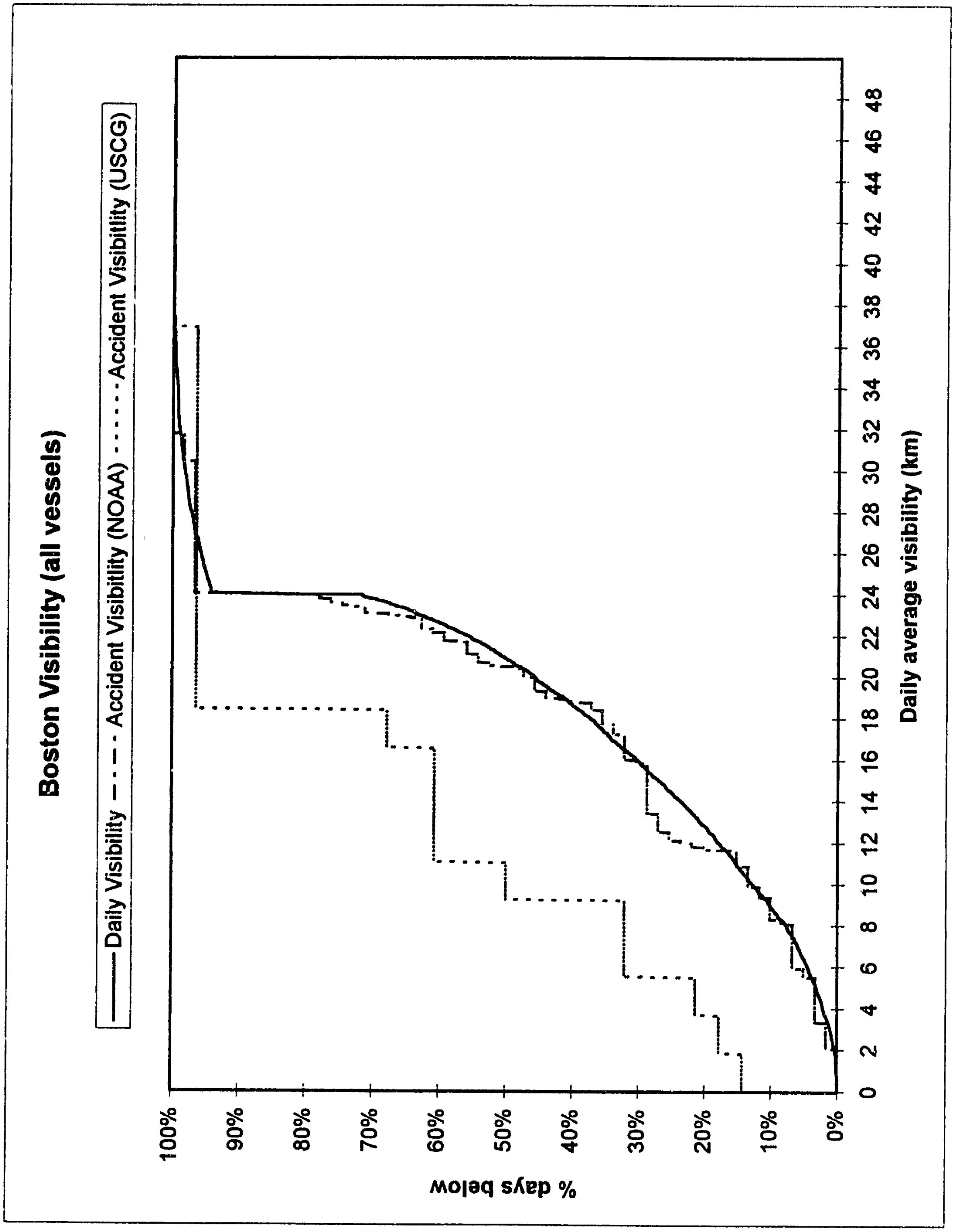


Figure A20- Cumulative distribution of visibility in Boston (all vessels).

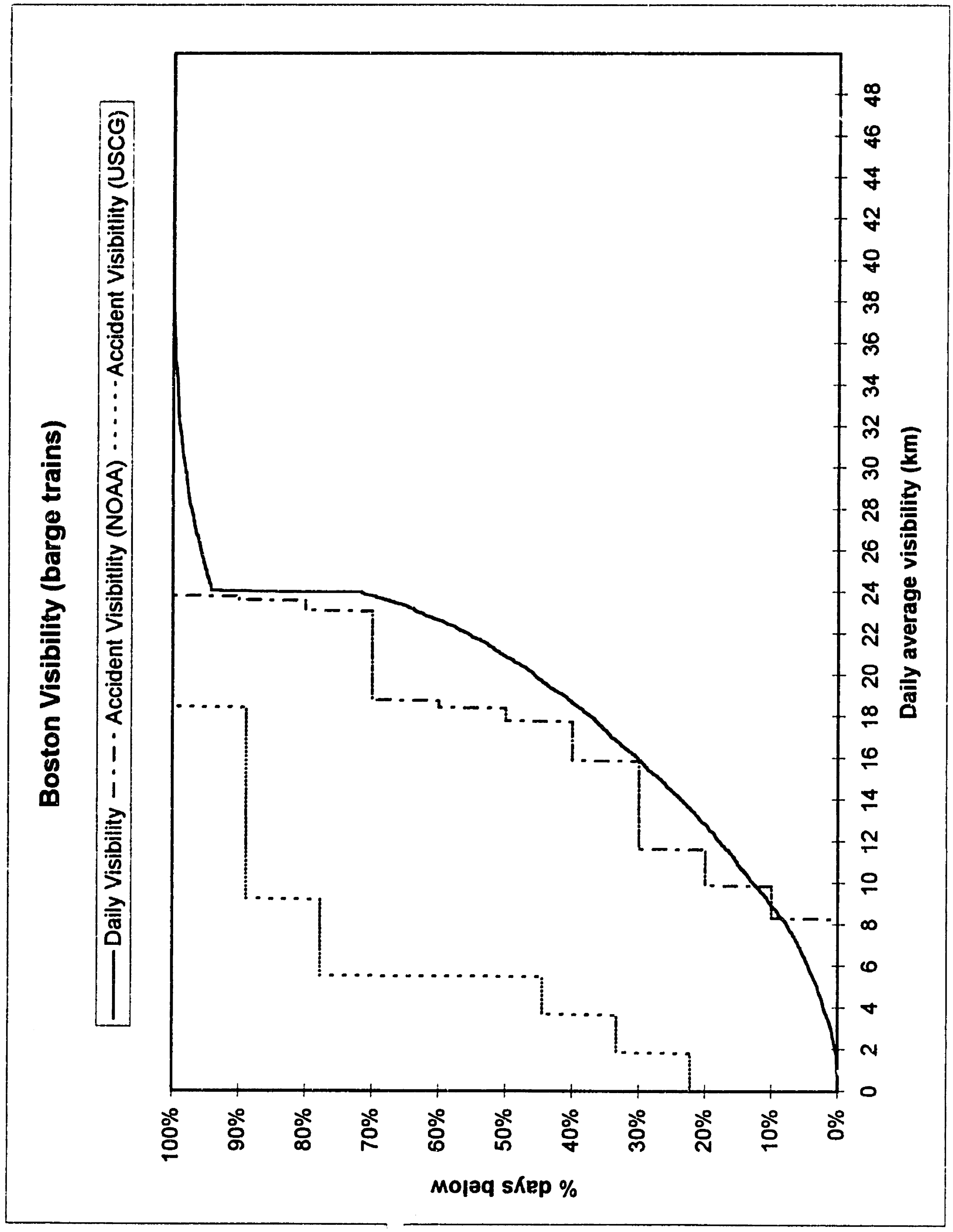


Figure A21- Cumulative distribution of visibility in Boston (barge trains).

