An Analysis of ICBM Navigation Using Optical Observations of Existing Space Objects

by

Weldon Barry Willhite

B.S. Mechanical Engineering, United States Naval Academy, 2002

SUBMITTED TO THE DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN AERONAUTICS AND ASTRONAUTICS
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2004

Signature of Author ....
Department of Aeronautics and Astronautics
May 14, 2004

Certified by ....
Richard E. Phillips, Ph.D.
Principal Member of the Technical Staff
The Charles Stark Draper Laboratory, Inc.
Technical Supervisor

Certified by ....
John E. Keesee, Col, USAF (retired)
Senior Lecturer, Department of Aeronautics and Astronautics
Thesis Advisor

Accepted by ....
Edward M. Greitzer, Ph.D.
H.N. Slater Professor of Aeronautics and Astronautics
Chair, Committee on Graduate Students

[This page intentionally left blank]

An Analysis of ICBM Navigation Using Optical Observations of Existing Space Objects

by

Weldon Barry Willhite

Submitted to the Department of Aeronautics and Astronautics
on May 14, 2004, in partial fulfillment of the
requirements for the degree of
Master of Science in Aeronautics and Astronautics

Abstract

This thesis investigates the potential of a space-based navigation concept known as Skymark to improve upon the accuracy of inertially-guided intercontinental ballistic missiles (ICBMs). The concept is to use an optical tracker to take line-of-sight measurements to nearby space objects with known ephemerides to update the state knowledge of the onboard inertial navigation system. The set of existing space objects that would be potentially useful for this application are tabulated, and a simulation determines their availability from realistic trajectories. A follow-on navigation simulation investigates the accuracy improvement potential in terms of Circular Error Probable at impact. Two scenarios are investigated, one in which the Skymark system is an add-on aid-to-inertial-navigation for an existing missile system, and one in which the Skymark system is completely integrated with a new inertial navigation unit. A sensitivity analysis is performed to determine how several performance factors affect Skymark accuracy. Finally, a brief discussion of some operational implementation issues is included.

Technical Supervisor: Richard E. Phillips
Title: Principal Member of the Technical Staff
The Charles Stark Draper Laboratory, Inc.

Thesis Advisor: John E. Keesee, Col, USAF (retired)
Title: Senior Lecturer, Department of Aeronautics and Astronautics

[This page intentionally left blank]

Acknowledgements

Working on this thesis has been an incredibly enriching experience, and so I am very thankful to the Charles Stark Draper Laboratory for providing the opportunity for me to perform this research and study at M.I.T. I would also like to thank the U.S. Air Force ICBM Systems Program Office and Northrup Grumman Mission Systems for sponsoring my work here at the Draper Laboratory.

I am especially indebted to Richard Phillips, my technical advisor, who was always available to answer my multitude of questions and provide exceptional guidance every time I found myself at a standstill. I would also like to express my gratitude to several other members of the Draper staff who have been supporting me in this research endeavor: Jim Shearer, Marv Biren, Bill Robertson, Ron Proulx, and Roy Setterlund.

My deepest thanks also are due to Colonel John Keesee, USAF (retired), my academic advisor. His brilliant ideas and expert advice helped to steer this research in the right direction and ensure the thoroughness of this study.

I would also like to thank my wife, Jennifer, who has supported me through this entire process. Thank you so much for encouraging me and being interested in my thesis, it has made a mighty difference!

Above all, I am thankful to God, who gave me both the ability and the strength to complete this work. Without Him I can accomplish nothing. He is my inspiration, motivation and reason for being.

Since ICBM accuracy values are classified, I have made assumptions of current accuracies based on unconfirmed values identified in open source literature.

This thesis was prepared at The Charles Stark Draper Laboratory, Inc., under internal project number 88002, contract number SUB HP 10786M8S (SLIN 0034), sponsored by the United States Air Force ICBM Systems Program Office and Northrup Grumman Mission Systems.

Weldon Barry Willhite

[This page intentionally left blank]

Contents

[This page intentionally left blank]

List of Figures

List of Tables

[This page intentionally left blank]

Chapter 1

Introduction

1.1 Thesis Motivation

Inertial navigation systems (INS) are the primary guidance technology enabling our nation's Intercontinental Ballistic Missile (ICBM) fleet. In a world where strategic systems cannot afford to rely on the presence of GPS, inertial navigation offers a fairly accurate stand-alone guidance alternative for strategic systems. Today, the instruments and sensors that comprise the inertial measurement unit (IMU) of an ICBM are very high precision instruments. However, even the best IMU has errors that grow over time, so that at impact, several thousand nautical miles and 20-30 minutes downrange, these errors may have grown to relatively significant levels. When using low yield or conventional warheads in particular, an accurate impact is imperative both for effectiveness and the minimization of collateral damage.

The goal is to find a robust, relatively inexpensive means of improving ICBM accuracy. There are several options. The addition of GPS has been considered, but its susceptibility to jamming has prevented its use in strategic systems. A second possibility, further improving the inertial instruments, would likely be an extremely expensive undertaking, as these sensors are already very accurate and costly. Some other method for in-flight aid to inertial navigation is sought.

1.2 The Skymark Concept

One idea proposed by the Charles Stark Draper Laboratory in Cambridge, MA, is for an add-on camera and software to incorporate the results of star and satellite angles-only observations to update the position knowledge of the INS. The concept, referred to as Skymark, is similar to the age-old method used by mariners to triangulate their position by taking line-of-sight measurements to specific landmarks. The Skymark idea uses an optical tracker to sight nearby space objects as landmarks in the sky, or "skymarks" as they will be referred to in this thesis, in order to estimate position in an angles-only fashion via triangulation. The basic concept of operations is as follows. A pre-launch process determines which space objects should be sighted using optimized selection algorithms, and uploads their ephemerides and associated pointing directions to the onboard flight computer. In flight, the camera makes line-of-sight measurements to the scheduled skymarks, using the star background as a frame of reference to determine the camera pointing direction. The missile INS flight computer maintains a continuous state estimate. The angular difference between where the skymark was expected to be seen (computed from *a priori* missile and skymark state knowledge) and its measured location on the star camera focal plane is calculated and used to update the missile state via Kalman filter equations.

The terms optical tracker and star camera will be used interchangeably in this thesis. Also, the capitalized term "Skymark" will be used to refer to the concept or the onboard system, while the lower-case "skymark" will be used to refer to the space objects observed by the system.

1.3 Circular Error Probable and Impact Error Sources

Circular Error Probable (CEP) is defined as the radius of a circle inside which there is a 50% probability of impact. The CEP at impact will be used as the accuracy figure of merit in this study. Any system hoping to reduce the CEP of a missile must, by definition, reduce the sources of error that cause accuracy to degrade. The factors that affect the CEP of an ICBM can be divided into three main groups: navigation system errors, atmospheric conditions, and target location knowledge error. The CEP at impact can be understood as a root-sum-square of these factors. Thus, knowledge of which factors dominate the CEP and which ones can be reduced is required to assess CEP improvement. The assumption of this paper is that the navigation system errors dominate the CEP equation. Furthermore, of the three categories listed, only navigation system errors are those easily improved upon by means of technology improvement. Therefore, the presumption of this paper is that an improvement in navigation accuracy maps directly to CEP improvement. For this reason, atmospheric conditions and target location knowledge will not be accounted for in assessing CEP improvement.

The navigation system errors for land-launched ICBMs are the position, velocity and attitude knowledge uncertainties associated with the IMU instruments. The Skymark concept aims to reduce these errors by means of optical observations of stars and nearby space objects. Stellar sightings provide the camera with self-attitude knowledge accurate to the level of its angular resolution. If tracker attitude knowledge can be successfully related to IMU attitude (which may not always be the case, as will be discussed in Chapter 3), the error in IMU attitude can also be reduced to a level concomitant with tracker measurement accuracy. This "attitude update" will cause an improvement in CEP consistent with the amount of correlation between IMU attitude and position/velocity knowledge. In fact, the Navy makes good use of this idea, as their Trident submarine-launched ballistic missile (SLBM) is guided by a stellar-inertial navigation system.

In general, however, position updates are much more effective at improving accuracy than attitude updates. Obtaining updated position and velocity estimates through angles-only observations of multiple nearby space objects is the main idea of the Skymark concept. When sighting nearby space objects, the tracker again uses the stellar background to obtain accurate pointing direction knowledge. By triangulating line-of-sight measurements of multiple space objects, the IMU position knowledge errors can be reduced to levels consistent with how accurately the position of the space object at sighting is known and how accurately its location can be measured by the tracker. In summary, each sighting of the star background can be used to update attitude knowledge, and multiple sightings of nearby space objects can be triangulated to update position knowledge. As will be seen in Chapter 2, having visible skymarks available along every trajectory at every time, while desirable, may not be feasible. In these cases, however, the optical tracker will yield some measure of accuracy improvement by performing attitude updates via stellar observations, as will be seen in Chapters 3 and 4.

1.4 Thesis Objectives

The primary objective of this research is to determine the potential accuracy improvement (in terms of impact CEP) offered by this concept. The scope of this thesis is to investigate the merits of the Skymark concept as applied to land-launched ICBMs. The analysis approach is to develop and run a series of realistic simulations that model various aspects of an operational Skymark system.

There are some obstacles, however, to performing this analysis in an absolute sense. For one, the exact performance of the navigation instruments in our nation's ICBMs is classified. For this reason, an error model simulating the position-velocity-attitude navigation error covariance matrix for the missile in flight must be created using unclassified information. Using general relationships as well as some parameterization, multiple cases will be investigated. The process of creating the IMU error models for these cases is described in detail in Chapter 3. A second difficulty arises from the fact that the accuracy with which the ephemerides of space objects may be known is also classified. Again, a parameterization is done, and various arbitrary accuracy levels are investigated. In this way, ranges of arbitrary capability levels will be studied for factors that are not public knowledge. Thirdly, some other parameters that affect impact accuracy are unknown because the Skymark system is still in the early phases of the research and development process. For example, the characteristics of the tracker, such as its measurement accuracy and sensitivity to the brightness of objects, are yet undetermined. For these parameters, a range of feasible values (based on commercially available equipment) will be defined and investigated. Furthermore, operations aspects such as the amount of time necessary to maneuver the camera between observations, calculate an updated position estimate, and perform any necessary post-update maneuvers are unknowns that must be mitigated through assumptions. A final unknown is the number of space objects necessary to compose a reasonably sized and valuable catalog for Skymark use. Determining this number is the primary subject of Chapter 2. Because there are so many variables in this study, a sensitivity analysis which determines the effect on the CEP of varying these parameters is a crucial part of the study. Presented in Chapter 4, this sensitivity analysis will help the decision maker determine which elements will yield the most improvement for the least expenditure of money. The remainder of this thesis will be divided into the following sections.

Chapter 2 includes a methodology for defining a set of usable space objects for the Skymark system. The attributes of a suitable skymark are presented and applied to the set of all existing earth-orbiting objects in order to extract the subset of potentially useful satellites. Secondly, the development of a simulation to determine how frequently these satellites are visible from realistic ICBM trajectories is discussed. The results obtained from this skymark availability study are presented and will serve as the foundation for future chapters.

Chapter 3 continues with a description of an operational simulation for determining the potential accuracy improvement of the Skymark system. Two implementation scenarios are investigated, one with the Skymark system as an add-on system to a current missile INS, and one with the Skymark system as a next-generation replacement navigation system including its own IMU. The goal of Chapter 3 is to determine the accuracy of the Skymark system if it were a present-day operational reality. To this end, values for the unknown parameters listed above are selected to represent

present-day capabilities (except for those parameters whose true values are classified, in which case an arbitrary value is assumed for unknown present-day capability). Furthermore, the set of space objects used in this simulation are those selected by the availability study of Chapter 2. The CEP improvement afforded by Skymark for both scenarios is presented as a present-day benchmark.

Chapter 4 contains the sensitivity analysis. Because there are so many unknowns in this study, it is crucial to understand how the variation of parameters affects system performance. Specifically, since Skymark is not a current operational reality, it is interesting to investigate the performance effects of improving capability parameters to values that may be feasible in the near-future. Important trade offs are identified and discussed, and the sensitivity of the CEP to each variable in question is presented. Finally, a simplified cost analysis, comparing operations cost to development cost, is discussed and viable near-term solutions are postulated.

Chapter 5 contains a summary of conclusions, a discussion of some of the significant issues surrounding the operational implementation of Skymark, and identifies areas meriting further study.

[This page intentionally left blank]

Chapter 2

Investigation of Satellite Availability

Initial Skymark studies at the C.S. Draper Laboratory, aimed at determining the validity of the concept, simulated Skymark measurements by using a computer-generated satellite constellation created for that purpose. Using this simulated space object catalog, these studies demonstrated that Skymark position updates have potential to significantly improve ICBM accuracy. This study aims to determine how well the Skymark system would perform if it were operational today and were thus to use a subset of existing space objects. To this end, the set of space objects that are actually in orbit around the Earth must be tabulated, and a simulation must be run to determine how frequently these satellites are visible from realistic ICBM trajectories. Using the results of this availability study, one can begin to assemble an appropriate operational space object catalog.

2.1 Defining the Qualities of a Suitable "Skymark"

Although there are more than 5,000 objects larger than 10 cm in Low Earth orbit [1], only a small percentage of them are appropriate or even necessary for Skymark use. Indeed, as a result of prior research at the Draper Laboratory, it is expected that a sufficient Skymark catalog will only require approximately 200-300 Earth-orbiting objects [2].

The first step in the approach to determining satellite availability is to determine the subset of current space objects that are potential candidates for the operational catalog. It is unnecessary to consider the vast majority of space objects that are inappropriate for Skymark use by virtue of various reasons (e.g. orbit location). Thus, a set of constraints must be imposed on the database of all space objects in order to bound the feasible set. In order to determine these constraints, the attributes of a suitable skymark must be defined.

As stated in the introduction, the accuracy of the Skymark system is dependent upon the accuracy of the predicted ephemeris and upon the accurate observation of the skymark sighted. Therefore, for an object to be useful, it must have an accurately known ephemeris as well as good observability from realistic ICBM trajectories. These requirements are the foundation for defining selection criteria for the Skymark catalog. The development of these criteria is explained in the following paragraphs.

Accurate ephemeris knowledge is crucial to Skymark because it has been shown in preliminary studies that CEP is proportional to ephemeris knowledge. Hence, satellites that are prone to maneuver should not be included in the operational catalog, and therefore only inactive space objects will be considered. Secondly, objects classified in the satellite database as “debris” will not be included as their ephemerides are also very uncertain. Third, because of uncertainty due to atmospheric drag perturbation at low altitudes, it is sensible to consider only those satellites whose perigee altitude is greater than about 800 km. This is a lower bound, and it is desirable to move this limit higher if possible.

Accurate tracker observations are equally important to the Kalman filter in the Skymark system. The accuracy with which the tracker can measure the line-of-sight direction to a nearby space object will dictate how accurately the observer location can be estimated. Because the tracker measurement uncertainty is angular, this accuracy will decrease as the distance to the object being sighted increases. Thus, only objects whose orbits include points sufficiently close to realistic ICBM trajectories should be considered. Current Skymark program accuracy goals combined with current commercially available optical tracker capability give rise to a maximum apogee altitude criterion of approximately 2,000 km. Secondly, since the scope of this thesis is land-launched ICBMs, only north-firing trajectories from the Midwest United States are considered in this study. Therefore, all sightings will be taken over northerly latitudes, roughly between 50° and 90° latitude. Since it is desirable to minimize the distance to the skymark, only objects that traverse this region should be included in the Skymark catalog. Therefore, only those satellites whose inclinations are in the range of 50° – 130° will be considered as potential candidates.

It is important to include a third requirement at this point. The second requirement, measurement accuracy, assumed that the skymark appeared bright enough to be detected and observed by the optical tracker. However, the selection criteria that derived from this requirement, low altitudes and high inclinations, say nothing about whether the skymark will be visible to the tracker. Brightness, however, is a slightly more difficult requirement to work with. Each time any specific satellite is sighted, its brightness is a complex function of the distance between the observer and itself, the sun-satellite-observer illumination angle, and the geometric and reflective properties unique to that satellite. Thus, a series of simulations must be run in order to determine which of the satellites that meet the first two requirements (accurate ephemeris and proximity to trajectories) are also frequently bright enough to be observed from realistic ICBM trajectories.

Current optical trackers have the capability to track objects as dim as about 6.0 instrument magnitude. Thus, the simulations will consider limiting magnitudes in the neighborhood of 6.0 when computing satellite availability.

The satellite selection criteria are summarized in Table 2.1. The criteria in this table that fall under the categories of ephemeris knowledge and measurement accuracy are straightforward and can be used to identify candidate skymarks. These potential space objects can then be tested for how well they meet the visibility requirement through simulation.

Ephemeris Knowledge	**Measurement Accuracy**	**Visibility**
• Listed in database as “inactive” • Not classified as “debris” • Perigee altitude greater than 800 km	• Apogee altitude less than 2,000 km • Inclination between 50° and 130°	• Visible from simulated feasible trajectory with brightness less than 6.0 magnitude (brighter)

Table 2.1: Satellite Selection Criteria

2.2 Extracting the Set of Feasible Space Objects

The next step is to search through a current database of space objects for candidates that meet the ephemeris knowledge and measurement accuracy criteria listed above. The database used is the satellite database for Satellite Tool Kit, updated December 30, 2003, and commercially available through Analytical Graphics, Inc® [7]. A short program was written to sift through this database and identify candidates for the Skymark catalog.

The preliminary filter searched the database for all entries classified as "inactive" but not classified as "debris," "coolant," or "metal object" (various database classifications for debris). Rocket bodies were not excluded from the search as they are large, reflective, and can be tracked with reasonable accuracy. A total of 3,069 space objects emerged. Their locations, plotted in terms of apogee altitude and inclination, are shown in Figure 2-1.

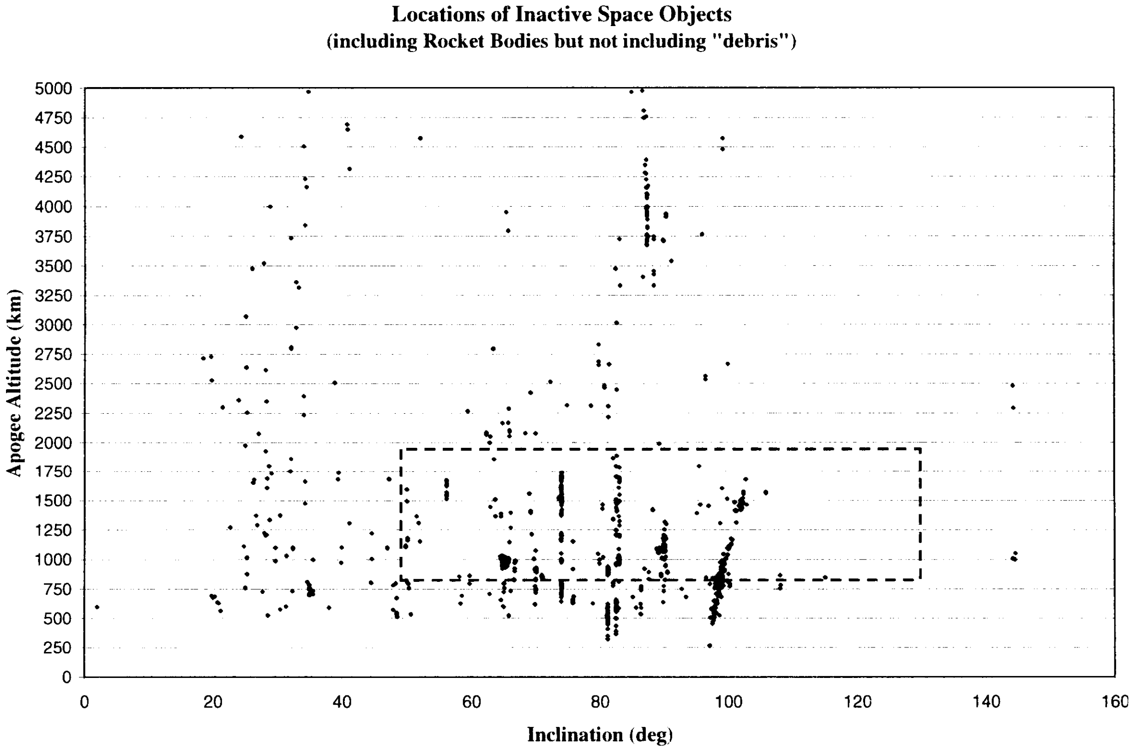


Figure 2-1: Locations of Inactive Space Objects

The outlined region indicates the approximate bounds of the altitude and inclination limits discussed earlier (approximate because only *apogee* altitude is plotted and a small percentage of the skymarks depicted are somewhat eccentric). Thus, this region represents all criteria imposed by the ephemeris knowledge and measurement accuracy requirements. It may perhaps be expanded in the future as optical tracker technology improves. However, it does not appear that an expansion of this box will afford a significantly larger number of space objects (the box should not expand downwards because of drag uncertainty at lower altitudes). This region is blown up in Figure 2-2.

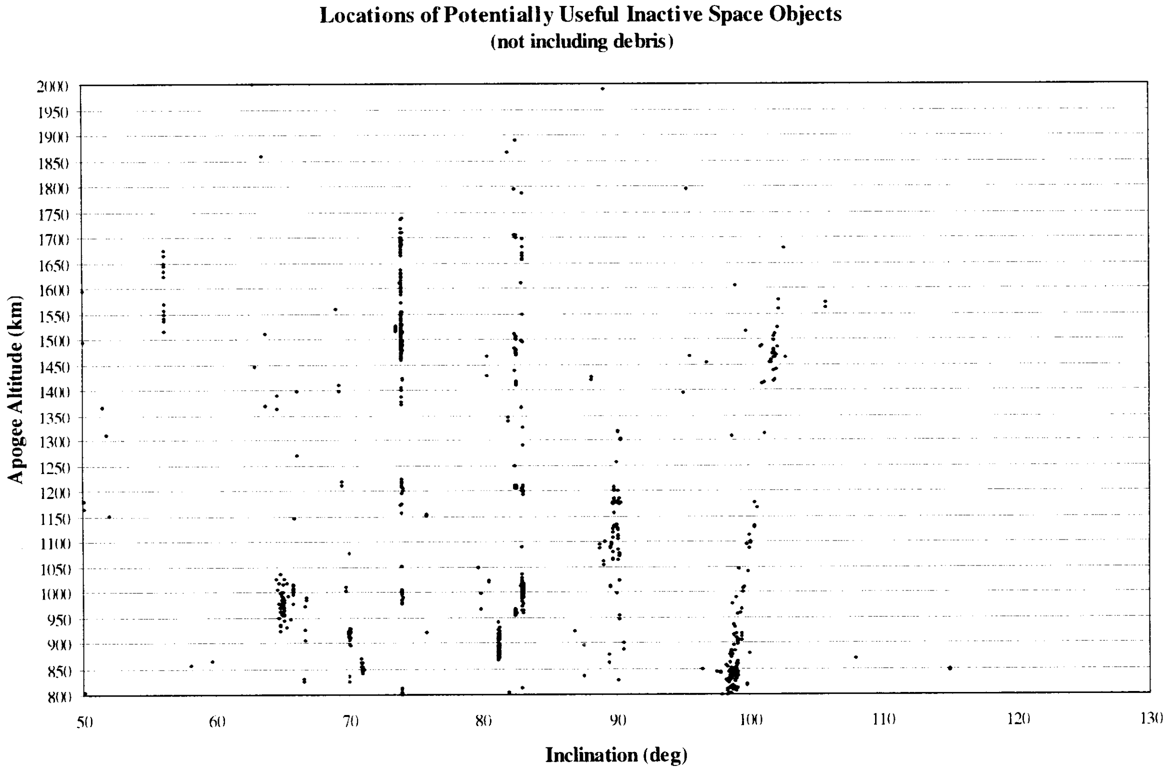


Figure 2-2: Locations of Potentially Useful Space Objects

All potential skymarks, 1,160 in total, are depicted in Figure 2-2. The task at hand is to find an appropriate Skymark catalog among these 1,160 objects. Table 2.2 interprets the data depicted above.

		Inclination Range				
		85 - 95	80 - 100	70 - 110	60 - 120	50 - 130
Altitude Range	800 - 900	2	54	80	84	84
	800 - 1000	5	190	234	298	298
	800 - 1100	26	385	436	518	518
	800 - 1200	55	418	479	562	564
	800 - 1500	68	525	890	978	981
	800 - 2000	68	548	1056	1145	1160

*Altitude Range is defined as the range that the space object always exists in

Table 2.2: Number of Potential Skymarks in Altitude/Inclination Ranges

This table shows the number of potential skymarks located in each altitude and inclination range of interest. The inclination range gets larger from left to right, and the altitude range increases from top to bottom. Thus, each entry in the table includes all the skymarks from entries above and to the left of itself in the table. Because lower altitudes and higher inclinations are more desirable (for measurement accuracy reasons), the goal is thus to find a useful skymark catalog that is as close to the upper left corner of this table as possible. Although it would also be desirable to increase the minimum altitude cutoff to 1000 km because of drag uncertainty in ephemeris predictions, a quick look at this graph and table will show that a significant number of potential skymarks exist in the 800 – 1000 km range, and thus this range is included in the study.

For the purposes of this availability study, all 1,160 potentially useful skymarks will be considered in the simulations described in the following sections.

2.3 Determining Satellite Availability via Simulation

In order to determine a potential satellite's usefulness to Skymark, a set of simulations must be run to determine how often it is visible from realistic ICBM trajectories. The methodology for developing these simulations is described in the following paragraphs.

2.3.1 Trajectory Assumptions

Obviously, one cannot expect to consider *all* trajectories for *all* times, and so a certain amount of discretization must be done without going to the point of losing generality. This is accomplished via the following assumptions. First, it is assumed that all launches occur from a point in the Midwest United States that is in the vicinity of true ICBM launch locations. Secondly, it is assumed that every launch is a north-firing or near-north-firing launch. Third, given the approximate maximum range of current ICBMs (6,000 nautical miles) and considering areas of the Earth that could be potential targets (land mass), ranges between 4,000 and 6,000 nautical miles and launch azimuths within 40° of north (320° – 40°) were chosen to bound the trajectory envelope for the study. It is thus assumed that by taking into account 4,000, 5,000 and 6,000 nm trajectories on launch azimuths of 320°, 0°, and 40°, the set of feasible trajectories is spanned. These nine trajectories comprise both the limits and center of the feasible region, and it is thus assumed that investigating satellite availability over these nine trajectories will give a sufficiently accurate measure of skymark availability.

