Feasibility of Autonomous Underwater Vehicles for Performing Benthic Surveys

by

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Abstract

Technological advances within the commercial fishing industry have contributed to the decline of global fishery stocks. Historical management strategies which neglected to incorporate adequate feedback are recognized among the factors contributing to this demise. The relevant conceptual shortcomings are discussed, and a practical suggestion is made. A particular application of an Autonomous Underwater Vehicle is presented in order to provide fishery managers with a free roaming "virtual presence" in the marine environment. Presented within the conceptual framework of the conscientious utilization of improved technology, this thesis attempts to demonstrate the feasibility of utilizing the unique characteristics associated with autonomous operation coupled with an underwater video imaging system. This combination of technologies is suggested as a potential tool intended to provide for long term sustainability of living marine resources.

In order to quantify the technical requirements of the proposed system, a camera test sled was fabricated to the approximate dimensions of the AUV Odyssey II and outfitted with a CCD underwater video camera, strobe, optical backscatter sensor, sonar, laser ranging and light meters. This system was then used to demonstrate the operational parameters necessary for successful underwater imaging from an autonomous platform. Data was gathered at the MIT pool, Benthos, Inc. test tank, and off of Bermuda. Analysis of the video data and a discussion of the merits associated with this approach, comparison of alternative technologies and suggestions for future developments are included.

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This work is dedicated to Dominic and Josephine Curcio, two of the finest people I know. I am blessed to have them as parents and role models.

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1.0 EXECUTIVE SUMMARY

Commercial fisheries are experiencing unprecedented declines in fishery stocks and harvest rates globally. Although worldwide degradation of marine environments contribute to this decline, overfishing due to the introduction of more sophisticated fishing equipment is the primary factor that may be attributed to this decimation. Improved harvesting efficiency has been the result of more sophisticated tools being employed to locate and harvest fish. Government policies worldwide have encouraged the development of fishing fleets with no understanding of the limits of natural resources. The improved technology and the belief in unlimited resources, along with an underlying attitude which assumes that economic factors will always maintain an optimal balance between resources and consumption has led to the current crisis. Fish species are becoming "commercially extinct" and fishing pressure in many cases continues to push consumption beyond the carrying capacity of the resource.

In order to attempt to reverse the negative trend of overfishing, regulation, education and cooperation on behalf of fishery managers and fishermen must be maintained. All constituents must foster a clear understanding of the impacts upon the very resource itself and take responsible action soon. Among the many things that may be done to assist in providing a remedy to this problem, timely and accurate information must be fed back to marine resource managers. The implementation of a feedback loop within the management structure may provide a capacity for measuring the effects of policy decisions and rehabilitation efforts. If a management strategy does not appear to be working, alternatives may be sought. If on the other hand, a management decision begins to show promise, the successful plan may be replicated elsewhere. It is through this association of success with action that progress may be facilitated.

A particular technology is proposed to allow for the generation of timely feedback to resource managers. This system consists of an Autonomous Underwater Vehicle (AUV) equipped with a video camera and recorder. The development of this particular tool is described along with an explanation of proposed operation and future utility. In order to demonstrate the effectiveness of this tool in performing marine survey work, a subset of the broader problem has been identified and isolated. Specifically, this tool is discussed with regards to its potential to survey benthic fauna such as sea urchins, lobster, haddock or cod. A discussion on the necessity to maintain a suitable degree of resolution for population studies is discussed, along with a detailed review of a particular set of hardware, and its capability.

The system chosen consists of an underwater Charge Coupled Device (CCD) camera with strobe, altimeter and laser ranging devices outfitted for the AUV Odyssey II. A test fixture was fabricated in order to qualify the performance of the camera system, and a series of tests were conducted in order to both quantify and qualify the limits of resolution. Test targets were photographed in two swimming pools at a series of altitudes. The recorded data was digitized and analyzed. Analysis consisted of evaluating the targets by plotting the 8 bit grayscale values along transects that bisected light and dark sections of the test targets. Where a series of light and dark bands were plotted, a distinct signature was detected in accordance with the patterns of light and dark areas. Depending on the separation between two dark bands, a "saddle" was observed accounting for the detection of the summed effect of these two bands and edge blurring. A relationship is proposed for normalizing the level of this saddle as a function of altitude above target and water clarity. By correlating this relationship to a qualitative analysis, a standard for determining the resolution of fixed targets may be generated. Future proposals include extending this data set to include data gathered in various marine environments, and determining a realistic quantifiable measure for resolution in the field.

The intention of this proposal is that this technique be refined and incorporated into future autonomous vehicle platforms so as to provide a real time, in-situ vehicle operation feedback system. In order for the AUV to fully demonstrate its capabilities as an autonomous benthic survey platform, this type of information processing will be necessary and useful.

1.2 Introduction - Scope of the Project

Commercial fisheries are currently facing dramatic and unprecedented problems directly associated with the steady decline of the general health of the oceans. Factors contributing to this decline include excessive fishing pressures globally, degradation of breeding habitats in near-shore areas, and toxins released into the marine environment. These stresses manifest themselves as decreased quantity and quality of commercially harvested marine species, along with a general degradation of marine environments and an overall decay of natural systems. The utilization of more sophisticated tools designed to harvest more fish with less effort has exacerbated these problems. The cost of incorporating technological advancement into society includes the management of wastes generated by industrial activity, the greater dependence upon an increasing supply of natural resources and the threat of destroying the very habitat which sustains life on the planet [Marx].

Unfortunately, the choice to employ modern technologies disregards a management plan based on a long term perspective. Feedback relating the health of fisheries has been lacking in the management scheme thus far. Without adequate information, managers have been harvesting marine resources at rates that exceed reproduction, thereby lowering the annual populations and accelerating the decline of fisheries one species at a time. This problem is primarily a management dilemma, with particular consideration weighing on the utilization of information as it pertains to the appropriate use of technology in the management and allocation of living resources [Griffin]. The wise use of technology may provide a realistic and suitable alternative to the haphazard process currently employed in the exploitation of living resources.

The utilization of an improved technology must be closely coupled with a moral responsibility in order to create a long term "sustainable" management scheme. An introduction to the current paradigm associated with resource allocation and utilization is presented with some discussion of the importance of feedback of information available to the managers of the resource. A more “enlightened” approach is presented which includes the responsible utilization of modern technologies with the aim of generating a management scheme that focuses on sustainability of the natural resource. Included in this discussion is the clarification of the difference between a technologically based system that is “efficient” and one that is “effective”. Within this new framework, a practical approach is described which demonstrates the utilization of a modern technology that is appropriate in the management of living marine resources, particularly benthic fauna.

The specific technology outlined in this paper includes an underwater video imaging system deployed aboard an Autonomous Underwater Vehicle (AUV). The relevance of benthic surveys within the broader context of living resource management applications is presented with particular emphasis on the viability of video technology in this role. The requirements for employing this technology will be discussed, along with an exploration of the potential that this approach exhibits relative to available alternatives. A detailed technical discussion follows which explains the methodology employed in the process of developing working hardware, baseline data gathering and evaluation of the results obtained. Conclusions are then drawn from reflecting upon the process undertaken and suggestions appropriate for future work within this framework follows.

Part I Considerations Related to Using New Technology in Fisheries Management

2.0 Defining The Problem

A short sighted attitude prevails with regard to the management of living marine resources. This attitude may have initially been founded on the necessity for survival, but once augmented by modern tools and sophisticated technologies, the pattern of management has proven to be self destructive. By definition, the "modern age" is characterized by the use of technology to make people's lives more productive and enhanced through devices intended to provide greater comfort for less effort. This mentality has the potential to spurn attitudes of greed, selfishness and short-sightedness [Cleveland]. This effect is felt particularly with regard to tangible goods which carry costs that inherently have ill-defined boundaries. Natural resources have traditionally been regarded as existing without any tangible and accountable costs. An underlying attitude that "the resources are plentiful" and "are there for the taking" presents significant problems when these resources become exhausted [Hamrin].

Renewable resources that are consumed in non-sustainable fashion leave future generations worse off than their predecessors. Many social economists [Marx; Pezzey] believe that future generations ought to be entitled to the same quality of life as current generations. The removal of future resources leads to "intergenerational inequality". In order to assure sustainability as opposed to the more immediate need of survival, a non declining per capita utility must be considered, leading to intergenerational equity [Pezzey]. In order for long term success to be possible, the "goose that lays the golden egg" must be preserved and kept healthy. In the past, much effort has been directed at harvesting the golden eggs as quickly as possible with little regard for the needs of the goose. In order for the fisheries to be capable of producing harvests in the future, the prevailing attitude of "survival" must be supplanted with a much more responsible attitude which demands "sustainability" as its primary goal.

In setting out to define a possible solution to this problem, it is necessary to first put the problem into a perspective relative to the general socio-economic context. Society and nature cannot be viewed as independent entities. Only by understanding the history of the societal and cultural origins of environmental degradation can society expect to fully understand the problems and begin to formulate reasonable solutions. “One might in fact ascribe the crisis to the discordance between two quasi-autonomous yet intricately interwoven histories: the history of humanity and the history of nature.” [Marx] The source of the potentially irreversible demise that society has burdened nature with may be due to specific belief systems and socio-economic structures. This paper does not attempt to identify the social and political history of the underlying basis for the biased cultural belief system, but only to bring into the discussion the importance that an understanding of the complex inter-connections between society, economy and nature bear on seeking realistic solutions to global environmental issues. The implementation of technology as it relates to management plans plays a significant role in the development of a sustainable, long term strategy for managing living resources.

2.1 The Old Paradigm

The underlying paradigm inherent in traditional living marine resource management schemes is based on three primary assumptions. These assumptions are; 1)"Resources are Infinite", 2) "Technology and Scientific Information (in any form) is always correct and always "good", and 3) "The Market System is self regulating and drives behavior".

First, the assumption of unlimited fisheries stems back hundreds of years to people who were overwhelmed by what appeared to be endless horizons and unending supplies to be harvested from the earth and sea. The reality is that it is possible that we are reaching the limit to the ocean's fishery resources [Canfield, 9/21/94]. A migratory species can be harvested at some annual rate without adverse effect on global stock, while global fishing practices tend to exceed this rate consistently. As a particular species becomes more depleted, larger percentages of the remaining stock are subsequently harvested, thereby accelerating the rate of decline of the particular species population. The fact is, there really are limits to the quantities of living marine resources present. These populations are maintained by natural ecosystem support factors and threatened due to external influences such as human induced stresses placed on the resource. These stresses can include direct reductions of stocks due to over-fishing, as described above, as well as indirect stresses such as habitat destruction and alteration. Most common among the various forms of habitat reduction is the elimination of wetlands which are directly related to fishery reproduction rates. Additional factors include pollutants in a variety of forms that all reach the marine environment from land, air and water based sources. These toxins may have a direct impact on living resources in the form of accelerated fatalities, as well as multi-generational impacts in the form of birth defects and reduced reproductive capacity. In general, all of these factors combine, and tend to reduce the population of the living marine resources significantly. This places a very "real" limit on the number of fish available for harvest in any given season.

The second assumption of the old paradigm is an artifact of post industrial society, with a foundation in the blind faith placed in all technological developments. Technology and scientific information are only beneficial to society provided moral responsibility is attached to their implementation. A classic and ongoing example of a misuse and long term adherence to an inappropriate technology is the case of the Mississippi River. Dikes and levees built to enhance navigation and maintain flood control along the river have repeatedly proven ineffective during the river's severe flood stages. In fact, the very historical presence of these containment systems is the reason that the river is now capable of generating such damage. It used to be that the river could safely overflow its banks and spill over into broad shallow flood plains. These natural buffers are now isolated from the river by concrete levees and developed with houses and towns. Two significant points are demonstrated here. First, the artificial control of a river tends to redirect sediments away from the delta region where they would otherwise settle and create natural flood protection. Second, people lured by a false sense of security then choose to develop structures in these natural flood zones. The result of this process is that when the technology does fail, as it has along the Mississippi numerous times, the results are disastrous. The lesson to learn from this is that it is probably far better to design human structures according to the natural system parameters rather than attempt to place insufficient controls onto nature. At the very least, humans would struggle a lot less if they attempted to better understand nature and adjust their behavior accordingly.

Society has historically disregarded the environment as a commodity, and in the process of focusing on human, social and industrial goals has tended to push the limits of development at the expense of the environment. "Environmental degradation largely results from the introduction of new industrial and agricultural production technologies. These technologies are ecologically faulty because they are designed to solve singular separate problems and fail to take into account the inevitable 'side-effects' that arise because, in nature, no part is isolated from the whole ecological fabric." [Commoner] A number of other contemporary authors present similar sentiments regarding the ill defined focus of industrial progress and recognize the effects on the environment.

The third assumption states that the market system is responsible for the basis of this country's economic machine and is self regulating. In general, the concept that buyers will purchase goods and services at some cost determined entirely based on "perceived need" substantiates the basis known as "supply and demand". This simple concept is responsible for setting "fair market price" within this economic system. The price of a good or service is essentially the "value" that the buyer and seller place on this commodity in terms of what each of them is willing to give up in exchange for what each of them receives. What is accurately reflected in the price of a commodity is the placement of this commodity relative to alternative commodities within the overall market. "The appropriateness of an assigned value for use in a resource decision depends on the degree to which its use in the decision enhances the resource owner's welfare."[Brown, T. 1984] In this manner, the market exhibits certain self regulating behavior with respect to the utility of commodities and the setting of prices. Provided acceptable alternatives are available, a consumer will be very likely to choose between alternatives based on price alone. If, on the other hand, a good is considered to be rare, that is, it is highly desirable, and no alternative exists, the good will demand a significantly higher price in the market, to a point that no buyer will pay above some ceiling price. In discussing "price", Brown argues; "First, prices exist for many goods, putting those goods on an approximate comparable basis. Second, price is a social phenomenon, resulting from exchanges involving many individuals. Third, it incorporates scarcity into the expression of value."

It is essential to gain some perspective of how society's belief system alters our perception of the value of fisheries. The cost associated with harvesting fish has been generally just inclusive of the cost of buying (or renting) a boat and gear, purchasing bait, fuel and other necessities, and the time spent fishing. We have a lot of existing information from which to establish a reasonable baseline relative to the cost of fishing. What is missing from this equation is the hidden costs associated with the long term impacts that the human activities have on the resource itself. The important question to ask here is whether or not the true cost of scarcity is incorporated into the market price of a good under the existing market structure.

As an integral component of fisheries, the true cost of "fish stocks" within the system has generally been ignored. In much the same way that air and water have been regarded as free to all consumers, fish have been regarded as being abundant and free. In a report by the World Resources Institute, economist Robert Repetto and others express concern that a restructuring of the accounting for natural resources is necessary. " There is a dangerous asymmetry today in the way we measure, and hence, the way we think about , the value of natural resources. Underlying this anomaly is the implicit and inappropriate assumption that natural resources are so abundant that they have no marginal value." [Pezzey] In addition, [T. Brown, 1984] adds that "because individuals do not pay the full cost of their use of the resource, there is incentive to use it past the point of maximum social welfare." Recently, society has begun to recognize the true costs associated with clean air and water, and in similar fashion is beginning to account for costs associated with an abundance of fish. These indirect costs include a certain amount of overhead that provides infrastructure to maintain uninterrupted market access and continuous flow of product through the market chain. Along with these obvious indirect costs come certain external costs associated with factors further removed from the direct handling of products and transfer of goods or services.

Along with the external costs associated with fisheries resources is the concept of "future value." In much the same way that an investor is interested in purchasing stocks or "futures" in the market, there are compelling reasons for society to invest now in the future worth of the ocean's living resources. The idea that natural resources were infinite is a fallacy associated with a strategy that is based on "borrowing from the future." The fisheries are an example of the eventual accountability required at some point in time when consumption consistently exceeds replenishment. Most fishermen would probably believe that the oceans were "teeming with fish" thirty years ago. While there probably were significant stocks at that time, a general lack of information prevailed regarding total global stocks, and pressures from foreign and domestic fleets were possibly underestimated.

Within the past decade, New England fishermen were granted financial assistance in the form of loans designed to assure a buyback of fishing vessels. Some of the money allocated included redirected funds originally intended to aid victims of an earthquake in California. This proposal, while offering certain appeal to some constituents, has not been widely accepted by fishermen who feel that their very livelihood and existence is threatened. Many become disenfranchised and question just what it is that they are going to do once they give up fishing. Personal observations and interactions with fishermen has proven that this is not a minor issue to address. Many of these people have never known an alternative lifestyle, and many are not so resilient as to easily conform to a different occupation. This is not to suggest that management decisions ought to be made exclusively with these perspectives in mind, but simply to demonstrate the complexity of the issue at hand. Of particular importance within this discussion is the recognition that the government strategy has been historically based on short term gains and prefers to use a "Band-Aid" approach to bail out rather than sustain a resource, a lifestyle and an industry.

Although the marine fisheries have been threatened due to global and domestic pressures for a very long time, two major factors can be identified that exacerbated the stresses placed on global fisheries. These factors are the increased number of vessels and the improved technology that have been generated over the past thirty years. In 1976, Congress elected to establish the Exclusive Economic Zone (EEZ) as a component of the Magnusson Act. This body of law created a 200 mile region around the wet perimeter of this country in which only US registered fishing vessels were allowed to operate. The purpose of this legislation was to protect the commercial viability of the rich fishing grounds that lie primarily in the coastal regions. This body of law was effective in and of itself in isolating these regions of rich and vital natural bounty. Unfortunately, the existing administration failed to stop there. The federal government provided federal loans guarantees and tax credits in order to build a large and technologically advanced fishing fleet. In very short order, the number of fishing vessels working within this EEZ doubled and then tripled. Within ten years, the impact on the fisheries has been estimated to be substantially worse than that made by the original foreign vessels working within this boundary. Despite the dramatic jumps in fish harvests, no regulations were put into place in order to prevent total collapse of the resource. Similar events were occurring throughout the world as developing nations also encouraged fishing as an industry.

Along with the sheer number of fishing vessels that were active in the US waters, the efficiency with which these vessels harvested improved significantly. This dramatic improvement in fishing efficiency can be directly associated with substantial improvement to the tools used by fishermen [Garber and Canfield 9/19/94]. Technological advances made as a result of developments in electronics and the filtration into commercial sectors of technologies originally developed for military use accelerated the level of complexity of the tools available to commercial fishing vessels. These tools, specifically underwater sonar and navigation aides allowed fishing vessels to observe variations in bathymetry, accurately return to the same location day to day, and spot large schools of fish that passed beneath the vessel. "New technology means that fishing is no longer limited by the captain's skills and the crew's strength. Spotter planes and helicopters search out fish. Directional sonar lets captains "see" shoals of fish and even distinguish between species. Satellites help vessels lay their nets precisely where fish have schooled in the past."[Norse]

Relative to the declines of the fisheries, particular technological and political landmarks can be identified. Among the technologies associated with fishing methods are the numerous electronic devices utilized both to locate fish and to communicate with other fishermen. In the late 1920's, sonar systems allowed fishermen to "see what was down there." In the 40's, long range navigation equipment capable of one quarter mile accuracy allowed fishermen to return to the best fishing areas without wasting time searching. By the late 40's autopilots and radar beacons were being used to steer straighter courses, operate confidently in fog and improve navigation. Through the 60's, developments in improved navigation tools allowed for accuracy down to a few hundred feet, and new netting materials allowed larger, stronger nets, including the revolutionary purse seines which caught more fish with less downtime. Rock hoppers (small wheels attached to trawl nets) were used by the late 70's that allowed fishing of boulder strewn areas that were previously inaccessible. Sensors were used in the 80's to allow fishermen to "see" fish entering their nets. In the 90's a network of orbiting satellites called Global Positioning System (GPS) allowed fishermen to plot a course to within 30 feet. Throughout this period improvements to boats, propulsion systems and refrigeration all extended the range of coverage and the amount of time a boat could stay at sea. The combination of all of these elements allowed for significant improvements in the efficiency of newer vessels, resulting in unprecedented harvests. People who were displaced from some other occupation also became capable of fishing successfully with no prior experience due to the improvements made to the fishing equipment. While society benefited due to the availability of abundant and affordable seafood products, the technology responsible for increasing harvest rates was slowly destroying the very resource that it was intending to consume. Figure 1 depicts the effects of technology on fishery landings.

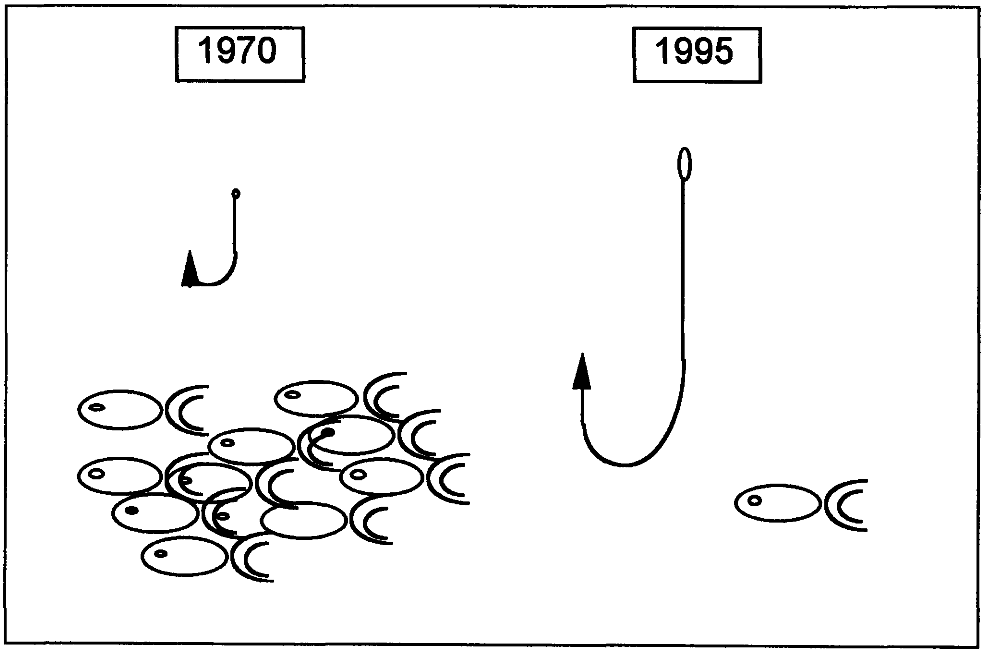


Figure 1. The amount of groundfish harvested in New England has dropped more than 60 percent in less than ten years. (National Marine Fisheries Service)

2.2 The New Paradigm

Society has begun to recognize that the three assumptions on which the old paradigm were based are no longer valid. Examples of the shortcomings of the previous attitudes are evident in some of the failures generated by that structure. The crash of the fisheries encompasses all three assumptions as a representation of the error associated with the old framework. Resources truly are limited, as evidenced by the failing fishing stocks. Sophisticated technology cannot be utilized in a vacuum. Reflection on the potential effects or costs associated with the use of an advanced technology must be carefully evaluated. A market system that is based on constant expansion cannot sustain itself indefinitely. The "externalities" that were previously ignored or considered to be free components of the system are now recognized to carry substantial price tags.

An expanding body of literature has emerged within the past decade which defines the new framework on which sustainable economic interaction with nature may be established. Inherent within this new paradigm is the understanding that there exists a strong inter-connected relationship between nature and economics. "Throughout our lifetimes, economic trends have shaped environmental trends, often altering the earth's natural resources and systems in ways not obvious at the time. Now, as we enter the nineties, the reverse is also beginning to happen: environmental trends are beginning to shape economic trends."[L.Brown, 1990] No longer are natural resources taken for granted as free and unlimited, but rather, tangible values are placed on resources, providing for accountability and intimately linking nature and economics.

Among the numerous examples of this new thinking is the contemporary case of the ongoing Exxon Valdez legal settlement. In this case, previously intangible natural entities are being economically evaluated, and damages in the form of monetary compensation have been awarded on this basis. These mechanistic accounting methods, no matter how inaccurate, link the previously intangible entities of nature into the existing economic system. Even in the absence of these techniques, people are beginning to place greater emphasis on the preservation and respect of natural systems. Examples of this type of thinking are evident in legal battles taking place over the protection of particular animal species and habitats. In these instances, no particular economic incentive is driving the activity, and it is recognized that the value to society for preservation of these entities may be purely intangible, but worthwhile.

Scientists are beginning to pay more attention to the inter-relations of the marine environment and their importance within the context of fishery management. Studies of the benthic habitat have demonstrated that harvesting methods may have dramatic adverse effects on the community of fauna and flora both within the benthic and in the near bottom region [Valentine]. Furthermore, the interactions and biodiversity of species in the benthic environment is poorly understood and may be critical to the overall health of the marine ecosystem [Auster, undated]. Recent literature has appeared suggesting that scientists might employ a new attitude with regards to the marine environment which tends to encompass the entire ecosystem of the oceans as opposed to individual species. The concept behind this thinking is that managers might have a better understanding of the intricacies and hierarchical structure within the oceans, and manage more effectively. Current fishing regulation practices which focus on "year classes" and dragging hardware tend to destabilize the web of interrelationships within the marine environment. A more enlightened approach is necessary, and a first step is to begin to more fully understand the complexity of the structure itself.

The role of science and technology within the new framework is addressed by [Marx] in his discourse on the disadvantages of choosing a "reductionist" approach as opposed to a "holism" concept in understanding natural systems. He goes on to say that industrial devastation is frequently linked to technological causes and it is the very scientists that are at one time blamed for creating technical advances that become burdened with the responsibility to search for feasible solutions. Marx advocates integrating societal needs into the scientific approach by encouraging non-scientists to become involved with scientists and vice versa. [Marx]

2.2 Common Property Resources

Living marine resources are subject to natural and human influences from a wide array of contributing sources. Among these impacts are the direct components such as short-sighted fishing practices, and less obvious land, air and water based human activities. To frame a single example, consider the impacts felt by the New England fishery by farming efforts in Ohio. Upon first glance, one might not immediately draw the connection between these seemingly unrelated activities. In fact, because the Mississippi River drains roughly 40% of the contiguous 48 states' watershed, activities of farmers in the midwest can have significant effects on the fisheries in the northeast. Many contaminants such as excess fertilizers, silt, oxidants and phosphates that enter the ground water network throughout this watershed eventually empty into the Gulf of Mexico at the mouth of the Mississippi River. Along with a number of other devastating factors associated with the management of the Mississippi River watershed, a general decay and loss of vital estuarine areas is being suffered. This estuarine area represents a breeding and feeding ground for roughly 70% of the migratory Northern Atlantic species. The impact of this decay upon a New England fishery is direct and obvious once this linkage is recognized and understood.

The above example is intended to point out the systemic relationship inherent in the natural water borne regime of this planet. Problems experienced in one discrete sector of the economic and social network cannot be unilaterally segregated from the remaining components of this complex system. Stakeholders in the success (or failure) of the system include entities directly and indirectly connected to a wide array of activities and levels of responsibility within the system. In this light, management of living marine resources can be recognized to encompass not only the fisheries managers, the fishermen, supporting businesses and so on, but also farmers, government agencies, regulatory bodies and corporate entities. The resources of the oceans represent a "common property" [Hardin]. The long term maintenance and success of this resource is dependent upon recognition of the intricate interactions of all "stakeholders" and real values associated with the resource at risk. No longer is it valid to expect that the government is capable (or willing) to come to the rescue of fishermen that have ignorantly brought about the demise of the very resource upon which their livelihoods depend. Granted, substantial arguments can be made that partially alleviate the full responsibility from the shoulders of the fishermen, but with the greatest potential for immediate loss, the fishermen stand the most to gain from pursuing the most effective long term strategies possible.

As a direct result of the historical perspective maintained regarding the management of living marine resources, many once bountiful fish species are currently threatened with extinction. Domestic economic incentives, philosophies, harvesting methods and international pressures have contributed to the demise and current condition of global fishery reserves. Despite international regulatory efforts designed to establish clear demarcations between national fishery grounds, and efforts intended to enforce these boundaries, many migratory species are threatened regardless of what particular waters they reside within. At the very foundation of most global fishing activity is a greed based incentive. Fishermen in one country are fearful that whatever they are unable to harvest while in their waters will be lost to a foreign vessel's catch. Furthermore, tremendous fishing pressure is extended globally in international waters by a large number of very large factory vessels from a handful of developed nations. Underlying this general attitude is a profound lack of long term goals and global perspective.

2.4 Sustainability

By switching the focus away from short term returns to a perspective which encompasses long term investment, fisheries managers may be able to establish a plan of action which strives to create "sustainable" fishery yields. The conceptual framework of this type of thinking involves the initial investment of time and resources in order to assure recovery of tangible returns indefinitely. Within the fishery industry, this implies the establishment of mechanisms, techniques and strategies that are focused on putting back into the system in excess of what is being taken out. At some equilibrium position in the future, the rate of removal from the system must be balanced by the rate of input. In a well established and functioning arrangement, the replenishment rate may be maintained by natural or human factors. Inherent within a system that is intended to sustain a natural process is the necessity for managers to be furnished with timely and accurate information on which to base management decisions. Any negative trends or impacts must be detected at the earliest stage possible using any available indicator within the system. This information must be used efficiently and effectively in such a manner as to reverse any negative trends before they are able to become threatening.

Information plays a critical part in the development and implementation of a plan of action that is aimed at sustainable resource development. A logical first step would be to determine the absolute population of a living resource, understand the requirements this resource has for survival, and recognize all of the existing threats, human and natural, to this resource's well being. Based on this "baseline", realistic approximations can be made regarding the rates that this resource can successfully be harvested without threatening future existence. Appropriate management would ensure that the rate of removal was safely below the maximum theoretical limit, as defined by the rate of stock replenishment once mortalities are accounted for. In fact, it would seem prudent to set a realistic threshold that safely allows for natural variability in the system, thus assuring stability through lean years.

A valid argument can be made regarding the necessity for maximizing the effectiveness of a resource base through careful management and a need for sustainability. Consider a very poor island nation that is entirely dependent upon a natural resource base for their survival. It would not be prudent for this nation to exploit the resource for immediate short term gain. There is really no reason that a developed nation should consider the situation any differently. [Pearce] refers to constraints which set resource harvest rates at "levels no higher than managed or natural regeneration rates," and he seems to imply a need to conserve the total stock of a natural resource by making tradeoffs between resources as necessary.

Formal fishery stock models and techniques of dynamic analysis have been proposed so as to maintain an optimal harvest relative to fish population [Butlin]. [Pezzey] advocates equilibrium growth models using renewable resources which allow for technological development. There are certain difficulties associated with implementing strategies such as this due to a dependency upon cooperation and behavioral changes by fishermen. These systems are also subject to externalities such as the increased costs associated with depletion of stocks which causes even greater pressure to catch more fish in order to survive. In any of the systems considered, the needs of future generations must be addressed, and consideration paid to the ability of these generations to achieve a sustainable level of existence. "Sustainable development is development that meets the needs of future generations without compromising the ability of future generations to meet their own needs"[WCED'87].

In formulating a solution option, the utilization of early detection as a form of feedback within the system must be considered in the light of all alternative management options. The implementation of a long term strategy must include proper information management and the careful utilization of available technologies. The integration of feedback into a control process provides the ability to maintain a system at some equilibrium. Placing feedback into a system has the effect of creating a "closed loop" structure, which by definition may be self regulating. Provided the feedback generates limiting behavior on the part of the inputs which tend to cause imbalance, and the feedback is self damping, the system will tend to oscillate about a desired point of equilibrium. In the absence of feedback, a system has the potential to proceed unchecked, and in certain instances, the system may have a tendency to quickly go out of balance. In the case of marine fisheries, the harvesting of fish from the natural environment without performing ongoing stock assessments and impact analysis is an example of a system lacking in adequate feedback. Figure 2 depicts the effects of operating a dynamic system in the absence of feedback control mechanisms. It can be seen that the incorporation of feedback relating critical information about the health of living resources may facilitate long term stability within the system. Simply altering the perspective of the fishery managers may be all that is necessary in order to generate useful system feedback.

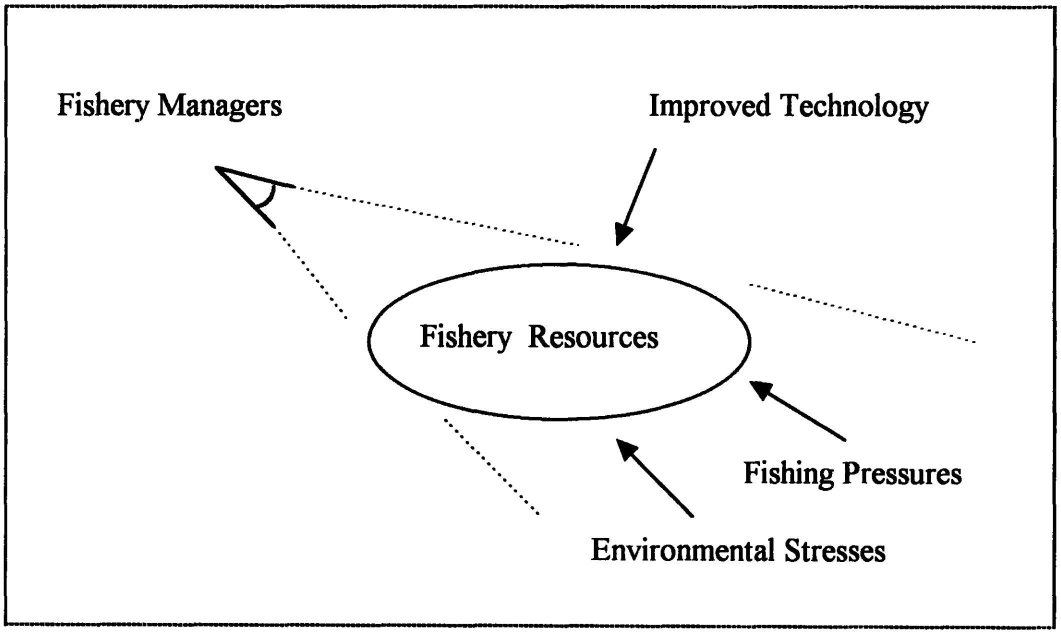


Figure 2. Perspective on resource management facilitates erroneous attitudes regarding the general health of fisheries. This may tend to omit critical information necessary for appropriate management strategies.

If any lessons are to be learned from past behavior, society must recognize the fallacy inherent in the old paradigm. With this, society must be prepared to take all of the experience, knowledge and tools that are the result of a long history of human development and blaze a new trail into the future. Regarding the erroneous belief that economics are separate from natural systems, humans must recognize the intricate relationship and the strict dependency between these two entities. The false idea that natural resources are infinitely abundant seems to be making a statement of its own. Regarding the role of technological development as a solution to all of the concerns facing modern society, sufficient evidence exists to demonstrate the fallacy in this belief. Within the framework of providing sustainable management of living marine resources, appropriate technology coupled with careful implementation may provide a realistic and sustainable solution. The dependence on technology must be supplanted by a healthy understanding of the use of appropriate technology as a simple tool that must be used responsibly.