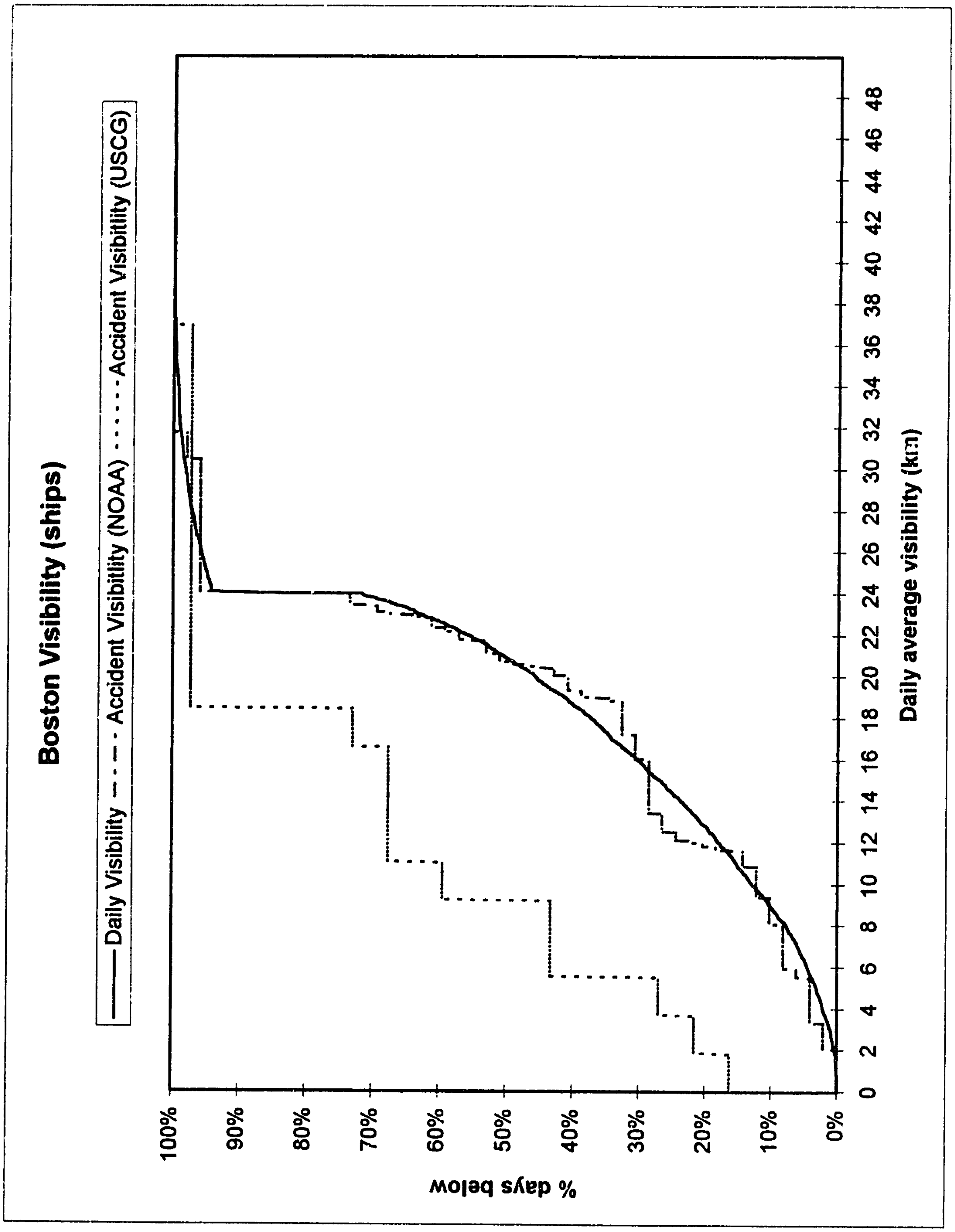


Figure A22 - Cumulative distribution of visibility in Boston (ships).

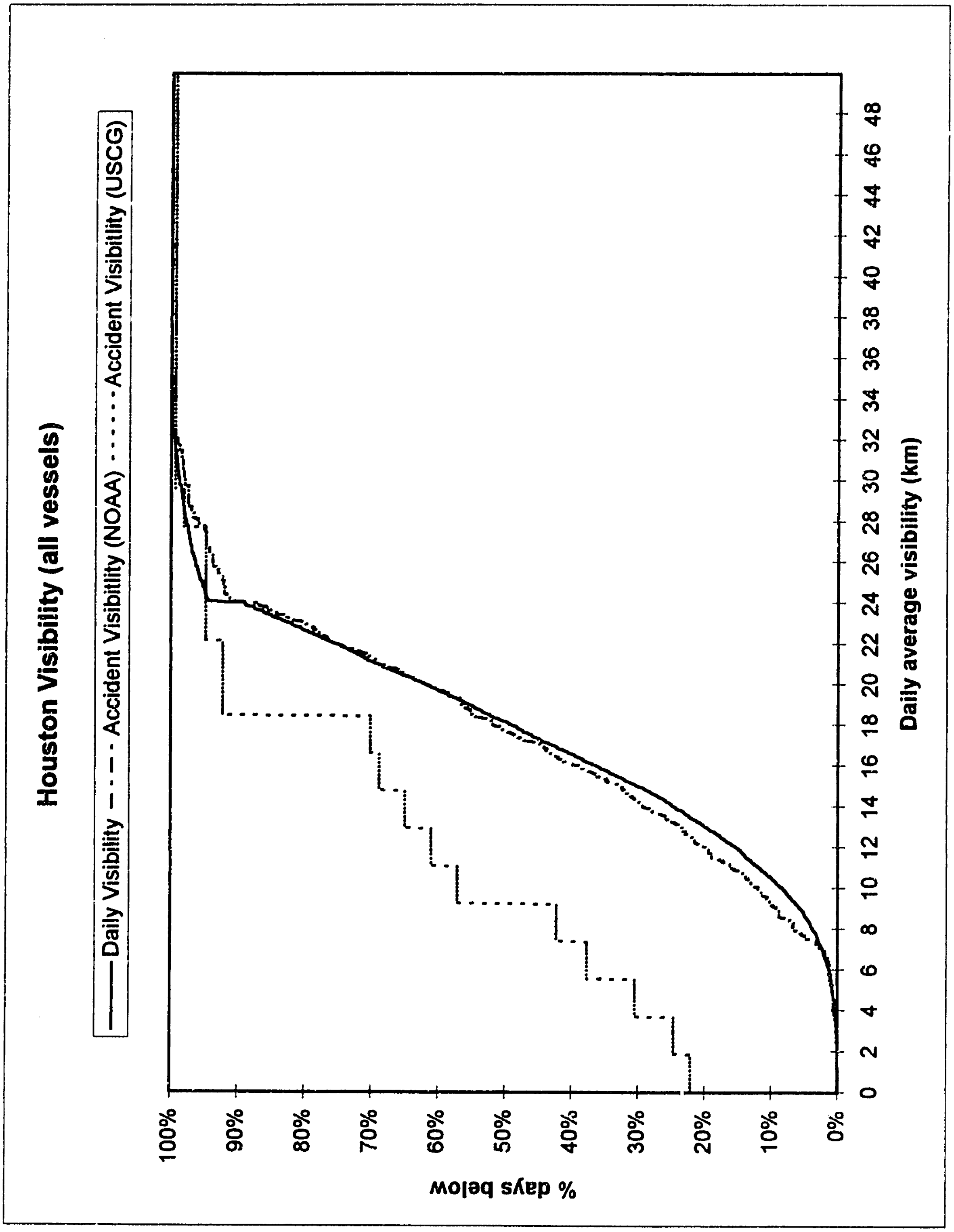


Figure A23 - Cumulative distribution of visibility in Houston (all vessels).

