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The Global Positioning System: Charting the Future
Summary Report

by a Panel of the
NATIONAL ACADEMY OF PUBLIC ADMINISTRATION
and
by a Committee of the
NATIONAL RESEARCH COUNCIL

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For
The Congress of the United States
and
The Department of Defense

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The National Academy of Public Administration is a nonprofit, nonpartisan, collegial organization chartered by Congress to improve governance at all levels — federal, state, and local. NAPA works toward that end chiefly by using the individual and collective experiences of its Fellows to provide expert advice and counsel to governance leaders. Its congressional charter, signed by President Reagan in 1984, was the first granted to a research organization since President Lincoln signed the charter for the National Academy of Sciences in 1863.

The unique source of the Academy's expertise is its membership. It consists of more than 400 current and former Cabinet officers, members of Congress, governors, mayors, legislators, jurists, business executives, public managers, and scholars who have been elected as Fellows because of their distinguished practical or scholarly contributions to the nation's public life.

Since its establishment in 1967, NAPA has responded to a large number of requests for assistance from various agencies and has undertaken a growing number of studies on issues of particular importance to Congress. In addition, NAPA has increasingly conducted projects for private foundations and has begun to work closely with corporations.

Its work has covered a wide range of topics, including: agriculture, education, health, human services, housing, urban development, prisons, courts, space, defense, environment, emergency management, human resources, organization and management analysis, and international public management.

The products of Academy studies represent the views of the participants and not necessarily the Academy as an institution.

THE NATIONAL RESEARCH COUNCIL

The National Research Council participation in the project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the National Research Council portions of the report were chosen for their special competencies and with regard for appropriate balance.

The National Research Council portions of this report have been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The National Academy of Sciences is a private, nonprofit self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Robert M. White is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth I. Shine is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. Robert M. White are chairman and vice-chairman, respectively, of the National Research Council.

Foreword

The National Defense Authorization Act for Fiscal Year 1994 (Public Law 103–160) mandated an independent study, funded by the Department of Defense, on the future management and funding of the Global Positioning System (GPS) program. This report presents the results of a joint study, which was conducted by the National Academy of Public Administration (NAPA) and the National Research Council (NRC) of the National Academies of Sciences and Engineering. A NAPA panel and an NRC committee examined several GPS policy, management, and technical issues.

Describing the need for this study, the Senate Armed Services Committee said: “It is clear that GPS offers the potential to revolutionize the movement of goods and people the world over. Civil and commercial exploitation of GPS could soon dwarf that of the Department of Defense and lead to large productivity gains and increased safety in all transportation sectors.”

Other studies in recent years have examined aspects of GPS and have contributed importantly to the successful development of the system. This report, *The Global Positioning System: Charting the Future*, builds on the work of its predecessors and is intended principally to advise Congress, the secretaries of defense and transportation, and through them the President and the American public, on actions needed to ensure the continued success of GPS in meeting essential military and civilian needs. The report examines the key areas for GPS — commercial, civil government, and international — as well as paramount national security interests. Recommendations to further improve the technology also are presented.

The report is the product of a collaboration between the two congressionally chartered academies. Each organization selected a group of distinguished and highly qualified experts to conduct their portion of the joint study. NAPA formed a panel chaired by James R. Schlesinger, former secretary of defense and secretary of energy. This group provided expertise in military and international affairs, government organization and operation, research and development, fiscal policy and private sector investment, and international commercial communications.

NRC asked Laurence J. Adams, former president and chief operating officer of Martin Marietta Corporation, to head its committee of outstanding individuals chosen from the aerospace and electronics industries, the transportation sector, and university and research centers specializing in astrodynamics, electrical engineering, communications, mapping, and other relevant areas.

Because each academy operates differently, the NAPA and NRC portions of this study followed different schedules with different institutional procedures. Nevertheless, the NAPA and NRC staffs worked closely together throughout this study, drafting joint outlines, exchanging information, attending both the NAPA panel and NRC committee meetings, and meeting frequently to work out details of the joint report. Summaries of the reports of both committees are included together in this document, delivered in response to the congressional request.

We wish to commend the two committees and their chairs, who so ably conducted this study over the past year. We also acknowledge the work of the talented and energetic staffs of the two study groups and the many people both in and out of government who contributed to this report.

R. Scott Fosler
President
National Academy of Public Administration

Robert M. White
President, National Academy of Engineering
Vice Chairman, National Research Council

FROM THE CHAIRMEN,
NAPA PANEL AND NRC COMMITTEE

THE FUTURE OF GPS

The Global Positioning System (GPS) is an outstanding technological achievement. It proved its military worth in the Gulf War extraordinarily well. And now GPS technology is becoming the basis of an astounding commercial success as well. Markets for GPS-based goods and services are exploding, and are likely to continue to grow rapidly over the next decade. GPS is now used to guide everything from sailboats to supertankers. It directs missiles and airliners through enroute flight to target or touchdown. And it will increasingly help automobiles navigate. The Department of Defense (DOD) deserves the nation's — and the world's — congratulations for nurturing this technology and bringing it to full operation.