Next, the portion of the trajectory where observations can be taken, as well as the number of observations that may be taken in that window, must be defined. To do this, the operational functioning of the system must be taken into consideration. Between engine cut-off and re-entry vehicle (RV) deployment, the system must have sufficient time for all scheduled observations, the calculation of an updated position estimate, and any necessary corrective maneuvering in preparation for RV deployment. Because the tracker will likely have to be bolted down somehow, it is assumed that the entire bus will have to maneuver between each sighting opportunity. Therefore, it is assumed that sightings will not be able to be any closer than approximately 2-3 minutes apart. Also, it is advantageous if the tracker can take multiple line-of-sight measurements to each skymark sighted as it crosses its field-of-view, allowing the tracker to better determine its position in space. The computational time necessary for post-processing the observation data to arrive at an updated position estimate is considered negligible. Finally, the time required for any necessary maneuvers prior to RV deployment is assumed to be approximately 2-3 minutes. For the purposes of this availability study, it will be assumed that RV deployment may be delayed until the onboard resources of battery power and maneuvering fuel are depleted. This may not always be the case operationally, as will be discussed in Chapter 4. It is further assumed, based on indications from prior study, that onboard resources will be depleted around apogee. Therefore, the assumption in this chapter is that the time between engine cutoff and apogee, a span of 10-15 minutes depending on range to target, is the window for performing Skymark operations. Based on the time assumptions described above, it is assumed that there is enough time in this window for four equally spaced sighting opportunities. The time from cutoff to apogee will thus be divided by four, and the sighting opportunities will be defined as occurring at the beginning of each of these four time segments in order to allow time for maneuvering prior to RV deployment at apogee.

In order to calculate this portion of each trajectory, a Matlab routine is used to calculate the missile state at cutoff from the inputs of launch coordinates, target coordinates, re-entry angle, and cutoff altitude. Next, a simple Keplerian Matlab routine is used to propagate the state from cutoff to apogee. The time from cutoff to apogee is divided by four, and the coordinates for each of the four "sighting locations" along each trajectory are calculated. To this point, 36 sighting locations (4 for each of the 9 trajectories) have been identified in earth-centered earth-fixed (ECEF) coordinates, and these 36 points are assumed to span the entire operational sighting envelope. Thus, the satellite availability simulation is a calculation of the number of potential skymarks that are visible from the sum of the four points on any given trajectory for all launch times.

2.3.2 Launch Time Assumptions

Nine discrete trajectories have been chosen; a set of discrete launch times for these trajectories must also be chosen. Because it is desired to capture all seasonal effects with respect to lighting conditions as well as satellite locations, an entire year must be simulated. It would be computationally impractical to consider a set of launches every minute for an entire year, and yet it is possible for a satellite to move in and out of view in such a small time period. Thus, a time interval for sampling must be chosen that will give accurate statistical results. The orbital period of the candidate space objects ranges from 100 to 120 minutes. The Nyquist sampling rule states that accurate results may be obtained by sampling at greater than 2.1 times the orbital frequency, or approximately 45 minutes. Because of computational constraints and the goal of obtaining the most accurate results, a time interval of 30 minutes is used. It is thus assumed that by sampling satellite availability at 30-minute intervals for an entire year, accurate results may be obtained.

2.3.3 Catalog Propagation

Finally, a method of computing the location of each potential skymark at all times of interest is needed. Because the goal of this simulation is simply to determine visibility, pinpoint accuracy is not required. However, a fair amount of accuracy is necessary, as an error on the order of tens of kilometers could affect the brightness that the simulation calculates. A single two-line element set (TLE), when propagated over long periods of time, becomes highly inaccurate, and thus not appropriate for this study. During previous Skymark efforts at the Draper Laboratory [2], a database was compiled consisting of unclassified two-line element sets for each day of the year 2003. The simulation will use this database to obtain ephemeris information that is at most 24 hours old, thereby avoiding significant satellite position errors. A program was written to extract the appropriate TLE data from this database, and write this data into a Matlab structural array. Thus, at the beginning of each day in the simulation, the appropriate part of the structure is accessed. As the day progresses, the ephemeris for each satellite is propagated forward to the time of interest using a separate Keplerian propagation routine with inputs of decimal Julian date and TLE epoch data.

2.3.4 Simulation Sequence of Events

The sequence of simulations is as follows. Beginning January 1st, and for each day of 2003, consider missile launches at thirty minute time intervals. The first launch is at midnight local time on the day in question. For every launch time, consider each of the nine trajectories. For each trajectory, consider in order each of the four stored sighting locations. Based on the launch time and the stored time interval to each of the sighting locations, the sighting time for each sighting opportunity is quickly calculated. The set of potential skymarks is then propagated to that time, and all satellites "in view" from the sighting location are tabulated. "In view" is defined as:

- The satellite is sunlit
- The observer is not looking directly into the sun to view the skymark (a 10-degree sun mask angle is defined)
- The earth does not eclipse the observer's view of the satellite

For each satellite in view, the simulation then runs a subroutine that computes the brightness of the satellite in question. This brightness calculation is somewhat more complicated and is described in the next section.

2.4 Calculating the Instrument Magnitude

The magnitude at which a skymark is "seen" by an optical tracker is a complex function of the distance between the observer and itself (R), the sun-satellite-observer illumination angle (α), and the geometric and reflective properties unique to that satellite. The difficulties arise with this last aspect. Short of doing intensive research into every candidate space object to determine its properties of reflectivity, shape, and cross-sectional area, one can merely estimate these properties in a general sense (e.g. by assuming an average reflectivity constant for all skymarks). However, amateur satellite observers have already done much of this work experimentally. In [6], for example, one can find a database including "intrinsic magnitudes" for many satellites. The intrinsic magnitude is defined as the visual magnitude viewed when the satellite is 1000 km from the observer and the satellite is 50% lit (the illumination angle is 90°). Because brightness also depends on the orientation of the satellite being observed (a random phenomenon for many of the objects investigated because they are inactive), this intrinsic magnitude can be viewed as the expected value of the brightness at $R = 1000$ km and $\alpha = 90°$. This database, however, does not include intrinsic magnitude values for many of the 1160 potential skymarks. The decision was thus made to only consider those space objects with available and consistent intrinsic magnitudes, a total of 709 of the original 1160 candidates.

Given the database of intrinsic magnitudes, it is relatively straightforward to extract the reflective and geometric properties of a specific satellite by isolating these properties in the equation for computing brightness. The equation used for calculating visual magnitude is as follows:

$$Mag = 5 * \log_{10}(R) - (2.5 * \log_{10}(I) + 18.8) \qquad \textbf{(2.1)}$$

where:

$$I = \frac{(2780 * \rho * r^2)}{3\pi * \left|\sin(\alpha) + (\pi - \alpha) * \cos(\alpha)\right|} \qquad \textbf{(2.2)}$$

R = Range from observer to skymark
I = Illumination angle dependent intensity
ρ = Satellite reflectivity
α = Sun-satellite-observer illumination angle
r = effective radius of satellite

If the satellite has reflectivity ρ, and effective radius r, the original equation, $Mag = f(\rho, r, R, \alpha)$, can be manipulated into the form $f(\rho, r) = f(Mag, R, \alpha)$. Knowing the intrinsic magnitude, and the range (1000 km) and solar angle (90°) that it applies to, the value of the function of ρ and r, which encompasses both geometric and reflective characteristics, can be calculated and stored. This "$\rho\, r$" factor can then be used in the original form of the equation to calculate magnitude for any range and illumination angle. In the simulation, the range is known because the coordinates of the skymark and the observer at the time of sighting are known. Secondly, the illumination angle is calculated by a subroutine that computes a unit vector to the sun for any given time. Finally, Equations 2.1 and 2.2 are used to compute the expected visual magnitude of the skymark from the inputs of range, illumination angle, and the previously computed "ρr" factor for the space object in question.

The brightness calculated by this routine, however, is still not the desired number. The magnitude calculated is visual magnitude, but the tracker is sensitive to a different frequency band. Assuming the use of a silicon-based star tracker, such as the Ball Aerospace CT-633, the instrument magnitude should be approximately .4 magnitudes brighter than the visual magnitude calculated [4]. Secondly, the intrinsic magnitudes assume that the satellites are being viewed from the Earth's surface, and thus account for atmospheric extinction. Assuming that atmospheric extinction causes brightness to degrade by approximately 0.2 magnitudes, this means that the same satellite viewed from outside the atmosphere will appear 0.2 magnitudes brighter under the same illumination conditions. To sum up, the equations used in the simulation are only valid to calculate the *visual magnitude* of an object as viewed *from the surface of the Earth.* Therefore, to adjust the calculated brightness for Skymark purposes, 0.6 magnitude should be subtracted (brighter) to obtain the instrument magnitude as viewed by the optical tracker at post-boost ICBM trajectory altitudes. In an effort to be conservative, this factor will be rounded to 0.5 magnitudes for use in the simulation.

2.5 Satellite Availability Tabulation

At each sighting location, the simulation determines which skymarks are "in view" and calculates their visual magnitudes. At this point a matrix is formed containing all pertinent sighting information, including the North American Aerospace Defense Command (NORAD) satellite number, brightness, range, and illumination angle for each of the satellites in view. This matrix is stored in 4-dimensional Matlab structural arrays with the dimensions being day number, time of day, trajectory number, and sighting location number.

Clearly, this simulation involves an extensive amount of computation, and in fact takes several days to run a simulation considering 9 trajectories at each of 48 launch times during each of 365 days, for a total of 157,680 launches. Furthermore, for each of these launches, the catalog of skymarks is propagated to a specific sighting time 4 times, and, at each of these times, every potential skymark in the catalog is checked for availability. At each one of these 788,400 sighting opportunities, an N-by-5 summary matrix containing all valuable sighting information is stored. This storage amounts to approximately four gigabytes of data that will require further programs to analyze. It is certainly desirable to run this simulation end-to-end only once, ensuring that all potentially relevant data is stored for later use.

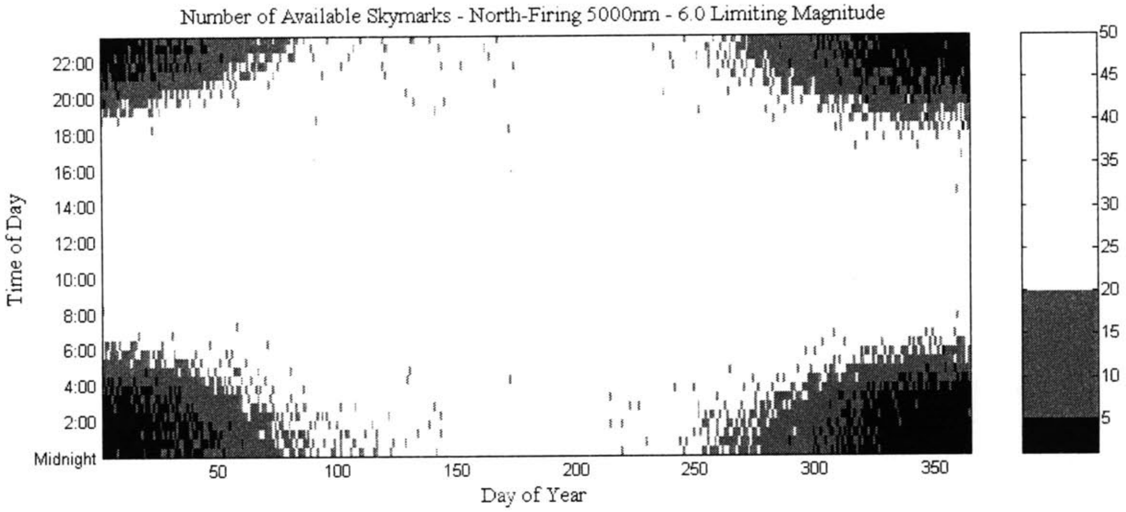
2.6 Skymark Availability Results

Once all sighting information has been stored, it can be accessed in a number of ways to present valuable results. In particular, it is desired to understand the effects of seasonal variations, limiting magnitude, and catalog size on satellite availability.

Ultimately, satellite availability will affect the performance of the Skymark system, as will be seen in the results of the next chapter. The graphs presented in this section display the number of bright skymarks available along a given trajectory by time of day and time of year of launch. The graphs for different trajectories are very similar, and therefore all nine will not be included in this section, but only those necessary to convey the important information. Results for all of the trajectories are included in appendix A. The north-firing, 5,000 nm trajectory will be the main one used in displaying the results since this trajectory is in the middle of the envelope for this study. Also, 6.0 is used as the baseline instrument magnitude cutoff value, as it is representative of present-day optical tracker capability. Unless otherwise noted, all graphs in this section account for all 709 potentially useful space objects.

2.6.1 Variations Due to Launch Time

Launch time is an important factor causing variation in satellite availability. Both time of day and time of year affect the number of bright skymarks available. This is not a surprising result, since lighting conditions are a key factor in satellite visibility. Figure 2-3 depicts the number of bright skymarks available from the north-firing, 5,000 nm trajectory by time of day and time of year, with a limiting magnitude of 6.0. This figure can be seen as a flattened sphere, since both axes are time and thus wrap around on themselves. The areas of black indicate times when 4 or less bright skymarks are available along the entire trajectory. The gray areas are those times when there are between 5 and 20 visible skymarks along the trajectory. Finally, the white areas of the graph indicate times when more than 20 bright skymarks are available. The table accompanying the graph helps explain the data depicted.

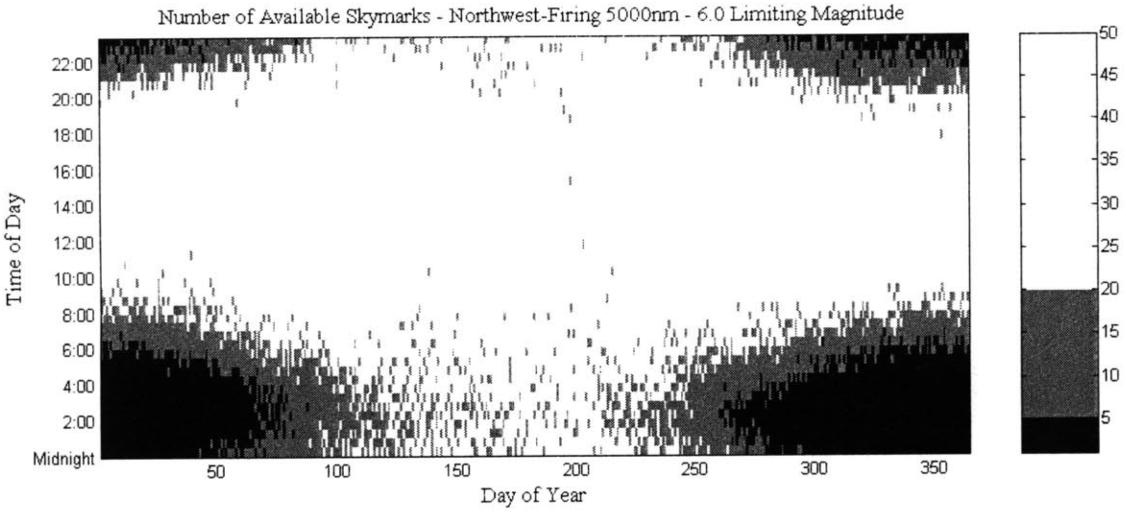


Number of Skymarks	1	5	20	50
Percent of Time at Least That Many Available	98.68%	93.23%	81.06%	25.98%

Figure 2-3: Number of Skymarks Available - 5,000 nm North-Firing Trajectory

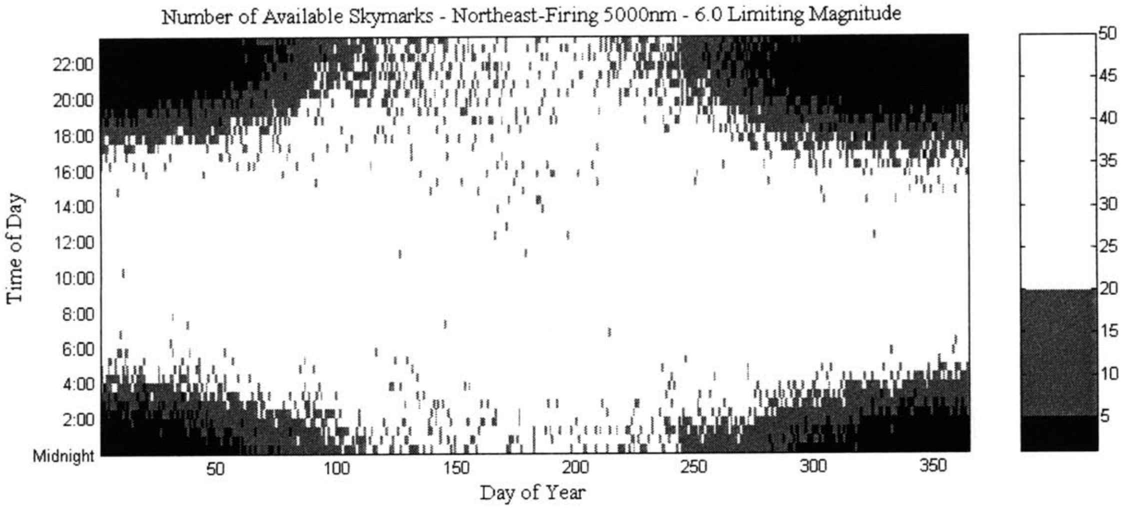
There are several key observations one can make from the figure and table above. First, the center of the black area is approximately midnight on the Winter Solstice. This result makes sense, as midnight on the winter solstice is the worst time of year for lighting conditions for a north-firing launch from the northern hemisphere. For this launch time, the sun is on the opposite side of the earth from the missile for much of its trajectory. Even as the missile comes up over the North Pole, the sunlight is still concentrated in the southern hemisphere, and most of the space objects that are actually sunlit and in-view are far away and have obtuse sun-satellite-observer illumination angles (they are back-lit). For this reason, all satellites in view appear very dim, and will not be seen by a tracker with a limiting instrument magnitude of 6.0. Therefore, unless a more sensitive tracker capable of viewing dimmer objects is used or the observation period is extended past apogee, Skymark performance may be adversely affected by launching in the vicinity of midnight and the Winter Solstice. However, as discussed in the introduction, performing stellar sightings in lieu of skymark sightings in this case will accomplish some measure of CEP improvement, the extent of which will be presented in the next Chapter.

A second phenomenon observed in Figure 2-3 is that, once the launch time exits the black region, the conditions very quickly become very favorable. Once the lighting conditions improve even slightly from the worst case, many bright skymarks appear. In fact, 81% of the time there are in excess of 20 bright skymarks visible along the trajectory, and 93% of the time there are at least 5 available. Furthermore, 26% of the time, under near-optimal lighting conditions there are in excess of 50 bright skymarks available. These times of maximum availability surround the best case scenario of launching at noon on the Summer Solstice. Having so many bright objects available is not a surprising result because a large catalog of 709 space objects is being considered. With appropriate lighting conditions, many skymarks become visible. The effect of launch time on satellite availability can be further seen by looking at graphs for the trajectories with northwest (320°) and northeast (40°) launch azimuths. Figures 2-4 and 2-5 show the analogous plots for the northwest and northeast firing trajectories, respectively.



Number of Skymarks	1	5	20	50
Percent of Time at Least That Many Available	94.34%	88.13%	72.27%	9.62%

Figure 2-4: Number of Skymarks Available - 5,000 nm Northwest-Firing Trajectory



Number of Skymarks	1	5	20	50
Percent of Time at Least That Many Available	93.96%	87.91%	71.51%	10.54%

Figure 2-5: Number of Skymarks Available - 5,000 nm Northeast-Firing Trajectory

It is clear from these graphs that they exhibit the same seasonal behavior as the north-firing trajectory. However, their areas of minimal satellite availability are offset from the north-firing trajectory by a couple of hours on the time of day axis. This result is to be expected. For instance, if an ICBM were launched to the northeast a few hours before midnight, it would find itself over the time zones where it is approximately midnight during the sighting window. The converse is true for the west-firing trajectories, and thus the worst time for firing to the west is a few hours after midnight on the Winter Solstice. Secondly, the black areas in the northeast and northwest trajectory graphs are slightly larger than the black area in the graph for the north-firing trajectory. The reason for this result is as follows. For a launch in the vicinity of midnight on the Winter Solstice, the north-firing trajectory heads over the North Pole directly into the sun, but the sun does not come into view until relatively late in its trajectory (it is concentrated on the southern hemisphere). For this reason, the missile does not come very close to sunlit space objects until it is well along in its trajectory, and since it is heading toward the sun, it is even later in the trajectory before these objects become visible due to favorable illumination angles (while the missile is approaching sunlit objects, it cannot see them because they are back-lit). As time moves away from the Winter Solstice, a north-firing missile launched at midnight will find favorable lighting conditions earlier in its trajectory. Because it travels over the North Pole, satellite availability at local midnight reappears sooner after the Winter Solstice than for the northeast and northwest trajectories, which do not even go above 70° latitude.

In discussing seasonal effects pertaining to satellite availability, it is necessary to note that for different launch locations, the graphs in this section may look very different.

For instance, if the launch location were in the southern hemisphere, the worst-case scenario would be launching on the Summer Solstice. If the launch site were on the equator, the Equinoxes would be the best-case and both the Summer and Winter Solstices would be equally worst-case.

2.6.2 Limiting Magnitude Effects

The next question of interest is the effect of the tracker sensitivity on satellite availability. In particular, it is desired to understand the extent to which the holes in satellite availability could be decreased by using a tracker capable of sighting dimmer objects. Figures 2-6 and 2-7 depict the satellite availability for the 5,000 nm north-firing trajectory if the tracker is capable of viewing objects down to 7.0 and 8.0 magnitudes, respectively.

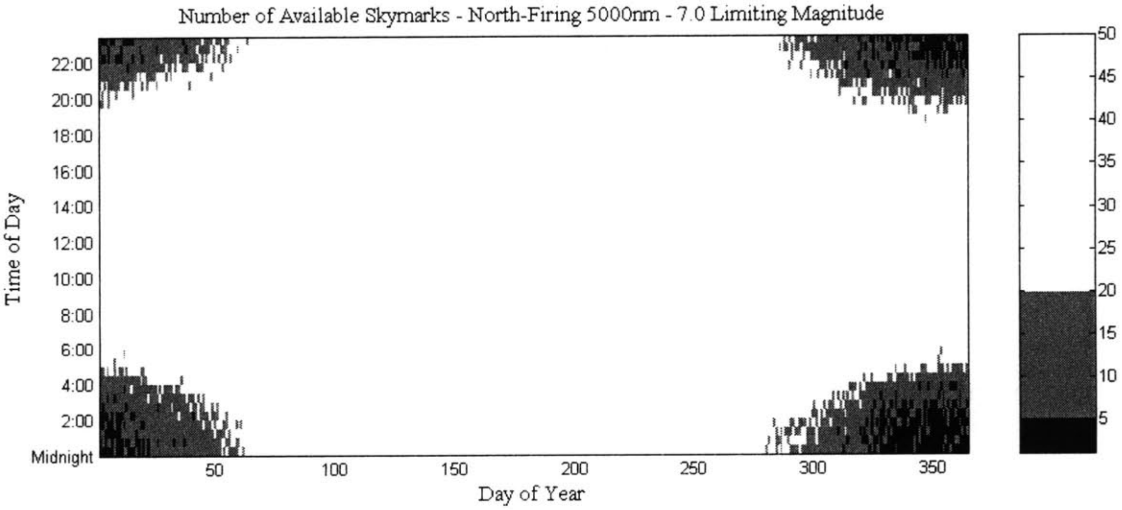


Figure 2-6: Number of Skymarks Available – 7.0 Limiting Magnitude

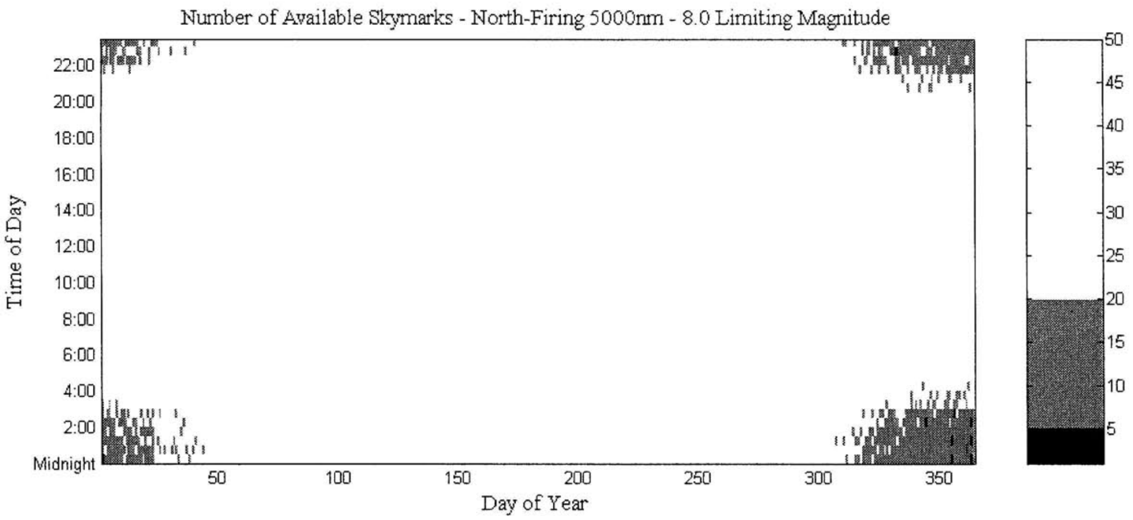


Figure 2-7: Number of Skymarks Available – 8.0 Limiting Magnitude

Table 2.3 summarizes the effect of tracker sensitivity as depicted in Figures 2-6 and 2-7.

At Least Number of Skymarks Available	**1**	**5**	**20**	**50**
Tracker Limiting Instrument Magnitude				
6.0	98.68%	93.23%	81.06%	25.98%
7.0	99.85%	97.43%	89.77%	78.49%
8.0	100%	99.93%	96.07%	88.56%

Table 2.3: Percent Availability Variation Based on Limiting Magnitude

These two figures show some very interesting results. First, with 7.0 as the limiting magnitude, 97.4% of the time the missile will see more than five visible skymarks along this trajectory. This is an improvement over the 93.2% of the 6.0 limiting magnitude case for this trajectory. Furthermore, for the 8.0 magnitude case, this increases to 99.9%. In fact, for the 8.0 magnitude case, there is at least 1 visible skymark along the trajectory for every launch considered and greater than 50 bright skymarks almost 90% of the time. Other trajectories have similar results. For all nine trajectories studied, a limiting magnitude of 8.0 guaranteed at least one bright skymark for 99% of launches, and at least five bright skymarks 95% of the time.