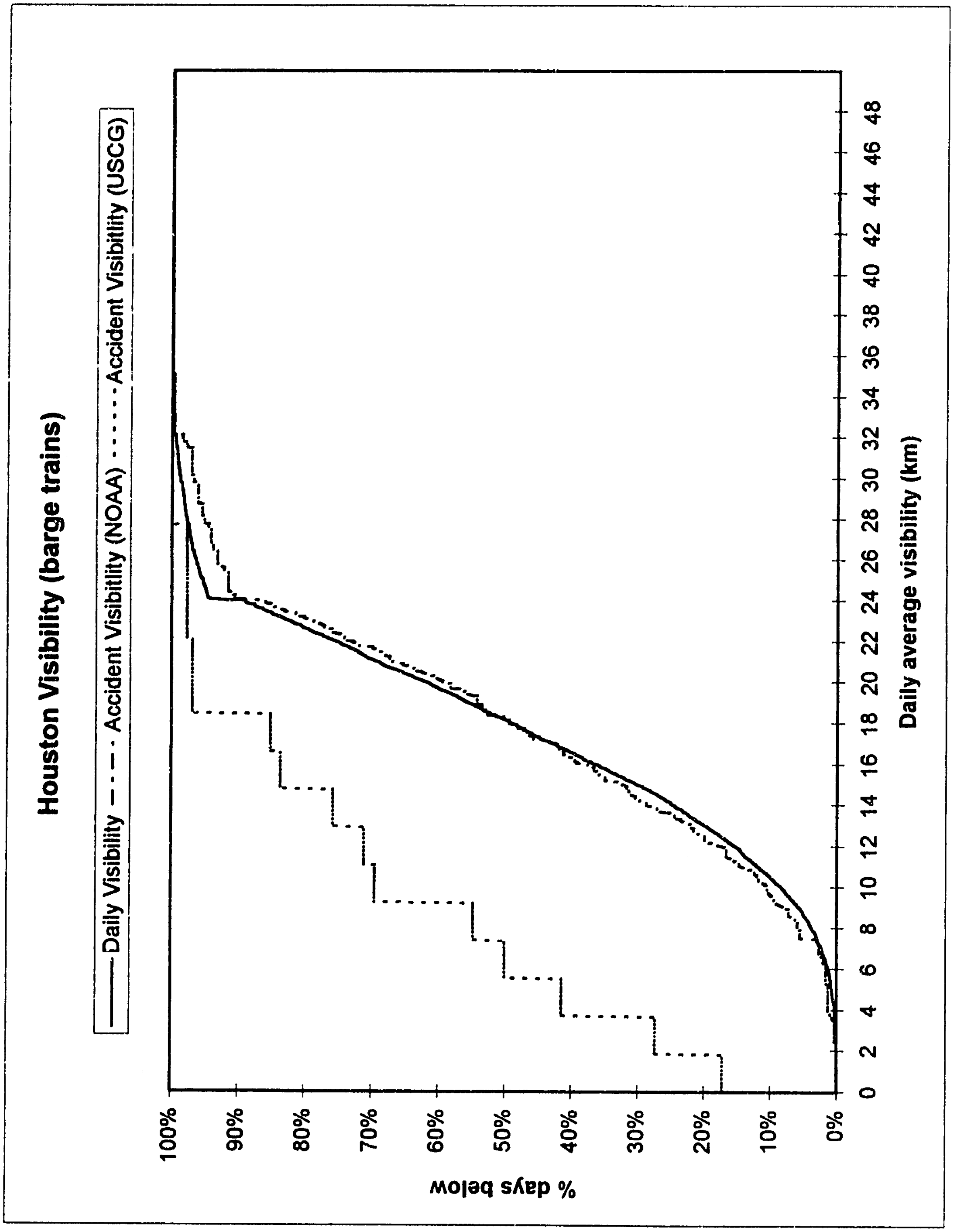


Figure A24 - Cumulative distribution of visibility in Houston (barge trains).