Congress asked the two prestigious academies for which we served to look at the future of GPS. We found that most aspects of GPS technology, governance and management, and funding are remarkably sound. Among the aspects of the system that are working well and should, therefore, be retained are operational control and funding of the basic GPS satellites by DOD; the aggressive application of GPS technology to public safety and public service needs by civil government agencies; and a dual-use policy that allows room for innovation and entrepreneurship in the GPS industry both at home and abroad.

The focus of our study, however, was on the future. The United States needs to maintain its leadership position in satellite navigation technology. DOD is about to initiate a new multi-year acquisition program for a follow-on generation of satellites that could lock GPS into current technology, resulting in a satellite system that could be little different in 2015 than it is in 1995. Without improvements, other nations may be encouraged to explore different, and possibly incompatible, satellite options. Our nation would be remiss to let this happen. In this regard, the National Research Council (NRC) was asked by Congress to review GPS technology and propose changes that could enhance military, civil, and commercial use of the system. The NRC found numerous technical improvements that would substantially benefit users at a modest cost. The implementation of the NRC's recommendations would enhance the military utility of the system, improve its value for a growing variety of civil government and commercial tasks, and help to maintain U.S. technological leadership.

An important factor that undercuts GPS satellite improvements and inhibits foreign willingness to rely on the system is Selective Availability (SA), which DOD uses to degrade the accuracy of the civilian GPS signal. The continued use of SA can negate the benefits of improvements in the system for civilian use. SA signal degradation increasingly is being overcome through the use of differential technologies with some additional cost and inconvenience. Further, SA sustains foreign doubts about the U.S. commitment to offer GPS as a global utility for the indefinite future. Some foreign governments and international organizations are understandably reluctant to make a full commitment to the system while DOD reserves the right to dither with the accuracy of the signal.

The continued use of SA has had, and will continue to have, the effect of encouraging the proliferation of differential systems and fueling speculation about the development of alternative systems that bypass GPS. More specifically, the NRC committee has determined that the effectiveness of SA has been significantly undermined by the widespread proliferation and ease of implementation of differential GPS. Additionally, the expected completion of the Russian

GLONASS system with accuracy equivalent to GPS without SA will further erode the usefulness of SA. Whatever deterrence value SA may still have is eroding rapidly.

DOD has been inclined to use SA as a crutch. Rather than depending on degradation of GPS signals through SA, DOD should depend on a strategy of denying radionavigation signals to an adversary in wartime. Viable approaches to this task exist, but they require the development and implementation of new doctrine, equipment, and training. The NRC committee offers a number of technical recommendations for improving the U.S. military's ability to deny potential adversaries the advantages of GPS, and these recommendations are buttressed by the policy prescriptions of the NAPA panel. The NAPA panel and the NRC committee believe that SA now should be turned to zero, though the option of reintroducing it should be retained for an interim period. During that period, DOD should embark upon a course that seeks to maintain the military advantages it derives from GPS through methods other than SA.

The NAPA panel believes that the nation needs to develop a strategic vision for the system that encompasses a wide range of military, civil, and commercial interests, both national and international. To this end, we have recommended a set of goals that aim to protect national security, encourage commercial exploitation of the system, and foster international acceptance of GPS and continued American leadership in satellite radionavigation technology. These goals provide a strategy for balancing the complex interests inherent in any technology as powerful and useful as GPS.

Institutional changes and adjustments — not major new bureaucracies — will be instrumental in implementing this vision and carrying out the nation's goals for GPS. A GPS Executive Board that addresses interests in GPS beyond those of the Departments of Defense and Transportation is needed. At a minimum, the Departments of State, Commerce, and the Interior should be represented on this Board. The Board should also formulate a strategy to increase the international acceptance and use of GPS, and coordinate federal, state, and local GPS activities at home.

An executive order is needed that promulgates the nation's goals for GPS and establishes the Executive Board. It should also reaffirm and strengthen America's commitment to provide the civilian GPS signal without discrimination or direct user charges. The full report discusses additional recommendations, but such an executive order would set the stage for the evolution of the U.S. government's approach to GPS that is needed for the future.

International acceptance of GPS is vitally important to continued growth in the use and applications of the system. We believe that the world will be a better place with the general acceptance of GPS, rather than a patchwork quilt of competing navigation technologies. International acceptance of GPS will advance American technological leadership and international aviation, communications, and trade — all activities in which the United States has a strong interest. However, the success of GPS will be compromised if the U.S. approach to GPS technology is perceived as chauvinistic or mercantilistic by foreign interests. Other nations should be given a voice in deliberations about the future of GPS. They should also be encouraged to share the cost of the system and its augmentations, and to continue their active involvement in advancing GPS technology through technical innovations and commercial adaptation.

One can foresee the evolution of new forms of governance, management, and funding for GPS. In the near-term, the speed at which GPS technology is progressing, the new prominence of civil and commercial uses of the system, and the rapidly increasing international interest in GPS all argue for a flexible governance structure. We believe that the recommendations of the NAPA panel and NRC committee will result in such a flexible arrangement.