Figures 2-8 and 2-9 are summary graphs of the effect of tracker sensitivity on satellite availability for the summer and winter, respectively, for the north-firing 5,000nm trajectory. These two figures take into account all launches for the 30 days surrounding the summer and winter solstice. The data points plotted are the minimum, maximum, and mean number of bright skymarks available for the time of year corresponding to the graph.

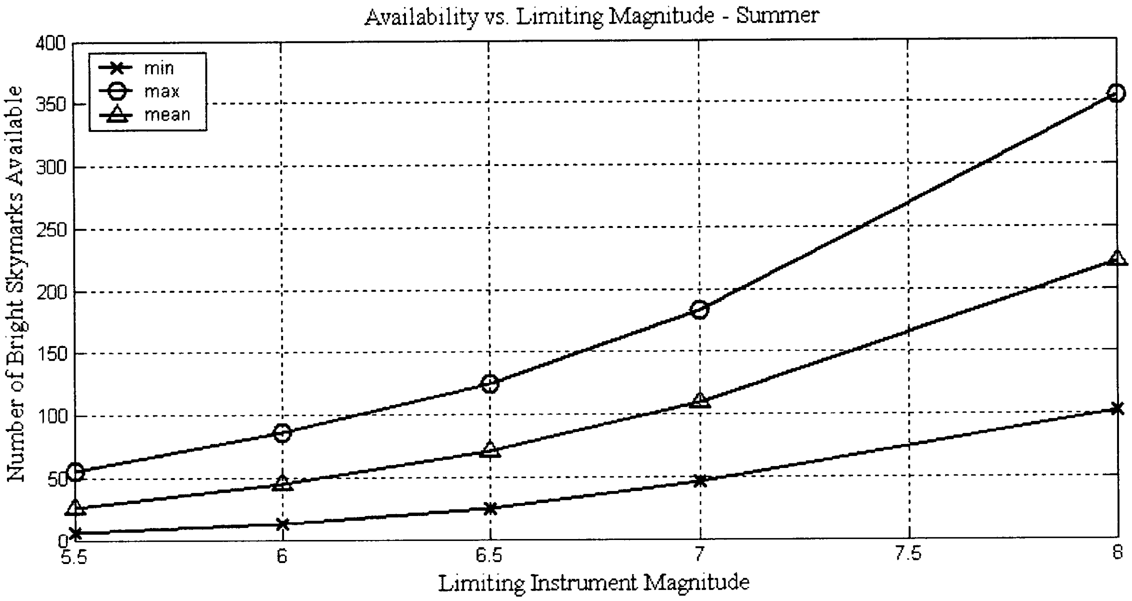


Figure 2-8: Effect of Limiting Magnitude on Availability – Summer

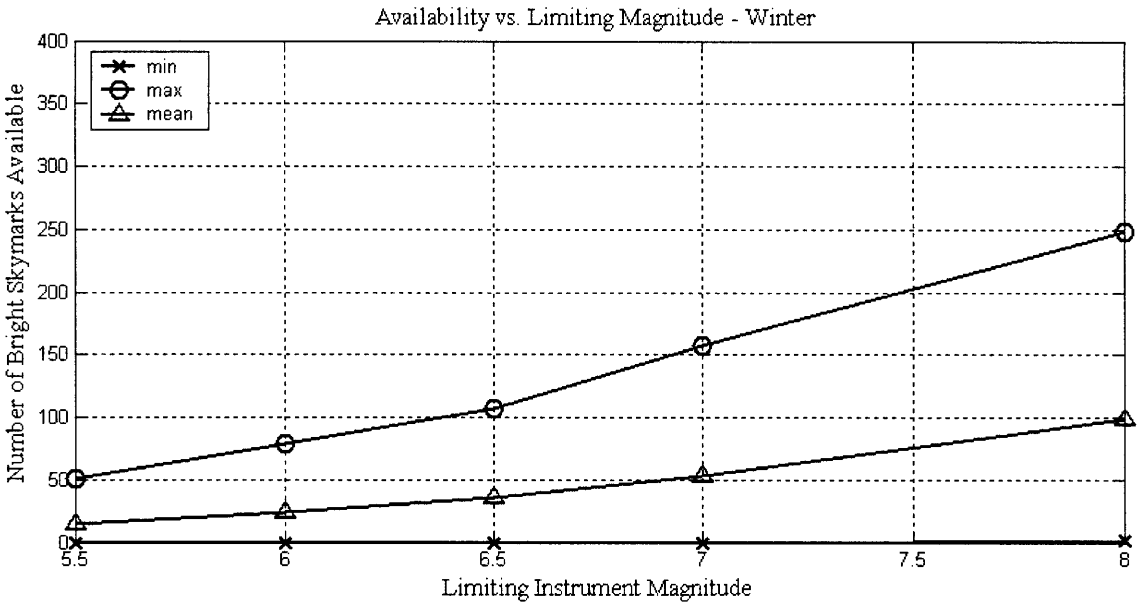


Figure 2-9: Effect of Limiting Magnitude on Availability – Winter

Figures 2-8 and 2-9 demonstrate the extent to which availability increases with tracker sensitivity. For example, in Figure 2-9 (wintertime) it is observed that with a tracker capable of viewing objects at magnitude 6.0 and brighter, there are, on average, 25 bright skymarks available along the trajectory. An increase in tracker sensitivity to view objects as dim as 8.0 magnitudes causes the average availability to increase to 100 bright skymarks, a rather significant increase. Secondly, these two figures display the difference in satellite availability between summer and winter. For example, in winter, the tracker must be able to view objects as dim as 8.0 to guarantee at least one available skymark in worst case. In the summer, however, there are no cases of zero availability, even when 5.5 is the limiting magnitude. A second interesting example is the maximum availability data point in the summer for the 8.0 limiting magnitude case. In this case, almost half of the 709 objects in the catalog are available along the trajectory. This makes sense, because when launching under best-case lighting conditions with a tracker capable of viewing very dim objects, the tracker will be able to see practically all objects that are not obstructed by the Earth.

It is clear that by increasing tracker sensitivity, holes in satellite availability can be significantly decreased in size. In subsequent chapters, the effect of these availability "holes" on the performance of the Skymark system will be investigated. Once the performance sensitivity has been determined, it may become evident whether or not the expense of improving the tracker is worthwhile.

2.6.3 Catalog Sizing Effects

The size of the space object catalog used operationally will also affect satellite availability. All of the previous figures assumed the original catalog consisting of 709 objects. If the operational cost of maintaining a large catalog and tracking a large number of objects proves too high, what does the satellite availability picture look like for smaller catalogs? By sorting the results from the simulation, the space objects in the original catalog of 709 can be ranked by order of importance. It turns out that some of the space objects are visible far more frequently than others. Figure 2-10 shows the percent of total visible sighting options available by using various catalog sizes. As can be seen in this figure, by using a catalog half the size of the set considered, only 10% of the potential sighting options are lost. In other words, a catalog consisting of the most frequently visible 350 skymarks allows for 90% of the total sighting options available by using a catalog including all 709 candidate skymarks. Clearly, many of the originally considered 709 objects are not very useful for Skymark purposes. Of course, reducing the number of objects in the catalog will cause the holes in satellite availability to grow slightly, but the impact on operational performance may be relatively small.

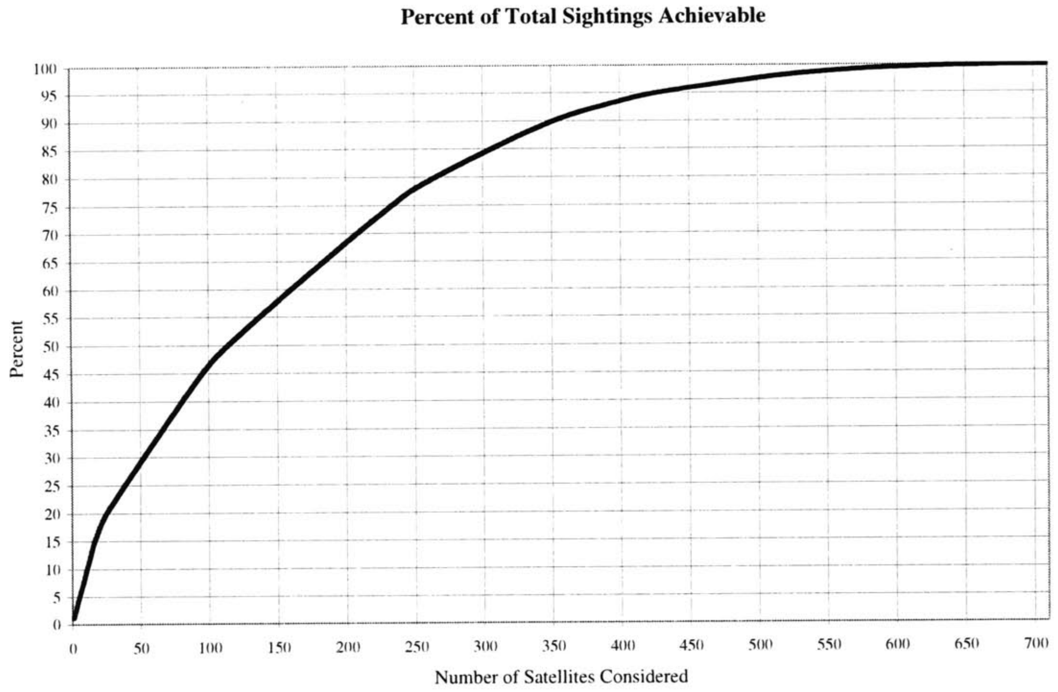


Figure 2-10: Percent of Sightings Achievable by Considering Smaller Catalogs

The following figures and summary table show satellite availability for various catalog sizes, all applied to the north-firing 5,000 nm trajectory, 6.0 limiting magnitude.

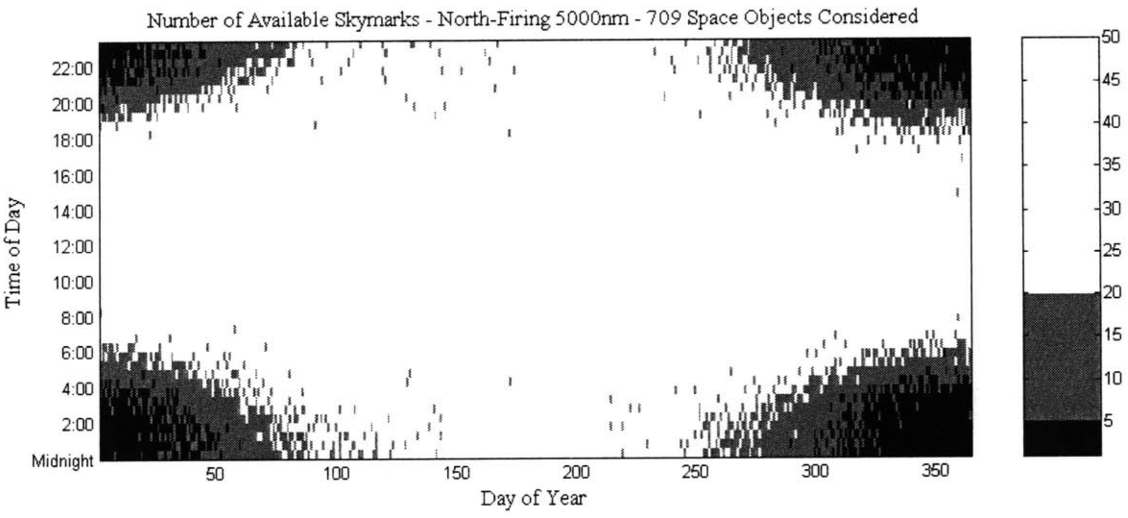


Figure 2-11: Satellite Availability Considering the Original Catalog of 709 Objects

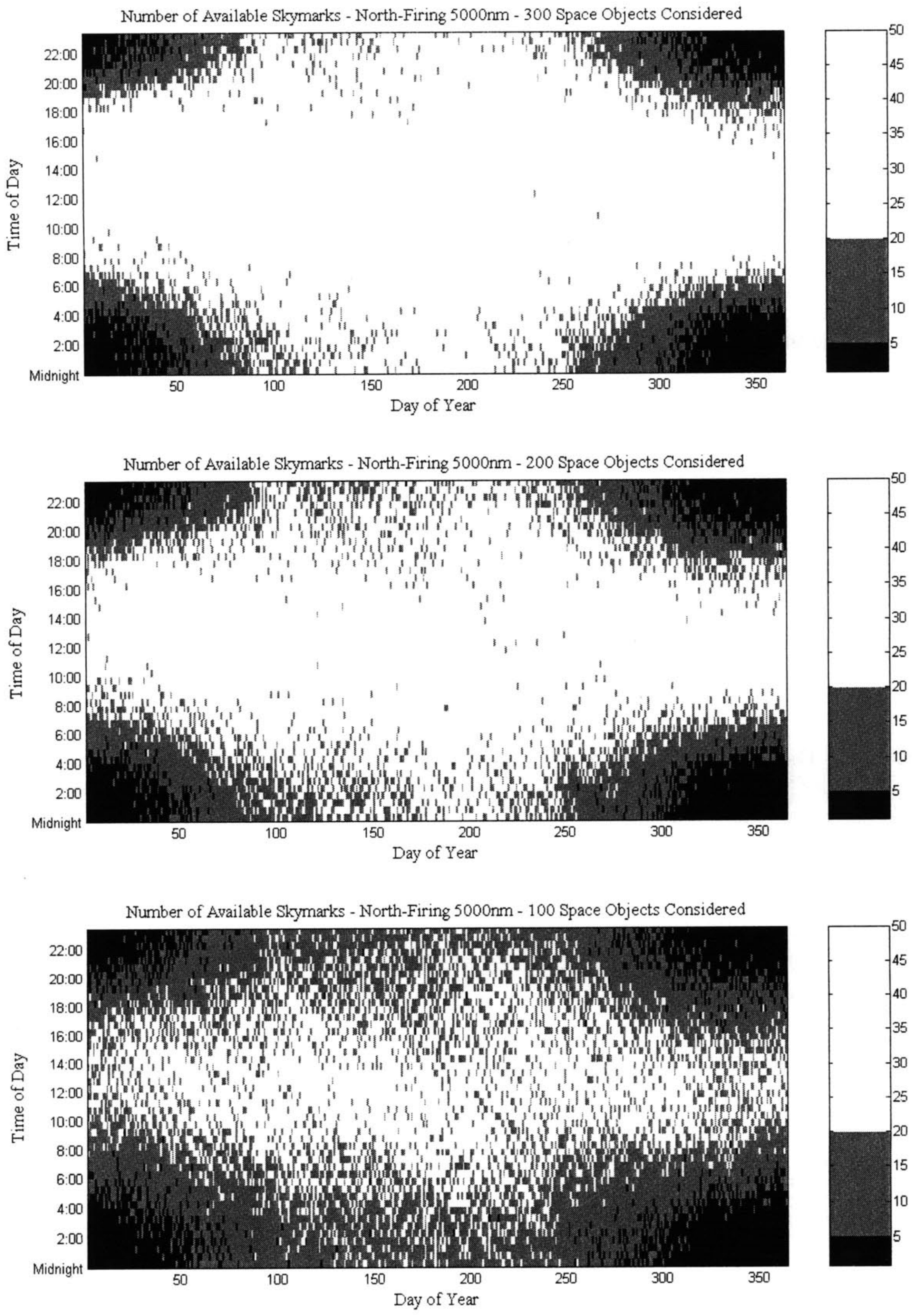


Figure 2-12: Satellite Availability for Catalogs with 300, 200, and 100 Objects

At Least Number of Skymarks Available	**1**	**5**	**20**	**50**
Space Objects in Catalog				
709 (all candidate objects)	98.68%	93.23%	81.06%	25.98%
Top 300	98.39%	92.02%	75.75%	12.61%
Top 200	97.75%	90.33%	66.44%	3.54%
Top 100	96.65%	87.03%	39.08%	0.03%

Table 2.4: Percent Availability Variation Based on Catalog Size

The information in table 2.4 shows how satellite availability is affected by the size of the operational catalog of space objects. Note that the difference between the percent availability numbers in a single column increases from left to right in this table. When all potential space objects are considered, there are 5 or more bright skymarks available over 93% of the time. This number drops only 1% when only the top 300 skymarks are considered. Even when only the top 100 skymarks are considered, 5 or more bright skymarks are available 87% of the time. A larger effect is seen closer to the right end of the table. The original catalog boasted greater than 20 bright skymarks 81% of the time. This percentage does not drop significantly for the catalogs of 300 and 200 space objects, decreasing to 76% and 66%, respectively. However, if only the top 100 objects are included, this number drops to 39%.

Figures 2-13 and 2-14 further display the effect of catalog size on availability and are presented in the same format as Figures 2-8 and 2-9.

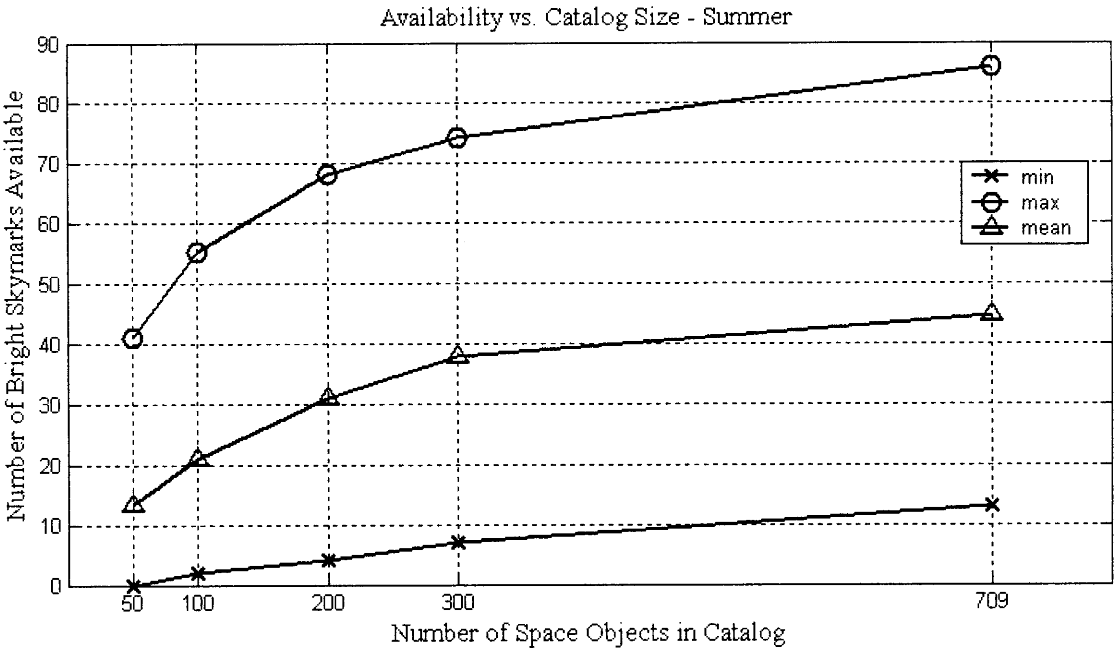


Figure 2-13: Satellite Availability vs. Catalog Size - Summer

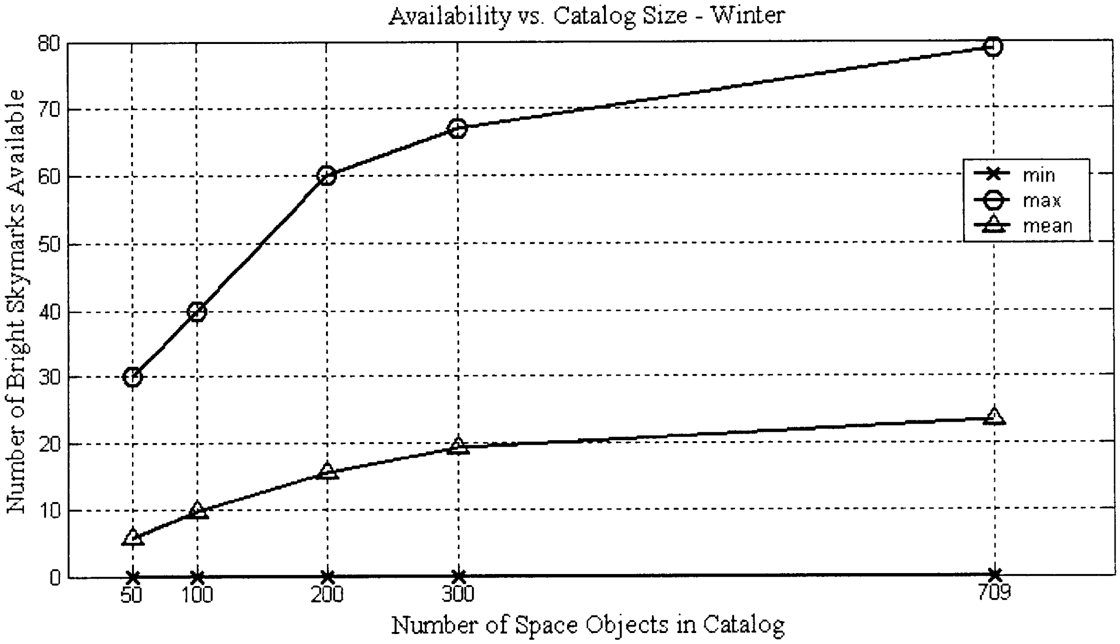


Figure 2-14: Satellite Availability vs. Catalog Size - Winter

There is not much difference between the availability numbers for the top 300 objects as opposed to the original catalog of 709. This is an expected result given the percent of sightings achievable curve in Figure 2-10. Therefore, it is not expected that using the top 300 objects will cause performance to degrade significantly. However, decreasing the catalog size to 100 objects, while not significantly enlarging the "holes" in availability, does significantly decrease the number of options available at each sighting opportunity, and thus is more likely to adversely affect performance.

2.7 Summary/Conclusions

In this chapter, the attributes of a suitable skymark have been identified, the set of potentially useful existing space objects has been tabulated, and a simulation has been created to determine their availability from realistic ICBM trajectories. The results of this availability study have shown several important realities regarding satellite availability. First, it was found that for the trajectories studied, there exist distinct holes in satellite availability due to poor lighting conditions for launches in the vicinity of midnight and the Winter Solstice. These holes are relatively small when considering a tracker capable of viewing objects as dim as magnitude 6.0, but not necessarily insignificant. It was also found that by increasing the tracker sensitivity enough to allow objects as dim as 8.0 magnitude to be seen, these holes in availability disappear completely for some trajectories, and are reduced to less than 1% for all others. An additional important finding of this study related to the size of the catalog necessary. Although a catalog of 709 space objects was considered, it was found that a significant number of them are visible very rarely, if at all, likely due to having a disadvantageous size, shape or reflectivity. In fact, the best half of the original catalog accounted for 90% of the visible options throughout the year. Therefore, when the top 300 skymarks were considered, the availability graph generated closely resembled its counterpart considering 709 objects. This is a promising result, because the operations cost involved in cataloging, maintaining, and accurately tracking a constellation of 300 objects is likely to be far lower than that for a constellation of 709. Perhaps the catalog could be reduced even further than 300 objects without significantly impacting operational performance, but this will be addressed in later chapters.

One idea that has been suggested to combat availability holes is to "plug" them by launching some small, highly reflective satellites dedicated to the Skymark system. This is certainly an option, but since the areas of minimal availability are a result of lighting conditions rather than an empty part of space with no orbiting objects, the artificial skymark would have to be either extremely reflective so as to make good use of poor lighting geometry, or perhaps be able to communicate somehow with the Skymark system. This is an idea meriting further study, but outside the scope of this thesis.

[This page intentionally left blank]

Chapter 3

Impact Accuracy Improvement

The objective of this chapter is to determine the amount of CEP improvement achievable by means of using Skymark observations to update the position knowledge of the INS. This improvement in CEP will be determined by simulating the navigation of the proposed Skymark system under the operational constraints and for the trajectories and launch times discussed in the previous chapter. In this chapter, the goal is to assess the performance of the Skymark system if it were operational today, and therefore several assumptions representing present-day capability will be made. In Chapter 4, the projected performance of future systems will be evaluated.

The skymark availability simulation in Chapter 2 accomplished several valuable things as precursors to the operational simulation. First, the skymarks in view at every sighting opportunity were tabulated, including such pertinent information as their brightness and range to the observer. Provided that the same trajectories and launch times are used for the operational Skymark simulation, this data can be used rather than taking the entire constellation into account at every sighting time. Secondly, the results of the availability study of Chapter 2 showed that satellite availability varies with both the time of day and time of year. We should expect to see the accuracy improvement offered by Skymark to vary correspondingly. Thirdly, the availability study showed how frequently specific skymarks were visible throughout the year. This allowed the 709 objects considered to be sorted by order of importance. Because it was found that many of the candidate space objects are not very useful, the top three hundred objects from this study will form the "operational catalog" used in this chapter. The effects of catalog size on performance will be studied as part of the sensitivity analysis of the next chapter.

3.1 Operational System Model

For the purposes of analyzing Skymark system performance, two implementation scenarios will be considered. First, the system could be implemented as an addition to a current system, using a camera and associated flight software to update the navigation state of a current INS. Secondly, the Skymark system could be a next-generation navigation system designed to replace a current one, including and being fully integrated with its own inertial measurement unit (IMU). There are important modeling differences between the two.

3.1.1 Skymark as an Aid-to-Navigation for a Current System

If the Skymark system is to be added to a current missile system, there is an important implementation constraint that must be taken into account. As the system would likely be bolted onto the bus, the tracker will not be able to be fully integrated with the current IMU. For this reason, a bias will likely exist between attitude knowledge of the tracker and the IMU, making the tracker unable to accurately relate its own attitude to that of the IMU. Therefore, attitude updates via stellar sightings are not a viable option in this implementation scenario. When sighting skymarks, however, the camera need only know the direction it is pointing with respect to the star background to obtain accurate line of sight measurements to the skymarks and triangulate its own position. Therefore, when bright skymarks are available, the system will operate as intended, but will not have the ability to fall back on stellar sightings at times when no bright skymarks are available. Fortunately, as seen in Chapter 2, this is a very small percentage of the time, especially as the tracker becomes more sensitive. Furthermore, it should be noted that when no skymarks are available, system accuracy will only degrade to the level of current unaided INS accuracy.

3.1.2 Skymark as a Next-Generation Navigation System

If a Skymark navigation system is to be a complete replacement for the current system, a completely new inertial system may be defined. Furthermore, the system can be designed to have the tracker fully integrated with the IMU, thereby allowing it to accurately relate both its position and attitude to that of the IMU. The navigation system on the Navy's Trident submarine-launched ballistic missile (SLBM) makes good use of in-flight attitude updates, significantly reducing impact CEP by obtaining a single stellar sighting. If Skymark is implemented as a new ICBM navigation system, attitude updates and position updates may both be performed. Therefore, in times of minimal skymark availability, attitude updates will afford some accuracy improvement through the correlations between INS attitude errors and position/velocity errors. Furthermore, attitude knowledge may be updated at each space object sighting as well by means of the stellar background.

