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Irving Lachow

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The Global Positioning System and Cruise Missile Proliferation: Assessing the Threat

Irving Lachow*

EXECUTIVE SUMMARY

At its inception, the Global Positioning System (GPS) was designed primarily to provide accurate, position, velocity, and time information to U.S. military users. However, the U.S. government predicts that by the year 2003, the number of civilian GPS users will be 51 times greater than the number of military users. As a result of the growing availability of GPS throughout the world, the U.S. government is facing a dilemma: the spread of GPS receivers provides economic benefits to the United States which can translate into technological and even political gains; however, the growing availability of GPS equipment also increases the likelihood that other nations will use GPS for military purposes. The Department of Defense is understandably concerned that some nations could use GPS to improve the accuracy of the weapons they might use against U.S. forces.

In sum, the tremendous popularity of GPS is providing the United States with both economic benefits and potential military risks. In order to determine an appropriate policy regarding GPS, policymakers must be given as much information as possible about the benefits and costs associated with the growing popularity of GPS. While the potential economic benefits have been estimated by a variety of groups, there has not yet been a systematic technical assessment of the military risks associated with the spread of GPS. This paper addresses the latter issue by examining the nature and magnitude of the threat posed to U.S. security by GPS-guided cruise missiles (GCMs).

The paper begins with a detailed, quantitative analysis of the lethality of GCMs. That analysis requires an examination of several factors, including the missiles' accuracy, range and payload. The probability of kill for individual cruise missiles is determined, as is the number of GCMs which are required to achieve a desired probability of destruction against both soft and reinforced targets. Both area and point targets are examined. It then provides an in-depth discussion of the survivability of GCMs against two U.S. countermeasures: electronic jamming and cruise missile interception.

It is possible, but unlikely, that GCMs will be used for nuclear weapons delivery in the near future. It is doubtful that a nuclear device produced in the Third World would weigh less than 500 kg. The only advanced cruise missiles that could carry such payloads beyond short ranges are those produced by developed nations. Thus, if lessdeveloped countries (LDCs) wished to obtain a highly capable cruise missile for nuclear delivery, they would have to purchase it from the United States, France, or the Former Soviet Union. None of these nations appears willing to sell capable land-attack cruise missiles, which are covered by the Missile Technology Control Regime.

Another disadvantage of using GCMs for delivering nuclear weapons is that they have a low to moderate probability of surviving against U.S. air defenses. Given that LDCs will probably have few nuclear devices in their stockpiles, the survivability of the vehicles they use to deliver these weapons must be as high as possible. In the foreseeable

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*Irving Lachow is currently a pre-doctoral fellow at the Center for Science & International Affairs. He will receive his Ph.D. from the Department of Engineering and Public Policy at Carnegie Mellon University in May, 1994. His doctoral dissertation examines the policy dilemma surrounding the growing use of GPS throughout the world. The author would like to thank the following people for their comments and suggestions: Eric Arnett, Owen Cote, Benoit Morel, Granger Morgan, Stefanie Schmidt, and Joanna Spear.

future, ballistic missiles will remain more survivable than the cruise missiles which are likely to be developed or purchased by LDCs.

GPS-guided cruise missiles can be good platforms for delivering chemical weapons (CWs) because of their accuracy and velocity. On the other hand, the small payloads of many cruise missiles, especially compared with those of strike aircraft, will limit the lethality of cruise missile-delivered CW warheads. Even if large CW payloads could be delivered by GCMs, their effect on U.S. forces would probably be minimal. Finally, it is important to note that U.S. forces already face the risk of CW attacks by ballistic missiles and aircraft in the Third World. The existence of GCMs capable of carrying chemical weapons would not substantially increase the dangers facing U.S. forces.

It seems likely that most of the GCMs which U.S. forces will face in the near future will be moderately lethal. Since the number of GCMs required to achieve a desired probability of destruction against a given target depends on lethality of individual cruise missiles, it is probable that several GCMs will have to be used against even soft targets. Attacks against reinforced point targets will require large numbers of cruise missiles. On the other hand, fewer GCMs are needed against area targets, whether they are soft or reinforced. However, several GCMs may be required to incapacitate such targets.

The key problem in protecting oneself from cruise missiles is detection. In the near term, the United States will probably be able to detect GCMs in most situations. "Poor man's cruise missiles" will be especially vulnerable to detection because of their larger radar cross sections. In the longer term, stealthy cruise missiles, which may be developed in ten to fifteen years by China, Iran, and Syria, will pose a bigger challenge. In all likelihood, upgrades in both ground-based and airborne radars will allow the United States to maintain its current detection capabilities.

Medium- to high-altitude cruise missiles will be vulnerable to interception by both aircraft and surface-to-air missiles. Low-altitude GCMs will pose a tougher problem for both systems due to ground clutter. In the future, higher quality terrain elevation data may allow GCMs to fly much lower. This will aggravate both the detection and interception problems facing U.S. forces. The U.S. military is upgrading several of its missiles to improve their performance against such targets. In all likelihood, U.S. air defenses will perform well against "poor man's cruise missiles." However, advanced GCMs may pose a tougher challenge in the decades to come. The United States is responding to that threat with a comprehensive plan to improve its cruise missile interception capabilities. Only time will tell whether the U.S. effort is successful.

Electronic jamming appears to be quite useful in decreasing the lethality of GCMs. The best jamming strategy would be to use airborne jammers because of their long line-of-sight to even low-flying GCMs. As is the case with manned interceptors, airborne jammers are most effective if they are airborne when attacking cruise missiles are detected.

Ground-based jammers can also be effective in decreasing the lethality of GCMs; however, they are handicapped by their short line-of-sight to low-flying cruise missiles. This is not a problem if the attacking missiles are using inertial navigation systems (INSs) with high drift rates. However, if those missiles are carrying high-quality INSs, they could still pose threats to a variety of targets (including reinforced targets), depending on a variety of factors discussed in Section 2.3. In addition, GCMs gain some anti-jam capabilities against ground-based jammers because of the physical shielding provided by a cruise missile's body.

In sum, GCMs will probably be moderately lethal at best. In addition, the survivability of individual GCMs will probably be low. Hence, the probability of a single GCM successfully completing a mission (i.e., reaching and destroying a given target) is quite low. This finding implies that many cruise missiles will have to be launched so that enough missiles reach a target to achieve a high probability of destruction. Given the

tremendous costs which could be associated with this strategy, it appears feasible only if cheap, "poor man's cruise missiles" are used. Such missiles can pose a threat to U.S. military assets, but they are much more effective weapons if used in a "terror" mode against civilian targets, which can be located quite accurately and are generally both large and un-reinforced. However, "poor man's cruise missiles" can play other roles in a conflict against the United States. For example, such missiles could be used to divert U.S. forces away from other parts of a battlefield. A GCM attack could also be combined with an attack by ballistic missiles in an attempt to overwhelm U.S. defenses. Finally, a successful GCM strike could have a large political impact. In sum, while GCMs are not likely to change the outcome of a conflict between the United States and a Third World power, their presence could be significant.

In examining the threat posed by GCMs, this analysis also discovered that the benefit of selective availability (SA) is greatest when GCMs have small vertical position errors (i.e., if they have accurate altimeters and/or if they perform steep terminal dives), small targeting errors, and large payloads. In other words, SA is most useful when Third World cruise missiles are the most capable. That is true because navigation errors are only one part of the total system accuracy. As other error sources grow, they begin to dominate the navigation errors, so that the difference between GCMs using the C/A-code with SA on and those using the C/A-code with SA off become negligible. SA is also effective in limiting GCM lethalities against point targets. On the other hand, the navigation errors introduced by SA make little difference against large targets.

Thus, SA will probably have little impact on the lethality of GCMs in the near term. As the capabilities of Third World cruise missiles improve, the benefits of SA will grow concomitantly. However, it is possible that the effects of SA will be undermined by the development of differential GPS (DGPS) systems, especially wide-area DGPS (WADGPS). It is possible that SA will become an anachronism exactly when it could be the most useful. Any decision regarding the utility of SA today must examine the likelihood that WADGPS will exist in the future.

Acronyms and Abbreviations

AAM	Air-to-Air Missile
AMRAAM	Advanced Medium-Range Air-to-Air Missile
ASCM	Anti-Ship Cruise Missile
AWACS	Airborne Warning and Control System
CEP	Circular Error Probable
CoCOM	Coordinating Committee on Multi-Lateral Export Controls
CONUS	Continental United States
CRPA	Controlled Radiation Pattern Antenna
CW	Chemical Weapons
DCW	Digital Chart of the World
DGCM	DGPS-guided Cruise Missile
DGPS	Differential GPS
DoD	Department of Defense
DoT	Department of Transportation
EOS	Earth Observing System
ERP	Effective Radiated Power
EW	Electronic Warfare
FSU	Former Soviet Union
GCM	GPS-guided Cruise Missile
GIS	Geographic Information System
GLONASS	Russian Global Navigation Satellite System
GNSS	Civilian Global Navigation Satellite System
GPS	Global Positioning System
HE	High Explosives
IFF	Identify Friend or Foe
INS	Inertial Navigation System
IR	Infra-Red
IRST	Infra-Red Search and Track
J/S	Jammer-to-Signal Ratio
LACM	Land-Attack Cruise Missile
LDC	Less-Developed Country
LDGPS	Local DGPS
LOS	Line-of-Sight
MTCR	Missile Technology Control Regime

NAVSTAR	Navigation Satellite with Timing and Ranging
OTA	Office of Technology Assessment
P-A	Power-Aperture Product
PPS	Precise Positioning Service
PRC	People's Republic of China
PRF	Pulse Repetition Frequency
RPV	Remotely Piloted Vehicle
S/N	Signal-to-Noise Ratio
SA	Selective Availability
SAM	Surface-to-Air Missile
SCV	Sub-Clutter Visibility
SPS	Standard Positioning Service
SSPK	Single-Shot Probability-of-Kill
TBM	Theatre Battle Management
TED	Terrain Elevation Data
TERCOM	Terrain-Contour Matching
UAV	Unmanned Aerial Vehicle
USGS	United States Geological Survey
VOD	Vertical Onstruction Data
VPE	Vertical Positioning Error
WADGPS	Wide –Area DGPS

1. INTRODUCTION

Although the Global Positioning System (GPS) was designed primarily to provide accurate position, velocity, and time information to the U.S. military, civilian use of GPS "has been an implicit consideration since its inception." [1] In 1983 President Reagan spurred by the Korean Airlines Flight 007 disaster--explicitly ordered the U.S. Department of Defense to make GPS available for international civilian use through the Department of Transportation. In the decade that has passed since that announcement, the number of civilian users has grown so rapidly that it now exceeds the number of military users.[2] The U.S. government predicts that by the year 2003, the number of civilian GPS users will be 51 times greater than the number of military users.[3]

The growing popularity of GPS has, in turn, pushed the rapid development of a commercial sector based on GPS-related technologies. For example, one consulting firm determined that sales of GPS hardware rose from $20 million in 1989 to $121 million in 1992.[4] Other industry watchers have predicted that by 1996, the GPS market will generate $6 billion in commercial and military sales (the vast majority of which would be to the civilian sector).[5] The following charts demonstrate the extraordinary rate of growth of the commercial GPS industry.[6]

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[1]Joint DoD/DoT Task Force, The *Global Positioning System: Management and Operation of a Dual Use System* (Washington, D.C.: Department of Defense (DoD)/Department of Transportation (DoT), December 1993). p. 1.

[2]The estimated number of military users is 17,000; the estimated number of civilian users is about *24,000*. The figures are taken from Department of Defense and Department of Transportation, *1992 Federal Radionavigation Plan* (Washington, D.C.: Department of Defense and Department of Transportation, 1992), p. 3-41.

[3]lbid., p. 3-41.

[4]"Finding the Future," *The Economist,* November 6, *1993, p.* 115. Given the fact that receiver prices fell by two-thirds during the same period, that implies a growth in sales of 1800 percent!

[5]Hale Montgomery, "Molding a National Technology Policy," *GPS World,* January 1993, p. 19.

[6]"Finding the Future," p. 115.

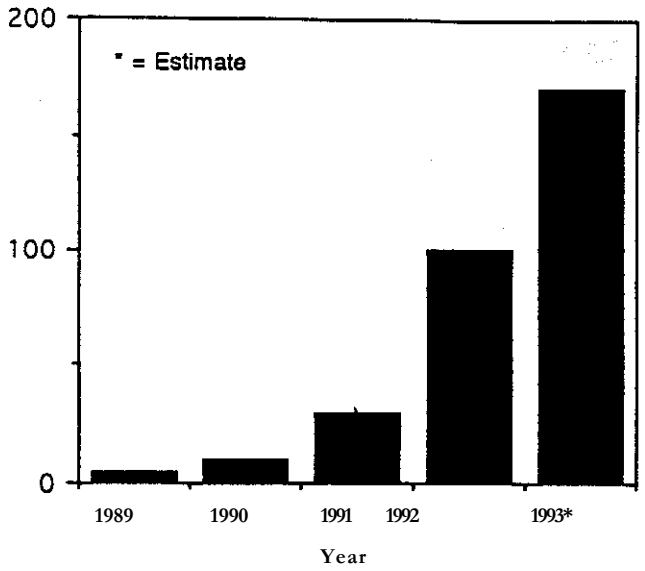

Figure 1.GPS Receiver Sales

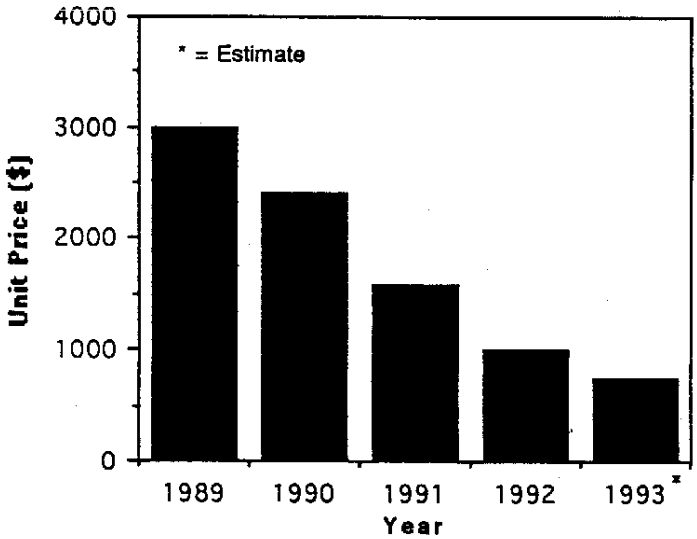

Figure 2. GPS Receiver Prices

One consequence of the growth of the commercial GPS industry is that the civilian sector has eclipsed the military sector in technological sophistication as well as sheer size. As a result, the DoD "is now able to purchase commercial GPS receivers that are not only less expensive than military versions, but also may surpass the military receivers technologically."[7] Another benefit of the growth in sales of GPS equipment is an increase in the number of GPS-related jobs. For example,

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[7]Lisa Burgess and Neil Munro, "New Uses for GPS Challenge Pentagon." *Defense News* , Vol. 8, No. 47 (November 29-December 5), 1993, p.8.

Commerce Secretary Ronald Brown has stated, "By the end of this decade, as many as 100,000 Americans will be working in what will be a $5 billion industry." [8]

It is evident that the growing popularity of GPS throughout the world provides economic and technological benefits to the United States. Unfortunately, another consequence of the growing availability of GPS equipment is the increasing likelihood that other nations will use GPS for military purposes. Industry and defense sources have confirmed that "commercial GPS technology is being bought by militaries worldwide." [9] The Department of Defense is understandably concerned that some nations could use GPS to improve the accuracy of weapons they might use against U.S. forces. [10]

There are some indications that the DoD has cause for concern. Pentagon intelligence officials have stated that "military researchers in China, Iran, and India are working to include U.S.-developed navigation technology [i.e., GPS] into their next-generation missiles."[11] Military officials are also worried about enemies (whether nations or terrorist groups) placing GPS receivers on inexpensive platforms such as recreational aircraft, thereby creating inexpensive, albeit accurate, cruise missiles that are often referred to as "poor man's cruise missiles."

In sum, the tremendous popularity of GPS is providing the United States with both obvious economic benefits and potential military risks. In order to determine an appropriate policy regarding GPS, policymakers must be given as much information as possible about the benefits and costs associated with the growing popularity of GPS. While the potential economic benefits have been estimated by a variety of groups, there has not yet been a systematic technical assessment of the military risks associated with the spread of GPS. This paper addresses the latter issue by examining the nature and magnitude of the threat posed to U.S. security by GPS-guided cruise missiles (GCMs). The policy implications of the assessments performed herein are discussed in the author's doctoral dissertation, *The Global Positioning System: Managing the Tensions Between Defense Needs and Civilian Applications.*

There are a variety of ways in which GPS could be used to augment the military capabilities of opposing forces; the topic of cruise missile guidance was chosen for two reasons. First, cruise missiles are a major concern of the defense establishment. For example, "a new report on missile proliferation currently being circulated among senior U.S. Defense Dept. officials indicates that low-flying cruise missiles are becoming the No.

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[8]Hale Montgomery, "The Winds of Change in Washington," *GPS World,* January 1994, p. 16.

[9]Burgess and Munro, "New Uses," p. 10.

[10]See, for example, Lisa Burgess and Neil Munro, "Pentagon Fears Loss of GPS Control," *Defense News,* Vol. 8, No. 30 (August 2-8, 1993), p. 8, and Burgess and Munro, "New Uses." pp. 8-10.

[11]Burgess and Munro. "Pentagon Fears," p. 10.

1 proliferation threat."[12] Second, GPS is the key that may allow developing nations to open the door which has remained closed to them for years: cruise missile guidance.[13] Military officials repeatedly refer to the potential threat of GCMs as being one of the most significant consequences of GPS availability throughout the world. For example, a recent article in *Defense News* referred to the use of GPS for cruise missile guidance five separate times; other potential uses of GPS by enemy forces were mentioned twice. [14] Other articles show the same pattern.

An assessment of the military threat posed by GCMs must take several factors into account:

> If one postulates a situation where the attack is feasible (i.e., the platform is available, the [cruise missile] has sufficient range, and the launch conditions are suitable), the outcome of a given attack will depend on the reliability, survivability, and lethality of the individual missiles and the number of missiles delivered. [15]

The probability that a given GCM will succeed in its mission can expressed as follows:[16]

$$P_S = P_{Re1} \times P_{Surv} \times P_{Leth} \qquad (1)$$

where,

P_S = Probability of success,

P_{Re1} = Probability that missile is reliable,

P_{Surv} = Probability that missile survives countermeasures, and

P_{Leth} = Probability that missile destroys or disables a target.[17]

I begin by performing a detailed, quantitative analysis of the lethality (P_{Leth}) of GCMs. That analysis requires an examination of several factors, including the missiles' accuracy, range, and payload. The probability of kill (P_k) for individual cruise missiles is determined, as is the number of GCMs which are required to achieve a desired probability of destruction against both soft and reinforced targets. Both area and point targets are examined. The paper then provides an in-depth discussion of the survivability (P_{Surv}) of GCMs against two U.S. countermeasures: electronic jamming and cruise missile interception. Both airborne and ground-based capabilities are examined. The issue of

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[12]"Cruise Missiles Becoming Top Proliferation Threat," *Aviation Week & Space Technology,* February 1, 1993, p. 26.

[13]See Section 1.3.

[14]Burgess and Munro, "New Uses," pp. 8-10.

[15]Edward R. Harshberger, *Long Range Conventional Missiles: Issues for Near-Term Development,* RAND Note N-3328-RGSD (Santa Monica, Calif.: RAND Graduate School, 1991), p. 92.

[16]1bid., p. 93

[17] PLeth will be referred to as Pk or SSPK (single-shot probability of kill) throughout the remainder of the paper.

GCM reliability (PR_el) is not analyzed in this paper. The reader should remember that the findings presented herein do not take that issue into account.

Two additional points must be stated. First, the analyses herein focus solely on cruise missile attacks against U.S. forces outside of U.S. borders. The paper does not consider attacks against the continental United States (CONUS) for several reasons. First, the likelihood of a GCM attack on the CONUS is remote given the range and payload limits of Third World cruise missiles and the likely response of the United States. Second, given its present capabilities, it is highly unlikely that the United States would be able to either detect such an attack or defend against it. Improving those capabilities would be extremely costly.[18] Third, cruise missile attacks against the CONUS are a risk without GPS. The real benefit of GPS is high accuracy; attacks against a city could be performed with cruise missiles using inertial navigation. In sum, "**A state that badly wanted to wreak destruction on a U.S. city could probably do so, whether it had advanced delivery systems or not (and whether the United States had effective antiaircraft or antimissile defenses or not) [emphasis in original]**."[19]

Second, the analysis is limited to land-attack cruise missiles (LACMs); that is, cruise missiles which attack land-based targets. I focus on LACMs because they are the type of cruise missile that could gain the most from GPS guidance. Anti-ship cruise missiles (ASCMs), the most common type of cruise missiles, are already possessed by more than 70 countries and are exported by most developed nations, including the United States, without compunction.[20]

1.1 GPS: A BRIEF DESCRIPTION

The NAVSTAR (Navigation System using Timing and Ranging) global positioning system consists of 21 satellites, plus 3 spares, in high-altitude (11,000 miles) orbits around the earth. These satellites allow anyone with a receiver to determine his/her position (latitude, longitude, and altitude) on the earth with a horizontal accuracy of 15 to 100 meters ($2d_{rms}$).[21] GPS can also provide accurate measurements of velocity down to 0.1 knots. The system is operational 24 hours a day and provides global coverage.

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[18]See William P. Delaney, "Air Defense of the United States: Strategic Missions and Modem Technology," *International Security,* Vol. 15, No.1 (Summer 1990), pp. 181-211.

[19]U-S. Congress, Office of Technology Assessment (OTA), *Proliferation of Weapons of Mass Destruction: Assessing the Risks,* OTA-ISC-559 (Washington, D.C.: U.S. Government Printing Office, August 1993), p. 69.

[20]Seth W. Carus, *Cruise Missile Proliferation* in *the* 1990s (Westport, Conn.: Praeger, 1992), p. 14.

[21]The $2d_{rms}$ measure corresponds to approximately a 95-98 percent probability, depending on one's assumptions about the distribution of the position errors. The 95 percent probability for vertical accuracy can also be expressed as a 2σ probability. The vertical position error of the system is larger than the horizontal because of the geometry of the satellites.

The idea behind GPS is not new: "the GPS system works by timing how long it takes a radio signal to reach us from a satellite and then calculating the distance from that time."[22] The real innovation of the system lies in its accuracy and accessibility. Because the time it takes for a signal to reach a receiver is measured in nanoseconds (10^{-9} seconds), time must be known with a very high degree of precision. Each satellite carries four atomic clocks to ensure that its time-keeping is precise. There is no way that each GPS receiver could be equipped with atomic clocks (they cost about $100,000 each). The system gets around this problem by using four satellite signals instead of three which allows the receiver to eliminate any timing offsets as long as they are linear.[23] In order to make accurate measurements in this way, the receiver needs to be well-synchronized with the satellites. The receiver does this by generating its own timing signals and determining the difference in phase between its code and the codes received from the satellites.[24]

The GPS satellites actually transmit two different codes; the Precision or P-code and the Coarse/Acquisition or C/A code.[25] The P-code is designed for military users. It is more accurate than the civilian code and is more difficult to acquire and jam. The C/A code is designed for use by non-military users. It is less accurate than the P-code, easier to acquire, and easier to jam than the P-code. To ensure that unauthorized users do not acquire the P-code, the United States has recently implemented an encryption segment on it. The new code, designated the Y-code, will now be available only to users with the correct deciphering chips.

In ideal conditions, GPS has an accuracy of approximately 15 meters with the Pcode and 30 meters with the CIA code. Fearing that the level of accuracy associated with the C/A code could threaten U.S. national security interests, the DoD included a feature in the GPS system called Selective Availability (SA) which introduces an artificial error into the CIA code. Authorized receivers have chips that can adjust for the artificial error, but most civilian receivers do not. The resulting signal that is available to the civilian community is known as the Standard Positioning Service or SPS. The SPS provides user with accuracies of about 100 meters ($2d_{rms}$) horizontally and 140 meters (95%) vertically.[26] The U.S. government promised that the SPS would become available

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[22]Jeff Hum, *GPS: A Guide to the Next Utility* (Sunnyvale, CA: Trimble Navigation, 1989), p. 18.

[23]A good explanation of why. four imperfect signals yield the same result as three perfect signals is given in Hum, pp. 25-30, footnote 11. It is also possible to utilize the signals from only three satellites if one has a very accurate clock in the receiver.

[24]The satellite signals are transmitted through the use of direct-sequence pseudo-random binary codes. See J. J. Spilker, "GPS Signal Structure and Performance Characteristics," *Global Positioning System,* Vol. 1, (Washington, D.C.: Institute of Navigation, 1980).