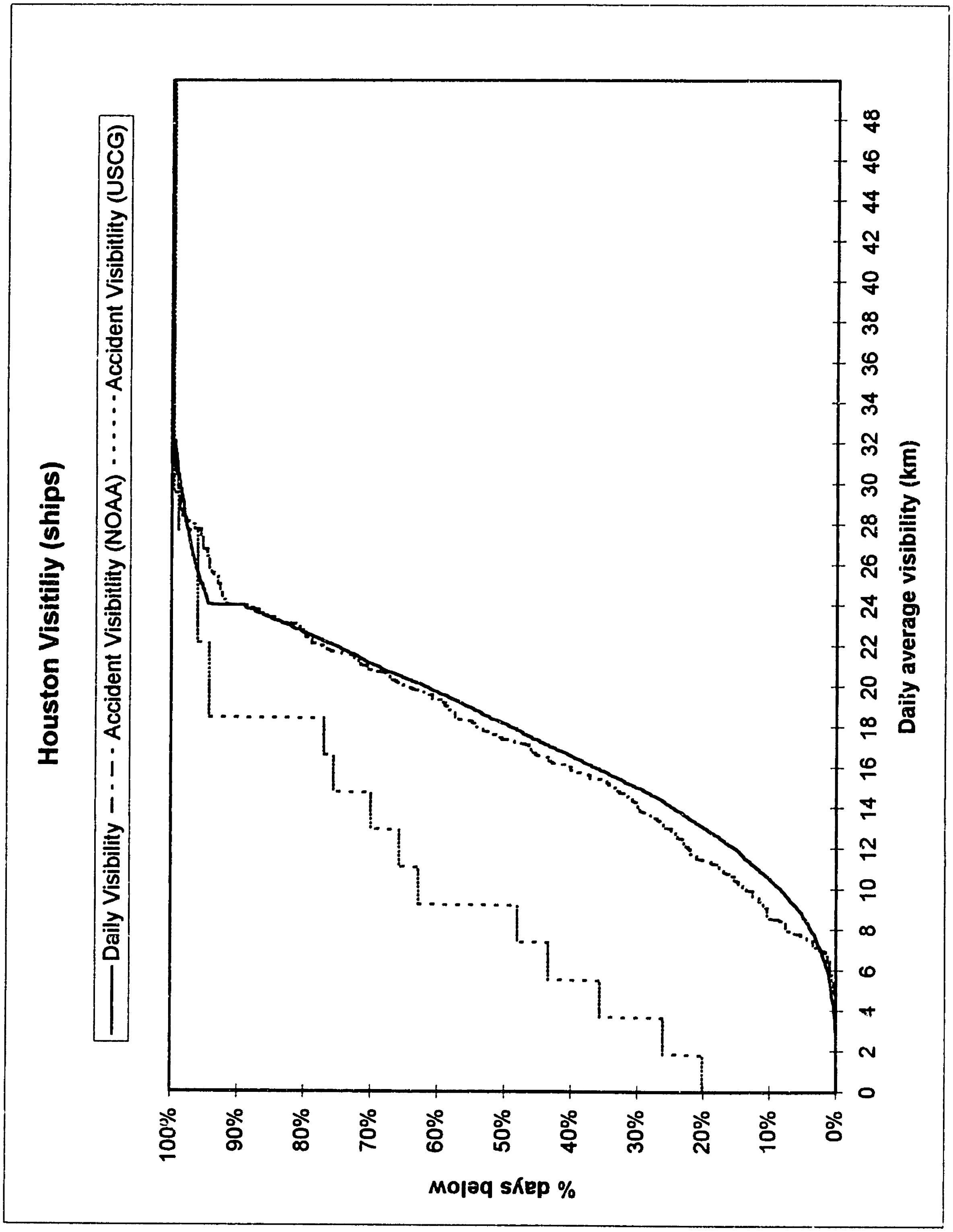


Figure A25 - Cumulative distribution of visibility in Houston (ships).

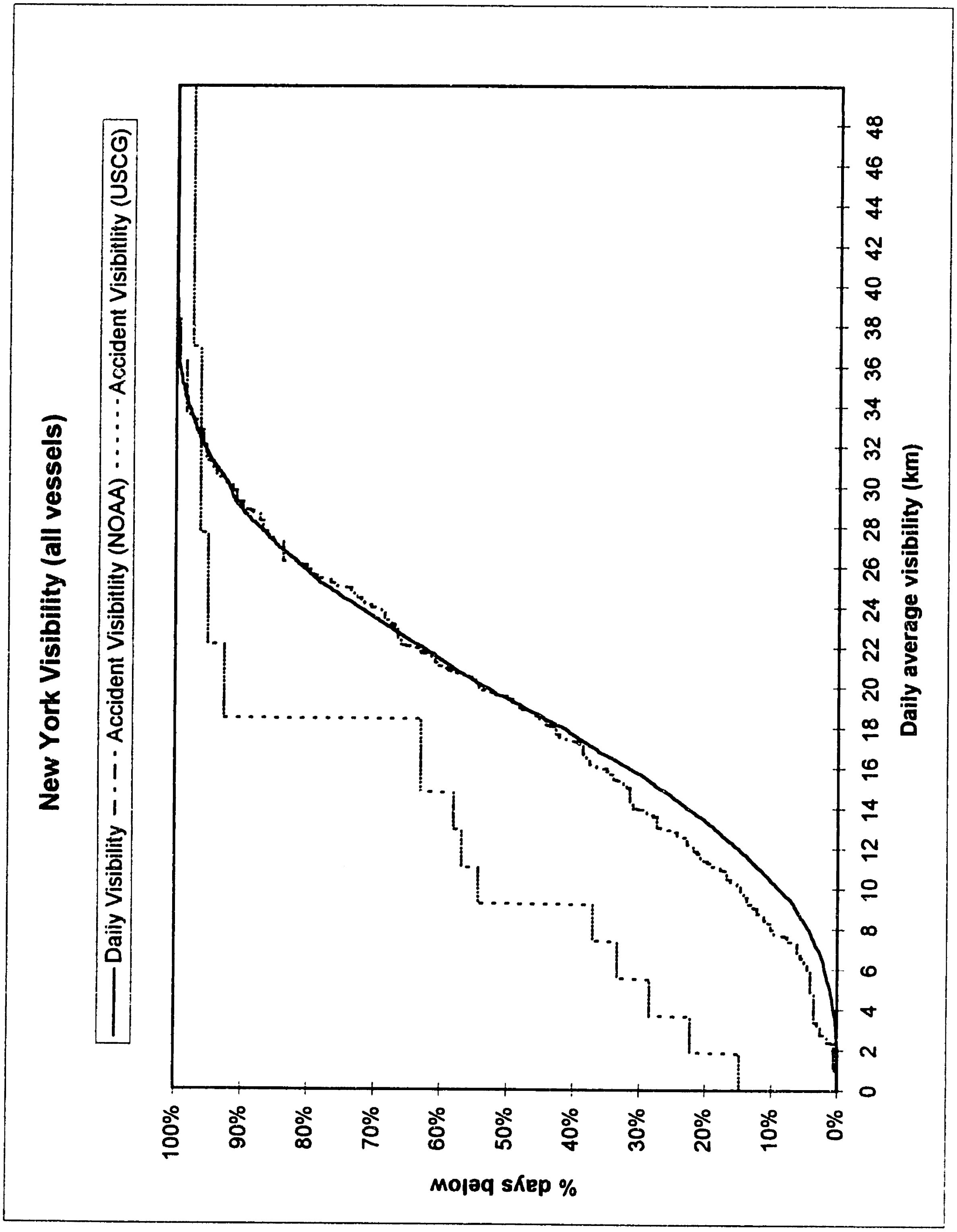


Figure A26 - Cumulative distribution of visibility in New York (all vessels).