There is an interesting trade off between IMU fidelity and tracker capability in this case. For instance, if a more accurate tracker is used, the IMU may be able to be less accurate and therefore much less expensive.

3.2 Simulation Inputs

At the current stage in the research and development of the Skymark concept, several operational parameters are yet to be determined. Many of these parameters will have a significant effect on the performance of the system. Because it is difficult to know exactly what values to assign these parameters, the sensitivity analysis of the next chapter is a crucial part of this study. This chapter aims to determine the accuracy improvement offered by Skymark if it were operational today. To this end, baseline values for the operational parameters must be wisely chosen in order to define a benchmark level of performance for the Skymark system. The rationale behind the baseline values chosen for this study is discussed below.

3.2.1 Inertial Navigation System Error Model

In order to assess the amount of *improvement* offered by Skymark, it is necessary to understand and correctly model the performance of the inertial system that it is improving. The true error models for current missile systems are known, but are classified, and therefore outside the scope of this thesis. However, it is crucial to create an error model that closely resembles INS characteristics. The form of this error model is a 9-by-9 error covariance matrix whose diagonal elements are the variances in position, velocity, and attitude knowledge with the covariances between them on the off-diagonals.

The values in the off-diagonal elements are a measure of the level of correlation between the variances on the diagonal that they correspond to.

An INS error model for the case of Skymark as a new system is the easier of the two to define. For this case, the unclassified error covariance matrix for a currently proposed replacement system requiring stellar updates is used. For this proposed system, the quality of the IMU is relatively poor (and therefore inexpensive), and therefore the diagonal elements in the state knowledge covariance matrix are relatively large, and the correlations on the off-diagonals are high as well. Without updates of some sort, the impact CEP for this model is very large. However, because of the high correlations between the already large position, velocity, and attitude errors, accurate sighting measurements cause the CEP to be reduced significantly. Since high fidelity inertial navigation systems are so expensive, this type of replacement system may offer a low-cost method of obtaining improved ICBM accuracy.

The error model for the second case, Skymark as an add-on system, is slightly more difficult to define. In this case, it is assumed that the relative magnitudes between the members of the covariance matrix diagonal are the same as for the previous case. In other words, the same basic relationships apply for the variances, but not necessarily the correlations. Using published accuracy values for the class of current land-launched ICBMs [3], the previous error model is first scaled to the corresponding accuracy levels. This scaling, however, preserves the high correlations present in the error model for the other case. For current systems, the correlations that build up through boost should be lower than those for the proposed new system, because the IMU for the current systems is much more accurate. Because the true correlation levels for current systems are unknown (because they are classified), this aspect is parameterized. In summary, the error model for the current system case is created in two steps. First, the magnitudes of the variances in the error model for the previous case are scaled down to levels that result in published ICBM accuracy. Next, the off-diagonal correlations are parameterized in order to investigate various correlation levels.

3.2.2 Optical Tracker Characteristics

There are two characteristics of the optical tracker that must be taken into account, sensitivity and angular resolution. The sensitivity of the tracker is a measure of how bright an object must appear in order to be detected and tracked. The angular resolution of the tracker determines the accuracy with which the tracker can measure the line-of-sight direction to an object. A little research into current and feasible near-future tracker capability is necessary. A limiting instrument magnitude value of 6.0 represents the approximate current state-of-the-art in tracker sensitivity, and will thus be used as the baseline value for this study. The effect of being able to view objects dimmer than 6.0 magnitudes will be investigated in the next chapter. Secondly, many present-day star trackers can measure objects with an angular resolution of about 5 arc-seconds (one-sigma noise). Therefore, this value will be used as the baseline for the study, with the effect of more accurate values investigated in the next chapter.

3.2.3 Space Object Ephemeris Knowledge

In order for the observer to accurately estimate its own position, it must possess accurate knowledge of the locations of the objects sighted at the time of sighting. The Kalman Filter in the flight computer uses the residual defined by the difference between the measured location of the skymark (on the focal plane of the tracker) and the predicted location of the skymark (on the focal plane) at the sighting time. Uncertainty in either the measurement accuracy or the skymark ephemeris knowledge will cause this difference to grow, in turn reducing the accuracy of the updated position estimate.

Like error models for current INS systems, the level of accuracy with which it is possible to track and predict the locations of satellites is a subject in which truth is not public knowledge. Therefore, some assumptions must be made based on general knowledge of satellite tracking and prediction. In general, satellite ephemerides are most difficult to estimate in the along-track direction (the direction of the satellite velocity) due to the high speed at which the satellite is moving. Errors in the cross-track direction are generally 2nd largest, and the radial direction position component is usually the most accurate of the three. Because true satellite ephemeris knowledge capability is unknown, a range of ephemeris accuracy values must be investigated. Three arbitrary levels of ephemeris knowledge errors will be considered in this thesis. These levels are seen in Table 3.1.

	Along-Track 1 Sigma Error (m)	**Cross-Track 1 Sigma Error (m)**	**Radial 1 Sigma Error (m)**
Excellent	30	30	10
Fair	100	50	25
Poor	300	75	50

Table 3.1: Three Levels of Space Object Ephemeris Knowledge Considered

The "excellent" and "poor" levels are assumed to bound present-day and near-future capability. The "fair" level of ephemeris knowledge is the one that is assumed for the baseline study in this chapter. The effects of using having more and less accurate satellite ephemeris knowledge are presented in the next chapter.

The simulation will assume that every time an object is sighted its position is known to the input level of accuracy. Therefore, in the simulation, satellite ephemeris prediction error growth over time is not accounted for. It is important to note that operationally this will not be the case. For one, the ephemerides of some objects will be known more accurately than others. Secondly, the amount of time since the catalog was last updated will affect how large these ephemeris knowledge errors are as well. However, for the purposes of this study, it will be valuable to learn the performance of the Skymark system based upon satellite ephemeris knowledge at sighting, and by investigating a range of accuracies this effect will become more evident. In this way, this study may show the level of tracking capability needed to make the Skymark concept worthwhile.

3.2.4 Space Object Catalog Size

In Chapter 2, it was determined that reducing the original set of 709 space objects to include only the 300 most important objects did not greatly hinder satellite availability since many of the originally considered objects are not frequently visible. However, satellite availability begins to degrade faster as the catalog size is reduced further. It seems logical, therefore, to consider the set of the 300 most important space objects as the baseline catalog for this simulation. Effects on performance of using larger and smaller catalogs will be investigated in the next chapter.

3.2.5 Number of Skymark Measurements

As discussed in Chapter 2, it is assumed that there is sufficient time between engine cutoff and apogee (where batteries and/or maneuvering fuel are expected to be depleted), a span of approximately 10-15 minutes, for four skymark sightings, calculation of an updated position estimate, and any necessary maneuvering prior to re-entry vehicle (RV) deployment. For the purposes of this chapter, the time between cutoff and apogee is thus assumed to be the window for Skymark operations, and the results will be based on four sighting opportunities with RV deployment at apogee. However, the time window for performing necessary system operations may be either larger or smaller than that assumed in this chapter. The window will decrease in size if circumstances call for earlier RV deployment, and may increase in size if sufficient resources (battery power and/or maneuvering fuel) are added to the baseline system. The effect on performance of the size of the sighting window will be discussed in the next chapter.

3.3 Simulation Flow

The trajectories, sighting locations, and space object catalog are already defined, as they are the same as those used in the availability simulation. Furthermore, the set of objects in view at each time and sighting location have been tabulated by running the availability simulation. The operational simulation begins by setting values for the parameters discussed in the previous section. These inputs are user-defined, and changed by modifying the simulation input file. The simulation then steps through each sighting opportunity and calculates the impact CEP obtained by utilizing each of the available (visible) objects at that sighting opportunity. This process becomes more timeconsuming as the tracker is capable of viewing dimmer objects, because a larger number of available objects will have to be considered. The object that reduces CEP the most is chosen, and the observer state knowledge covariance matrix is updated. For the case of Skymark as a new system, a stellar attitude update is accomplished at each sighting opportunity as well, by virtue of the star background in the camera pointing direction. Again, in this chapter, it is assumed that each trajectory includes four sighting opportunities.

It should be noted that pre-defining sighting locations and selecting the best skymark at each sighting opportunity sequentially and independently, while a reasonably good method, is not optimal. An optimal selection and scheduling algorithm would choose the most effective *combination* of skymarks by taking into account all objects visible along the entire sighting window (as opposed to four pre-defined trajectory locations). Operationally, an algorithm of this type could run on the ground pre-launch to determine the optimal sighting schedule. An algorithm of this kind was the subject of [5], but lies beyond the scope of this thesis.

3.4 Results

This results section will include the baseline results for the two operational system models (Skymark as a new system and as an add-on system) based on the input parameter values described above. As in the availability simulation, the results do not vary significantly from trajectory to trajectory, and therefore only the results for the north-firing 5,000 nm trajectory will be presented in this section. The corresponding graphs for the remaining trajectories can be found in Appendix A. Recall the satellite availability graph for this trajectory with limiting instrument magnitude 6.0 from the results section of Chapter 2. This graph will be considered as it applies to and affects the two operational scenarios.

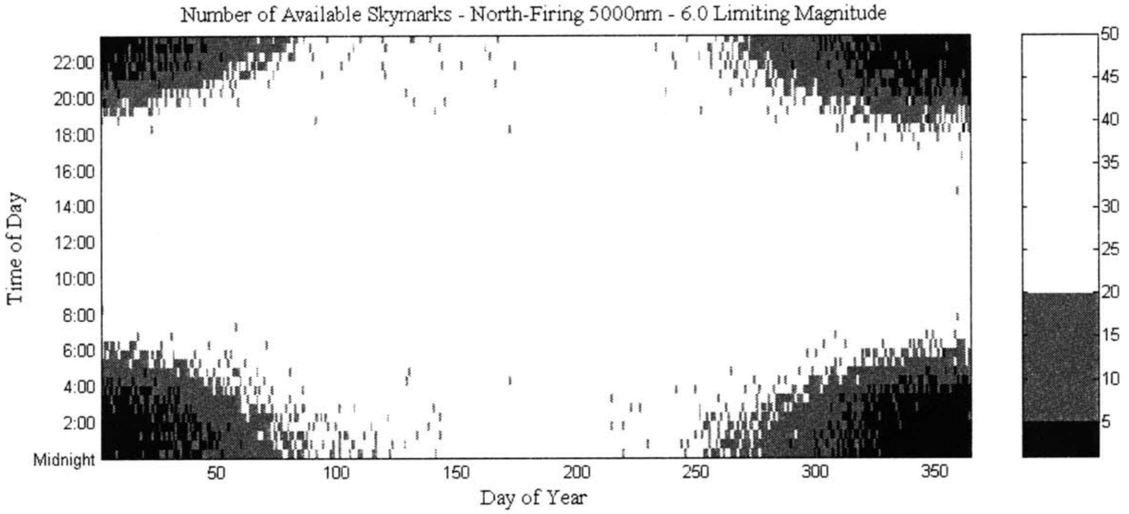


Figure 3-1: Number of Skymarks Available - 5,000 nm North-Firing Trajectory

3.4.1 Skymark as a New System

Figure 3-2 is a graph in the same format as Figure 3-1, displaying the performance of the Skymark system, in terms of impact CEP, based on launch time. The color mapping scheme is on the right-hand side of the figure and its units are meters. Therefore, an impact CEP less than 60 meters is plotted white, between 60 and 80 meters is depicted as gray, and in excess of 80 meters is colored black.

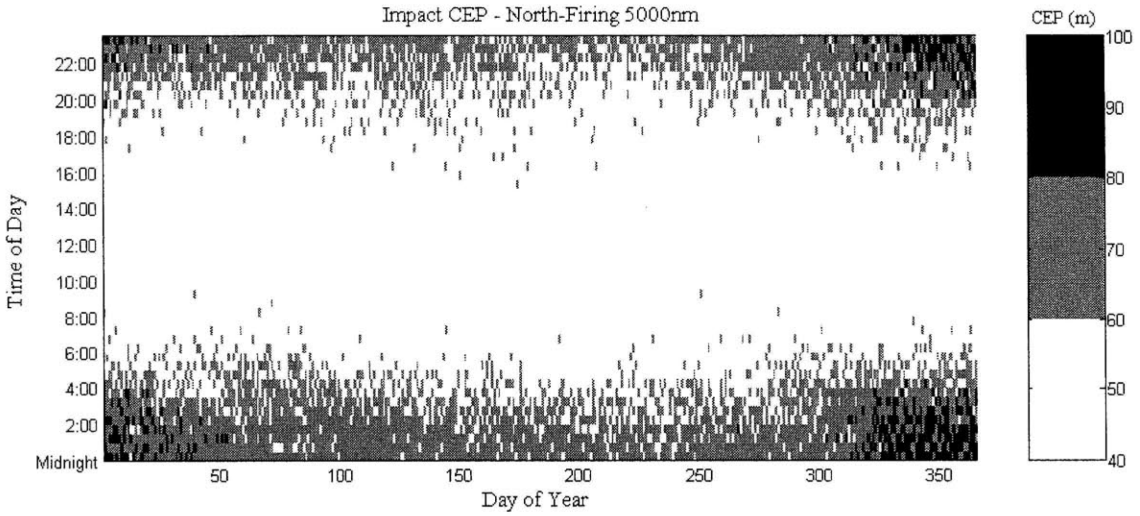


Figure 3-2: Impact CEP (m) - 5,000 nm North-Firing Trajectory

As expected, Figures 3-1 and 3-2 are similar, which suggests a certain amount of correlation between satellite availability and Skymark system performance. Both graphs have gray/black areas primarily in the corners, which represents launching in the vicinity of midnight and the winter solstice. Furthermore, both graphs are white for nearly all launches during the daytime. However, it is also evident that performance is not always dictated solely by satellite availability. The goal is to understand the extent to which satellite availability affects performance. By looking at the two figures above, it can be inferred that some effect exists. It is difficult to understand exactly how correlated these two figures are, however, because of the exact color mapping values chosen. Figure 3-3 ties these two graphs together. This figure demonstrates the effect of satellite availability on Skymark performance by plotting a data point for every launch investigated.

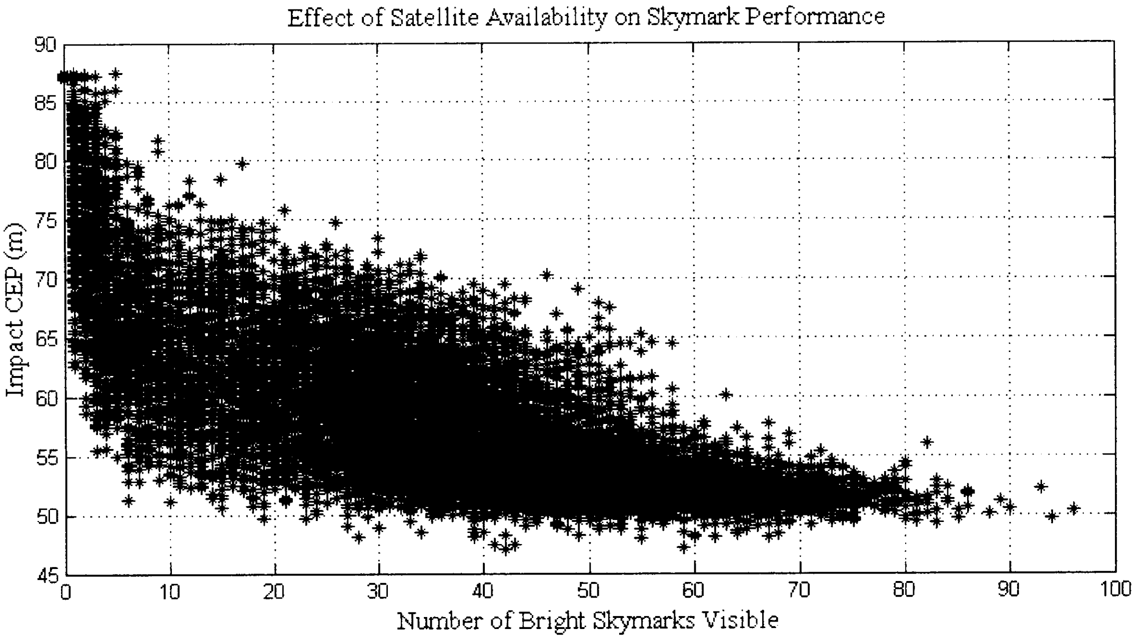


Figure 3-3: Impact CEP vs. Satellite Availability, Initial CEP 1005 m

Figure 3-3 gives some insight into why figures 3-1 and 3-2 are similar, but not identical. Clearly, if less than 4 bright skymarks are available, performance is poor. However, once about 4 or 5 skymarks are visible, there is a steep, favorable change in performance. Best-case performance is about 50 meters CEP, occurring first when 6 bright skymarks are available and remaining up to maximum availability. This result reflects the fact that to achieve the minimum possible impact CEP (based on tracker measurement accuracy and satellite ephemeris knowledge), it is only required that a few bright skymarks be in near-optimal geometry with respect to the observer to resolve three independent axes of position knowledge errors. This *can* be accomplished when only a handful of skymarks are available, but occurs with low probability. As the number of bright skymarks available increases, the probability of having favorable viewing geometry increases, and thus in the graph there is a downward (favorable) slope in worst-case performance as availability increases. For this reason, it is feasible, although unlikely, that equal or better sighting geometry can exist when 5 bright skymarks are available than when 80 or more are available. In Figure 3-3 it is seen that the best-case launch when 5 skymarks are available produces an impact CEP of 55 meters. There is also a point on the graph for a launch with 82 bright skymarks available that resulted in a CEP of 56 meters. This probabilistic tie between availability and performance is why a small portion of the gray/black area of the availability graph becomes white in the performance graph, and, conversely, why some of the white area in the availability graph is gray in the performance graph.

Figure 3-3 also gives a good deal of insight into the accuracy of the system in question. First, the minimum and maximum impact CEP observed are around 47 and 87 meters, respectively. It appears that the mean impact CEP is somewhere between 50 and 60 meters. In times of no satellite availability, attitude updates alone result in a CEP of about 87 meters. This is a promising result, and is due to the fact that the low quality IMU has built up very large correlations between attitude and position/velocity knowledge errors through boost, and improvements in attitude knowledge are thus very effective in reducing CEP. It is interesting that the worst case CEP, approximately 87 meters, is always the result when there is no satellite availability, and is also sometimes the result when between 1 and 4 skymarks are available. This is true because, in this baseline case, the possibility exists for a stellar sighting to be more advantageous than a skymark sighting for a given viewing opportunity. For example, if only one or two skymarks are visible from a given point in the trajectory, but they are far away, and their ephemeris is not known very accurately (the baseline case used a “fair” quality satellite ephemeris), they may not be as effective in reducing CEP as a 5 arc-second stellar attitude update in a near-optimal direction. In general, Skymark position updates are certainly more effective in reducing CEP than attitude updates, which rely on improvement in position knowledge via the correlation between attitude knowledge and position knowledge. However, under certain unlikely circumstances, as has been seen in this section, an attitude update can indeed prove more effective.

Figure 3-4 offers a better view of the performance distribution. As seen in this figure, 70% of the time the impact CEP is between 50 and 60 meters. Furthermore, the CEP is reduced to less than 70 meters in excess of 90% of the time. This is a very significant improvement over the unaided inertial system, which had a CEP of approximately 1000 meters before any measurements. Again, the reason for such vast improvement in this case is the extremely high correlations between position, velocity and attitude in the IMU state knowledge error covariance matrix.

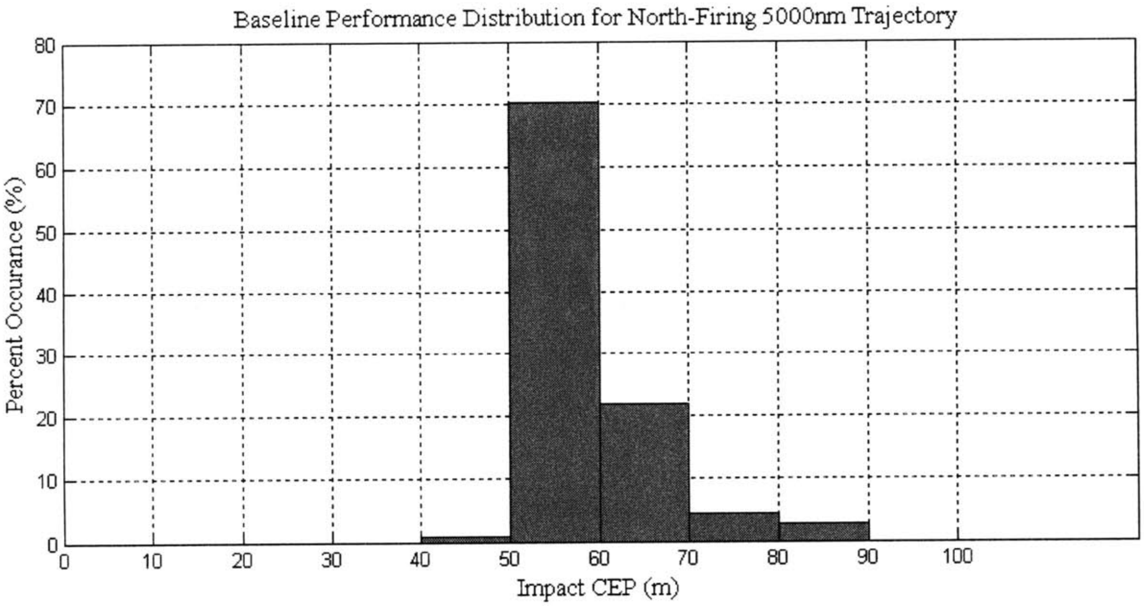


Figure 3-4: Baseline Performance Distribution for Skymark as a New System

3.4.2 Skymark as an Addition to a Current System

In order to investigate the merits of adding an optical tracker and some Skymark computer hardware to a current missile system, a realistic accuracy value for a current system must be used to make the comparison. An unaided INS accuracy value of 200 meters CEP was chosen because it is approximately equal to published accuracy levels for the current class of inertially guided ICBMs [3]. Recall the INS error covariance model used for this case. Because the true error covariance matrix is classified, the covariance matrix used for the "new system" was scaled down enough to the produce this published accuracy. However, this scaling preserved the high cross-correlations between attitude, velocity and position present in the original matrix, which applied to a low quality IMU. Because the IMU on a current system is much more accurate than that modeled for the new Skymark system, the correlations that build up through boost should be lower than those for the proposed new system. As seen for the new Skymark system, high correlations improve the effectiveness of each measurement in reducing the impact CEP. Although high correlation levels are therefore desirable for Skymark performance, note that the actual correlation level is a function of the IMU characteristics and is otherwise not a "controllable" parameter. The true correlation levels for current ICBM systems are classified. Therefore, three arbitrary cross-correlation levels were chosen for use in this study, representing high, medium and low correlation levels.

As a note, a correlation matrix has ones on the diagonal and a fraction on each of the off-diagonals that expresses the level of correlation between two members of the diagonal. If an off-diagonal entry is 0.99 for example, the two diagonal elements it refers to are said to be 99% correlated. The correlation matrix for the original "new system" error model had several off-diagonal entries that were approximately 0.99. This original error model, scaled down to approximate published accuracy levels for current systems, was used as the high correlation error model for this case. For the medium correlation error model, the correlations were all reduced by half, making the maximum correlation between any two diagonal elements approximately 49%. The low correlation error model reduced the correlations to 10% of their original level.

The performance results for the three correlation levels are shown in Figures 3-5, 3-6 and 3-7. As is evident from these figures, higher correlations allow for larger reductions in state knowledge errors, and thus, impact CEP.