[25]The P-code is a week-long pseudo-random number sequence (approximately 6 x 10^{12} bits long) with a bandwidth of 10..23 MHz. The CIA code is 10.23-bit Gold Code with a bandwidth of 1.023 MHz.

[26]The specifications are taken from the *1992 Federal Radionavigation Plan,* p. A-38.

beginning in 1993, "on a continuous, worldwide basis with no direct user charges for a minimum of ten years."[27] The signal that is available to authorized foreign and military users-the encrypted P-Code-is known as the Precise Positioning Service or PPS. It provides users with accuracies of 21 meters ($2d_{rms}$) horizontally and 29 meters (95%) vertically.[28]

1.2 DIFFERENTIAL GPS

Differential GPS (DGPS) is a method of operating GPS which allows the user to obtain extremely high accuracies while circumventing the effects of SA. The concept behind DGPS is simple. A receiver is placed at a surveyed location (i.e., a location whose position is known precisely). The GPS signals which arrive at that location contain errors which offset the position of the surveyed point by some amount. The errors in the GPS signal are determined by comparing the site's known position with its position according to GPS. Correction terms can then be calculated and passed on to the user. Those correction terms allow the user to eliminate many of the errors in the GPS signal. [29]

Because SA works by introducing artificial errors into the satellite signal (the satellite clock signal is "dithered" and the position of the satellites is misrepresented), DGPS is very successful at canceling out most of the SA degradation. The accuracy of DGPS positioning varies, depending on the user's range from the ground station, the timeliness of the corrections, the geometry of the satellites, and the user's equipment. However, most sources report accuracies in the 1-5 meter (1σ) range, which corresponds to 3-14 meters (2drms) [30] In this paper, I assume that cruise missiles using DGPS will have an accuracy of 10 meters (2drms).

Despite its benefits, DGPS techniques do have some limitations: both the user and the DGPS reference receiver must be looking at the same set of satellites; the accuracy of the correction signals decreases with distance from the reference location; corrections are limited in range; and the up-link correcting signals can be easy to jam. These problems, especially the latter two, could prove to be serious impediments for using DGPS in a military arena The susceptibility of DGPS signals to jamming will be difficult to overcome

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[27]1992 Federal Radionavigation Plan, p. 3-43.

[28]Ibid.

[29]All bias errors are eliminated. The remaining errors vary randomly and therefore cannot be corrected in this manner. Fortunately, the random errors contribute little to a users position uncertainty; that is why DGPS signals are so accurate.

[30]See, for example, W. Hundley, et al., "Flight Evaluation of a Basic GA-Code Differential GPS Landing System for Category I Precision Approach," Navigation: Journal of the Institute of Navigation, Vol. 40, No. 2 (Summer 1993), pp. 161-178.

because commercial DGPS transmissions must comply with international standards for both frequency and data rate.[31]

One way around the line-of-sight limits of DGPS corrections is to use low-frequency transmissions which "bounce" off the ionosphere. According to the U.S. government, "Coverage provided by local area differential GPS (LDGPS) can vary from a few miles to about 150 miles [240 km], depending on the transmission media selected."[32] Other sources quote ranges between 100 km and 500 km for DGPS services over land.[33] Because of this range limit, medium- to long-range cruise missiles utilizing DGPS will have to fly over several DGPS stations on their mission. Not only is this an expensive solution, it may not prove useful if a cruise missile's target is beyond the range of the last reference site. For example, if a target lies 300 km inside another nation's border, the corrections provided by a DGPS station at the border will not be applicable when the missile arrives at the target.

A new solution to the range limits facing DGPS has been developed by several companies, such as John E. Chance Inc. and Inmarsat. The solution adopted by these providers is known as wide-area DGPS (WADGPS). Wide-area DGPS is similar to local DGPS except that many local stations collect the differential corrections and then send corrections to a central facility which uplinks them with satellites. The satellites can then broadcast those corrections to paying users who are within the area of coverage. Because users are receiving their corrections from satellites rather than from ground stations, they can travel long distances (e.g., across continents) without ever losing DGPS guidance. The implications of Third World access to WADGPS are discussed later in this paper.

1.3 GPS AND CRUISE MISSILE GUIDANCE

The reason GPS can have such a significant impact on cruise missile proliferation concerns the inherent limits of inertial navigation systems (INSs).[34] Although INS packages are commercially available and have the advantage of being jam-proof, they have one major drawback: physical forces (e.g., variations in gravity) affect the gyroscopes and accelerometers used in inertial navigation systems and create errors which accumulate over time.

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[31]Mchard B. Langley, "Communication Links for DGPS," *GPS World,* May 1993, pp. 47-51.

[32]Joint DoD/DoT Task Force, *The Global Positioning System,* p. 31.

[33]The 100 km figure is courtesy of Groundfire Communications Inc. Although their system uses low frequency (1.6-2.5 MHz) signals, the range of their equipment is limited at high latitudes (e.g., above 50 degrees) by ionospheric disturbances. The 500 km figure is taken from V. Ashkenazi, et al., "Wide-Area Differential GPS: A Performance Study; *Navigation: Journal of the* Institute *of* Navigation, Vol. 40, No. 3 (Fall 1993), pp. 297-319.

[34]An inertial navigation system consists of gyroscopes, accelerometers, and some type of processor.

Traditionally, the navigation errors due to inertial drift have been large enough to undermine the military utility of INSs for all but short range missions. Even the United States, which possesses the most advanced INSs in the world, had to develop the terrain contour matching system (TERCOM) to update the inertial guidance systems on its Tomahawk cruise missiles.[35] However, the last decade has seen tremendous growth in inertial navigation technologies. Despite the advances in the field, several obstacles exist which have made Third World acquisition of high-quality INSs difficult. The biggest obstacle is that high accuracy gyroscopes, accelerometers, and INSs themselves are export-controlled by the Coordinating Committee on Multilateral Export Controls (CoCOM) and the Missile Technology Control Regime (MTCR). For example, the CoCOM limits gyroscopes to drift rates of 0.1 deg/hr (at linear accelerations of less than 10 g) and INSs to navigation errors of 0.8 nmi/hr (CEP). [36]

Figure 3 shows CEP as a function of inertial drift for the three inertial navigation systems under study and compares these accuracies with the accuracy afforded by the SPS. [37] The drift error of the 10 deg/hr INS surpasses the position error of the SPS almost immediately. For the 1 deg/hr INS, the drift error surpasses the GPS error in approximately two minutes. For the 0.1 deg/hr INS, the two errors are equal after ten minutes. In assessing the availability of these systems, note that the 10 deg/hr INS is an extremely low quality system: a less-developed country (LDC) will almost certainly be able to do better. The 1 deg/hr INS is approximately equivalent to systems which are used on commercial aircraft. The 0.1 deg/hr INS is a high quality system which falls under export restrictions.

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[35]The chances that an LDC could develop a terrain-matching guidance system are remote. To begin with, terrain matching technologies are export controlled. In addition, the technical complexity and massive infrastructure required to use a TERCOM-like system are daunting. See Harshberger, pp. 46-52.

[36]*Code of Federal Regulations,* Vol. 15, Ch. VII, Part 799, Section 799.1, Item 7A03A. The CEP (circular error probable) of a weapon or vehicle is a measure of horizontal accuracy which expresses the radius within which an object will be 50 percent of the time. For example, if 100 missiles with a CEP of 30 m were launched at a target. 50 of those missiles would land within 30 m of the target.

[37]The graph is based on an inertial navigation model found in Harshberger, p. 121. Although the model expresses its navigation errors in deg/hr rather than nmi/hr, the model does include the errors due to both gyroscopes and accelerometers. An excellent discussion of all the errors which have to be included in such a model is given in Morris M. Kuritsky and Murray S. Goldstein, "Inertial Navigation," *Proceedings of the IEEE*, Vol. 71, No. 10 (October 1983). pp. 1156-1176.

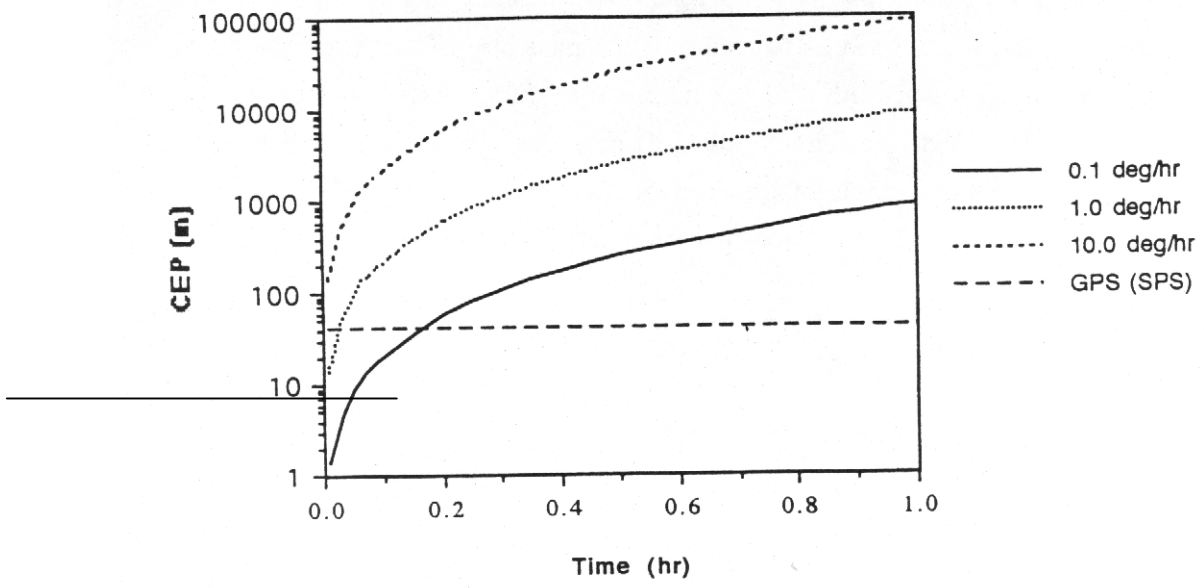

Figure 3. Navigation errors for inertial navigation systems and GPS.

Clearly, cruise missiles traveling for longer than a few minutes would be much more accurate if they used GPS for cruise missile guidance rather than inertial navigation. The simplest and most inexpensive strategy would be to utilize a GPS receiver as the sole source of navigation information (i.e., position and velocity). However, this approach has one major disadvantage: if a GCM using GPS for navigation is jammed, it will lose all guidance. This vulnerability to jamming virtually obviates the military utility of such a guidance system. The most natural strategy a developing nation could adopt-and certainly the most effective-would be to integrate a GPS receiver with an inertial navigation system.[38]

[38] There are many other advantages inherent in the synergism of GPS and INS guidance. See, for example, Duncan B. Cox, Jr., "Integration of GPS with Inertial Navigation Systems," *Global Positioning System,* Vol. 1 (Washington, D.C.: Institute of Navigatiin, 1980)

2. CRUISE MISSILE LETHALITY

Lethality is defined as the ability of a weapon to destroy a given target. The lethality of a cruise missile will depend on four things: the missile's effective accuracy, the size and type of the missile's warhead, and the nature (i.e., hardness) of the target. In order to calculate a GCM's effective accuracy one must consider several factors; notably, a missile's navigation accuracy, the angle of its terminal dive, and its targeting errors.[40] In sum, the effective accuracy of a GCM, which will be expressed as CEP_{eff}, is given by the following equation:

$$CEP_{eff} = \sqrt{CEP^2 + R_t^2 + R_d^2} \qquad (2)$$

where,

CEP = a cruise missile's navigation accuracy,
R_t = the targeting error, and
R_d = the error due to a cruise missile's terminal dive.[41]

This paper examines three types of warheads: conventional munitions, chemical weapons, and nuclear weapons. When studying conventional munitions, I assume that Third World cruise missiles carry standard high explosive (HE) warheads (e.g., TNT). Fragmentation warheads and sub-munitions are not analyzed.[42] The analysis also does not take into account the kinetic energy of the cruise missiles themselves.

The hardness of targets is usually defined in terms of the peak overpressure they can withstand, for example: "A 40 psi [pounds per square inch] blast would completely demolish a typical unreinforced building, but it might be unable to destroy a properly hardened, above-ground bunker. Other types of targets, such as radars, trucks, and missile launchers are much 'softer' and would be likely to suffer heavy damage from only

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[40] The targeting errors are crucial because terminal guidance is extremely difficult to accomplish for LACMs. Thus, GPS guidance must be used for both mid-course and terminal stages of flight. If effective terminal seekers were available to LDCs, then GPS guidance could be used to get a cruise missile to a specific area, at which point a terminal seeker would guide the cruise missile to its target. An excellent discussion of terminal guidance technologies is presented in Harshberger, *Long-Range Conventional Missiles*, pp. 106-109.

[41]Technically, Rd, which depends on a missile's vertical position accuracy as well as the dive angle, should be expressed as a radius to be root-sum-squared with the other errors: however, the errors due to a cruise missile's terminal dive will only appear in the down-range direction. Hence, including those errors will cause the error footprint of a GCM to be more elliptical than circular. That effect will be ignored in these calculations.

[42].4n excellent analysis of the damage sub-munitions can cause to military assets is presented in Benoit Morel and Theodore A. Postol, "A Technical Assessment of the Soviet TBM Threat to NATO," in Donald L. Hafner and John Roper; eds., *ATBMs and Western Security* (Cambridge; Mass.: Ballinger, 1988). For a discussion of technical challenges involved with dispensing sub-munitions, see Harshberger, pp. 111-113.

5 or 10 psi of blast."[43] This analysis is limited to "soft targets", which can be destroyed by 10 psi, and "reinforced targets which can be destroyed by 40 psi. "Hardened targets" are not examined because the blast overpressures required to destroy them are on the order of hundreds or even thousands of psi, and the likelihood that Third World cruise missiles would be able to destroy such targets is extremely remote.

A useful measure for quantifying the lethality of a weapon is its probability of kill (P_k). One can determine the probability of kill that a cruise missile of a given CEP has against a given target using the following formula:[44]

$$P_k = 1 - 0.5^{\left(\frac{R_L}{CEP_{eff}}\right)^2} \qquad (3)$$

where,

R_L = the range at which the effects of the weapon either destroy the target or render it unable to function in a useful way.

The values for R_L which are used in this paper were taken from a report released by the Defense Nuclear Agency.[45] They are reproduced in the table below:

Table 1. Lethal Radii (m) for Various Payloads and Targets

Amount of HE (kg)	Soft Targets (10 psi)	Reinforced Targets (40 psi)
400	40	17
125	32	13
50	23	10

It is important to note that the amount of high explosives carried by a cruise missile is not equivalent to the payload carried by that missile. Typically, 50-75% of a cruise missile's payload is taken up by the metal casing surrounding an HE warhead. Thus, 400 kg of HE would have to be carried by a cruise missile with a payload of 800-1600 kilograms. The relationship between P_k and R_L, assuming a warhead carrying 400 kg of HE is used, is shown in Figure 4.

[43]Morel and Postol, "A Technical Assessment," p. 98.

[44]Ibid., p. 103.

[45]*Evaluations of Collateral Damage* (La Jolla, Calif.: Science Applications Inc., 1976).

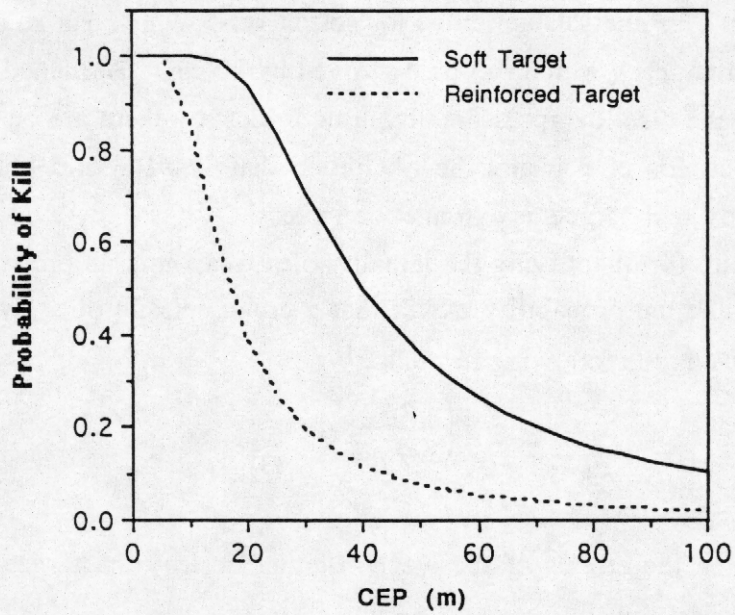

Figure 4. Probability of kill vs. CEP for Soft and Reinforced Targets.

2.1 ACCURACY

As stated previously, the effective accuracy of a GPS-guided cruise missile depends primarily on three things: the navigation errors of the cruise missile, its dive angle, and the precision with which a target's location is known. Navigation errors can be divided into two components: horizontal and vertical position errors. Table 2 lists the navigation errors associated with GPS.[46] The next section examines the errors associated with a missile's terminal dive.

[46]The 2drms values were taken from the sources indicated in Table 2. The CEP and 50% values were calculated from the 2drms estimates. 2drms is a common measure of accuracy in navigation applications. It is equal to 2.8a or about 2.4(CEP), assuming a Gaussian distribution. In other words, a missile with a 2drms accuracy of 100 meters will have errors which are less than 100 meters in magnitude approximately 95 percent of the time. For more details, see Richard S. Burington and Donald C. May, Jr., *Handbook of Probability and Statistics with Tables* (New York: McGraw-Hill, 1970).

Table 2. Navigation Accuracy (meters) Using GPS

	SA on[a]	SA off[b]	P-Code[a]	DGPS[C]
Horizontal ($2d_{rms}$)	100	36	21	10
Vertical ($2d_{rms}$)	140	50	29	14
Horizontal (CEP)	42	15	9	4
Vertical (50%)	45	16	9	4

a=*1992 Federal Radionavigation Plan*
b = Logsdon, Tom, *The NAVSTAR Global Positioning System* (New York: Van Nostrand Reinhold, 1992).
c = Estimated from literature.

The vertical position uncertainties associated with the SPS can be quite large. Large uncertainties in the vertical position of GCMs will force those missiles to fly at higher altitudes in order to avoid the possibility of flying into either natural or man-made objects. For example, a GCM using the SPS will have to fly at least 140 m over terrain to be 98 percent confident that it will not crash into that terrain. In order to minimize their altitude, GCMs will have to obtain accurate vertical position information. One way to do that is to use DGPS for guidance. Another option is for LDCs to purchase radar altimeters. Radar altimeters are available in two classes: those used for commercial aviation, and those used for general aviation. In the former case, the altimeters are extremely precise-typical errors are within 3 meters-and also extremely expensive; $15,000 is a common price. Radar altimeters used for general aviation are cheaper-$1,500-2000-but also less accurate; typical errors range from 30 to 60 meters. Both kinds of radar altimeters can have reduced accuracies over rough terrain.

2.1.1 Terminal Dive Errors

Cruise missiles can attack their targets in one of two ways; they can either fly directly into a target or they can perform a terminal dive into a target. [47] The former approach requires a cruise missile to know its vertical position with a high degree of accuracy, otherwise it runs the risk of either flying over its target or flying into the ground. A less risky strategy is for a cruise missile to dive towards its target. In that case, a GCM's targeting error will depend both on the magnitude of that missile's vertical position uncertainty and on the angle of the missile's dive. If a cruise missile performs a near-vertical dive towards a target, the down-range miss distance due to vertical position errors

[47] I am grateful to Dr. Eric Arnett for suggeting that I examine the terminal dive issue.

(VPEs) will be negligible. However, as a cruise missile dive approaches the horizontal axis, the miss distance will become significant. Table 3 illustrates the down-range errors associated with GCMs performing 20-60° dives. In future calculations it shall be assumed that GCMs perform terminal dives at 45° angles.

Table 3. Error Budget (meters) for A GPS-Guided Cruise Missile

	SA on	SA off	P-Code	DGPS
Hot. Error (CEP)	42	15	9	4
Vert. Error (50%)	45	16	9	4
Miss Distance 20-60° Dive	27-129	10-47	6-27	3-14

There are two ways to minimize these errors: either cruise missiles can perform a near-vertical dive, or they need to obtain accurate vertical position data. An analysis of the former method indicated that it is not likely to be used.[48] There are two problems in performing vertical dives. First, cruise missiles can require a large amount of space in order to roll over into a steep dive. For example, the minimum altitude required for a Tomahawk-like cruise missile traveling at 800 kph to roll over into a vertical dive is approximately 1250 meters. A cruise missile flying at that altitude would be an easy target for air defense systems. The other drawback is that a cruise missile performing a vertical dive would gather a great deal of velocity.[49] If a cruise missile which was designed for sub-sonic velocities became supersonic, it could easily lose its control surfaces (e.g., fins and wings) and begin tumbling. This occurrence would greatly decrease the accuracy of the cruise missile.

A better option for an LDC would be to obtain accurate vertical position information for its cruise missiles using the methods described above. Table 4 compares miss distances for cruise missiles using radar altimeters with miss distances for cruise missiles using GPS guidance only.

[48]Details of these calculations are available from the author. Much of the information on this topic was provided by Dan Raymer of the RAND Corporation.

[49]A cruise missile diving from a height of t250 meters would add almost 600 kph to its nominal velocity. Thus, any cruise missile (lying faster than 594 kph before the dive would achieve supersonic velocities during its dive.

Table 4. Down-Range Errors (50% meters) Due to VPE				
	SA on	SA off	P-Code	DGPS
No Alt. 20-60° Dive	27-129	10-47	6-27	3-14
Low Qual. Alt. 20-60° Dive	17-144	17-144	17-144	17-144
High Qual. Alt. 20-60° Dive	2-8	2-8	2-8	2-8

The best accuracies are obtained when a high-quality altimeter is used. A GCM using DGPS for its vertical positioning will not do much worse. The low-quality altimeter leads to the largest down-range errors of all three cases; however, its use will allow GCMs to fly much lower than those using the SPS. It appears that the best strategy for a GCM would be for it to use a high-quality altimeter throughout its flight. Another benefit of this arrangement is that altimeters cannot be jammed. Hence, accurate vertical position information will be available throughout the flight of a GCM. In fact, it would be prudent for GCMs to carry at least a low-quality altimeter in case these missiles are jammed.[50] Thus, there seem to be two prudent options available to developing nations. If they can afford to place high-quality altimeters on their cruise missiles, they should probably do so. Otherwise, their best strategy would be to use GPS, especially DGPS, for vertical positioning, while carrying low-quality altimeters as backups in case GPS guidance is lost.

2.1.2 Targeting

An important issue which needs to be addressed is the problem of targeting. The most accurate cruise missile in the world would be militarily useless if one did not know where to aim it. The errors associated with a target's position must be combined with the guidance errors of a cruise missile in order to determine the weapon's true accuracy vis-a-vis a given target. For example, suppose the position of a command post were known to within 75 meters (lσ) in the horizontal plane; a cruise missile with a horizontal position error of 50 m (lσ) would have a total error of 90 meters (lσ) with respect to that target.

The three best, and possibly only, sources of targeting data open to LDCs are remote sensing images, commercially available maps, and GPS receivers themselves. The utility of each source depends to a great extent on the goals of a particular customer. For

[50]If a GCM is electronically jammed, it will lose GPS guidance in both vertical and horizontal planes. Although an inertial navigation system could provide information on the GCM's horizontal position, an altimeter would be needed to provide vertical position data.

some applications (e.g., targeting military targets), accurate location information is crucial. On the other hand, if a user wishes simply to strike somewhere in a populated section of a major city, then high accuracy may be less important that convenience, accessibility, and/or cost.

2.1.2.1 Remote Sensing

At the present time, only six countries-the United States, the former Soviet Union (FSU), France, the People's Republic of China (PRC), India, and Japan-have launched and are operating earth remote-sensing satellite systems.[51] However, several of these nations, notably the United States, the FSU, and France, sell satellite images on the open market. Thus, any nation (or person, for that matter) can obtain access to information provided by remote sensing images.

In this section, I examine the targeting capabilities that a Third World nation is likely to obtain from access to such images. Satellites have several physical characteristics which determine the utility of their images for targeting: the resolution of their cameras, the revisit period of the satellites, and the correlation accuracy of the system. The resolution of a camera or image can be defined as, "the area on the ground that a single pixel (a light-sensitive picture element) sees at any given instant."[52] The smaller the resolution of an image, the more detail one can see. The revisit period is the time it takes for a satellite to pass over the same area on the earth's surface. The shorter the revisit time, the more frequently one can obtain images of a given area. Table 5 shows the resolution and revisit times for existing remote-sensing systems. [53]

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[51]Future systems are planned by four other nations--Argentina, Brazil, Canada, and Israel-as well as the European Space Agency. Mary Umberger, "Commercial Observation Satellite Capabilities." in Michael Krepon, et al., eds., *Commercial Observation Satellites and International Security* (New York: St. Martin's Press, 1990). p. 10.