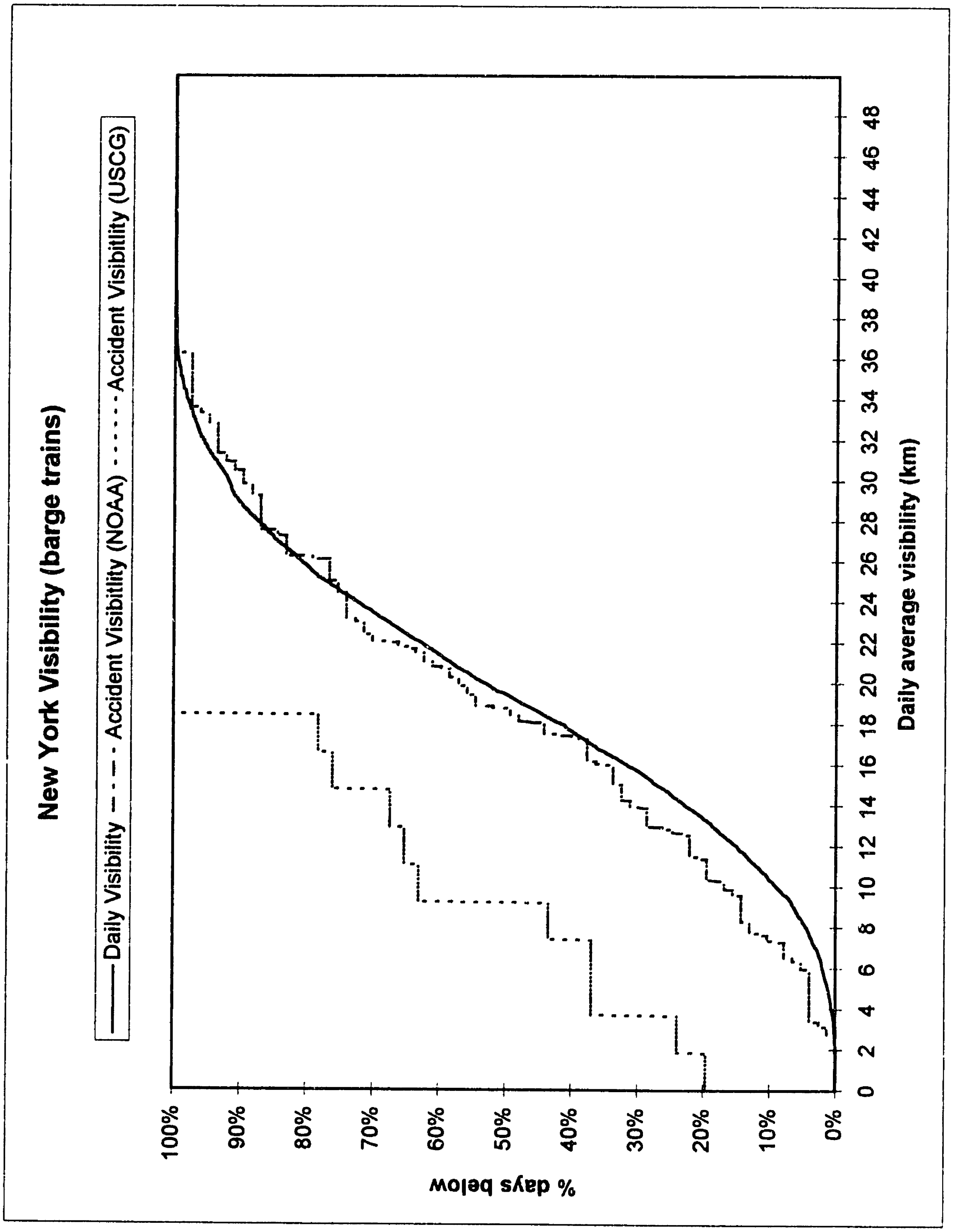


Figure A27 - Cumulative distribution of visibility in New York (barge trains).

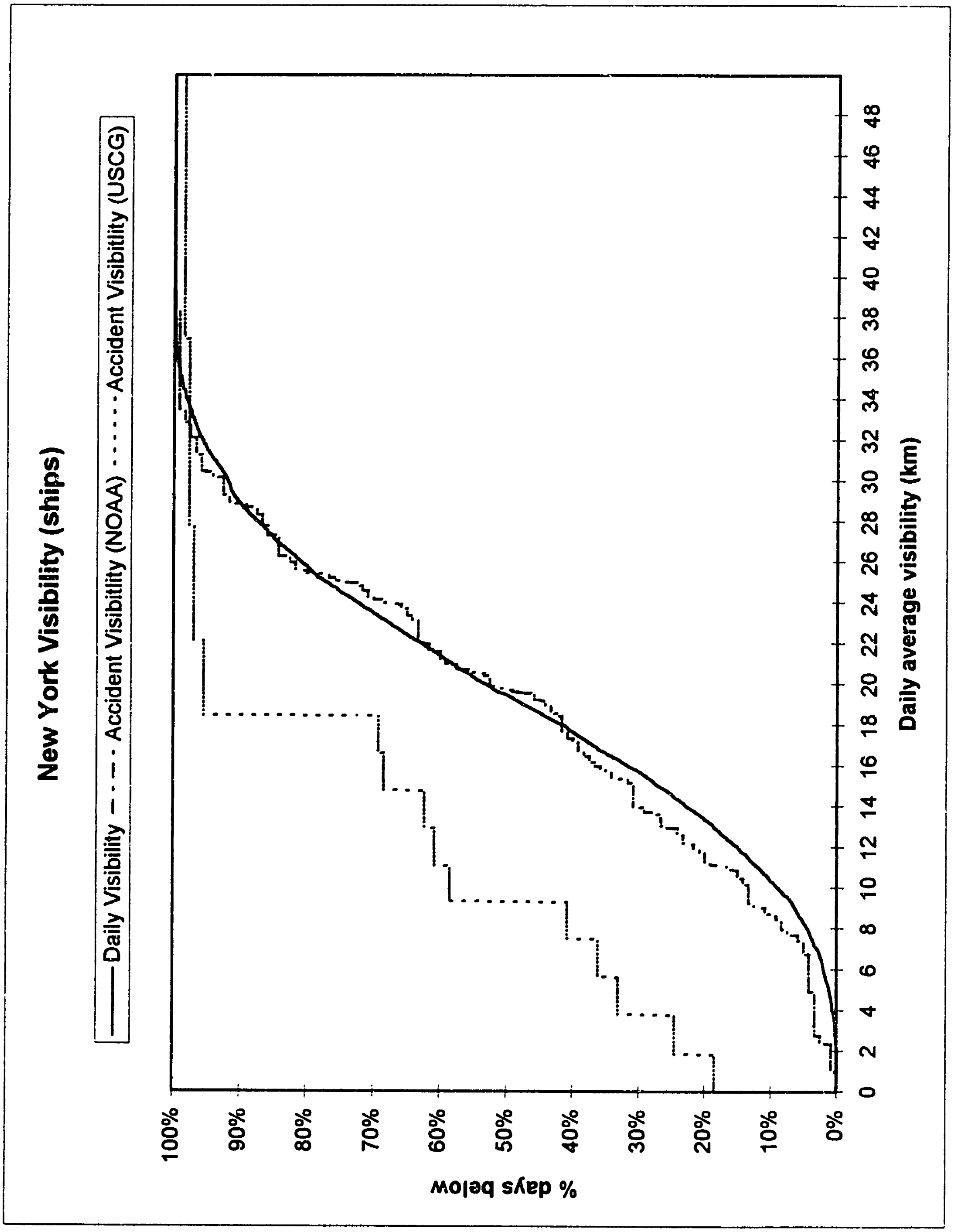


Figure A28 - Cumulative distribution of visibility in New York (ships).