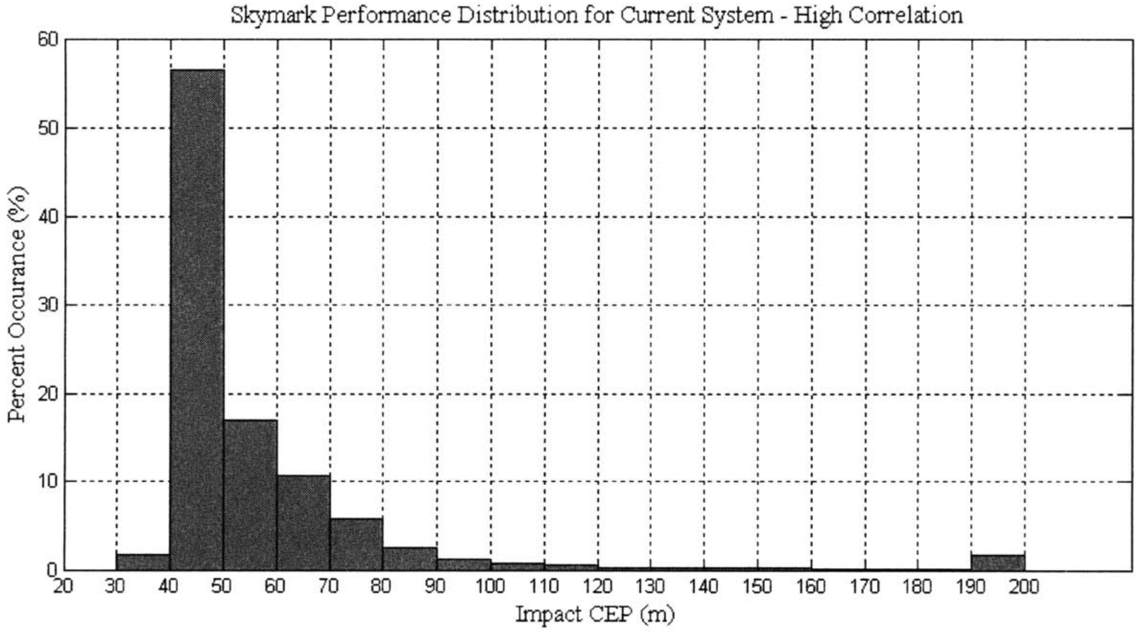


Figure 3-5: Skymark Performance Distribution for Current System - High Correlation

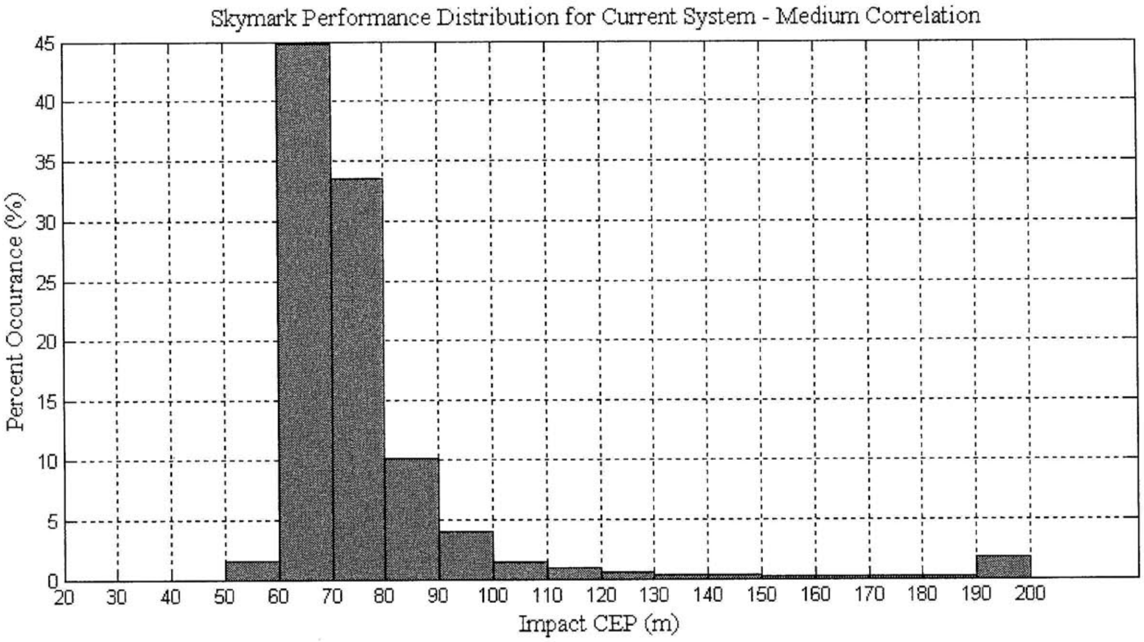


Figure 3-6: Skymark Performance Distribution for Current System - Medium Correlation

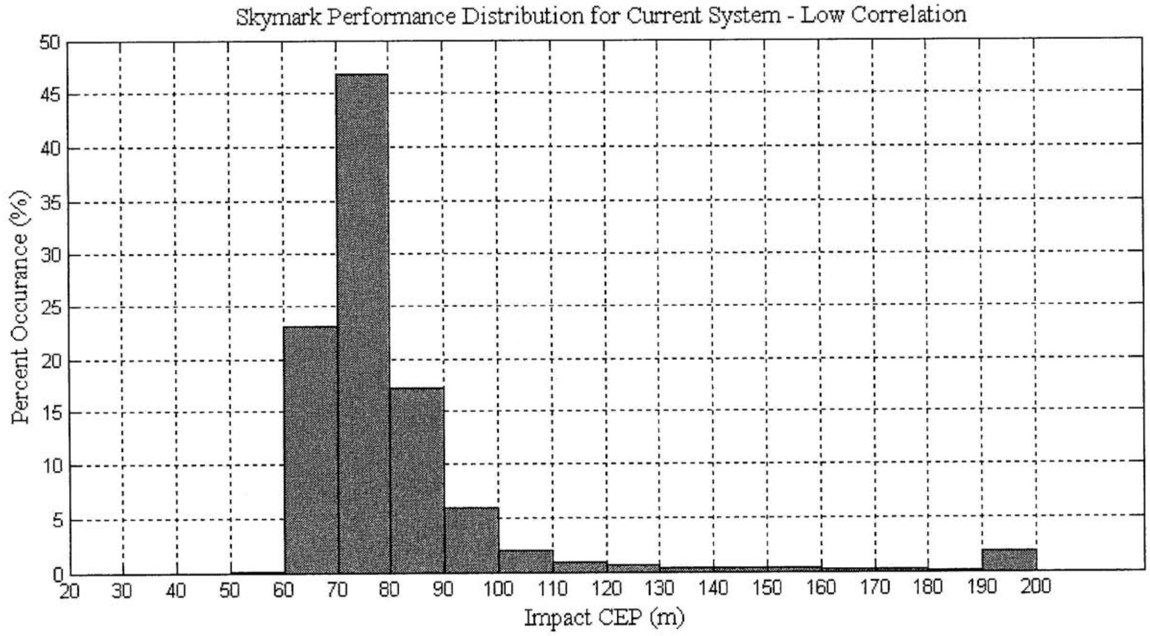


Figure 3-7: Skymark Performance Distribution for Current System - Low Correlation

A couple observations are noteworthy from these three figures. First, there is not much difference in performance between what was defined as medium and low correlation levels, while the error model with extremely high correlation levels significantly outperforms the other two. Secondly, an equal number of simulated launches are in the 190-200 meter bin for each of them. This is because there is extremely little (in fact, negligible) CEP improvement when there exists a hole in skymark availability for this case. The large bias between the tracker and IMU, modeled as an operational constraint (refer to section 3.1.1), is larger than the attitude estimation errors of the IMU in this case, and thus stellar-only measurements are incapable of improving the attitude knowledge of the IMU. Therefore, regardless of the correlation levels present, the missile accuracy will equal its unaided inertial navigation accuracy when there are no bright skymarks available.

Figure 3-8 displays the effect of skymark availability on impact CEP for the medium correlation level case. Plotted in this graph is the minimum, maximum, and mean impact CEP calculated for all occurrences with varying numbers of available skymarks. For example, over all launches when 10 bright skymarks were available, the minimum, maximum, and mean impact CEP achieved were approximately 60, 118, and 80 meters, respectively.

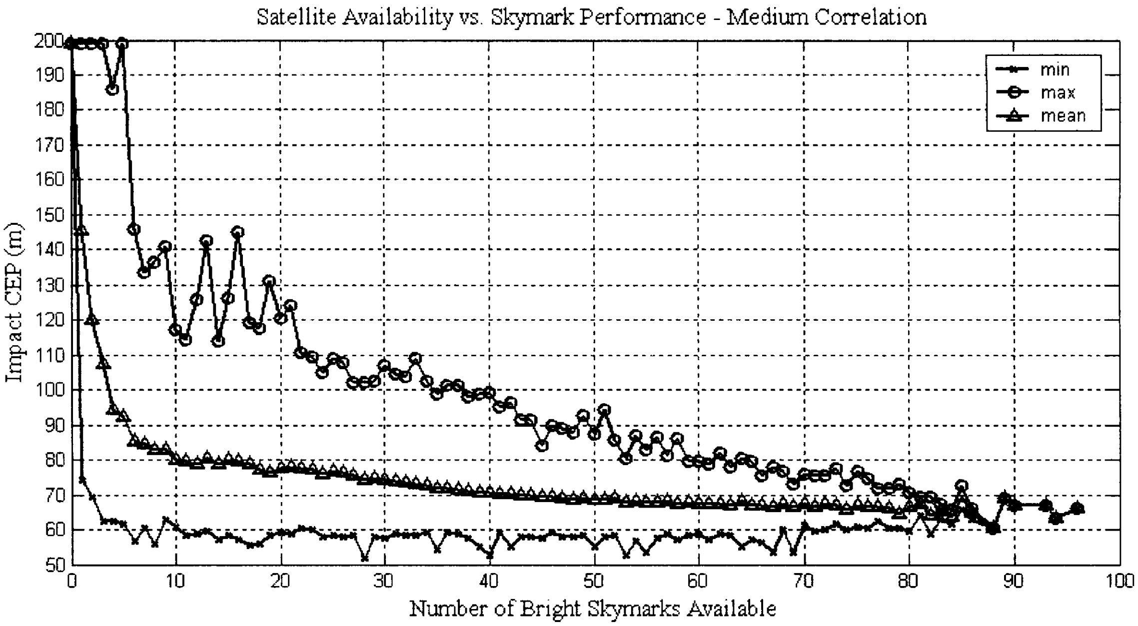


Figure 3-8: Satellite Availability vs. Skymark Performance – Medium Correlation

Figure 3-8 has the same general shape and information as that of Figure 3-3 for the case of Skymark as a new system. Note that when there are zero bright skymarks available, there is always no improvement in CEP. However, if only a few bright skymarks are available along the trajectory, the worst case improvement is negligible, but the mean and best case both have significant improvement. It is necessary that more than 5 skymarks be available before the CEP is guaranteed to be reduced considerably (when 6 are available the worst case is 146 meters CEP). Mean impact CEP levels out to approximately 70 meters as availability increases. Furthermore, mean impact CEP does not reduce to less than 100 meters until 4 or more bright skymarks are available. Availability is certainly a key issue, as it is very desirable to be guaranteed at least 5 bright skymarks. As seen in Chapter 2, this occurs approximately 93% of the time with a limiting magnitude of 6.0, and 99.9% of the time with 8.0 as the limiting magnitude. Note also that as availability increases, the worst-case CEP improvement increases because the probability of obtaining favorable viewing geometry increases. In fact, when 35 or more skymarks are visible from the trajectory, the worst case CEP is less than 100 meters (a 50% reduction in CEP).

3.5 Summary and Conclusions

This chapter has set out to demonstrate the performance of the Skymark system as a replacement to current guidance technologies as well as an addition to a current ICBM guidance system. To this end, an operational simulation was run with realistic trajectories and existing space objects. In an effort to determine the present-day accuracy improvement offered by Skymark, several inputs defining capability were chosen to reflect the current state-of-the-art.

For the case of Skymark as a new system, it was found that a low quality IMU, with an unaided CEP of 1 kilometer, could be updated via Skymark position and attitude updates to produce an impact CEP guaranteed to be less than 100 meters. This is a very promising result. Financially, this means is that a less expensive inertial navigation unit could be used on future generations of ICBMs in combination with a Skymark optical tracker and flight computer. The published CEP of the current class of ICBMs is approximately 200 meters. Even in worst case, the next-generation Skymark system outperforms published unaided accuracy for current systems by more than 50%. Furthermore, if Skymark is to be a next-generation system, it will likely perform better than the results shown, because, by the time it is implemented, the state-of-the-art in tracking capability will improve, and there will be more orbiting space objects to choose from.

For the case of Skymark as a bolt-on aid-to-navigation for a current ICBM inertial guidance system, it is more difficult to determine the actual Skymark benefit since truth error models for current inertial systems are classified. Three different error models, with different levels of correlation between attitude, position and velocity errors, were created as described in section 3.1.1. It has been observed that the medium and low correlation error models resulted in similar performance, and were significantly outperformed by the error model with high correlations. It was also observed that holes in satellite availability cause performance to degrade to original inertial guidance accuracy, regardless of error model used, because the large bias between the tracker and IMU negates the utility of star-only observations. The effect of satellite availability on performance for the error model with medium correlation levels is shown in Figure 3-8. For this case, it has been observed that, as long as at least 4 bright skymarks are available, the average impact CEP is reduced to below 100 meters. Furthermore, as availability increases, worst-case CEP decreases, and drops below 100 meters once there are 35 skymarks from which to choose. Because of its inability to update the attitude knowledge of the IMU via stellar sightings, Skymark performance in this case is much more sensitive to satellite availability than in the case where the Skymark system is a new system.

Chapter 4

Skymark Sensitivity Analysis

The performance of the Skymark system as a whole is dependent upon several operational capability factors. Baseline values for these parameters, assumed to represent current capability levels, were used in the simulation runs discussed in Chapter 3. These baseline values define a benchmark for Skymark system accuracy. In this chapter, the effect of varying these parameters will be investigated and discussed. This chapter will investigate the same four capability factors, defined in Chapter 3, that affect Skymark accuracy: optical tracker measurement accuracy and limiting magnitude, the accuracy with which the space object's ephemeris is known, and the size of the space object catalog. In this chapter, further simulations will vary each parameter individually, holding all others at their baseline values, in order to determine the individual effects of each factor on Skymark performance. Next, a simplified cost analysis will identify some interesting trades between development cost and operations cost. Ultimately, a decision maker will need to weigh the potential performance enhancement against the cost associated with improving each capability factor. Finally, the sensitivity of Skymark performance to the duration of time available for performing observations will be investigated. This analysis is kept separate from the other sensitivities because the duration of the sighting window is not simply a technological capability issue as the others are.

While the baseline analysis of Chapter 3 addressed the performance of Skymark applied as both a new ICBM guidance system and as an addition to a current missile's inertial navigation system, the case of Skymark as a new system will be the focus in this chapter. The goal of the sensitivity analysis is to identify important trends, and most of the results presented in this chapter apply to both cases. There are a couple of important differences, however, which will be discussed later in the chapter.

4.1 Sensitivity to Tracker Angle Measurement Uncertainty

The angular resolution of the Skymark tracker will determine how accurately it can measure the line-of-sight direction to a nearby space object. Because the measurement uncertainty is angular, the ability to estimate the cross-axis position components of an object degrades as the range to the object increases. Many present-day commercial star trackers boast an angular uncertainty (modeled in the simulation as Gaussian white noise) of approximately 5 seconds of arc, and thus this value was chosen for the baseline case in Chapter 3. Because this level of measurement accuracy is common at present, it is unnecessary to analyze performance for trackers with larger angular uncertainty. It is interesting, however, to investigate the effect of improving tracker measurement accuracy. Based upon some background research into optical trackers, it appears that an optimistic, yet feasible, near-future system could reduce angular measurement uncertainty to approximately 1 arc-second. The sensitivity analysis will thus consider three levels of tracker accuracy: baseline (5 arc-seconds), optimistic near-future (1 arc-second), and the midpoint between them (3 arc-seconds).

Figure 4-1 depicts the effect of improving tracker measurement accuracy while holding all other parameters at the baseline level. Figure 4-1 is in the same form that all of the sensitivities will be shown. For each level of tracker accuracy, the minimum, maximum, and mean impact CEP over all simulated launches is plotted. In each of the following sensitivity figures, the north-firing 5,000 nm trajectory is the reference trajectory, and launches every hour on every 7th day throughout the year were considered.

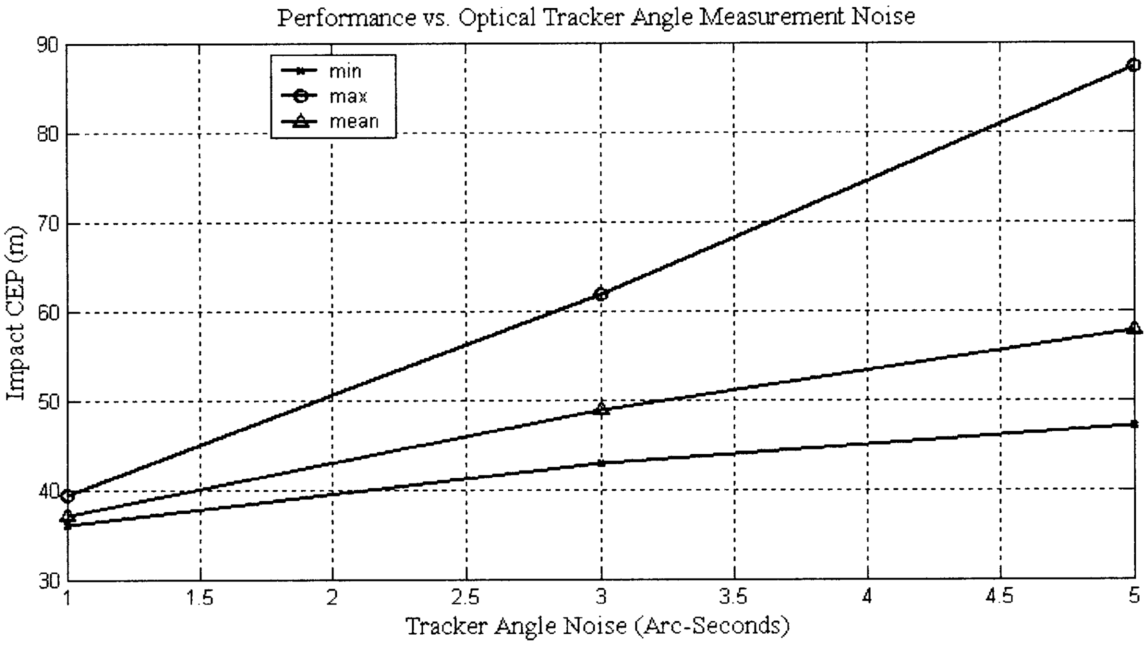


Figure 4-1: Skymark Performance vs. Optical Tracker Angle Measurement Uncertainty

Figure 4-1 displays a good deal of information valuable for understanding the effects of measurement accuracy on performance. First, however, observe the baseline case (5 arc-seconds) plotted along the right edge of the graph. These reference data points, corresponding to the baseline analysis of Chapter 3, will be plotted on all of the graphs in this chapter. First, it is observed that the worst case launch for the entire year results in a CEP of approximately 87 meters. From Figures 3-2 and 3-3 in the results section of Chapter three, we realize that this worst-case must have occurred due to minimal skymark availability, and therefore reflects a launch in the vicinity of midnight and the winter solstice. Secondly, as found in Chapter 3, the best-case and mean of all launches are approximately 47 and 58 meters, respectively. From Figure 3-3 we know that the most accurate launches occur when there is enough skymark availability to produce excellent viewing geometry. Note in Figure 4-1 that the average accuracy of the system, 58 meters, is much closer to the best case than the worst case. This is expected since, on average, there is sufficient satellite availability.

Now note the effect of improving the measurement accuracy while holding all other parameters at their baseline values. As expected, impact accuracy improves (CEP decreases) as the uncertainty in angular measurements decreases. Figure 4-1 clearly shows a favorable trend in all three lines depicted. However, the slope of the worst-case line is significantly larger than the slope of the other two lines. Because the worst-case line represents those times when stellar attitude updates are performed due to a blackout in satellite availability, the performance increase for this line is only dependent upon how accurately the attitude knowledge of the IMU can be updated. The other two lines, however, represent using Skymark position updates, and impact accuracy in this case is dependent upon both the accuracy of the measurements *and* how well the skymark's ephemeris is known. The reason that the slope of these two lines is not as large as that of the worst-case line is because the quality of the satellite ephemeris is held at the baseline "fair" level, and is bounding how accurately the missile position can be estimated. In fact, as seen in this graph, unless the ephemeris knowledge is improved as well, attitude updates perform almost as well as Skymark position updates once the angular measurement uncertainty has been reduced to 1 arc-second.

4.2 Sensitivity to Tracker Limiting Magnitude

Tracker sensitivity (not to be confused with the primary use of the word "sensitivity" in this chapter) is a measure of how bright an object must appear in order to be detected and tracked. Some present-day commercial star trackers have the ability to view objects as dim as magnitude 6.0. This is the baseline value that was used in Chapter 3. Figure 4-2 depicts the effect on performance of using a more sensitive tracker capable of detecting objects dimmer than magnitude 6.0. Once again, note the baseline performance results, same as before, plotted this time on the left edge of the graph.

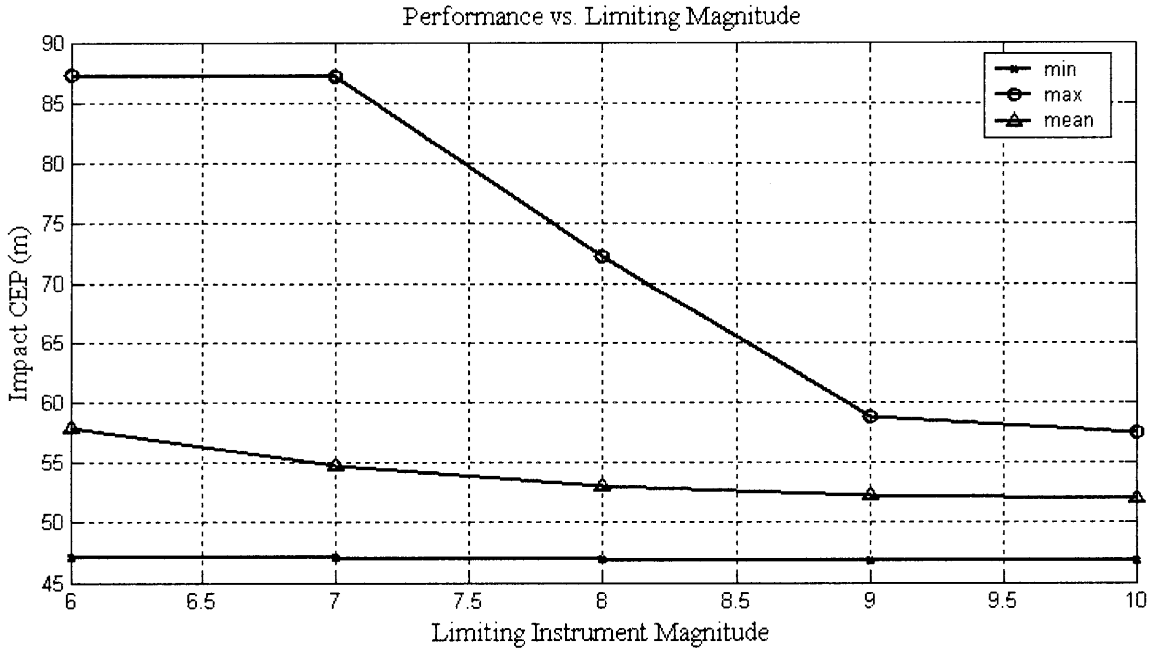


Figure 4-2: Skymark Performance vs. Optical Tracker Limiting Instrument Magnitude

In this figure, each of the three lines does something a little different than the others. First, note that the best-case line does not improve at all as the limiting magnitude increases (dimmer). This is because so many objects are visible during best-case lighting conditions (a launch in the vicinity of noon and the Summer Solstice) even when the limiting magnitude is 6.0. Under these conditions, allowing the tracker to view dimmer objects, thereby adding more objects to choose from, will not affect the performance of the system since the dimmer objects are likely further away and therefore less likely to be chosen. Even the average performance line does not change significantly, improving average CEP by only about 5 meters with such a large increase in limiting magnitude (each integer magnitude represents a factor of ten brightness difference). Again, this result is expected, since there are usually a good number of skymarks visible at magnitude 6.0 or brighter. The worst-case line is by far the most interesting line in Figure 4-2. Recall that with 6.0 as the limiting magnitude, the worst-case launch had zero skymarks visible due to poor lighting conditions. Plenty of skymarks were still "in view" under these conditions, but they were too dim too be detected by the baseline tracker. Thus the question: what level of brightness must the tracker be able to detect in order to reduce or even eliminate the holes in satellite availability that occur at certain times of the year? This is the question that the worst-case line in Figure 4-2 answers. If the tracker can view objects as dim as 7.0 magnitudes, the worst-case is the same as with 6.0. This result, coupled with the improvement in the mean impact CEP line between these two points suggests that the holes in availability were reduced, but not completely eliminated. This was also seen in Figure 2-6 (satellite availability for 7.0 limiting magnitude). When the tracker can view objects as dim as 8.0, however, the worst-case impact CEP improves significantly, demonstrating that all of the satellite availability holes have been eliminated, as seen in Chapter 2. Still, even though every launch for the entire year has non-zero skymark visibility at this point, the further improvement in the worst case between magnitudes 8.0 and 9.0 demonstrates that even cases of minimal availability are eliminated by improving to 9.0. Finally, as the line moves to 10.0 magnitudes, performance in the worst-case does not appreciably improve, suggesting that limiting magnitude is no longer the driver of the worst case line, and further increases will not help much. At this point, accuracy for the worst case launch is driven by the fact that, at midnight on the Winter Solstice, all sunlit (potentially visible) skymarks are relatively far away from a north-firing missile and therefore cannot be measured very accurately with the baseline angle measurement uncertainty of 5 arc-seconds.

4.3 Sensitivity to Skymark Ephemeris Knowledge

In order for the observer to accurately estimate its own position, it must possess accurate knowledge of the locations of the objects sighted at the time of sighting. The Kalman Filter in the flight computer uses the residual defined by the difference between the measured location of the skymark (on the focal plane of the tracker) and the predicted location of the skymark (on the focal plane) at the sighting time. Uncertainty in either the measurement accuracy (see Section 4.1) or the skymark ephemeris knowledge will cause this difference to grow, thereby diminishing system accuracy.

In order to investigate the effects of varying the uncertainty in the skymark ephemeris, three discrete levels of ephemeris quality were defined based upon general knowledge of satellite tracking errors (i.e. that along-track errors are generally greater than cross-track). The baseline ("fair") values were assumed to represent current capability. The highest quality values were chosen to represent an optimistic near-future capability, and the lowest quality values are included in the study in case the baseline values are an overestimate of current tracking capability (true current capability is unknown). Thus the parameterization is assumed to span the actual current and future capability. Recall these three levels in Table 4.1.

	Along-Track 1 Sigma Error (m)	**Cross-Track 1 Sigma Error (m)**	**Radial 1 Sigma Error (m)**
High	30	30	10
Fair	100	50	25
Poor	300	75	50

Table 4.1: Three Levels of Space Object Ephemeris Quality

It should be noted that the values assumed for these three levels are defined in the simulation as the ephemeris uncertainty *at time of sighting*. Of course, the uncertainty in the epoch state will have to be even smaller because ephemeris errors grow when propagated to the sighting time. How much more accurate the epoch states must be to ensure a sighting ephemeris uncertainty equal to or less than one of these defined levels will depend on how frequently the objects in the catalog are tracked and their ephemerides updated. Figure 4-3 shows the effect of varying the ephemeris knowledge on performance.