[52]Ibid., p. 9.

[53]The table is based on information presented in Umberger, "Commercial Observation," p. 11.

Table 5.	Characteristics of Commercial Remote Sensing			Satellites
Satellite (country)	Launch Date	Resolution (meters)	Revisit Cycle (days)	Number of Channels
Radarsat (Canada)	1992	15-30	3	1
ERS-1 (ESA)b	1989	25-30	3	1
SPOT (France)	1986	10-20	5a	4
IRS-1 (India)	1987	36-72	22	4
MOS-1 (Japan)	1987	50	17	4
JERS-1 (Japan)	1991	25	not available	7 (and radar)
KFA-1000) (FSU)	early 1980s	6	14	2
Landsat 4, 5 (USA)	1982, 1984	30-120	16	7
Landsat 6 (USA)	1991	15-120	16	8

[a]The revisit cycle varies as a function of the latitude of the overflown area because the SPOT satellites are in a polar orbit. The value given above is the average revisit time for mid-latitudes according to SPOT Image Corp.
[b]ESA = European Space Agency.

The correlation accuracy of a satellite photograph represents the accuracy with which one can compare two images of the same area Using computer-based correlation techniques, value-added firms can locate and identify objects that would otherwise be beyond the resolution capabilities of a satellite.[54] For example, the following table lists the resolution requirements for five levels of analysis for various targets. [55]

[54]A value-added firm provides services or products which enhance satellite images.

[55]The table is based on material presented in Jeffrey T. Richelson, "Implications for Nations Without Space-Based Intelligence-Collection Capabilities," in Krepon, et al., *Commercial Observation Satellites*, p. 60 and Peter D, Zimmerman, "Introduction," in Ibid., p. 204.

Table 6. Ground Resolution Requirements (meters) for Various Targets[a]					
Target	Detection[b]	General ID[c]	Precise ID[d]	Description[e]	Analysis[f]
Aircraft	5	2	1	0.2	0.05
Airfield Facilities	6	5	3	0.3	0.2
Bridges	6	5	2	1	0.3
Command Headquarters	3	2	1	0.2	0.1
Missile Sites (SAM)	3	2	1	0.3	0.05
Ports & Harbors	30	15	6	3	0.3
Radars	3	1	0.3	0.2	0.02
Railroads	15-30	15	6	2	0.4
Roads	6-9	6	2	0.6	0.4
Rockets & Artillery	1	0.6	0.2	0.05	0.05
Supply Dumps	2-3	0.6	0.3	0.03	0.03
Urban Areas	60	30	3	3	0.8

[a]The source does not specify whether resolution is defined as pixel size or white-dot size, but the table is internally consistent.
[b]Detection = A target of the given type is clearly present but no details are apparent.
[c]General Identification = There is little or no doubt that the target has been properly classified. Class of bridge, number of buildings, etc., can be discerned.
[d]Precise Identification = Discrimination within target type is possible (e.g., the type of plane).
[e]Description = One can observe components of targets.
[f]Technical Analysis = Detailed analysis of equipment (including components) is possible.

Comparing Table 6 with Table 5, it appears as though developing nations would have a difficult time detecting and identifying most targets which might be of military interest. However, target detection can be affected by several other factors, some of which are independent of the physical characteristics of a satellite:

> ... the actual ability to spot objects may be greater with changes in the contrast of light objects against a dark background (or vice versa), and certain ground patterns. The special skills of imagery interpreters, computer enhancement, the use of imagery interpretation keys, and access to collateral information (which may be derived from open sources, clandestine human sources, or SIGINT [signal intelligence]) are additional factors that enhance the ability to extract information from images. [56]

In fact, a series of case studies was sponsored by the Carnegie Endowment to determine what could actually be seen from space using commercial remote-sensing satellites. In the studies, images obtained from SPOT, Landsat, and KFA-1000 satellites were interpreted by professional value-added firms.[57] The following table summarizes the results of the case studies. It shows the level of resolution that was required by image interpretation experts in order to obtain three levels of knowledge (as defined in Table 6) about various targets. The targets listed below correspond to those in Table 6 except for three-ports & harbors, railroads, and urban areas-which were omitted because they would be clearly visible in SPOT and Landsat images. The following quote provides a good introduction to Table 7:

> The case studies that follow are examples in which the interpretation and exploitation of today's commercial remote-sensing satellites has been pushed to the unclassified limit. They illustrate what any nation with a modest intelligence budget and experience gained from interpreting aerial photographs could do. As such, these studies are a clear indication of where widely available satellite images could play roles in modern war and in international relations.[58]

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[56]Richelson. "Implications," p. 59.

[57]Note also that the experts confirmed that the actual resolution of the KFA-1000 was 12 meters, not 6 meters as is advertised.

[58]Zimmerman, "Introduction," p. 203.

Table 7. Imagery Interpretation Results for Various Targets

Target	Detection	General ID	Description
Aircraft	P	P	P
Airfield Facilities	MSS	TM	P
Bridges	MSS/TM	TM/XS	XS/P
Command Headquarters	MSS	TM/P	P
Missile Sites (SAM)	MSS	MSS/TM	P
Radars	P	P	-
Roads	MSS	MSS	TM/XS
Rockets & Artillery	MSS/TM	XS/P	-
Supply Dumps	MSS	P	P

MSS = Landsat multi-spectral scanner; 80-meter resolution
TM = Landsat thematic mapper; 30-meter resolution.
XS = SPOT extended spectrum scanner; 20-meter resolution
P = SPOT panchromatic sensor; 10-meter resolution.

It is evident that all the targets listed above can be readily identified and all but two radars and "rockets & artillery"-can be described in detail. Clearly, a developing nation' could obtain excellent targeting information if it were able to acquire the capabilities outlined above. Hence, the crucial variable in determining how well a Third World nation can detect and identify targets is its accessibility to value-added firms and/or technologies.

Further analysis reveals that it may be possible for developing nations to gain access to such capabilities. Remote sensing interpretation skills are taught at public and private institutions in both the United States and Europe. The same skills are also taught in the Third World. For example, Kenya has trained over 200 technicians to interpret images from Landsat satellites.[59] Egypt has a remote sensing center with advanced data- and imaging-processing facilities capable of processing both Landsat and SPOT images. In addition, the Egyptian facility is known to train citizens of Arab and African nations.[60] Other remote-sensing service and education institutions exist in Vietnam, Bangladesh, Iran,

[59]Louis J. Levy and Susan B. Chodakewitz, 'The Commercialization of Satellite Imagery: Implications for Cross-Border Conflict," *Space Policy,* Vol. 6, No. 3 (August 1990), p. 211.

[60]Ibid., p. 213.

South Korea, and Sri Lanka. Imagery enhancement services are available from over 150 venders in 42 countries. Such services either process the images "in shop" or provide products such as computers, digitizing systems film, mapping systems, and a broad array of software.[61] Thus, dedicated users could process raw satellite data themselves; the software, computers, and maps are all readily available.

It appears that LDCs should be able to identify most targets fairly well; however, that is only half of the battle. Once a target has been identified, its location must be determined. Because cruise missiles without terminal seekers must use GPS throughout their flight, targeting errors become a key component of a GCM's effective accuracy. Thus, a key question for Third World nations, and for this assessment, is: how accurately can targets be located? If satellite images are used, experts believe that it is theoretically possible for LDCs to locate objects to within 1 or 2 pixels.[62] However, there are at least two major obstacles LDCs would have to overcome to achieve such accuracies. First, because each control point has a +/- 0.5 pixel error, several points are required in a good geometric configuration somewhat near the target.[63] The further the control points are from the target, the more points are required. Second, terrain elevation data (TED) is required for transforming a satellite image into latitude/longitude coordinates. If accurate TED is not available, errors on the order of several pixels could be introduced.

If Third World nations cannot obtain their own accurate targeting information from satellite images, they might be able to purchase it. The SPOT Image Corporation has a product called SPOTView™ that provides accurate geo-coded and ortho-corrected images for mapping applications. For images taken of the CONUS, SPOTView™ can provide horizontal position accuracies of 15 meters or better (which corresponds to a 1.5 pixel error for SPOT's panchromatic band). The reason that SPOT can achieve such accuracies over the CONUS is that they use U.S. Geological Survey (USGS) maps to get accurate control points and digital terrain elevation models called DTEDs from the U.S. Defense Mapping Agency (DMA) for accurate terrain elevation contours.

For images outside of the United States, SPOT cannot guarantee a given level of accuracy because that depends on the availability and quality of control points and TED, both of which must be supplied by the client. If that information is not highly accurate, the position accuracy of the SPOTView™ products will be degraded. One way that LDCs

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[61]Umberger, "Commercial Observation," p. 13.

[62]Communication with Frank Pont of Environmental Research Institute of Michigan. The following discussion is based on information obtained in that communication.

[63]A control point is a feature whose location is known with a high degree of accuracy. They often represent easily identified geographical features such as road crossings. Control points are used to "line-up" satellite images with maps or databases.

might be able to obtain accurate control points is by using GPS to survey cites on the ground near a target. In fact, control points based on GPS, which can have accuracies of one to five meters if DGPS is used, can be more accurate than those obtained from maps. On the other hand, the feasibility of actually obtaining control points next to a target is questionable. That is especially true if the targets are U.S. interventionary forces. It is more likely that LDCs would be able to obtain GPS control points for terrorist attacks against civilian targets.

In sum, if LDCs are able to survey several points around a target with a GPS receiver, they will probably be able to obtain targeting errors on the order of 15 meters. As mentioned above, it is unlikely that LDCs would be able to get GPS receivers close enough to U.S. forces to obtain such accuracies. However, U.S. forces might be vulnerable at certain times, such as when they are disembarking at a port. It would not be difficult for an enemy of the United States, whether a nation or a terrorist group, to survey a port before U.S. troops arrived. In general, however, it would be much easier for LDCs to survey control points near a civilian target, such as a government building or a power plant. It is worth noting that if Third World nations could survey points around a target with a GPS receiver, they might be able to simply place a receiver at the target itself; that would provide them with a targeting error of one to five meters. I discuss this option at greater length below.

A more significant obstacle for Third World military planners is that images from high resolution satellites might be unavailable during a conflict. For example, during the Gulf War, SPOT stopped selling its images to commercial customers.[64] While other satellites might continue to sell their images during a war, those satellites could have larger resolutions than those available from SPOT (see Table 5). If that were indeed the case, the targeting errors of GCMs would increase even if several good control points could be obtained. For example, if images were available from India's IRS-1 satellite, then a 1.5 pixel error would result in at least a 54 meter targeting error.

What if Third World mission planners had accurately surveyed the region in which U.S. troops were deployed? While that circumstance would provide LDCs with accurate control points, they would still need photographs showing the location of U.S. assets relative to those points. If high-resolution satellite images were not available, then the location of the U.S. forces would not be known with a high degree of accuracy (assuming aerial photographs could not be taken). In that case, targeting errors would be dominated by the low resolution images of the U.S. troops.

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[64] *Space Business News,* August 20, 1990. USA's Landsat continued to sell its images "as required by public law," but those images had resolutions of 30 m--three times those of SPOT's panchromatic images.

A final problem facing Third World nations is that most satellites take at least two weeks to overfly the same region. Referring to Table 5, one can see that the shortest revisit period listed is three days--a significant period of time during a military conflict. Third World mission planners trying to coordinate an attack against U.S. forces would have to face the possibility that targets could have moved since their last satellite image had been taken. Because satellite image processing can be quite time consuming, it is doubtful that LDCs would be able to obtain near real-time targeting data on their own. Clearly, there are some targets, such as airfields and command bunkers, which are stationary- However, such targets are often hardened and heavily defended precisely because they are not mobile.

2.1.2.2 Maps

Another way developing nations might obtain targeting information is to use maps. While conventional maps are readily available, many do not provide object locations in an absolute coordinate system (i.e., latitude and longitude). They also do not provide accurate elevation contours which are crucial for cruise missile missions. The most useful maps for targeting purposes would be digital charts which could be combined with geographic information systems (GISs) to provide detailed, flexible, computer-based databases. At the present time, the only global map which provides these capabilities is the Digital Chart of the World (DCW). This map is publicly available through the U.S. Geological Survey (USGS) for $200.

The DCW provides a great deal of information. It is organized into 17 thematic layers including political boundaries, coastlines, cities, transportation networks, land cover and elevation contours. The DCW is also easy to use; it can be run on a PC-class computer, and it has user-friendly interfaces. However, the drawback of the DCW is that its level of detail is based on a 1:1,000,000 scale. While this scale is useful for a variety of purposes, it is too coarse to allow targeting of individual buildings or even neighborhoods. Thus, developing nations using the DCW will not be able to obtain the level of resolution which is available from remote sensing images. On the other hand, the DCW could be used in conjunction with satellite images to provide a developing nation with a more complete picture of another nation's infrastructure.

2.1.2.3 GPS

Another option left to Third World nations is to use GPS itself for targeting. A GPS receiver could be used to locate a particular target to within several meters (see section on DGPS). In fact, if surveying techniques are used, a target's position can be determined to accuracies of less than a meter. Another benefit of using GPS for targeting is that locations can be determined directly in the GPS coordinate frame (WGS-84), although latitude-longitude coordinates can also be used. One drawback of this method is that an

individual must be at the target for several minutes to several hours, depending on the level of accuracy required. While this requirement might not pose a problem for most civilian targets, it could pose a challenge for many military targets. In addition, this method involves locating targets individually, so obtaining information on several dozen targets would be time-consuming. On the other hand, this technique would be ideal for targets which are easily accessible, such as warehouses, airports, and government buildings.

2.1.2.4 Summary

If Third World nations are able to place a GPS receiver at a target, they will be able to obtain targeting accuracies of several meters. This scenario is most likely when civilian structures that are easily accessible are targeted. If GPS receivers are used to obtain several control points around a target, targeting accuracies of 15 meters are possible. This scenario is expected for those targets which can be approached but not reached by individuals with GPS receivers. If accurate control points and TED cannot be obtained, or if low-resolution images of target locations are used, targeting errors will be larger than 15 meters. This scenario will probably describe Third World attempts to target U.S. forces in the field. In all three cases, the long revisit cycles of most satellites indicate that LDCs will have a difficult time targeting mobile assets.

2.2 RANGE & PAYLOAD

Range and payload have been grouped into a single category because the two characteristics are closely related: a delivery vehicle is designed to carry a certain payload over a given distance. If the payload is lightened, the range of the vehicle can be extended. The payload of a delivery system is simply the amount of "weapon" the system can carry. Attackers usually want to maximize the payload of their weapons to cause the most damage possible to the enemy. However, the relationship between a weapon's size and the amount of damage it can do depends on the physical characteristics of the weapon. For example, the amount of damage one can cause with high explosives is highly dependent on the size of the warhead. The same is true of chemical weapons (CW). In contrast, nuclear weapons are devastating regardless of their physical size.[65]

The range of a delivery vehicle is important because it limits the targets which can be attacked. The range which a given nation requires is highly dependent on the geopolitical situation of that country. For example, in the Middle East, ranges of several hundred kilometers could be considered strategic, whereas the strategic systems of the United States have ranges of several thousand kilometers.

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[65]A nuclear device weighing several hundred kilograms can release energy which is equivalent to many thousands of tons (a.k.a. kilotons) of TNT.

It follows that the types of delivery systems a nation will attempt to acquire are highly dependent on the geography of that nation as well as its political-military goals. Targets which are far from a nation will require "long-range" weapons. Similarly, reinforced targets, whether civilian or military, will require larger payloads and greater accuracies than soft targets.

There are two approaches LDCs can take to acquire LACMs; they can either develop the missiles themselves or they can purchase them. If they choose to develop their own cruise missiles, developing nations have three options: they can design a missile from scratch, they can modify non-combat vehicles such as unmanned aerial vehicles (UAVs), or they can simply use general aviation aircraft to create a "poor man's cruise missile." If LDCs wish to purchase cruise missiles, they can follow two possible avenues: the first is to purchase ready-made LACMs from willing vendors; the second is to purchase ASCMs and modify them for land-attack roles.

If the former strategy is followed, it is likely that the LACMS developed in the Third World nations would use GPS for guidance. If the latter approach is taken, it is not clear that the cruise missiles acquired by LDCs would use GPS for guidance. For example, many ASCMs use inertial navigation as items to get them near their targets where radar seekers take over. In short range applications, INSs might be able to provide adequate guidance to hit large targets, especially if the missiles were supersonic (see Figure 3). On the other hand, developing nations could attempt to either supplant or augment the original guidance packages on such missiles with GPS receivers.

At the present time, only one LACM is in service in the Third World: the Israeli Popeye. Argentina is working on a LACK the MQ-2 Bigua, by converting an Italian Mirach-100 reconnaissance drone. There were reports before the Gulf War that Iraq was working on a LACM called the Ababil, but the current status of that program is unknown. Table 8 compares the range/payload characteristics of the Bigua and Ababil against those for a common Chinese ASCM, the HY-2 Silkworm, and a Soviet strategic cruise missile, the AS-6 Kingfish. The AS-6 Kingfish can be used either for land-attack or anti-ship missions. It can fly up to Mach 3.5 and can carry nuclear weapons.

Table 8.	Range and Payload Characteristics of Several Cruise Missiles[a]			
	MQ-2 Bigua	Ababil	HY-2 Silkworm	AS-6 Kingfish
Range	900 km	500 km?	95 km	560 km
Payload	40-70 kg	200 kg?	513 kg	1000 kg

[a]All data are taken from Carus, pp. 126-140.

One can see that the three cruise missiles developed by LDCs either carry small payloads to long ranges or carry large payloads to short ranges. This is typical of most cruise missiles in existence, the vast majority of which are ASCMs. In fact, there are few cruise missiles in the world with payloads of 500 kg or greater.[66] Most anti-ship cruise missiles have payloads of less than 200 kg. To make matters worse, if these missiles carried conventional warheads, perhaps only 25-50% of the payloads listed above would actually consist of high explosives.

Similarly, the MQ-2 Bigua is the only existing Third World LACM with a range in excess of 500 km; most Third World cruise missiles have ranges of 200 km or less. While short range cruise missiles might be useful for some missions, their utility for many situations is limited. Many nations which appear likely to acquire GCMs-Iran, Iraq, North Korea, China, India-have hostile relations with at least one neighboring country. It seems likely that these nations would want to acquire GCMs with the capability to reach vital targets in their neighboring countries. Note, for example, how Iraq extended the range of their Scud-B missiles from 300 to 650 km before their war with Iran in order to be able to attack Baghdad.[67] North Korea appears to be extending the range of their ballistic missiles, which are also based on the Soviet Scud-B, in order to reach Japan.[68]

There are two reasons why few capable (i.e., long-range, large-payload) LACMs have been developed in the Third World: technological obstacles, and the MTCR.[69] Building a capable LACM is not easy. Aside from the guidance problem, which has

[66]See Eric H. Amett, *Sea-Launched Cruise Missiles and U.S. Security* (New York: Praeger, 1991). p. 30.

[67]"Iraqi Missile Movements Shrouded by Darkness," *Flight International,* January 30-February 5, 1991, p. 7. Note that the price of this extended range was a reduction in payload from 985 kg to 500 kg.

[68]David C. Wright and Timur Kadyshev, "An Analysis of the North Korean Nodong Missile." *Science & Global Security, Vol.* 4 (1994), pp. 1-32.

[69]The MTCR is a non-binding agreement which limits the sale of all types of missiles with ranges greater than 300 km, regardless of their payload. Originally, the MTCR guidelines applied to delivery vehicles with ranges in excess of 300 km and payloads larger than 500 kg. The guidelines were changed on January 7, 1993. See Ian Anthony, et al., "Arms Production and Arms Trade." *SIPRI Yearbook 1993: World Armaments and Disarmaments* (Oxford: Oxford University Press, 1993). p. 464. A more detailed description of the MTCR is found in: Ian Anthony, ed., *Arms Export Regulations* (Oxford: Oxford University Press, 1991), pp. 219-227.

traditionally been the biggest hurdle, engineers have to worry about propulsion, the materials for the cruise missile body, and the flight control system of the missile. Even when a cruise missile is built and tested, which is not an easy task, mission planners still have to obtain targeting information and decide which route the cruise missile will take to its target.

Clearly there are many technical obstacles facing Third World nations which hope to develop their own advanced LACMs. Another option for such countries would be to purchase LACMs from the developed world. High-quality LACMs have been produced by France, Israel, Sweden, the United States, and the FSU.[70] However, the MTCR has restricted purchases of LACMs from these nations. Of the nations that have developed advanced LACMs, only Israel has not declared support for the regime.

One option available to LDCs is to convert UAVs, RPVs (remotely piloted vehicles) and drones into GCM. These vehicles are generally used for battlefield surveillance and reconnaissance. Hence, they are usually designed to carry small payloads such as cameras, which are often placed on the wings. UAVs can have long ranges, but the primary characteristic which concerns military planners is their loiter time over a given target. Thus, UAVs are usually built to stay in the air for long periods of time--a characteristic which does not necessarily translate into long ranges because UAVs often circle at very slow speeds. Given these reservations, it is definitely possible for LDCs to convert some UAVs into cruise missiles, as Argentina did with the Mirach-100.[71] In fact, the next generation Mirach, called the Mirach-600, will be a very capable delivery system. It will be able to carry 300-500 kg payloads out to a range of more than 2000 km and will have a velocity of 1100 kph.[72]

Another approach which LDCs could take is to use the airframes of existing aircraft. A nation could, for example, use the airframe and engine of a general aviation aircraft (see Section 2.1.3).[73] One advantage of this approach is that "poor man's cruise missiles" would be relatively inexpensive compared to the cost of either developing or purchasing advanced cruise missiles. Many general aviation aircraft can also carry large payloads to long ranges (see Section 3.1.3). However, there are drawbacks to this strategy. Cruise missiles created from general aviation aircraft would almost certainly be

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[70]Carus, *Cruise Missile Proliferation,* pp. 126-140. The most capable systems belong to France, the United States, and the FSU.

[71]The Mirach is not a typical UAV because it is designed for "strike" missions as well as for surveillance, reconnaissance, target location and acquisition, electronic warfare, and defense saturation. See Kenneth Munson, *World Unmanned Aircraft* (New York: Jane's Publishing Inc., 1988), p. 65.

[72]lbid., p. *66*.

[73]A cruise missile of this type would be inexpensive and easy to acquire, hence the nickname: "poor man's cruise missile."

large with substantial wing areas. Such cruise missiles would be much more observable to enemy radars than a smaller, stealthier version. Second, many pleasure aircraft fly slowly (see Section 3.1.3). Slow-flying cruise missiles will spend more time under enemy radar, which could make them more susceptible to interception and jamming. These two factors would make a "poor man's cruise missile" more susceptible to enemy defenses than most cruise missiles which are on the market today.

A Third World nation might be able to overcome some of the drawbacks mentioned above by placing GPS receivers on fighter planes rather than general aviation aircraft. For example, during the Gulf War, American intelligence discovered that Iraq had developed three radio-controlled MiG-21 drones which were outfitted for CW disposal.[74] Although MiG-21s are not state-of-the art aircraft, they are capable of flying at supersonic velocities at both high and low altitudes. They can also carry two 500 kg bombs and two 250 kg bombs to ranges of greater than 1000 km (the specific range depends on the altitude and velocity at which the plane flies).[75]

2.2.1 Chemical Weapons

Cruise missiles have several characteristics which make them useful platforms for delivering chemical weapons. The primary advantage of GCMs is their accuracy. Because the technologies involved in CW delivery are similar to those used in crop dusting, GCM can dispense CWs "in an aerosol over a wide area" which is the most effective method dispersal pattern.[76] In addition, their velocity is much better suited for delivering chemical weapons than that of ballistic missiles. On the other hand, cruise missiles also have some disadvantageous characteristics of CW delivery. The small payloads of many cruise missiles limit lethality of a CW warhead: "Chemical weapons must be delivered in great quantities to approach the potential lethality of nuclear and biological weapons."[77]

Even if large CW payloads could be delivered by GCMs, their impact on U.S. forces would be minimal: " . . . against well-protected troops or civilians, they [chemical weapons] will be less lethal than even conventional explosives."[78] Finally, it is important to note that U.S. forces already face the risk of CW attacks by ballistic missiles and aircraft

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[74]Rick Atkinson, *Crusade: The Untold Story of the Persian Gulf War* (Boston: Houghton Mifflin, 1993). p. 223.
[75]*Jane's All the World's Aircraft 1992-93* (Surrey, UK: Jane's Information Group Limited, 1992). pp. 215216.
[76]OTA, *Proliferation of Weapons,* p. 52.
[77]Ibid. Aircraft can carry three to ten times as much CW as Scud-B missiles, which have payloads of 1000 kg--much larger than those of most cruise missiles. See John R. Harvey, "Regional Ballistic Missiles and Advanced Strike Aircraft: Comparing Military Effectiveness," *International Security,* Vol. 17., No. 2 (Fall 1992). p. 73.
[78]Ibid., p. 73.

in the Third World. The existence of GCMs capable of carrying chemical weapons would not substantially increase the dangers facing U.S. forces.