3.0 What Can Be Done?

In attempting to formulate a workable solution to the fisheries management dilemma, a number of potential schemes may be developed. At the core of the process behind solution seeking must be an understanding of the complexity of the network of interactions involved in the marine ecosystem, the desires of interested constituents, and the realm of potential solutions. Paramount among the varied interests represented must be a common goal that includes the desire to formulate a solution that strives for sustainability. Along with embracing this new criteria, incorporation of feedback as described must be included so as to close the loop in the system. Utilization of the latest technological advances must be done with utmost care and an understanding that the ignorant acceptance of technology in the past is partially responsible for the current problems. The incorporation of new tools within this process must include a thorough understanding of the subtle difference between incorporating tools that are "efficient" and those that are "effective". Modern business guru Peter Drucker defines these terms as follows: "Effectiveness is knowing which wall to put a ladder against, efficiency is being able to climb the ladder quickly." We must come to terms with where the walls are and what ladder we will use.

Borrowing from Drucker, it is our task to determine what wall to place the ladder against as we set about to propose a solution to the fisheries management problem. In order to get the ladder against the correct wall, one must now consider the system as it exists today and evaluate what intervention is most suitable given the tools at our disposal. It is evident that this problem is both complex and diverse. In order to attempt to demonstrate the potential for the establishment of a positive solution to this dilemma, a single aspect of the larger problem will be focused upon, and a solution possibility will be introduced. Due to the utilization of improved tools aimed at locating fishery stocks, fishing efforts have been able to harvest larger quantities of fish with less extended effort. Up until the time that fish stocks became noticeably reduced, these harvesting efforts were returning catches that economically more than justified the costs of using the newer technologies. In general, the improved technology resulted in an improved "efficiency of harvest" without improving the overall system efficiency. In some instances, when decline of commercial stocks had been recognized, managers chose to reduce the length of time available for harvesting a given species. This approach was often met with anger on behalf of fishermen, and a tendency to attempt to fish exhaustively within the allotted "open" season. This type of management practice has not proven to be successful for long term species management. Particular shortcomings of this approach include a lack of understanding of the natural requirements for fishery reproduction and population recovery, as well as a knowledge of a safe minimum population limit to ensure long term stability.

As an illustration of a single threatened component within the marine habitat, consider first the various species of benthic fauna. This list, by no means exhaustive, includes such commercially viable species as flounder, cod, haddock, scallop and a number of other crustaceans and bivalves. These various forms of bottom dwelling marine creatures are generally slow moving and except for the cod, do not tend to mobilize over large areas of seafloor. For this reason, these species lend themselves to some form of visual observation or survey. In the past, any census data generated for the purpose of integration into management plans has been obtained primarily by spotters from the National Marine Fisheries Service (NMFS) aboard fishing vessels or by tallying catch and bycatch in the nets and trawls of related fisheries. This method, although highly regarded by those actively involved in its use, tends to leave a lot of questions unanswered concerning the true status of the fisheries and an understanding of the health of the habitat itself. For this reason, within the scope of this thesis, it is intended that a unique and novel approach be taken for generating realistic benthic fauna census data through the use of underwater video surveillance hardware. It is intended that statistical data be generated through use of this hardware to be incorporated into ongoing management plans.

In considering the specifics of applying technological approaches to the problems facing marine resource managers, we must evaluate the options available. In order to do this, we may first want to identify the needs of the managers. It is evident that one of the significant pieces that is lacking in the management process is accurate and detailed information regarding benthic habitat and fauna. The biological components appear to be the parts that are least understood, yet most critical in formulating realistic management plans [Pederson]. Ecologists study animal and plant abundance by estimating density, size or any other available information. In obtaining statistics from the marine environment, practical restrictions limit the scope and efficiency of a similar study. For this reason, great care must be exercised prior to undertaking a survey, so as to assure that the information obtained is both significant and accurate. The purpose and procedure of a study must be thought out very carefully prior to the selection of appropriate tools. Once the decision is reached regarding the tools to use, a plan can be construed regarding the method to follow.

Tracing the development of technological innovations with regards to observing deep sea benthic community reveals a close relationship between the tools developed and the level of knowledge available to biologists. There are compelling reasons to pursue the development of more advanced tools that may enhance scientists understanding of benthic communities. In fact, some recent advances in deep sea biology can be attributed to particular technical innovations which produced tools to do jobs that were previously unavailable. The development of SCUBA apparatus created significant opportunity for humans to explore the oceans directly. Throughout the past twenty years, the evolution of manned and unmanned submersibles has broadened this scope. The deep sea sled and ROVs (Remotely Operated Vehicle) offered a substantial improvement in the tools available for in-water photography and video imaging. An ROV is effectively a towed frame although they typically have propulsion, they are always attached to a surface control unit via an electro-mechanical tether. Various sensory instruments may be mounted on the ROV platform, including typical water property sensors and video or still photography cameras.

The ROV as a tool for performing benthic surveys has been recognized for its ability to provide information relative to densities of benthic species without the need to process samples. The predecessor to the ROV had been primarily the trawl, or large net, that was dragged over the bottom in order to gather species samples. This technique is still in use today but substantial arguments can be made to justify the use of some form of remote camera for this purpose. In general, photographic or video formats provide spatial distribution and continuous information on habitat characteristics Trawl information is integrated over the trawl path, so no fine scale information is provided. By capturing samples however, trawls offer a level of detail that otherwise might not be available. The recent innovation of the AUV (Autonomous Underwater Vehicle) offers certain features of the ROV platform with some compromises and some advantages. With the development of an AUV, some of the distinct advantages that the ROV presented (real-time video 'telepresence', spatial and temporal information, behavior) were maintained. The AUV offers tetherless operation, intelligent vehicle operation and eventually autonomous behavior, rendering them potentially much more effective than tethered survey tools.

Numerous biological surveys may eventually be performed by AUVs. Future operations might initially include video surveys, CTD profiling and sub bottom profiling. The goal at first must be to use the AUV to replace surveys that are currently performed using more cumbersome techniques and tools. Current capabilities of existing AUV platforms are limited to rather simple routines such as bottom following and obstacle avoidance. Progress in vehicle control software has been very rapid, and much more sophisticated operating routines are emerging presently. The acceptance of this platform will require satisfactory demonstration of the successful operation as a research tool. In terms of photographic and video survey platforms, the current tool of choice is the ROV. The AUV as a platform, even at the current state of development is fully capable of offering significant operational advantages over ROV operations in many situations. By eliminating the necessity to operate the vehicle by a tether, the surface vessel requirements are substantially reduced. With this reduction in complexity comes reduced operational costs and the need for operators on station. The AUV is significantly simpler to operate, and may be deployed and operated from small to medium ships of opportunity, and left on station despite rough surface conditions. Future evolution of this technology includes the use of underwater docking and recharging stations, a network of vehicles and improved in-situ sensor suites and artificial intelligence software. Once the operational capabilities are proven, numerous scientific applications are likely to evolve.

The implementation of this improved technology may offer substantial benefits to benthic habitat and fishery management studies. By providing the ability to really see what is happening in the marine environment, managers are afforded both knowledge and evidence that substantiates any claims regarding the health of the marine environment. In the same way that the evolution of sonar tools allowed fishermen to see the fish they were hunting, managers will now be able to see the impacts of harvesting and other influences upon benthic environments. Providing vision to fishermen was significant in terms of increasing their efficiency as harvesters. There is no reason to doubt that offering a similar advantage to marine managers would be less advantageous.

3.1 Responsible Utilization of Tools

The responsible management of a living resource involves far more than simply the utilization of the latest technological advances. An important distinction must be made between a management practice that is efficient and one that is effective. Modern tools may readily provide for efficiency if measured in terms of harvest achieved relative to effort extended or dollar spent. Conversely, one might evaluate an alternative strategy in terms of effectiveness using criteria such as long term sustainability which includes multi-generational attributes. Consider the fisheries as an example of a living resource that utilizes advances in technology in order to improve the rate at which fish are harvested. More advanced and sophisticated tools at the disposal of irresponsible fishery managers will only lead to a substantial decrease in the magnitude of the living resource itself.

In conjunction with the advancing state of technology, proper management demands for accurate and detailed feedback with regard to the health of the resource itself. This component of the management scenario requires a particular set of tools and persons well versed in the utilization of the tools and the information yielded by them. As any good farmer is well aware, nutrients must be put into the soil at some rate relative to the demands placed upon the land in order to assure long term returns. In a similar fashion, fisheries must incorporate information relative to the overall health and productivity of the habitat and particular species in order to be well managed. It is not so important that the fisheries managers replace nutrients into the ecosystem (as does the land based farmer), but that they recognize the critical signs relating to the overall health (or decay) of the natural system before dramatic declines in productivity occur. This may be one of the critical pieces of information that is lacking for proper long term management of wild fisheries.

A shift in the responsibility shared by fishermen is integral to the success of long term objectives concerning living marine resources. It has been too easy for fishermen to place blame for their hardships on the shoulders of well intentioned scientists and policy makers, many of whom have been hindered by inadequate information. "They (fishermen) correctly see that fishery science is inexact, but wrongly deduce that the scientists' estimates of a safe catch are always too low. Even if they trusted the fisheries managers, many fishermen would worry more about paying the mortgages on their boats." [Norse] Along with being open minded about the potential that new information and strategy offered by scientists may be valid, fishermen must adopt an attitude of "ownership" of the fisheries and abandon the once useful attitude where they perceived themselves as hunters in the wild. "If a fisherman regards a certain stock of fish as his property, the theory runs, he will want to protect and conserve it, just as a farmer would try to improve the productivity of his land." [Norse]

Two steps may be taken that offer potential for reversing the negative trends associated with the destruction of benthic habitats. The first is that information regarding the effects of human activities must be well understood and shared among all constituents. This information must be gathered, analyzed and evaluated by scientists, fishermen and managers alike. Fishermen must adopt an active role in the management of marine species and make good use of this information. By becoming owners of the resource as opposed to hunters, fishermen are more likely to participate actively in the long term management of the resource. Second, in order to facilitate the understanding of the dynamics associated with benthic habitats and fisheries, the habitat must be observed and monitored. This is where the AUV equipped with video survey tools fits into the management scheme outlined.

4.0 How Can This be Done?

The proposed hardware consists of an underwater video camera system mounted on an Autonomous Underwater Vehicle (AUV). This arrangement provides a platform from which species population census may be made. The essential elements of this hardware include the AUV platform itself, the video imaging system, and some method for evaluating the data obtained. The platform consists of a submersible, unmanned vehicle that has been developed at MIT in the Sea Grant Underwater Vehicles Lab. Odyssey is approximately two meters long, sixty centimeters in diameter and weighs roughly 200 kg. It is capable of operating to 6500 meters depth and cruising at five knots.

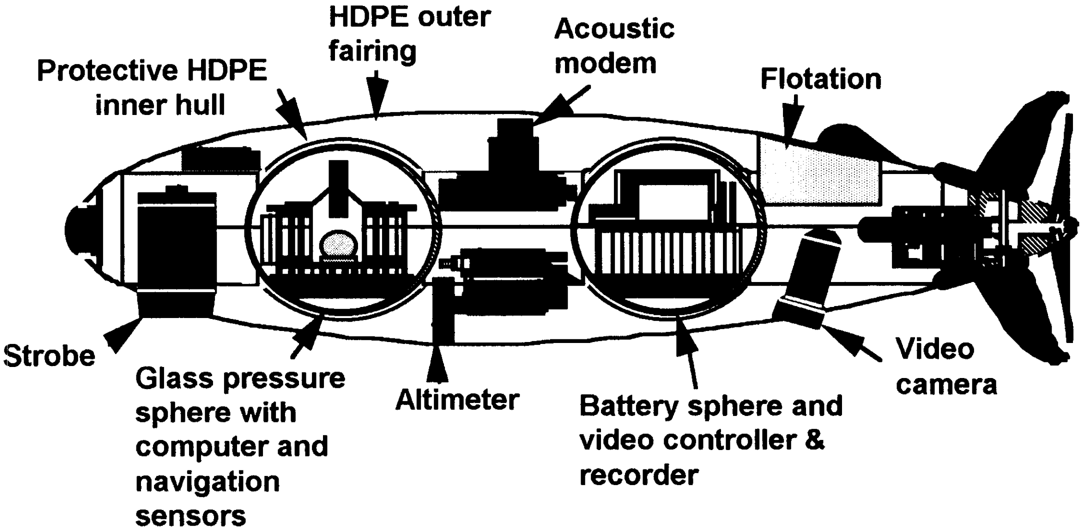


Figure 3. The Odyssey II vehicle in a typical deep-survey configuration.

The video system is mounted within this vessel and records continuous video, or still images (on video format). Currently, all data is stored within the vessel on Hi-8mm tape, and can only be recovered when the vessel is out of the water. Future developments may allow for data recovery while in-situ and eventual evolution of artificial intelligence software may allow for on board data analysis and subsequent control of survey parameters. Figure 3 shows a schematic representation of the Odyssey II vehicle with camera, strobe and other vehicle components. A detailed description of the hardware chosen is included in the technical section of this paper.

Certain limitations are evident relative to the use of an ROV or towed camera sled relative to obtaining real time video data. Due to the physical limitations imposed by water upon the transmission of electromagnetic and sound waves, real time data obtained by a video camera cannot be effectively transmitted using a wireless link to a surface vessel. For this reason, data must be stored on board the vessel for future evaluation. This limitation restricts the ability of an operator to view information in real-time and adjust survey strategy accordingly. The current approach would be to perform a reconnaissance survey over a large area of the bottom first. Analysis of this data would guide future deployment routines. While this approach may be cumbersome initially, advantages will be gained in the long term by the ease with which the detailed surveys are performed. Future developments of intelligent software capable of analyzing the data "on the fly" will eventually eliminate this hindrance entirely.

A proposed deployment of this vehicle as described might involve performing a randomly directed photographic survey of a general geographic area of seafloor. Once the data is recovered and analyzed, future detailed surveys may then be proposed and carried out. The ultimate effect of performing this type of survey is the establishment of a data base that facilitates ongoing observation of a particular species or habitat. This method of benthic monitoring is intended to allow for rapid feedback before conditions reach crisis proportions and fisheries begin to face the risk of crashing. Numerous additional benefits may be attributed to this method of survey, including the ability to observe behaviors such as feeding, breeding or sheltering while species are in-situ. Additional benefits may be gained through the ability to observe any illegal harvesting activities as well as impacts that may adversely affect the marine environment. Such impacts may be the result of intentional human activity, such as illegal dumping, as well as natural occurrences such as annual storm events. In any case, a strong argument can be mounted to justify the utility of establishing a "virtual presence" within the marine environment.

The AUV offers a potential solution to bridge this critical gap in the management feedback loop. This is not the sole method that may be employed to this end, but it may prove to be the most cost effective both in the long and short term. An AUV equipped with a video camera can be deployed in the vicinity of a fishery resource that is actively harvested. Regular observations of the habitat and the species may be performed over time. Critical "red flag" indicators must be identified that warrant restrictive action on the part of the fishery managers. At times when these indicators justify action, limits, closures and protection of the habitat and / or species must be enacted. Continued observations may then be made so as to monitor the recovery and establish future harvesting regulations. It is within this feedback loop that the most accurate and up to date information is exchanged, and ultimately the most effective management practice is established. The difference between approaching this scenario with and without this feedback can be compared to a farmer harvesting his crops one year to the next without setting any seed aside for future seasons, or making any provision for fertilizing the fields. In short order the land no longer is capable of supporting future harvest.

The AUV platform offers a unique opportunity for fisheries managers in that it allows for the gathering of information which may have previously been impossible to obtain by any other method. Critical information about species interaction and overlap would be available providing information that cannot be determined by conventional methods. [Goudey] states that "an important role for fisheries scientists is stock assessment and their principal tool is the sampling trawl and sampling dredge. The direct counting of animals in-situ is an attractive method of stock assessment, eliminating the vagaries of present trawl and dredge sampling methods. A system that could visualize the bottom without contacting it would offer both reliability and stealth." [Auster, through personal contact] points out some additional examples of the types of data that can be collected from a series of recorded images, including; species composition, abundance, spatial relationships, fauna-habitat relationships, size distribution, interspecific associations and scales of patchiness. Certainly, one could imagine a number of additional applications for an AUV equipped with video imaging capability. As a tool for providing the necessary feedback to fisheries managers, the specific utility described above justifies incorporation into existing management schemes. Figure 4 depicts the benefits afforded by incorporating feedback into a dynamic system.

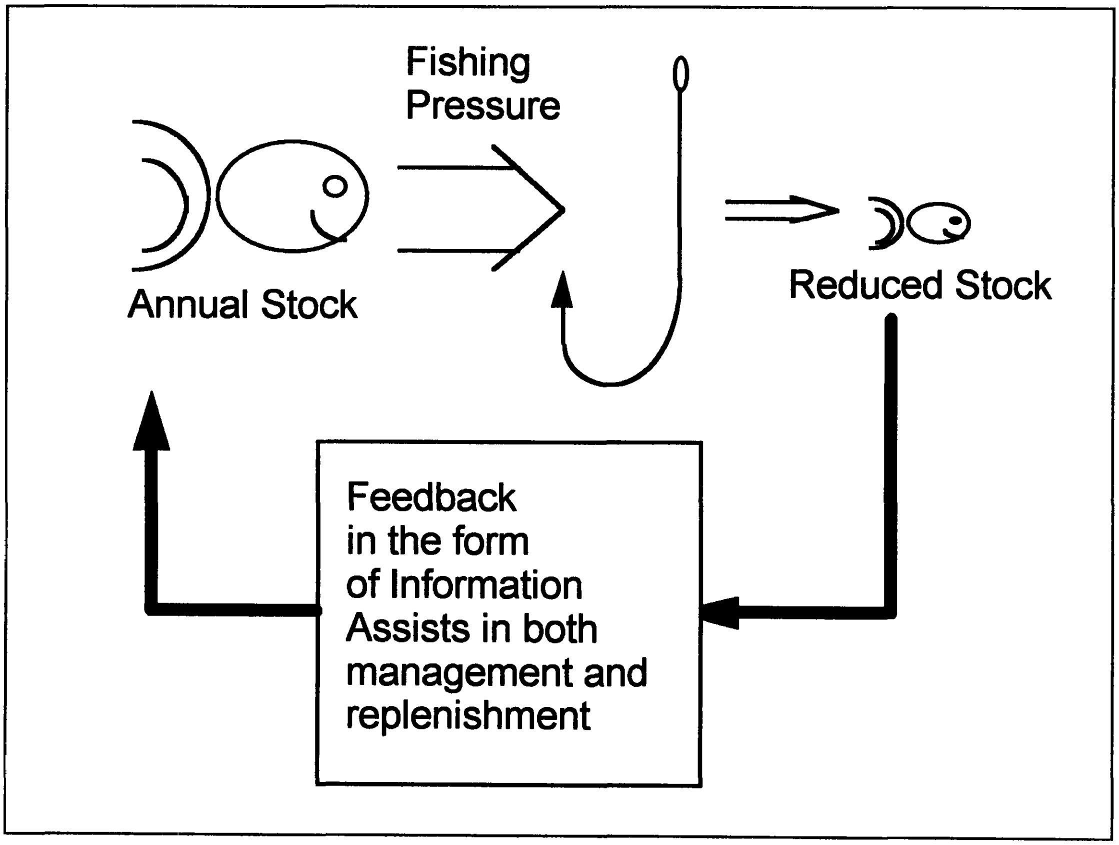


Figure 4. Adding Feedback into the otherwise open loop system allows for control and the ability to maintain a dynamic equilibrium.

5.0 Proposed Operational Scenario

Sea Urchins resident in coastal Maine waters are chosen as a representative benthic fauna for the purpose of focusing this discussion. In order to obtain useful population and distribution data of benthic fauna, specifically sea urchins in this case, a practical strategy must be developed for gathering data. It is recommended that any strategy be devised after consulting with existing data sets. This operating scheme assumes that all data gathering will ultimately be performed using the AUV equipped with the given video equipment. Taking into account the current operational capabilities of the Odyssey II class vehicles, current and future strategies will be proposed independently. First, an operational strategy that could be implemented immediately will be recommended. Then, a recommended future strategy will be described, with the understanding that this may evolve considerably depending upon the status of operational development and lessons learned from initial deployments.

The use of video and photographic techniques as benthic survey tools has been accepted by marine biologists as a viable method form obtaining important information about species and habitat [Valentine]. Two typical survey sampling methods are classified broadly as quadrat and transect. A quadrat sample is typically that taken with a still camera, and represents a measured area of coverage. Species density and distribution is evaluated and then extrapolated over a broader area of the region. Errors associated with this technique are due to an inability to detect or identify individual organisms within the field of view as well as lack of information regarding behavior characteristics of mobile organisms [Valentine]. Within transect sampling, strip or line transects may be used. A strip transect is similar to the quadrat technique described but the area of coverage tends to be a long narrow region as compared to a relatively square or circular area. Using this technique, estimates of population density and distribution assume that species identified occur with equal probability regardless of their location within the field of view. The line transect technique attempts to quantify more accurately the population of mobile species that tend to escape detection due to avoidance behavior. This method applies some statistical corrections to the data by applying a detection function to the data based on the location within the field of view that mobile organisms appear. The accuracy of all of these approaches depends upon the reliability of the information relating the size of the field of view to images captured. This is not a trivial matter when platform pitch and roll are considered. The AUV ultimately may offer some assistance here by detecting and recording these variables for incorporation into field of view calculations.

Upon review of existing data, an analysis of the widespread coverage of sea urchins throughout the Gulf of Maine may be established. A series of broadly separated samples can be made initially in order to determine the regional distribution throughout the Gulf of Maine. As it is impractical for the AUV to travel long distances in order to take a statistically significant number of initial samples, it may prove worthwhile to take a number of samples distributed over a representative geographical area before relocating to a new region [Barry and Baxter]. From this data it is intended that an initial distribution assessment be made. Once the initial distribution is understood, statistical sampling is recommended in order to validate the initial assumption regarding this distribution.

Once the initial broad area sampling is taken, specific detailed samples may be made using higher spatial resolution. The initial sampling might utilize the greatest available altitude and single frame grabs spaced every two to three minutes apart. The operation of the vehicle might be to follow a particular depth profile, perhaps by traveling along a shoreline over a constant depth for some prescribed distance. Upon reaching the limit of travel in one direction, perhaps one to two nautical miles, the vehicle would then travel away from shore until a new depth is reached, turn back in the direction of deployment, and travel again the distance back to the starting point while maintaining a fixed altitude. This routine would be carried out for a number of iterations over depth, and in a number of locations geographically. The data may then be plotted as population observed relative to depth, and replication can be used to substantiate the data.

Once the geographically segregated data is obtained, the focus would shift to performing a local survey. This type of operation would be intended to allow an eventual assemblage of a "mosaic" image of the area covered. It is recognized that the technical requirements associated with generating a mosaic are not trivial. Considering the current stage of the AUV's development, it would be most practical to recommend that data be gathered to form a faux mosaic only. With this in mind, the data must be gathered as carefully as possible so that a general representation of an entire rectangular section of sea floor may be generated. This requires that the swath width of the image be maintained very carefully and that navigation be performed with precision to determine, through calculation based on vehicle navigation data, the true location represented on any frame.

In order for a reliable swath width to be maintained, the altitude of the vehicle above the bottom must be maintained or at least measured and recorded throughout the survey. Corrections may be made to the images after the survey is complete in order to normalize the data. Described in detail in the technical section of this report, the use of parallel lasers allow for very accurate image scaling, and are useful for normalizing the data.

For the vehicle to maintain accurate positioning at all times throughout the survey, the use of external navigation aides is recommended. The use of an external array requires the positioning of at least three pingers, and the system accuracy depends upon the degree of accuracy to which the exact location of these pingers are surveyed in place. The existing system employing a Long Base Line (LBL) external array achieves reliable accuracy with pinger separation of approximately 1.5 km [Bellingham].

[Bellingham] Alternative methods to the LBL system are available to the AUV, but are not suitable for most system operations such as benthic surveys. These alternatives include: dead reckoning, Doppler velocity log, and inertial guidance. Dead reckoning is a system by which heading and speed are measured and recorded. From this information, ongoing calculations of location are made. An inherent problem with this navigation technique is that operation in the presence of currents will confound velocity measurements and these errors will accumulate over time, constantly increasing the size of the error circle. The use of a Doppler velocity log helps to reduce the error term by measuring vessel velocity relative to the ground. This is accomplished by measuring the Doppler shift of a signal bounced off of the seafloor. This system is capable of accuracy to within 10 percent of the distance traveled, but may be useless at very high altitudes. Inertial guidance systems similar to those used by aircraft are restrictive both due to power requirements and performance. Inertial guidance systems are rated in terms of drift rate, and the systems currently employed aboard commercial aircraft are generally good to about 0.5 nm per hour (1/2 knot). This error may be acceptable for traveling at aircraft speeds, but mounted on a vessel that itself may only move at 2 to 5 knots, this represents an error of between 10 and 25 percent. These systems tend to be very expensive, and considering the error, the Doppler velocity log is a much better option.

Where the use of an external navigation aid is prohibitive, the vessel will have to be able to accurately maintain dead reckoning starting from some known location as confirmed using GPS on the surface prior to launch. Numerous systems have been proposed for this purpose, but this discussion is beyond the scope of this paper. The current navigation system available on the Odyssey II platform utilizes external baseline navigation aides most effectively, and in the absence of such aids, set and drift may introduce unaccountable error. Ultra Short Base Line (USBL) systems may be used to track the vehicle as opposed to control its navigation. This system is used from a surface vessel to track the range and bearing of the AUV. This system is capable of accurately tracking within about 1 to 1.5 km in the shallow waters typical of a benthic survey. The implementation of a well planned deployment strategy may be the best way to avoid problems concerning navigation. The vehicle can be operated for short duration outside of the baseline, but careful placement of pingers relative to water depth and intended vehicle traverse can assist in improving navigation accuracy.

It would be entirely practical to ignore a navigation system entirely for benthic survey work and simply command a traverse along a constant depth profile for a fixed distance, turn in the direction of deeper water, return for the same distance as before, and continue. The vehicle can quite easily be tracked using the USBL system described throughout the deployment. To aid vehicle location on the surface, the vehicle is equipped with a radio beacon that may be picked up with a radio directional finder quite effectively. Should the vehicle surface at night, a highly visible (at least 3km) strobe light has proven to be very satisfactory in field operations for immediate spotting.

5.1 Additional Utility as a Benthic Survey Tool

Once the statistical data has been gathered, it will be valuable to gather certain habitat and behavior data using this system. Habitat data is inherently present in any image captured, where local geological and flora information is readily available in the images. In order to generate reliable time series data, the vessel will need to either remain on station for an extended period of time, or have the ability to return to a given location with accuracy and repeatability. The ability to do either falls back to the degree of accuracy possible through the navigation system employed. Using external acoustic navigation aids, the Odyssey II has successfully been able to maintain 1 to 2 meter accuracy. In terms of bottom observations, this accuracy will be more than sufficient in order to allow evaluation of the data gathered. The use of geological features will allow the analyst to recognize a particular location provided the altitude is sufficient so as to provide adequate coverage of an area. The ability of the vessel to remain on station also will require the vehicle to stem any current without making headway. This implies an ability to maintain pitch, roll and yaw in currents that may range from 0 to 5 knots. Currently, the Odyssey II vehicle has not proven a capability to do this effectively in very low currents. In the presence of greater currents, the ability to hover is practically equivalent to the existing control system's capability to maintain a constant altitude above the seafloor during deployment. In very low current conditions, the vehicle tends to demonstrate dynamic instability, where adjustments made to elevators and rudder produce little if any modification to vehicle pitch and yaw. This problem is inherent in any submerged craft, and could only be realistically addressed through the incorporation of a dynamic control system functioning within the vehicle. No plans are in the works to address this issue.

5.2 Considerations Regarding Survey Approach

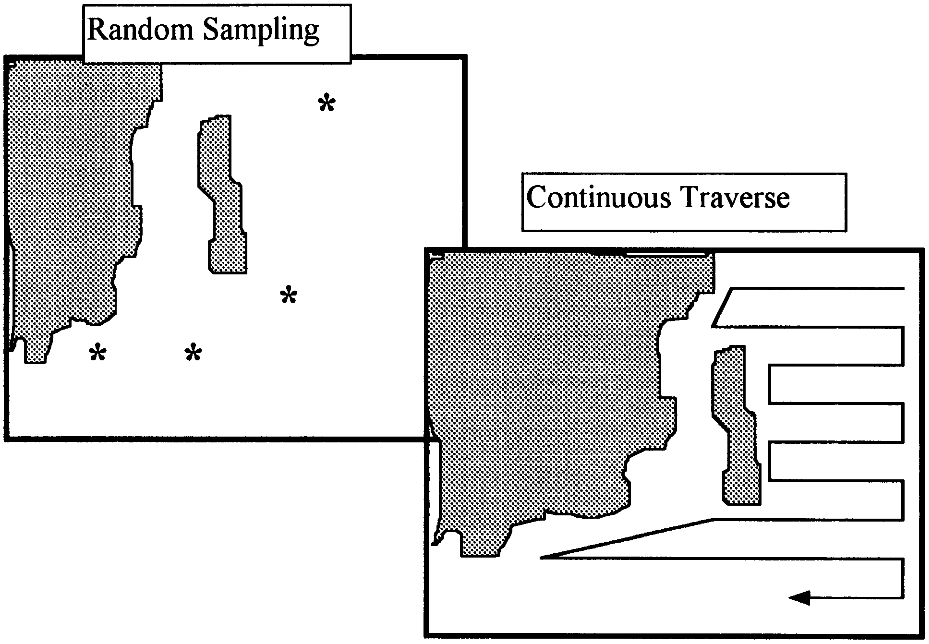


Figure 5. Two Proposed Survey Strategies. Random and Transect methods are recommended by [Auster, undated and Davis]. The random approach can be accompanied by local short passes widely distributed throughout a region of interest.

The approach used for performing a survey is just as significant as the hardware selected. For many studies, randomizing the data both in time and in spatial relationship is important. [Auster, 1995; Barry and Baxter] all describe a variety of sampling strategies, including transect and a random approach, as depicted in Figure 5. It is significant to first attempt to understand the broad perspective and then attempt to formulate a sampling strategy. Species may have local abundance and be distributed in patches, or around a geological feature such as the lee of an island. The survey ought to take this into account. Figure 6 demonstrate the importance of understanding the effect of patchiness, and the utility of planning a survey routine according to the anticipated population distribution.

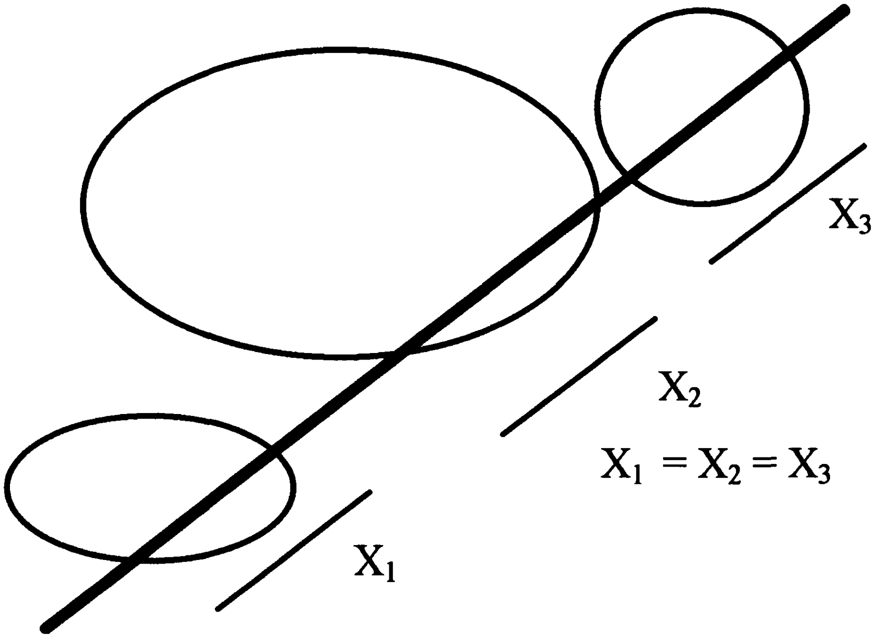


Figure 6. The importance of understanding "patchiness". In using random surveys, some information must be obtained regarding the distribution of patches throughout the region of interest. In this figure, all three "X" dimensions are the same length, although they represent vastly different populations in each patch traversed.

5.3 Economic Justification for Improving Survey Capability

In considering the costs associated with any management practice, one must weigh all of the alternatives carefully. Relative to performing ongoing benthic surveys, managers could allow resource consumption to continue without any feedback or they could employ a variety of alternative technologies to achieve the same results. Thorough evaluation demands consideration of all costs obvious and hidden. A significant external cost includes the cost to the industry and to society resulting from total depletion of a resource. This cost has received widespread attention by numerous authors in the past few years, and bears mentioning here as it is closely coupled to an effective management scheme intended to maintain long term stability of a living resource. At a more subtle level in the economic evaluation scheme, one must recognize the increased costs associated with increasing levels of imbalance that an unstable system exhibits. Far less energy (resource) is required to stabilize a system that exhibits minute variations from an equilibrium position (be it static or dynamic) than one that has already exhibited dramatic departures from neutrality. The cost of prevention at an early stage in the development of a management plan is often a small fraction of what is necessary to implement corrective action later on.

Relative to earlier discussions regarding the old paradigm approach which was "borrowing from the future," the employment of this proposed technological strategy would be an investment in the future. While the true costs of owning, operating and managing an AUV are uncertain presently, the costs are likely to be on the same order of magnitude as ROV hardware without the additional costs of operating a surface vessel. A commercial ROV equipped with camera hardware can be purchased for approximately $50k. The tether and necessary surface equipment might bring the total package cost up to approximately $100 to 200k. Daily surface vessel operations including facility to manage a tether may run $30 to 50k including crew, fuel and overhead. The AUV could realistically become available for commercial use within two to three years at a cost of approximately $150 to 200k. This is on par with an equivalent ROV. The substantial savings offered by the AUV are in the daily operational costs. An AUV the size of Odyssey can be realistically operated by two people aboard a common fishing boat or deployed from a modest dinghy, and operated from shore. The selection of an appropriate surface vessel is no longer contingent upon the ability to manage a tether, but rather upon the distance off shore and the sea conditions. The daily operation of a suitable fishing vessel or ship of opportunity can be as low as a few hundred dollars per day. It seems reasonable that this cost may be justified by fishery managers as a valuable investment in society's future.

6.0 Integration into existing Management Scheme

The mere introduction of improved technologies does not imply that they present tangible value to society. Among all of the constituents within a society, a consensus relative to the goals and philosophy of a particular technology is required in order to assure the proper use of that technology. It is through the conscientious integration of this technology into a strategy that is based on long term objectives including sustainable management of resources that success may be possible. The invention of the hammer would have been meaningless unless someone learned to use it effectively to build shelters and other accouterments of value to society. Numerous tools have been developed that offer the potential for direct utility provided they are used appropriately, but present enormous threat if used with malice. The simple example of a hammer may again be used. As a tool used in construction, the hammer is indispensable, however, in the hands of a crazed lunatic, the modest hammer may posses lethal capabilities. In order for a new technology to be of value to society, the use of the technology must be accompanied by a community-wide acceptance of the spirit in which the innovation was conceived. A "fresh" technology such as is prescribed here, can only be of benefit provided community consensus allows for better management and honors the "new" assumptions regarding the role of technology, science and finite resources in the management scheme. It is a choice that must be made, not only by the managers of a technology application, but also by those in the position to monitor and control its use.