In the long run, a new governance structure for a global navigation network, of which GPS would be a part, may evolve. Such a structure could include direct international participation in, and foreign contributions to, the creation and maintenance of this network. However, it is premature to commit to such an arrangement at this time.

The U.S. government will nevertheless need to respond aggressively to opportunities and challenges as they arise. A watchful Congress will be a valuable ally in the process of shaping the evolution of GPS. The development and deployment of GPS was the critical first step. The recommendations of the NAPA panel and the NRC committee build on this success, and help to chart the future of GPS.

James R. Schlesinger
Laurence J. Adams

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List of Acronyms

A-S Anti-Spoofing
DGPS Differential GPS
DOD Department of Defense
DOT Department of Transportation
drms Distance root mean square
ECDIS Electronic Chart Display Information System
FAA Federal Aviation Administration (part of DOT)
FRP Federal Radionavigation Plan
GLONASS GLObal Navigation Satellite System
GPS Global Positioning System
Inmarsat International Maritime Satellite Organization
LADGPS Local Area Differential GPS
NAPA National Academy of Public Administration
NCA National Command Authority
NRC National Research Council
OCS Operational Control Segment
Pos/Nav Positioning/Navigation
PPS Precise Positioning Service
RAIM Receiver Autonomous Integrity Monitoring
SA Selective Availability
SPS Standard Positioning Service
WAAS Wide Area Augmentation System
WADGPS Wide Area Differential GPS

List of Figures and Tables

Joint Study Charter

NAPA TASKS

1. How should the GPS program be structured and managed to maximize its dual utility for civilian and military purposes?

2. How should the GPS program infrastructure be funded to assure consistent, sustainable, and reliable services to civilian and military users around the world? In consideration of its worldwide user community, are there equitable cost recovery mechanisms that may be implemented to make the GPS program partially or fully self-supporting without compromising U.S. security or international competitive interests?

3. Is commercialization or privatization of all or parts of the GPS consistent with U.S. security, safety, and economic interests?

4. Is international participation in the management, operation, and financing of GPS consistent with U.S. security and economic interests?

NRC TASKS

1. Based on presentations by DOD and the intelligence community on threats, countermeasures, and safeguards, what are the implications of such security-related safeguards and countermeasures for the various classes of civilian GPS users and for future management of GPS? In addition, are the selective availability and anti-spoofing capabilities of the GPS system meeting their intended purposes?

2. What augmentations and technical improvements to the GPS itself are feasible and could enhance military, civilian, and commercial use of the system?

3. In order to preserve and promote U.S. industry leadership in this field, how can communication, navigation, and computing technology be integrated to support and enhance the utility of GPS in all transportation sectors, in scientific and engineering applications beyond transportation, and in other civilian applications identified by the study in the context of national security considerations?

Overview and Tasks

Two decades ago, the United States initiated a military satellite system to improve navigation of its ships, aircraft, and vehicles and to target weapons more accurately. Although the system was developed by the Department of Defense (DOD), it was also expected to serve civilian needs. The resulting Global Positioning System (GPS) is an unqualified success — a technological triumph that is revolutionizing the way the world moves people and goods and helping to synchronize the global information flow.

Explosive growth in commercial applications, far beyond anyone's expectations, including those of its military designers, has brought GPS to the marketplace; it guides buses and delivery trucks, for example, and tells a lot surveyor where to drive a corner stake. It enables pilots and ship navigators to know their exact position, helps farmers identify where to plant crops, and will increasingly help automobile drivers find the best way to their destination. Worldwide revenue from GPS-related products and services, currently about $2 billion, is expected to exceed $30 billion annually by 2005.

GPS is elegant in design, extensive in application. A constellation of twenty-four satellites broadcasts signals to Earth. With signals from as few as four of these satellites, it is possible to determine one's position, time, and velocity accurately in three dimensions. With the addition of ground reference stations — called differential GPS — signal accuracy is improved and one's position can be known to within a few meters. With even more sophisticated equipment, accuracy to within centimeters is possible for applications such as the measurement of Earth movements. GPS works in daylight and at night, in dense fog and the foulest weather, the world over.

Congress directed this joint report by the National Academy of Public Administration (NAPA) and the National Academy of Sciences to provide guidance on the future of GPS (see box on following page and Appendix A). Congress wanted to know how GPS should be governed, managed, and funded in the future and how its technology could be improved.

To conduct its portion of the study, NAPA formed a panel of experts in defense management, government organization, intelligence and security, international trade and finance, science policy and management, technology assessment, and telecommunications. The NAPA panel addressed policy, management, and funding issues. Biographies of the panel and principal staff are provided in Appendix B. To conduct its part of the study, the National Academy of Sciences established an expert committee, through the National Research Council (NRC), the operating arm of the National Academy of Sciences and the National Academy of Engineering. The NRC Committee on the Future of the Global Positioning System, hereafter referred to as the NRC committee, addressed technological issues. Appendix C contains biographies for the committee members.