2.2.2 Nuclear Weapons

It is possible but unlikely that any Third World cruise missiles will be used for nuclear weapons delivery in the near future. There are several reasons for reaching this conclusion. First, it is doubtful that a nuclear device produced in the Third World would weigh less than 500 kg.[79] The only advanced cruise missiles that could carry such payloads beyond short ranges are those produced by developed nations. Thus, if LDCs wished to obtain a highly capable cruise missile for nuclear delivery, they would have to purchase it from the United States, France, or the FSU. None of these nations appears willing to sell capable LACMs, which are covered by the MTCR.

However, there appear to be two ways in which Third World nations could acquire nuclear-capable cruise missiles. They could purchase and modify ASCMs, especially those from the FSU, or they could place nuclear weapons on "poor man's cruise missiles." The disadvantage of these options is that neither delivery vehicle would have a high probability of surviving against U.S. air defenses (see Section 3.3). Given that LDCs will probably have few nuclear devices in their stockpiles, the survivability of the vehicles they use to deliver these weapons must be as high as possible. In the foreseeable future, ballistic missiles will remain more survivable than either high-flying supersonic cruise missiles or "poor man's cruise missiles."

Another reason that Third World nations might not place nuclear weapons on cruise missiles in the near future is that they gain little advantage by doing so. GCMs have one key advantage over other delivery systems: their accuracy. High accuracy is certainly important for delivering both conventional munitions and chemical weapons, but is it vital for delivering nuclear weapons? The answer is no, unless LDCs wish to attack hardened targets such as underground bunkers and command posts. Such attacks are certainly possible, but their likelihood is unknown. In addition, hardened targets would be well protected, so that the survivability of a GCM would have to be high for such an attack to succeed. In sum, unless LDCs attack hardened military targets, GCMs provide few advantages over ballistic missiles or manned aircraft for nuclear weapons delivery. That situation could change if some Third World nations develop advanced, highly-capable cruise missiles.

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[79]Eric H. Amett, "The Most Serious Challenge in the 1990s? Cruise Missiles in the Developing World," in Eric H. Annett and Thomas W. Wander, eds., *The Proliferation of Advanced Weaponry: Technology, Motivations, and Responses* (Washington, D.C: American Academy for the Advancement of Science, 1992), p. 111.

One final point: it is not apparent that any nations which currently do not possess nuclear weapons will develop them within five years. However, even if they did so, such nations (e.g., Iran, Pakistan) either have or are attempting to purchase ballistic missiles.[80] There is clearly a perception in the Third World that ballistic missiles are the delivery vehicle of choice for nuclear payloads. Whether that perception will change remains to be seen, but for now there is reason to agree with the view that, " . . . it is unclear whether any nation in the Third World would adopt cruise missiles as the primary means for delivering nuclear weapons."[81]

2.3 LETHALITY ANALYSIS

2.3.1. Point Targets

Having examined the accuracy, range and payload of GCMs, it is now possible to assess the lethality of these weapons under the assumption that they are conventionally armed. That is accomplished by combining the relevant variables into an effective CEP. In the following calculations, it is assumed that GCMs perform 45-degree terminal dives. Four different targeting accuracies will be considered: 5 m, 15 m, 30 m, and 50 m.[82] The analysis also examines GCMs using no radar altimeters, low-quality altimeters, and high-quality altimeters.

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[80] *OTA, Proliferation of Weapons,* pp. 63-68.

[81] Carus, *Cruise Missile Proliferation,* p. 80.

[82] A 5 m targeting error assumes that a GPS receiver was placed at the target. A 15 m targeting error assumes that 10 m-resolution images are available with good control points. A 30 m targeting error assumes that either 10 m-resolution images are available without good control points, or that 20 m- resolution images are used with good control points. A 50 m targeting error assumes that either 20 m -resolution images are available without good control points, or that 30 m-resolution images are used with good control points. It should be noted that targeting errors much larger than 50 m are distinctly possible; see Table 5.

Table 9. Effective CEP (meters) of Cruise Missile With No Radar Altimeter

Targeting Error	SA on	SA off	P-Code	DGPS
5m	63	23	14	8
15 m	65	27	20	16
30 m	70	38	33	31
50 m	80	55	52	50

Table 10. Effective CEP (meters) of Cruise Missile With Low-Quality Radar Altimeter

Targeting Error	SA on	SA off	P-Code	DGPS
5 m	62	48	46	45
15 m	63	50	48	48
30 m	68	56	55	54
50 m	79	69	68	67

Table 11. Effective CEP (meters) of Cruise Missile With High-Quality Radar Altimeter

Targeting Error	SA on	SA off	P-Code	DGPS
5 m	42	16	11	7
15 m	45	21	18	16
30 m	52	34	31	30
50 m	65	52	51	50

The most lethal GCMs are those using high-quality radar altimeters, followed by those using GPS only, followed by those using low-quality radar altimeters. Selective Availability appears most useful in the two former cases. SA is less useful in the latter case because the VPEs of such missiles are large; hence, the degradation in horizontal position accuracy due to SA does not cause a significant change in the overall accuracy of the missiles. For the same reason, the benefits associated with using DGPS for guidance are minimal when low-quality altimeters are used. Similar reasoning explains why the benefits of SA are more pronounced when targeting errors are small: as the targeting errors begin to

dominate the overall CEP of the GCMs, the guidance errors become less important and the effect of SA diminishes.

The following six tables examine the probability of kill values associated with the CEPs calculated above. Three different cruise missiles are examined: those carrying 400, 125, and 50 kg HE payloads. For each cruise missile, two scenarios are studied: the first assumes that the GCMs use low-quality radar altimeters; the second assumes that high-quality altimeters are used.

Table 12. Pk (%) for Cruise Missile with 400 kg of HE and Low-Quality Radar Altimeter

	SA on		SA off		P-Code		DGPS	
T. E.	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi
5 m	25	5	38	8	41	9	42	9
15 m	24	5	36	8	38	8	38	8
30 m	21	4	30	6	31	6	32	7
50 m	16	3	21	4	21	4	22	4

T. E. = Targeting Error
10 psi = Soft Target
40 psi = Reinforced Target

Table 13. Pk (%) for Cruise Missile with 400 kg of HE and High-Quality Radar Altimeter

	SA on		SA off		P-Code		DGPS	
T. E.	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi
5 m	47	11	99	54	100	81	100	98
15 m	42	9	92	37	97	46	99	54
30 m	34	7	62	16	68	19	71	20
50 m	23	5	34	7	35	7	36	8

T. E. = Targeting Error
10 psi = Soft Target
40 psi = Reinforced Target

Table 14. Pk (%) for Cruise Missile with 125 kg of HE and Low-Quality Radar Altimeter

	SA on		SA off		P-Code		DGPS	
T. E.	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi
5m	17	3	27	5	28	5	30	6
15 m	16	3	25	5	27	5	27	5
30 m	14	3	20	4	21	4	22	4
50 m	11	2	14	2	14	3	15	3

T. E. = Targeting Error
10 psi = Soft Target
40 psi = Reinforced Target

Table 15. Pk (%) for Cruise Missile with 125 kg of HE and High-Quality Radar Altimeter

	SA on		SA off		P-Code		DGPS	
T. E.	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi
5 m	33	6	94	37	100	62	100	91
15 m	30	6	80	23	89	30	94	37
30 m	23	4	46	10	52	11	55	12
50 m	15	3	23	4	24	4	25	5

T. E. = Targeting Error
10 psi = Soft Target
40 psi = Reinforced Target

Table 16. Pk (%) for Cruise Missile with 50 kg of HE and Low-Quality Radar Altimeter

	SA on		SA off		P-Code		DGPS	
T. E.	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi
5m	9	2	15	3	16	3	17	3
15 m	9	2	14	3	15	3	15	3
30 m	8	1	11	2	11	2	12	2
50 m	6	1	7	2	8		8	2

T. E. = Targeting Error
10 psi = Soft Target
40 psi = Reinforced Target

Table 17. Pit (%) for Cruise Missile with 50 kg of HE and High-Quality Radar Altimeter

	SA on		SA off		P-Code		DGPS	
T. E.	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi
5 m	19	4	76	24	95	44	100	76
15 m	17	3	56	15	68	19	76	24
30m	13	3	27	6	32	7	33	7
50m	8	2	13	3	13	3	14	3

T. E. = Targeting Error
10 psi = Soft Target
40 psi = Reinforced Target

As expected, there are significant differences in the lethalities of the various GCM configurations. When low-quality altimeters are employed with 400 kg-payload GCMs, GCMs pose a moderate threat to soft targets and little threat to reinforced targets.[83] If high-quality altimeters are used, GCMs with 400 kg payloads can pose serious threats to both soft and reinforced targets if accurate guidance is used (i.e., "SA off" or better), and if targeting errors are small. The targeting requirements are more stringent for hard targets than for soft targets. Also, GCMs using DGPS are much more lethal against hard targets than those with "SA off"--level accuracies.

GCMs carrying 125 kg payloads and using low-quality altimeters can pose major threats to soft targets if both accurate guidance and small targeting errors are present. They pose a marginal threat to soft targets if SA is on. However, these cruise missiles pose little threat to reinforced targets when low-quality altimeters are utilized. While the threat profile for 125 kg-payload GCMs using high-quality altimeters is similar to that for 400 kg payload GCMs, two observations are worth mentioning. First, the difference in lethality between GCMs using DGPS and those using "SA off" is more pronounced for the 125-kg payload missiles. A second point of interest is the abrupt drop in lethality for DGCMs as the targeting errors grow from 5 to 15 meters. This behavior is observed to some extent in all three cases. It shall be discussed below.

GCMs with 50 kg payloads utilizing low-quality altimeters pose low-to-marginal threats to soft targets and almost no threat to reinforced targets. If high-quality altimeters

[83]This discussion focuses on each missile's SSPK. Statements regarding the threats posed by GCMs must be considered in that light. A discussion of the potential threat of attacks by several cruise missiles against a given target is provided below. Also, the term "payload" refers to the amount of HE carried by each missile, not to the general amount of weight they can carry.

are used, the threat profile of these missiles is similar to the previous case except that the Pks are smaller.

Some general trends can be gleaned from the discussion above. As mentioned above, a steep drop in lethality against hard targets occurs as targeting errors grow for cruise missiles using accurate guidance systems (e.g., DGPS).[84] For example, referring to Table 15, one can see that a DGCM with a 5 m targeting error has a SSPK of 0.91 versus reinforced targets. However, as the targeting error grows to 15 m, the SSPK plummets to 0.37. To understand the reason for such a dramatic change, one must refer back to Figure 4. That figure shows that a significant drop in lethality occurs as the CEP of a cruise missile varies about the lethal radius of the missile.

For example, according to Table 1, the lethal radius of a reinforced target facing a 400 kg-payload missile is 17 meters. Examining Figure 4, one can see that a CEP of about 10 meters yields a SSPK of about 0.9 while a CEP of 25 meters yields a SSPK of about 0.25. Hence, a change of 15 meters in CEP leads to a drop in SSPK of approximately 0.65. In contrast, the difference in that missile's SSPK as its CEP drops from 25 meters to 50 meters is about 0.15. Thus, it is clear that marked changes in the probability of kill against a given target can occur if the CEP of a missile varies about the lethal radius of that target. On the other hand, the P_k of a missile will not vary much with large changes in CEP if those changes occur at values which are far from the lethal radius. In conclusion, small changes in targeting can make a significant difference for cruise missiles with highly accurate guidance systems.

Another interesting trend is that the differences in lethality for the various navigation options (e.g., SA on, DGPS) diminish as targeting errors increase in magnitude. The reason for this phenomenon was alluded to earlier; as targeting errors increase, they begin to dominate the navigation errors associated with high-accuracy guidance systems. As navigation errors become negligible compared to targeting errors, the differences between various guidance options also become negligible. The same logic explains why there are larger variations in the lethality of GCMs using high-quality altimeters than there are for GCMs using low-quality altimeters. The VPEs associated with low-quality altimeters are large enough to "drown out" the differences between the various navigation options.

It is possible to make some general statements regarding SA and DGPS. The United States will gain maximum benefit from Selective Availability when attacking GCMs have small VPEs (e.g., by using high-quality altimeters), small targeting errors, and large payloads. In other words, SA provides the most protection when enemy cruise missiles

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[84]The drop in lethality is quite dramatic for 125 kg- and 50 kg-payload GCMs; it is somewhat smaller for the 400 kg version.

are the most capable. Similarly, attacking GCMs gain the most out of using DGPS when they have small targeting and vertical position errors. Also, there is a general trend that can be stated as follows: the larger the GCM payload, the greater the (relative) benefit that missile gains from DGPS.85 There is one apparent exception to this trend: when targeting errors are very small (e.g., 5 meters), the benefits of DGPS guidance decrease as GCM payloads increase. It appears, however, that this observation is an anomaly due to the fact that the values of P_k cannot exceed 1.0.

The tables above describe the probability of a single GCM destroying a given target. What happens if several cruise missiles are launched at a given target? The probability that a target will be destroyed by several missiles with a given probability of kill, assuming that all of the missiles have the same P_k, is given by the following equation:[86]

$$P_d = 1 - (1 - P_k)^{Nm} \qquad (4)$$

where,

P_d = Desired probability of destruction,

P_k = Single-shot probability of kill, and

N_m = Number of missiles required.

Another way of looking at the relationship given above is to ask: how many missiles are required to achieve a desired probability of damage for a target? By asking that question, military planners can determine how many missiles need to be launched against a given target.[87] Given that information, and a list of targets, military planners will be able to calculate how many missiles are required in their arsenal. The relevant equation is:[88]

$$N_m = \frac{\ln(1 - P_d)}{\ln(1 - P_k)} \qquad (5)$$

Figure 5 illustrates this relationship.[89]

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[85]The benefit of DGPS guidance was determined by comparing the P_ks of GCMs using SA to those using DGPS. The difference between the two P_ks indicated the relative benefit of DGPS guidance for that particular case.

[86]Harshberger, Long-Range *Conventional Missiles,* p. 94.

[87]It is important to remember that N_m expresses the number of missiles which must hit the target; it does not take into account the issues of missile reliability or survivability. Military planners must keep those factors in mind when determining how many missiles are required for a given mission. For example, suppose that three GCMs are needed achieve to given P_d. If the P_{surv} and P_{Rel} of those missiles are 0.6 and 0.8, respectively, then six GCMs would have to be launched for military planners to be confident that three GCMs made it to the target.

[88]Harshberger, p. 94.

[89]The values of N_m have been rounded up to the nearest integer under the assumption that military planners would rather exceed than fail to meet a desired probability of destruction.

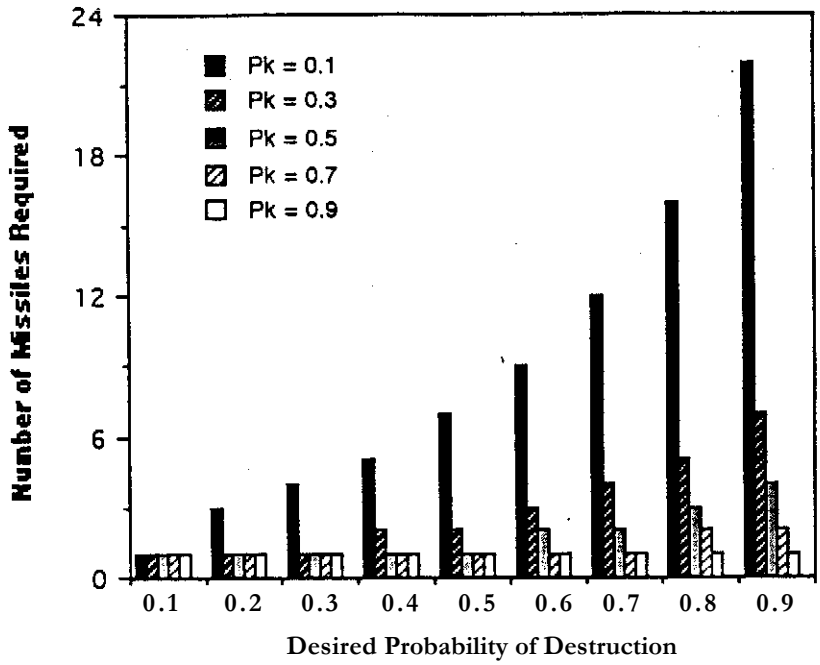

Figure 5. Number of missiles required vs. desired probability of destruction.

It is evident that large numbers of missiles are required to achieve high probabilities of destruction when the P_ks of individual missiles are low. Similarly, few missiles are required when the SPX of the individual missiles are high. Using the equations presented above, one can determine the number of cruise missiles required for various missions based on the P_ks calculated in Tables 12-17. For example, Table 18 shows the number of missiles that would be required to achieve a P_d of 0.7 assuming that the attacking missiles used high-quality altimeters and carried 125 kg of HE.

Table 18. Number of Cruise Missiles Required to Achieve A Probability of Destruction of 0.7a

	SA on		SA off		P-Code		DGPS	
T. E.	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi
5m	3	20	1	3	1	2	1	1
15 m	4	20	1	5	1	4	1	3
30m	5	30	2	12	2	11	2	10
50m	8	40	5	30	5	30	5	24

[a]It is assumed that the attacking cruise missiles carry 125 kg HE warheads and use high-quality radar altimeters.
T. E. = Targeting Error
10 psi = Soft Target
40 psi = Reinforced Target

As expected, if accurate navigation data and targeting information are available, LDCs require few cruise missiles to destroy either soft or reinforced targets. As the lethality of the individual GCMs decreases, more missiles are required to achieve a desired probability of destruction. Table 18 clearly demonstrates that reinforced targets face little probability of destruction if Third World nations do not have lethal cruise missiles and highly accurate targeting data; the number of "poor man's cruise missiles" which would be required for that task is extremely high.

It must be remembered that the case discussed above is for a medium-sized missile. If the attacking GCMs carried smaller payloads, more missiles would be required than shown in Table 18. Similarly, if the GCMs carried larger payloads, fewer missiles would be needed. It is important to remember that the equations above calculate the number of missiles which must *hit the target*. The number of GCMs which must actually be launched will be higher depending on the reliability and survivability of those missiles. Thus, there might be trade-offs which favor one kind of missile over another. For example, suppose that the SSPK of a large GCM is 0.8 and its probability of survival is 0.5, while the SSPK of a smaller cruise missile is 0.6 and its P_{Surv} is 0.7. The probability that the larger missile will reach and destroy its target is 0.4; the probability that the smaller missile will do the same is 0.42. In this case, it would be wiser for the attacker to use the smaller missiles. This point is vitally important. It will be discussed in greater detail after the topic of cruise missile survivability is examined.

Although Table 18 does not present any information which could not have been inferred from Table 15, it does clarify the fact that Third World military planners face trade-

offs in deciding whether certain targets are worth attacking. For example, if an LDC is able to use DGPS for guidance, they will have a 70% chance of destroying a reinforced target with three GCMs if they can acquire targeting data with an accuracy of 15 meters of better. One could frame the same problem in another way: a developing nation might have a specific number of GCMs they wish to use effectively. They could use charts such as Table 18 to determine which targets they wish to attack given the characteristics of their missiles and the quality of their targeting information. The United States could use the same data to determine which targets might be the most likely to be attacked.

2.3.2 Area Targets

The lethality calculations performed above assumed that GCMs were attacking point targets. While such calculations are useful for the purposes of this paper, it would also be useful to examine how those calculations would change if area targets were attacked. If an area target is attacked, its lethal range must be defined to begin at the "edge" of the target. Any attacks within that "edge" would be direct hits. Assuming for simplicity that an area target is circular with radius RA, its effective lethal radius, designated R_{Leff}, is defined by the following expression:

$$R_{Leff} - R_A + R_L$$

Thus, the probability of kill for an area target, which shall be called $P_{k,area}$, is given by the formula:

$$P_{k,area} = 1 - 0.5^{\left(\frac{R_{Leff}}{CEP}\right)} = 1 - 0.5^{\left(\frac{R_A + R_L}{CEP}\right)} \quad (6)$$

To see how the lethality of GCMs changes when area targets are attacked, two calculations shall be performed. The first case examines cruise missiles with 125 kg payloads of HE, high-quality altimeters, and 30 meter targeting errors against three area targets. The second case examines cruise missiles with 50 kg payloads of HE, low-quality altimeters and 50 meter targeting errors. The radii of the targets, which are assumed to be circular, are 10, 25, and 50 meters, respectively. The results are presented in Tables 19 and 20. Tables 15 and 16 are reproduced as Tables 21 and 22 to facilitate comparisons between point and area targets. The relevant P_ks in those Tables are italicized.

Table 19. P_k (%) for Cruise Missile with 125 kg of HE, Low-Quality Radar Altimeter and 30 m Targeting Error vs. Area Targets

	SA on		SA off		P-Code		DGPS	
Radius	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi
0 m	6	1	7	2	8	2	8	2
10 m	11	4	15	6	15	6	15	6
25 m	23	13	28	16	29	17	30	17
50 m	45	33	54	41	55	42	56	43

Radius = Radius of Area Target
10 psi = Soft Target
40 psi = Reinforced Target

Table 20. P_k (%) for Cruise Missile with 50 kg of HE, High-Quality Radar Altimeter and 30 m Targeting Error vs. Area Targets

	SA on		SA off		P-Code		DGPS	
Radius	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi
0 m	23	4	46	10	52	11	55	12
10 m	36	13	65	27	72	32	74	33
25 m	57	31	86	58	90	65	92	67
50 m	82	64	98	91	99	94	99	95

Radius = Radius of Area Target
10 psi = Soft Target
40 psi = Reinforced Target

Table 21. P_k (%) for Cruise Missile with 50 kg of HE and Low-Quality Radar Altimeter

	SA on		SA off		P-Code		DGPS	
T. E.	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi
5 m	9	2	15	3	16	3	17	3
15 m	9	2	14	3	15	3	15	3
30 m	8	1	11	2	11	2	12	2
50 m	*6*	*1*	*7*	*2*	*8*	*2*	*8*	*2*

T. E. = Targeting Error
10 psi = Soft Target
40 psi = Reinforced Target

Table 22. Pk (%) for Cruise Missile with 125 kg of HE and High-Quality Radar Altimeter

	SA on		SA off		P-Code		DGPS	
T. E.	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi	10 psi	40 psi
5 m	33	6	94	37	100	62	100	91
15 m	30	6	80	23	89	30	94	37
30 m	***23***	***4***	***46***	***10***	***52***	***11***	***55***	***12***
50 m	15	3	23	4	24	4	25	5

T. E. = Targeting Error
10 psi = Soft Target
40 psi = Reinforced Target

As expected, the larger the area of a target, the higher the lethality of a given cruise missile will be against that target. Bigger targets are simply easier to hit. It should be noted, however, that large targets may not be destroyed by a single cruise missile strike. Thus, the lethality calculations above may be somewhat misleading. The calculations above also show that the lethality of GCMs increases with target area in roughly equal proportion against both soft and reinforced targets; there is no preferential increase against a particular kind of target.

The reader can see that if large targets are attacked, GCMs which were moderately lethal against point targets become extremely lethal. Similarly, GCMs which posed. little threat to point targets can pose a moderate threat to area targets. Another interesting observation is that the effects of SA diminish the larger a target is. In other words, SA carries little benefit if GCMs are attacking a large target. Similarly, the benefits of using DGPS for guidance diminish as a target's area grows.

In conclusion, area targets, whether soft or reinforced, are easier for GCMs to hit than point targets. The increased lethal radius of area targets diminishes the impact that SA and DGPS have in affecting a GCM's lethality. It is therefore logical to assert that targeting errors and VPE would also have less of an affect on a GCM's lethality against area target. In both cases, the role played by these factors will decrease in proportion to a target's area.

3. CRUISE MISSILE SURVIVABILITY

The survivability of a cruise missile is a measure of its ability to penetrate enemy defenses. In order to assess how well a GCM can accomplish that task, two separate but related problems must be examined. First, the ability of U.S. forces to detect a cruise missile attack must be assessed. A determination must then be made regarding the effectiveness of various countermeasures in eliminating the threat posed by GCMs. The ability of U.S. forces to perform these tasks depends critically on both the physical characteristics of GCMs and the capabilities of U.S. assets.

The physical characteristics of GCMs are examined by focusing specifically on the altitude at which cruise missiles can fly, their observability to enemy radars, and their velocity. The paper then studies the capabilities of U.S. forces. The ability of both ground-based and airborne radar platforms to detect GCMs is assessed. The paper then examines the effectiveness of interception by manned aircraft and surface-to-air missiles. Finally, the utility of electronic jamming as a response to a GCM attack is determined.