Effective use of detailed feedback by managers is critical for the overall management scheme to be effective, thereby justifying the use of the AUV based video platform. In general, a management plan of action must address the total demands placed on a resource in terms of the rate of resource consumption, impacts upon the resource by external pressures such as habitat destruction, behavior modifications (imposed upon the species itself) and critical reductions in populations. The aforementioned AUV, is simply a new and improved tool available to the community of scientists involved in marine resource management. The proper utilization of this tool requires responsible use including interpretation and dissemination of the information obtained through its deployment. It is not within the scope of this paper to address in detail the strategy that may best utilize this tool, but only to make clear the potential hazards associated both with not using an effective feedback tool, and more-so the risks of misuse of the very tool intended to provide more accurate information to the manager. It is easily conceived how a fishery could be rapidly depleted due to the increased efficiency which may be gained through the employment of a sophisticated form of fish detection hardware. The intention of providing "telepresence" in the marine environment is not to allow for a thorough cleansing of the sea floor by greedy fishery persons, but rather to provide a clear and detailed depiction of the true status of the fishery itself. There is very little that an engineer involved in the development of a controversial tool can do to prevent misuse of the tool itself other than to warn of the potential destruction that this tool is capable of wielding.

Part II Technical Approach For Developing Benthic Surveys using AUV Based Video Systems.

7.0 Potential Survey Requirements

Our objective is to develop a tool to perform benthic surveys. These surveys are defined to include observations of the habitat and the resident flora and the fauna primarily in, but not limited to coastal zones. As a test case we consider counting sea urchins in New England waters. Of particular interest is the habitat, the behavior, and the population of urchins in Maine coastal waters.

Sea urchins are harvested throughout the Gulf of Maine as a seafood product for domestic consumption and commercial export. Eaten raw, the roe (gonads) is served in Sushi bars, and commonly referred to as "uni." Japan is the primary consumer of exported urchin product, with the Maine urchin being retailed as a supermarket grade commodity. Commercial harvest has been taking place for approximately six years, with nearly 50 million pounds of urchin removed from Maine last year alone [Canfield, 3/15/94]. It is now the second most valuable seafood industry in Maine, following lobster.

The resilience of these creatures to harvesting efforts is not well understood. Urchins are primarily harvested by divers operating out of small craft (10 to 30'). Some dragging has been attempted, but the operation tends to damage the shells of the urchins. Any stock removed in this fashion tends to have a reduced commercial grade and may not be suitable for export. Dragging as a form of harvest has not been widely accepted, and many believe that dragging efforts destroy habitat as well as commercial stock. Recent legislation has been introduced that is intended to reduce the impact that the divers and draggers have been making on the urchin population. This has become a political issue as well as a natural resource concern. Currently, much more information is needed regarding the habitat requirements, the behavior, reproduction and the impact of harvesting on the survival capability of the urchins.

Strongylocentrotus droebachiensis, commonly known as the green sea urchin, is common throughout the Gulf of Maine. They are approximately spherical in shape, roughly 5 to 10 cm in diameter at maturity, with (2-5 cm) long sharp spines and green to black in color. Mature urchins of this variety have spines that range from 2 to 3 cm in length. These creatures tend to populate in large carpet like clusters when migrating across exposed regions of sea floor. Little has been documented of this migratory behavior and rate of travel, but it is believed that they travel in search of food.

Commonly referred to as the "feed line" by urchin harvesters, a distinct boundary exists between an abundant supply of kelp and the barren, rocky sea floor. This is often recognized as an ideal place to find urchins. Kelp growing in the shallow waters tends to be present in large quantity to depths of approximately 30 to 50 feet. When a cluster of urchins reaches a food source, the lead urchins tend to stop marching, and settle in to eat. The next rows of urchins will climb over the lead group, and settle in just ahead. This behavior continues until the entire carpet is stationary, or has broken into smaller groups congregating around food sources. Once in the vicinity of rich food supplies, the urchins tend to become well distributed and well anchored to the rocks.

Urchins that have been able to forage successfully for extended periods of time (on the order of months) will tend to change color and texture in such a way as to resemble their habitat. These camouflaged urchins are very difficult to detect even by trained divers viewing from as close as a meter. The spines on these urchins tend to shorten considerably (to less than 1cm), the body texture becomes less rigid, and the body color becomes reddish brown. At any given time throughout the year it is possible to observe sea urchins either on the march or settled in. This implies that detection will need to be flexible enough to account for urchins that are difficult to observe at the base of large sea weed clusters as well as those in carpets that may be two levels deep.

Commercial quality of sea urchins is dependent upon the roe content, graded both for its color and texture, and priced by weight. The quality of the roe tends to vary seasonally, and tremendous disparity in quality may exist over very short geographical regions of harvest. Urchins found in deeper (down to roughly 100 feet) waters tend to have lower roe content and are generally identified by their longer sharper spines and smaller, darker shells. While it is generally understood that the higher quality urchins reside in the shallower waters, excessive harvesting pressure has driven efforts to find urchins into deeper waters. Additionally, urchins with very low roe content are often harvested despite their low market value at times when demand is very high. Some biologists fear that this may interrupt a critical link in the reproduction cycle and ultimately be detrimental to the long term survival of the species.

In order to more fully understand the biological and behavioral characteristics of sea urchins (and other benthic fauna), a tool is needed that will allow the rapid and economic evaluation of urchin populations along the New England coast. In the remainder of this work, an evaluation is made of some potential hardware which may facilitate this type of survey. A single option is selected and evaluated in more detail through the development of a test which is believed to be a suitable approach for analyzing the effectiveness of this hardware for performing this type of benthic survey. The physical parameters affecting the operation of the survey system are addressed. The selected hardware is discussed, data gathered with this hardware is analyzed and evaluated. Finally, suggestions for future work in this area are made.

7.1 Physical Considerations

Water clarity in the coastal regions typical of Maine vary tremendously throughout the year, and from region to region. In periods of extreme calm over rocky areas, visibility may be as high as 10 to 15 meters. Storm events and river estuaries are primary sources of turbidity that can reduce visibility down to 1 meter or less. In areas just outside of slow moving rivers and streams there tends to be a very high degree of siltation throughout the year, with extreme high present during spring runoff. These areas are zones of regular siltation that tend to become very turbid during moderate disturbance due to storms or wave action.

A number of natural and manmade obstacles exist in the coastal Maine waters that may make operations difficult. Water current throughout the coastal Maine region can reach 2 to 4 knots or higher in localized areas. Lobster pot buoys and lines, which present navigational and operational hazards, are quite prominent throughout any region with large populations of sea urchins. Coastal terrain is very steep and irregular with numerous navigational hazards unmarked on USGS charts. Some obstructions are poorly marked, or are only recognized by locals familiar with the area. This encumbrance may make operation of any vessel difficult to the unfamiliar helmsman. Taken in combination with the lobster pot markers and the swift currents, these difficulties make the operation of towed instrumentation hazardous. Proper care and precautions are highly recommended before undertaking any survey work in the coastal Maine area.

7.2 Illumination Concerns

One of the greatest challenges facing the underwater photographer lies in the selection and proper application of illumination. No significant amount of ambient light penetrates beyond approximately 300 feet in sea water. Depending upon latitude and degree of clarity, light in the blue-green end of the spectrum may penetrate to depths of 80 to 100 feet. Light is attenuated through two primary phenomena, absorption and scattering. Absorption is the processes in which light photons are lost from the beam. In water most photons are lost as a conversion to thermal energy. Scattering involves a change in the direction of the photons without loss of the photons themselves. This is typically due to the presence of suspended particles and organic matter within the water. Both absorption and scattering can be wavelength dependent, and, in water, a minimum in the attenuation curve occurs in the blue-green region, with attenuation becoming severe in the ultraviolet and infrared regions. Figure 7 demonstrates the relationship between attenuation and wavelength.

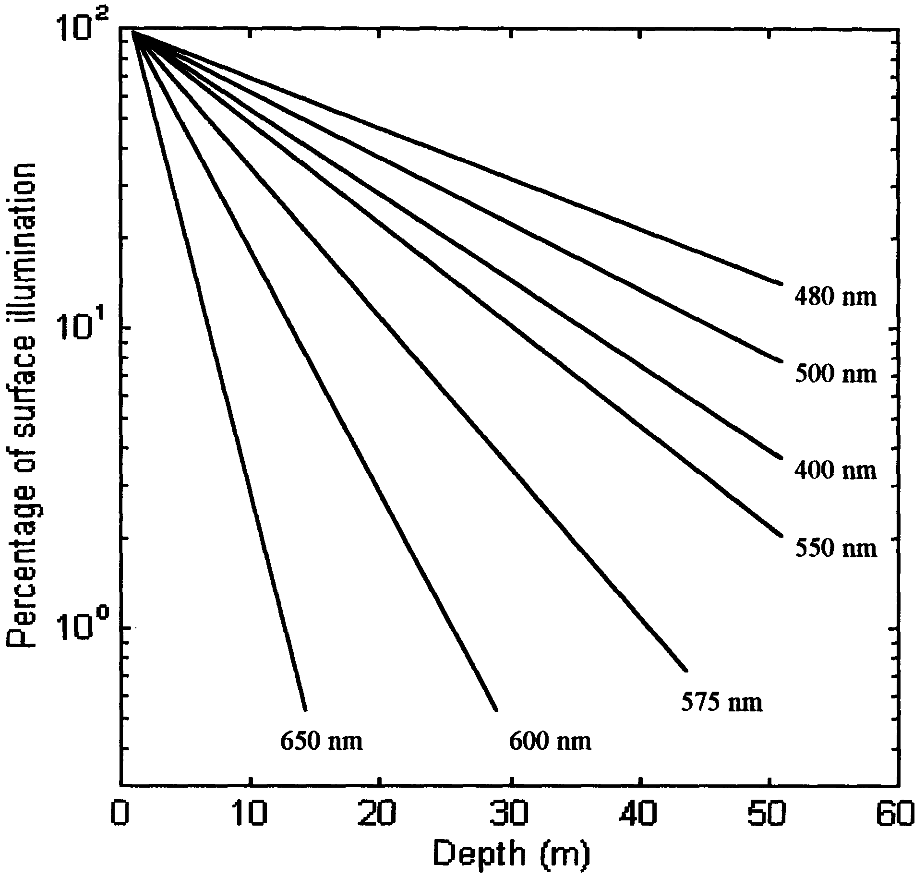


Figure 7. Approximate attenuation of downward illuminance as a function of water depth and wavelength of light for clear tropical water. [after Mertens] Notice that there is a decrease in attenuation around the 480 and 500 nm wavelengths.

To generate the highest quality images, ambient lighting may not be relied upon, in general, for providing sufficient illumination. The use of a strobe will help to provide a known quantity of light for a given scene. The most energy-efficient method would be to measure the ambient light using a light meter, and determine whether the lighting conditions require the firing of the strobe. This is not necessary for any reason other than conserving battery life. In any case, effect of the strobe must be well understood in order to assure proper exposure, as the only available adjustments that may be made in-situ come from the dynamic range of the video camera itself. If the strobe has the capability to "bloom" the CCD by providing excessive amounts of light, there is nothing that can be done once the system is deployed and operating.

Along with recognizing the need to provide a known light source, optical backscatter may cause substantial degradation of image quality. Backscatter is the reflection of light off of particles suspended within the illuminated volume of water. When there is an abundance of very small particles (including some micro-organisms) present in the water column this effect can produce images that appear to have been photographed in a snow storm. There are two options available for preventing the negative effects of backscatter. The first is to separate the camera and light source so as to achieve as oblique an angle as possible. This causes reflected light in the water column to be directed away from the camera. The second approach is to use polarizing filters on the light source and the camera. The two filters must be oriented so that their axis are perpendicular to one another. This same effect may be accomplished by using circularly polarized filters and setting the two polarization orientations in opposite directions. Figure 8 demonstrates the use of polarizing filters to reduce backscattered light.

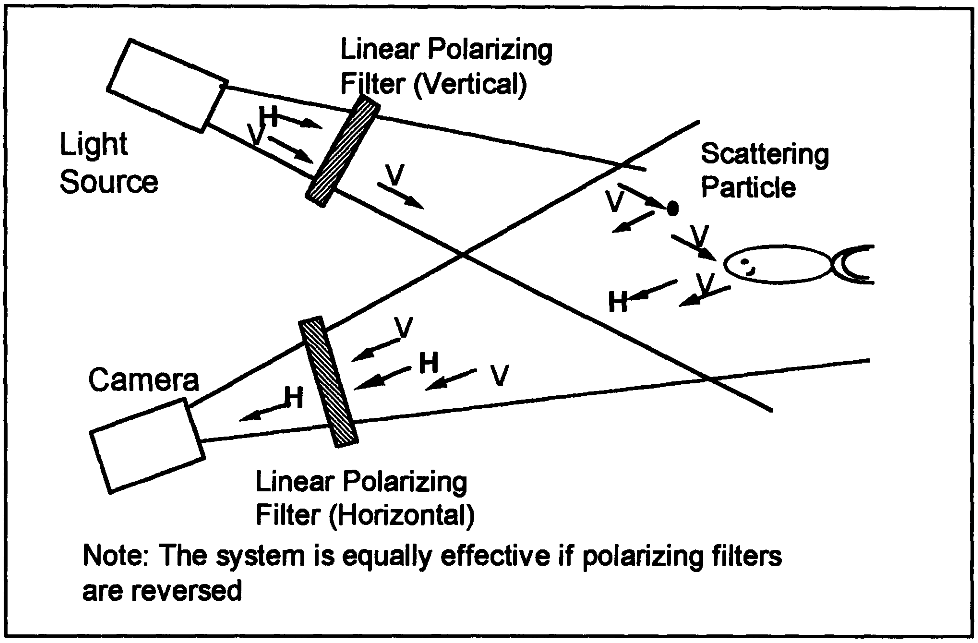


Figure 8. Linearly cross-polarized filters used to reduce backscatter from particles suspended in water. Circularly polarized filters would produce the same results. [after Mertens]

7.3 Criteria for Evaluating Resolution

Early on in the development of this system, it was decided that the most critical technical issue to address on using an imaging system for benthic survey work would be the potential resolution of the system. It would be necessary to determine whether or not a single sea urchin could be identified under various lighting and clarity conditions. If so, at what range could they still be identified was the next question. The greater the available altitude that a survey could be performed at, the greater the area of coverage per unit time. Thus, the resolution issue became the primary concern to be addressed.

The key to being able to identify any particular feature resident in the benthic habitat captured in a still or video image comes down to the issue of resolution. The ability to distinguish shape, texture and relief are required for a viewer to correctly assess the presence of a specific object viewed in a photograph or video recording. It is the contrast provided between the light and dark areas on an image that allow for the interpretation of an 'edge' or boundary. These edges are what translate into a shape in our interpretation of the images. Observing the shape, analyzing the shadows and perception of texture, allows a human observer to determine that the region of light and dark shading is in fact the object that they believe it to be.

Consider viewing a standard eye chart from twenty feet away. If you have typical vision, all of the letters on at least the first few lines are distinguishable to you. At some point as you observe increasingly smaller rows of letters, the lines of letters appear to be a wavy blend of light and dark markings. Smaller lines of letters further down the chart appear to be a single dark horizontal line. As you slowly move closer to the chart, the dark wavy line begins to take on more and more distinction, and you begin to make out individual letters. The once solid line below also begins to become less solid looking, and it too eventually reveals greater detail. This is all the effect of being able to resolve the distinction between the light and dark edges of information recorded on the chart.

[Mertens] analyzes an imaging system's ability to resolve detail based upon the use of a modulation transfer function (MTF). This analysis measures response to a continuous sine wave using a direct Fourier transformation applied to a signal generated by imaging carefully measured, equally spaced white and black bands. He recognizes that image contrast is directly affected by the attenuation coefficient of water and notes a "rule of thumb" approximation [Duntley, 1966] for estimating the water attenuation coefficient. After presenting a detailed analysis of how to calculate the resolving power of a system using the MTF, [Mertens] concludes that approximate methods to assess a system's capability for detecting "small bottom-dwelling animals - such as sea urchins, starfish, anemones, worms and fish" are generally more useful than the MTF approach. His reasons include; an inability to specify differences between real objects, such as different animal species, in terms of the required sine wave response, the potential for substantial path length variations between objects imaged in the center of the swath and those at the edges, and the difficulty in applying a standardization to film interpretation processes due to the "human element involved." These practical limits justify the use of a qualitative analysis method for evaluating image resolution.

8.0 Available Options

8.1 Photography (Still and Video)

Two readily available types of underwater photography are appropriate to this type of survey; still and video photography. Underwater still photography consists of the same basic elements as are used on land. The typical underwater camera consists of a pressure housing that either encases a standard (i.e. 35mm SLR or other) camera, or is a camera designed specifically for underwater use (such as the Nikonos line). For underwater video systems, two options exist. The first option is to take a standard land based video camera (VHS camcorder, etc.) and enclose it in a pressure housing. The second option is to purchase a video camera designed for underwater operation. These tend to provide significantly improved image reproduction, although they are generally more expensive. In either case, the basic photographic considerations must be made as would be appropriate on land, with additional concerns due to physical limitations imposed by the water.

8.2 Laser Line Scan

As an alternative approach to photography, we shall consider a recent innovation using a system based on laser based light reflection, the laser line scan. Laser Line Scan is a method in which a single laser source is traced across the sea floor, with a detector tracking the reflected light source. In essence, this system is taking a very large number of reflection measurements of very small areas and assembling them together to form a complete image. The system is able to obtain satisfactory images in water of relatively high turbidity, often too turbid for standard photography practices [Carey]. Concerns regarding the use of this relatively new technology include the cost of operating the system, the resolution of the images generated, the general availability of this hardware, and any operational restrictions (e.g. hazards to the towed instrument head).

8.3 Side Scan Sonar

Side scan sonar is not considered as an alternative technology, as it is impractical for a variety of reasons. The first drawback to this system is the resolution available using standard systems. The typical range resolution, defined as the minimum distance between two objects perpendicular to the line of travel that will be recorded on paper as separate objects, is approximately 0.4 meters [Flemming]. This is insufficient to resolve urchins. More sophisticated systems, such as color enhanced sonar technologies, increase both cost and complexity, yet still lack sufficient resolution. Side scan may prove to be most useful in mapping species habitats or large scale patches of a habitat. [Auster, 1992; Able] Particular applications and difficulties associated with this technique have been investigated. In general, while being ruled out for this particular application, this tool may prove most effective once a general association is developed between urchin habitat types and large scale behavior patterns including migration and feeding, and for providing very broad coverage for ongoing habitat monitoring. However, for specific census data and small scale behavior characteristics, side scan sonar systems with the desired resolution are either unavailable, or very expensive, or both.

9.0 Evaluate The Alternatives

9.1 Laser line scan

We first evaluate Laser line scan as an option for performing the desired survey work. The quoted cost for this system has been given as approximately $5k per 24 hour period [Carey]. This system can operate in all ambient lighting conditions, although it is best to operate in the low light conditions such as in deep water or in the dark, where the laser provides the only source of light for the photo-multiplier. The laser system requires care in handling the equipment, especially in handling the delicate mirror assembly used for tracking the signal. While this apparatus is all housed within the towed fish, mishandling or jarring, such as might occur if the towfish grounds can render the system inoperable. This presents a significant deterrent for operating this system in the rough terrain that is likely to be encountered in Gulf of Maine waters. Power consumption of the system evaluated is approximately 200 Watts input. While this may present a problem for deployment off of vessels of opportunity, an appropriate surface vessel is included in the quoted cost.

The resolution of images captured by this system depends on the beam swath-width selected. In general, it is possible to achieve images on the order of 4 to 5 attenuation lengths, and a swath width of approximately 20 foot (6.1 m). One sweep is represented by 2048 pixels. Using the 20-foot-swath width, this results in a resolution of approximately 8.5 pixels per inch (3.3 pixels / cm), or the equivalent of 0.12" (0.305 cm) per pixel. Towed at a rate of 4 knots, this translates to a coverage of approximately 1 km^2/day. Maximum range of the system is theoretically (not yet accomplished, and assuming an attenuation of 20 to 25 foot) 180 to 200 foot (55 to 61 m) wide swaths. At this width, and with a maximum tow speed of 6 knots, this represents a coverage of approximately 16 km^2/day with a resolution of approximately 0.85 pixels per inch (0.33 pixels / cm), or approximately 1.2" (3.05 cm) per pixel. Based on the scale selected, the speed of the towing vessel is chosen and rather careful maintenance within a narrow range of speed is required. Some systems are capable of adjusting speed of the scan to accommodate changes in tow rate. Images have been mosaiced together to form a total coverage of a large area, but in practice, this may present significant challenges due to the rapidly changing bathymetry representative of Maine's coast.

Two types of data recovery and storage are available, depending on the system selected. They are digital image capture or immediate conversion to video signal. If a digital image is selected, the data generated will be on the order of 1 Megabyte per second. This may present certain hindrances in operation, but data storage systems are developing rapidly and some immediate data analysis and reduction may be performed concurrent with data collection in order to reduce the amount of data stored. If an analog video signal is selected, it may be stored using standard video recorders for later analysis or digitization. This technique may eliminate some of the detail that is available in digital data format, but for many applications, this is acceptable. Additionally, much data that is captured and stored digitally may be redundant (consider a gray sea floor with minimal variation) and certain data compression techniques may be practical.

9.2 Video

A wide variety of underwater video cameras are commercially available, generally based on Charge Coupled Device (CCD) imagers. These circuits are commonly used in consumer video products. The imager is a matrix of pixels, typically separated by about two microns. When light strikes a section of the CCD, an electrical signal is generated that depends on the intensity of the light at each pixel. Information is "harvested" from the CCD by sequential access to the lines of the array. The effective shutter speed of the device is controlled by the electronic control circuitry. The data can be digitized and stored in digital format for future manipulation and editing, or saved in an analog form on video tape. There are two common standards in the industry for CCD imagers. These are classified as interline transfer and frame transfer. The interline type device transfers the data off of the CCD chip in the same fashion as standard television signal is painted to a picture tube. All of the odd rows are swept within approximately 1/60th of a second, and the even rows are then swept in the next 1/60th of a second. With interline, often the even rows are erased when the odd rows are read, and vice versa. The frame transfer type device harvests the rows of data in sequence, making this preferable to the interline style when strobe lighting will be used. This ensures that all rows of pixels contain usable information.

The benefit of the CCD circuitry is in its capability to perform very well in low light conditions with intensification to as low as 10^{-6} lux [Benthos Model 4203 TV ICCD], but for normal underwater use, 0.5 to 5.0 lux is common. Resolution is typically on the order of 400 to 500 lines horizontal, some are equipped with zoom and / or pan and tilt capability. Prices for this hardware varies considerably, but it is possible to purchase a high quality camera with an operating depth of 1500 meters for approximately $3500.00. Surface hardware would consist of a video monitor, and some form of recording device would be required. All of the necessary equipment is readily available through standard commercial outlets.

There are compelling reasons to select video as the platform of choice for benthic surveys. Numerous studies have been done with varying degrees of success using still and video imaging systems, and much literature on the subject identifies the use of video as preferable [Auster, undated; Barry; Michalopoulos et al.]. In general, the use of video appears to have made significant impacts in the quality of information delivered. Among the benefits that are offered by video, are; immediate data retrieval (no turn-around time for processing required), the ability to provide insight into the habitat that a sample originated from, and the study of the avoidance behavior of fish, which leads to more accurate population estimates. Significant error may be present in population counts that are unable to detect species because they have avoided the towed instrument itself. Using video, this behavior may be witnessed, and more accurate estimates of populations made. Species diversity and abundance are recognized for their importance in understanding community structure and comparisons of one species to another. This level of detail in a benthic survey cannot be accomplished using laser line scan hardware. Still photography may capture some of this, but the inconvenience associated with that format may render it undesirable.

9.3 Make a Selection (video vs. laser line scan)

Based on the choice between the two practical options presented (side scan sonar being eliminated), video is chosen. Reasons for excluding laser line scan include; First, this technology is rather expensive, and unnecessary for this application. While the resolution is acceptable, the rate of data recovery is somewhat slow and lends itself more to a continuous coverage in much the same manner as side scan sonar. Second, the image produced by this process is generated by a beam directed straight down from the tow fish. The resulting images tend to lack three dimensional characteristics, making it difficult to detect the differences between objects such as a sea urchin and a rock or a sand dollar. Finally, the operation of a towed fish at a narrowly controlled speed over the bottom, in conjunction with a carefully maintained altitude is not trivial in rapidly varying bottom topography and currents ranging from 2 to 4 knots. Although [Hellemn] argues that laser line scan represents the intermediate step between side scan sonar and video as a tool for performing benthic habitat surveys, this particular technology does not appear to lend itself well to this application.

Given that video is selected, it is appropriate to point out some of the hindrances that are associated with this selection, and to identify (where possible) methods for dealing with these drawbacks. First, using video implies some method to record an analog image on a video tape or in digital format on a suitable medium. Current direct-to-digital cameras suitable for underwater use are both large and expensive, and are eliminated from further consideration for this project based on these constraints. The video output from an underwater video camera may be digitized and stored on a digital recording medium. Digital storage as an option must be considered very carefully, as a single video frame may consist of 300k-bytes (~500 x 600 pixels at 8-bits each) of data, thus demanding very large storage capacity. Using analog video format the system will need to either house a recording unit, or be limited to a tether over which video transmission may travel to the surface for subsequent recording. If a housed video recording system is selected, the taping mechanism will need to be operated remotely, or turned on at the onset of a mission, and turned off at the end of the mission. If this method is to be used effectively, the tape will need to operate continuously, or be timed to record for short duration with periods of delay between recording sessions. In this manner, the images may be obtained over a wider physical area, and the resulting still images may be recovered after the mission. Power for lighting will present a real limitation to the video based system, so battery selection must be made carefully.

How the data will be evaluated once it is gathered can have some effect on the technology selection. If tape storage is selected, consideration must be made to the amount of time that will be required for someone to view all of the data on the tape. If a person must sit for hours and view a vast amount of video tape in order to draw useful conclusions, this cost must be taken into account. The alternative to direct viewing of excessive video tapes is the use of some form of artificial intelligence which can extract and compile the desired data directly from the tapes. As this technology is not commercially available currently, the only practical method for analyzing video tapes is by direct viewing. The use of a digital storage medium does not facilitate any alternative method either, but may provide a better starting point if future software analysis methods are intended. It should be noted that there are products available that generate a digital image from a video tape should the need arise, and that the process of digitizing a video image discards a certain amount of information. For this reason, it is recommended that direct storage on video format be used.

9.4 Select a possible platform

The platform that will carry the imaging system must be selected. Among the techniques considered are; direct capture using a hand held system by a scuba diver, a towed, non-powered camera sled suspended from a surface vessel, a Remotely Operated Vehicle (ROV) operated from a surface vessel and an Autonomous Underwater Vehicle (AUV).

The currents in the Gulf of Maine can be on the order of 4 to 5 knots at times. These currents can make operating a small craft very difficult, and scuba diving with any form of control may be impossible. Operating a still or video camera while trying to swim, or while towing or dangling a camera system from a surface craft is very unlikely to provide suitable results, therefore we rule out scuba at this point. The operation of a towed camera sleds or ROV is plausible, but the potential for entanglement of the tether with the numerous lobster pot markers throughout the region must be considered.

ROV's are a realistic alternative for underwater imaging, but carry with them certain prohibitive characteristics. Among the drawbacks to an ROV for this type of work are the difficulties associated with tether management and the reduction of vehicle travel imposed by the tether. The cost associated with use of an ROV increases with the depth of operation and the tether requirements. Most of the difficulty associated with operating ROVs is attributed to tether management hardware and feasibility. For very large underwater vehicles with long tethers, the surface vessel requirements can become excessive.

Autonomous operation offers an attractive alternative to any technique mentioned and the potential for utilizing an AUV in this application is tremendous. The AUV is ultimately capable of performing in a similar fashion to the best ROV without the hindrances imposed by a tether or requirements of a full time operator. For example, the AUV Odyssey II, a vehicle still in the development stage, is fully capable of performing all of the necessary functions to successfully complete a desired survey routine. This allows greater lateral mobility relative to other proposed options. The AUV, due to the removal of a tether, eliminates some of the concerns regarding potential entanglement with lobster buoys and other obstructions. Eventual developments that will allow fully autonomous operation will further enhance the operational possibilities of this platform. With a fully charged battery set, the Odyssey II vehicle is currently able to operated continuously for approximately three to four hours. This is sufficient time to perform a reasonable video survey before charging batteries and loading a fresh video tape. This AUV is capable of performing benthic surveys with sufficient coverage of the coastal region, and of safely navigating in coastal environments.

9.5.0 Proposed AUV / Camera System

9.5.1 Components

Based upon the need to transport a video camera system (including power and possibly some form of artificial illumination), the desire to operate without a tether, and the intention to operate the camera system remotely or in some pre-programmed mode, the decision to utilize an AUV was reached. A suitable platform of this nature is the Odyssey II class vehicle under development at MIT Sea Grant Program, in Cambridge, MA [Bellingham]. An existing system has been mounted aboard the Odyssey II vehicle, and this system was used for initial testing. With the eventual inclusion of customized artificial intelligence software aboard the vessel, this platform will ultimately be able to take images, analyze the information obtained, and determine the best plan of action for adequate statistical coverage.

Along with providing data on the populations and locations of various benthic fauna, video systems equipped with pencil beam lasers are useful for providing quantitative information regarding the size of objects and species imaged. One elegant concept uses three lasers to provide a size reference and determine platform altitude [Tusting and Davis]. Two parallel laser beams of fixed separation are mounted alongside the camera. In every image recorded, there will be two spots representing this absolute distance, thereby providing the built-in measuring reference. A third laser is mounted in parallel to the light source. Because the camera lasers are mounted at a fixed angle relative to the strobe laser, a triangle pattern is imaged on the seafloor, with the distance between the two parallel spots and the single light depending on the vehicle altitude. (To obtain altitude, multiply the observed spacing by the tangent of the angle between camera and horizontal and add the result to the known offset determined by the length Y in Figure 9.). There are certain drawbacks to this system. In silty mud, or in very irregular surfaces (including heavy weeded areas) the laser spots may be undetectable. On sloping terrain, error may be introduced due to the perceived displacement of the laser spots.

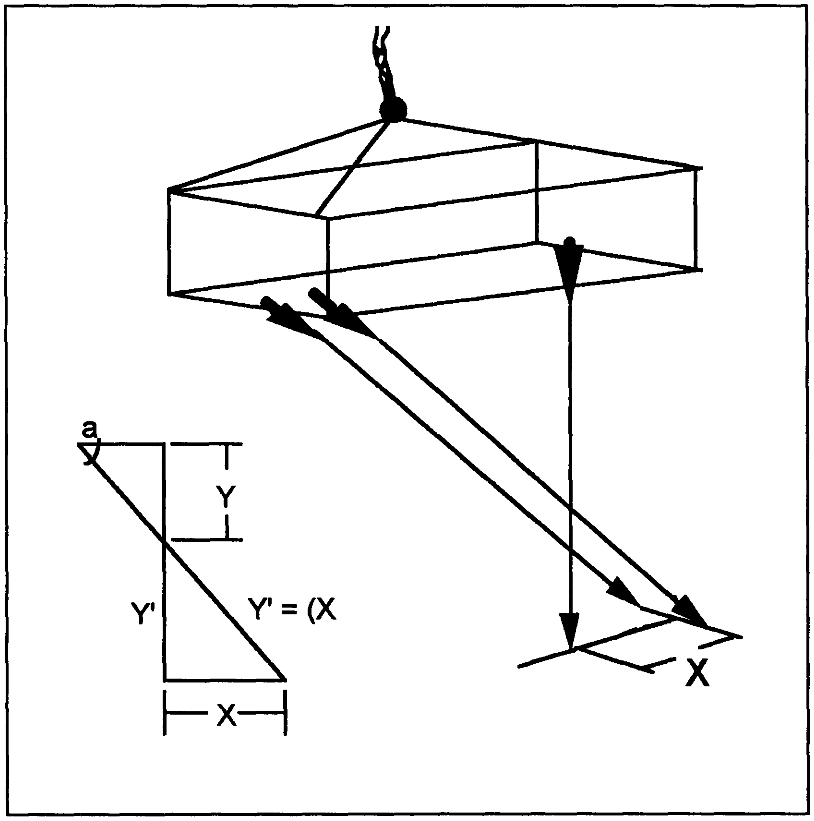


Figure 9. Wireframe representation of a tow sled employing three pencil beam lasers for reference measurements. The bold arrows depict the lasers, two in parallel with the camera, one aligned vertically. The fixed distance between the two parallel beams provides a standard dimension for easy object measurement. The geometry between the three lasers provides for altitude measurement [after Tusting and Davis].

9.5.2 AUV System description

A description of the components in the imaging system for the AUV follows, with discussion of the AUV system as it pertains to underwater imaging. The specific AUV used is the Odyssey II vehicle as mentioned previously. Detailed component descriptions and technical specifications appear in the Appendix at the end of this report. The camera used is manufactured by [Deep Sea Power and Light of San Diego, CA]. This imager is housed in a titanium case with a pressure rating to 10 kpsi. The output from the CCD unit is fed directly into a Sony Model TR-81 Hi-8 mm Camcorder that is housed within a 17" glass sphere. The camcorder receives commands directly from the Odyssey on board mission computer, including signals to operate, stop, fire strobe, etc. It is up to the mission operator to determine at the outset of a mission how the camera operation will be handled. The camera, camcorder and electronic control circuits all draw current from the 12 volt DC supply of the AUV. The strobe operates off of the 24 volt DC supply of the AUV. Commands to fire the strobe, and telemetry such as encoded data for presentation directly onto the final image, are all handled by control circuitry provided by [Pisces Design, Inc. of San Diego, CA]. Using the telemetry component, the vessel's computer is able to encode onto the tape the date, time, depth, and other useful information. This information is encoded onto an unused portion of the video signal. In order to view the recorded images along with the encoded data, a specialized playback unit is necessary.

Aboard the Odyssey class vehicles, the camera is mounted in the aft section of the craft, at an angle of approximately 30 degrees forward of vertical. The strobe is mounted far forward in the bow, pointing directly down. This arrangement is desirable as it tends to reduce back scattered light from the strobe creating "snow" effects on images. Having the camera tilted slightly forward tends to provide a sense of depth and image "relief" due to the slight shadows that are imaged. This lighting configuration is generally considered the most beneficial for observing benthic fauna [Auster, personal conversation; Mertens]. Figure 10 demonstrates the relative placement of the camera and strobe, as used on the test sled fabricated for this study and similarly used aboard Odyssey II. A description of the sled, its components, and its use follows.