HOW GPS WORKS

Before discussing the findings and recommendations of the NAPA panel and the NRC committee, it is useful to review how GPS works, and how it is governed and managed today. The twenty-four Earth-orbiting GPS satellites transmit radio signals giving each satellite's position and the time it transmitted the signal. These signals can be received on Earth with an inexpensive device (around $400 and up). The distance between a satellite and a receiver can be computed by subtracting the time that the signal left the satellite from the time that it arrives at the receiver. If the distance to four or more satellites is measured, then a three-dimensional position on Earth can be determined. GPS positioning capability is provided at no cost to civilian and commercial users worldwide at an accuracy level of 100 meters.[1] This accuracy level is known as the Standard Positioning Service (SPS). The U.S. military and its allies, and a select number of other authorized users, receive a specified accuracy level of 21 meters,[2] known as the Precise Positioning Service (PPS).

The full accuracy capability of GPS is denied to users of the SPS through a process known as Selective Availability (SA). This purposeful degradation in GPS accuracy that is accomplished by intentionally varying the precise time of the clocks on board the satellites and by providing incorrect orbital positioning data in the GPS navigation message. SA is normally set to a level that will provide 100-meter positioning accuracy to users of the Standard Positioning Service, although other levels of accuracy can be used at the discretion of the National Command Authority (NCA). Accuracy of GPS with SA turned to zero would be in the range of 10 to 30 meters; Selective Availability also can be turned up to well above 100 meters.

In practice, several additional sources of error other than SA can affect the accuracy of a GPS-derived position. They include unintentional clock and ephemeris errors, errors due to atmospheric delays, multipath errors, errors due to receiver noise, and errors due to poor satellite geometry. Further, characteristics of GPS other than accuracy also affect the uses and adequacy of GPS. These other operational characteristics include integrity, availability, continuity of service, and resistance to radio frequency interference.

The technical and operational characteristics of GPS are organized into three distinct segments: space, operational control, and user equipment. The GPS signals, which carry data to both user equipment and ground control facilities, link the segments together into one system. Figure 1 shows the relationship of the three segments.

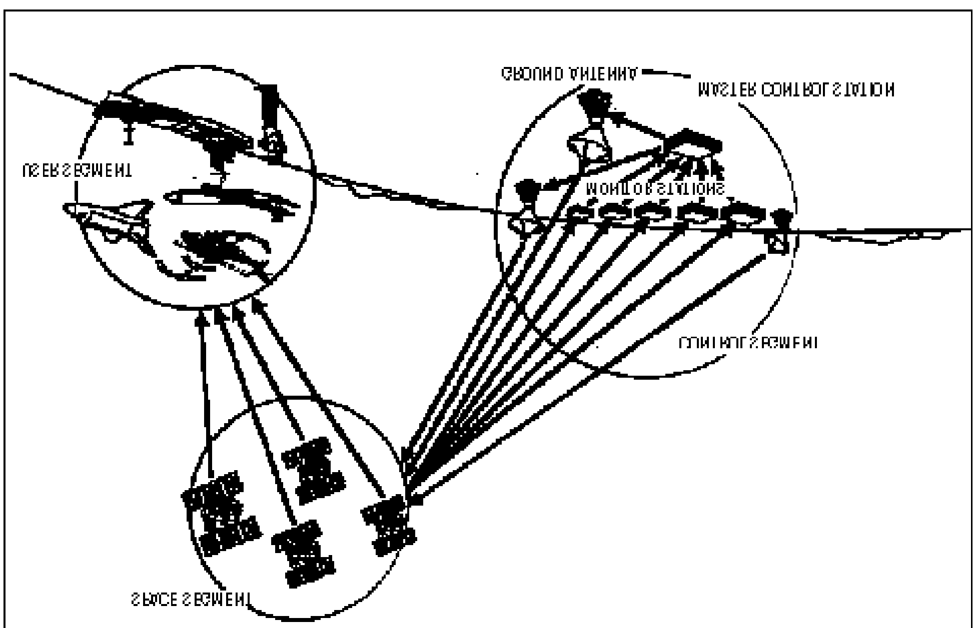


Figure 1: Major GPS Segments

How Differential GPS Works

Differential GPS (DGPS) is the most widely used method of GPS augmentation and significantly improves the accuracy, integrity, and availability of the basic GPS signal. In fact, the term “augmentation” has almost become synonymous with DGPS. DGPS makes use of GPS reference stations, the locations of which have been geodetically surveyed and are known with very high accuracy. These stations observe GPS signals in real time and compare their ranging information to the ranges expected to be observed at the stations’ fixed positions. The differences between observed ranges and predicted ranges are used to compute corrections to GPS parameters, error sources, or resultant positions. These differential corrections are then transmitted to GPS users, who apply the corrections to their received GPS signals or computer position.

Depending on the user application, DGPS reference stations can be permanent, elaborate installations, or they can be small, mobile GPS receivers that can be moved to various well-surveyed locations. The equipment used to broadcast differential corrections, the type of radio datalink used, and the size of the geographic area covered by the DGPS system also vary greatly with the application. No matter what type of system is used, however, the navigation and positioning capabilities that will be available to any DGPS user within the covered area will be much better than what is available from a stand-alone GPS receiver using the Standard Positioning Service.