3.1 CRUISE MISSILE CHARACTERISTICS

3.1.1 Altitude

The altitude at which a cruise missile flies is extremely important because it determines the line-of-sight (LOS) limit at which most radars will be able to see the missile (see Section 3.2.2). The lower a GCM flies, the shorter a radar's (or jammer's) horizon. In other words, low-flying missiles will not become visible over the horizon until they are very close to a radar. Thus, if a defender wishes to detect low-flying missiles at long ranges, he/she must use an airborne platform. While airborne radars can potentially detect low-flying cruise missiles at long ranges, they face some obstacles which are not as severe for ground-based radars (e.g., clutter).

Low-flying cruise missiles are also hard to intercept. However, the lower a cruise missiles flies, the greater the probability that it will collide with or "clobber" terrain or manmade objects. Thus, there is a trade-off between decreasing the probability that a cruise missile will be intercepted and decreasing the probability that it will be clobbered. Third World mission planners would undoubtedly attempt to choose a survival corridor which maximizes a cruise missile's probability of survival. Their chance of success depends to a large extent on three factors: the VPE of the missile, the quality of the terrain elevation data available, and the availability of vertical obstruction data (VOD).

3.1.1.1 Vertical Position Errors

The vertical position accuracy of Third World GCMs was discussed in Section 2.1. It was found that GCMs can obtain the smallest VPEs by using high-quality altimeters, although the accuracies associated with DGPS are also quite good. Cruise missiles using the SPS should use low-quality altimeters if high-quality altimeters cannot be obtained or are too expensive.

3.1.1.2 Terrain Elevation Data

Another factor influencing a cruise missile's altitude is the information that mission planners have regarding the path the cruise missile will take to its target. Even though GPS-guided cruise missiles may not take a terrain-following course, they will want to fly as low as possible to escape detection. In order to do so, the cruise missiles must fly high enough to avoid both natural obstacles, such as hills, and man-made obstacles, such as radio towers.

Accurate elevation data can be obtained from satellite images. Resolution from SPOT images, for example, can be as low as 7-15 meters for elevation measurements if good control points are available. The ability of a Third World nation to obtain accurate control points also affects the quality of the TED they can get for the same area. For example, given good control points, either based on USGS data or GPS, SPOT satellites can provide elevation measurements with accuracies of 7-15 meters.

Other satellites can provide elevation data as well. The Russian Almaz-1 provides synthetic aperture radar (SAR) images with a resolution of 15 meters.[90] The ESA's ERS-1 carries a SAR and a radar altimeter. Its follow-on, the ERS-2, will support improved versions of both types of radars.[91] Japan's JERS-1 carries a SAR which reportedly has a resolution of 18 meters.[92]

Terrain elevation information can also be obtained from public domain databases. Wolf and Wingham conducted a comprehensive survey of digital elevation models available in the public domain.[93] The results of their research can be summarized as follows: "We have established that at 100 m resolution coverage exists of most of the developed world . . .. for much of the world we are unable to confirm the existence of such data, and our

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[90]SAR images are able to show the elevation contours of a given area. James R. Asker, "Commercial Remote Sensing Faces Challenges on Three Fronts," *Aviation Week & Space Technology,* July 18. 1993, p. 59. See also *Aerospace Daily,* September 17, 1990, p. 443.

[91]Michael Mecham, "Europeans Prepare to Build On Early ERS Satellite Success," *Aviation Week & Space Technology,* July 18, 1993, p. 69.

[92]Paul Proctor, "Japan Plans New Generation of Remote Sensing Satellites," *Aviation Week & Space Technology,* July 18, 1993, p. 67.

[93]Michael Wolf and Duncan Wingham, "The Status of the World's Public-Domain Digital Topography of the Land and Ice," *Geophysical Letters, Vol.* 19, No. 23 (December 2, 1992), pp. 2325-2328.

experience is that in these regions it will prove difficult to obtain digital elevation data, if, indeed, it exists at all."[94] The two databases which do provide information for the whole globe-one from the National Oceanographic and Atmospheric Administration, the other from the University of Graz-have resolutions on the order of 10 km.

However, the Digital Chart of the World, which was described earlier, provides elevation data with accuracies ranging from 60-300 meters (rms) depending on the region. The average accuracy of the map is around 150 meters (rms). Thus, the DCW appears to be the best commercial source of elevation data on a global scale, especially for regions such as Africa, Asia, and the Middle East. It is available on computer disk and is compatible with GIS applications.

3.1.1.3 Vertical Obstruction Data

In order for cruise missiles to fly low to the ground, mission planners must know the features of the terrain they are flying over. However, in many areas man-made objects can be tall enough to intersect the flight path of low-flying cruise missiles. For example, U.S. cruise missiles can fly as low as 10 m over water, 30 m over smooth terrain, and 100 m over rough terrain.[95] At such altitudes, objects that are not included in the terrain data-including items such as buildings, power lines, or storage facilities-become significant
hazards.[96]

It appears that detailed information about man-made objects is not commercially available. Some information is provided by civil aviation authorities so that recreational aircraft do not fly into buildings, but the safety margins are so large that they are all but useless for military missions where low-altitude flight is essential. If VOD is not available, a missile's minimum safe altitude depends on the area it flies over. If the area is urban, there may be many man-made obstacles; if the area is rural, there may be fewer obstructions. How high must cruise missile fly to avoid such obstacles? Mission planning personnel have indicated that a reasonable cut-off altitude for significant vertical obstructions is 200 feet, or 60 meters.[97]

3.1.1.4 Analysis

The altitude at which a cruise missile flies will depend on three factors: the vertical position accuracy of the missile, the missile's data on the terrain elevation it is flying over, and data on man-made vertical obstructions. As discussed earlier, it is assumed that a cruise missile will be using some type of radar altimeter. The low-quality altimeters will

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[94] Ibid., p.2325
[95] Arnett, *Sea-Launch Cruise Missiles*, p.6.
[96] See Harshberger, *Long-Range Conventional Missiles,*p. 119.
[97] Ibid.

provide accuracies of 30-60 meters, while the high-quality altimeters will provide accuracies of about 3 meters. Two sources of TED will be available for LDCs: satellite images and maps.[98] If satellite information is available, accuracies on the order of 7-15 meters are possible. The only map that would provide good TED is the DCW. Users of this data should have accuracies of 212 meters (2σ). The following Tables compare the vertical position accuracies for cruise missiles utilizing only GPS guidance against those utilizing radar altimeters. [99]

Table 23. Cruise Missile Vertical Position Accuracy (2σ--meters)

Using GPS

TED	SA on	SA off	P-Code	DGPS
SPOT	141	50	30-33	16-21
DCW	254	218	214	212

Table 24. Cruise Missile Vertical Position Accuracy (meters)

Using Altimeters

TED	Low-Quality Altimeter	High-Quality Altimeter
SPOT	31-62	8-15
DCW	214-220	212

Tables 23 and 24 clearly show the advantages of obtaining both high-resolution TED and accurate vertical position information. The uncertainty associated with the DCW, which is by far the best source of TED besides satellite images, dominates the errors due to the navigation system. If SPOT (or other good quality) satellite images can be obtained, then the navigation errors become significant. In that case, GCMs using the SPS have by far the worst vertical position accuracy. Unless they are using DGPS for guidance, GCMs

[98]How likely is each case? If an LDC were involved in an armed conflict with the United States, it is possible that satellite-based TED would be unavailable. In that case, the likelihood that LDCs would have high accuracy TED during the war would depend on how much mission planning they had accomplished before the conflict. If a nation spent several years mapping out the TED of regions where the U.S. forces would later be, then the lack of timely satellite information during the war would not affect the altitude at which a cruise missile could fly, although it would affect targeting. If extensive mission planning had not been carried out, then data from the DCW would have to be used.

[99]The numbers represent the overall vertical position uncertainty of a cruise missile. For example, a cruise missile utilizing a low quality altimeter and the DCW can be 95% certain that it knows its altitude to within 214220 meters. The actual altitude at which a cruise missile will fly depends on the type of terrain it is flying over and the flight mode of the missile (i.e.. terrain clearance, terrain following, or terrain avoidance). These modes of flight are discussed shortly.

should use either type of altimeter described above. The smallest VPEs are achieved when a high-quality altimeter is used; however, even the larger VPEs associated with a low-quality altimeter are better than the errors which occur when SPS is used. Finally, it is worth noting that GCMs using the C/A-code with SA turned off will generally have larger VPEs than GCMs using low-quality altimeters.

Land-attack cruise missiles will fly over two basic types of terrain: smooth and rough. There are three modes of flight a cruise missile can use to fly low over such terrain. [100] The first strategy is known as terrain clearance. In this mode, a cruise missile maintains a relatively constant height over the terrain at an altitude which overflies the tallest obstacle on the flight path. This is the simplest strategy, and the most likely to be used by LDCs, but it is also the least effective in terms of maximizing a GCM's survivability.

Another mode is terrain following. In this mode, a cruise missile maneuvers in the vertical plane to match the contours of the terrain as closely as possible. While this technique minimizes the probability that a cruise missile will be detected, it is also the most difficult to execute given the strenuous maneuverability and control system requirements it places on a cruise missile. It appears unlikely that an LDC would be able to utilize this strategy in the near future. A final strategy is known as terrain avoidance. With this strategy, a cruise missile maintains a constant altitude below the level of the highest obstacle in its path, but maneuvers in the horizontal plane to avoid tall obstacles. This approach is a hybrid of the previous methods. It is possible that some GCMs could adopt this approach, depending on the capabilities of the missiles and the terrain.

In addition to the mode of flight a cruise missile uses, the contours of the terrain must be taken into account. For example, Tomahawks, which have state-of-the-art altimeters, and are provided with excellent TED and VOD, probably have overall vertical position uncertainties of only a few meters. In addition, Tomahawks operate in a terrain following mode. Yet, these missiles fly at altitudes of 30 meters over smooth terrain and 100 meters over rough terrain. One can conclude from this observation that even with extremely accurate elevation information, cruise missiles must be given some buffer. Assuming that the buffers that are used by Tomahawks are also used by Third World cruise missiles, Table 25 estimates the overall vertical accuracy of these weapons over smooth and rough terrain (the numbers are accurate to within 10 meters):

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[100] The following discussion is based on material presented in Bernard Kovit, "Low-Altitude Penetration," *Space/Aeronautics,* May 1965, p. 78.

Table 25. Cruise Missile Altitude (meters -- 2σ) Over Terrain

Scenario	Smooth Terrain	Rough Terrain
Low-Quality Altimeter + SPOT	140	210
Low-Quality Altimeter + DCW	300	370
High-Quality Altimeter + SPOT	100	170
High Quality Altimeter + DCW	300	370

It appears that Third Worl cruise missiles will be abe to fly 100-300 meters above smooth terrain, and 170-370 meters over rough terrrain. The rest of the paper will assume that GCMs are flying over smooth terrain.

3.1.2 Observability

Another crucia element of a cruise missile is its observability. The usual measure used to rate a vehicles's observability is its radar cross section (RCS). The higher the RCS, the easier it is for a radar to "see" an object. The table below gives some typical RSC values for aircraft and cruise missiles. [101]

Table 26. The Radar Cross Section of Various Vehicles

Vehicle	Radar Cross Section (m^2)
Boeing 747	100
Large bomber or jetiner	40
Medium bomber of jetliner	20
Large fighter	6
Small fighter or 4-passenger jet	2
Small, single engine aircraft	1
Tomahawk LRCM	0.1

[101] Estimates for RCSs of the aircraft are from Merrill I. Skolnik, *Introduction to Radar Systems* (New York: McGraw –Hill, 1980), p.44. The RCS of the Tomahawk is from George N. Lewis and Theodore A. Postol, "Long-range Nuclear Cruise Missiles and Stability," *Science & Global Security,* Vol. 3 (1992), Nos. 1-2, p.56. Also, the reader should be aware that RCS varies with the frequency of the radar and the angle at which the targets are iluminated.

The numbers given in Table 26 are notional; the RCS of such vehicles can be larger than the numbers quoted here if the vehicles are not optimally designed or if they are physically larger. Thus, a "poor man's cruise missile" would probably have an RCS in the 1-2 square meter range.

Since radar is the primary means of detecting delivery vehicles, minimizing one's RCS is of primary importance to attackers. Stealth technologies are a move in exactly that direction. U.S. policy-makers are understandably concerned about the spread of such technologies. [102]

3.1.3 Velocity

The velocity of a cruise missile is important for three reasons: it can affect the ability of a defensive system to engage the missile (see Section 3.3), it determines how long an INS will drift after a GCM is jammed (see Section 3.4), and it affects the probability that the missile will be detected by airborne radars (see Section 3.2.1). Each of these topics will be discussed below. The velocity at which a cruise missile can fly depends mostly on the type of engine the missile is using.[103] Utilizing high-efficiency turbofan engines, cruise missiles should be able to fly up to 800 kph; utilizing turboprops, they will probably fly between 150 and 400 kph; using jet engines, they can reach supersonic velocities.

The performance capabilities of a missile's engines also directly influence the range/payload characteristics of a cruise missile. In general, missiles with high performance engines will be able to fly longer and faster with heavier payloads than missiles with low performance engines. For example, a Cessna CitationJet, which uses two Rolls-Royce/Williams FJ44 turbofan engines, has a maximum cruising speed of 704 kph, a maximum payload of 2940 kg, and a typical range of 2780 km. In contrast, the Beechcraft King Air, which uses two Pratt & Whitney PT6A-21 turboprop engines, has a maximum cruising speed of about 450 kph, a maximum payload of 1570 kg, and a maximum range of about 2000 km. [104]

A "poor man's cruise missile" is likely to fly slowly; one can expect them to have velocities on the order of 150-400 kph. If high efficiently turbofans can be obtained and integrated into a high-quality cruise missile, its velocities will probably approach 800

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[102]See "Top Proliferation Threat," p. 26, and David A. Fulghum, "U.S. Developing Plan to Down Cruise Missiles," *Aviation Week & Space Technology*. March 22, 1993, pp. 46-47.

[103]Other factors include the weight of the missile, the altitude at which it is flying, and the amount of fuel it carries.

[104]The aircraft specifications are taken from *Jane's Aircraft,* pp. 367 and 337, respectively.

kph.[105] It is doubtful whether LDCs will be able to develop supersonic cruise missiles in the foreseeable future. However, they might be able to convert supersonic fighter aircraft into cruise missiles, or they could buy supersonic ASCMs from. nations like the former Soviet Union and covert them into LACMs.[106]

3.2 CRUISE MISSILE DETECTION

The problem of cruise missile detection is vital for the simple reason that countermeasures cannot be taken unless U.S. forces know they are under attack.[107] In a tactical military environment, American forces will field both airborne and ground-based surveillance radars. Those types of radars will almost certainly be operational 24 hours a day to ensure that U.S. forces are not surprised. In addition, the surveillance platforms will be connected to other assets such as tracking radars, fire-control radars, jammers, airborne interceptors, and surfact-to-air missile (SAM) units.

3.2.1 Airborne Radars

There are a variety of options for implementing airborne radars: radars on airplanes, radars aboard aerostats, radars aboard airships, and radars mounted on unmanned air vehicles (UAVs). This paper focuses on plane-mounted radars, specifically airborne warning and control systems (AWACS) aircraft, because these are the types of systems the United States would use in a regional conflict.[108]

Airborne radars have several characteristics which make them good platforms for detecting cruise missiles. First, airborne radars have a much larger radar horizon than ground-based radars. This means that cruise missiles can be detected much earlier than when ground-based systems are used. Thus, an airborne radar can provide warning of a cruise missile attack much earlier than air defenses can. In addition, it might be possible for airborne radars to actually detect cruise missile launches. This information could be used to attack the cruise missile's launch site (whether they are ground-based launchers,

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[105]The cruise missiles being developed by China and India will probably have velocities in this range.

[106]For example, Iran is said to have ordered a dozen Tu-22M3 Backfire bombers which are probably equipped with the Kh-15 (AS-16 Kickback) anti-ship cruise missile. The Kh-15 has a range of 150 km and reaches terminal velocities of Mach 5 (>6000 kph). See Steven Zaloga, "Russia Exporting Top-of-the-Line Weapons," Armed Forces Journal International, December 1992, pp. 42-43, and "Nuclear Notebook," Bulletin of the Atomic Scientists, Jan./Feb. 1993, p. 56.

[107]A vital part of the detection problem is identifying whether given targets are friendly or hostile. This issue is often referred to as the identification friend or foe (IFF) problem. The analyses herein assume that U.S. forces are able to successfully deal with the IFF issue.

[108]A discussion of the other types of airborne radars is provided in both Delaney, Air Defense, and Arthur Charo, Continental Air Defense: A Neglected Dimension of Strategic Defense (Cambridge, Mass.: Center for Science and International Affairs Occasional Paper #7, 1990).

airborne platforms, or seaborne platforms)-a much more effective strategy than, simply shooting down cruise missiles one by one.

Despite their many advantages, airborne radars also face several problems. The most daunting challenge facing airborne systems is clutter rejection. When airborne radars look down towards the ground, they receive returns from the terrain. These radar returns are called clutter. In order to be able to detect a low-flying target, a radar must be able to distinguish between the return from a target and clutter. This is a technologically demanding task requiring advanced processing capabilities and large power-aperture (P-A) products.

The AWACS deal with the clutter problem by using pulse Doppler radars with high pulse repetition frequencies (PRFs).[109] A pulse Doppler radar detects moving targets by comparing the Doppler shift due to clutter with that for a moving platform. The Doppler shift (f_d) due to a moving object is given by: [110]

$$f_d = \frac{2v}{\lambda} \qquad (7)$$

where,
v = the relative velocity between an object and the radar platform, and
λ = the wavelength of the radar.

Because the Doppler shift is proportional to the relative velocity between an object and a radar, the shift for ground clutter will be due to the motion of the radar platform only.[111] Similarly, when ground-based pulse Doppler radars are employed (e.g., the one used with the Patriot surface-to-air missile), the target's Doppler shift will be due to its own motion only. In contrast, returns from a cruise missile moving towards the radar will experience a shift due to both the missile's velocity and that of the radar platform. Hence, the Doppler shift due to the missile will be in a region which is not occupied by ground clutter. The diagram below illustrates this point. [112]

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[109]Curtis D. Schleher, *Introduction to Electronic Warfare (EW)* (Dedham. Mass.: Artech House, *1986),* p. 217. A discussion of the advantages and disadvantage of high-PRP radars is found in Schleher, pp. 216217. A discussion of multiple-PRF radars is found in David H. Mooney and William A. Skillman. "PulseDoppler Radar," in Merrill I. Skolnik, ed., *Radar Handbook* (New York: McGraw-Hill, 1970), pp. 19-13-19-15.

[110]John C. Toomay, *Radar Principles for the Non-Specialist* (New York: Van Nostrand Reinhold, 1989), p. 89.

[111]Other types of clutter which can be problematic include clouds, rain, and wind. See Schleher, *Introduction to EW,* pp. 213-215, and William W. Shrader, "MTI Radar," in Skolnik, *Radar Handbook,* pp. 17-9-17-11.

[112]See Schleher, *Introduction to EW*, p. 283.

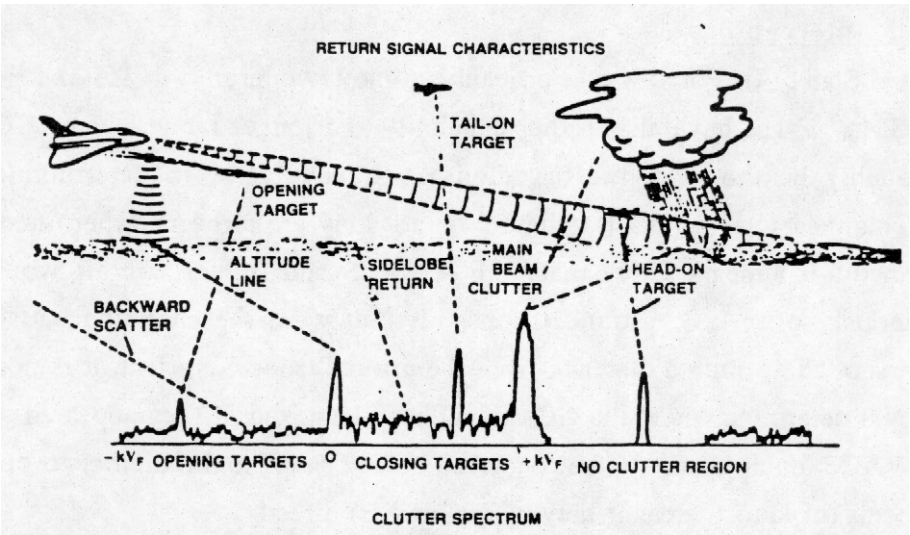

Figure 6. Clutter spectrum for airborne pulse-Doppler radar.
From: *Introduction to Electronic Warfare,* by D. Curtis Schleher (c) 1986, Artech House, Inc., Norwood, MA. Used by permission.

One can see that the signal from a target heading towards an AWACS (also called a closing target) sticks out from the clutter. The greater the velocity of the attacking missile, the more visible it will be. However, the situation becomes more difficult if a target is not moving toward an AWACS (e.g., tail-on targets or opening targets). In that case, the relative velocity of the missile will be in the same region as the ground clutter, which will make it harder to pick out the Doppler shift due to the missile.

The solution to the former problem lies in the processing capabilities of the radar.[113] A measure of a radar's ability to detect a target buried in clutter is its subclutter visibility (SCV). Radars using pulse Doppler processing are able to achieve SCVs in the 80 to 90 dB range.[114] Given the observation that SCVs in the 30 to 50 dB region provide "reasonable performance against moderate' size targets (e.g., RCS = lm^2) in ground clutter," it appears that AWACS should be able to detect non-stealthy cruise missiles in most situations. [115]

Assuming that AWACS can detect cruise missiles in clutter, at what range will those missiles be seen? The AWACS was designed to detect fighters with radar cross sections of 7 square meters at a range of at least 370 km. [116] Using this specification to establish the performance of the AWACS radar, one finds that a 1 m^2 target will be

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[113]For a detailed discussion of this topic, see Ibid., pp. 213-217, and Mooney & Skillman, pp. 19-7-1929.
[114]Schleher, *Introduction to EW, p.* 216.
[115]Ibid. AWACS radars also have extremely low sidelobes--better than -50 dB--which increases their ability to pick targets out of sidelobe clutter. See Ibid., pp. 294-295.
[116]David Hughes, "USAF Will Develop Major Radar Upgrade for Its E-3 AWACS Fleet," *Aviation Week & Space Technology,* January 23, 1989, p. 49.

detected at a range of least 228 km, and a 0.1 m^2 target will be seen at a range of 128 km.[117]

3.2.2 Ground-Based Radars

Ground-based radars have one major disadvantage when compared with airborne radars: they have a much shorter LOS to low-flying targets. The line-of-sight range from a radar to a given target is expressed by the following formula: [118]

$$R_{LOS} = \left(\sqrt{H_R} + \sqrt{H_{CM}}\right)\sqrt{\frac{8}{3}R_E} \qquad (8)$$

where,

R_{LOS} = line-of-sight range (m),

H_R = Altitude of radar (m),

H_{CM} = Altitude of target (m),

R_E = Radius of the earth = 6.378×10^6 (m).

Thus, the maximum detection range against cruise missiles flying at altitudes of 100-300 meters will be 41-71 kilometers if a radar's antenna is at ground-level.[119] If a radar's antenna were elevated, that radar's LOS would increase as shown by the formula above. In this paper, it is assumed that the antennas of ground-based radars are at ground-level--a worst case scenario for the United States.

The U.S. military has a large number of surveillance radars which could be used to detect cruise missiles. However, this paper is concerned mainly with the radars which would be used with land-based air defense systems. The best system for detecting low-flying missiles might be the Improved-HAWK (I-HAWK). The I-HAWK SAM was designed to engage low-altitude targets. The system uses two types of surveillance radars: one for detecting medium to high altitude targets, and one for detecting low altitude targets. Depending on which type of radar is used, the I-HAWK system is capable of detecting a 1

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[117]These estimates are made by using the fact that a radar's detection range is function of a target's RCS raised to the one-fourth power. Hence, the difference in detection range between a target with an RCS of *7 M2* and one with an RCS of 1 m^2 *is* $7^{0.25}$ or a factor of 1.6. Dividing 370 km by 1.6 yields a detection range of ***228*** km.

[118]Skolnik, *Introduction to Radar Systems,* p. 457.