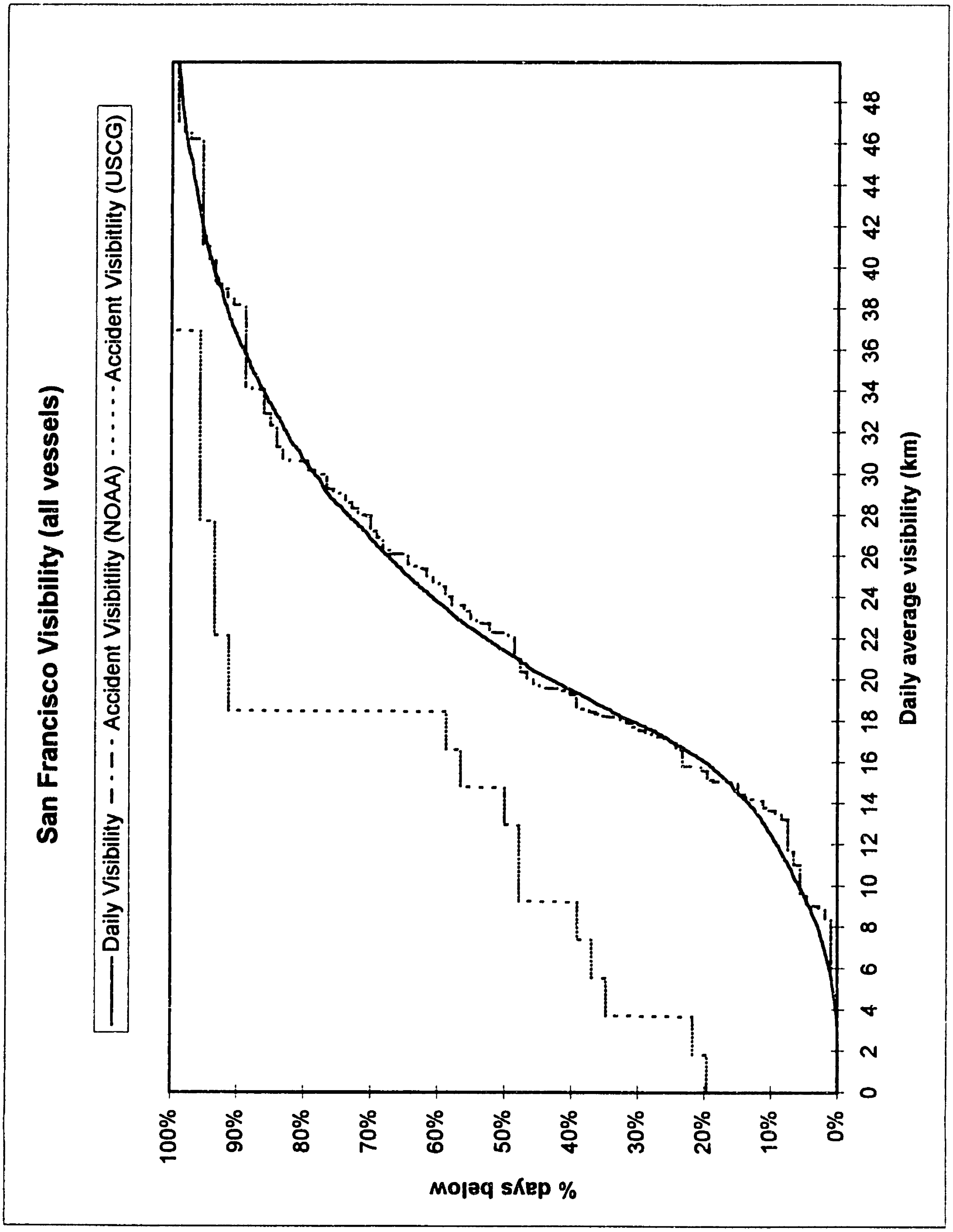


Figure A29 - Cumulative distribution of visibility in San Francisco (all vessels).

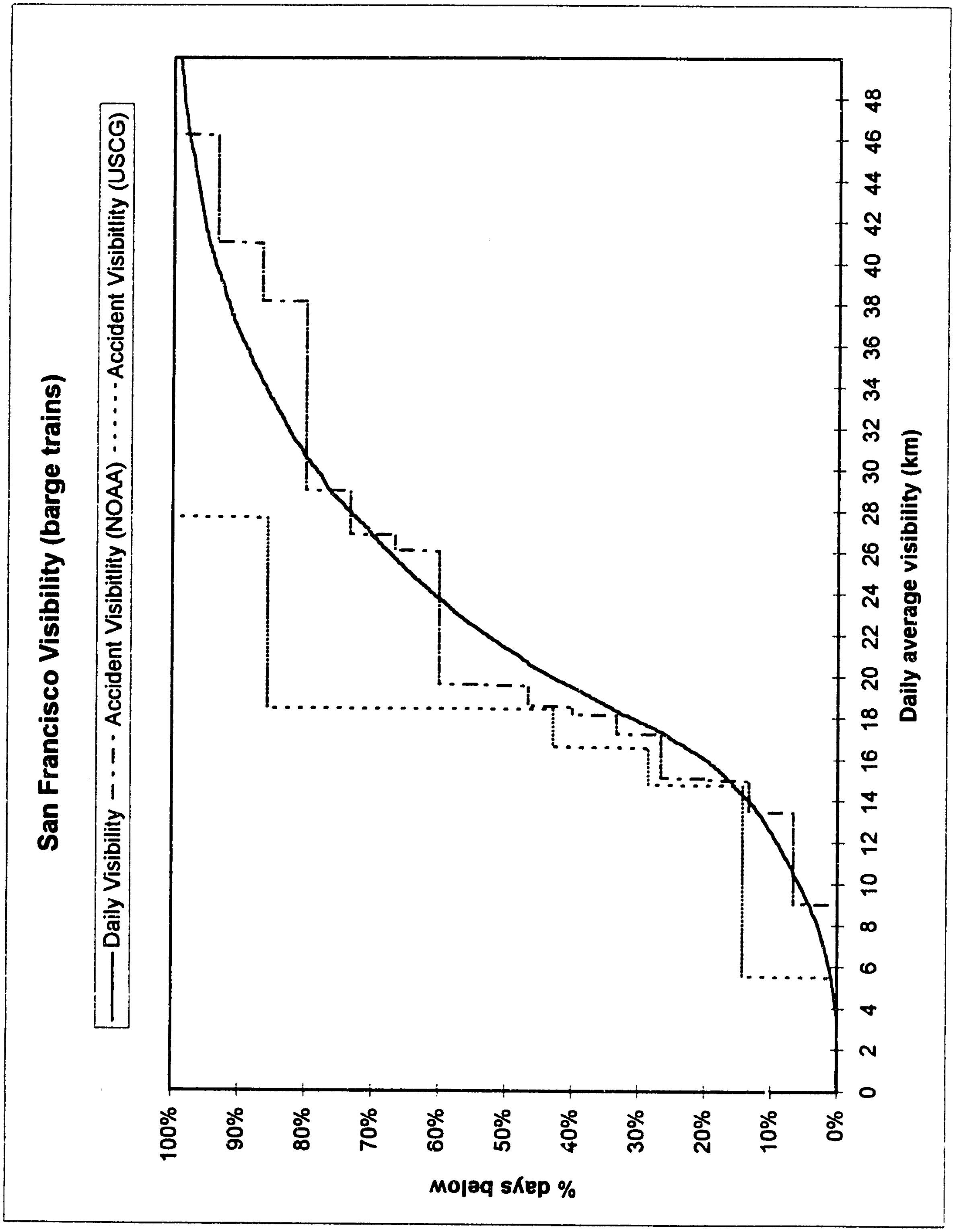


Figure A30 - Cumulative distribution of visibility in San Francisco (barge trains).