Differential systems can be local-area (LADGPS) or wide-area (WADGPS). The former broadcast differential corrections over a limited geographic area; the latter can cover a continent or more. For civil applications, DGPS can provide sub-meter accuracy.

Many techniques and technical systems designed to improve the capabilities of the basic GPS system have been proposed, are under development, or are already in operation. In addition to differential GPS, these techniques include software and hardware improvements within GPS user equipment and the integration of GPS user equipment with other navigation/positioning systems.

HOW GPS IS MANAGED

Responsibility for the day-to-day governance and management of the GPS program and operation of the system rests primarily with DOD. Management is carried out primarily by the U.S. Air Force under policy set by the Office of the Secretary of Defense, with guidance by the DOD Positioning/ Navigation (Pos/Nav) Executive Committee.[3] This committee, chaired by the under secretary for acquisition and technology, receives input from DOD commands, departments, and agencies. It coordinates with the DOT Pos/Nav Executive Committee, a civilian counterpart that is chaired by DOT’s assistant secretary for transportation policy.

The DOT Pos/Nav Executive Committee coordinates GPS policy recommendations for the secretary of transportation, provides policy and planning guidance to the department’s administrations on navigation and positioning matters, coordinates with similar committees in other federal agencies, and provides unified departmental comments on proposed rule making by other government agencies that bear on radionavigation and positioning.

The official source of planning and policy information for each radionavigation service provided by the U.S. government, including GPS, is the Federal Radionavigation Plan (FRP). DOD and DOT jointly develop the FRP and update it biennially. The FRP attempts to provide users with the optimal mix of federally provided radionavigation systems and reflects both DOD’s responsibility for national security and DOT’s responsibility for public safety and the transportation economy.

[1] Accuracies for GPS are usually expressed in terms of 95 percent probability.

[2] PPS accuracy, as specified here in 95 percent probability, is usually specified in spherical error probable (SEP) of 16 meters (50 percent probability).

[4] GPS provides an internationally available service, similar in many respects to a public utility. The system requires a substantial up-front capital investment, has decreasing average costs, is

generally available to anyone, and therefore is a natural monopoly; that is, it is more efficient to have one instead of many providers.

[5] *Accuracy* is the degree of conformity between the estimated or measured position or velocity of a platform at a given time and its true position and velocity. *Integrity* is the ability of a system to provide timely warnings to users when the system should not be used for navigation. *Availability* of a navigation system is the percentage of time that the services are usable, for example, an indication of the ability of the system to provide usable service within the specified coverage area.

[6] A public good has two major characteristics: first, once the public good has been paid for and is available, an additional user imposes no cost on the system and does not diminish its availability to others; second, it is impossible or very expensive to prevent anyone from using it. In addition, a public good usually benefits a large segment of the citizenry.

[7] SA is a purposeful degradation in GPS navigation and timing accuracy that is accomplished by intentionally varying the precise time of the clocks on board the satellites, which introduces errors into the GPS signal. With SA, the civilian signal on which the Coarse Acquisition (C/A) code is transmitted, is limited to an accuracy of 100 meters, 95 percent probability. Military receivers with the appropriate encryption keys can eliminate the effects of SA and obtain an accuracy of approximately 21 meters (95 percent probability).

[8] The Coarse Acquisition (C/A) code is broadcast on the L-band carrier signal known as L_1, which is centered at 1575.42 MHz.

9 DGPS is based upon knowledge of the highly accurate, geodetically surveyed location of a GPS reference station, which observes GPS signals in real time and compares their ranging information to the ranges expected to be observed at its fixed point. The differences between observed ranges and predicted ranges are used to compute corrections to GPS parameters, error sources, and/or resultant positions. These differential corrections are then transmitted to GPS users, who apply the corrections to their received GPS signals or computed position.

[10] GLObal Navigation Satellite System or GLONASS is a space-based radionavigation system also consisting of three segments just as GPS does. GLONASS is operated and managed by the military of the former Soviet Union. The GLONASS space segment also is designed to consist of 24 satellites arranged in three orbital planes. The full GLONASS constellation is currently scheduled to be completed in 1995. GLONASS does not degrade the accuracy of its civilian signal by SA or similar techniques.

11 Recent measurements with SA turned to zero have ranged from 5 meters to 10 meters (95 percent probability). However, the accuracy without SA greatly depends on the condition of the ionosphere at the time of observation and user equipment capabilities.

[12] Anti-Spoofing (A-S) is the encryption process used to deny unauthorized access to the military Y-code. It also significantly improves a receiver's ability to resist locking onto mimicked GPS signals, which could potentially provide incorrect positioning information to a GPS user.