[119]The term "maximum detection range" is used because a radar might not detect a cruise missile right away. Radars use a search pattern to detect targets. Each time a section of sky is searched, there is some probability that a target will be detected. It may take many passes to detect a given target, depending the probabilities of detection and false alarm of the radar, the power-aperture product of the radar, and the radar cross section of the target.

m2 target at a range of 48-79 km.[120] If a target has an RCS of 3 m^2, the detecting range improves to 63-104 km. [121] It is worth noting that the HAWK radars are being upgraded to increase their ability to detect low-altitude targets and to allow them to engage multiple targets simultaneously.

It is possible that the United States' most powerful air defense surveillance radar is the one associated with the Patriot system. One source has estimated that a radar with characteristics similar to those of the Patriot's radar can potentially detect 1 m^2 targets at a range of around 270 km.[122] Even if this estimate is inaccurate, it is probably safe to assume that the Patriot's surveillance radar is more capable than that of the I-HAWK.

The Patriot system was initially designed to detect and intercept medium to high altitude targets; it has been upgraded to improve its performance against low-flying targets. For example, between 1988 and 1991 the Patriot radar gained the ability to use pulse Doppler processing to increase its clutter rejection capabilities.[123] Other advantages of this system are its ability to simultaneously track up to 100 targets, and the fact that the Patriot engagement control center "can display the air picture from an E-3 Sentry AWACS aircraft via an automatic data link ... "[124]

Whatever radar U.S. forces use, the detection range of the system will probably be limited more by its LOS to a cruise missile than by the capabilities of the radar. For example, if a cruise missile is flying at an altitude of 100 meters, a ground-based radar will not be able to see the missile until it is at most 41 km away. Both radars described above could detect a 1m^2 GCM at longer ranges if they were able to see it sooner.

3.3 CRUISE MISSILE INTERCEPTION

U.S. air defenses generally follow two doctrines: forward defense and defense in depth. The goal of the former strategy is "to destroy the attacker as far out as possible, preferably before it leaves its launch pad or airfield."[125] The goal of the latter is to have layers of defense from extremely long ranges all the way back to a target. A defense in depth doctrine would employ manned interceptors for long-range engagements and SAMs for medium- to short-range interceptions. Anti-aircraft guns could also be used as a final line of defense. This paper focuses on manned interceptors and SAMs.

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[120]*Jane's Land-Based Air Defense 1993-94* (Surrey, UK: Jane's Information Group Ltd., 1993) p.282.
[121]Ibid.
[122]George N. Lewis and Theodore A. Postol, "Responding to the Stability Threat Posed by Long-Range Nuclear Cruise Missiles," unpublised manuscript, September 15, 1991.
[123]*Jane's Air Defenses,* p.284.
[124]Ibid., p.287.
[125]Schleher, *Introduction to EW,* p.340.

3.3.1 Manned Interceptors

The United States Air Force would probably employ two aircraft-F-15s and F-16sto intercept LACMs. F-15s have all-weather capability and longer ranges than F-16s, so they would probably be the first line of defense. A key factor in determining the effectiveness of manned interceptors is whether or not they are airborne when incoming GCMs are detected. It appears likely that both AWACS and fighter aircraft would be airborne continuously over U.S. ground troops. If that were the case, then attacking GCMs could be spotted at quite a distance from the ground troops. In fact, it is possible that AWACS could determine where the GCMs had been launched, if they appeared within range of the AWACS' equipment. If that occurred, U.S. forces could attempt to destroy the launch platforms (or launch areas if they were GLCMs) directly.

After the GCMs were detected, AWACS would probably be able to track the missiles fairly well. The AWACS could then guide the interceptors to the GCMs until the fighters were close enough to use their own radars. If the interceptors were unable to shoot down the GCMs, the AWACS could then notify ground-based defenses of the attacking cruise missiles, giving them the GCMs' direction and velocity.

If manned interceptors were not airborne when GCMs were detected, they would have to scramble, find and intercept the cruise missiles before they reached their targets. That could be difficult, depending on the velocity of the attacking missiles. Another potential problem facing interceptors is that they may have to scan large areas of airspace to find incoming GCMs, depending on how well they are vectored to their targets by AWACS. In addition, the radars on board fighter aircraft have a limited power-aperture product due to size constraints. Because of the clutter problem, it is not clear how well these types of radars will be able to track low-flying targets.

Assuming that manned interceptors are able to detect and track their targets, they have to engage those targets. U.S. fighters would probably try to first engage cruise missiles at medium ranges (10-100 km) with air-to-air missiles (AAMs), such as the AIM-7 (Sparrow) and AIM-120A (AMRAAM or Advanced Medium Range Air-to-Air Missile). The Sparrow has a range of 45 km and uses semi-active radar for guidance, which means that the plane must illuminate the target for the Sparrow. The latest version of the Sparrow, the AIM-7M, can perform anti-clutter processing to detect low-flying targets. In addition, the AIM-7M has a new active radar fuze which greatly improves its perfomance at low altitudes.[126]

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[126]See Section 3.3.2 for a detailed discussion of the obstacles facing interceptors using semi-active radar.

The AMRAAM is also a medium-range missile. It has several advantages over the Sparrow, including a higher speed, greater range (50 km vs. 45 km), better maneuverability, and increased resistance to electronic counter measures. In addition, the fact that the AMRAAM uses an active radar terminal seeker means that a plane can fire the missile and then "forget" about it: the missile can detect the target on its own. Despite its advantages, it is not clear if the AMRAAM will be more capable of destroying GCM than the Sparrow.

If neither of the medium-range AAMs succeeded in destroying a GCM, the fighter aircraft would move to closer ranges (less than 10 km). At short ranges, the AIM-9 (Sidewinder) could be used in addition to the longer range systems. In contrast to the two missiles described above, which use radar for terminal guidance, the Sidewinder uses an infra-red (IR) seeker. The advantage of this seeker is that it is not affected by the RCS of the target. While using an IR seeker is beneficial in some encounters (e.g., against aircraft using jet engines), this approach may have problems in low-altitude engagements against cruise missiles because of the thermal radiation coming from the ground. In essence, the Sidewinder will have to deal with IR clutter. Because GCMs may have small IR signatures, the IR clutter problem could be significant.

Overall, the prospects for manned interception of cruise missiles appear to be marginal to good. According to William Delaney, Assistant Director of the Lincoln Laboratories, the most advanced air-to-air missiles, such as the Sparrow, will have a 50 percent probability of succeeding in, a given encounter. [127] Thus, it is likely that several AAMs will have to be used to destroy a GCM.

3.3.2 Surface-To-Air Missiles

There are currently three land-based SAMs which could be used against GPS-guided cruise missiles: Patriot, I-Hawk, and Chaparral. The Patriot air defense system is the newest and most capable SAM fielded by U.S. forces. It is designed to intercept medium- to high-altitude, high-speed targets. The Patriot system should be able to intercept high-flying, supersonic cruise missiles and will do well against cruise missiles flying several hundred meters above the ground. However, if GCMs are able to fly at low altitudes, the Patriot will become less effective. For example, the minimum engagement altitude and range of the Patriot are 60 and 3000 meters, respectively.

A better system for engaging cruise missiles that are flying at low altitudes might be the I-HAWK SAM. Its radars were designed to process ground clutter and it is capable of

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[127] Personal communication with William P. Delaney, January 14, 1993.

illuminating and tracking multiple low-altitude targets to counter saturation attacks.[128] In addition to the radar upgrades mentioned earlier, HAWK missiles are going to receive new fuzes to improve their performance against both tactical ballistic missiles and cruise missiles. [129] Although one source lists the I-HAWK's minimum engagement altitude at 60 m. another source states that the I-HAWK can handle targets flying as low as 15 m.[130]

Another system which might be of some use is the Chaparral SAM. [131] Unlike either the HAWK or the Patriot, Chaparral was specifically designed to intercept lowaltitude targets at short ranges. For example, the minimum engagement altitude is 15 meters and the minimum effective range is only 500 meters.[132] It is worth noting that both the HAWK (including the I-HAWK) and Chaparral systems have been used extensively by Israel in its many conflicts with Arab states: "By March 1989 Israeli Air Force missile units had shot down 42 Arab aircraft by Basic HAWK, Improved HAWK and Chaparral SAMs." [133]

One problem facing both the Patriot and HAWK SAMs is that their missiles use semi-active radars for terminal guidance.[134] The disadvantage of using semi-active guidance is that the radar return from the illuminated target may be quite small for cruise missiles. If the air defense missile is looking down at its target, it will have to pick out the GCM's radar signal from the ground clutter. That may be a difficult task given the limited power-aperture and processing capabilities of air defense missiles.

A potential solution to the problem described above is to engage incoming cruise missiles head-on rather than from above. However, that strategy may face another difficulty: fuzing. It has been documented that at least one air defense missile, the Patriot, uses a "broad, side-looking beam" for intercepting aircraft.[135] When this beam detects an object, it assumes that the object is its desired target and it detonates the missile's warhead. However, if a cruise missile is flying at low altitudes, the Patriot SAM will have to fly

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[128]See *Jane's Air Defense*, pp. 227-282.

[129]Ibid., pp. 278-279.

[130]The former source is *Jane's Air Defense,* p. 282; the latter source is Schleher, *Introduction to EW,* p. 350.

[131]Chaparral is a system from the 1960's which was designed to fire modified Sidewinder (AIM-9D) missiles. However, the system is being upgraded to meet future short-range air defense requirements. *Jane's Air Defense, p.162.*

[132]Ibid., p. 163.

[133]Ibid., p. 279.

[134]The problems described in the following two paragraphs also affect AAMs attempting to engage low-altitude targets. Note, for example, that the new Sparrow will have both increased clutter rejection capabilities and an active radar fuze.

135George N. Lewis and Theodore A. Postol, "Vidoe Evidence on the Effectiveness of Patriot during the 1991 Gulf War," *Science & Global Security,* Volume 4 (1993), p.58.

parallel to the ground to hit the cruise missile head-on. The problem here is that the Patriot might fly by an object which would be detected by its sensors. If that occurs, the Patriot will think it is flying by a cruise missile and explode. The U.S. military is clearly aware of the fuzing difficulties facing its SAMs and is planning to upgrade both the fuzing mechanisms of both the Patriot and the HAWK interceptors.[136]

Overall, it appears that land-based air defenses could do well against GCMs. It is difficult to be more specific because there are so many potential variables at work. For example, SAMs using semi-active guidance will have to deal with a significant clutter problem if they approach targets from above (the Most likely scenario). It is hard to predict how well U.S. systems will perform in such engagements. The U.S. military is aware of the problems facing its air defense systems and is taking steps to correct those problems. While the upgrades that are planned for the Patriot and HAWK SAMs will undoubtedly improve the performance of these systems against GCMs, it is possible that the GCMs which the United States will face in the future will provide a greater challenge as well. For example, low-flying cruise missiles incorporating stealth technologies are much harder to detect and intercept than "poor man's cruise missiles."

3.3.3 Summary

It is difficult to give an overall assessment of the ability of the United States to intercept GPS-guided cruise missiles. It appears that U.S. forces will be able to intercept the types of cruise missiles they are likely to face in the near future: "poor man's cruise missiles," converted ASCMs, and converted UAVs. Patriot should be able to intercept medium- to high-altitude weapons and supersonic missiles without much difficulty. The capability of Patriot against low-flying cruise missiles is more uncertain, but both the IHAWK and Chaparral SAMs should do reasonably well against such targets. Manned interceptors are likely to do well against medium- and high-altitude cruise missiles, but may have a harder time against low-altitude missiles.

Whatever defense is used, a concentrated attack on a specific target by a large number of missiles might pose a problem for U.S. forces. For example, if 20 or 30 GCMs attacked a given SAM cite, that air defense unit might not be able to simultaneously track and intercept all the missiles; some would probably get through. The U.S. military has developed air defense systems which are capable of tracking multiple targets in order to prevent saturation attacks from succeeding. It appears that only time will tell whether the United States has accomplished its goal.

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[136]A description of the improvements planned for the Patriot are described in *Jane's Air Defense,* p.288.

From the point of view of Third World nations, saturation attacks appear to be a good strategy if individual missiles are inexpensive and have a low probability of penetrating U.S. air defenses. These characteristics describe "poor man's cruise missiles" well. Hence, it is possible that such attacks could be launched against U.S. forces by Third World nations. The feasibility of this strategy for an attacker would depend on the specifics of a given situation (e.g., the number of cruise missiles available, their physical characteristics, the type and number of air defenses, the type and number of targets) and the costs of this plan relative to other strategies.

It is also important to point out that a cruise missile attack, even if it does not succeed in causing a great deal of damage, could greatly complicate matters for U.S. forces. For example, an LDC could launch both ballistic and cruise missiles against U.S. targets simultaneously. The different characteristics of these two vehicles-ballistic missiles would be high-velocity, high-altitude targets while cruise missiles would be low-velocity, low-altitude targets-could stress the abilities of U.S. air defenses.

Another issue to keep in mind is that detecting and intercepting a cruise missile attack would occupy a variety of U.S. assets, including surveillance systems (both airborne and ground-based), $C^3$1 (command, control, communications, and intelligence) resources, tracking and IFF cedars, manned interceptors, and several air defense systems. All these assets might be diverted from other, more important roles, in order to address the cruise missile threat. In that sense, even "poor man's cruise missiles" could play a militarily significant role in a conflict with the United States.

A final issue which might be of concern to the U.S. military is the cost associated with intercepting Third World GCMs. Ground-to-air and air-to-air missiles can be quite expensive. In addition to the missiles themselves, the costs of the support systems for both ground-based and airborne interceptors (e.g., radars, personnel, fuel) must be taken into account. In contrast to the U.S. systems, the costs associated with a Third World GCM will probably be quite modest-especially if "poor man's cruise missiles" are developed. For example, U.S. Army Major General Jay Garner estimated an enemy "could spend $50 million to build 100 low-cost cruise missiles," while the United States is planning on spending $5 billion on its Corps SAM system. [137] The key calculation is whether the cost of not intercepting GCMs is lower than the costs of intercepting them.

[137] Burgess and Munro, "New Uses," p. 10. In all likelihood, the cost estimates for the "low-cost" cruise missiles are too high, and those for the Corps SAM are too low.

3.4 JAMMING

Another countermeasure which could be useful against GCMs is electronic jamming. GPS signals are susceptible to jamming for two reasons: they are transmitted at known frequencies and their power is extremely low when they reach the earth (the C/A-code has a typical power amplitude of 10^{-16} Watts-that's a billionth of a billionth of the power of a typical light bulb). The spread-spectrum techniques employed by the GPS system amplify the power of the C/A-code by 60 dB (a factor of a million), but even with that gain, the signal strength of GPS remains weak and, therefore, easily susceptible to jamming. However, there are some anti jam technologies which could be used to further increase a user's resistance to electronic suppression.

The benefit of utilizing jamming against GCMs is that it is a relatively inexpensive and simple defense which does not draw U.S. forces away from other missions. [138] On the other hand, the cruise missiles themselves will not be destroyed; they will simply lose GPS guidance. At that point, the missiles will rely on their back-up navigation systems, which almost certainly will be inertial navigation systems.[139] Although INSs offer the advantages of being both jam-proof and easily acquired, they have one significant drawback: the physical forces affecting an INS cause its position uncertainty to grow with time. This "inertial drift" will cause the accuracy of a cruise missile to decrease the longer an INS is used. Thus, the net effect of jamming a GCM is to decrease the accuracy, and hence the lethality, of that weapon. The specific drop in lethality depends on the range at which a missile is jammed, the quality of its INS, and the velocity of the cruise missile.

The effectiveness of jamming also depends on timing. Jamming a GCM during its mid-course can have a different impact than jamming a GCM during its terminal phase. For example, if a cruise missile is using a terminal seeker, then jamming during the terminal phase would not be useful. Another important consideration is that GPS receivers are often able to reacquire lock soon after exiting a jamming environment. [140] Thus, a GCM which is jammed during its mid-course will have to be continually jammed or it might be able to reacquire GPS and get back on its original flight path. This paper assumes that GCMs are jammed continually from the time they come into the line-of-sight of the jammer until they reach their targets. It is also assumed that the jammers are co-located

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[138]A jammer basically consists of a power generator, some signal processing equipment, and an antenna.

[139]Some kind of altimeter will also be required.

[140]A P-code receiver developed for the military by Magnavox can reacquire track in 26 seconds or less. See Anil K. Aggarwal, "Euronav™--A State of the Art Military GPS Receiver," IEEE Position, Location and Navigation Symposium, Orlando, Fla., 1988.

with the GCM's targets. In other words, the ground-based jammers are sitting at the targets and the airborne jammers are flying directly over the targets.

Interestingly, it is probably easier for American forces to jam DGPS radio links than it is to jam GPS signals. [141] Because DGPS signals are usually transmitted via standard radio frequencies, it would be a straightforward task for U.S. troops to monitor a transmitted DGPS signal and determine its source. U.S. forces could then either jam (or spoof) the signal or could attempt to physically destroy the transmitter. Even if more robust DGPS communications links were developed, DGPS corrections would be useless once a GPS receiver was jammed.

Another problem associated with jamming is that one can jam one's own forces. If, for example, a U.S. ground-based jammer based at an airfield is emitting electromagnetic energy at GPS frequencies, any U.S. planes utilizing GPS which fly in front of that jammer will risk being jammed. Given the rapid spread of GPS receivers among all the services, it is possible that self-jamming could become a problem much like friendly fire. One potential solution is to use jammers with directional antennas (i.e., jammers which transmit their energy in narrow beams). Directional antennas would decrease the probability of self jamming and also provide higher gain for the jamming signals. In order for these jammers to be effective, their operators will have to be continuously tracking their targets, otherwise the GCMs would be able to reacquire the GPS signals. Thus, effective use of directional jammers is highly dependent on the ability of U.S. forces to detect and track cruise missiles. If attacking cruise missiles cannot be tracked, jammers will have to be transmitting continuously. This could disrupt one's own military operations.

3.4.1 Inertial Aiding

Inertial navigation systems can serve another function besides acting as a "back-up" guidance package: they can make GPS receivers more resistant to jamming. INSs accomplish this feat by tracking the dynamics of the host vehicle, which allows the tracking loops in a GPS receiver to narrow their bandwidths which, in turn, prevents noise from entering the system.[142] The amount of jammer suppression associated with inertial aiding is about 10-15 dB (a factor of 10-30). This paper assumes that the GCMs attacking U.S. forces are inertially aided and that they gain 13 dB of jammer resistance from that arrangement.

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[141] Although DGPS transmissions are generally more powerful than the GPS L-Band signals, they do not gain the benefits of the spread-spectrum signal structure associated with GPS. A good discussion of DGPS transmissions is presented in Richard B. Langley, "Communication Links for DGPS," *GPS World,* May 1993, pp.47-51.

[142] A more technical discussion of this issue can be found in a variety of sources, including Cox, "Integration of GPS."

3.4.2 GPS Receiver Loss-Of-Lock

In order for GPS receivers to function properly, the GPS signal must be strong enough to be distinguished from the background noise present in the atmosphere. The relationship between the GPS signal power and the noise signal power is call the signal-to-noise ratio and is denoted by: SIN. The value of SIN varies with different receivers, but is probably around 30 dB for civilian equipment.[143]

The power of a jammer is often expressed in terms of the signal it is trying to disrupt. The term that is used is the jammer-to-signal ratio or J/S. The magnitude of J/S required to jam a given GPS user depends on the S/N of the receiver and the anti-jam capabilities of the system. If no anti jam technologies are present, the only jammer resistance in the system will be provided by the spread-spectrum nature of the GPS signals. Hence the general relationship, assuming a C/A-code receiver is used, is: [144]

$$\left(\frac{J}{S}\right)_{dB} = 60 + (AJ)_{dB} - \left(\frac{C}{N}\right)_{dB} \qquad (9)$$

If no anti jam technologies are used, the equation reduces to:

$$\left(\frac{J}{S}\right)_{dB} = 60 - \left(\frac{C}{N}\right)_{dB} \qquad (10)$$

3.4.3 Range From Jammer At Loss-Of-Lock

Given the JSR required to jam a given GPS receiver, we must next determine the range from the jammer at which this threshold is reached. The range at which the jamming power is sufficient to reach or surpass the threshold value of the receiver is given by: [145]

$$R_J = \frac{\lambda}{4\pi}\sqrt{\frac{J_0}{S}\left(\frac{J}{S}\right)_T^{-1}} \qquad (11)$$

where,

R_J = the jamming range (m),

λ = the wavelength of L_1 GPS carrier (m),

J_O = the effective radiated power (ERP) of the jamming signal,

S = the power of the GPS signal,

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[143] Aggarwal, "Euronav™," p. 162.

[144] The equation uses C/N rather than S/N to indicate that this is the signal strength after processing. See N. B. Hemesath, "Performance Enhancements of GPS User Equipment," *Global* Positioning *System, Vol. 1* (Washington, D.C.: Institute of Navigation, 1980) p. 104.

[145] G. Frost and B. Schweitzer, "Operational Issues for GPS-Aided Precision Missiles," Institute of Navigation National Technical Meeting, San Francisco, Calif., January 20-22, 1993.

$\left(\frac{J}{S}\right)_T$ = the JSR required to jam the GPS receiver.

Figure 7 shows jamming range as a function of jammer power for a typical civilian receiver. If the receiver is unaided, it will be jammed when the JSR is equal to 30 dB, 146 If the receiver is inertially-aided, a JSR equal to 43 dB is required. One can see that the jamming range in the latter case is reduced by a factor of about 4.5 (the square root of 20).

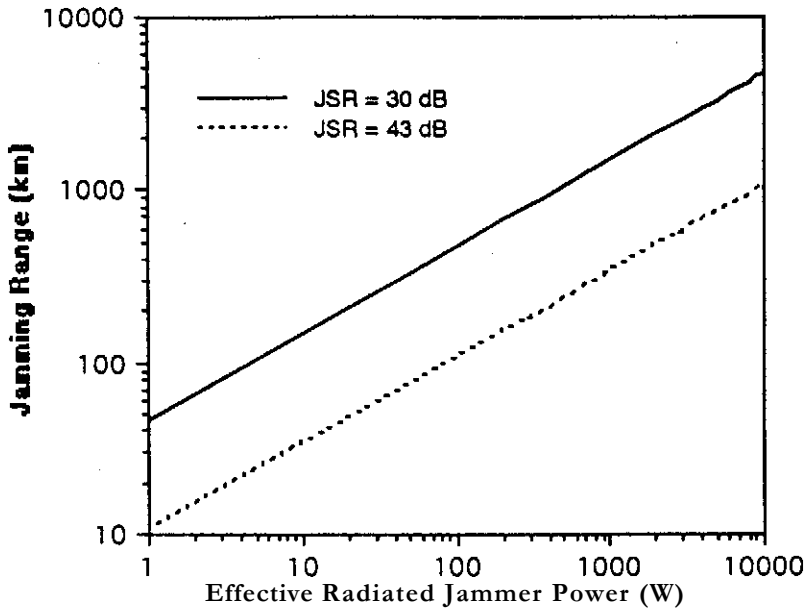

Figure 7. Jamming range vs. Jammer power.

Given the effective radiated power (ERP) of a jammer, one can determine the range at which a GCM will be jammed. It is then possible, given the drift rate of a missile's INS and its velocity, to calculate a cruise missile's CEP as a function of that jamming range. Finally, the errors due to inertial drift and those due to navigation uncertainties, including targeting errors and errors due to the terminal dive, can be combined to obtain the net CEP of a jammed GCM. However, the first step is to examine the differences between airborne and ground-based jammers.

3.4.4 Airborne vs. Ground-Based Jammers

In assessing the utility of jamming as a countermeasure against GCMs, one must be careful to examine both ground-based and airborne jammers. Ground-based jammers can be extremely large and powerful. Additionally, a large number of inexpensive, low power

[146]This value was derived using the equations above. It has been confirmed experimentally by John I. R. Owen, "A Review of the Interference Resistance of SPS GPS Receivers for Aviation," *Navigation: Journal of The Institute of Navigation,* Vol. 40, No. 3 (Fall 1993). pp. 249-259.

jammers could be used to protect an area. On the down side, powerful jammers make prime targets for attacking forces. Another disadvantage of ground-based jammers is due to the fact that GPS antennas must be mounted on top of cruise missiles in order to see the NAVSTAR satellites. Thus, a cruise missile's body can physically shield a GPS antenna from jamming signals. GPS receivers can gain an extra 10-20 dB of jammer rejection from this shielding.[147] Finally, the LOS limitations faced by ground-based jammers can be a serious handicap against low-flying cruise missiles.

Airborne jammers have several advantages which make them ideal for use against GPS-guided cruise missiles. First, airborne jammers are not limited to short jammer horizons. Second, because a GPS antenna must be mounted on top of a cruise missiles to have a clear view of the NAVSTAR satellites, a cruise missile's body will not provide any protection against airborne jammers.