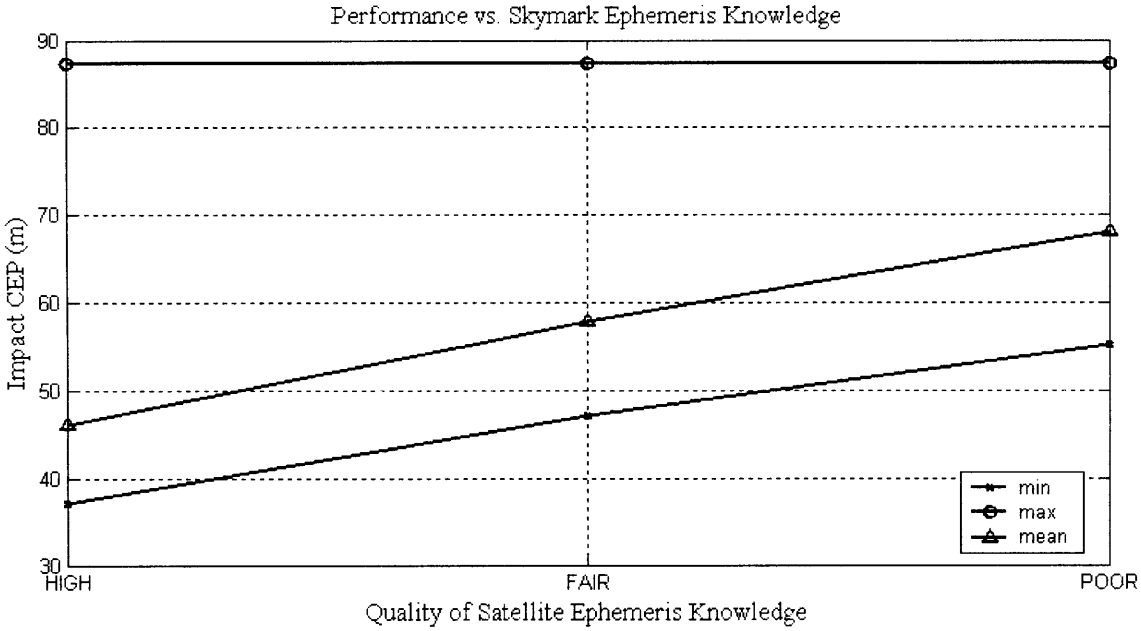


Figure 4-3: Skymark Performance vs. Quality of Skymark Ephemeris Knowledge

Unlike the two previous figures, Figure 4-3 has the baseline values plotted in the middle of the graph, since the "fair" quality was chosen for the baseline assessment. In this figure, it is seen that the mean and best-case impact CEP improves by approximately 10 meters with each increase in ephemeris quality. Interestingly, with a high quality ephemeris, the mean impact CEP, 46 meters, is slightly better than the best case CEP for the baseline ephemeris quality. Finally, it is noted that the worst-case CEP does not change, and this is due to the fact that no skymarks are visible in worst-case.

4.4 Sensitivity to Space Object Catalog Size

The fourth sensitivity to be investigated is the sensitivity of system accuracy to the number of objects in the space object catalog. Like limiting magnitude, the size of the catalog will affect skymark availability. The goal now is to determine the effect of catalog size on performance. Figure 4-4 is the graph of this sensitivity.

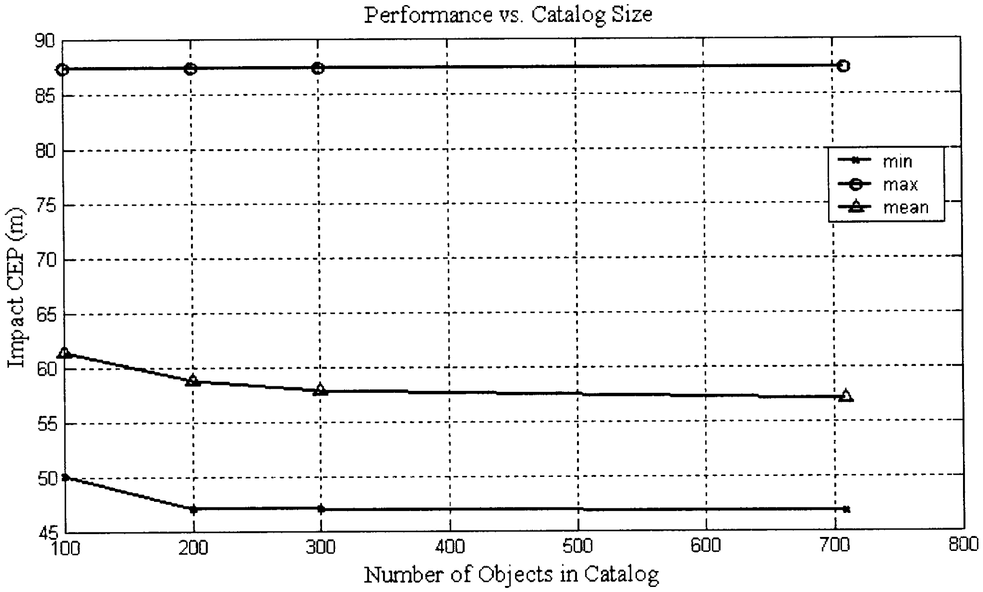


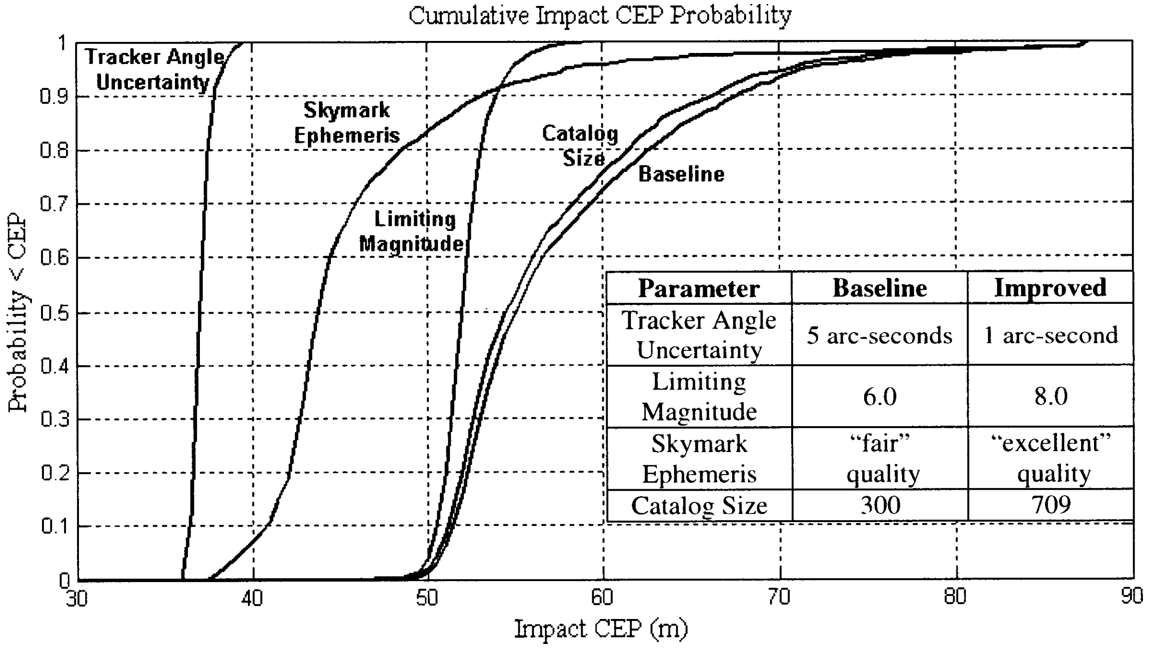
Figure 4-4: Skymark Performance vs. Space Object Catalog Size

As seen in this figure, the difference in performance between using a catalog of baseline (300 objects) size and the entire original catalog of 709 objects is practically negligible. Even decreasing to 200 objects does not significantly affect performance. The change begins to become significant when the catalog size is reduced further, however. Again, the worst-case line is unchanged since there are no skymarks available in worst case. The results presented in Figure 4-4 are not unexpected. As previously seen, many of the original 709 objects considered are not very useful as they are infrequently bright enough to be detected. It has also been seen that with 6.0 as the limiting magnitude, unless lighting conditions are near the worst-case, there is usually plenty of availability, and thus reducing the catalog size to 200 or 300 objects does not significantly reduce sighting options. Recall that even though the number of skymarks available does affect impact accuracy, it has been observed that this is a probabilistic phenomenon, depending on obtaining good sighting geometry from the options available.

4.5 Conclusions Obtained From Individual Sensitivities

Before proceeding further, it is important to summarize what has been learned thus far from the individual sensitivities presented in Figures 4-1 through 4-4. All values for the parameters were chosen to reflect either current or potentially feasible near-future capabilities. It appears that system accuracy is most sensitive to the tracker angular uncertainty. This is not surprising, since the accuracy with which the tracker can estimate the position of a nearby space object is directly related to the accuracy improvement in its own position estimate. Furthermore, worst-case performance (driven by the absence of skymarks) is improved drastically by improving measurement accuracy, because the efficiency of stellar updates is a strong function of angular accuracy. Only one other parameter, when improved, improves worst case performance, and that is camera sensitivity (to allow for viewing dimmer objects). This is intuitive, since there are two ways to improve CEP when no skymarks are available, either by increasing the effectiveness of stellar updates via increased measurement accuracy, or by causing more skymarks to be visible via increased camera sensitivity. The other two parameters, skymark ephemeris knowledge and catalog size, cannot affect worst case performance while the limiting magnitude (6.0) restricts skymark availability. Of course, skymark ephemeris knowledge significantly affects both mean and best case system performance. Therefore, improving limiting magnitude may eliminate worst-case skymark availability holes, but more accurate ephemeris knowledge is arguably more valuable because it significantly improves mean accuracy. Finally, system accuracy is not very sensitive to catalog size when 200 or more objects are in the catalog because many of the 709 originally considered space objects are not very useful.

Figure 4-5 is a summary performance graph depicting cumulative probability as the four factors are improved *individually*. These graphs show the probability (y-axis) that the impact CEP will be less than the corresponding x-axis value. The results plotted for each individual parameter correspond to improving that individual parameter to a value considered reasonable for near-future capability.



Parameter	Baseline	Improved
Tracker Angle Uncertainty	5 arc-seconds	1 arc-second
Limiting Magnitude	6.0	8.0
Skymark Ephemeris	"fair" quality	"excellent" quality
Catalog Size	300	709

Figure 4-5: Cumulative CEP Probability Obtained by Improving Parameters Individually

Figure 4-5 summarizes graphically many of the things that have already been discussed. For instance, all of the curves plotted have fairly steep slopes at least up to about 70% on the y-axis because there is a high likelihood of sufficient skymark availability to produce good viewing geometry. Two of the parameters, skymark ephemeris accuracy and catalog size, have the same general shape as the baseline curve, because they are similarly affected by holes in satellite availability. The other two, limiting magnitude and angle measurement uncertainty, have similar shapes because they have both diminished the adverse worst-case effects of satellite availability holes. By increasing the limiting magnitude the holes in availability disappear, and by decreasing the angular measurement uncertainty, stellar sightings become more effective.

Clearly, reducing the tracker angular uncertainty is the most effective means of reducing CEP. This is because accurate measurements not only improve the accuracy of the skymark sightings, but also cause stellar updates to be very effective when skymark availability is low. Recall that this will not be the case if Skymark is added to a current missile system, because the current cannot make good use of stellar attitude updates. Again it is seen that the two most effective accuracy-improving parameters, tracker angular uncertainty and skymark ephemeris knowledge, both have to do with the accuracy of the tracker's observations. In fact, the overall accuracy of the sighting "measurement" can be understood as a root-sum-square of these two components. Therefore, if one parameter is dominating the effectiveness of the measurement, the other parameter, when improved individually, will afford little accuracy improvement. It would appear that the choice of nominal operating point, defined by the baseline parameter values, is such that these two parameters contribute comparably to system accuracy improvement.

An additional noteworthy item from Figure 4-5 is the fact that two of the curves, those depicting improvement in skymark ephemeris knowledge and limiting magnitude, have a clear intersection point. As previously stated, greater ephemeris accuracy is much more effective in reducing CEP, but because it does not eliminate the problem of skymark availability, the limiting magnitude improvement performs better in worst-case. We see in this figure that the ephemeris accuracy curve outperforms the limiting magnitude curve 90% of the time, which makes sense given the small size of the availability holes for the baseline limiting magnitude, seen in Chapter 2. Finally, as expected, there is very little performance improvement gained by increasing the catalog to the full original size of 709 objects.

4.6 Skymark as an Addition to a Current Missile

Most of the trends depicted above apply in the same fashion to the case of Skymark as an addition to a current missile system. The primary difference is that in this case the system will not be able to fall back on stellar attitude updates when no skymarks are visible, thus skymark availability holes translate to system performance holes. Therefore, for this case, the worst-case curve in the angle measurement sensitivity graph (Figure 4-1) will be a horizontal line, and only one parameter, tracker limiting magnitude, will affect worst-case performance. Since the system must have skymarks available in order to improve impact accuracy, the limiting magnitude must be increased to 8.0 or dimmer in order to eliminate holes in performance. However, as has been seen, availability holes are the exception rather than the rule, and the decision-maker must determine if it is worth it to develop a more sensitive tracker in order to eliminate the holes in availability. Since missile accuracy will only degrade to current INS guidance accuracy when no skymarks are available, one may be inclined to accept current accuracy levels a very small percent of the time (less than 5%) rather than spend the money to develop an improved tracker.

4.7 Relationships Between Parameters and Cost

The focus now shifts back to considering Skymark applied as a new system. The accuracy results for each of the capability parameters have been presented individually, but it is necessary to understand the relationships between them and how they affect system cost. It should be noted that the actual cost associated with improving individual capabilities can vary significantly, and estimating this specific cost is outside the scope of this thesis. That said, there exists an important tradeoff between development cost and operations cost. The angle measurement uncertainty and limiting magnitude of the tracker are capabilities that require a one-time development cost to improve. Maintaining and updating the ephemerides of the space object catalog is a recurring, or operations, cost. Therefore, increasing the size of the catalog or the fidelity with which space object ephemerides are updated increases the cost of operations. Although the actual costs associated with capability improvement are outside the scope of this thesis, a general understanding of cost relationships is still very useful in gaining insight into this problem. For example, a strategic system, which by definition must always be operational, will likely have higher costs associated with operations than development. Since the Skymark system is only the navigation system for an IBCM, its development cost is composed solely of developing and integrating the tracker, IMU (if Skymark is a replacement navigation system), and flight computer. However, implementing Skymark operationally creates a potentially large operations cost due to the fact that it relies on accurate and updated space object ephemerides. This cost includes not only maintaining and tracking the set of objects in the catalog, but also ensuring timely and accurate communication of that tracking data to the missile silos. Even though NORAD currently monitors most Earth-orbiting objects, it will likely require an increased tracking effort in order to track a strategic set of objects with high precision. This may itself cause a development cost, should more advanced satellite tracking equipment be deemed necessary. The extent of the increased effort necessary will be dictated by the number of objects in the catalog and how accurately they must be tracked. It is therefore fortunate that system accuracy is not very sensitive to the size of the catalog, and therefore a relatively small catalog can be used without significantly hindering performance. Figure 4-6 is a cumulative probability graph that displays the performance achievable by means of improving certain combinations of parameters. The development cost curve shows the improvement in performance by improving tracker characteristics, and the operations cost curve refers to using the largest catalog with the most accurate level of ephemeris knowledge. Thirdly, the curve that is labeled with an arrow depicts the accuracy of the system when the two most influential parameters, tracker angular uncertainty and skymark ephemeris knowledge, are both improved to their assumed future capability levels. Finally, the curve for all improvements represents the best accuracy achievable provided that there are enough resources available to improve all parameters to their most effective values.

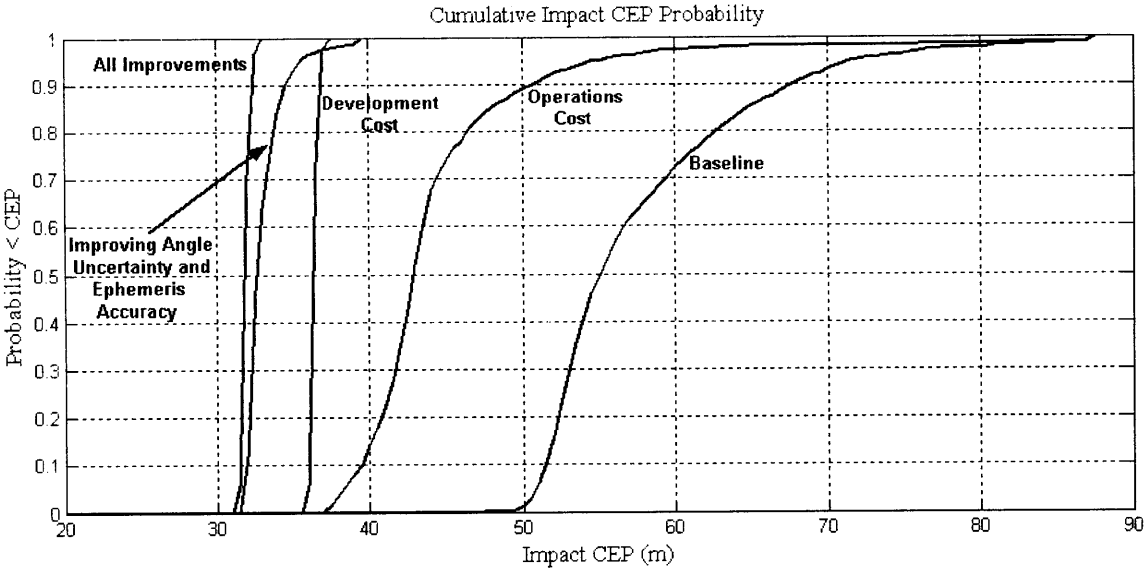


Figure 4-6: Accuracy Probabilities Achieved by Improving Combinations of Parameters

Even without knowing the actual development and operations costs associated with capability improvement, this graph provides much valuable information. First, it can be seen that by improving the two tracker characteristics, the results are very similar to those for improving all parameters. Secondly, in the Operations Cost curve, it is known that the accuracy improvement over baseline is due almost entirely to the improvement in the skymark ephemeris accuracy rather than the catalog size. It can also be inferred that the difference between the development cost curve and the curve for all improvements is due to the improvement in skymark ephemeris accuracy, because changes in catalog size would not cause such a large horizontal shift in the graph. It is also interesting to note that, when all improvements are made, the accuracy of the system approaches the level of accuracy of the skymark ephemeris knowledge, approximately 30 meters. This is because the only non-trivial source of navigation error remaining is in the accuracy of the predicted skymark ephemeris at sighting. It is noteworthy that, with all capabilities improved, navigation system errors have been minimized. At this point, the other sources of error that contribute to impact CEP (atmospheric conditions and target location knowledge errors), which were previously disregarded, are likely comparable if not greater than the residual navigation system errors. Therefore, further reductions in navigation system errors will have a diminished effect because these errors no longer dominate the impact CEP.

Some important conclusions can be made from Figure 4-6. It is evident from the figure that the two most effective improvements are those for tracker angle measurement accuracy and skymark ephemeris knowledge. In fact, when these two improvements are made in combination, as seen in the curve with the arrow, the results are extremely close to the results for all improvements. Therefore, for the case of Skymark as a new system, it appears that the best course of action would be to choose a small catalog (perhaps around 200 – 300 objects) whose objects' ephemerides must be known very accurately, and develop a tracker with a small angular uncertainty. In this way, both the development cost of increasing the tracker sensitivity (to view dim objects) and the operations cost of maintaining and tracking a large catalog are unnecessary. Because a very accurate tracker can make good use of stellar attitude updates, skymark availability holes need not be eliminated, thereby saving the cost of developing an incredibly sensitive tracker. In fact, under this scenario, stellar updates alone (4 in total – one at each of the 4 sighting opportunities) yield an impact CEP of approximately 40 meters while position updates via skymark sightings perform only slightly better, reducing CEP to as low as 32 meters. Secondly, the size of the catalog can be relatively small, thereby allowing more ground-based tracking attention to be focused on each space object in the set. Furthermore, one could even argue that in this case the space object catalog itself is unnecessary and the system should rely solely upon stellar attitude updates. Obviously, this argument does not apply to the case of Skymark as an addition to a current ICBM inertial navigation system because it cannot make good use of attitude updates. For that case, the performance holes due to times of limited skymark availability can only be eliminated by using a very sensitive tracker. Under these circumstances, a decision-maker must decide if it is worth it to develop a more sensitive tracker that will eliminate availability holes. It can certainly be argued that only tracker angular uncertainty and skymark ephemeris knowledge should be improved in this case as well. This course of action will provide significant accuracy improvement when there is sufficient skymark availability (almost all of the time), and accuracy will only degrade to current INS accuracy levels when there are holes in availability.

4.8 Duration of Sighting Opportunity Window

The amount of time available in-flight for Skymark operations is a final factor that will affect system accuracy. It is kept separate from the other four, however, because it is not simply a technological capability issue. Recall the rationale behind the trajectory timeline assumed in the baseline analysis of Chapter 3. First, it is expected that battery power and/or maneuvering fuel will be depleted around apogee, and thus all necessary operations are modeled as occurring prior to apogee, about when RV deployment takes place. Constrained by this cutoff-to-apogee operations window, it is further assumed, based on prior study, that this amount of time (approximately 10-15 minutes depending on range to target) is sufficient to perform four independent optical observations, maneuver between them, compute an updated position estimate, and perform any necessary maneuvers in preparation for RV deployment.

It is now of interest to investigate the accuracy of the system should the window of available time for operations be either larger or smaller that the cutoff-to-apogee window assumed in Chapter 3. This operations window determines how many observations can take place and how late in the trajectory updates can occur. Figure 4-7 is a typical trajectory timeline that will be referred to in this section.

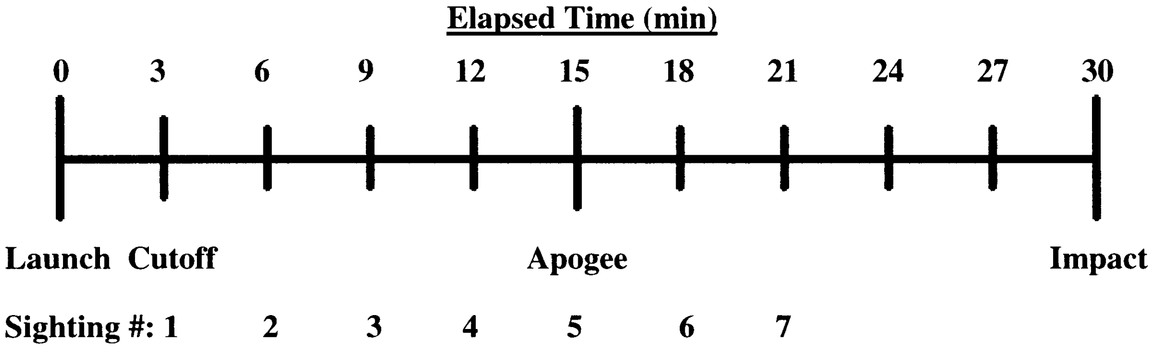


Figure 4-7: Approximate Trajectory Timeline

Note from this figure that the first sighting opportunity occurs immediately following cutoff, and subsequent observations occur in three minute intervals. For the baseline case, the 4th and final sighting takes place at approximately the 12th minute, leaving a couple of minutes prior to apogee for computation and necessary maneuvering.

Updating missile state knowledge late in the trajectory is more beneficial than earlier updates for two reasons. First, post-update INS errors will have less time to grow between the update and impact. Secondly, there are generally fewer visible skymarks at the low altitudes of early updates (particularly in winter), reducing the likelihood of significant CEP improvement. Figure 4-8 illustrates this effect numerically.

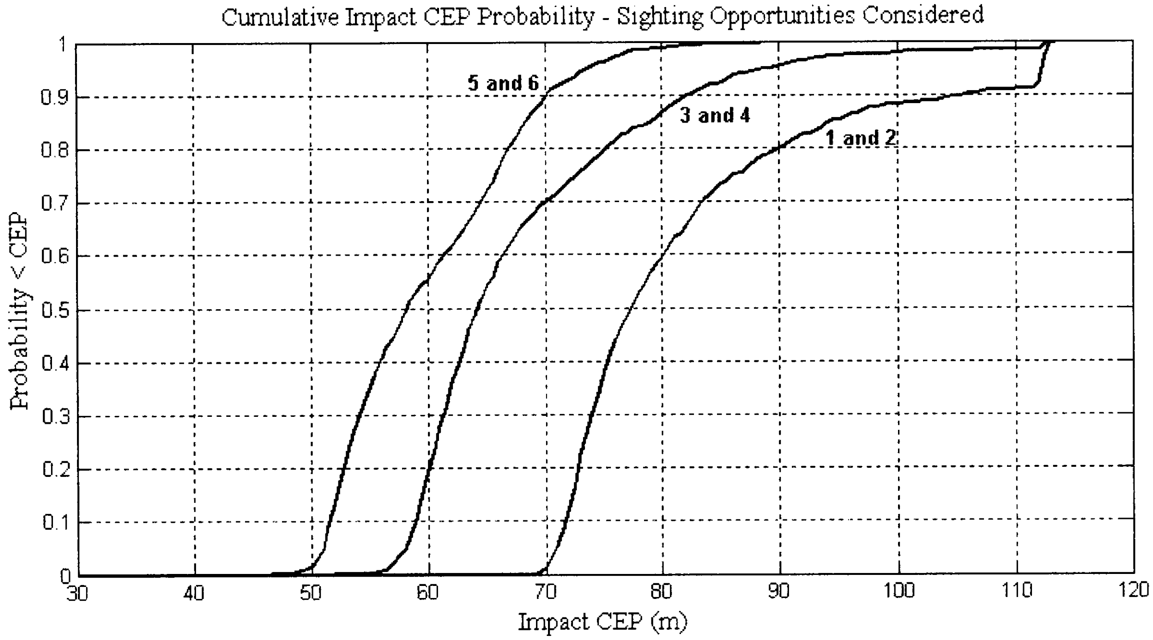


Figure 4-8: Impact CEP Probability Due to Sighting Trajectory Location

In this figure, only two sighting opportunities out of the seven shown on the timeline above are used in the simulations behind the three distributions. The midpoint of the distributions moves from a CEP of 77m to 58m as sightings are performed later in the trajectory.

It is clear that later updates are more beneficial. The operational system, however, will take advantage of the maximum number of sighting opportunities that power and RV deployment constraints will allow. The baseline analysis assumed the observation window to be the 10-15 minutes between cut-off and apogee. However, this will not necessarily be the case operationally.

For instance, when launching against an adversary possessing well-positioned ICBM radar detection sites, the missile may break radar horizon well before apogee. In order to reduce probability of detection, RVs and any accompanying decoys must be released prior to breaking radar horizon. In this case, there may not be enough time for four sighting opportunities. If radar detection is not a crucial issue for a launch, however, operations may continue until either battery power or maneuvering fuel is depleted. The baseline battery power assumption constrained the end of the operations window at apogee. However, if sufficient battery power is available, further sightings may be performed, as denoted in Figure 4-7 by sighting opportunities 5, 6 and 7. This option of increasing battery life to perform observations later in the trajectory is certainly advantageous for system accuracy, as has been seen in Figure 4-8.

There are some mission-dependent scenarios that may affect the duration of the sighting window as well. For instance, if one is considering an ICBM with multiple independently-targeted re-entry vehicles (MIRVs) as opposed to a single RV, Skymark operations may be constrained by the RV deployment schedule (since the deployment ΔV is a function of trajectory location), thereby decreasing the observation window. Conversely, if a smaller payload, such as a large conventional bomb or ground-penetrating warhead, were used, there may be fuel and power onboard to spare, thereby increasing the operations window. In fact, if the window were increased enough, it may be possible to use initial observations to calibrate the IMU in-flight so that it will provide more accurate state estimates later in the trajectory.