[13] Wide-Area Augmentation System (WAAS) is a wide-area DGPS concept planned by the FAA to improve the accuracy, integrity, and availability of GPS to levels that support flight operations in the National Airspace System from en route navigation through Category I precision approaches. WAAS will consist of a ground-based communications network and several geosynchronous satellites to provide nationwide coverage. The ground-based communications network will consist of 24 wide-area reference stations, two wide-area master stations, and two satellite uplink sites. Differential corrections and integrity data derived from the

ground-based network, as well as additional ranging data, will be broadcast to users from the geostationary satellites using an "L_1-like" signal.

14 Receiver Autonomous Integrity Monitoring (RAIM) is a method to enhance the integrity of a GPS receiver without requiring any external augmentations. RAIM algorithms rely on redundant GPS satellite measurements as a means of detecting unreliable satellites or position solutions.

15 Information based on an analysis by Michael Dyment, Booz• Allen & Hamilton, 1 May 1995.

16 A preliminary analysis of the L-band spectrum allocation that was conducted by Mr. Melvin Barmat, Jansky/Barmat Telecommunications Inc., Washington D.C., January 1994.

Issues Addressed by NAPA

The NAPA panel assigned the highest priority to maintaining the military advantages associated with GPS. Its initial preference was to isolate this dominant influence and then address the commercial, international, management, and funding issues. The panel's deliberations, however, led to the conclusion that national security and other issues could not be treated separately. National security could only be addressed simultaneously with consideration of the commercial and international aspects of GPS in assessing appropriately the available options. The panel found that the best approach for preserving national security is one that also adapts to the rapidly evolving commercial and international dimensions shaping the future of GPS.

SYNOPSIS OF MAJOR RECOMMENDATIONS

The NAPA panel concluded that GPS is an invaluable asset that is rapidly becoming a *de facto* "global utility."[4] To maintain U.S. leadership in satellite radionavigation, the NAPA panel recommends that:

- The President adopt explicit national goals to guide GPS policy making and implementation.
- The United States underscore its commitment to make GPS available free of direct charges to all users.
- To sustain its military advantage, DOD develop the capability to counter adverse use of GPS and other radionavigation signals. Selective Availability, which degrades the civilian GPS signal, is not fulfilling the purpose for which it was created. It should be turned down to zero immediately and deactivated after three years.
- The United States develop a more effective mechanism of governance by broadening civil agency participation in U.S. policy making and providing a greater voice for civilian, commercial, and international interests in the future evolution of GPS.
- Stable federal funding of GPS for national security and public safety be continued, while pursuing contributions from other nations as international participation grows.

National Goals for GPS

The NAPA panel recommends the following national goals for GPS, including augmentations funded by the U.S. government, and urges that they be adopted. The goals are:

• Protect the security of the United States and its allies and seek to counter or limit the hostile use of the system by others.
• Maintain an efficient, effective, dual-use geopositioning capability providing responsive, highly accurate, and reliable positioning, velocity, and timing information worldwide.
• Maintain U.S. leadership in GPS technology by encouraging its evolution, growth, and commercial applications.
• Maintain GPS as a global resource by considering international interests and concerns in GPS governance and management.
• Establish policies governing the availability, use, and funding of GPS that are — and are seen to be — stable, consistent, and workable for all major users of the system.
• Provide a flexible management structure capable of adapting rapidly to changing technical and international circumstances.
• Consistent with the other national goals, limit the overall burden on the U.S. taxpayer.

In short, GPS goals should aim to protect national security, encourage commercial growth, and foster international acceptance and continued U.S. leadership in this field.

POWERFUL FORCES ARE DRIVING CHANGE

Powerful forces are shaping the future of GPS. Such forces will affect the ways the United States maintains the military advantage inherent in GPS, which the NAPA panel believes is paramount. These forces include:

• **GPS as a potential weapon of war and terrorism.** The United States, having developed GPS, rightly wants to retain the military advantages of this technology for its own and allied forces and to deny these advantages to enemies. Consequently, the United States must devote greater energy to achieving countermeasures. As with other technologies, other nations will acquire GPS-like capabilities. How fast this happens depends, in part, on policies and actions of the U.S. government. In the longer term, the increased availability of accurate positioning capabilities will undoubtedly pose an increased threat to U.S. and allied military interests.
• **Rapidly growing commercial markets.** Sales of GPS-related products and services are expected to grow to more than $30 billion annually by early in the next century. GPS capability will be integrated into many other widely used technologies throughout the world. There is great potential for still other uses of GPS.
• **Use by much larger segments of the general public.** GPS is still relatively unknown to the general public; users number only in the hundreds of thousands. As GPS becomes a key part of vehicular navigation systems and mobile communications, millions of people will come to know and depend on it.
• **Further potential technological improvements.** Technical improvements can and are being made to the basic satellite system to provide higher levels of accuracy, integrity, and

availability.[5] Other improvements are possible in user equipment and in enhancements and augmentations to the basic system.

• **International markets and influences.** A rapid expansion is occurring in international markets as well. Foreign manufacturers and service providers interested in capturing these markets are pressing their governments for a strong U.S. assurance of continued GPS signal availability and for increased international participation in system governance and management. Foreign unease with reliance on a U.S. military-controlled system provides incentive for international development of a competing global navigation system under multilateral control.