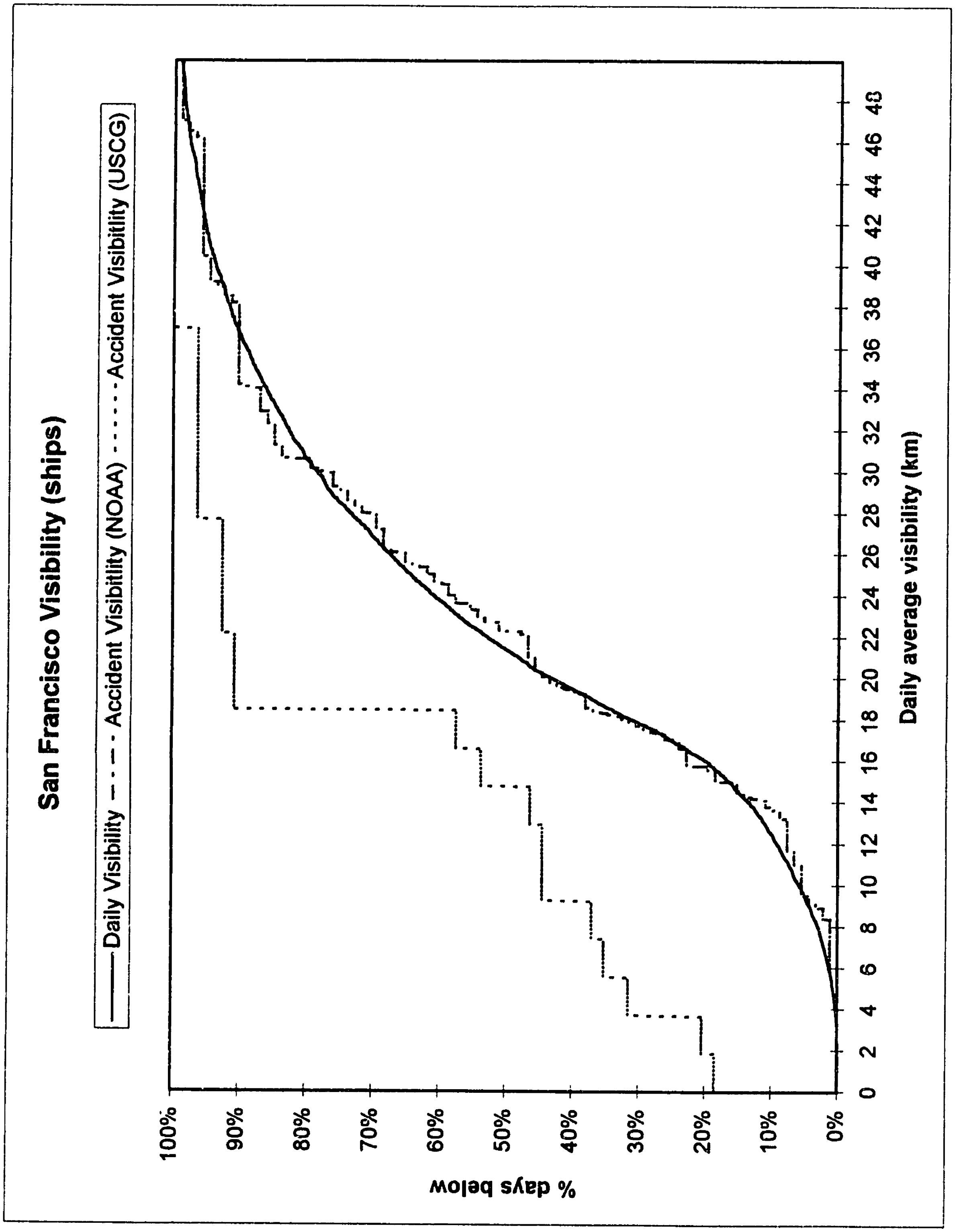


Figure A31 - Cumulative distribution of visibility in San Francisco (ships).

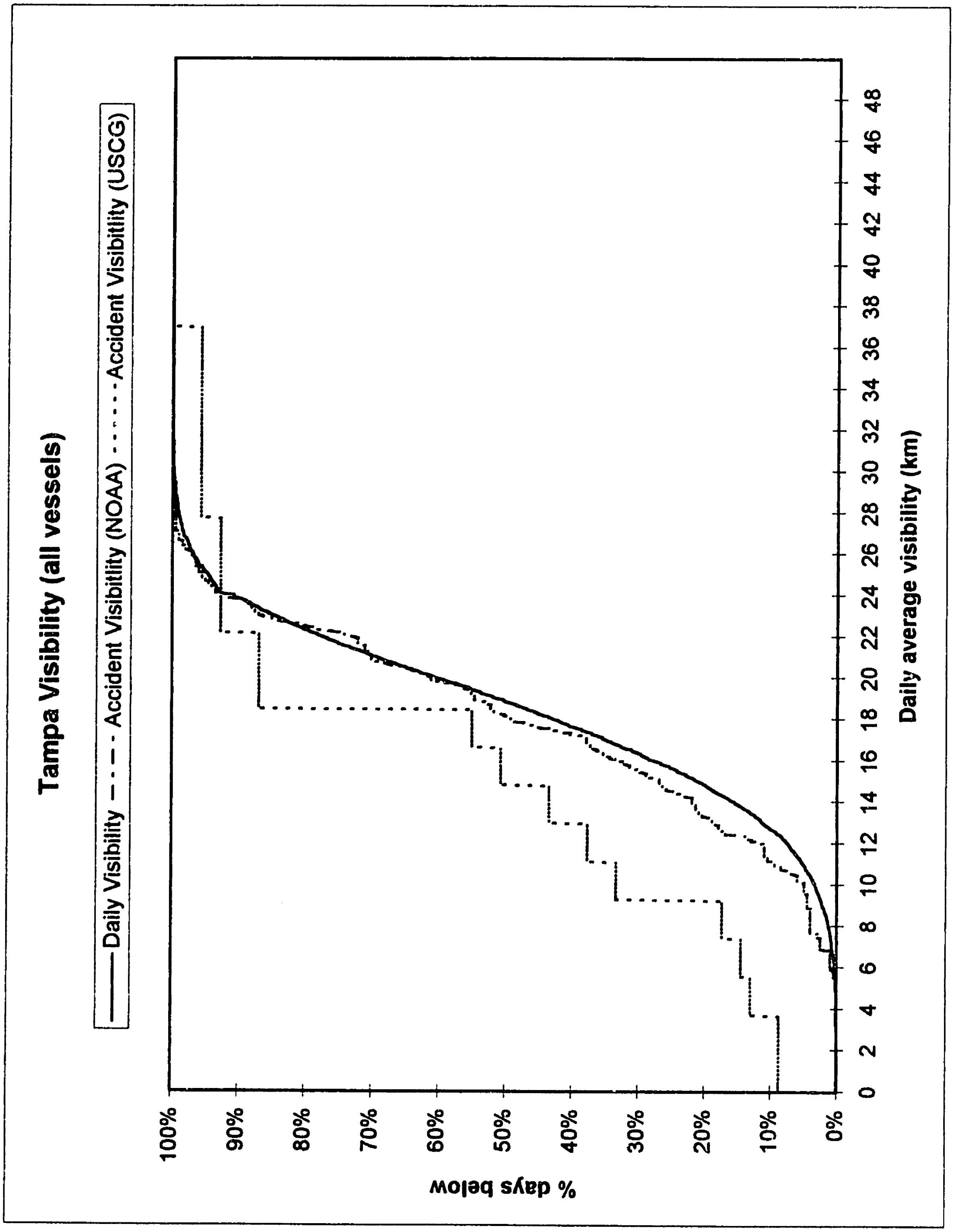


Figure A32 - Cumulative distributions of visibility in Tampa (all vessels).