Figure 4-9 demonstrates the effect on performance of enlarging or reducing the sighting window.

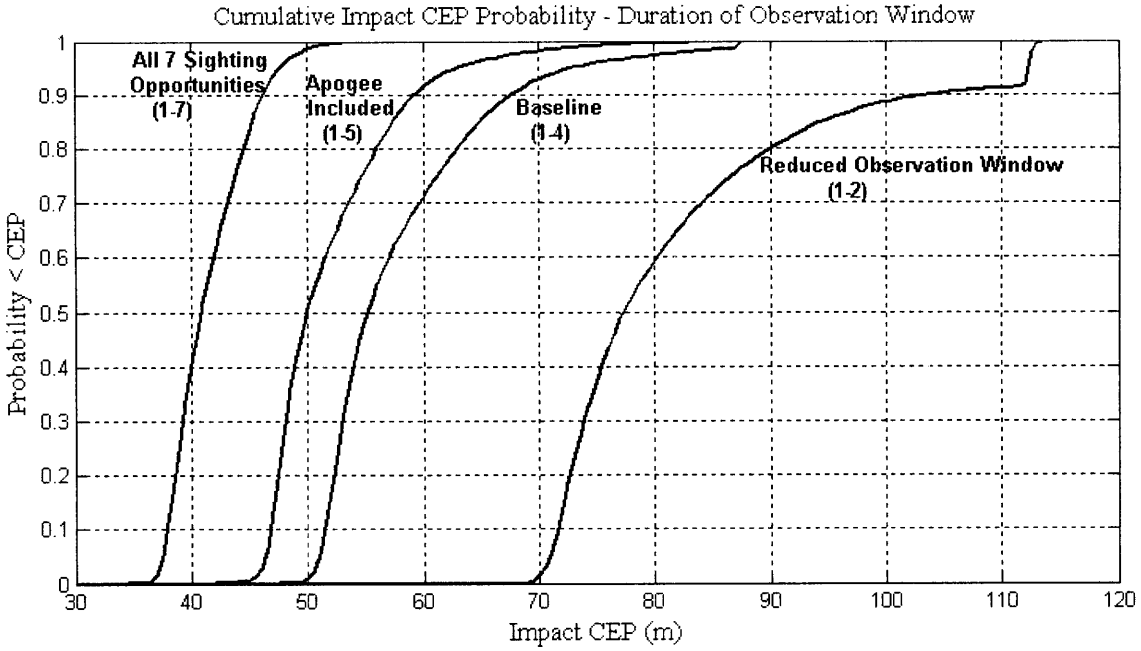


Figure 4-9: Impact CEP Probability Due to Size of Sighting Window

The "Reduced Observation Window" distribution is the result of using only sighting opportunities 1 and 2 from the timeline, in the case where early RV deployment is required (e.g. to avoid radar detection). The "Apogee Included" curve represents enlarging the baseline operations window to include a sighting at apogee (sighting opportunities 1 – 5 in the trajectory timeline). Clearly, the best accuracy results are obtained by further increasing the available operations time to include all seven sighting opportunities in the timeline above. In fact, the worst-case accuracy for the distribution considering all seven sighting opportunities is approximately the same as the best-case accuracy for the baseline observation window. The impact accuracy of this distribution does not degrade as much as the others in worst case because satellite availability holes are significantly reduced by allowing observations to be taken late in the trajectory.

[This page intentionally left blank]

Chapter 5

Conclusions and Implementation Issues

The primary goal of this research has been to determine the potential performance enhancement attainable for a land-launched ICBM by using a Skymark system to aid navigation. The results of this study have been presented in Chapters 3 and 4. In this chapter, a summary of conclusions from this study will first be presented. The second section of this chapter will consist of a brief discussion of a few noteworthy issues that must be addressed prior to Skymark becoming an operational reality. These implementation issues are presented in this chapter for the sake of completeness, so that the reader may gain an understanding of not only the theoretical performance improvement offered by Skymark, but also what it would take to make the system operational. Next, this chapter will include with a discussion of areas meriting future study. Finally, a few concluding remarks will be stated at the end.

5.1 Summary of Conclusions

In Chapter 2, it was found that satellite visibility is dependent upon lighting conditions. Certain times of day and year offer very poor satellite availability as sunlit objects (potentially visible) are far away and back-lit, and thus appear extremely dim.

The availability simulation of Chapter 2 demonstrated that, for the trajectories considered, the optical tracker must be able to view objects as dim as 8.0 magnitudes in order to eliminate these deficiencies in skymark availability.

In Chapter 3, the objective was to determine the accuracy improvement achievable (in terms of CEP at impact) if the Skymark system were operational today. Recall that for the purposes of this thesis, the CEP at impact was assumed to be dominated by navigation errors, while other error sources (atmospheric conditions and target location knowledge errors) were not accounted for. A realistic operational simulation was developed and run using baseline input parameter values designed to represent present-day capability. It was found that, under these conditions, the Skymark system significantly improved navigation for two implementation scenarios.

For the case of Skymark as a next-generation navigation system, using a low quality IMU with unaided INS CEP of 1 km, the impact CEP achievable was found to be less than 100 meters in all cases, including worst-case lighting conditions when the system could only perform stellar attitude updates. This vast improvement over inertial navigation (greater than 90%) was found to be due to the extremely high correlations between attitude knowledge and position/velocity knowledge in the error model for the low quality IMU. In comparison with present-day unaided inertial navigation system accuracy (published impact CEP approximately 200 meters), this next-generation navigation system was thus always greater than 50% more accurate.

For the case of Skymark as a navigation addition to a current inertial system, it was found that Skymark observations improved impact CEP by more than 50% except in the infrequent case of minimal skymark availability, corresponding to launching in the vicinity of midnight and the winter solstice. At these times, accuracy degraded to unaided INS levels because it is assumed that the "add-on" tracker is unable to accurately relate stellar sightings to IMU attitude. It is noteworthy that the improved accuracy afforded by the Skymark system was similar for both implementation scenarios, despite their vastly different unaided accuracy levels. Thus it is evident that the impact accuracy achieved by using Skymark updates is dependent upon the accuracy of the observations rather than the unaided navigation accuracy of the INS. This is fortunate because it means that comparable accuracy may be achieved by using a lower quality (less expensive) IMU as part of the Skymark system.

From the results in Chapter 3, it can be concluded that the Skymark-aided system, in both cases, is very robust. Even when space objects are not visible, or for some reason their ephemerides are not accurate or up-to-date, the first scenario makes good use of stellar sightings while the accuracy in the second scenario only degrades to current unaided ICBM accuracy. However, almost all of the time, significant improvements can be made by observing nearby space objects.

In Chapter 4, a sensitivity analysis was performed by varying the baseline system parameters of tracker accuracy, tracker sensitivity, catalog size, and skymark ephemeris knowledge within reasonable bounds. Because some of the true values for these parameters are unknown, the sensitivity analysis was a crucial part of the study. It was found that certain parameters had a much greater effect on system accuracy than others. In particular, it was found that the two most important parameters are the accuracy with which the space object ephemerides are known and the accuracy with which their locations in space can be measured by the tracker. A simplified costing analysis was performed, comparing operations cost with development cost. It is a fortunate result, in terms of the cost of operations, that a relatively small space object catalog including only the most useful 200 to 300 satellites performs near-equivalently to a catalog containing all potentially useful existing space objects. Finally, it was postulated that improving tracker measurement accuracy and skymark ephemeris knowledge while decreasing the size of the operational catalog to 200-300 objects could provide a cost-effective means of significantly improving the accuracy of the operational system.

5.2 Operational Implementation Issues

In order to make Skymark operational, several implementation issues must be addressed. Most of these are derived from the fact that the system requires accurate and up-to-date space object ephemeris information. Several important considerations are briefly described below.

5.2.1 Constellation Definition and Evolution

Obviously, the true operational space object catalog will have to be defined. A similar procedure to the one outlined in Chapter 2 may be used. Based upon the number of space objects that NORAD is capable of tracking at the desired accuracy level, the best set of existing objects must be chosen. Based upon the number of objects in the catalog and true trajectories, there may be some locations where existing space object availability is sparse. In this case one may opt to launch some artificial satellites to improve the spacing in the constellation.

Once the operational catalog has been initially defined, it will have to be re-evaluated on a periodic basis. Over time, new space objects will be launched, others may de-orbit, and current members of the operational catalog will drift from their places in the current constellation. This is particularly true because Skymark is primarily interested in inactive objects, which by definition do not perform orbital maintenance maneuvers. Therefore, the optimal set of objects will change over time, and a procedure for redefining the catalog periodically will have to be instituted.

5.2.2 Optimal Catalog Update Frequency

The skymark ephemeris knowledge *at sighting time* has been the parameter used in the simulation for determining Skymark system performance. Operationally, the Skymark system will propagate the latest NORAD-updated skymark epoch state to the time of observation in order to predict the skymark position at sighting time. As the time between epoch and sighting increases, the quality of this prediction degrades. Therefore, the ephemeris knowledge at sighting time will vary depending on how frequently the ephemerides of the objects in the catalog are updated. Based upon how quickly the ephemeris knowledge degrades with time, the optimal catalog update frequency can be estimated based on the accuracy of the updated epoch state (which may vary somewhat) and the desired ephemeris knowledge at sighting time.

Secondly, the satellite tracking equipment used to update the space object catalog must be taken into consideration. If greater accuracy than presently exists is desired, more advanced tracking equipment may need to be developed. Consideration may be given to using space-based tracking equipment vs. ground-based. The accuracy with which each of the strategic space objects can be tracked will be a function of the quality of the tracking equipment and how much tracking attention can be afforded to each member of the catalog.

5.2.3 Ensuring Accurate Communication of Catalog Data

Once the ephemerides of the space objects have been updated by satellite tracking equipment, new epoch states for each object, along with corresponding covariance matrices describing the expected accuracy of these states, must be communicated to the missile silos. Because this is a strategic system, this communication must be accomplished both efficiently and accurately. In fact, there must be absolute certainty that none of the ephemeris data was communicated in error. This may be accomplished by utilizing a robust error detection and correction algorithm. A further consideration is the method of communicating the data, whether landlines or a satellite communication link, or both, should be used. Furthermore, the communication between NORAD and the individual missile silos must be assured using a robust communications hierarchy. Several aspects of this communications problem have already been addressed by means of a communications demonstration at the Draper Laboratory [2].

5.2.4 Pre-launch Skymark Selection Process

Prior to launch, the optimal sighting schedule for the launch must be computed. This will likely require a computer on the ground to run a simulation similar to the Skymark simulation used in this study. Recall that the Skymark simulation created for this study simply chose the most effective (greatest effect on CEP) skymark at each of four pre-determined sighting locations sequentially. While this method is good enough for the purposes of this research, it is not optimal. An optimal selection and scheduling algorithm would choose the most effective combination of skymarks by taking into account all objects visible along the entire sighting window. This type of algorithm was the topic of a previous study performed at the Draper Laboratory [5]. This is the type of algorithm that must be developed as part of the Skymark implementation process.

Since a strategic weapon may have to launch on short notice, this optimized scheduling algorithm will likely have to run on a semi-continuous basis, always using the most recently updated catalog. Furthermore, as the optimal sighting schedule will be different for different trajectories, the algorithm will have to consider all feasible trajectories based upon the target set for the missile.

5.2.5 Integration of Skymark System with Current INS Systems

If a Skymark tracker and software is to be added to the inertial navigation system of an existing missile, there are some integration issues that must be resolved. In terms of hardware, one must decide how to best attach the tracker and accompanying wiring to the bus of the current system. In terms of software and data interface, a method must be devised for obtaining the current INS state from the existing computer, updating it using Skymark observations, and returning it to the missile computer. Additional Skymark flight software, and potentially a new flight computer, will be required.

5.2.6 Skymark System Robustness

With strategic systems, robustness is crucial. Events with potential to disrupt the system must be mitigated prior to development of a strategic system. This is why our nation's ICBMs cannot afford to depend on the presence of GPS, and therefore are currently inertially guided. In terms of the Skymark system, any event that prohibits accurate and timely catalog updates will certainly hinder system performance. For example, an adversary-initiated high altitude burst has the potential to perturb the orbits of the objects in the catalog by heating and raising the atmosphere (although many of the objects in the catalog may be high enough to be unaffected), thereby causing inaccuracies in the latest catalog information. Secondly, if an enemy were to destroy any satellite tracking equipment, whether ground-based or possibly space-based, there may be a significant decrease in the frequency and accuracy with which the catalog can be updated. Thirdly, if a communication link were to fail, whether due to an act of war or other cause, catalog update delays may result.

It should be noted at this point that since the events listed above constitute acts of war against the U.S., they are very unlikely to occur at random outside of a wartime environment, as retaliation would likely ensue. Furthermore, since ICBMs are strategic weapons that will only be used as a last-resort retaliation against an equally significant attack, this system will only be used under wartime circumstances. Therefore, the times when the system may be called upon in the future are also the times that system-disrupting events are the most likely to occur.

For this reason, prior to the development phase of a system like Skymark, one must question the robustness of the system. If the events listed above were to occur, what are the likely consequences in terms of system performance? Each of the previously mentioned situations could cause delays in obtaining catalog updates. These delays will cause the ephemeris knowledge at sighting time to degrade because of the increased amount of time that the latest updated epoch state must be propagated forward. Because skymark ephemeris accuracy affects missile accuracy, as has been shown, this will in turn cause missile accuracy to degrade. However, despite these possibilities, the Skymark system as described in this thesis is still very robust. In the case of Skymark as a new system, performing attitude updates via stellar sightings has been shown to be a reasonably good option during times when skymark sightings are unavailable or inappropriate. As seen in Chapters 3 and 4, these attitude updates produce a relatively accurate impact CEP through the high correlations between attitude, position and velocity knowledge present in the error model for a replacement IMU. In the case of Skymark as an improvement to a current inertial system, system accuracy will only degrade to current INS navigation accuracy if skymark sightings are temporarily unobtainable.

5.3 Areas Meriting Future Study

This study has concluded that there is navigation improvement potential for land-launched ICBMs by means of using observations of nearby space objects against a star background. Herein reasonable values have been assumed for classified unknowns including trajectories, IMU error models, and space object ephemeris knowledge levels. Because these items have been found to affect results, a further study using true values for these parameters would be valuable in obtaining results of even higher fidelity. Furthermore, in this study, other input parameters representing capability were varied within reasonable bounds in order to demonstrate their relative influence on navigation accuracy. A simple generalized cost analysis compared aspects corresponding to development cost with those contributing to the cost of ongoing operations. A more in-depth cost analysis, investigating the specific cost of improving various aspects of the system, would be a very useful endeavor.

A third area meriting further research is to investigate the merits of the Skymark system as applied to submarine launched ballistic missiles (SLBMs). United States

SLBMs currently perform a single in-flight stellar attitude update. However, is it possible, or even beneficial, to modify the technology to sight nearby space objects or to perform multiple stellar sightings? Also, could the Skymark concept be integrated into an existing SLBM easier than an ICBM because a stellar tracker is already present? These questions are certainly worthy of future study.

Finally, the Skymark concept, as it has been referred to in this thesis, is really nothing more than optical triangulation, an age-old method of navigation. Are there other potential applications in air and space for this concept? Obviously, since GPS is much more accurate than optical triangulation to fast-moving objects, it is likely that the beneficial applications of this concept will be limited to the military or to locations in space where GPS does not exist. One application that has already been proposed is improving the navigation of a Mars Lander using satellites currently in Mars orbit.
A second potential area that has been postulated is for navigation of military unmanned aerial vehicles (UAVs) in the event of a GPS outage.

5.4 Concluding Remarks

It has been shown in this thesis that the Skymark concept has potential to significantly reduce navigation system errors for ICBMs, thereby improving impact accuracy. The concept holds potential as both an upgrade to a current missile system and as a complete replacement for a current navigation system. If a Skymark-type system were developed as a next-generation system, there is significant cost-reducing potential due to the fact that a lower quality inertial navigation unit could be used. This study has shown that the Skymark concept would be beneficial if implemented at present using currently existing space objects and current state-of-the-art tracker technology. It has also been seen that future technological improvements also hold significant accuracy-improving potential. It is thus concluded that the Skymark concept merits further study as an aid to inertial navigation for ICBMs.

[This page intentionally left blank]

Appendix A

Graphs for All Trajectories Investigated

This appendix includes satellite availability and accuracy improvement results for all nine trajectories defined in section 2.3.1. The nine trajectories, again, are 4,000, 5,000 and 6,000 nm trajectories on each of 320°, 0° and 40° launch azimuths. Because the results for all trajectories exhibited similar trends, only those for the north-firing, 5,000 nm trajectory were presented in the body of the thesis. The first graph on each page is analogous to Figure 2-3, the second and third to Figures 3-2 and 3-4, respectively.

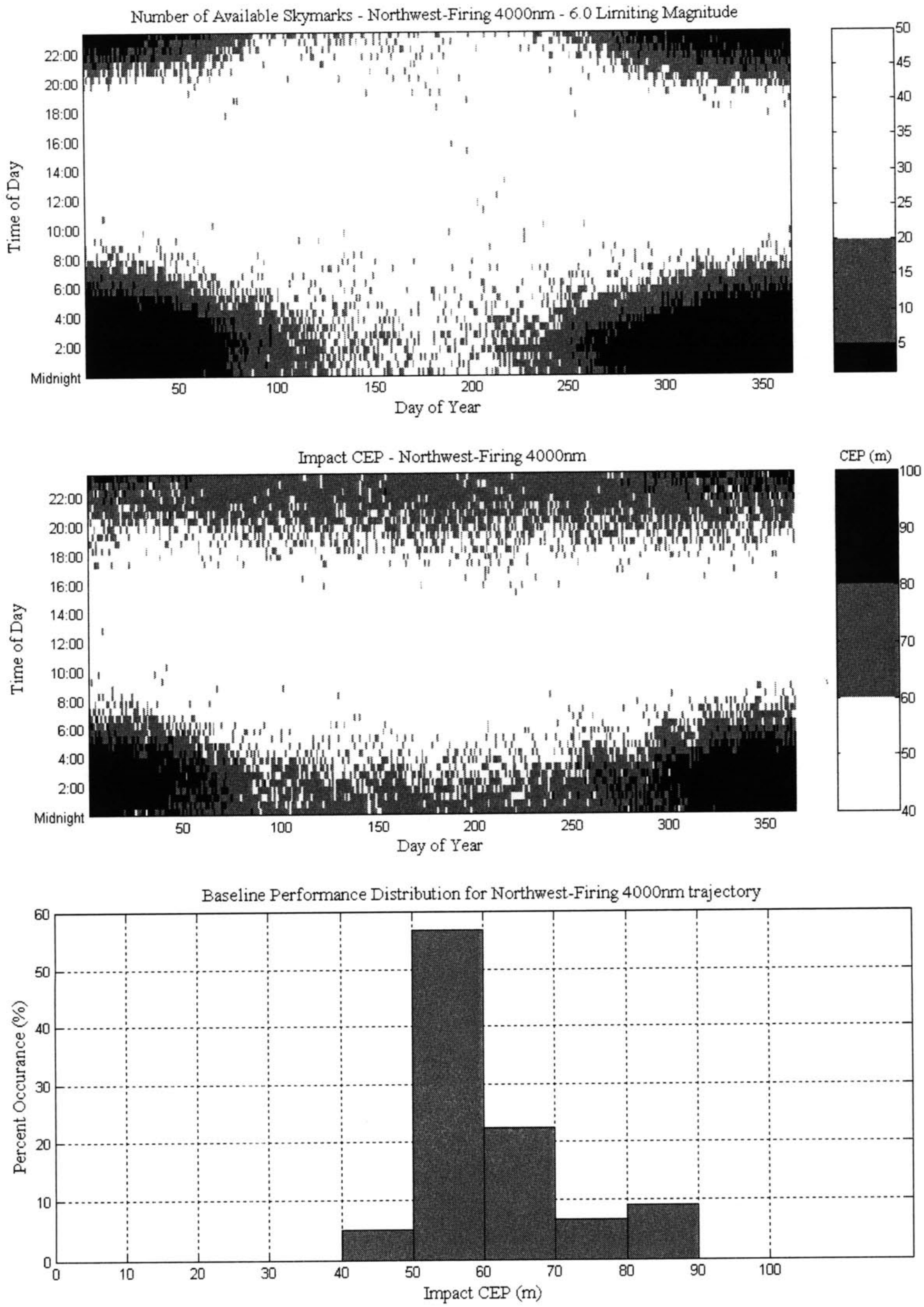


Figure A-1: Satellite Availability and Impact CEP results for Northwest-Firing 4,000 nm Trajectory (Launch Azimuth 320°)

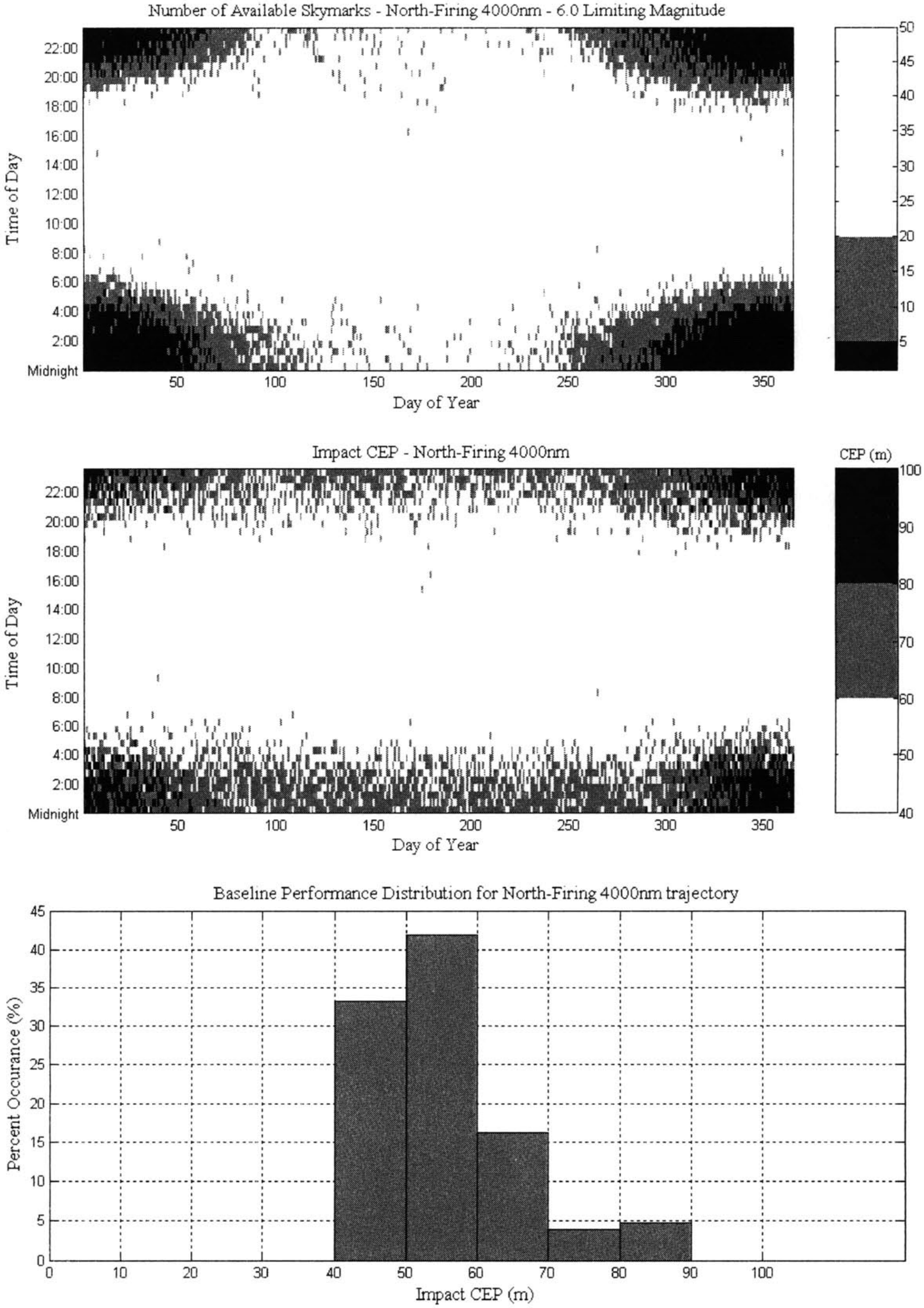


Figure A-2: Satellite Availability and Impact CEP results for North-Firing 4,000 nm Trajectory (Launch Azimuth 0°)

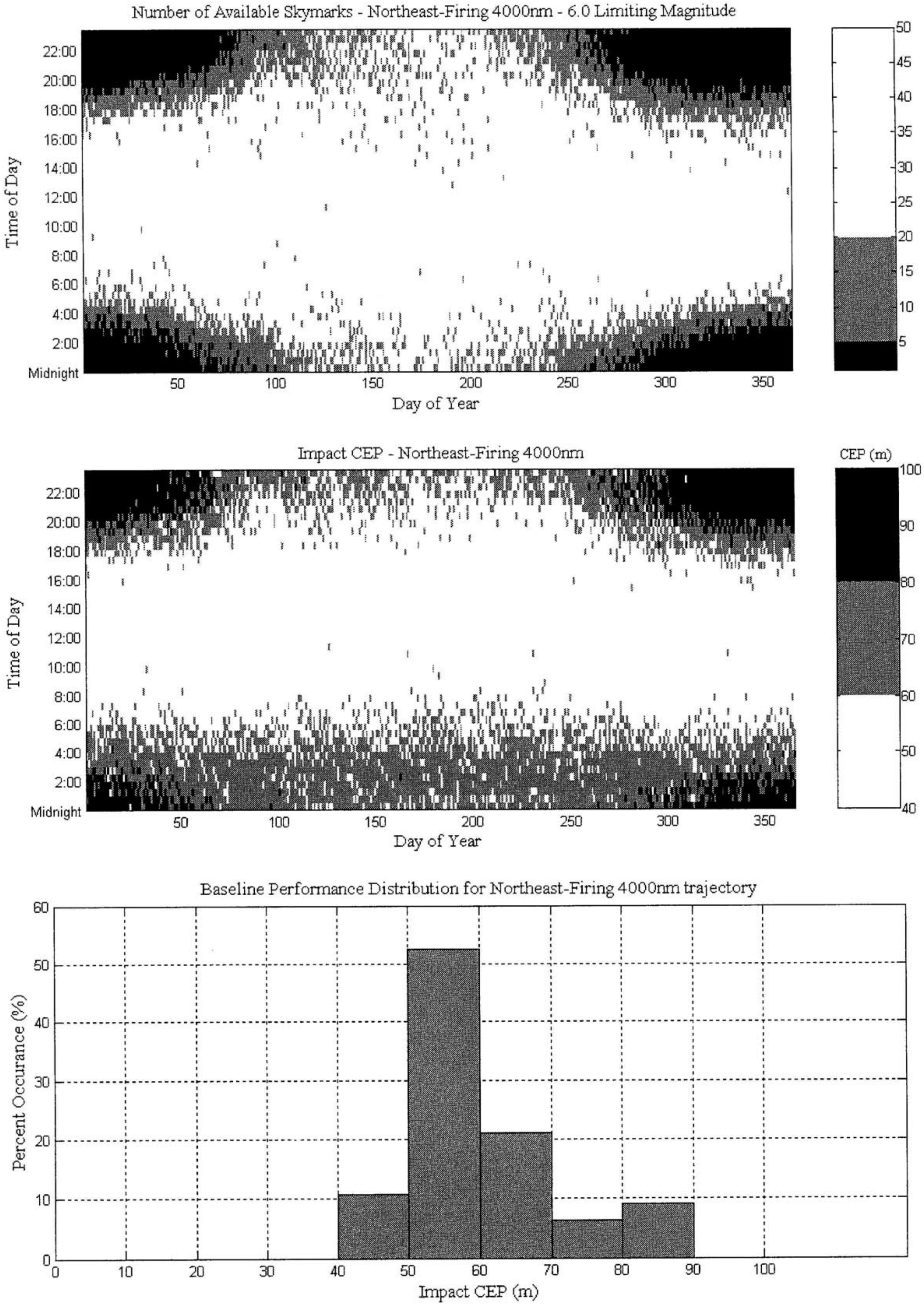


Figure A-3: Satellite Availability and Impact CEP results for Northeast-Firing 4,000 nm Trajectory (Launch Azimuth 40°)