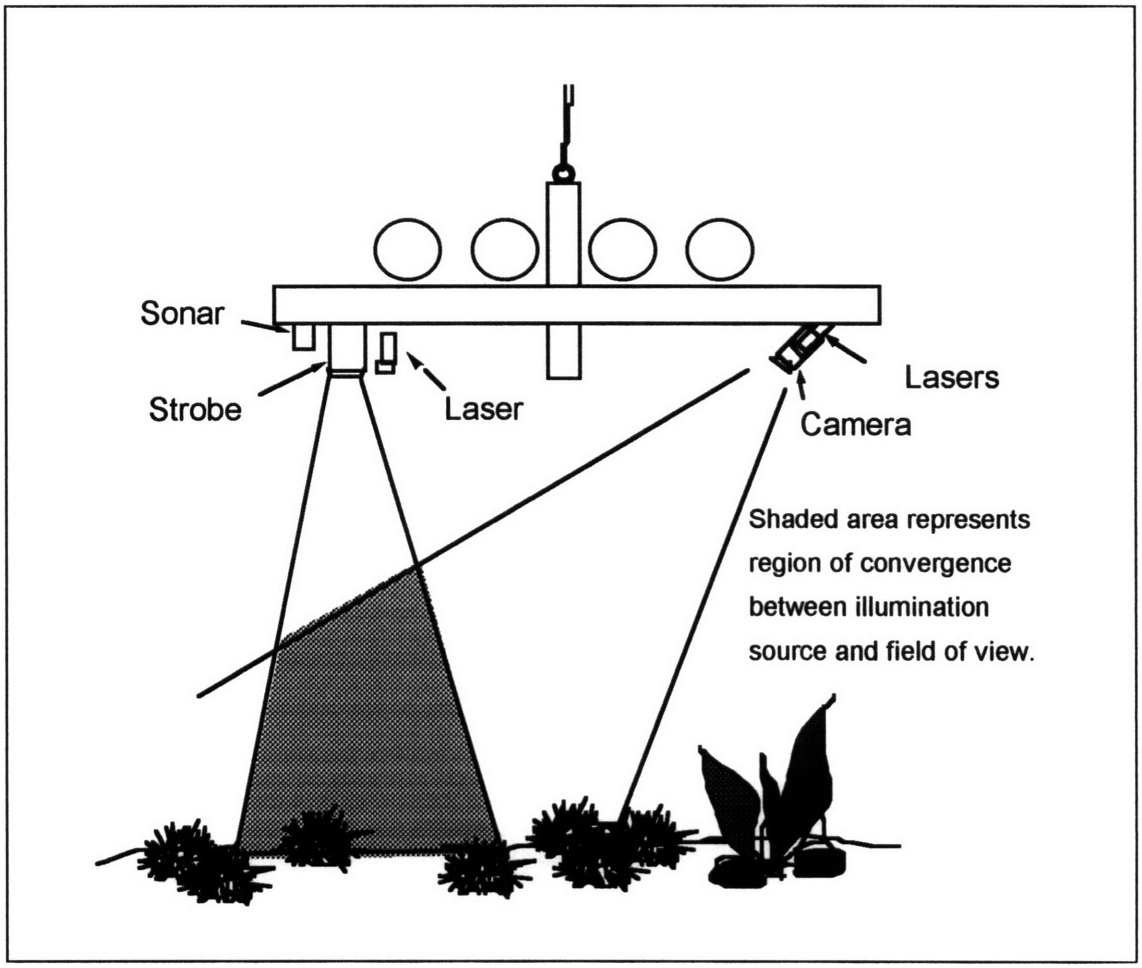


Figure 10. Overlap between illumination source and camera field of view. Placing the camera and light source at an angle creates slight shadows which tend to provide image relief. In addition, this orientation helps to reduce backscatter of light due to suspended particles.

10.0 The Test Sled

The schedule of the existing Odyssey II vehicle made it clear that the vehicle would not be generally available for video system testing. For this reason, it was decided to fabricate a suitable test fixture that simulates the physical characteristics of the Odyssey vehicle. It was decided that it would be highly desirable to view the video images in real time, allowing immediate corrections to the sled's altitude, and to evaluate the image quality in varying conditions. Thus, a 300 foot tether system was developed, with two separate cables segregating the 12 and the 24 volt systems. We initially selected an existing 300 foot electro-mechanical tether for the sled. This cable carries two co-axial lines suitable for video signals. Since this tether did not have a sufficient number of wires for all signals, a second tether was fabricated. Details of the two tethers are presented in Appendix A of this report.

The camera system used on the test sled consists of a CCD black and white camera. The imager housed within the 18 cm long by 5 cm diameter titanium housing is a modified Sony XC-73 camera, consisting of a 768 (horizontal) by 494 (vertical) pixel array. This unit is a frame grabbing system, as described earlier, suitable for use with a strobe light source. The camera was designed to operate at low illumination levels in the region of approximately 1 lux. Power consumption is approximately 5 Watts, operating at 12 volts dc. The strobe unit is manufactured by [Photosea Systems of Del Mar, California], and marketed as the model 1500 SX. The unit is housed in a 24 cm long by 11 cm diameter anodized aluminum case, and weighs approximately 6 lb. in air (1 lb. in water). The strobe intensity is 150 Joules, consuming approximately 8 amps peak and 4 amp average (over 3 seconds) power, operating at a nominal 24 volt dc. The strobe is rated for a maximum operating depth of 600 meters.

The test sled itself was constructed using extruded fiberglass structural members. These were assembled using stainless steel hardware and a two-part epoxy recommended by the manufacturer specifically for this material. Once the basic structure was fabricated, the camera and strobe were mounted in the same orientation and position as on the Odyssey II vehicle (Figure 11). With the two heaviest components mounted (camera and strobe), flotation was added to achieve neutral buoyancy. The flotation chosen was a set of fish net floats, each providing approximately 3.8 kg buoyancy. With four floats attached, the system was just slightly positive in buoyancy. Two 10 lb. (4.5 kg) lead dive weights were added, and two more floats were then added. The system with final weight and floatation was then approximately 1.5 kg negatively buoyant, with the two dive weights attached. A release mechanism was configured so that if the sled became entangled, and required considerable upward force for recovery, the dive weights would be released, leaving the sled roughly 7.5 kg buoyant. Additionally, the tether system was attached to allow recovery by pulling the sled in a direction opposite to the direction that it was being pulled when it entangled.

The optical backscatter sensor [D&A Instrument Co. model OBS-2], operates at 12 volts and has an analog output. This sensor was mounted and successfully tested in air. Final in water calibration is still required. The three lasers were mounted in a configuration similar to the manner described by [Tusting and Davis]. The lasers provide a capability for calibrating object size within image frames by providing two bright spots of light at a fixed spacing in every image. The forward laser was mounted along side the strobe, in a vertical orientation. The two aft lasers were mounted in parallel to the camera allowing for constant alignment to the camera orientation. Two light meters [International Light Inc.] were mounted so that one meter pointed in the same direction as the camera lens at all times, and the other was mounted facing directly up to measure downwelling ambient light. Signal conditioning electronics for the light meters were mounted on the sled, allowing a dc 0 to 9 volt signal to be carried by the tether. This was done to eliminate the potential for noise sources along the long cable imposed on an otherwise low voltage, low current source. The circuit created for this purpose is presented in Appendix A, and consists of a simple op-amp used to convert the milli-amp photo-detector current into a dc voltage with linear output characteristics within the range of interest.

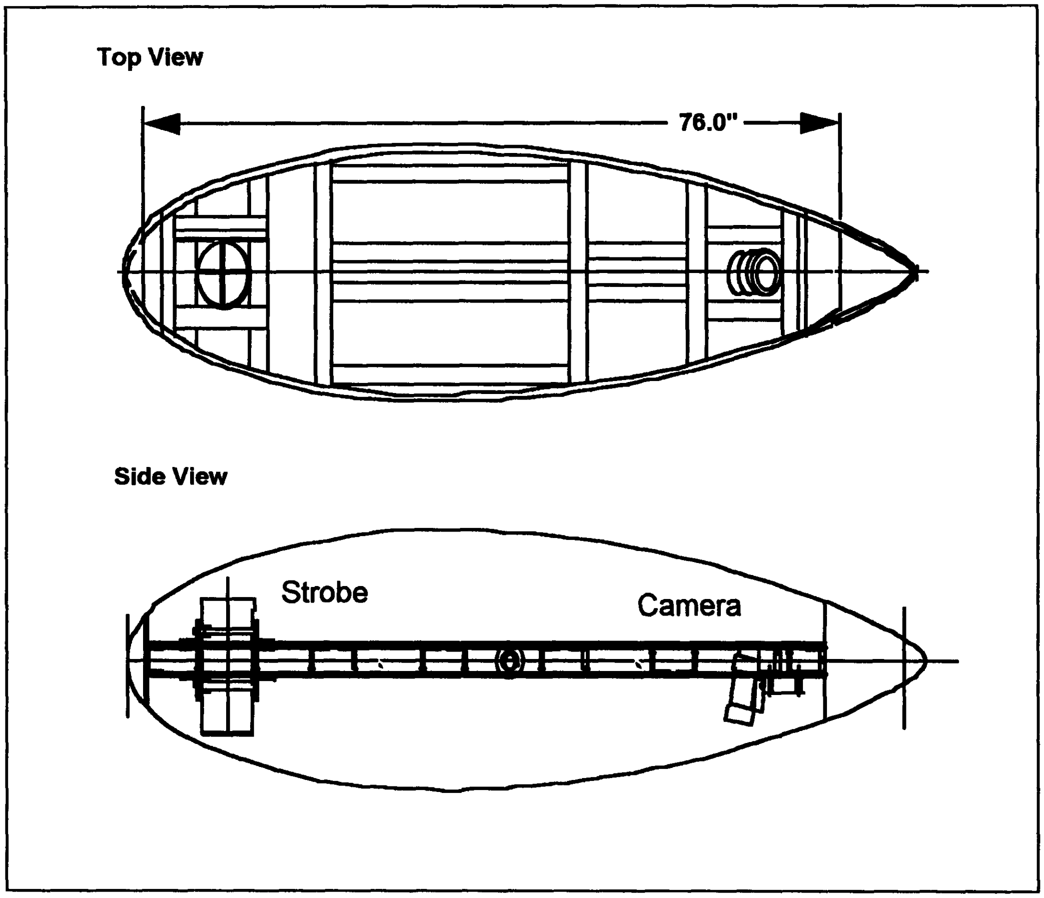


Figure 11. Schematic Layout of the test sled fabricated for this study. The camera and strobe placement was chosen to reproduce the spacing and alignment present on the Odyssey II vehicle.

10.1 Experimental Procedure

Once the basic structure of the sled was complete, ancillary equipment was installed and tested. Among the systems included on the sled were an optical backscatter sensor, three pencil lasers, and two light meters. A high resolution (+/- 10cm) sonar similar to the system utilized on the Odyssey vehicle was installed as an altimeter. The output from the sonar was delivered to a surface computer using an RS 232 serial interface. Initial plans intended to use an RS 485 interface due to the proposed transmission length, as RS 232 is only intended to operate at a maximum distance of 50 feet. Difficulties associated with operating the RS 485 board led to the decision to attempt to drive the signal over a longer distance. Tests performed in the laboratory proved successful, but the sonar has yet to be operating in water for confirmation.

The entire system was assembled, and tested first in the 12 foot (3.6 m) deep MIT pool. For the first tests, the light meters, the sonar, the optical backscatter and the strobe were not installed. This allowed us to focus our attention on the camera system exclusively. Data was gathered at various depths using a variety of black on white printed targets. Figure 12 demonstrates the 40 mm target used, the remainder of the test targets appear in Appendix C of this report. Video images were recorded onto tape, and analyzed. Further testing was done using a 20 foot (6.1 m) indoor pool at Benthos, Inc. in North Falmouth, MA. During these trials, the sonar and light meters were not yet working, so they were not included in tests. As above, results and discussion are presented in subsequent sections of this report.

Prior to taking the test fixture to open waters, an opportunity arose to install the camera and strobe system into the Odyssey II vehicle and run sea trials in Bermuda. This was done using the existing hardware on the AUV including the vehicle's own optical backscatter sensor, sonar and power system. In these trials, seafloor was video taped as the vehicle performed a variety of runs. As described earlier, data cannot be analyzed immediately when operating in the vehicle, so analysis had to wait until the day's operations were complete. Upon review of the data gathered, it was determined that the images obtained in the bright light while operating over a shallow highly reflective bottom were bleached out due to excessive light. The CCD unit installed in this camera system was initially selected to operate in the very dark environment of the deep ocean, operating with a flash. It was determined that the camera was not able to adjust its internal gain settings sufficiently to accommodate very bright conditions. Several attempts were made to manually adjust the camera gain settings, but these offered no greater range than the camera's automatic setting. We realized that neutral density filters might provide adequate light reduction, but were unavailable. In order to make best use of the opportunity to operate under these conditions, a set of filters were fabricated using pieces of polarizing filter material. It was found through trial and error that two sets of orthogonally oriented polarizing filters provided sufficient light reduction (in air) to capture images without "blooming". This configuration was taken out into shallow waters and a variety of tests were performed, again using a set of black on white targets at various ranges.

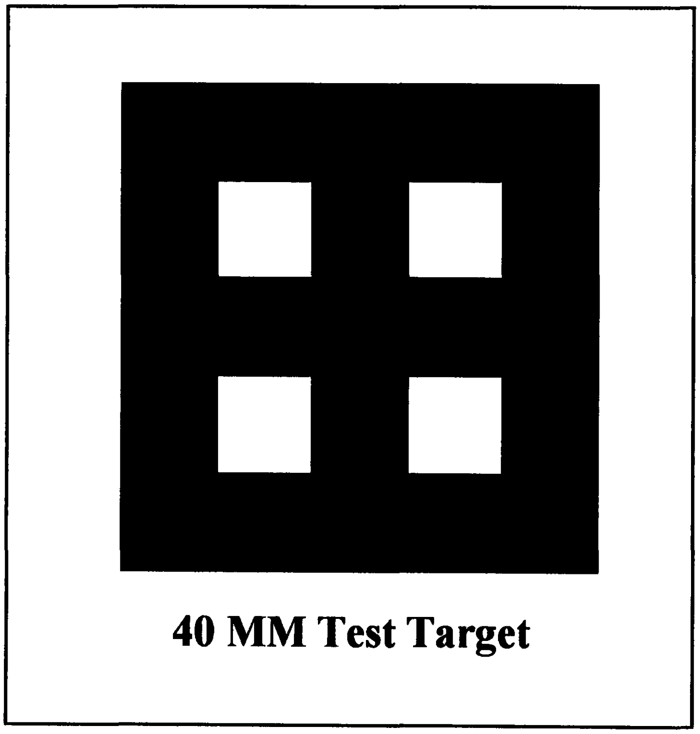


Figure 12. The 40 mm Test Target. (Target size reduced here).

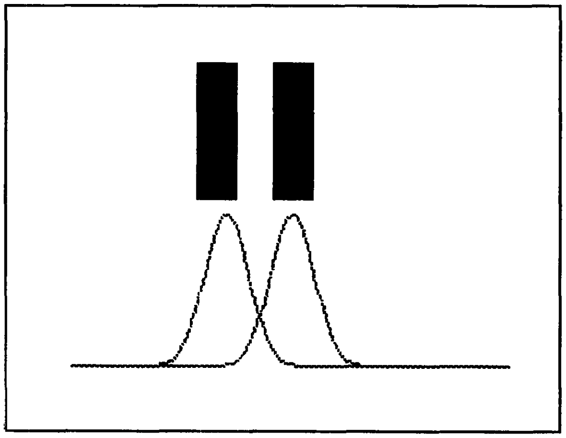
11.0 Protocol for Evaluating Resolution

The desired outcome of this study is the generation of a realistic and useful tool for predicting the appropriate altitude limitations that will be imposed on the camera system based on the size of objects to be imaged and on the effects of the optical clarity of the water on resolution. This discovery is a critical component of establishing the practical ability to perform benthic surveys using AUVs. We set out to establish a method which will allow us to determine a relationship between resolution and altitude of vehicle above bottom. This information is intended to eventually be processed and analyzed by a computer aboard the AUV. In order to do this, we need to understand what we consider to be a *resolved* image.

Consider observing two equal sized black squares separated by their width, on top of a white background. If you were to step back from these two squares a sufficient distance, you would, at some distance, report only seeing a single black object. Similarly, if two black bands of equal width and separation are printed onto a white background, and imaged from progressively increasing distance, at some distance, a single black image would appear. The individual curves of intensity relative to location along a traverse of the target are broadened by a variety of processes (Figure 13). Two such curves placed at close proximity to one another will produce a third curve equal to the sum of their individual values. The concept of this approach was taken from a discussion of the Rayleigh criterion [Halliday and Resnick; Hall], as well as a similar discussion by [Mertens]. The goal is to mathematically characterize a "resolvable" image.

Figure 13 demonstrates the effect of spacing and overlap on the "blurring" of consecutive bands. A "saddle" in the curve will begin to appear as two bands are brought closer to one another. We set out to develop a relationship between this saddle depth as a percentage of peak height relative to altitude above target. In order for the quantitative data to bear some significance on the actual data that we may gather with this hardware, some correlation must be drawn between the saddle depth ratio, as defined and a subjective poll which establishes a threshold of resolvability.

Once a mathematical correlation can be drawn between a simple set of black and white patterns relative to subjective evaluation, a theoretical resolvability threshold limit may be established for a particular target over a series of altitudes. A family of curves can then be generated for various target sizes relative to altitude. As all of this data was gathered in clear pool water, the next step is to correlate this data set to water clarity based on tests in various turbidity conditions. This will ultimately create a third dimension to the Cartesian based family of curves previously generated, and allow for estimation of minimum altitude required for resolving a particular size detail using this hardware.



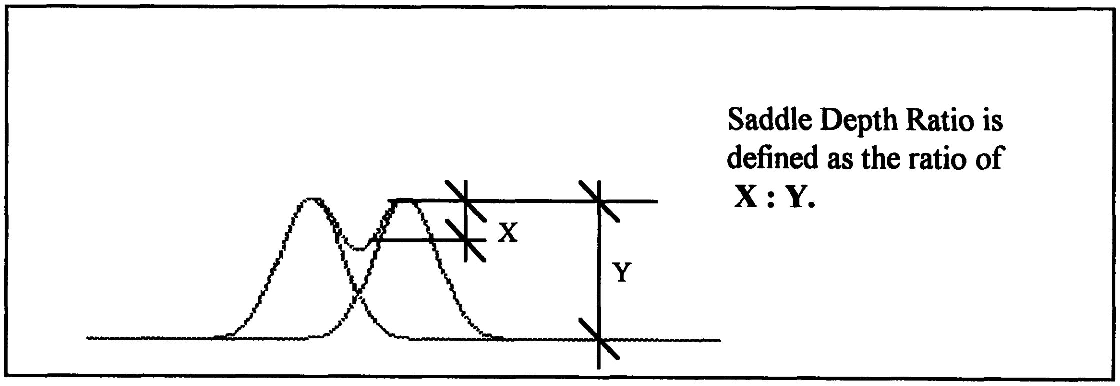
As black bands are separated, the two grayscale intensity curves will become more distinguishable from one another.

Figure 13. Resolution of Two Black Bands. The effect of spacing on the "overlap" of the grayscale intensity curves generated by two black bands is seen here.

11.1 Testing for Resolution

Determination of resolution is done in two ways. First, a calculation is performed for the theoretical "resolvability" of a given size mark. This quantitative method is based on the number of pixels available and the projected area at a given altitude. Correlation may then be drawn relative to the theoretical and the experimental results under "ideal" conditions, as represented by a clean freshwater swimming pool. These results can then be compared to the physical data obtained in the field, both graphically and mathematically.

In order to establish a testable criteria for performing quantitative image resolution an analytical process similar to that recommended by [Duntley, 1963] was generated. We propose to use the depth of the "saddle" that occurs between two regions of light relative to the maximum amplitude in the bright regions as the criterion for resolution. Figure 14 shows schematically this phenomenon. The value of the saddle depth ratio will range between 0 and 1, respectively representing the low and high resolution limits.



Saddle Depth Ratio is defined as the ratio of **X : Y.**

Figure 14. Saddle Depth Ratio. Defined as the proportion between the depth of the saddle and the amplitude of the grayscale intensity curves, this ratio is proposed in order to quantify the analysis of resolution.

The first issue to confirm is *desired* resolution. In a sense, this question is asking at what altitude can an image of an urchin that is being photographed be resolved. To generate a baseline of data, targets were made with 5, 10, 20, 30, 40, 65 and 80 mm black blocks, horizontal and vertical lines on white backgrounds. These targets were laminated in plastic and weighted so that they could be deployed on a piece of fishing line. The test sled was suspended above these targets (or collections of targets) at a variety of altitudes.

The resolution of a target may be initially understood as the minimum number of pixels required to capture a desired detail. Considering the imaging system used, 500 pixels across a 90 degree horizontal field of view will result in image sizes which depends upon altitude. At a 20 foot altitude, a swath of 40 foot width is captured by the 500 pixels. This calculates to roughly one pixel per inch of coverage. Using a criterion developed for signal processing, the Nyquist criterion [Pratt] would specify that a minimum sample rate of at least twice the highest frequency signal be used. This analysis, although not intended specifically for this type of data interpretation, would imply that for a single pulse of black on white background (representing a single cycle of signal), a minimum of two pixels must be used to capture the event. This criteria will be used as a comparison against the saddle depth ratio values that we generate using imaged targets at various altitudes.

The objective is to observe a series of images of a single target taken at various altitudes above the bottom with lighting held constant. From the images captured, analysis was made of the saddle depth ratio in order to correlate the values calculated to a qualitative analysis of the images themselves. As altitude increases, the saddle that occurs between two regions of light becomes shallower to a point where the direct observation of the image proves to be difficult to "resolve" as two distinct lines. The saddle depth as a function of peak height is recorded at some point where the image is un-resolvable by human observers. Based on a family of curves, it is intended that a relationship between this depth / height will allow autonomous determination of whether or not two distinct targets can be resolved.

We need to relate the saddle-depth ratio to the qualitative perception of resolution. This will allow us to determine the threshold value (under given conditions) that corresponds to the limit of resolvability. These threshold values are arrived at through comparing quantitative results with qualitative tests. The qualitative tests included the generation of a series of image plots representing a single target imaged at a series of altitudes. The targets were scanned and digitized as described below, normalized so that pixel size is kept constant from one image to the next. The targets were plotted to appear at the same size as they would on a standard 14" video monitor. Three subjects were asked to view the images from a seated position at a distance of 2 feet from the images. Each subject was told that the target contained a large black and white grid and a number of black rectangles. They were asked to identify the targets that had one black rectangle and those that had two. The series of targets consisted of eight images of the 40mm target, captured in one foot increments of altitude from 8 to 15 feet. This range was chosen in order to bracket the proposed bottom following altitude of the AUV Odyssey (3-4 meters). The results of this test series is included in the "results" section of this report.

These tests were performed under somewhat ideal conditions and care must be taken when attempting to extrapolate useful criteria from this data. In practice, results are likely to fall short of these limits due to physical phenomena such as available light, lack of substantial bottom contrast and water clarity. Additionally the presence of non-homogenous (due to salinity and temperature gradients) waters [Mertens] may cause multiple in-water diffraction effects, resulting in further reductions in image resolution. In general, the reader is cautioned against setting unrealistic expectations for results obtained in the field relative to the those obtained under controlled conditions. Future work in the area of establishing a correlation between test data in controlled settings and benthic fauna data gathered in the marine environment is recommended.

12.0 Results

The analog images from the pool tests were recorded onto HI-8mm video tape. They were captured into data files (rgb format) on a UNIX workstation. Since the camera was a black and white imager, the effective result was 8-bit (256 level) gray scale digitization. Images were then cropped to include only the photographed targets and a minimum of background data. From this, the data was converted to binary format and analyzed using MATLAB routines on a PC. Once in this format, the images were analyzed by plotting the grayscale values for various transects across the images. Each image was cropped to produce a linear transect orthogonal to white and black bands on the targets. By plotting a single row of this matrix as intensity vs. position, a graphical representation of the detected contrast is made (Figure 15).

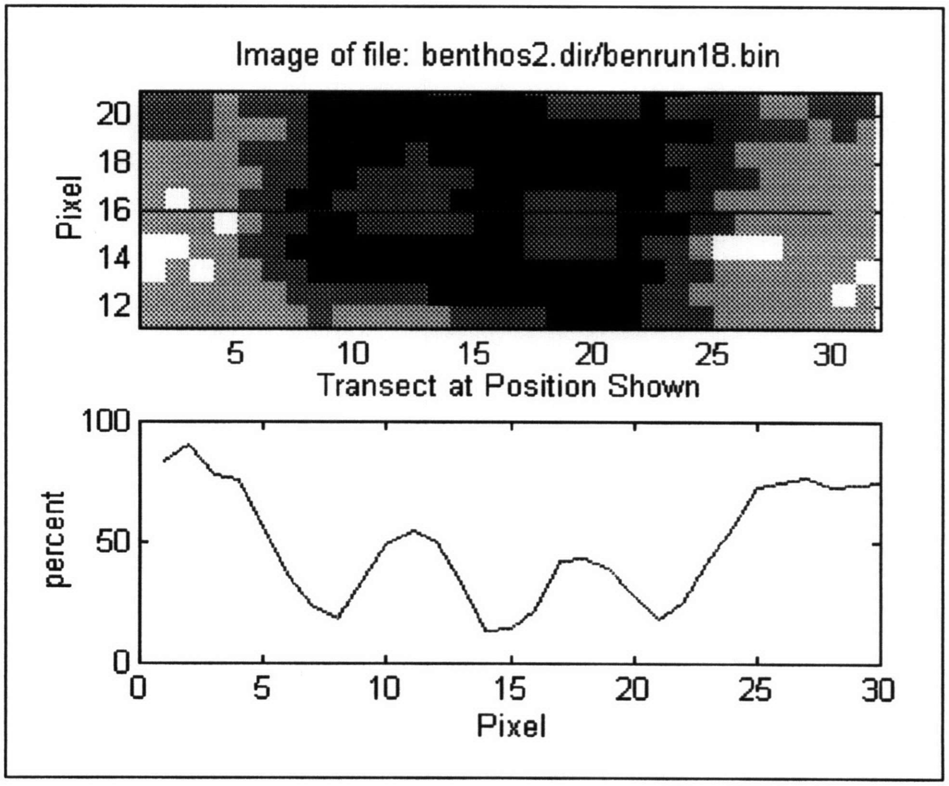


Figure 15. Sample transect across a region of light and dark bands on test target. The saddle between the regions of light and dark is very evident on this plot. The transect line lies along the bottom edge of the pixel row selected.

In order to quantify resolution, we took a series of images of a single (40mm) target, at various altitudes, plotted transects through the light and dark bands at each step, measured the saddle depth relative to amplitude. These values are presented using the following series of graphs.

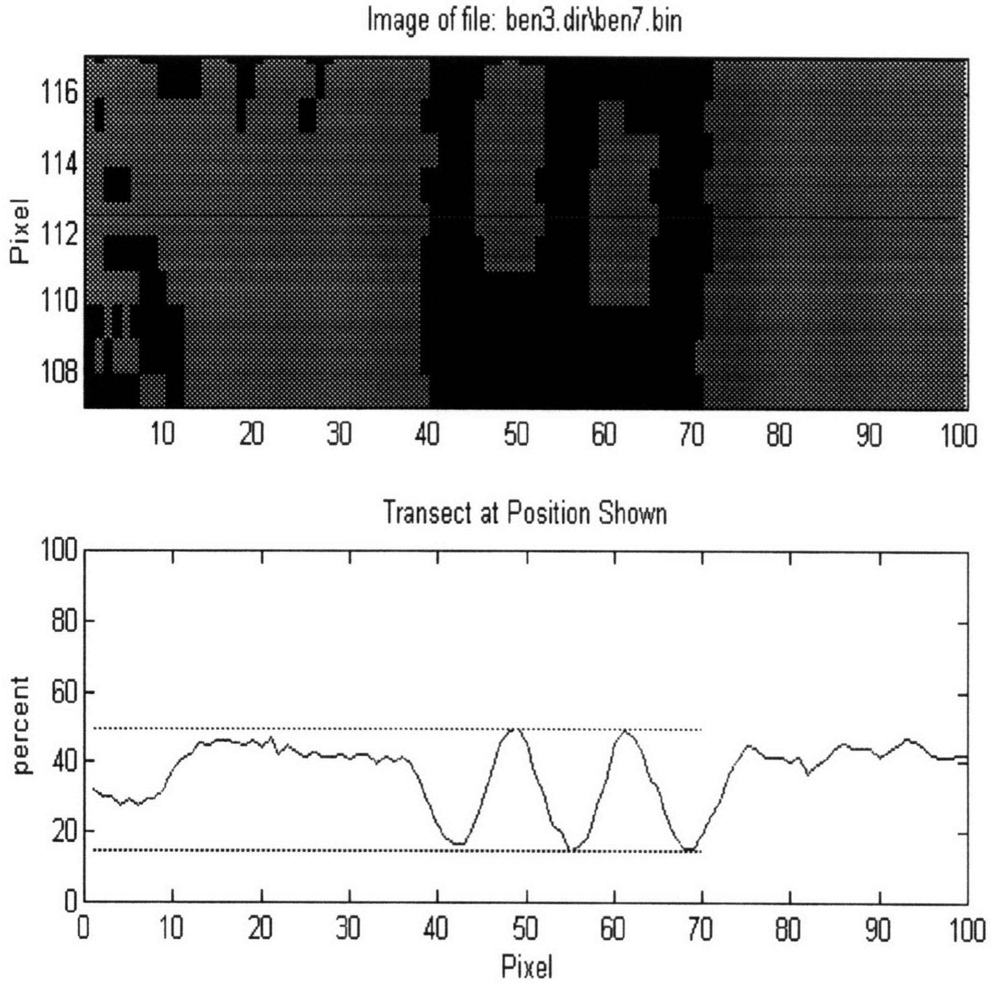


Figure 16. 40mm target, Image captured at 8 foot altitude, transect taken at row 112. Maximum and minimum grayscale intensity values taken between limits of 40 and 70. Resulting maximum value of 49.5%, minimum value of 14.5%. Resulting saddle depth ratio of 0.707.

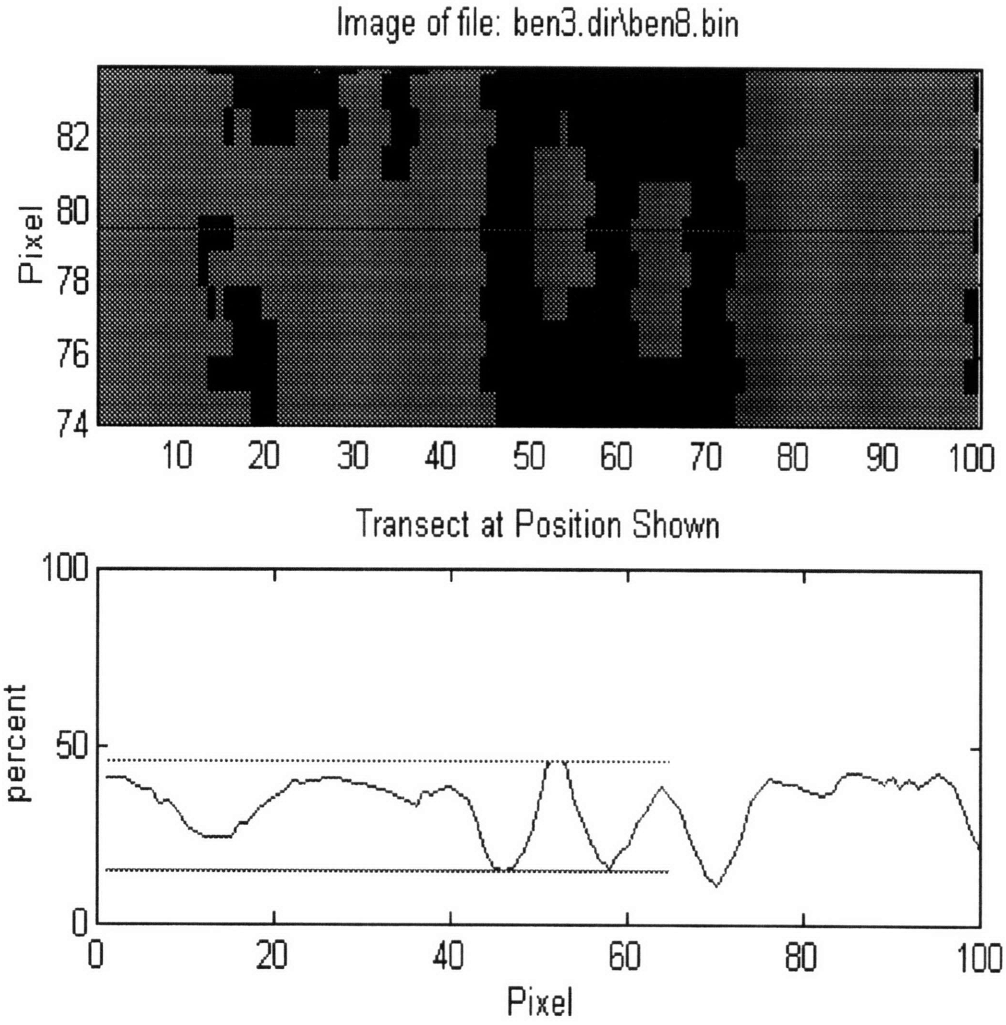


Figure 17. 40mm target, Image captured at 9 foot altitude, transect taken at row 79. Maximum and minimum grayscale intensity values taken between limits of 44 and 65. Resulting maximum value of 46%, minimum value of 15%. Resulting saddle depth ratio of 0.674.

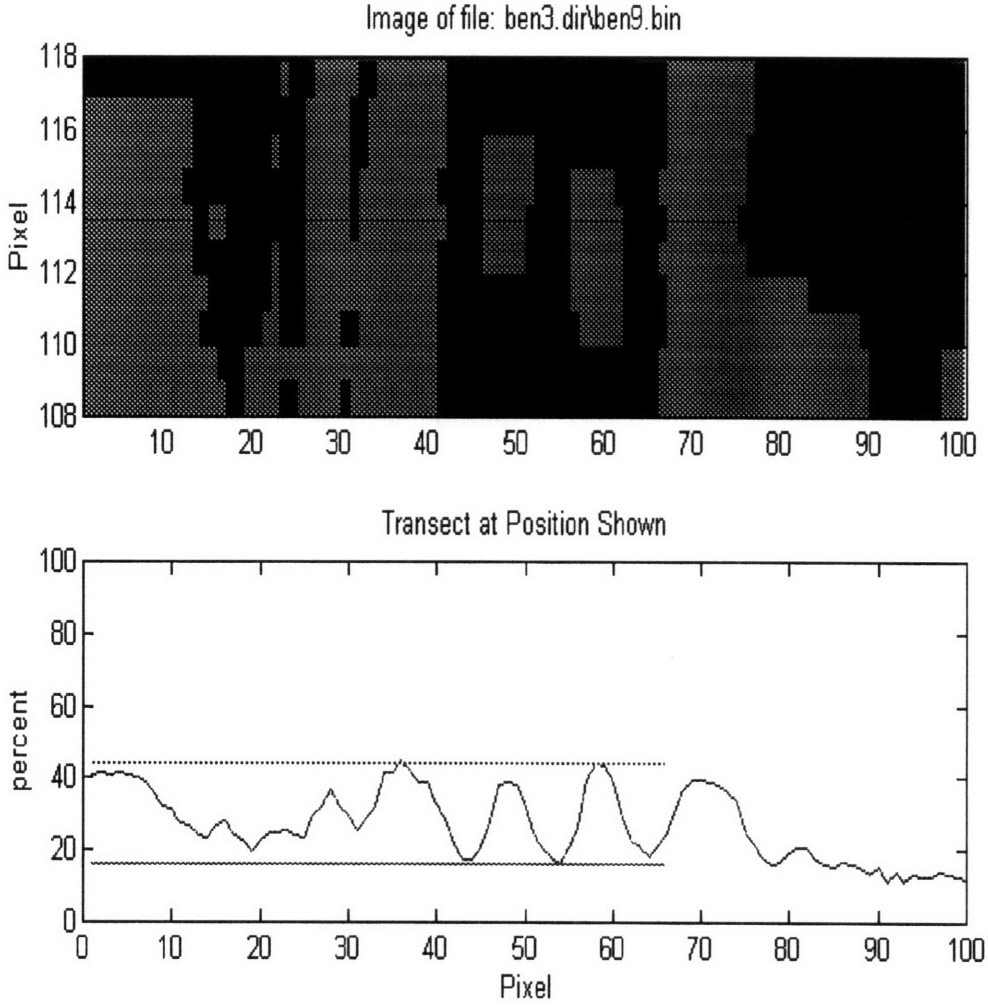


Figure 18. 40mm target, Image captured at 10 foot altitude, transect taken at row 113. Maximum and minimum grayscale intensity values taken between limits of 44 and 65. Resulting maximum value of 44%, minimum value of 16%. Resulting saddle depth ratio of 0.636.