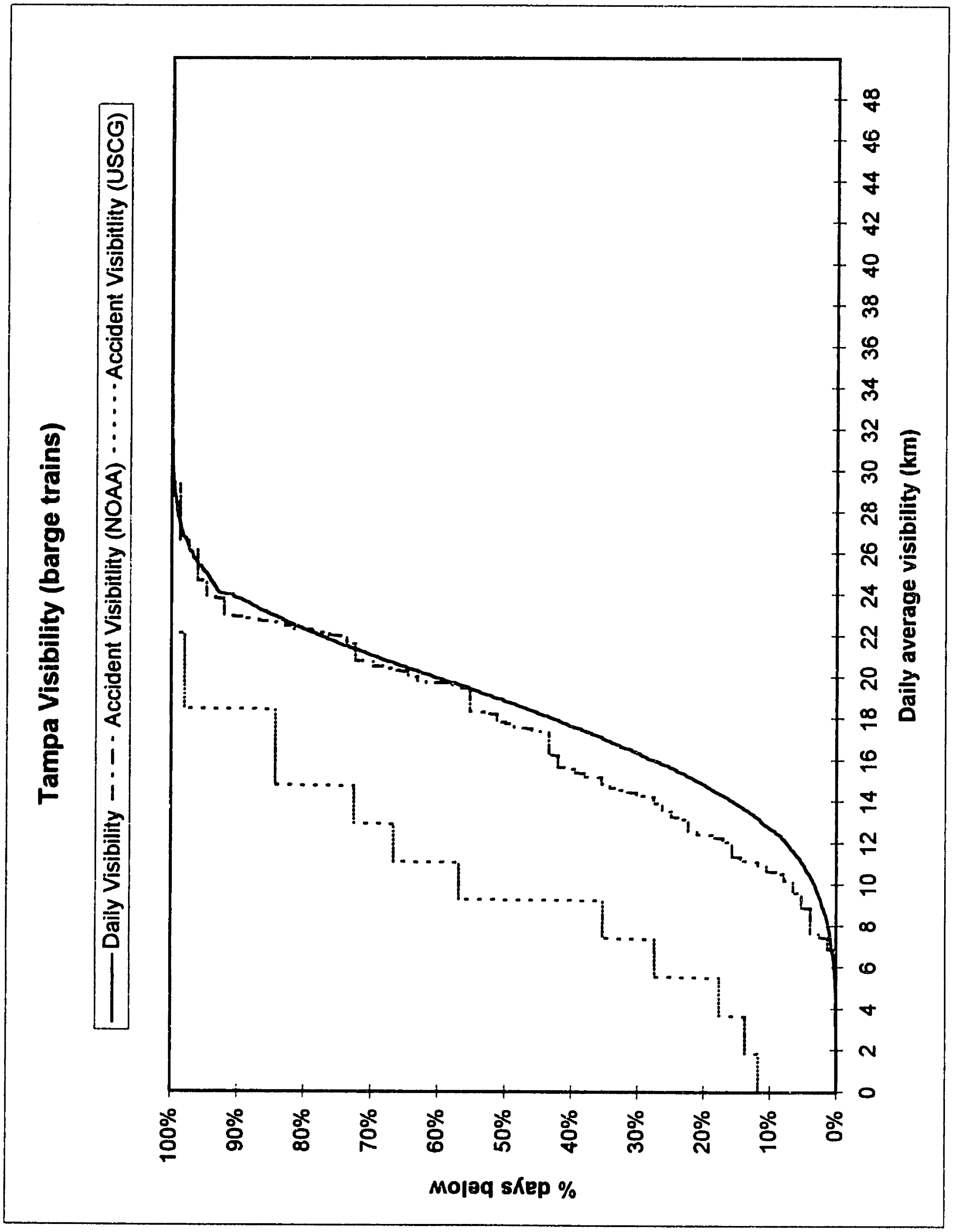


Figure A33 - Cumulative distributions of visibility in Tampa (barge trains).

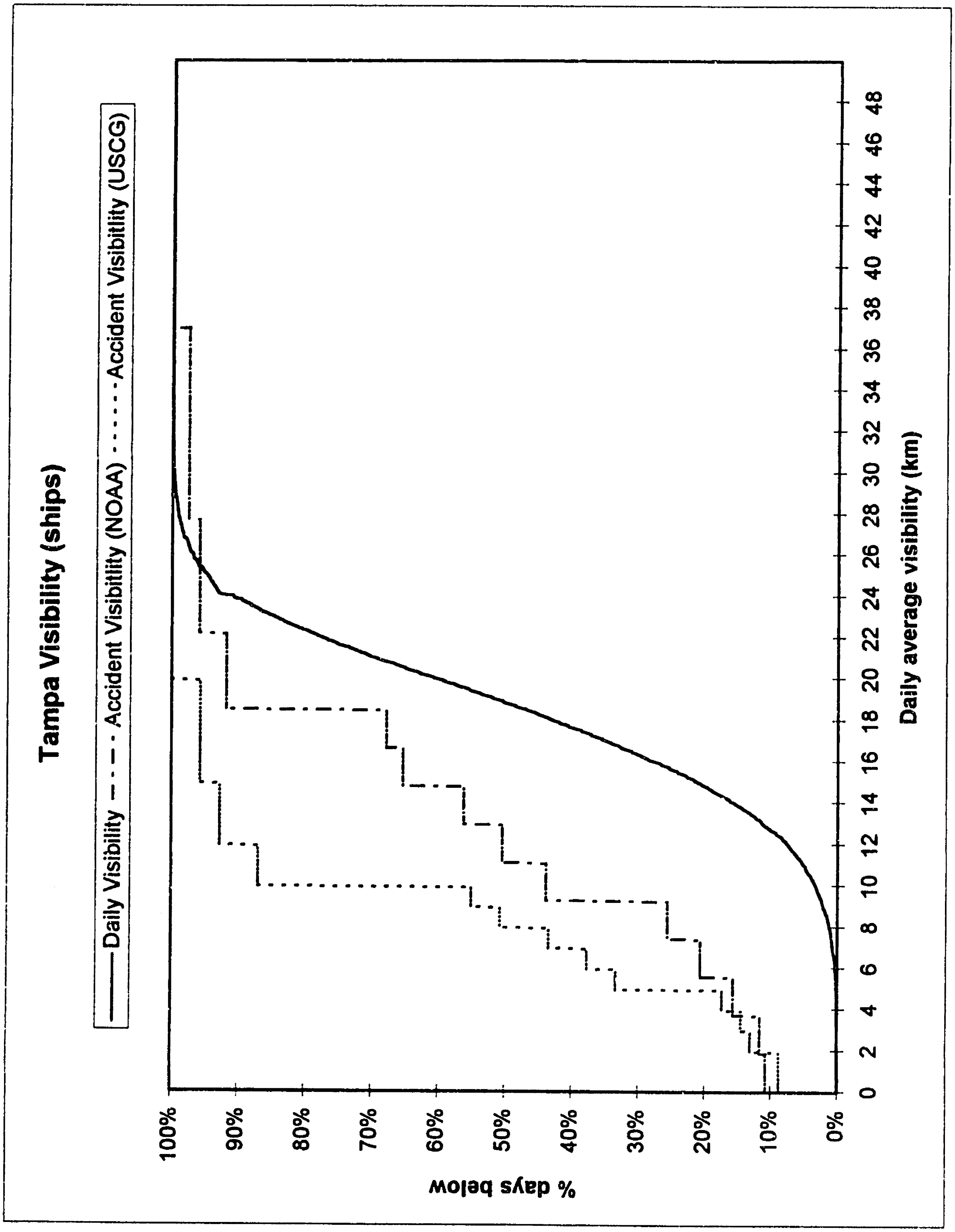


Figure A34 - Cumulative distributions of visibility in Tampa (ships).

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