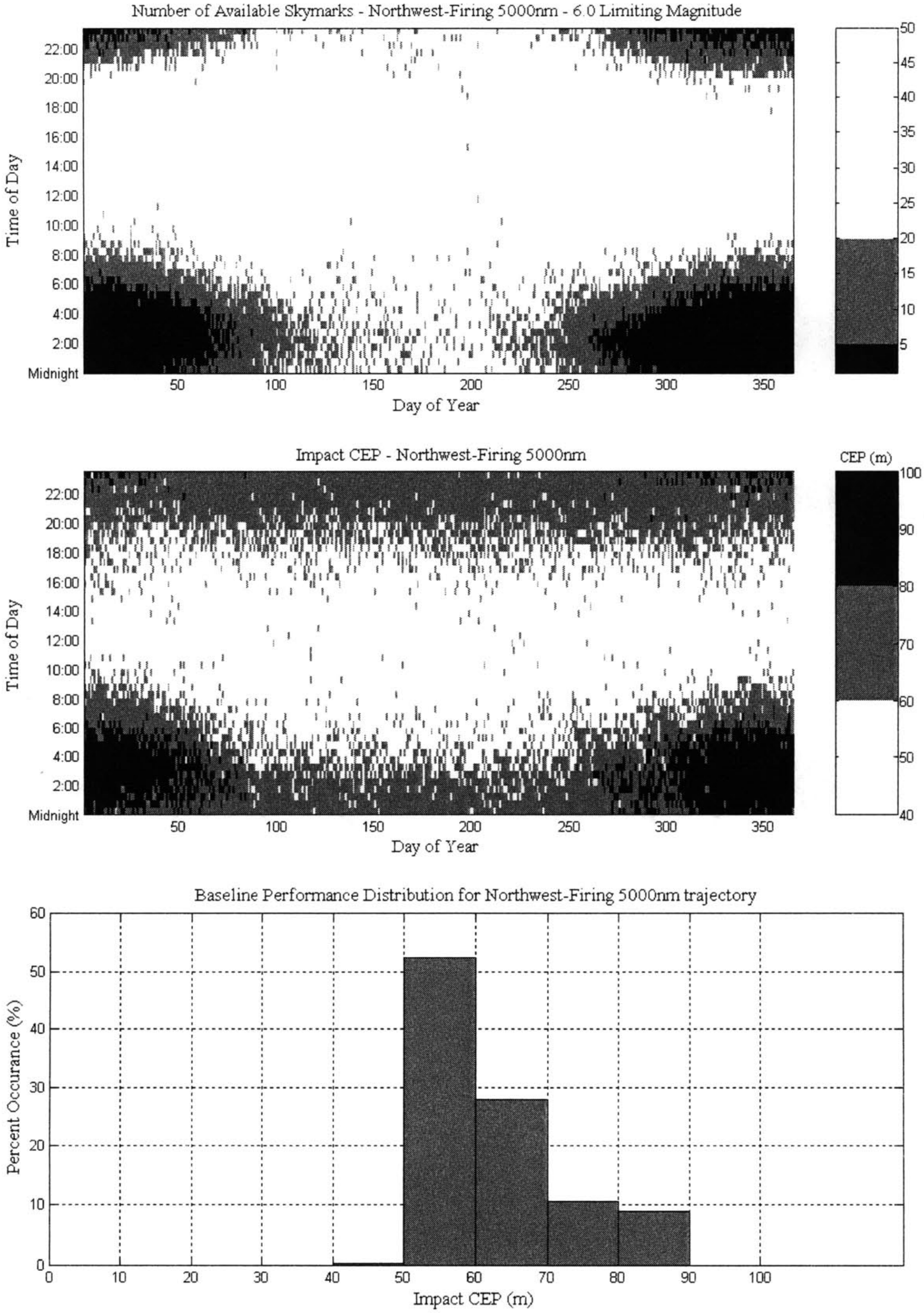


Figure A-4: Satellite Availability and Impact CEP results for Northwest-Firing 5,000 nm Trajectory (Launch Azimuth 320°)

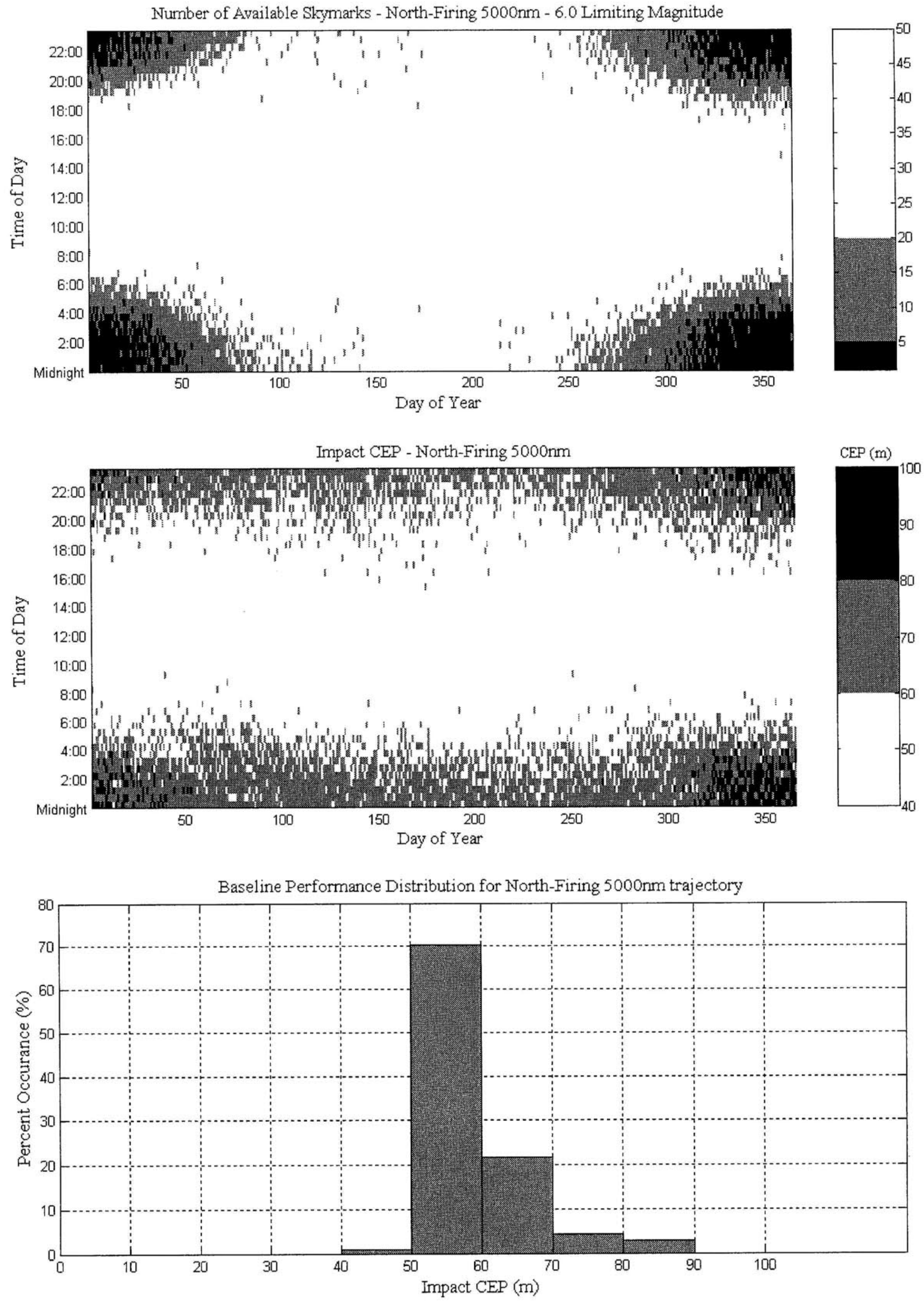


Figure A-5: Satellite Availability and Impact CEP results for North-Firing 5,000 nm Trajectory (Launch Azimuth 0°)

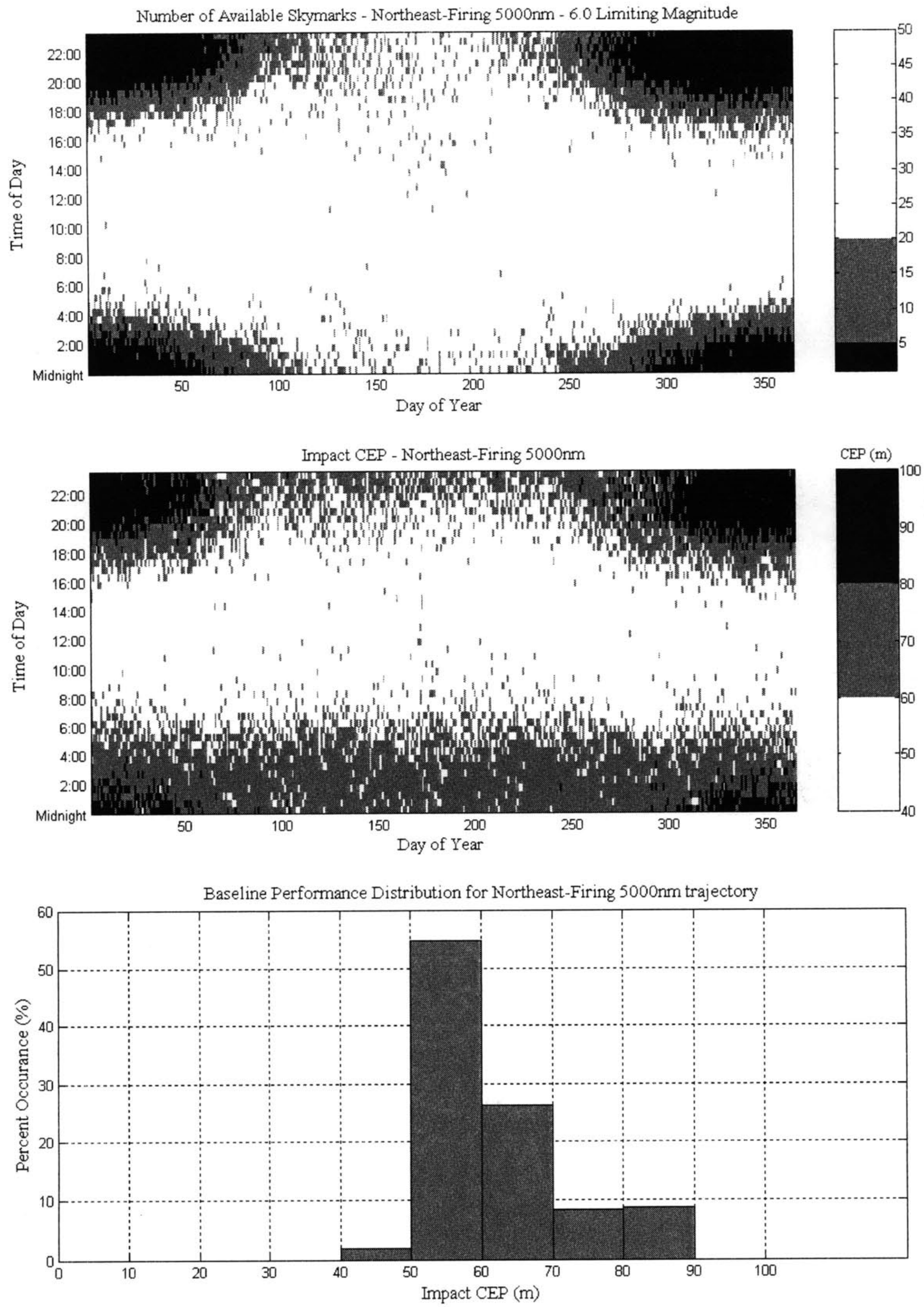


Figure A-6: Satellite Availability and Impact CEP results for Northeast-Firing 5,000 nm Trajectory (Launch Azimuth 40°)

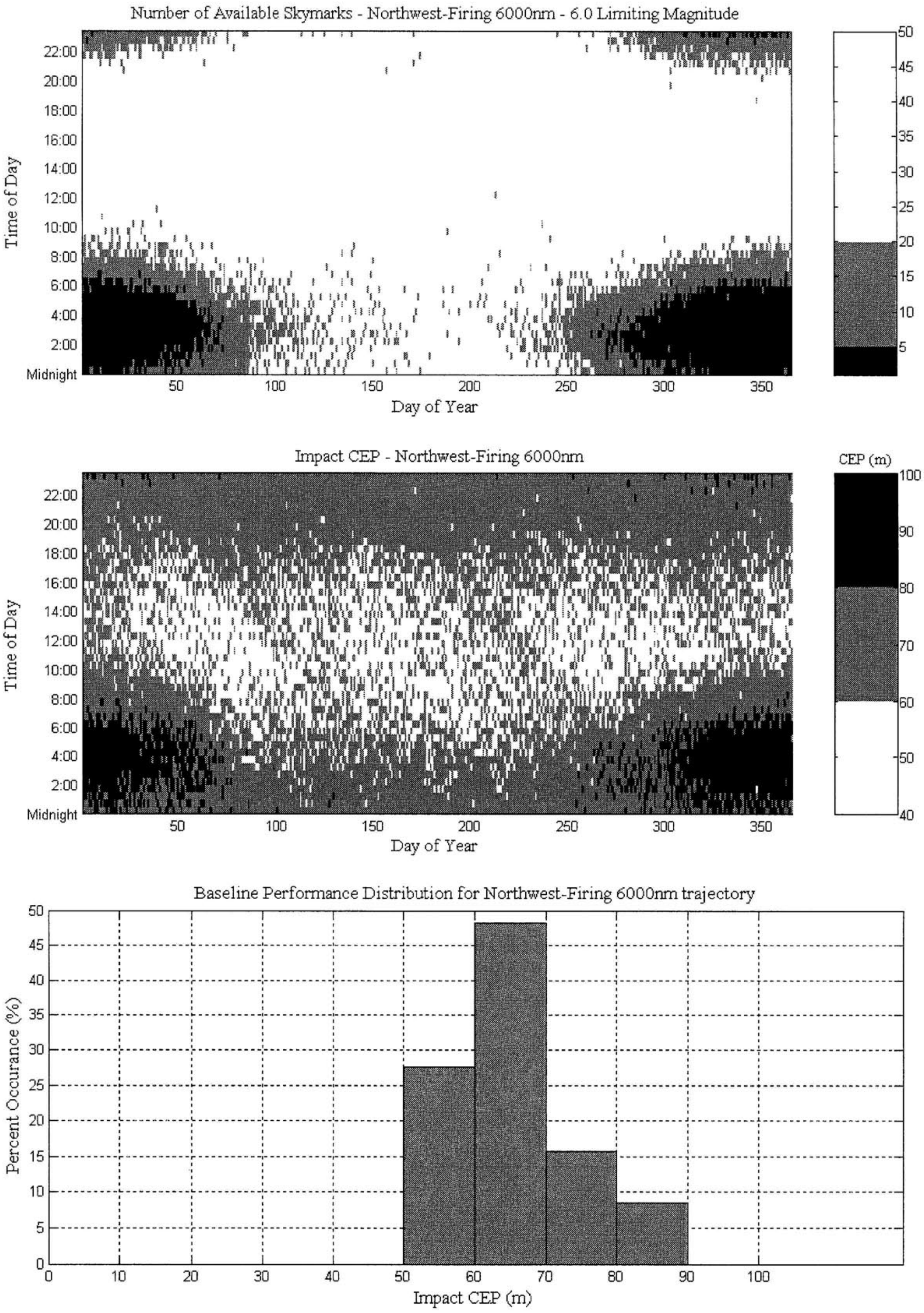


Figure A-7: Satellite Availability and Impact CEP results for Northwest-Firing 6,000 nm Trajectory (Launch Azimuth 320°)

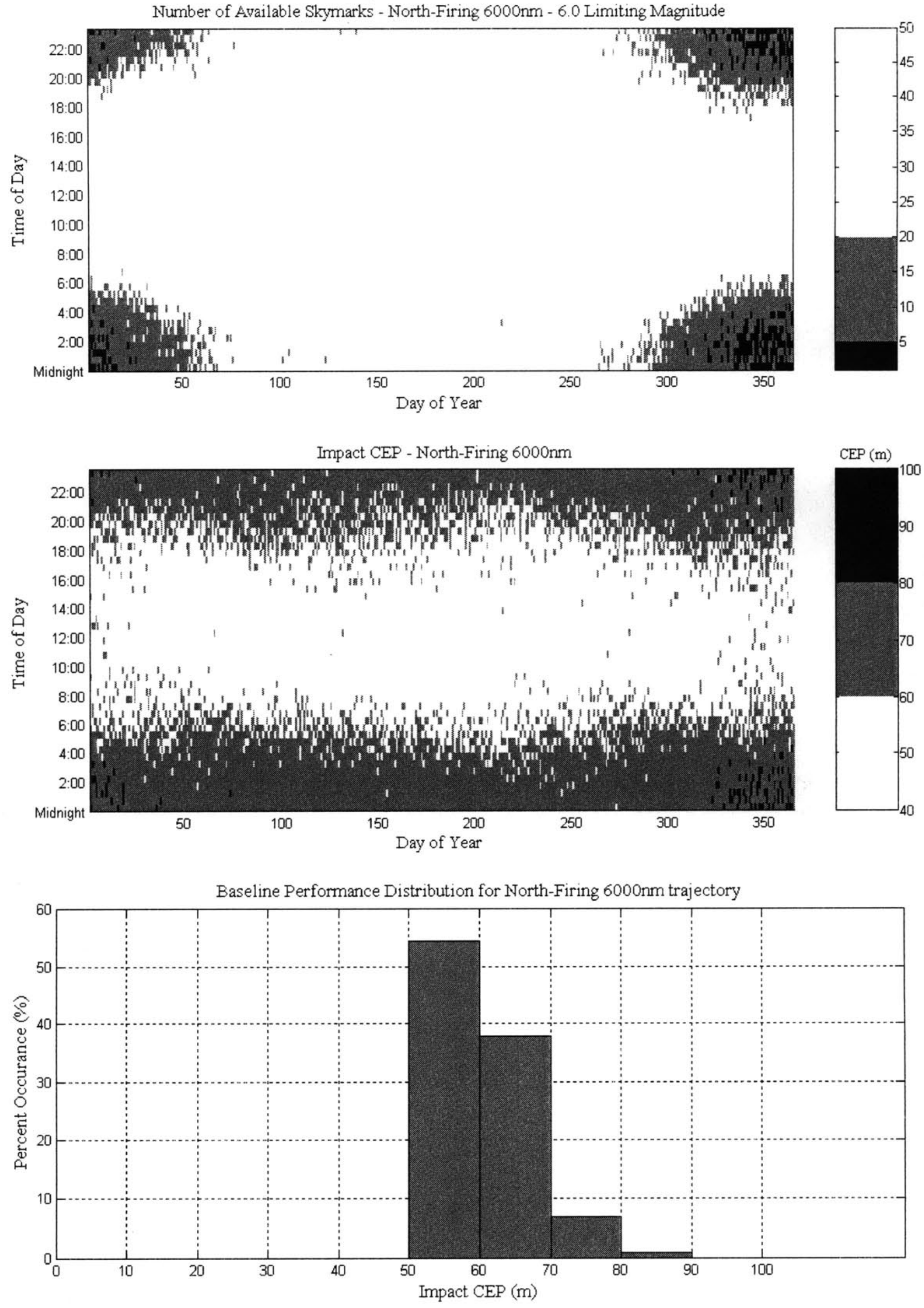


Figure A-8: Satellite Availability and Impact CEP results for North-Firing 6,000 nm Trajectory (Launch Azimuth 0°)

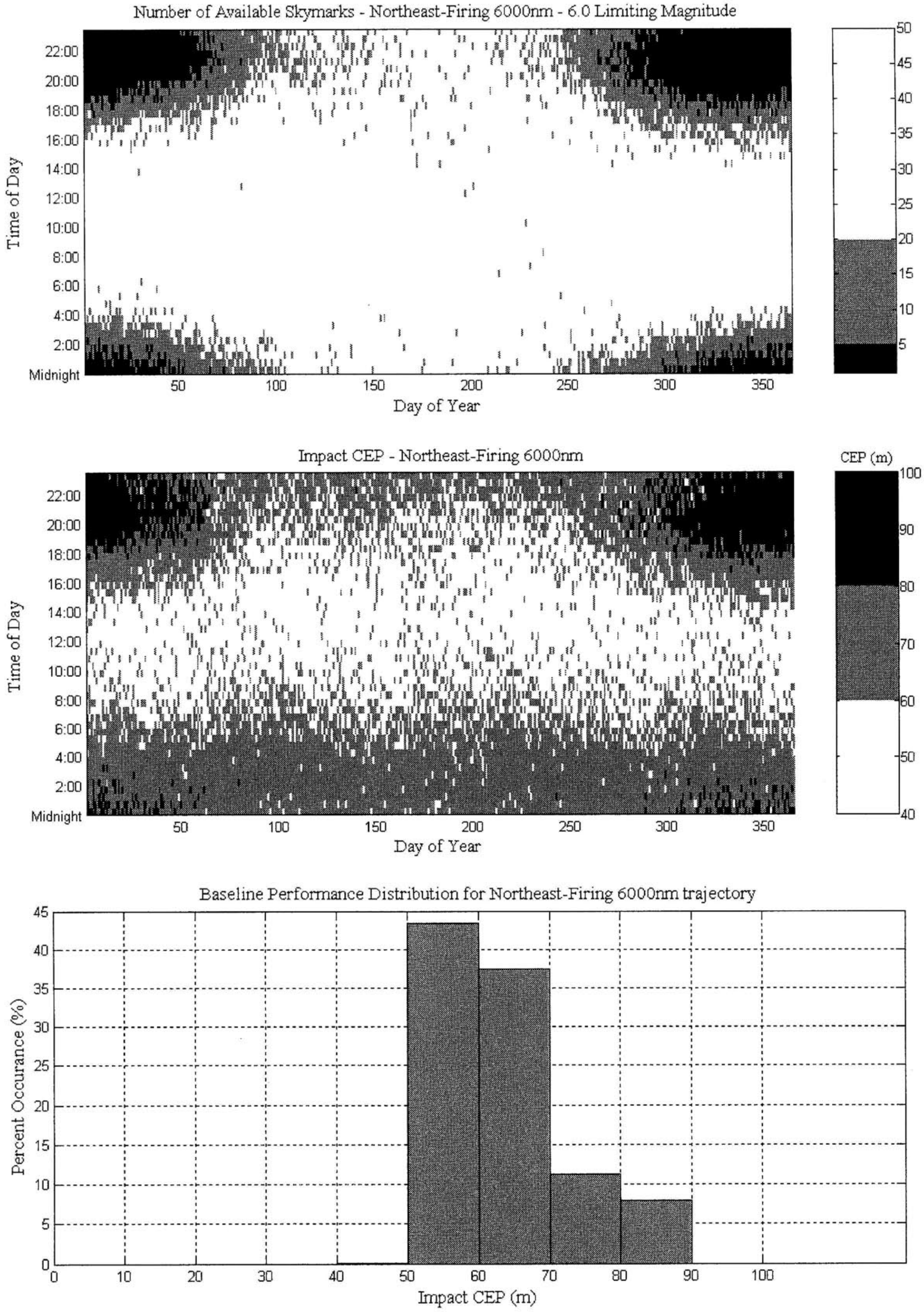


Figure A-9: Satellite Availability and Impact CEP results for Northeast-Firing 6,000 nm Trajectory (Launch Azimuth 40°)

Bibliography

[1] Alfriend, K. T and Lewis, D.L. "Estimation of the Low Earth Orbit Space Object Population Using a Non-Vertical Staring Radar," *Space Debris*. European Space Agency Publications, Darmstadt, ESOC, 1993, pp. 329-336.

[2] Biren, M. et al. "Skymark Rooftop Demonstration and Communications Demonstration Final Report," Charles Stark Draper Laboratory, Inc., Cambridge, MA, Publication Pending.

[3] Blake, B. *Jane's Weapon Systems*, 19th ed., Jane's Information Group, Inc., Alexandria, VA, 1988.

[4] Das, A. "Color Index Computation for the NASA Standard Fixed Head Star Tracker," The Journal of Astronautical Sciences, Vol.XXX, No. 3, July-Sep 1982 pp. 287-301, Figure 1.

[5] Kaptuch, James. "Skymark Selection Algorithm for a Space-Based Navigational Concept," Master of Engineering Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, September 2002.

[6] McCants, Mike. "Mike McCants' Satellite Tracking Web Pages," Catalog of Satellite Visual Magnitudes [online database], URL: http://users2.ev1.net/~mmccants/programs/ [cited 20 April 2004]

[7] Analytical Graphics, Inc. Satellite Database [online database], URL: http://www.agi.com/resources/satdb/satdb1.cfm [cited 20 April 2004]