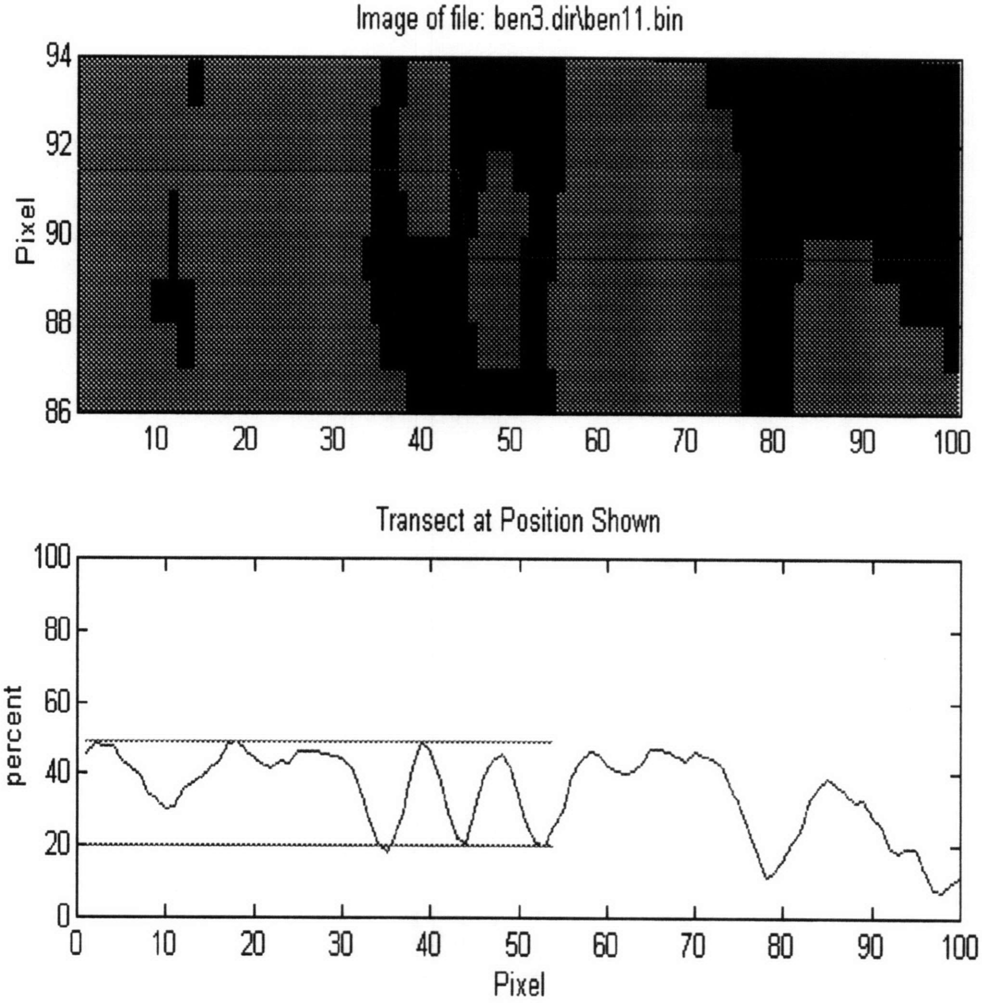


Figure 19. 40mm target, Image captured at 12 foot altitude, transect taken at rows 91 and 89. Maximum and minimum grayscale intensity values taken between limits of 37 and 54. Resulting maximum value of 49%, minimum value of 20%. Resulting saddle depth ratio of 0.591.

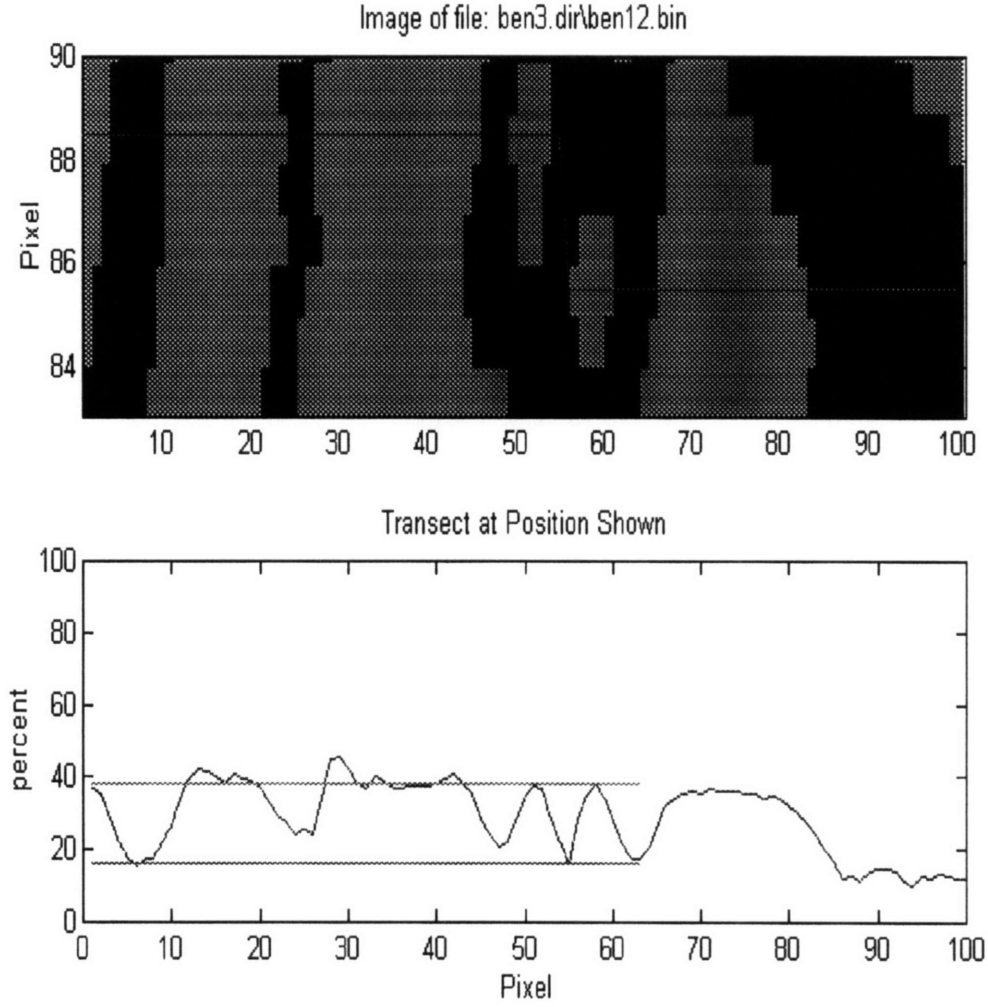


Figure 20. 40mm target, Image captured at 13 foot altitude, transect taken at rows 88 and 85. Maximum and minimum grayscale intensity values taken between limits of 45 and 63. Resulting maximum value of 38%, minimum value of 16.5%. Resulting saddle depth ratio of 0.565.

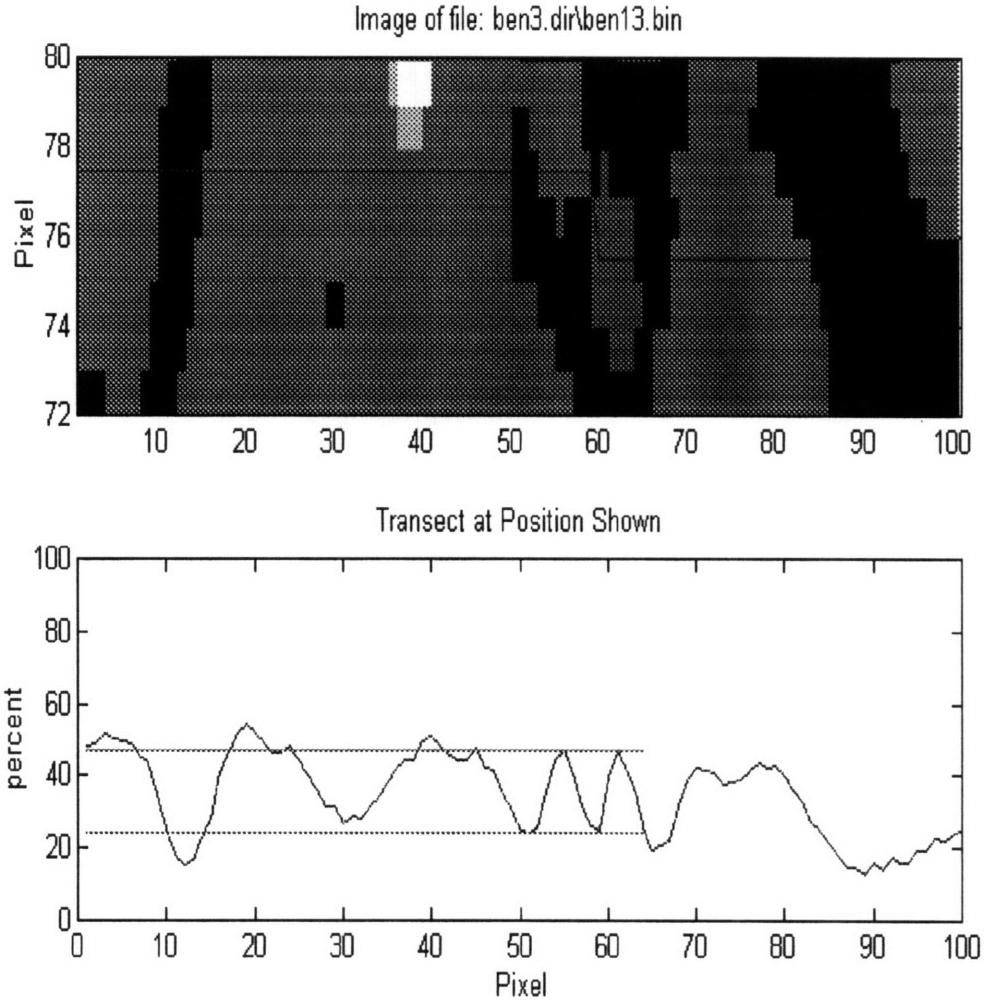


Figure 21. 40mm target, Image captured at 14 foot altitude, transect taken at rows 77 and 75. Maximum and minimum grayscale intensity values taken between limits of 48 and 64. Resulting maximum value of 47%, minimum value of 24%. Resulting saddle depth ratio of 0.489.

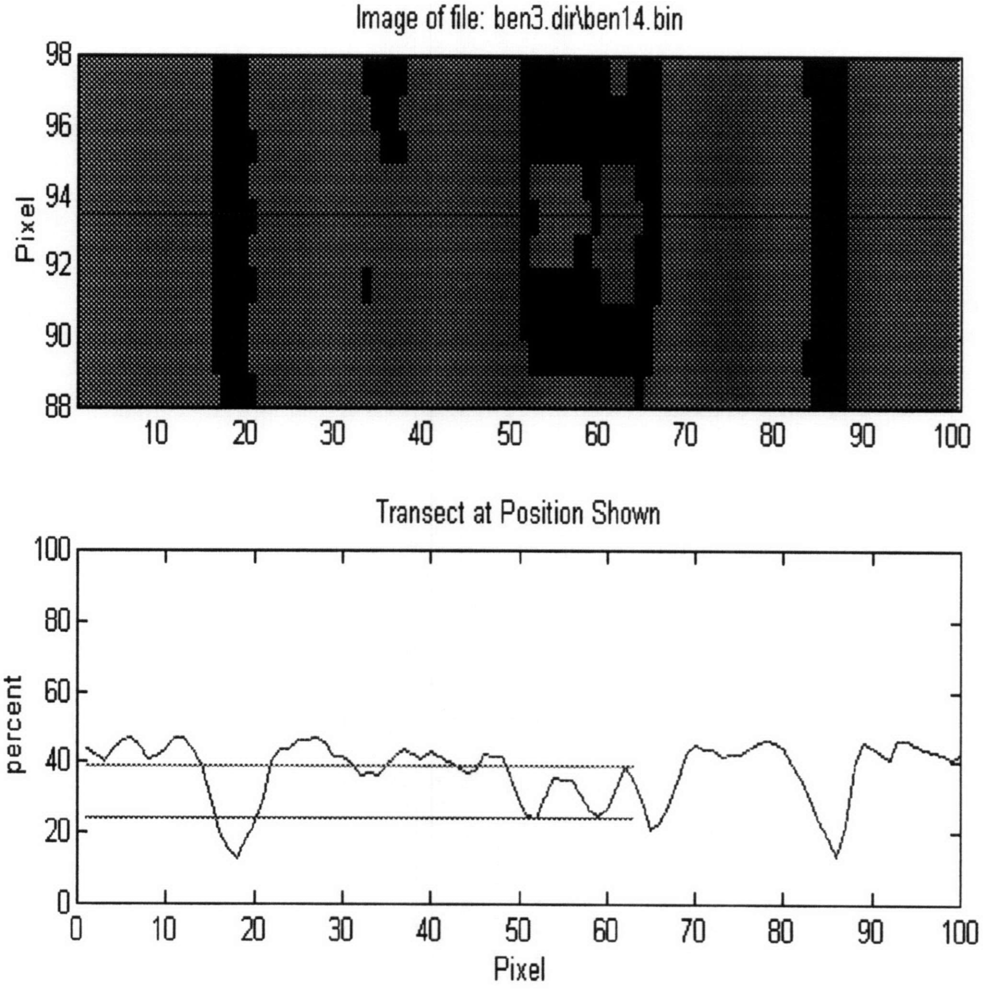


Image of file: ben3.dir\ben14.bin

Transect at Position Shown

Figure 22. 40mm target, Image captured at 15 foot altitude, transect taken at row 93. Maximum and minimum grayscale intensity values taken between limits of 52 and 63. Resulting maximum value of 39%, minimum value of 24%. Resulting saddle depth ratio of 0.384.

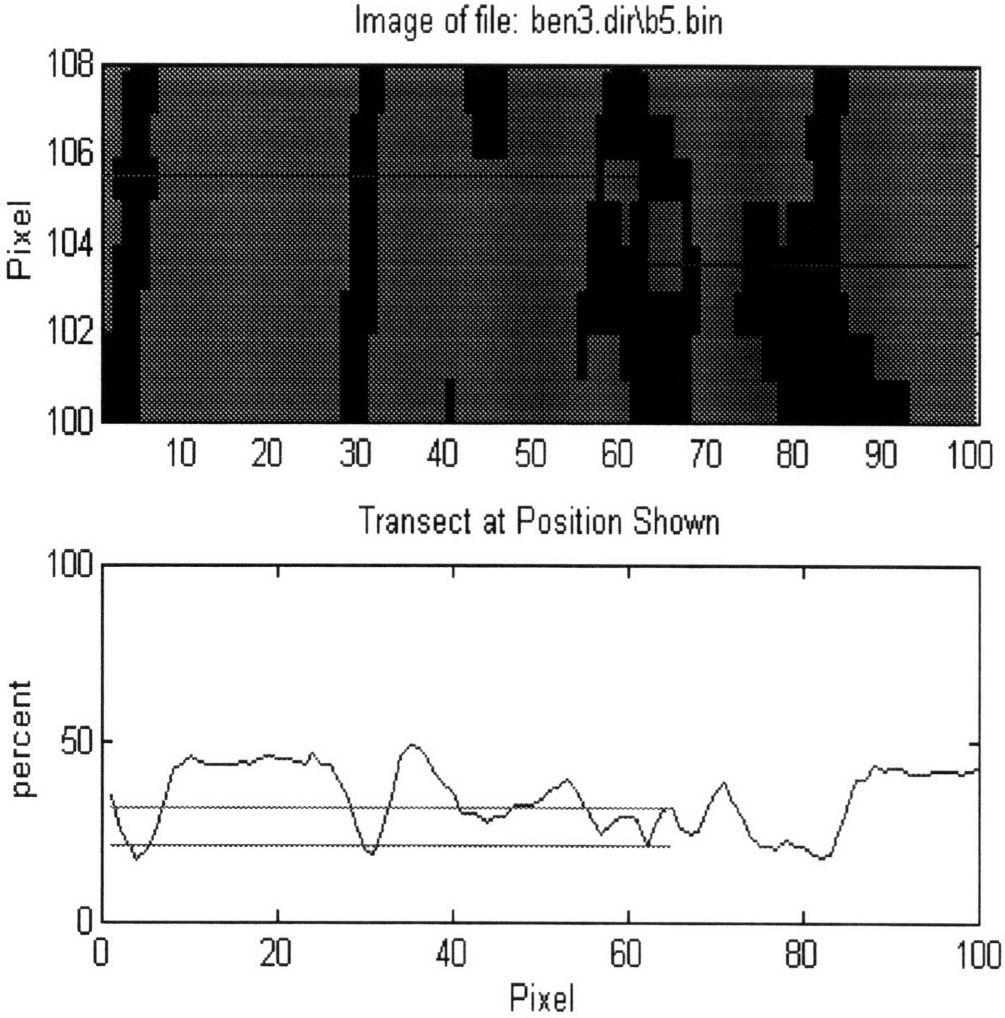


Figure 23. 40mm target, Image captured at 18 foot altitude, transect taken at rows 103 and 105. Maximum and minimum grayscale intensity values taken between limits of 58 and 65. Resulting maximum value of 32%, minimum value of 21.5%. Resulting saddle depth ratio of 0.328.

In order to obtain qualitative data, the same series of 40 mm targets were imaged so as to represent their actual size as viewed on a standard 14" video monitor from approximately two foot distance. Figures 24 through 30 demonstrate a series of images produced at varying altitudes above the 40 mm target.

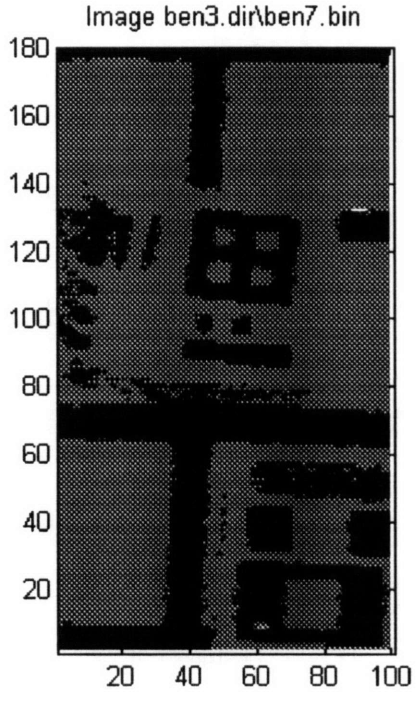


Figure 24. 40 mm target imaged at 8 foot altitude, viewed at apparent size.

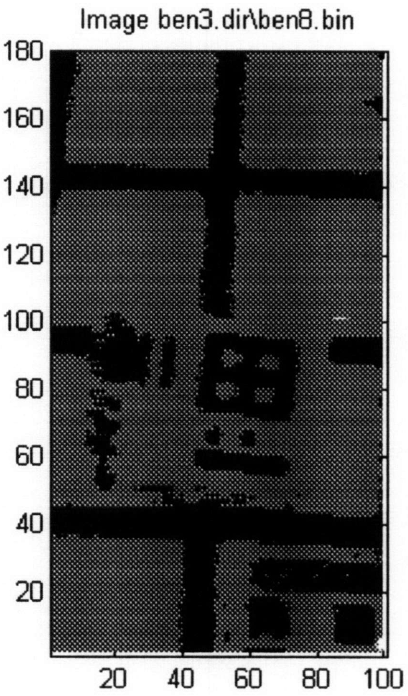


Figure 25. 40 mm target imaged at 9 foot altitude, viewed at apparent size.

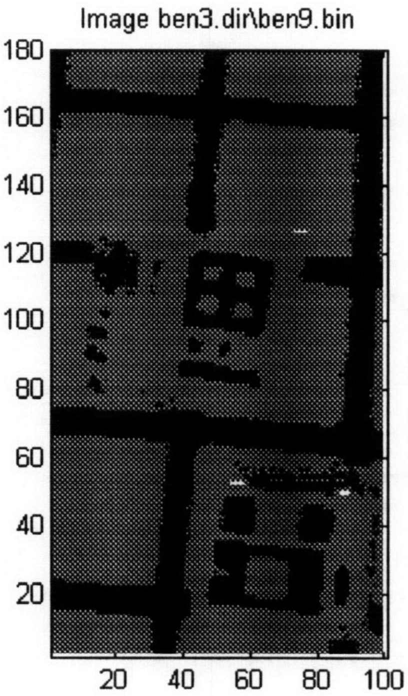


Figure 26. 40 mm target imaged at 10 foot altitude, viewed at apparent size.

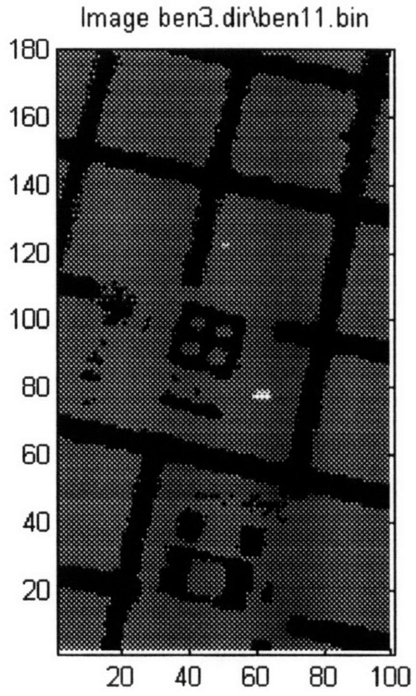


Figure 27. 40 mm target imaged at 12 foot altitude, viewed at apparent size.

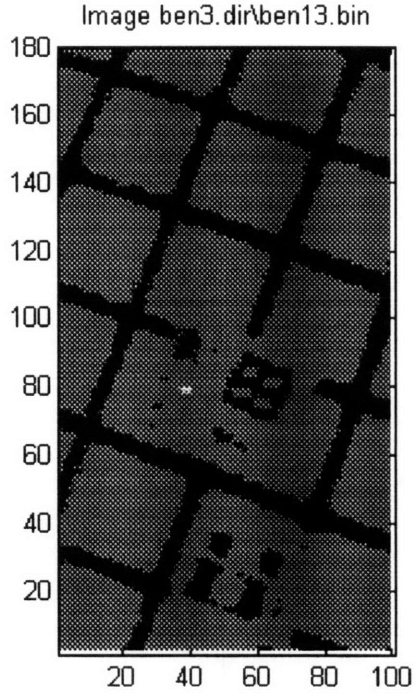


Figure 28. 40 mm target imaged at 14 foot altitude, viewed at apparent size.

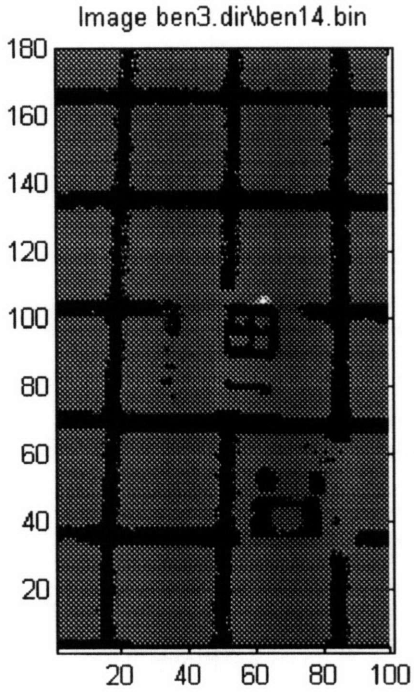


Figure 29. 40 mm target imaged at 15 foot altitude, viewed at apparent size.

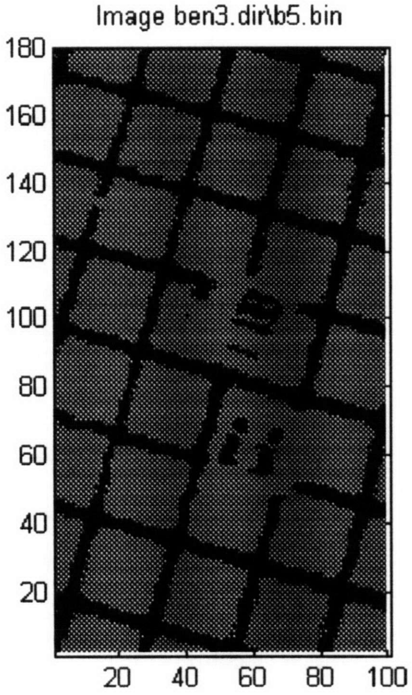


Figure 30. 40 mm target imaged at 18 foot altitude, viewed at apparent size.

A relationship between the quantitative data produced using transects of target images and the qualitative data using a viewer observing images of similar targets was attempted. All of the 40 mm targets appear to be resolvable by three people questioned. Using this camera (approximately 500 x 600 pixels), we are able to calculate the approximate area represented by a single pixel at a given altitude. For an altitude of 15 feet, a single pixel represents approximately 19mm. Considering the Nyquist[1] criteria, we would want to represent an object by at least two pixels. For a target of 40 mm, the altitude of 15 feet is just sufficient to be represented by two pixels. Limitations of pool depth restricted increasing altitude further.

From the qualitative data presented, it is safe to say that an observer is capable of resolving 40 mm details at the maximum altitude selected. The image obtained at 13 foot altitude was very dark, and the loss of image quality is attributed to a poorly captured image prior to digitizing. Provided sufficient data exists for a similar analysis using the 20 mm target, a similar series of plots would be produced. Although this data set was not gathered in its entirety, a set of specific 20 mm targets were captured. The images below represent the two of importance to this discussion.

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[1] Nyquist frequency is commonly referred to when sampling data. In order to avoid aliasing of signal, the rule based on this theorem is to sample at twice the highest frequency present.

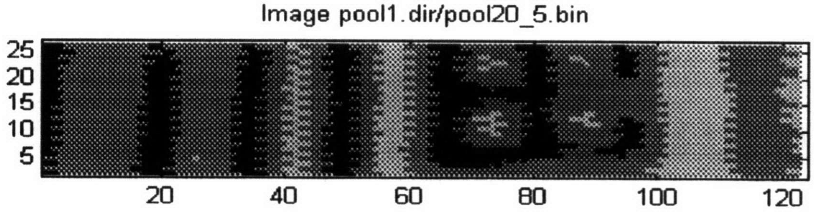


Figure 31. Image of 20 mm target taken at 5 foot altitude

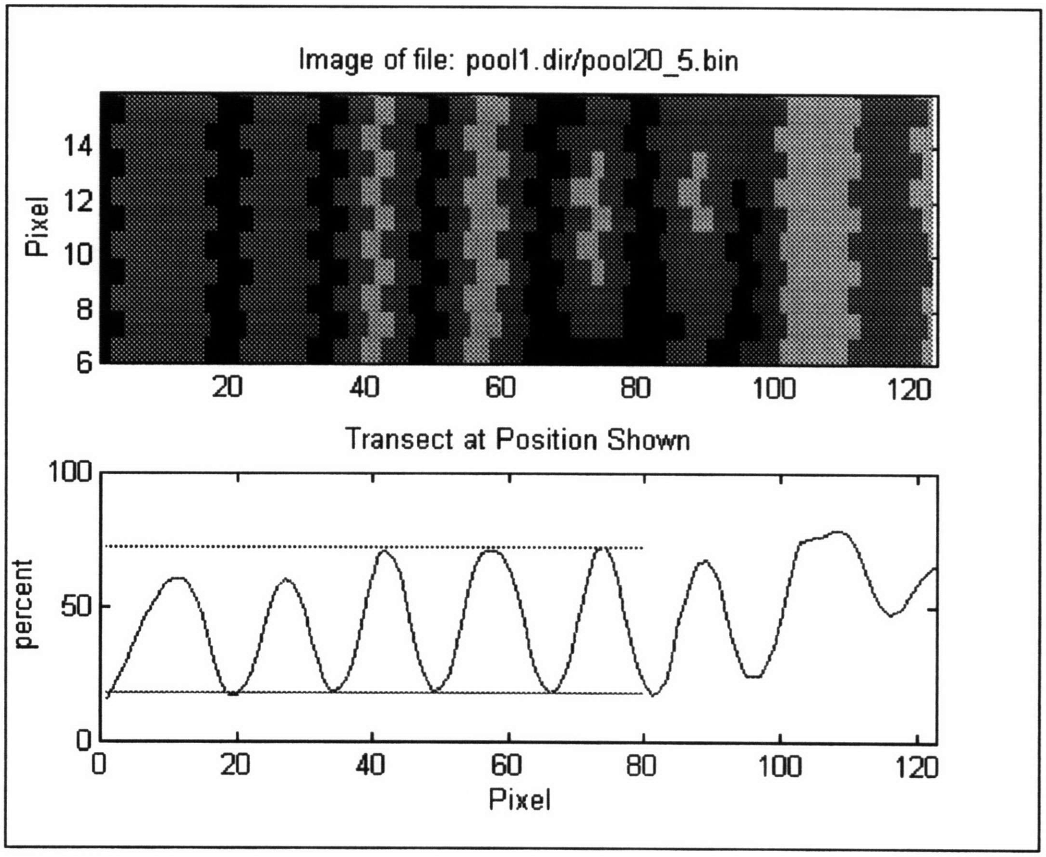


Figure 32. 20 mm target, image captured at 5 foot altitude, transect taken at row 11. Maximum and minimum grayscale intensity values taken between limits of 35 and 70. Resulting maximum value of 72%, minimum value of 18%. Resulting saddle depth ratio of 0.750.

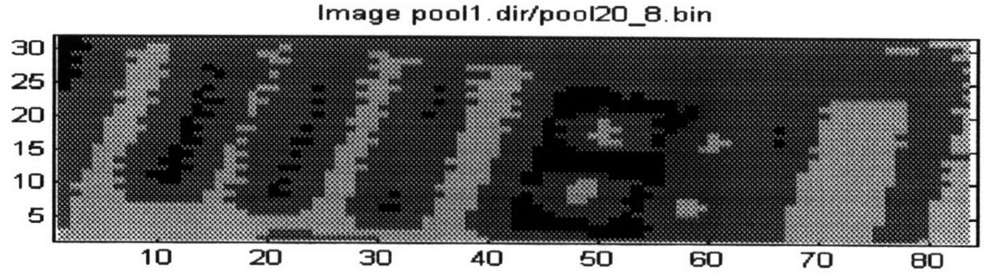


Figure 33. Image of 20 mm target taken at 8 foot altitude.

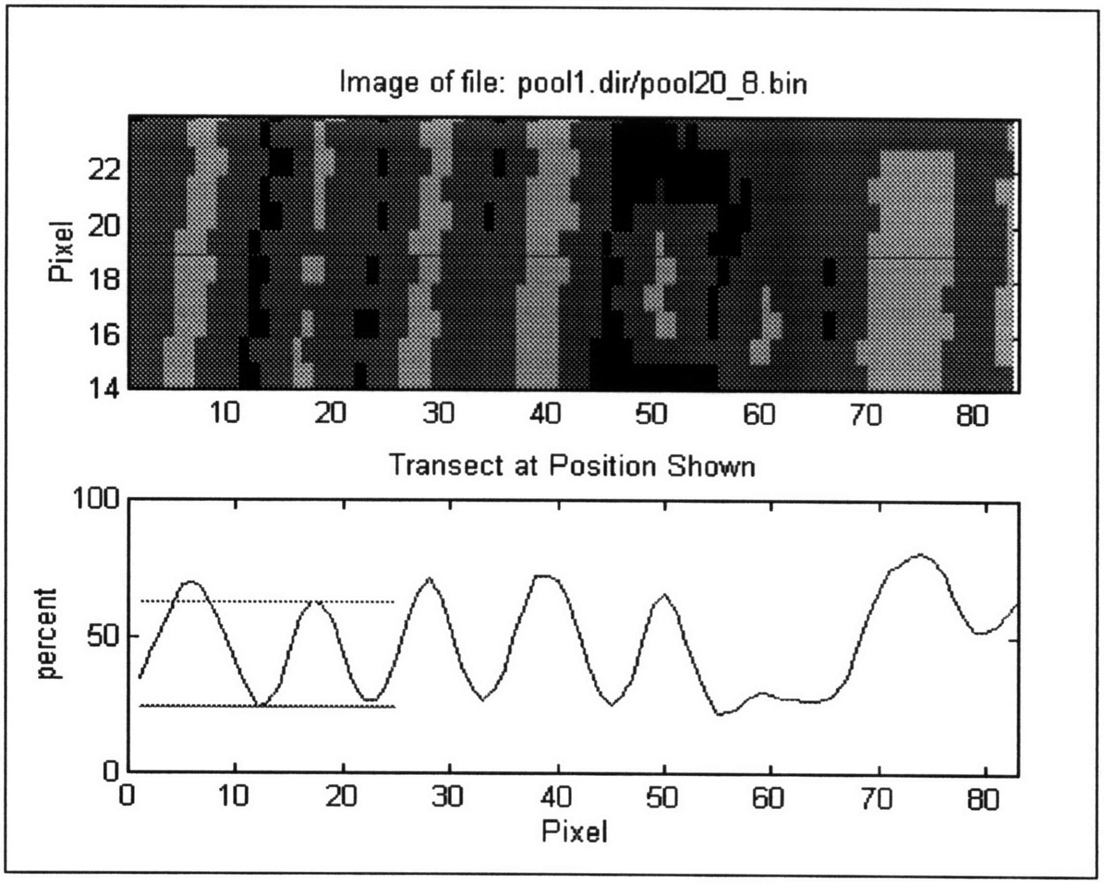


Figure 34. 20 mm target, image captured at 8 foot altitude, transect taken at row 19. Maximum and minimum grayscale intensity values taken between limits of 8 and 25. Resulting maximum value of 63%, minimum value of 24%. Resulting saddle depth ratio of 0.619.

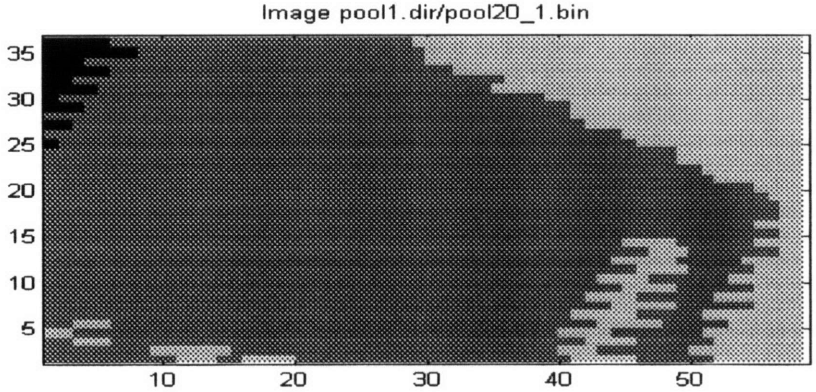


Figure 35. Image of 20 mm target taken at 12 foot altitude.