Because these forces operate in concert, not independently, policy makers do not enjoy the luxury of developing categorical responses. Comprehensive policies to address interrelated challenges are necessary. The United States must not only stay at the leading edge of technological development but also must establish a governance and management framework capable of balancing the various national goals set for GPS. The key is to design a flexible framework for reconciling the competing demands on the system in ways that respond to the national interest.

THE UNITED STATES NEEDS A NATIONAL STRATEGY FOR GPS

Early in its deliberations, the NAPA panel recognized the need for a clearly articulated national strategy to guide U.S. efforts and serve as the basis for both protecting national security and providing a position, velocity, and timing capability acceptable and usable worldwide. Therefore, the panel developed a set of national goals shown in the box on the following page.

EVOLVING GPS GOVERNANCE

Two fundamental questions now confront U.S. policy makers responsible for GPS: Who governs and manages it? Who pays for it?

The Department of Defense has successfully developed and fielded this highly useful satellite-based system. DOD deserves both public gratitude and congratulations for this impressive technological achievement. DOD's governance and management structure worked well during two decades of development. But demands on the system are widening and becoming far more complex than before, and rival systems may emerge. The Department of Transportation (DOT) has been given a stronger role as representative of civil interests but is still a relatively weak partner to DOD. Governance and management will need to evolve further to meet effectively the challenges of the future. Proliferating civilian users — domestic and foreign — will need to be better represented in federal policy making on GPS.

As to funding, the NAPA panel concluded that the value of GPS is extraordinarily high, both as a vital and proven military system and as a stimulus to the national and international economies. GPS constitutes a national asset that the nation should continue to own, support financially, and offer as a global utility. To date, DOD has borne the costs of providing a national program benefiting the entire world. In the future, where possible, those who benefit from availability of the GPS signals should contribute toward the cost of providing them. In the panel's view, system enhancements and augmentations that benefit national security or public safety should receive federal support; those that benefit primarily the private sector should be paid for, insofar as possible, by the beneficiaries. If other nations agree to contribute, DOD's financial burden should be reduced.

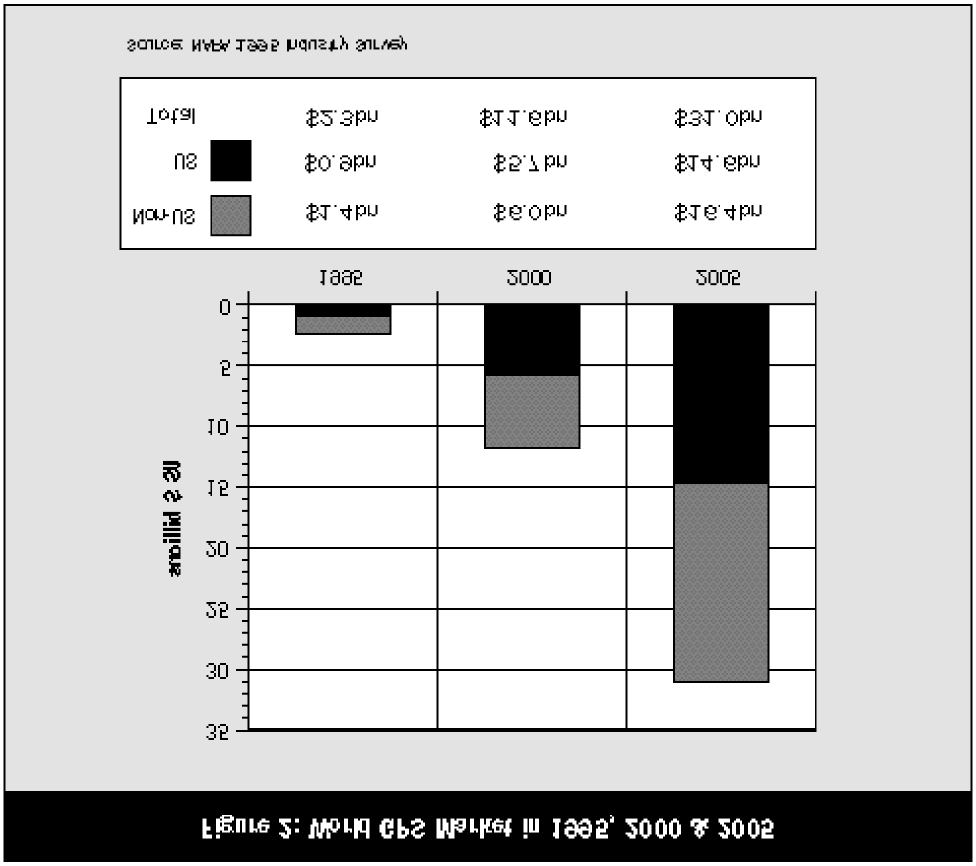
GPS is fast becoming a global information resource. Few technical obstacles to international diffusion remain, and great advantages accrue to other nations in adopting a system that provides accurate timing and location data at no direct cost. As GPS becomes an invaluable global information utility, foreign governments will, nevertheless, increasingly wish to have a voice in setting policy for the system and will likely become more unhappy with the current *ad hoc* approach to international consultation. Some foreign governments already express a preference that an international organization be responsible for GPS governance and policy making, even though ownership and operation of the GPS satellites would remain in the hands of the U.S. government. U.S. willingness to provide a meaningful voice in GPS governance to the international community might well be accompanied by foreign financial support for maintaining and augmenting the system.