However, airborne jammers face some of the same problems as airborne interceptors. First, the airborne platforms must have enough warning time to intercept the incoming cruise missiles. This means that a cruise missile must be detected by an AWACS. Second, jammers must jam attacking cruise missiles far enough from their targets that the cruise missiles' accuracies degrade significantly, otherwise airborne jamming would be of little benefit. The only way that airplanes could accomplish that task is if they were already airborne. Finally, the interception must be coordinated in space and time to prevent the jamming of friendly forces.

The following two sections assess the capabilities of both ground-based and airborne jammers against GCMs.

3.4.4.1 Ground-Based Jamming

The LOS limits facing an electromagnetic jammer are the same as those facing a radar. Thus, cruise missiles flying at altitudes of 100 and 300 meters will be jammed at ranges of 41 and 71 km, respectively, assuming that the jammers they face are powerful enough to cause loss-of-lock at those ranges.[148] In fact, as Figures 8 and 9 demonstrate, low-flying missiles can achieve fairly high accuracies against ground-based jammers if they use high-quality INSs.

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[147]Frost and Schweitzer, (page number unavailable).

[148]Using equation (11), one sees that for inertially aided cruise missiles, jammers must transmit ERPs of 15 and 45 Watts to jam GCMs out to 41 and 71 km, respectively. However, if one assumes that the GPS receivers on the GCMs gain an extra 15 dB of anti jam capability due to shielding from the cruise missiles' bodies, the jammer ERP requirements climb to about 460 and 1400 Watts, respectively.

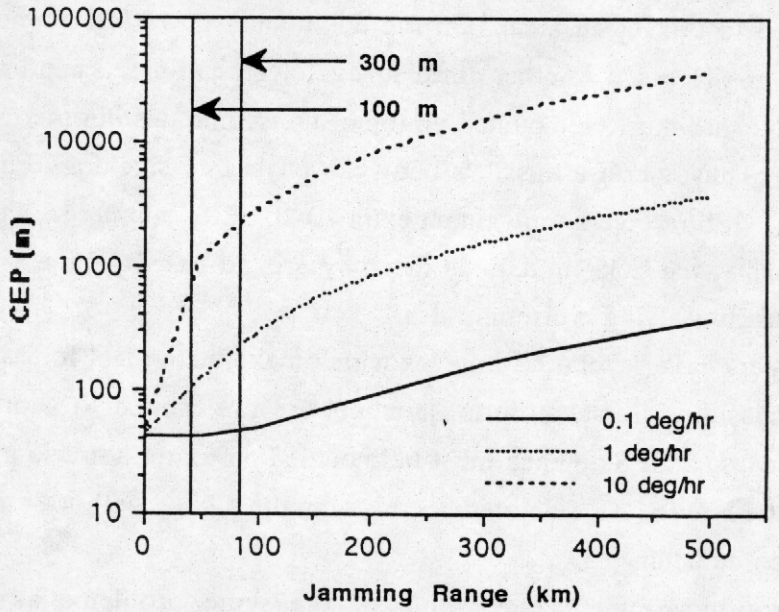

Figure 8. CEP vs. jamming range for GPS-guided cruise missiles.

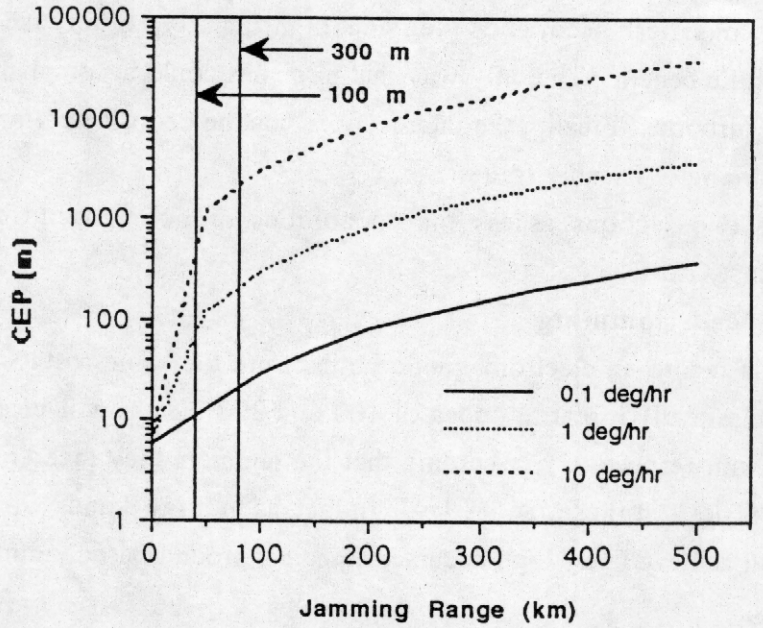

Figure 9. CEP vs. jamming range for DGPS-guided cruise missiles.

Tables 27 and 28 show how LOS limits affect the CEP of a jammed GCM.

Table 27. Approximate CEP (meters) Given LOS Limits with SPS Guidance

CM Altitude	0.1 deg/hr	1 deg/hr	10 deg/hr
100 m	40	100	700
300 m	50	200	2000

Table 28. Approximate CEP (meters) Given LOS Limits with DGPS Guidance

CM Altitude	0.1 deg/hr	1 deg/hr	10 deg/hr
100 m	10	70	400
300 m	20	200	2000

The most striking finding is the difference in CEP due to the higher drift rate of the 10 deg/hr INS. A cruise missile utilizing a 0.1 deg/hr INS will be almost as accurate when jammed at the LOS limit of a ground-based jammer as it would be if it were not jammed at all-even at an altitude of 300 meters. However, as the inertial drift rates increase, the accuracy of a jammed cruise missile begins to drop. In addition, the importance of a cruise missile's altitude grows concurrently with the growth of an INS's drift rate; a cruise missile utilizing a 10 deg/hr INS will have a much lower CEP if it flies at 100 m than if it flies at 300 m. Similarly, the benefits of using DGPS are most evident when high-quality INSs are used: as the drift rates of the INS become large, the navigation errors due to INS drift drown out the initial navigation error due to the GPS guidance.

The total error of a jammed cruise missile at its target will be the root-sum-square of the errors due to INS drift, the errors due to its vertical position uncertainty (including those due to the cruise missile's terminal dive), and targeting errors. The latter errors were described in Section 2.1. Combining the CEPs calculated previously with the CEPs derived above leads to the following effective CEPs for a cruise missile flying at 100 meters facing a ground-based jammer (assuming the cruise missile dive angle is 45 degrees).

Table 29. Effective CEP (meters) of Cruise Missile Using SPS and a Low-Quality Altimeter Jammed at LOS = 41 km (100 m Altitude)

Targeting Error	0.1 deg/hr	1.0 deg/hr	10 deg/hr
5 m	63	111	702
15 m	65	112	702
30 m	70	114	702
50 m	80	121	703

Table 30. Effective CEP (meters) of Cruise Missile Using SPS and a High-Quality Altimeter Jammed at LOS = 41 km (100 m Altitude)

Targeting Error	0.1 deg/hr	1.0 deg/hr	10 deg/hr
5 m	42	100	702
15 m	45	101	702
30 m	52	104	702
50 m	65	112	703

Table 31. Effective CEP (meters) of Cruise Missile Using DGPS and a Low-Quality Altimeter Jammed at LOS = 41 km (100 m Altitude)

Targeting Error	0.1 deg/hr	1.0 deg/hr	10 deg/hr
5 m	46	83	403
15 m	48	85	403
30 m	55	88	404
50 m	68	97	406

Table 32. Effective CEP (meters) of Cruise Missile Using DGPS and a High-Quality Altimeter Jammed at LOS = 41 km (100 m Altitude)

Targeting Error	0.1 deg/hr	1.0 deg/hr	10 deg/hr
5m	12	70	400
15 m	18	72	400
30m	32	76	401
50 m	51	86	403

When 0. 1 deg/hr INSs are used, the drift errors are small enough that a jammed GCMs' CEP is dominated either by navigation or targeting errors. On the other hand, when 1.0 deg/hr or 10 deg/hr INSs are used, the inertial drift errors dominate all other error sources. Referring back to Tables 12-17, it appears that the P_ks associated with GCMs using 1.0 or 10 deg/hr INSs will be small. For example, the most lethal case-a missile with a payload of 400 kg of HE using a 1.0 deg/hr INS-will have a SSPK of only 0.21 against soft targets. The scenarios examined below assume that jammed GCMs utilize 0.1 deg/hr INSs.

Table 33. Effective P_k (%) of Cruise Missile with 400 kg of HE Using SPS Jammed at 100 m Altitude

	Low-Quality Alt.		High-quality Alt.	
Targeting Error	10 psi	40 psi	10 psi	40 psi
5 m	24	5	47	11
15 m	23	5	42	9
30 m	20	4	34	7
50 m	16	3	23	5

Table 34. Effective P_k (%) of Cruise Missile with 400 kg of HE Using DGPS Jammed at 100 m Altitude

	Low-Quality Alt.		High-quality Alt.	
Targeting Error	10 psi	40 psi	10 psi	40 psi
5 m	41	9	100	75
15 m	38	8	97	46
30 m	31	6	66	18
50 m	21	4	35	7

Table 35. Effective P_k (%) of Cruise Missile with 125 kg of HE Using SPS Jammed at 100 m Altitude

	Low-Quality Alt.		High-quality Alt.	
Targeting Error	10 psi	40 psi	10 psi	40 psi
5 m	16	3	33	6
15 m	15	3	30	6
30 m	13	2	23	4
50 m	10	2	15	3

Table 36. Effective P_k (%) of Cruise Missile with
125 kg of HE Using DGPS Jammed at 100 m Altitude

	Low-Quality Alt.		High-quality Alt.	
Targeting Error	10 psi	40 psi	10 psi	40 psi
5 m	28	5	99	56
15 m	27	5	89	30
30 m	21	4	50	11
50 m	14	3	24	4

Table 37. Comparison of Effective P_ks (%) of Cruise Missiles with
125 kg of HE Using SPS & DGPS Jammed at 100 m Altitude

	Low-Quality Altimeter				High-Quality Altimeter			
	10 psi		40 psi		10 psi		40 psi	
T. E.	SPS	DGPS	SPS	DGPS	SPS	DGPS	SPS	DGPS
5m	16	28	3	5	33	99	6	56
15 m	15	27	3	5	30	89	6	30
30m	13	21	2	4	23	50	4	11
50 m	10	14	2	3	15	24	3	4

T. E. = Targeting Error

Table 38. Effective P_k (%) of Cruise Missile
with 50 kg of HE Using SPS Jammed at 100 m Altitude

	Low-Quality Alt.		High-quality Alt.	
Targeting Error	10 psi	40 psi	10 psi	40 psi
5m	9	2	19	4
15 m	8	2	17	3
30 m	7	1	13	3
50m	6	1	8	2

Table 39. Effective Pk (%) of Cruise Missile with 50 kg of HE Using DGPS Jammed at 100 m Altitude

	Low-Quality Alt.		High-quality Alt.	
Targeting Error	10 psi	40 psi	10 psi	40 psi
5 m	16	3	92	38
15 m	15	3	68	19
30m	11	2	30	7
50 m	8	1	13	3

As expected, the most lethal GCMs-and the only ones which pose a serious threat to reinforced targets-are those which combine DGPS guidance with high-quality altimeters and small targeting errors. The benefits of DGPS diminish significantly if low-quality altimeters are used or if targeting errors are large. GCMs using low-quality altimeters pose roughly the same threat as GCMs utilizing the SPS and high-quality altimeters. These missiles pose low to marginal threats to soft targets, depending on their payload. GCMs using the SPS and low-quality altimeters pose little threat to soft targets unless their payload is large; in that case, the threat is marginal (P_k = 0.24 at best) .

Overall, it appears that ground-based jamming can be quite effective in minimizing the lethality of GCMs. Cruise missiles utilizing INSs with draft rates above 1.0 deg/hr will pose little threat to soft targets, let alone reinforced targets. However, GCMs using INSs with drift rates of 0.1 deg/hr can pose a serious threat to military targets. In particular, large-payload missiles that use both DGPS and high-quality altimeters, and have small targeting errors, will obtain high P_ks against reinforced targets.

Area targets will face significant threats from jammed GCMs using 0.1 deg/hr INSs. GCMs using 1.0 deg/hr INSs may pose a risk to large area targets if they are using DGPS and have small targeting errors. Otherwise, the threat posed by such missiles will be minimal. GCMs using 10.0 deg/hr INS pose little threat to area targets unless those targets have radii of several hundred meters.

Finally, two points should be remembered. First, this analysis assumed that Third World GCMs would be flying at an altitude of 100 meters. While it is unlikely that such cruise missiles will be able to fly lower in the near future, they might fly higher (e.g., at 300 meters). If that were the case, cruise missiles utilizing 1 deg/hr INSs or worse would be much less lethal than the ones analyzed above (see Tables 20 and 21). If 0.1 deg/hr INSs were used, the, lethality of the higher flying cruise missile would be slightly

diminished. Of course, cruise missiles flying at 300 m would be much easier to detect and shoot down than those flying at 100 m.

Second, it was assumed that the cruise missiles modeled above were flying at 800 kph. If the cruise missiles were using turboprops rather than turbofans (i.e., if "poor man's cruise missiles" were used), they would probably fly between 150 and 400 kph. At best, such cruise missiles would take twice as long to reach their targets after they were jammed as those examined here. Because INS drift errors vary approximately as time squared, the navigation errors of jammed GCMs traveling at 400 kph would be four times as large as those computed above. If the GCMs were flying at 200 kph, those CEPs would be 16 times as large. Hence, jamming will probably be quite effective against "poor man's cruise missiles." By the same token, jamming is likely to be less effective against supersonic cruise missiles. For example, a jammed GCM flying at 1600 kph (Mach 1.3) would have a navigation CEP which is one-fourth as large as that of a GCM flying at 800 kph. A GCM flying at Mach 3 (about 3600 kph) would have a navigation CEP which was 20 times smaller.

The following tables calculate the CEPs due to inertial drift for cruise missiles flying at 400 kph. One can see that GCMs using the SPS pose little threat to either point or area targets. DGCM flying at 100 meters pose a significant threat to point targets if they are using 0.1 deg/hr INSs. DGCMs flying at 300 meters have low Pks against point targets, but can threaten area targets if they use the highest quality INSs.

Table 40. Approximate CEP (meters) Given LOS Limits with SPS Guidance and Velocity = 400 kph

Altitude	0.1 deg/hr	1 deg/hr	10 deg/hr
100 m	160	400	2800
300 m	200	800	8000

Table 41. Approximate CEP (meters) Given LOS Limits with DGPS Guidance and Velocity = 400 kph

Altitude	0.1 deg/hr	1 deg/hr	10 deg/hr
100 m	40	280	1600
300 m	80	800	8000

In contrast, the following tables perform the same calculations for cruise missiles flying at 1600 kph. It is evident that supersonic cruise missiles have much smaller inertial

drift errors than subsonic cruise missiles. In fact, supersonic GCMs using 1.0 deg/hr INSs can be quite lethal. Even GCMs using 10.0 deg/hr INSs can threaten large area targets if the missiles fly at 100 meter altitudes.

Table 42. Approximate CEP (meters) Given LOS Limits with SPS Guidance and Velocity = 1600 kph

Altitude	0.1 deg/hr	1 deg/hr	10 deg/hr
100 m	10	25	175
300 m	13	50	500

Table 43. Approximate CEP (meters) Given LOS Limits with DGPS Guidance and Velocity = 1600 kph

Altitude	0.1 deg/hr	1 deg/hr	10 deg/hr
100 m	3	18	100
300 m	5	50	500

3.4.4.2 Airborne Jamming

As mentioned earlier, an airborne jammer will have a much longer LOS than a ground-based jammer. For example, a jammer at an altitude of 2 km will be able to see GCMs flying at an altitude of 100 meters out to 190 km. [149] Another advantage of airborne jammers is that GCMs will not have the extra 10-20 dB of jammer rejection they gain against ground-based jammers from the cruise missile's body shielding. Thus, the ERP required to cause an inertially-aided GCM to lose lock at a range of 190 km is only 310 Watts rather than the 9940 Watts which would be required if 15 dB of anti-jam were present due to shielding.

Because airborne platforms can jam GCMs at much longer ranges than groundbased jammers can, GCMs jammed by these platforms will be less accurate than those jammed by ground-based jammers. Figures 10 and 11 show CEP as a function of jamming range assuming an airborne jammer is flying at a height of 2 kilometers.

[149] 1f the cruise missile was flying at an altitude of 300 m, the LOS would be 200 km. Thus, a significant change in a cruise missile's altitude--from 100 to 300 m--has a major impact on the LOS of a ground-based jammer but almost no effect on the LOS of an airborne jammer.

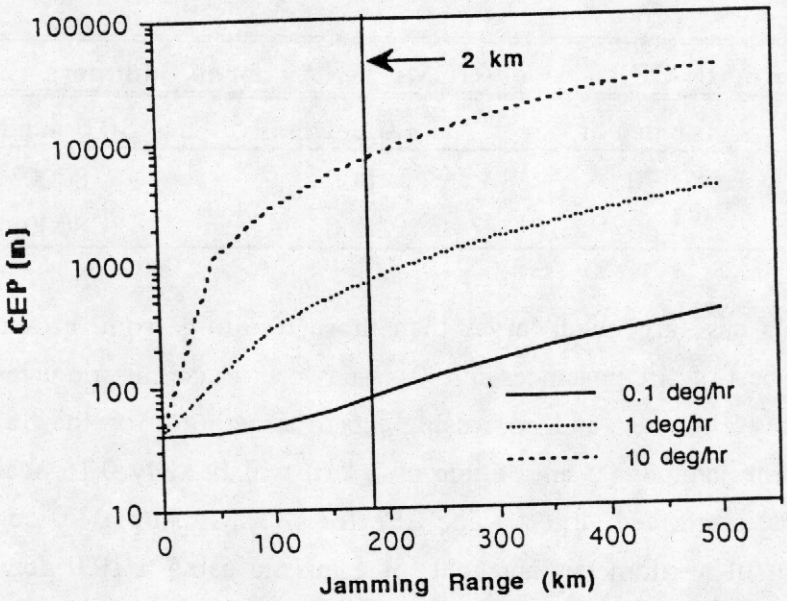

Figure 10. CEP vs. jamming range for airborne jammer against GCM using SPS.

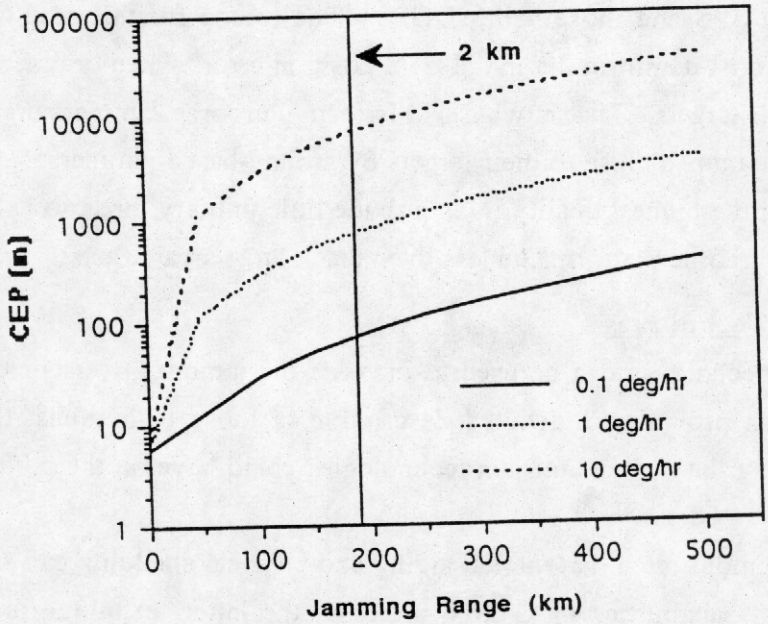

Figure 11. CEP vs. jamming range for airborne jammer against GCM using DGPS.

The findings of these two graphs can be summarized in Table 44.

Table 44. Approximate CEP (m) of GCMs vs. Airborne Jammers (2 km)

Guidance	0.1 deg/hr	1.0 deg/hr	10.0 deg/hr
SA	90	800	8000
DGPS	80	800	8000

The drift errors in this case are much larger than those resulting from ground-based jamming. Even in the best of circumstances-a 400 kg-payload cruise missile using DGPS guidance, a high-quality altimeter, and possessing a 5 m targeting error-the SSPK of a GCM facing an airborne jammer (at an altitude of 2 km) will be only 0.16 against soft targets and 0.05 against reinforced targets. The CEP for a GCM using a 1.0 deg/hr INS would be on the order of a kilometer, and that for a missile using a 10.0 deg/hr INSs would be eight kilometers!

Again, one can see that the lethality of a jammed GCM is highly dependent upon the quality of its INS. Another finding is that there is almost no difference between cruise missiles utilizing the SPS and those using DGPS. The reason for this result is that the errors due to inertial drift dominate the initial GPS position errors when cruise missiles are jammed far from their targets. That is why GCMs facing airborne jammers are less lethal than those which are jammed close to their targets by ground-based jammers. In fact, even those GCMs utilizing the highest quality INSs provide little military threat to U.S. forces if they are jammed by airborne platforms, unless they attack large area targets.

3.4.5 Anti-,lam Techniques

A variety of techniques can be used to increase the jamming resistance of a GPS receiver. Rather than providing a detailed description of those techniques, this section proceeds by discussing the impact anti-jam technologies could have on the performance of
GCMs facing U.S. jammers.[150]

It has been demonstrated that inertial aiding and physical shielding can significantly increase the anti-jam capabilities of GCMs, although the latter technique is not useful against airborne jammers. The only other anti-jam technologies that are likely to be a problem for U.S. jammers are adaptive null-steering antennas (also known as controlled

[150] The interested reader should refer to Hemesath, "Performance Enhancements; and Irving Lachow, "GPS and Cruise Missile Proliferation: Assessing The Impact of Anti-Jam Techniques on Mission Performance," Institute of Navigation 49th Annual Meeting, Cambridge, Mass., June 21-23, 1993.

radiation pattern antennas or CRPAs).[151] CRPAs have several characteristics which make them extremely useful. First, they can suppress several jammers simultaneously.[152] Second, they work against most types of jamming signals.[153] Finally, they provide a great deal of jammer suppression. Theoretically, CRPAs can give a user up to 50 dB of jammer rejection. In practice, the amount of jammer rejection one can obtain depends on the dynamics of the vehicle on which a CRPA is mounted and on the type of jamming signal. It is probably safe to assume that a GCM using a CRPA would be able to gain at least 25 dB of jammer suppression. [154]

Despite the tremendous benefits a Third World nation can gain by using a CRPA, there are two major obstacles which an LDC must overcome. First, CRPA technologies are extremely advanced. It is highly unlikely that an LDC will be able to develop CRPAs in the near future. Second, CRPAs are export controlled. Hence, acquisition of a CRPA from the developed world would not be easy. Thus, it appears doubtful that U.S. forces will face GCM utilizing CRPA technologies any time soon. However, if LDC are able to acquire CRPAs, the affect they will have on GCM mission performance against jammers will be significant. For example, Table 45 shows the tremendous increase in jammer power required to jam GCMs at their LOS limits if CRPAs are used.[155] It assumes that a ground-based jammer is used, and that the cruise missile is flying at either 100 m or 300 m altitude. Clearly, the acquisition of CRPA technologies should continue to be of concern to the United States.

Table 45. Jammer ERP Requirements (W) vs. Anti-Jam Technologies

LOS Range (km)	INS only	INS + Shielding	INS + Shielding +CRPA
41	15	460	145,000
71	45	1500	437,000

[151]GCMs using a terrain avoidance flight plan might be able to place natural obstacles between themselves and ground-based jammers. However, this strategy requires knowledge of jammer locations which might be difficult to obtain since most jammers are mobile. It also would not work well against airborne jammers.

[152]A typical CRPA used by the United States is a seven element phased-array antenna which can simultaneously null six separate jammers. A three element CRPA. which can jam two jammers simultaneously, is being designed for the Tomahawk.

[153]Many anti-jam techniques have trouble with broadband jammers.

[154]Mark Hewish, "Integrated INS/GPS Takes Off In The US," *International Defense Review,* February 1993, pp. 172-174.

[155]Inertially-aided GCMs facing ground-based jammers will be able to gain 28 dB of jammer suppression without CRPAs, and 53 dB of jammer suppression with CRPAs. GCMs facing airborne jammers will have 13 dB of jammer suppression without CRPAs, and 38 dB with CRPAs.