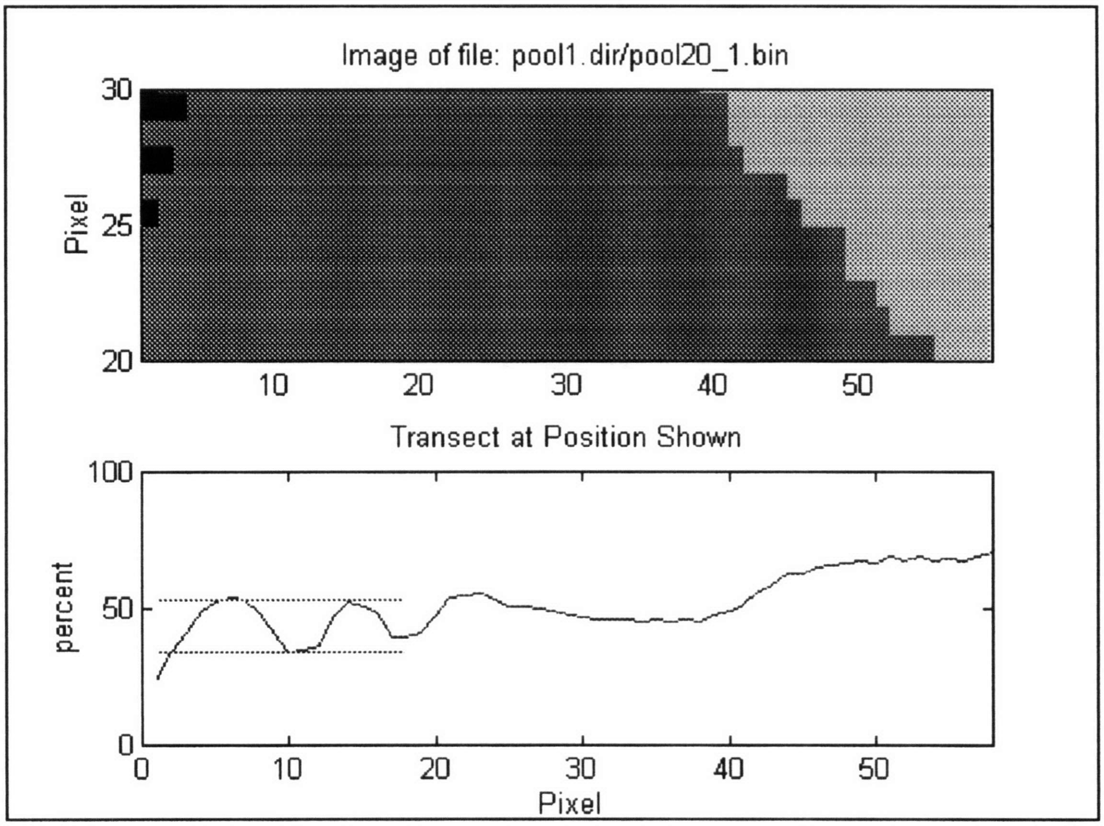


Figure 36. 20 mm target, image captured at 12 foot altitude, transect taken at row 25. Maximum and minimum grayscale intensity values taken between limits of 5 and 18. Resulting maximum value of 53%, minimum value of 34%. Resulting saddle depth ratio of 0.358.

Using the information gained from the preceding curves, a plot of the saddle-depth-ratio vs. altitude is made for the 40mm series. The 12 foot data point appears to be skewed, possibly due to errors introduced during digitization. In any case, all images of the 40 mm target appear to be qualitatively resolvable through this series of altitudes.

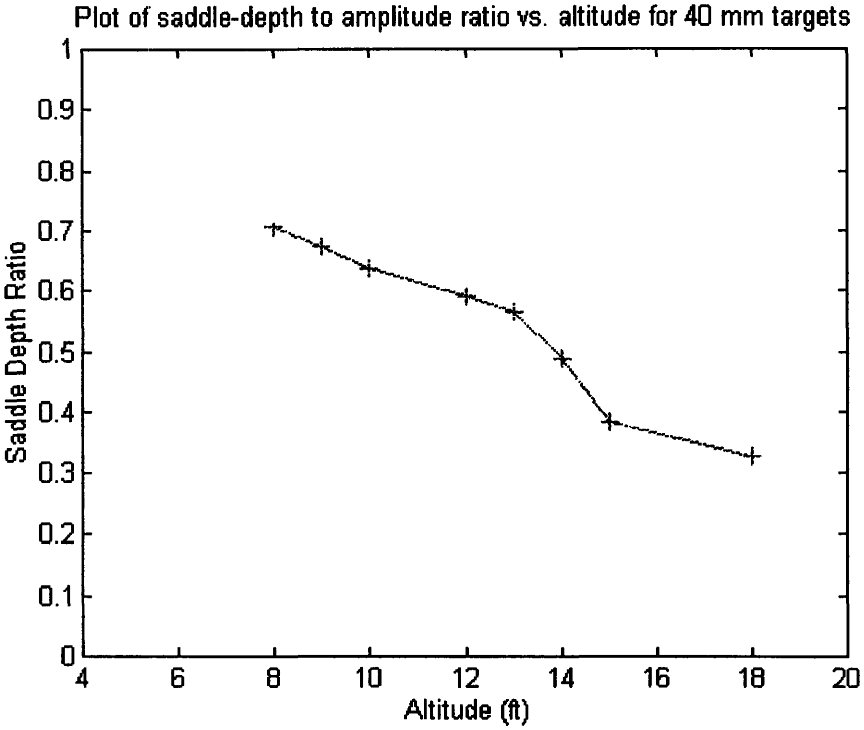


Figure 37. Saddle depth ratio vs. Altitude for 40 mm targets. Saddle depth ratio is taken as a percentage of the depth of the saddle between two intensity peaks relating to light and dark bands on the original image.

Using the data obtained with 20 mm targets, and including this data onto the 40 mm saddle depth ratio curve, we see a similar trend with both data sets (Figure 38). The only conclusive information that can be inferred from the 20 mm data at this time is that at 12 foot altitude, one cannot clearly identify the 20 mm squares in the image. Using this as a theoretical limit for resolvability for this size target under these conditions, we attempt to quantify the saddle-depth ratio that correlates with this cutoff point.

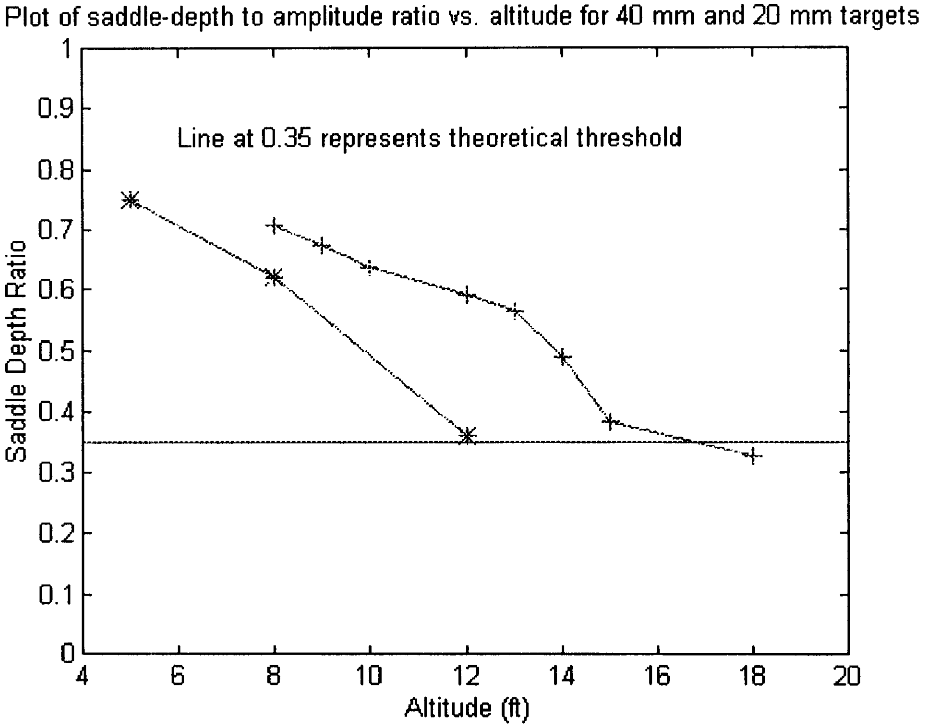


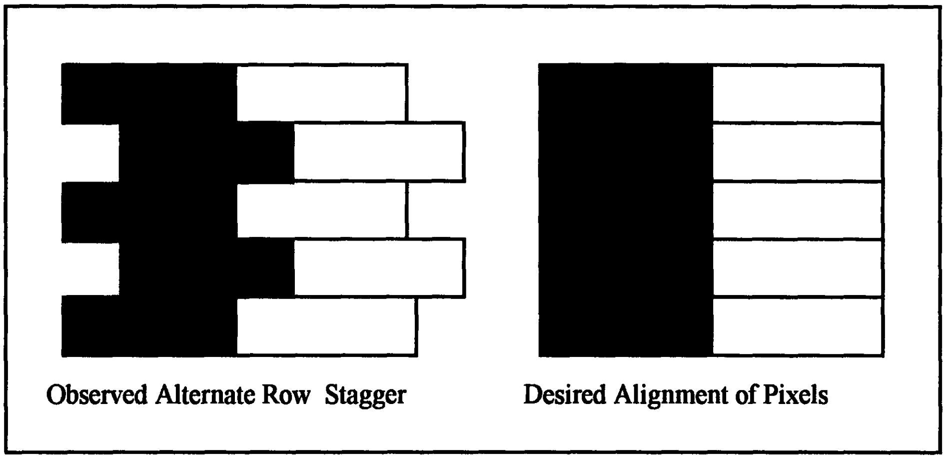
Figure 38. Saddle-depth ratio for 20 mm and 40 mm targets. Plotted along with the existing 40 mm data set, the 20 mm data begins to suggest a trend. The theoretical line at 0.35 represents the apparent ratio at which the 20 mm target is clearly unresolvable.

Although the data set is limited, we can now interpret the qualitative data, from the 20 mm targets primarily, and suggest a theoretical saddle-depth ratio of approximately 0.35 as a cutoff. The line drawn represents the point on the 20 mm curve that corresponds to 12 foot altitude. Interpolating for the 40 mm data, this would suggest a cutoff of approximately 16 to 18 foot altitude. As mentioned previously, for this camera, a single pixel would represent approximately 18 mm at 15 foot, and about 22 mm at 18 foot altitude. Using the 20 mm target, at 12 foot altitude, the calculated effective pixel width is approximately 15 mm. This represents about 1.5 times the target size.

What can be determined from this analysis is that the theoretical resolution limit correlates to the qualitative method described, as well as to the calculated value based on pixel count and visual field size.

13.0 Digital Data Analysis Concerns

Upon observation of the data using MATLAB, it was determined that at some point in the process of digitizing the data, many images were modified in what appeared to be a shift of alternate lines of pixels. What should have appeared as a distinct light and dark band appeared more like interwoven fingers. Using MATLAB to make adjustments to the array in which the data was stored, an attempt was made to restore the images to their original condition. Future data manipulation might include averaging of two or three consecutive rows during transect evaluation. It was necesary to address the pixel stagger issue first, so that averaging did not introduce additional noise into the data. The diagram below depicts the observed effect, and a representation of the desired outcome after processing the data.


Observed Alternate Row Stagger

Desired Alignment of Pixels

Figure 39. A Graphical representation of adjacent columns of mis-aligned pixels.

Although the observed stagger was not uniform throughout any given data file, the MATLAB routine that was written in order to improve the data quality did produce positive results. The routine requires the user to select between even or odd rows and to set the desired offset. Results of running this program are shown in the following series of images.

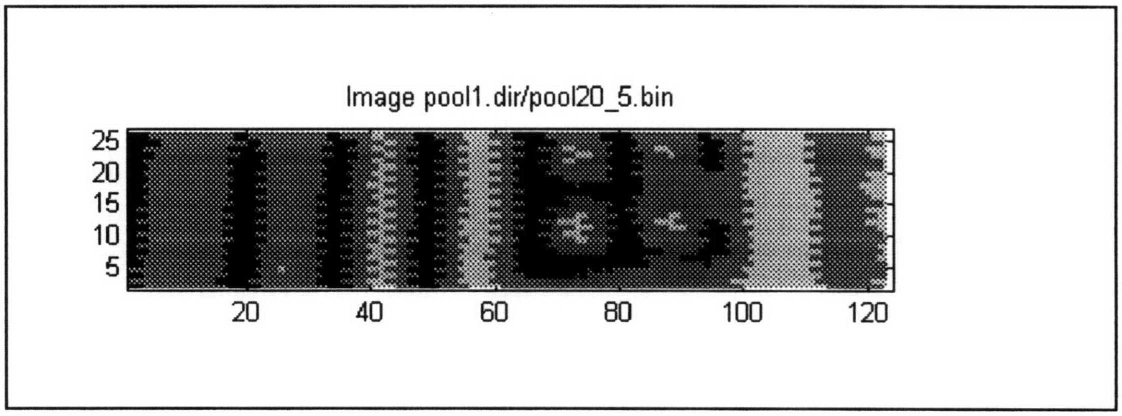


Figure 40. Original image as captured using digitizer. 20 mm target at 5 foot altitude.

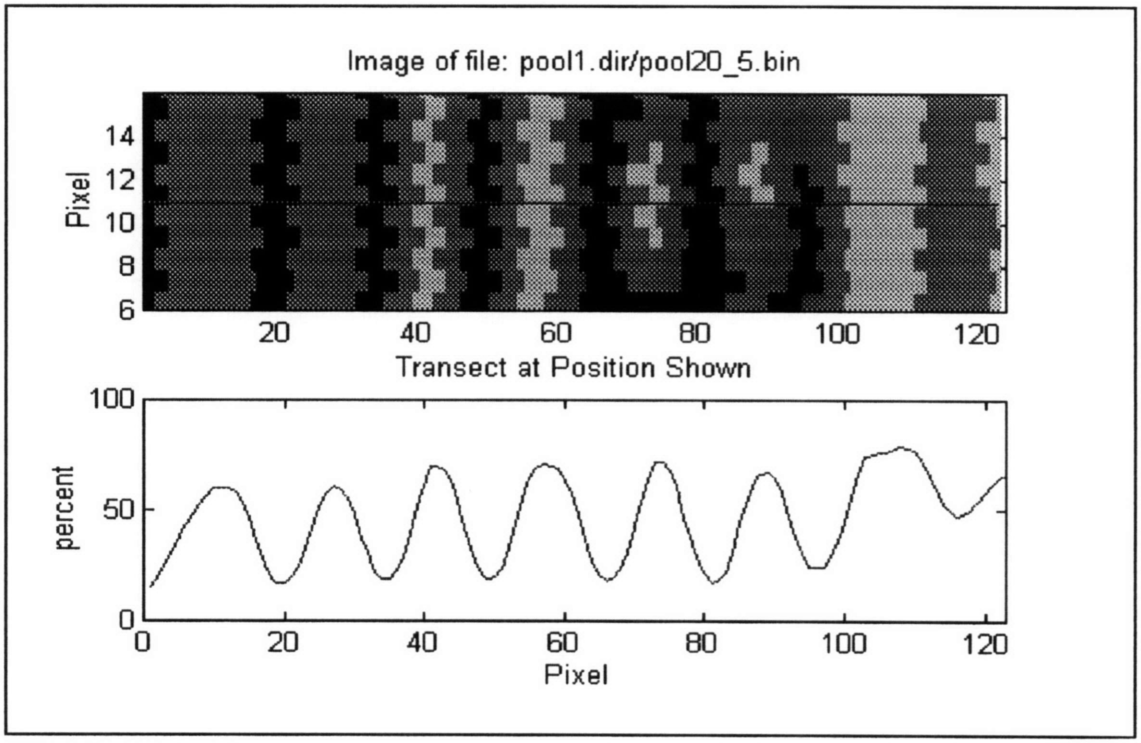


Figure 41. Transect taken through image shown in Figure 40 above, with plot of grayscale intensity at this transect. 20 mm target at 5 foot altitude.

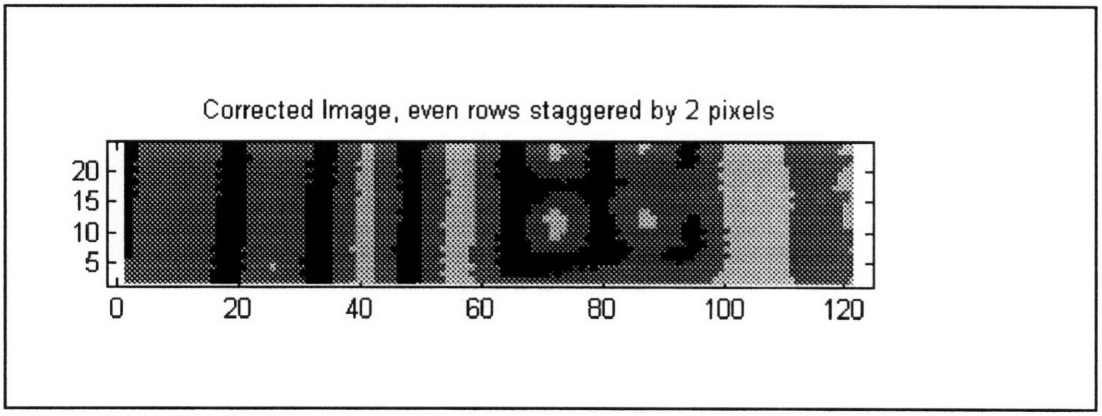


Figure 42. Image of 20 mm target at 5 foot altitude after passing through the MATLAB routine designed to correct pixel row stagger. This image was adjusted by moving even rows 2 pixels right.

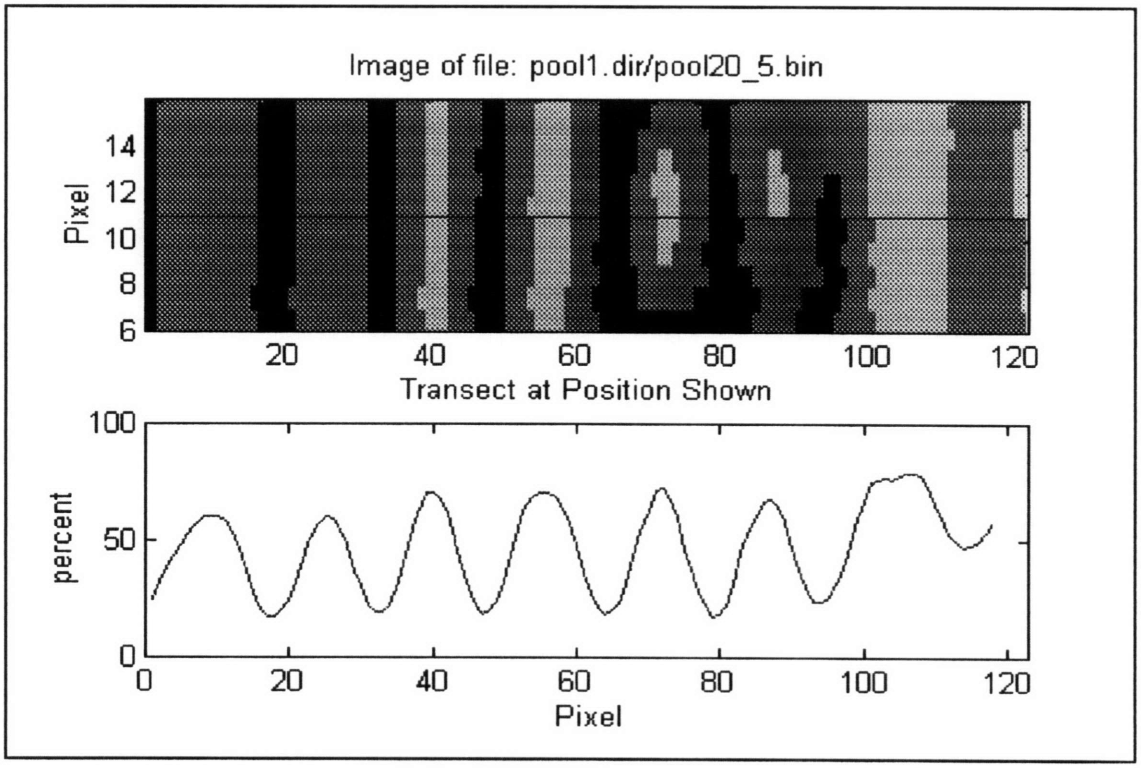


Figure 43. Transect of previously staggered image after passing through MATLAB routine. Compare this to Figure 41 above.

Results of the manipulation using MATLAB are presented in Figures 40 through 43, while Figure 44 is a listing of the program written for this purpose. The process of shuffling the array contents is demonstrated as an example of the type of potential algorithms which may be used in-situ for improving the quality of imaged data prior to analysis. It is not clear what caused the mis-alignment of alternate rows of pixels, or whether this phenomenon is common when digitizing images.

```
function m = stag(imag,col,row,start,howfar)

% This function is used to stagger the data in a
% previously viewed data file (array format), and
% push alternate rows (user selected odd or even)
% by the amount desired.

begin=rem(start,2);
begin=begin+1;

for i = begin: 2 : row-2,
 j=col-howfar;
 new(i,1:j) = imag(i,howfar+1:col);
 new(i+1,1:j) = imag(i+1,1:j);
end
m=new;

image(m);
colormap(gray(256));
set(gca,'ydir','normal','aspect',[j/i 1],'xlim',[-inf inf]);
title( ['corrected image ' file]);
axis('image');

return;
```

Figure 44. MATLAB routine, “stag.m’ used to correct stagger in data files.

13.1 Methods of Easing Autonomous Object Identification

Once the data sets were repaired as described above, two sample image enhancement techniques were attempted. The first approach is intended to increase the level of resolution by expanding the data to the full 8 bit range. This is accomplished by determining the maximum and the minimum grayscale value in a given image. Subtracting the minimum value from every pixel causes black to be represented by a zero value, and the maximum is now equal to the old maximum minus the old minimum. The next step is to multiply all values by a proportion of the difference between 256 and the new maximum in order to expand the new range of values so that the new maximum becomes 256 (8 bits) and the minimum remains at zero. This is done using the equation below, and automated using the MATLAB routine listed in Figure 45.

$$\textit{New Value} = \textit{Old Value}\left[\frac{256}{\text{max.} - \text{min.}}\right]$$

```
function y = expand(x)

% This function is intended to make full use of the 8-bit range of grayscale.

black = min(min(x));
white = max(max(x));
y = 255*(x - black)/(white - black);
[m,n] = size(x);
if nargout < 1
        image(y);
        colormap(gray(256));
        set(gca,'ydir','normal','aspect',[n/m 1],'xlim',[-inf inf]);
        title( 'Expanded Image' );
end
return;
```

Figure 45. MATLAB routine used to expand data to full 8-bit range.

The following images demonstrate the effectiveness of using the MATLAB routine above. An additional routine was developed in order to reduce the biasing effect that the laser spots exhibit. This routine was tested successfully, although it was not incorporated into the data sets below. The routine is included in Appendix B along with the other useful MATLAB routines.

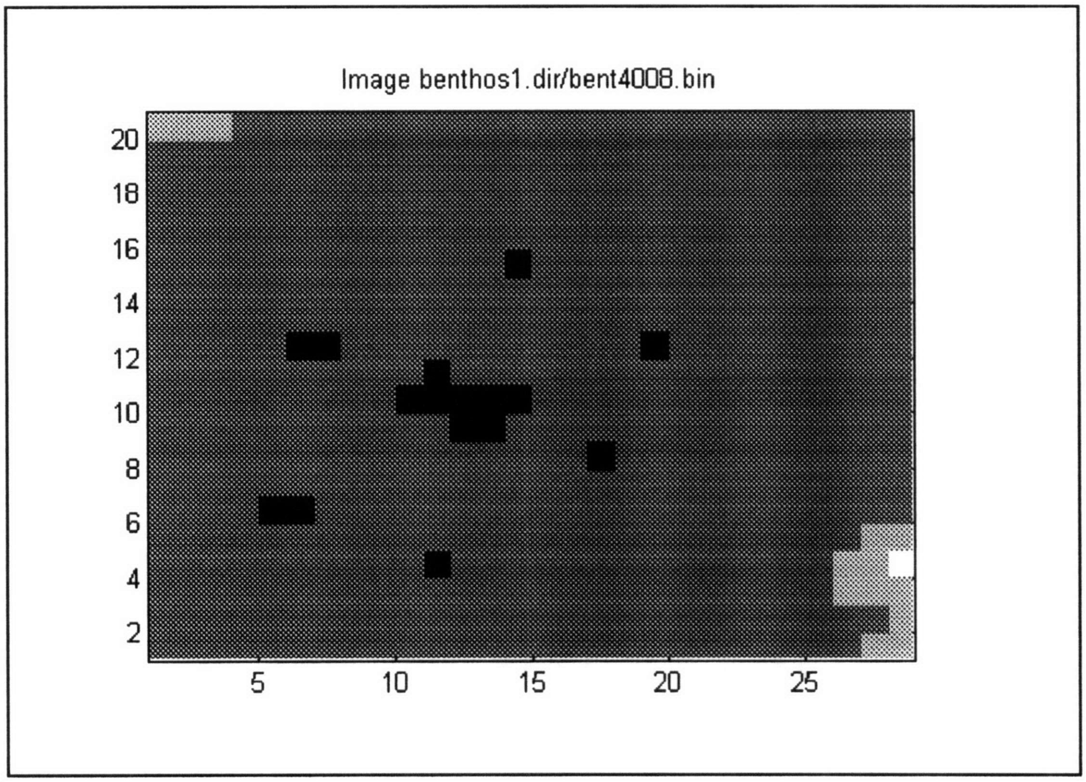


Figure 46. Image of 40 mm target at 8 foot altitude with no processing.

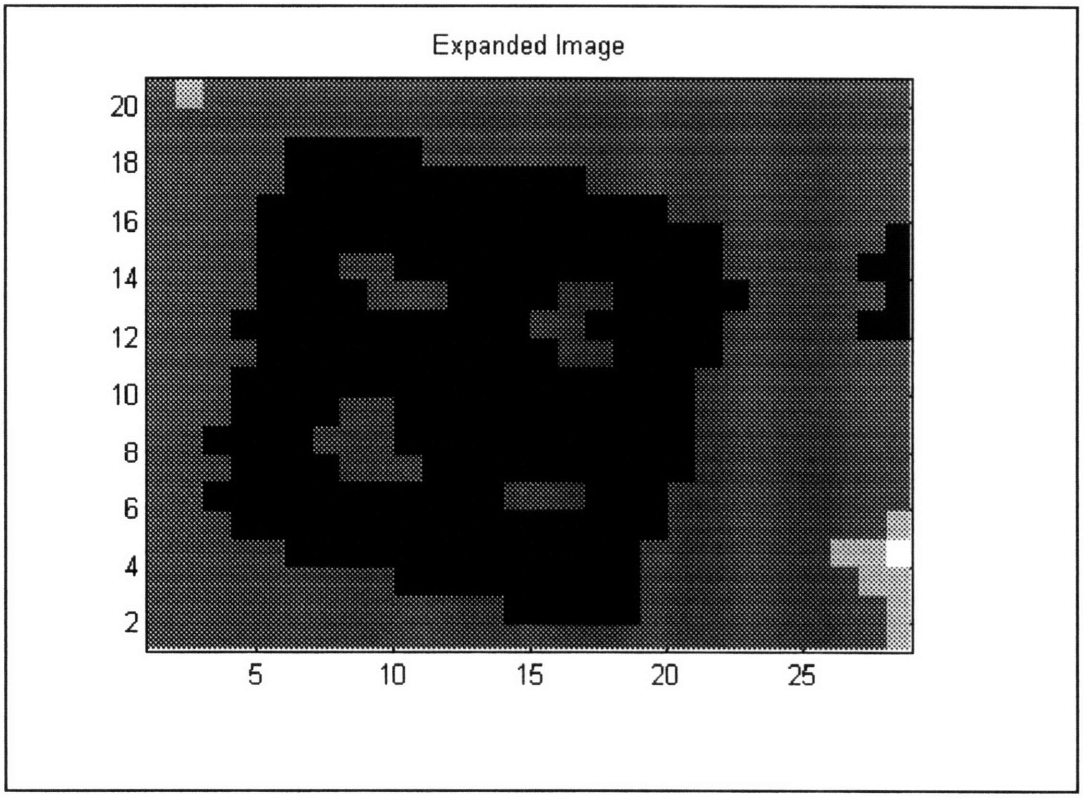


Figure 47. Image of 40 mm target taken at 8 foot altitude, after passing through MATLAB routine, 'expand.m', designed to broaden the range of grayscale values.

A second approach was taken in order to create more distinct contrast between edges. This approach used an exponential function applied to all data points. Coined 'egamma', this routine applies a geometric expansion to all points. The effect is that points are forced to one extreme or the other. The value of gamma is selected by the user prior to applying this function. A drawback to this approach is that data that resides in the middle is lost, along with detail. Selection of gamma takes a bit of trial and error, in order to obtain satisfactory results. Additional manipulation of the data might offer further refinement to the data. The future development of some form of a digital filter will be necessary in order to facilitate in-situ data analysis aboard an AUV.

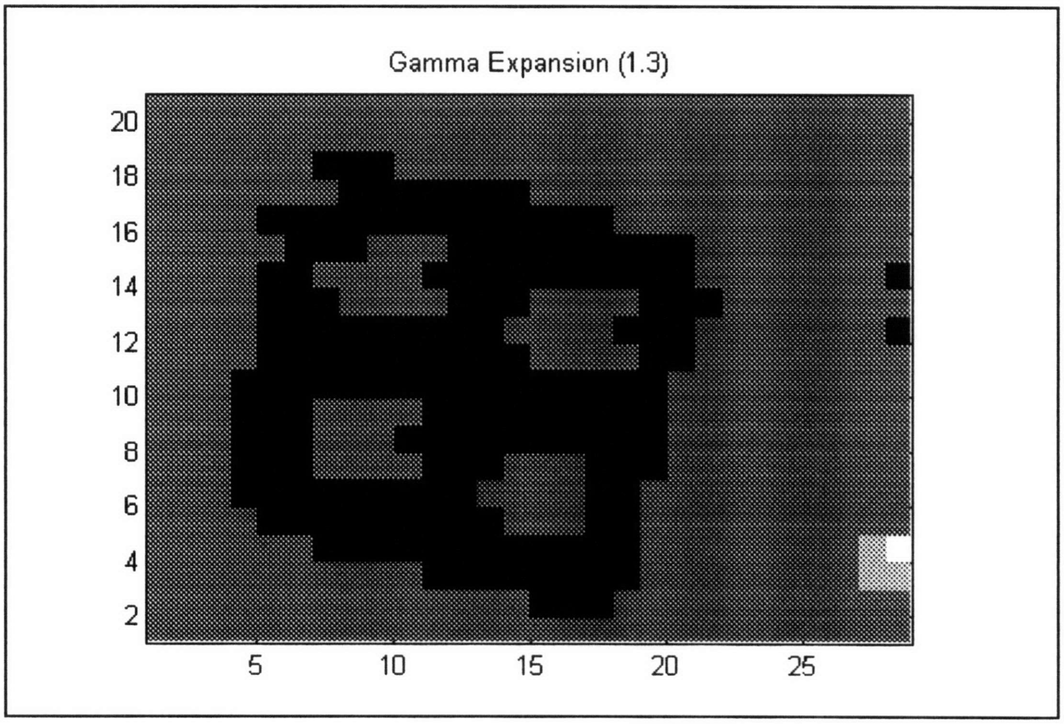


Figure 48. Image of 40 mm target at 8 foot altitude, after using MATLAB routine, 'egamma.m', designed to stretch all points towards the two extremes and reduce the occurrence of pixels with neutral grayscale values.

```
function y = egamma(x,g)

% This function is used to exaggerate the low and high end grayscale
% values, reducing the mid-scale grays. The intention is to improve
% contrast, the trade-off is loss of data, hence loss of detail.

white = max(max(x));
y = white*(x/white).^g;
[m,n] = size(x);
if nargout < 1
        image(y);
        colormap(gray(256));
        set(gca,'ydir','normal','aspect',[n/m 1],'xlim',[-inf inf]);
        title( ['Gamma Expansion (' num2str(g) ')'] );
end
return;
```

Figure 49. MATLAB routine 'egamma.m' designed to expand geometricaly.

14.0 Recommendations and Conclusions

Based upon the laboratory and field evaluations, some recommendations for future applications of this apparatus follow. These recommendations include discussions of lighting, turbidity, resolution and future investigations.

14.1 Lighting

It became evident that a practical component of any AUV based video imaging system must accommodate a broad dynamic range. In order for this hardware to be practical in spanning the extreme dark of abyssal conditions and bright tropical waters, a broader dynamic range is necessary. One approach that will allow us to utilize the existing hardware to the fullest extent possible is to perform a preliminary light metering evaluation for the given conditions prior to deployment. From this, a suitable neutral filter may be fitted to the camera prior to launch. The intention here is to bracket the dynamic range of the camera's automatic gain settings by roughly bringing the amount of incident light to the middle of the adjustable range. Any slight fluctuations from this setting due to cloud cover or strong reflections will then be compensated for by the camera itself. Currently available commercial camera systems already possess such desired broad dynamic range. If cost is not a limiting variable, it may prove most prudent to purchase a camera that is able to operate within the lighting conditions typical of benthic surveys, and may in fact have more sophisticated light metering capability as well.

To calibrate the proposed system it is suggested that a simple test fixture be assembled and data gathered. This fixture is intended to allow a standardization of the appropriate neutral density filters for any given lighting conditions. The setup consists of a moderate sized aquarium or test tank, light meters and a complete set of filter elements as depicted in Figure 50. The first step is to black out the walls, top and sides of the tank to restrict any light from entering. Place the camera at one end of the tank, with a light meter positioned next to the lens so that it will receive equal intensity of light as strikes the camera. Set a light source of sufficient intensity so as to simulate tropical sunlight conditions in parallel to the camera. Place a test target at the far end of the tank. Beginning with no filter on the light source, record the incident light, and monitor the video output from the camera. At this setting, the image will be bloomed. Begin to place neutral filters (set #1) in front of the camera lens until the image stops blooming. Repeat this test for decreasing intensity of light, by placing a second set of neutral filters (set #2) in the path of the incident light. Considering the criteria described [by Mertens] and discussed earlier under the section on "resolution", evaluate the various intensity settings relative to the ability to resolve the image using this system.