3.4.6 Summary Of Jamming

The effectiveness of jamming as a countermeasure against GCMs depends on a variety of factors, including the range at which a GCM is jammed, the quality of the INS system a GCM is using, the type of guidance a GCM is using, and the velocity of a GCM. The analysis performed above indicates that electronic jamming will probably be quite useful in reducing the lethality of GCMs U.S. forces are likely to face. In comparing the utility of ground-based and airborne jammers, I found that airborne jammers provide more protection due to their longer LOS to low-flying cruise missiles. However, it will be difficult for airborne jammers to take advantage of that characteristic unless they are already airborne when GCMs are detected-a situation' which appears likely.[156] Ground-based jammers appear to do a good job in reducing GCM lethality, but they could potentially jam friendly forces which are in front of them. In sum, both types of jammers are useful in reducing the threat of GCMs, but airborne jammers have several advantages which make them preferable.

3.5 JAMMING VS. INTERCEPTION

Each of the countermeasures studied in this paper has some advantages and some disadvantages. The chart below summarizes those that have been discussed in this paper.

	Jamming	**Interception**
Advantages	Inexpensive. Jammers are dedicated to task.	Cruise missiles destroyed. More effective at close ranges.
Disadvantages	Cruise missiles not destroyed. Self-jamming possible. Quick GPS reacquisition possible. Anti-jam capabilities possible.	Clutter problem. Expensive. Forces diverted from other missions. Vulnerable to saturation.

Clearly the utility of jamming and interception as responses to an attack by GCMs will depend on the specifics of a given situation. In addition, the lack of information available in the literature regarding the performance of U.S. air defenses and aircraft against cruise missiles make any attempts at prediction extremely speculative. While it is reasonable to state that both jamming and interception will work well in some situations, it cannot be said with certainty in which cases jamming would be a better option than interception and vice versa. Such decisions will be made by the U.S. military establishment.

[156] Another option might be for the United States to place jammers on balloons or aerostats.

4. FUTURE TECHNOLOGIES

4.1 SATELLITE NAVIGATION

In the next five to ten years, two GPS-related advancements are likely: WADGPS availability outside the United States, and commercially available satellite navigation signals. Another relevant system which could affect cruise missile navigation is the Russian Global Orbiting Navigation Satellite System (GLONASS). All three topics are discussed below.

4.1.1 Wide-Area DGPS

At present, WADGPS is limited to a few companies that offer services for the CONUS only (e.g., John E. Chance, Inc.). However, other companies may begin to offer this service on a world-wide basis.[157] For example, Inmarsat is considering the possibility of transmitting WADGPS corrections from its next generation of satellites (called Inmarsat3) which are scheduled for launch beginning in 1995.[158] Users would be able to obtain accuracies on the order of five to ten meters over areas as large as continents. [159]

4.1.2 Commercial Satellite Navigation

A number of commercial satellite navigation systems are currently being developed. For example, one of the largest GPS receiver manufacturers, Trimble, recently announced a partnership with Orbital Communications-a company that builds and launches small satellites.[160] Orbcomm is planning on launching a constellation of small communications satellites beginning in 1994.

> By 1995, 26 of them [the satellites] will be in orbit-enough to ensure that one is always visible from anywhere on the ground. The satellites will be capable of passing messages to and from subscribers wherever they may be. Trimble and Orbcomm will develop hand-held units that serve as both GPS receivers and Orbcomm terminals. That would give customers a basic positioning and messaging unit for as little as $50.[161]

Other satellite systems that will provide positioning information include: Japan's Multifunctional Transport Satellites, which will be launched beginning in 1999; Motorola's Iridium communications satellites, which will be launched beginning in 1998; and the

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[157] Hale Montgomery, "LEOs, Ships, GPS Follow-On, and U.S. Airports," *GPS World,* May 1993, pp. t6-17.

[158] Keith McDonald, "Econosats: Toward an Affordable Global Navigation Satellite System," *GPS World,* September 1993, p. 46.

[159] Ibid.

[160] "Finding the Future," p, 115.

[161] Ibid.

Inmarsat-3 satellites mentioned above.[162] In addition, both the international civil aviation community and the European Community are seriously considering the development of a dedicated civilian-owned satellite navigation system called the Global Navigation Satellite System (GNSS). Although it is not yet clear whether the GNSS will include GPS or GLONASS signals, there appears to be movement toward an independent system.[163]

4.1.3 GLONASS

There is another source of satellite-based navigation which is beyond U.S. governmental control: GLONASS. GLONASS is similar to GPS in many ways, including the fact that it transmits two signals, one designed for military use and one for civilians. However, in contrast to GPS, the Russian system does not have the equivalent of Selective Availability; hence their civilian signal is as accurate as the GPS C/A-code without SA.[164] So far, GLONASS has had some problems: it only had 13 satellites in orbit and operational as of May, 1993; it has had several system-wide failures; and there are few commercially available receivers.[165]

However, the future of GLONASS is by no means bleak. An advisory study was recently conducted at the behest of Commission of European Communities with the goal of "analyzing the potential of satellite navigation systems for European users."[166] The project manager of that study made the following remarks at a recent conference: "As long as Europe has no control at all over any navigation satellite system, it is preferable to have more than one alternative . . . a European initiative toward participation in the space segment of a GNSS should be considered, especially GLONASS."[167] The Europeans appear interested in GLONASS for three reasons:

> …a completed GLONASS satellite constellation would provide better coverage and accuracy than GPS for European civil users; combined use of GPS and GLONASS would solve some integrity needs for aviation applications ... and it represents 'one possible area of cooperation with Russia,' a matter of political interest to some nations in post-Cold War Europe. [168]

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[162]Burgess and Munro, "New Uses," p. 8.

[163]See McDonald, "Econosats."

[164]Its 2_{drms} accuracy is about 30 meters; by comparison, the accuracy of the C/A-code without SA is about 28 meters 2_{drms}. The accuracy of GLONASS is taken from: Pratap N. Misra et al., "GLONASS Performance in 1992: A Review," *GPS World,* May 1993, pp. 28-38.

[165]Ibid., p. 38.

[166]"Newsfront," *GPS World,* November 1993, p. 12.

[167]Ibid.

[168]Ibid.

While there are some political aspects to this problem which the United States cannot control, it is clear that the limited accuracy of the SPS plays a key role in increasing the attractiveness of GLONASS to the European Community.

4.2 SATELLITE IMAGING

4.2.1 Targeting

The analysis performed earlier showed that targeting errors significantly decreased the overall accuracy of GCMs. The present trend toward higher resolution remote sensing systems may provide LDCs with targeting errors of less than five meters in the future. Several nations are already beginning to sell such images on the open market: "France has been actively seeking users for its Helios military reconnaissance satellite-which has an announced resolution of 1 meter .... Germany is believed to be developing a 1-2 meter-class system, and the Chinese are talking to potential customers…" [169]

Even U.S. companies are hoping to provide higher resolution images in the next decade. For example, Lockheed has asked the U.S. Department of Commerce for permission to operate a Commercial Remote Sensing System which would provide images with a 1-meter resolution.[170] The reason for Lockheed's position is clear: "Lockheed and other companies have joined with lawmakers to press for an easing of government curbs on higher resolution imaging satellites in order to compete with foreign systems offering resolutions of 1 meter or better."[171]

4.2.2 Terrain Elevation Data

In the near future, more accurate elevation data may become available. For example, NASA has asked the Department of Defense to declassify maps which contain elevation contours with an accuracy of five meters or better. NASA would use those maps to help interpret data from its Earth Observing System (EOS), a 17-satellite constellation planned for launch in 1998.[172] In addition, "Spot is considering enhancements, such as 5meter resolution and simultaneous stereo capability, on its next-generation spacecraft," that would increase the accuracy of their elevation data. [173] Although it is not clear when these

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[169]Jeffrey M. Lenorovitz, "Industry Presses CIA to Ease Curbs on Imaging Satellites." *Aviation Week & Space Technology,* June 21, 1993, p. 80.

[170]Jeffrey M. Lenorovitz, "Lockheed Wants Australia to be Satellite Partner," *Aviation Week & Space Technology,* July 5, 1993, p. 70.

[171]Ibid.

[172]Liz Tucci, "U.S. Agencies Seek Mapping Data From Pentagon,' *Space News,* Vol. 4, No. 25, June 21-27, 1993, p. 7.

[173]James R. Asker, "Commercial Remote Sensing Faces Challenges on Three Fronts," *Aviation Week & Space Technology,* July 13, 1992, p. 59.

events will occur, it is likely that more accurate elevation data will become available in five to ten years.

4.3 OTHER TECHNOLOGIES

4.3.1 Terminal Guidance

Given the technological sophistication associated with terminal seekers for LACMs, it appears highly unlikely that LDCs will able to develop such technologies in the near future. Because technologies that could be used for terminal guidance are export controlled, it will be difficult for Third World nations to purchase terminal seekers legally. Overall, the likelihood that U.S. forces will face GCMs using advanced terminal seekers in the near future is quite low. However, if China or other advanced LDCs are able to develop advanced cruise missiles, those odds might change.

4.3.2 Inertial Navigation Systems

I demonstrated that the drift rate of an INS is extremely important in determining the performance of a GCM in jamming environments. The lethality of jammed GCMs decreases extremely quickly unless high quality INSs (i.e., 0.1 deg/hr or better) are used. At present, high-quality gyroscopes and accelerometers are export controlled- Hence, it is unlikely that LDCs will be able to acquire such components from the West in the near future. However, Third World nations may have another option: Soviet-made inertial navigation systems. The Soviet Union was able to develop good quality inertial systems for its missiles and fighter aircraft. Many of the state-owned companies that produced those navigation systems are trying to privatize and are desperate for hard currency. It is probable that some of those companies would be willing to sell their products to Third World buyers, especially since Russia is not an official member of either CoCOM or the MTCR.

LDCs also have a financial incentive for purchasing INSs from the FSU. Because of the relatively low cost of labor in the FSU compared with Western nations, and the weakness of the ruble, buyers would be able to purchase systems for a fraction of the price they would pay in the West. The savings could be significant because high-quality INSs are expensive. For example, 0.1 deg/hr gyroscopes, which are export controlled, probably cost between $20,000 and $50,000 in the United States.[174] Given the fact that the FSU offers higher quality INSs for lower prices than those which are available in the West, it would not be surprising if higher quality inertial navigation systems began to spread throughout the world.

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[174]Private communication with John Deyst of C.S. Draper Labs.

4.3.3 Anti--Jam Technologies

Another set of technologies that are of concern to the United States are those which could provide GCMs with increased resistance against electronic jamming. I demonstrated above that CRPAs can have a significant effect on the performance of GCMs in a jamming environment. The export of CRPAs should remain tightly controlled. Other anti-jam technologies (e.g., filtering and beam-steering antennas) are not export controlled. However, most of those technologies are technically challenging and, more importantly, can be defeated with countermeasures such as broadband jamming.

4.4 CRUISE MISSILE DEVELOPMENT

While some advances in the range/payload and velocity characteristics of Third World cruise missiles should be expected in the near future, those advances will probably be incremental rather than revolutionary. In order to make small, long-range cruise missiles capable of carrying significant payloads, developing nations would have to obtain efficient turbofan engines and lightweight materials for the airframe. While lightweight materials can probably be obtained, turbofan engines are harder to come by: " . . . all known engine programs [in the developing world] are for turbojet engines rather than for the more efficient turbofan engines. This suggests that it may be some time before small long-range cruise missiles appear in the Third World."[175]

On the other hand, the DoD has performed a study which concluded that, "Syria, Iran and China will all have cruise missiles with some low observable or stealth capabilities between 2000 and 2010."[176] The report predicts that all three countries will have chemical and biological warheads for these cruise missiles. China is also expected to have a nuclear weapon which can be carried by its cruise missile. The latter possibility is a serious concern: "Prevailing Pentagon opinion is that 'the Chinese are going to sell hardware ... certainly without hesitation to Syria, Iran and North Korea.'"[177] Another nation that appears to be working on cruise missiles is India. Although not much is known about that program, "a computer model used to simulate the effects of wind on missiles" has been developed.[178] The Indian cruise missile is likely to use GPS for guidance and carry a 450 kg warhead, [179]

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[175]Carus. *Cruise Missile Proliferation,* p. 79. For a discussion of airframes and materials see Carus, pp. 71-76.

[176]"Cruise Missiles Becoming Top Proliferation Threat," p. 26.

[177]Ibid.

[178]George Leopold and Vivek Raghuvanshi, "India Steps up Cruise Missile Efforts," *Defense News*, Vol. 8, No. 30, August 2-8, 1993, p. 3.

[179]Ibid.

Hence, U.S. policymakers must face the possibility that several states will possess nuclear-capable, stealthy cruise missiles in ten to twenty years. While GPS might be used by some Third World cruise missiles (e.g., India), the United States cannot assume that GPS will be used by all of them. The development of more advanced cruise missile detection and interception capabilities is a must. As we shall see below, the U.S. military is already planning a major effort to upgrade its ability to detect and intercept cruise missiles.

4.5 U.S. IMPROVEMENTS

The United States is developing a plan to detect and intercept cruise missiles: "The plan links U.S. ground and air-based sensors, Air Force and Navy interceptor aircraft, rapid data transfer and specially modified air-to-air missiles into a high-tech net to snag cruise missiles."[180] The tactical portion of this plan relies on the following elements (in no particular order): [181]

1) Infrared search and track (IRST), long-range radar, and low-altitude intercept capability of F-14Ds.
2) Look-down, shoot-down radars of F/A-18s, F-16s, and F-15s.
3) Improved infrared and/or radar sensors on the AIM-9X Sidewinder, AIM-7 Sparrow, improved AMRAAM, and Phoenix long-range missile.
(4) Sensitivity upgrades for E-2 Hawkeye (the Navy's version of AWACS) and E-3 AWACS early warning radars, and the addition of infrared sensors for better detection of small cruise missiles.
5) The combining, sorting, and rapid transfer of data from IRST, radar, and perhaps later, acoustic sensors throughout the joint services' current Theater Battle Management (TBM) architecture.

The U.S. Army is also planning to upgrade its assets to deal with future cruise missile threats. The two main thrusts of the Army's efforts are improvements in the Patriot's radars and interceptors (the new system will be known as the PAC-3) and a new air defense system, known as the Corps SAM, which will probably replace the HAWK. 182

Finally, it is worth noting that a new radar technology, called Mountain Top, is being developed by the U.S. Navy: "It is intended to locate and mark low-flying enemy cruise missiles or stealthy aircraft for destruction by the Navy's Standard anti-air missile or

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[180]Fulghum, "U.S. Developing Plan," p. 46. This plan is part of the U.S. Air Force's Air Defense Initiative

[181]Ibid., p. 47.

[182]"Army Expects to Bear Burden of Cruise Missile Defense," *Aviation Week & Space Technology*. March 22. 1993, p. 46.

the Army's Patriot anti-aircraft missile."[183] This new technology is significant because it is designed to detect targets beyond the horizon. The ability of radars to detect targets beyond their LOS range would yield drastic improvements in the performance of air defense systems. In other words, Mountain Top would go a long way towards eliminating the advantages associated with low-flying cruise missiles.

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[183]Robert Holzer, "New Radar Multiplies Range of U.S. Missiles," *Defense News,* Vol. 8, No. 44 (November 8-14), 1993, p. 1.

5. FINDINGS

5.1 LETHALITY ASSESSMENT

5.1.1 Nuclear Payloads

It is possible, but unlikely, that GCMs will be used for nuclear weapons delivery in the near future. There are several reasons for reaching this conclusion. First, it is doubtful that a nuclear device produced in the Third World would weigh less than 500 kg. The only advanced cruise missiles that could carry such payloads beyond short ranges are those produced by developed nations. Thus, if LDCs wished to obtain a highly capable cruise missile for nuclear delivery, they would have to purchase it from the United States, France, or the FS U. None of these nations appears willing to sell capable LACMs, which are covered by the MTCR.

Another disadvantage of using GCMs for delivering nuclear weapons is that they have a low to moderate probability of surviving against U.S. air defenses. Given that LDCs will probably have few nuclear devices in their stockpile, the survivability of the vehicles they use to deliver these weapons must be as high as possible. In the foreseeable future, ballistic missiles will remain more survivable than either high-flying supersonic or "poor man's cruise missiles."

Another reason that Third World nations might not place nuclear weapons on cruise missiles in the near future is that they gain little advantage by doing so. GCMs have one key advantage over other delivery systems: their accuracy (their other advantage might be cost). However, unless LDCs attack hardened military targets such as underground bunkers and command posts, the high accuracies which can be obtained by GCMs do not outweigh the larger payload and higher survivability of ballistic missiles. In addition, hardened targets would be well protected, so that the survivability of a GCM would have to be quite high for such an attack to succeed. It is important to note that the attractiveness of using GCMs for nuclear weapons delivery could change if Third World nations such as China develop advanced, highly-capable cruise missiles.

5.1.2 Chemical Payloads

GPS-guided cruise missiles can be good platforms for delivering chemical weapons because of their accuracy and velocity. On the other hand, the small payloads of many cruise missiles, especially compared with those of strike aircraft, will limit the lethality of a cruise missile-delivered CW warhead. Even if large CW payloads could be delivered by GCMs, their effect on U.S. forces would probably be minimal. Finally, it is important to note that U.S. forces already face the risk of CW attacks by ballistic missiles and aircraft in

the Third World. The existence of GCMs capable of carrying chemical weapons would not substantially increase the dangers facing U.S. forces.

5.1.3 Conventional Payloads

A detailed discussion of the lethality of conventionally-armed GCMs is provided in Section 2.3. I found that the SSPK of GCMs depends on five variables: the horizontal navigation accuracy of a missile (which depends on the navigation mode of a missile and/or the quality of its inertial guidance system), its vertical position errors (which depend on the navigation mode of a missile and/or the quality of its altimeter, and on the angle of its terminal dive), its payload, its targeting accuracy, and on the size and hardness of a given target. It seems likely that most of the GCMs which U.S. forces will face in the near future will be moderately lethal. Since the number of GCMs required to achieve a desired probability of destruction against a given target depends on lethality of individual cruise missiles, it is probable that several GCMs will have to be used against even soft targets. Attacks against reinforced point targets will require large numbers of cruise missiles. On the other hand, fewer GCMs are needed against area targets, whether soft or reinforced. However, several GCMs may be required to incapacitate such targets.

5.1.4 Future Trends

In the future, GPS-guided cruise missiles could become more lethal for several reasons. First, their range/payload characteristics are likely to improve. Second, the accuracy of these missiles could grow in the next decade due to the increasing availability of high resolution satellite images, and because of the spread of WADGPS services throughout the world. It is also possible that advanced inertial navigation systems and, more remotely, terminal seekers, will become available in the Third World.

5.2 SURVIVABILITY ASSESSMENT

5.2.1 Detection

The key problem in protecting oneself from cruise missiles is detection. In the near term, the United States will probably be able to detect GCMs without much difficulty. "Poor man's cruise missiles" will be especially vulnerable to detection because of their larger radar cross sections. In the longer term, stealthy cruise missiles, which may be developed in ten to fifteen years by China, Iran, and Syria, will pose a bigger challenge. In all likelihood, upgrades in both ground-based and airborne radars will allow the United States to maintain its current detection capabilities.

5.2.2 Interception

Medium- to high-altitude cruise missiles will be vulnerable to interception by both aircraft and surface-to-air missiles. Low-altitude GCMs will pose a tougher problem for both systems due to ground clutter. In the future, higher quality TED may allow GCMs to fly much lower. This will aggravate both the detection and interception problems facing U.S. forces. The U.S. military is upgrading several of its missiles to improve their performance against such targets. In all likelihood, U.S. air defenses will perform well against "poor man's cruise missiles." However, advanced (e.g., stealthy) GCMs may pose a tougher challenge in the decades to come. The United States is responding to that threat with a comprehensive plan to improve its cruise missile interception capabilities. Only time will tell whether the U.S. effort is successful.

5.2.3 Jamming

Electronic jamming appears to be quite useful in decreasing the lethality of GCMs. The best jamming strategy would be to use airborne jammers because of their long LOS to even low-flying GCMs. As is the case with manned interceptors, airborne jammers are most effective if they are airborne when attacking cruise missiles are detected.

Ground-based jammers can also be effective in decreasing the lethality of GCMs; however, they are handicapped by their short LOS to low-flying cruise missiles. This is not a problem if the attacking missiles are using INSs with high drift rates. However, if those missiles are carrying high-quality INSs they could still pose threats to a variety of targets, including reinforced targets, depending on a variety of factors discussed in Section 2.3. In addition, GCMs gain some anti-jam capabilities against ground-based jammers because of the physical shielding provided by a cruise missile's body.

5.2.4 Future Trends

In the far term, cruise missile survivability may increase. GCMs will probably be able to fly lower as better guidance and terrain elevation data will become available. It is also likely that cruise missiles will become less observable. The United States is planning upgrades of its capabilities to offset these potential developments. First, a follow-on to the AWACS is forthcoming. Second, improvements are planned in the detection and interception capabilities of manned interceptors. Finally, a new air defense system, the Corps SAM, will be developed and the Patriot will be upgraded. Given these advances, U.S. forces may be able to counter foreseeable improvements in cruise missile survivability.

5.3 THE OVERALL THREAT

In the near future, GCMs will probably be moderately lethal at best. In addition, the survivability of individual GCMs will probably be low. Hence, the probability of a single GCM successfully completing a mission (i.e., reaching and destroying a given target) is quite low. This finding implies that many cruise missiles would have to be launched so that enough missiles would reach a target to achieve a high probability of destruction. The best strategy for an LDC might be to launch a saturation attack against a specific target in the hopes of overwhelming that target's defenses and achieving a high Pd. Given the tremendous costs which could be associated with this strategy, it appears feasible only if cheap, "poor man's cruise missiles" are used. In other words, until advanced cruise missiles are available in the Third World, U.S. forces are likely to face attacks by inexpensive, low-tech GCMs. If large numbers of GCMs are not available, then the threat facing U.S. forces will be minimal.

"Poor man's cruise missiles" can pose a threat to U.S. military assets, but they are much more effective weapons if used in a "terror" mode against civilian targets, which can be located quite accurately and are generally both large and unreinforced. However, "poor man's cruise missiles" can play other roles in a conflict against the United States. For example, such missiles could be used to divert U.S. forces away from other parts of the battlefield. A GCM attack could also be combined with an attack by ballistic missiles in an attempt to overwhelm U.S. defenses. Finally, a successful GCM attack could have a larger political effect than a military one. For example, Henry Sokolski, a former Pentagon official, has pointed out that "there was an unlucky Scud that came within 300 meters of a pier where there was an enormous amount of ammunition and some very critically important supply ships. Next time [using GPS], they won't miss." [184] A GCM strike against such targets probably would not change the outcome of a war, but a significant loss of life could force U.S. policymakers to rethink their involvement in a Third World conflict. In sum, while GCMs are not likely to change the outcome of a conflict between the United States and a Third World power, their presence may not be insignificant.

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[184]Jeff Fager, producer, "No Miss"; *60 Minutes,* December 26, 1993.

5.4 SELECTIVE AVAILABILITY

The benefit of selective availability is greatest when GCMs have small VPEs (i.e., if they have accurate altimeters and/or if they perform steep terminal dives), small targeting errors, and large payloads. In other words, SA is most useful when Third World cruise missiles are the most capable. That is true because navigation errors are only one part of the total system accuracy. As other error sources grow, they begin to dominate the navigation errors, so that the difference between GCMs using the C/A-code with SA on and those using the C/A-code with SA off become negligible. SA also works best when point targets are attacked, for the simple reason -that the larger navigation errors introduced by SA make little difference against large targets.

In the near term, SA will probably have little impact on the lethality of GCMs. As the capabilities of Third World cruise missiles improve, the benefits of SA will grow concomitantly. However, it is possible that the effects of SA will be undermined by the development of DGPS systems, especially WADGPS. It is possible that SA will become an anachronism exactly when it could be the most useful. Thus, any decision regarding the utility of SA today must examine the likelihood that WADGPS will exist in the future.

5.5 DIFFERENTIAL GPS

As with SA, the lethality of cruise missiles utilizing DGPS is greatest when other error sources are small, when larger payloads are used, and when point targets are attacked. It was found that DGCMs are quite sensitive to changes in the magnitude of targeting errors, especially if those changes occur around the lethal radius of a given target. The benefits of DGPS are minimal once a cruise missile is jammed.

LDCs will face some problems when attempting to use LDGPS techniques in a military environment. First, ground-based DGPS transmitters will be limited by range considerations. Sending DGPS corrections to a low-flying missile beyond a transmitter's LOS will require either low-frequency signals or relay stations. In either case, DGPS ground stations would have to be located fairly close to a target in order for local DGPS to be useful. A final problem facing users of LDGPS is that its radio signals are easy to trace and jam. Cruise missiles utilizing WADGPS would not be range limited in any way and their signals could be somewhat harder to jam. [185] It is apparent that the issue of WADGPS will play a key role in the debate surrounding GPS availability to the civilian community.

[185] Because WADGPS corrections would be transmitted by satellites, they could benefit from physical shielding against ground-based jammers. Also, the transmissions could be sent using spread-spectrum. techniques which would give the signals some resistance to jamming.