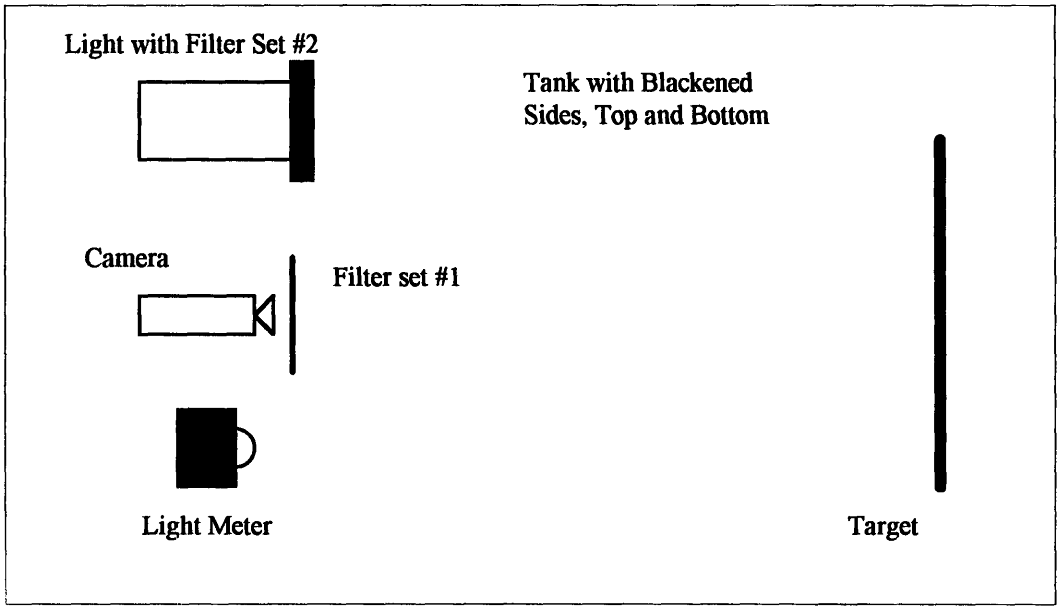


Figure 50. Proposed test tank for camera range analysis, using light meter and neutral filters in front of light source and camera.

14.2 Turbidity and Water Clarity

In very turbid water, the camera may prove incapable of imaging anything beyond some distance limited by water clarity. In this case, the only possible adjustment would be to move the camera closer to the subject. At some point it may be entirely impractical to move closer to the subject, and this distance would represent the practical limitation imposed by turbidity. In general, the presence of minute suspended particles contributes to turbidity in all but the clearest of waters. The impact upon imaging due to turbidity is the adverse effect due to the backscatter of light off of these particles.

There are techniques for reducing the adverse effect imposed by back scattered light upon the captured image. The first approach is to physically separate the camera and light source to achieve nearly orthogonal orientation between the two. This minimizes the field of view of light source and imager overlap. The second approach is to incorporate the use of orthogonally oriented polarizing filters over the light source and the camera lens. The use of polarizers in this manner exploits the polarization selection inherent in scattering. Both of these techniques have been successfully employed [Mertens]. Within our system, the camera to strobe separation is maintained as far apart as practical on the platform used.

14.3 Resolution

Where the resolution of the existing system is inadequate, two options are available. The first suggestion is to autonomously reduce the field of view by decreasing vehicle altitude, with a corresponding increase in image resolution. This could be accomplished using a feedback system similar to that suggested for compensating lighting inputs. A relationship between desired target size and turbidity would have to be determined, and an algorith would have to be developed based on this relationship. In this case, an altitude based on previously measured turbidity data would be maintained in order to capture a desired target size. As an alternative to an active control mechanism intended to provide a desired image resolution, the pixel count on the imaging system may be increased. This solution requires a capital investment, and as mentioned previously, would accomplish a greater degree of system resolution, but would still require active vehicle control in order to maintain constant image size.

14.4 Future Work

Once all of the technical details of the underwater imaging system are worked out, and practical AUV operation is proven, there are certain second order issues that may need to be addressed. Among these issues are concerns regarding the accuracy of the data that is collected. Particular focus may be made regarding the "flight" effect that an autonomous vehicle has on finfish and on benthic fauna. It is a natural reaction for animals to flee from predators, and it is no surprise that the presence of this large, slow moving mechanical fish might be interpreted by some species as presenting imminent danger. If indeed a large number of the fauna that is being studied do exhibit this behavior, it must be accounted for in order to gain accurate population assessments. The question of actual size of targets imaged may be of particular concern to biologists and zoologists. The use of the pencil lasers is intended to allow for a standard of measure being provided within the field of view at all times. In reality, the laser points may not be adequately visible when projected into deep clusters of weed, silty bottom, or steeply sloping terrain. An independent study is recommended in order to address this issue solely, as it can readily be deemed necessary for qualifying the validity of any data that ultimately is gathered using this hardware.

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12 Volt Tether - Dimensions

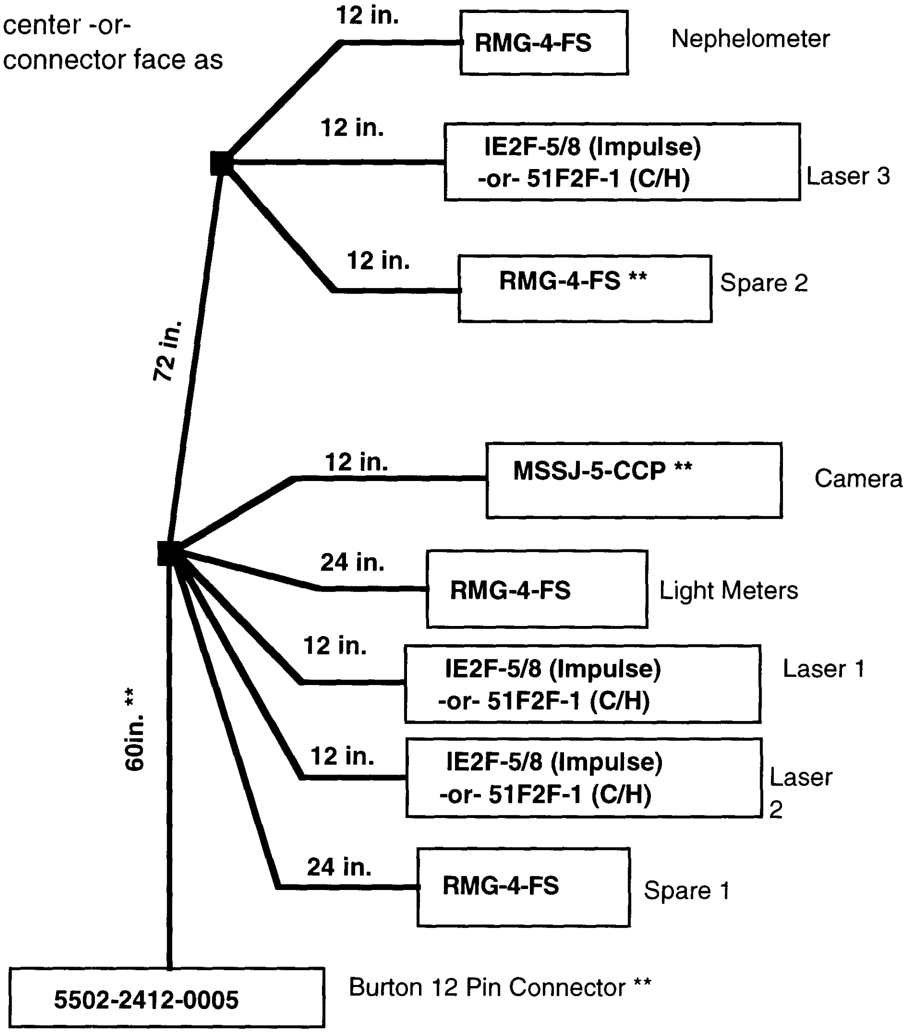
Joseph Curcio
MIT Sea Grant - Photographic Sled System

Rev. 5
2/28/95
1 of 2

Use minimum #22AWG conductor custom cable with two coax and seven single strands throughout assembly.
Use smallest "T" and "Y" junctions possible.

All lengths minimum,
(+/- 1")
center to center -or-
center to connector face as applies.

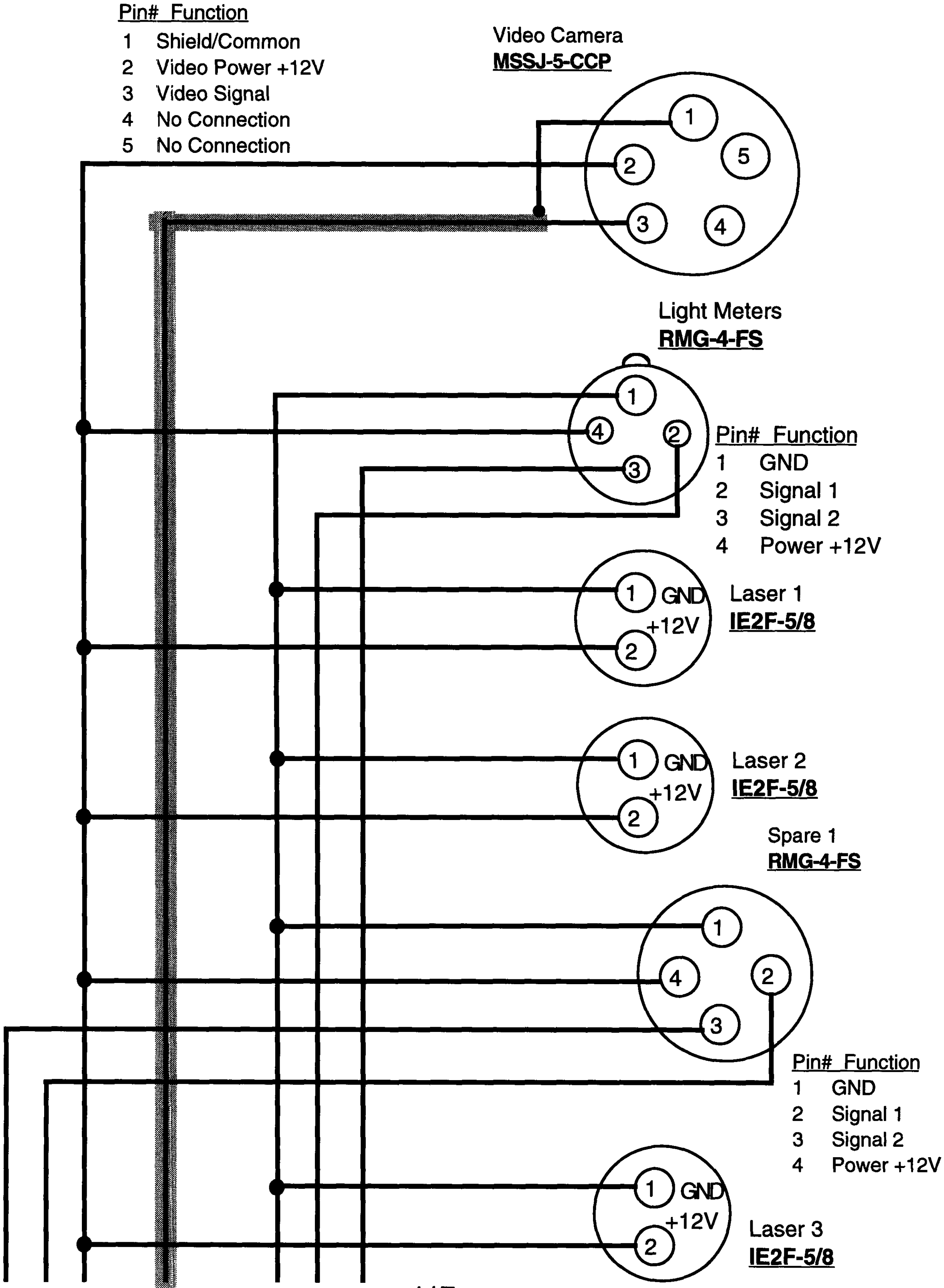
**** Components to be supplied by vendor**

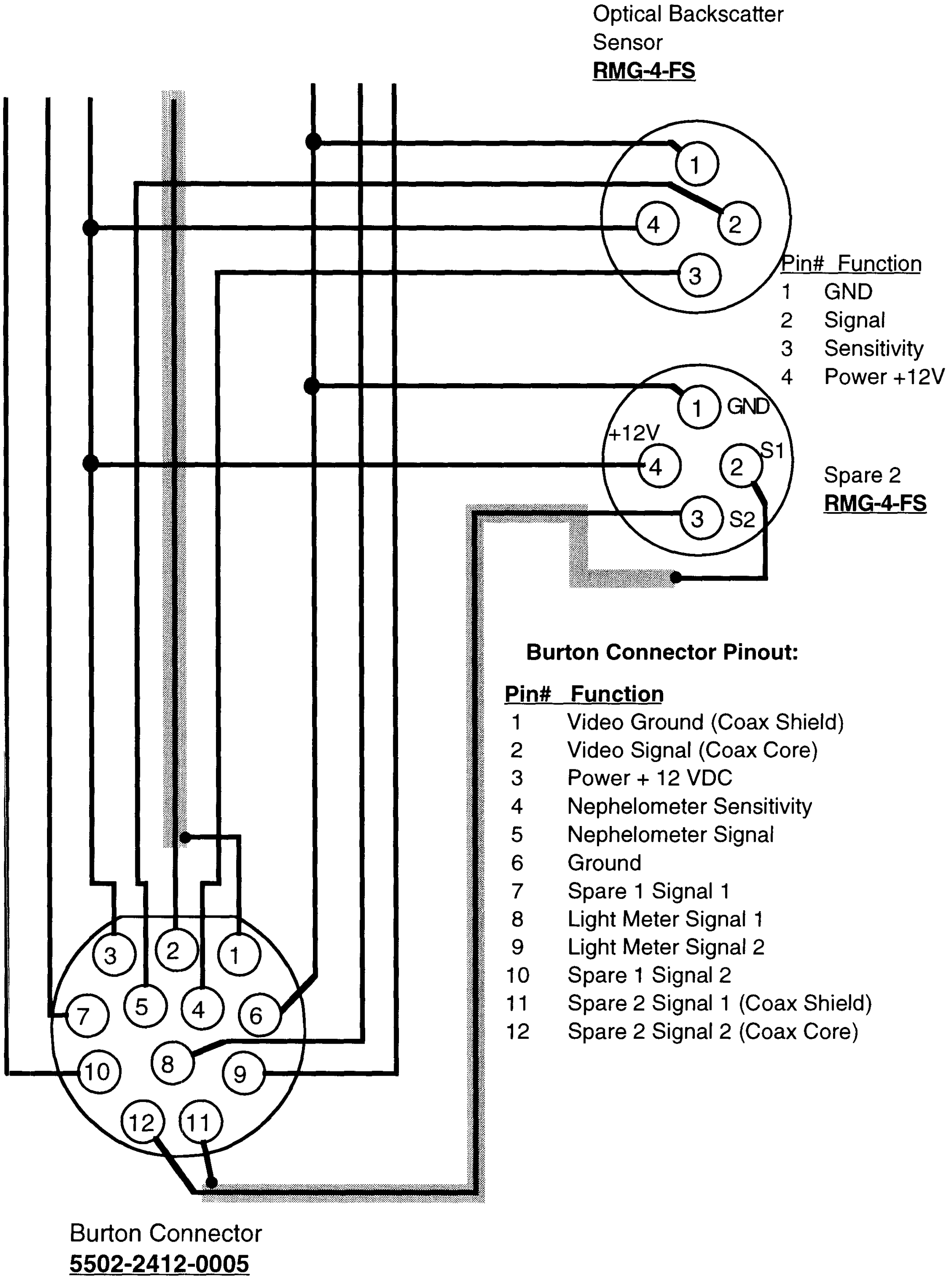


12 Volt Tether - Schematic

Rev. 5
2/28/95
2 of 2

Joseph Curcio
MIT Sea Grant Photographic Sled System





Pin#	Function
1	GND
2	Signal
3	Sensitivity
4	Power +12V

Burton Connector Pinout:

Pin#	Function
1	Video Ground (Coax Shield)
2	Video Signal (Coax Core)
3	Power + 12 VDC
4	Nephelometer Sensitivity
5	Nephelometer Signal
6	Ground
7	Spare 1 Signal 1
8	Light Meter Signal 1
9	Light Meter Signal 2
10	Spare 1 Signal 2
11	Spare 2 Signal 1 (Coax Shield)
12	Spare 2 Signal 2 (Coax Core)

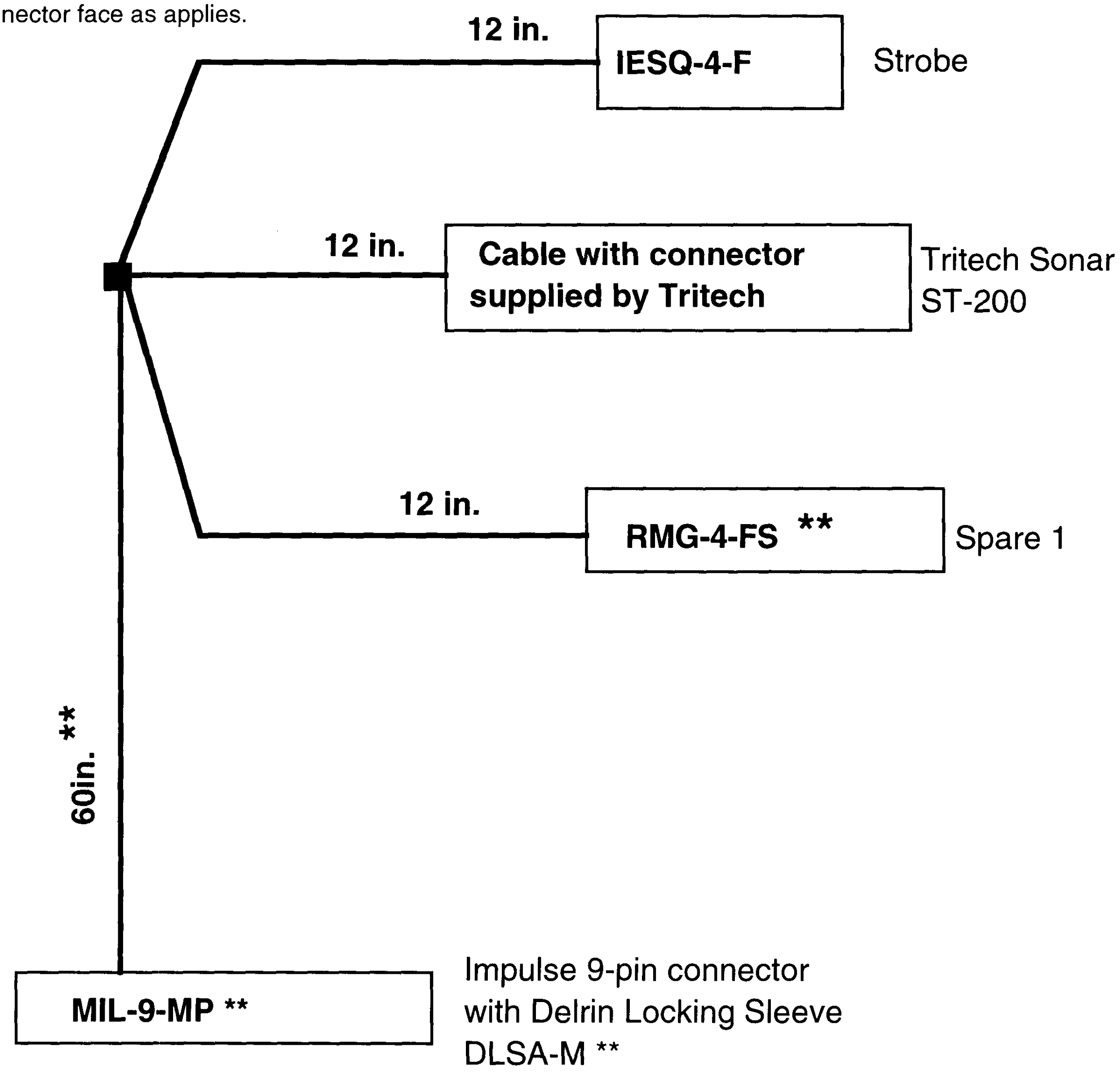
24 Volt Tether - Dimensions

Rev. 3
2/28/95
1 of 2

Joseph Curcio
MIT Sea Grant - Photographic Sled System

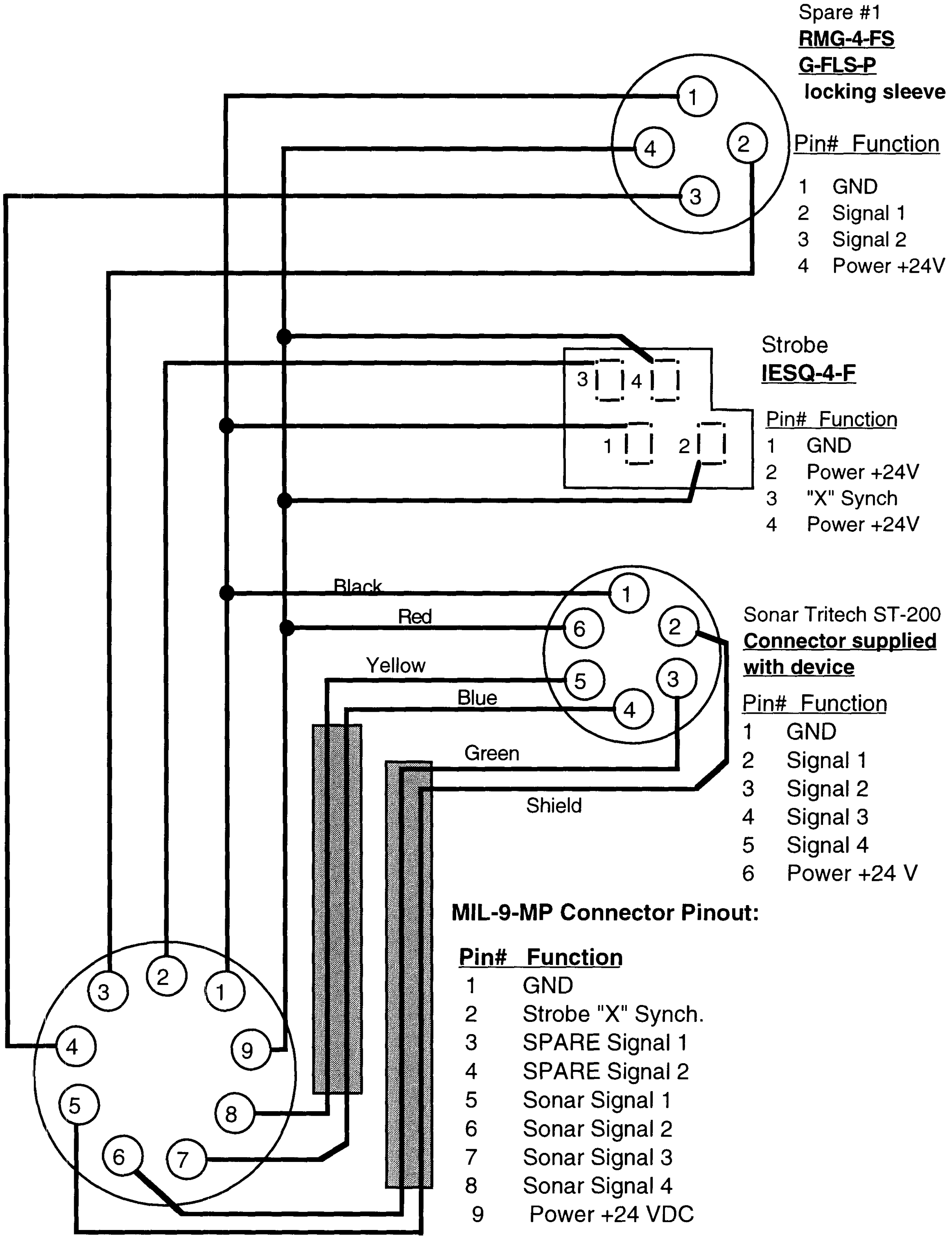
Use minimum #22 AWG conductor custom cable with two coax and seven strands throughout throughout assembly
Use smallest "T" and "Y" junctions possible.

All lengths minimum, (+/- 1")
center to center -or- center to
connector face as applies.



24 Volt Tether - Schematic
Joseph Curcio
MIT Sea Grant Photographic Sled System

Rev. 4
5/21/95
2 of 2



Spare #1
RMG-4-FS
G-FLS-P
locking sleeve

Pin#	Function
1	GND
2	Signal 1
3	Signal 2
4	Power +24V

Strobe
IESQ-4-F

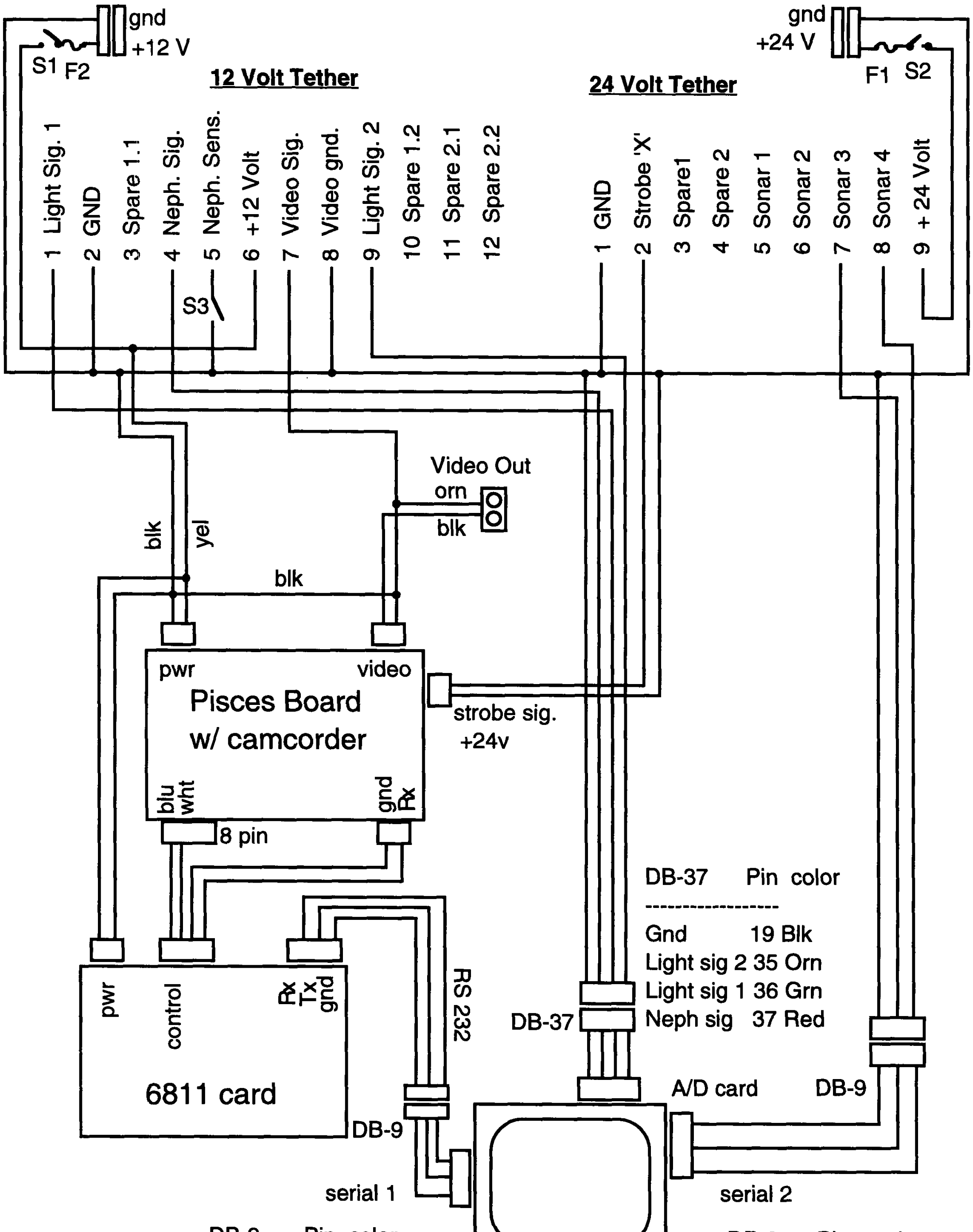
Pin#	Function
1	GND
2	Power +24V
3	"X" Synch
4	Power +24V

Sonar Tritech ST-200
Connector supplied with device

Pin#	Function
1	GND
2	Signal 1
3	Signal 2
4	Signal 3
5	Signal 4
6	Power +24 V

MIL-9-MP Connector Pinout:

Pin#	**Function**
1	GND
2	Strobe "X" Synch.
3	SPARE Signal 1
4	SPARE Signal 2
5	Sonar Signal 1
6	Sonar Signal 2
7	Sonar Signal 3
8	Sonar Signal 4
9	Power +24 VDC



DB-37	Pin	color
Gnd	19	Blk
Light sig 2	35	Orn
Light sig 1	36	Grn
Neph sig	37	Red

DB-9	Pin	color
Ser. Rx	2	Red
Ser. Tx	3	Whi
Gnd	5	Grn

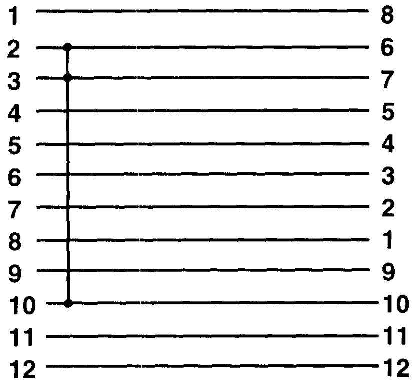
DB-9	Pin	color
TXD +	2	Pur
Net com	3	Blk
TXD -	7	Blu

TITLE: **Camera Test Sled Surface controls**	REV. **1.0**	DATE: **5/19/95**
MIT SEA GRANT COLLEGE PROGRAM	1 of 2	BY: **J.Curcio**

12 Volt Tether Interface pinout

AMP CPC connector P/N 206043-3	Burton Connector P/N 5502-2412-0005

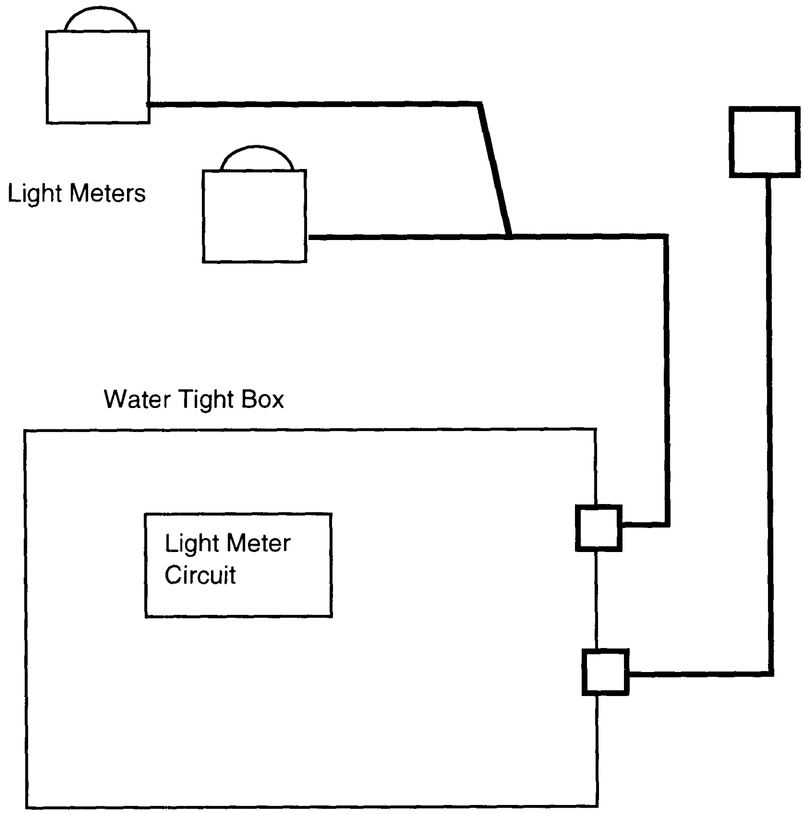
AMP Pin Number **Burton Pin Number**



OBS Brand Nephelometer Jumper Cable (12" length)

12 Volt Tether Pin Number	OBS Sensor Pin Number	Function
1	2	GND
2	4	Signal
3	3	Sensitivity
4	1	Power +12V

TITLE: **Camera Test Sled Surface controls**	REV. **1.0**	DATE: **5/19/95**
MIT SEA GRANT COLLEGE PROGRAM	2 of 2	BY: **J.Curcio**

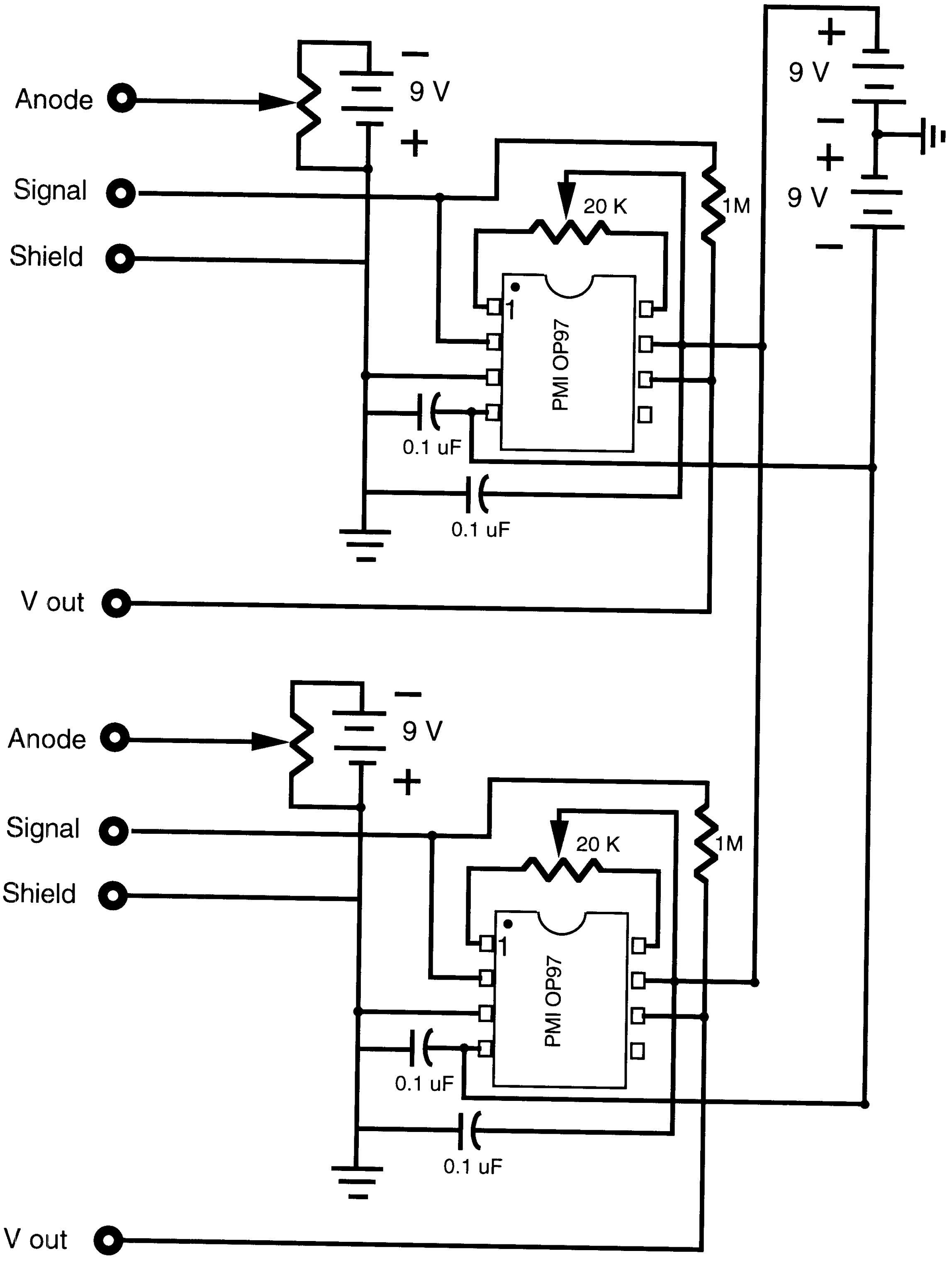


RMG-4-MP

Pin	Function	Color
1	gnd	yel
2	sig1	pur
3	n/c	whi
4	sig2	red

	Bulkhead	Light Meter	
1	red	whi/blk	n/c
2	orn	blk	anode 1
3	yel	whi/brn	Sig 1
4	grn	brn	shld
5	blu	wht/red	n/c
6	vio	blu	anode 2
7	blk	vio	Sig 2
8	brn	gra	shld
9	whi	yel	n/c

TITLE: **Light Meter Electronics**	REV. **1.0**	DATE: **5/19/95**
MIT SEA GRANT COLLEGE PROGRAM	1 of 2	BY: **J.Curcio**



TITLE: **Light Meter Electronics**	REV. **1.0**	DATE: **5/19/95**
MIT SEA GRANT COLLEGE PROGRAM	2 of 2	BY: **J.Curcio**

Appendix B - MATLAB Routines

1) ASPVIEW.M This Routine is used to plot images at their correct aspect relative to their apparent size, as if viewed on a standard 14” monitor.

```
function y = aspview(file,m,n)

% Function to image files in aspect appropriate
% to the true size of the image

fid = fopen(file);
x = fread( fid, 'uchar' );
fclose(fid);
y = reshape( x(1:m*n),m,n)';
image(y);
colormap(gray(256));
set(gca,'ydir','normal','aspect',[m/n 1],'xlim',[1 110], 'ylim',[1 170]);
title( ['Image ' file]);

return;
```

2) BINVIEW.M This routine is used to view a binary file (stored as a .bin file) containing the grayscale values for the digitized images.

```
function y = binview(file,m,n)

% This function is used to image a binary grayscale value file. (.bin)
% Also, this routine will provide appropriate aspect ratio to image

fid = fopen(file);
x = fread( fid, 'uchar' );
fclose(fid);
y = reshape( x(1:m*n),m,n)';
image(y);
colormap(gray(256));
set(gca,'ydir','normal','aspect',[m/n 1],'xlim',[-inf inf]);
title( ['Image ' file]);

return;
```

3) BINV2.M This routine is used to remove the bright white pixels produced by the laser light sources. These pixels would otherwise bias the entire image when using EXPAND.M or EGAMMA.M.

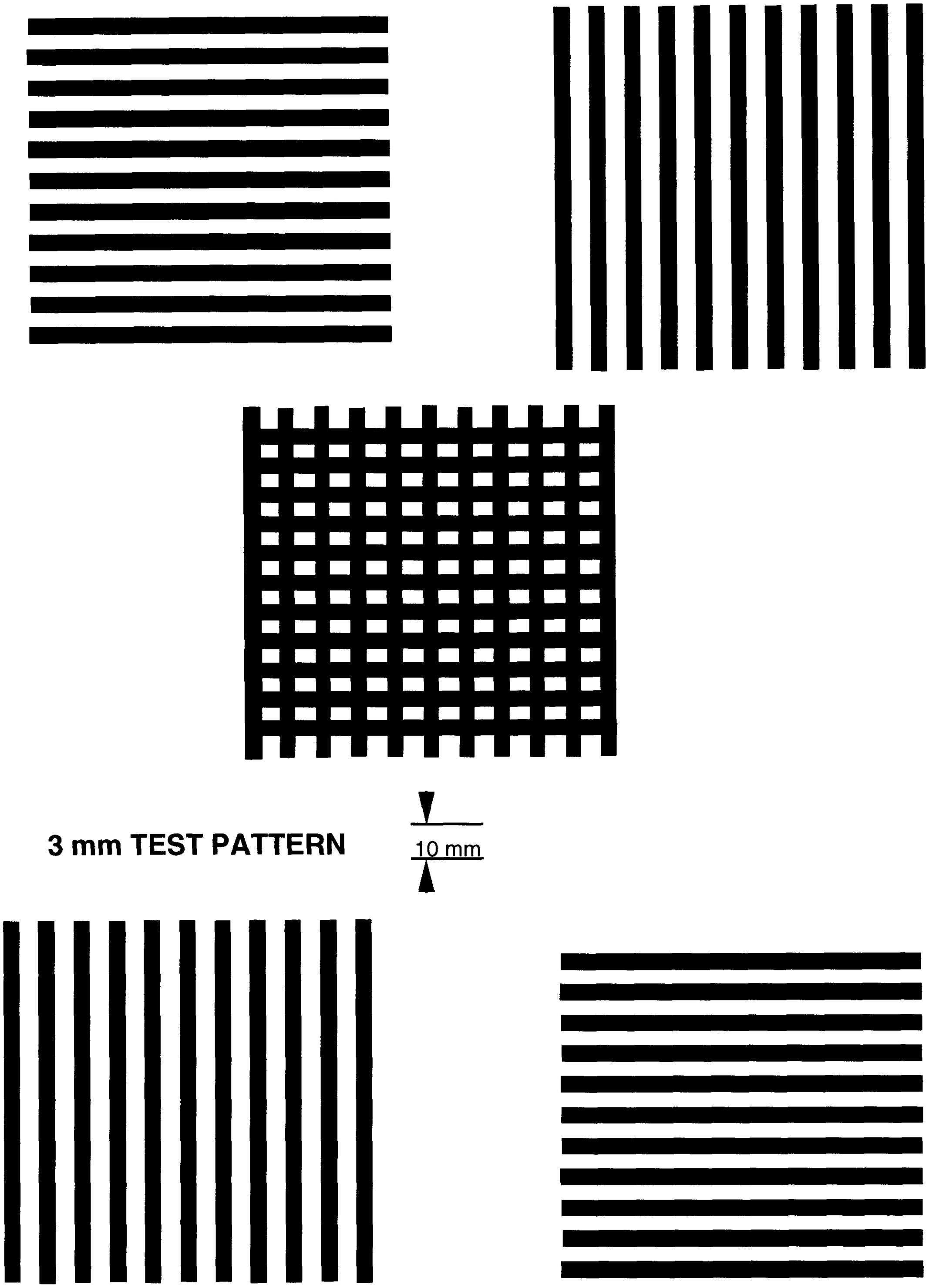
```
function y = binv2(file,m,n)

% This function is used as a low-pass filter in order to eliminate any
%  biasing that the laser spots produce.

fid = fopen(file);
x = fread( fid, 'uchar' );
fclose(fid);

% The next line may substitute for  sending the size with the call.
%[n,m]=size(x);

for i=1: m*n;
        if x(i) > 150,
        x(i) = 150;
        end;
end;

y = reshape( x(1:m*n),m,n)';
image(y);
colormap(gray(256));
set(gca,'ydir','normal','aspect',[m/n 1],'xlim',[-inf inf]);
title( ['Image ' file]);

return;
```

4) TRANS2.M This routine produces a transect of a selected region of a datafile. It is intended to be used after viewing the image once, in order to determine the location of the transect and the range to set for obtaining the local maximum and minimum. These values are used to calculate the saddle depth ratio.

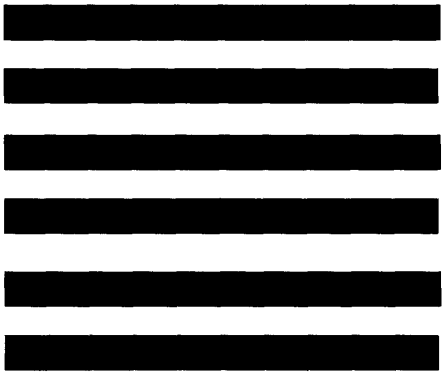
```
function z=trans2(fname,a,cut,lok,hik);

% This function transects a previously viewed file (in array format), and
% produces a truncated view of the transect region, as well as a set of high
% and low values within a range as selected by user.

[n,m] = size(a);
clf;
ymn=cut-5;
ymx=cut+5;
subplot(2,1,1),image(a);
colormap(gray(256));
set(gca,'ydir','normal','ylim',[ymn ymx]);
ylabel('Pixel');
title(['Image of file: ',flame]);
hold;

% method to plot the cut on top of the image
v=[1:m];
plot(cut*(ones(size(v))),'r');
subplot(2,1,2),plot((a(cut,1:m)/2.56),'b');
title ('Transect at Position Shown');
xlabel('Pixel');
ylabel('percent');
axis([0 m 0 100]);
hold;

% Determining the max and min values within range
lokmax=max(a(cut,lok:hik))/2.56
lokmin=min(a(cut,lok:hik))/2.56
v=[1:hik];
plot(lokmax*(ones(size(v))),'g');
plot(lokmin*(ones(size(v))),'m');

return;
```

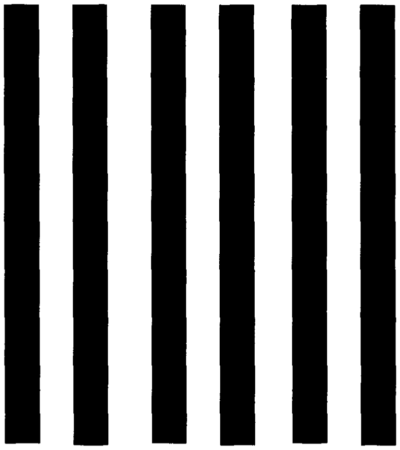
5) TRANSECT.M This routine is used to create the transect cuts through an image. The user is expected to select the row first, having previously viewed an image using BINVIEW.M.

```
function z=transect(fname,a,m,n,cut);

clf;
ymn=cut-5;
ymx=cut+5;

subplot(2,1,1),image(a);
colormap(gray(256));
set(gca,'ydir','normal','ylim',[ymn ymx]);
ylabel('Pixel');
title(['Image of file: ',fname]);
hold;

% method to plot the cut on top of the image

v=[1:m];
plot(cut*(ones(size(v))),'r');

% Plot the cut section
% Note: To use this routine to transect a
% previously staggered file, decrease m by
% variable 'howfar' from stag.m

subplot(2,1,2),plot((a(cut,1:m)/2.56),'b');

title ('Transect at Position Shown');
xlabel('Pixel');
ylabel('percent');
axis([0 m 0 100]);
return;
```



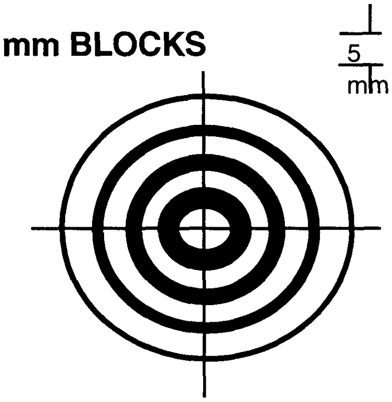
3 mm TEST PATTERN

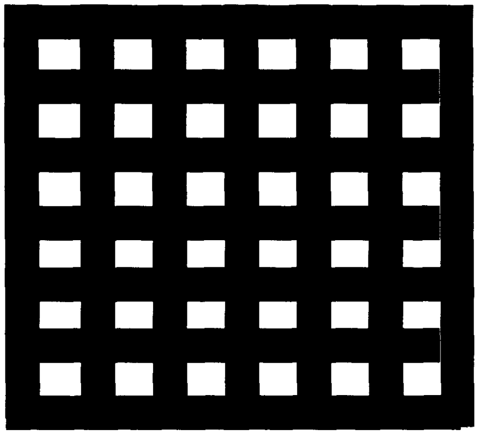


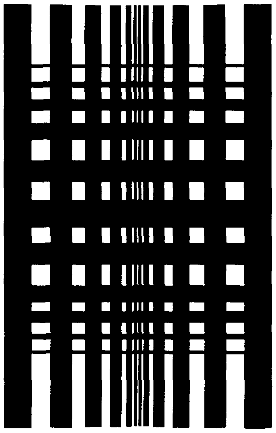


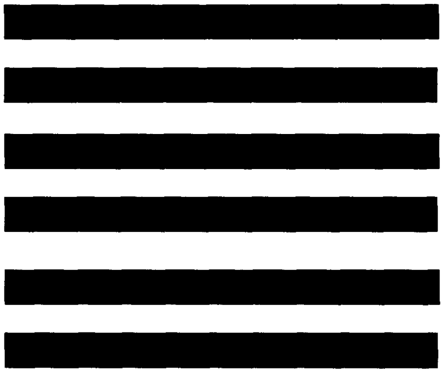
5 mm TEST PATTERN

5 mm BLOCKS

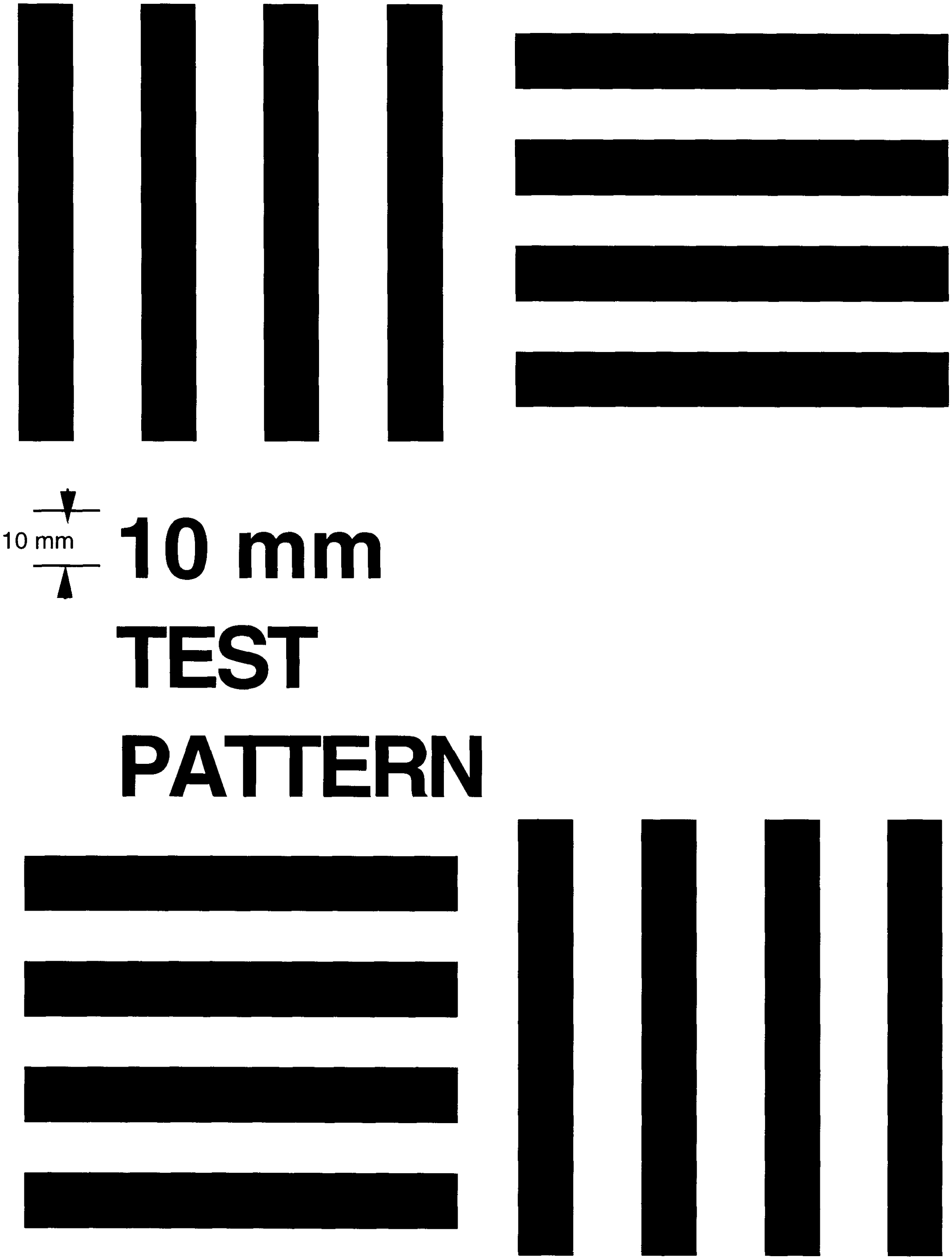


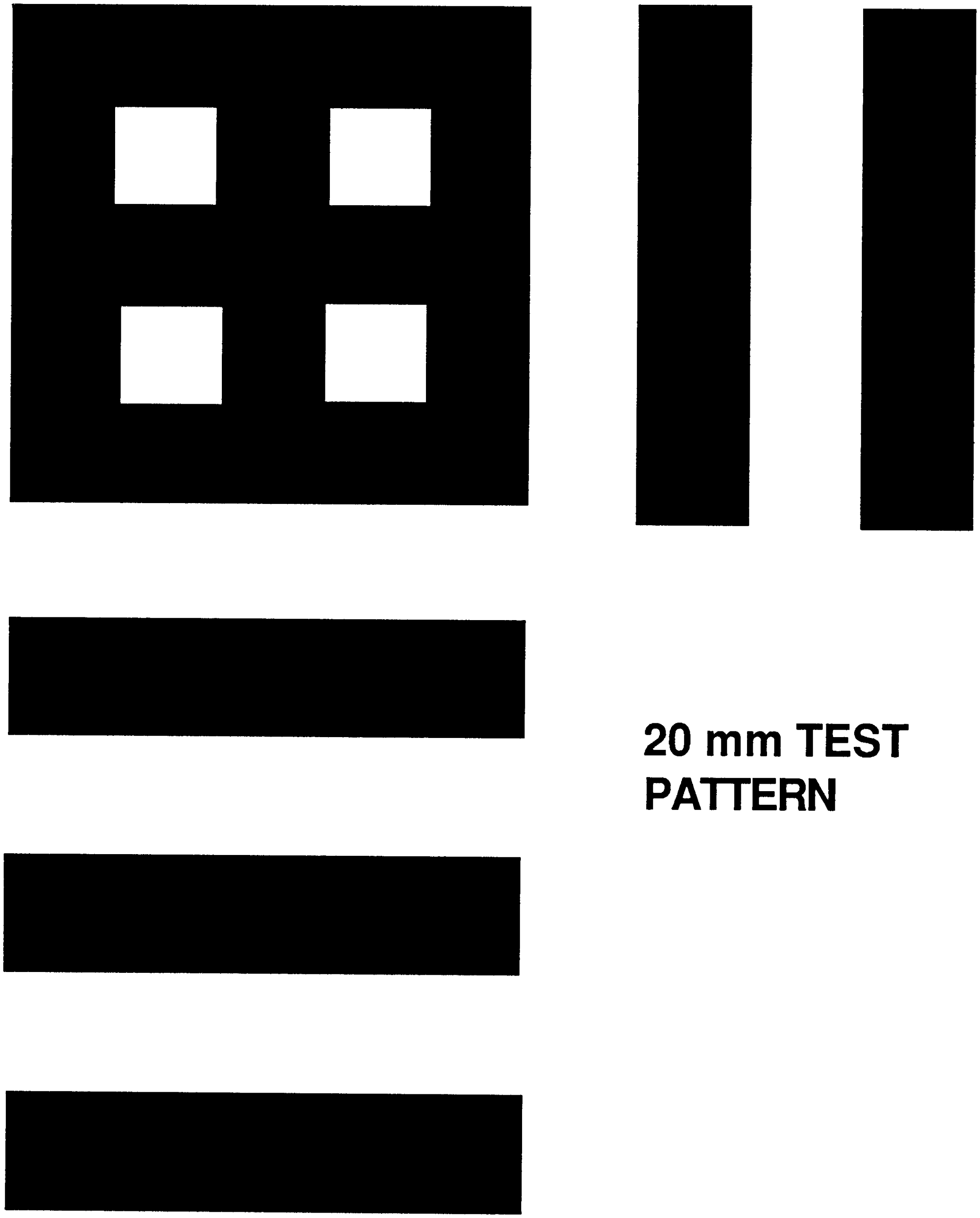




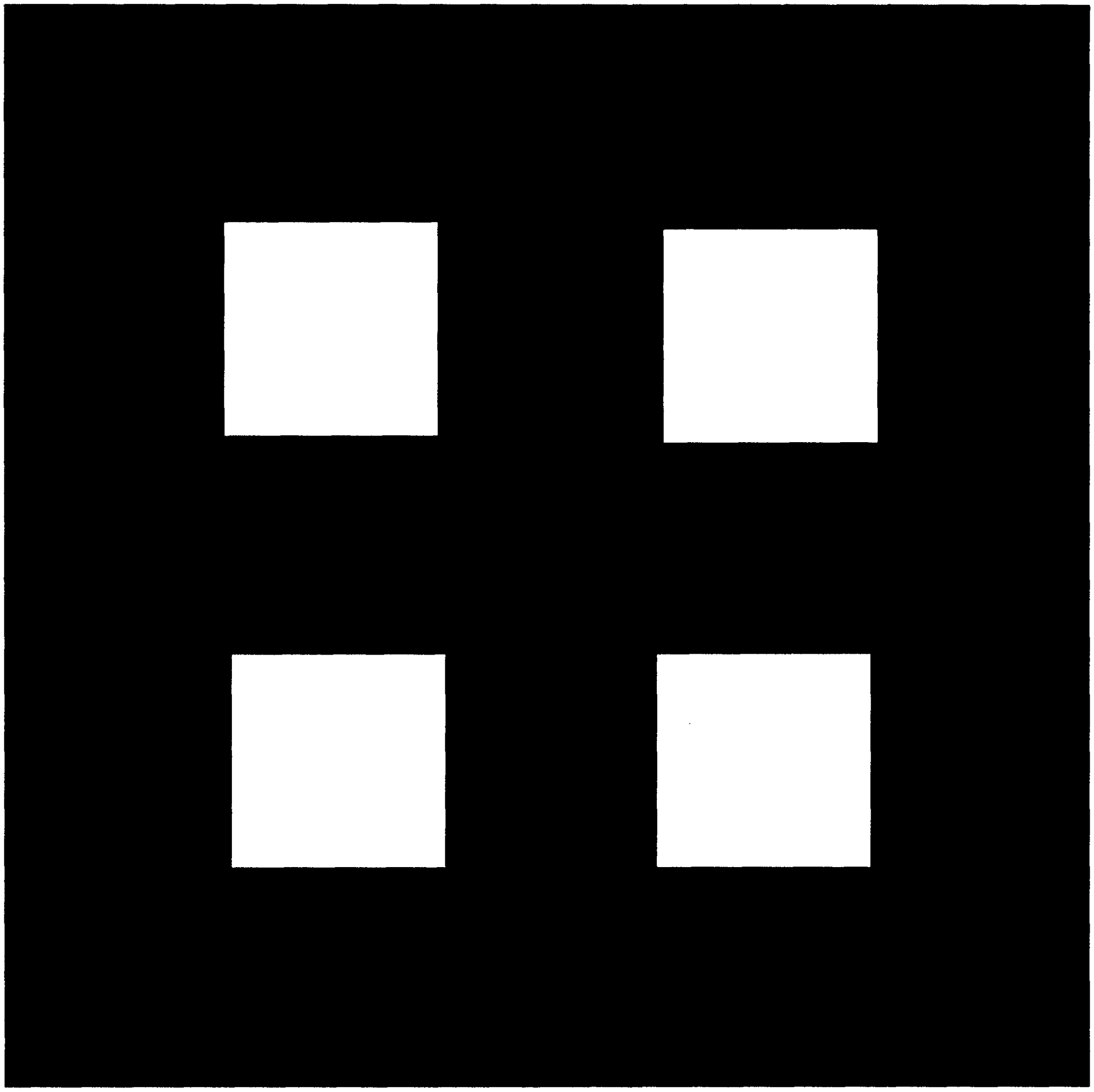


Appendix C note: targets reduced to fit margins



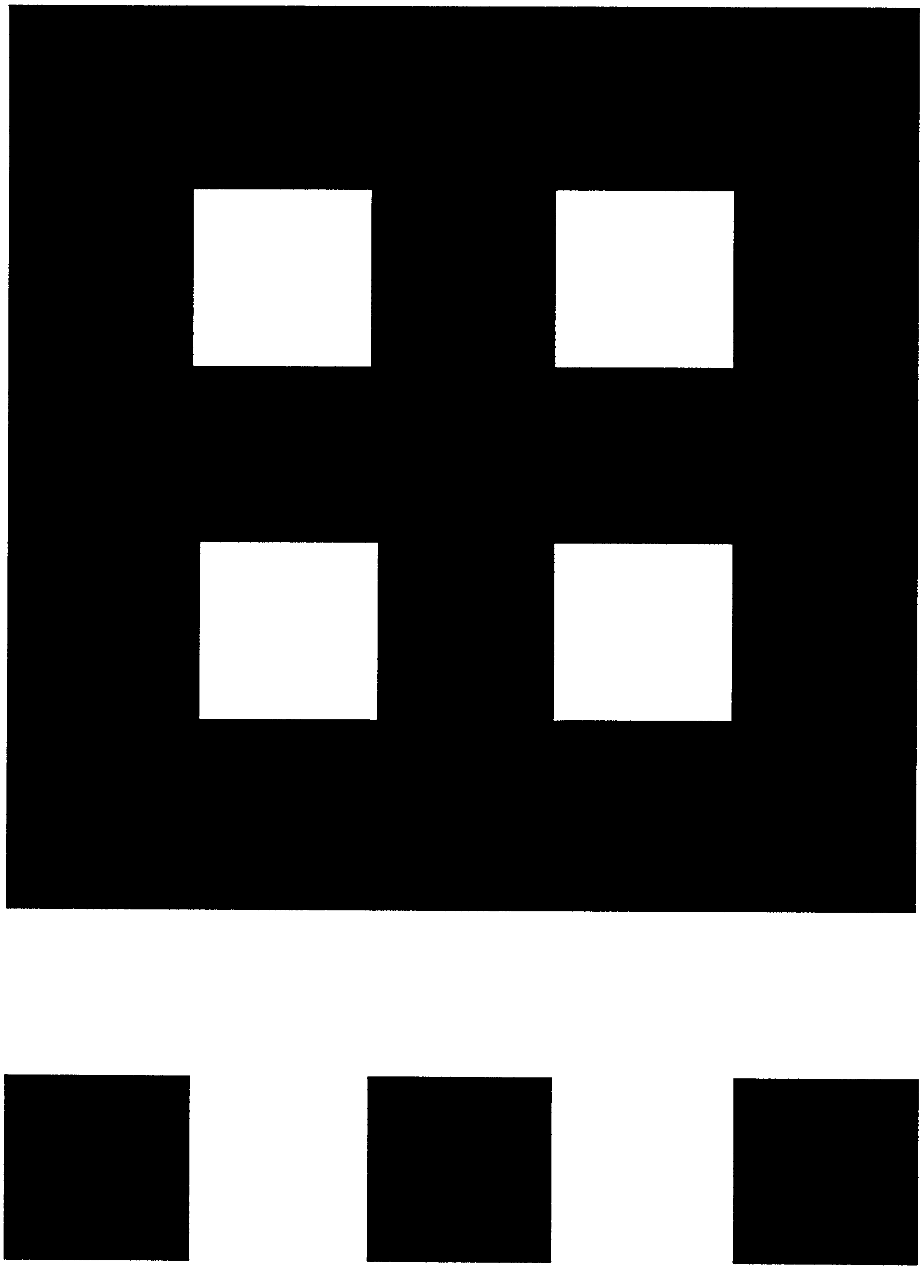


20 mm TEST PATTERN



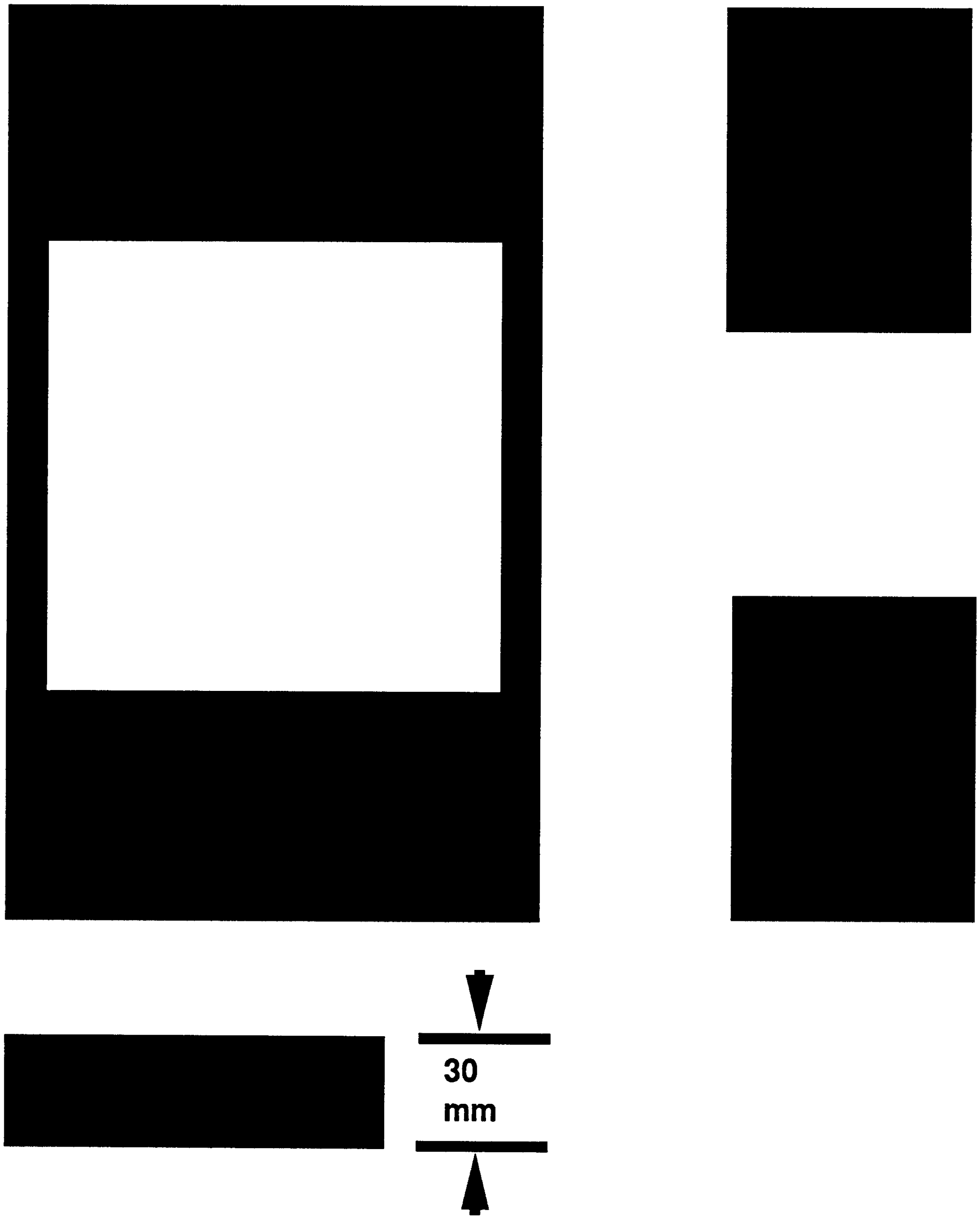
30 mm TEST TARGET

NOTE: TARGET SHOWN ACTUAL SIZE

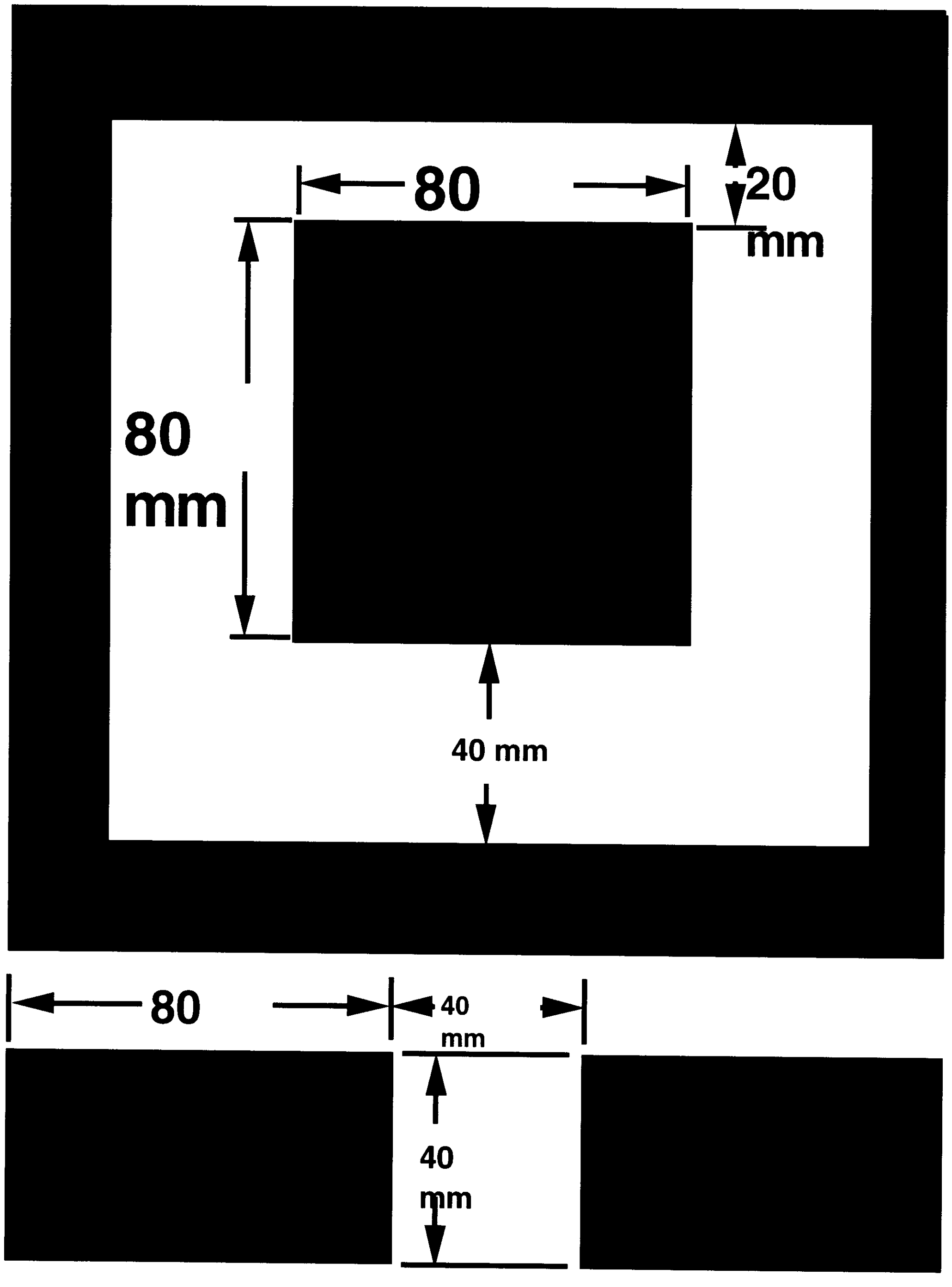


40 mm TEST PATTERN

NOTE: PATTERN REDUCED TO FIT PAGE



65 mm TEST PATTERN


80
20
mm
80
mm
40 mm
80
40
mm
40
mm