BURGEONING GPS MARKETS

At earlier stages in the development of GPS, military requirements drove the evolution of the satellite system; civilian and commercial needs were subordinate. Final management responsibility for GPS still resides with DOD. Nonetheless, as with computers, microelectronics, and other technologies, commercial applications and technologies are increasingly leading their military counterparts, and commercial developments are setting the terms for many of the debates over the future of GPS. The commercial demand for GPS products and services now overshadows military demand, with nine out of ten receivers being sold to civilian or commercial users. Many in the private sector wonder how DOD will accept and manage the growing dependence of civil users on the system's continued availability, a dependence which increasingly circumscribes the military's freedom to control the application of GPS.

The markets for GPS applications are diverse, dynamic, and expanding rapidly in the United States and abroad. Opportunities for U.S. GPS product and service vendors of all sizes are growing. Considered from a larger perspective, the growth of civilian use means that people are increasingly enjoying the considerable peacetime benefits of GPS technologies in the areas of increased productivity and cost savings, public safety, and convenience.

NAPA's project team surveyed seventy companies in an effort to achieve a clear understanding of GPS markets. Responses obtained from forty-nine of those companies indicated that the estimated size of global GPS markets is currently about $2 billion. These markets are growing at an annual rate of about 38 percent and are expected to grow to at least $11 billion by 2000. By 2005, the world market is expected to reach $31 billion, 55 percent of which will be outside of the United States. (See Figure 2.) Other studies by the European Commission and a major U.S. consulting firm support the conclusion that GPS markets will grow rapidly.



Why is the use of GPS growing so rapidly? One key reason is that the price of basic GPS user equipment is dropping as a result of technological progress, increasing scale economies, and competition among vendors. Another reason is that qualitative improvements in GPS-based technologies are bringing greater accuracy and reliability to traditional users of positioning and navigation data. The NAPA survey confirmed that prospects for GPS in air navigation are particularly bright because alternative systems generally pale in comparison when all relevant factors are taken into account.

The synergistic combination of lower prices and improved performance characteristics is creating entirely new GPS applications. As noted earlier, the explosive growth of GPS is already impacting the automobile industry. America's leading automobile companies are anticipating a huge market for GPS in the area of automobile navigation, an application that is already catching on among Japanese consumers. Consumer recreational use is another growth market; as prices drop and inexpensive personal positioning technologies become accessible to the public, GPS receivers may become ubiquitous among hikers, boaters, tourists, and other recreational users.

Future growth in the use of GPS will be accompanied by the integration of GPS with other technologies, such as telecommunications, remote sensors, data storage technologies, and liquid crystal displays. The combination of GPS with communications technologies, for example, has led to automatic vehicle location software that provides a central dispatcher with the exact location of each vehicle in a fleet. It also holds out the prospect for reducing auto theft through automatic tracking of stolen vehicles.

Both U.S. and foreign governments continue to wield considerable influence over the pace and direction of GPS market development. U.S. businesses are largely satisfied with the current management of the GPS satellite system at the moment but are concerned about future policy stability and international acceptance. As entire industries and essential civil government services become dependent on GPS, these questions will become increasingly important.

The willingness or reluctance of foreign governments to embrace GPS as a central component of a future global navigational satellite system could greatly affect the fortunes of U.S. GPS vendors in the long term. Currently, some foreign governments maintain a cautious attitude toward the system out of concern for the DOD-dominated management arrangements and for the political leverage and economic benefits that would accrue to the United States as the owner and operator of a *de facto* global satellite radionavigation system.

Similarly, U.S. civilian government agencies such as the Federal Aviation Administration (FAA) and the U.S. Coast Guard have a powerful impact on GPS markets as a result of their role in providing differential services for air transportation and maritime use, augmentations that improve the accuracy of the basic GPS signal. Constructing and maintaining such systems translates into large hardware, software, and service contracts for U.S. firms, and the commercial sector generally welcomes the proactive approach that government agencies have taken toward differential services. Equipment manufacturers cite the incorporation of GPS into public infrastructure as the second most important measure that the government could take to promote GPS-based industries (the first is to ensure policy stability). Still, U.S. private companies that provide differential services, while supportive of government use, oppose government competition. Freely available government-provided augmentations to GPS will impinge upon markets otherwise open to private providers.

Finally, the military has a strong effect on GPS markets. First, it has the lead role in setting policy for the system. Second, at least for the moment, it is a major purchaser of GPS equipment for its own use. However, the military's policy of degrading the civilian GPS signal through SA tends to constrain the growth of commercial applications. Research conducted for the NRC, as well as the NAPA survey, indicate that the market impact of eliminating SA would be favorable and could be quite substantial in some product categories, as shown in Figure 3.

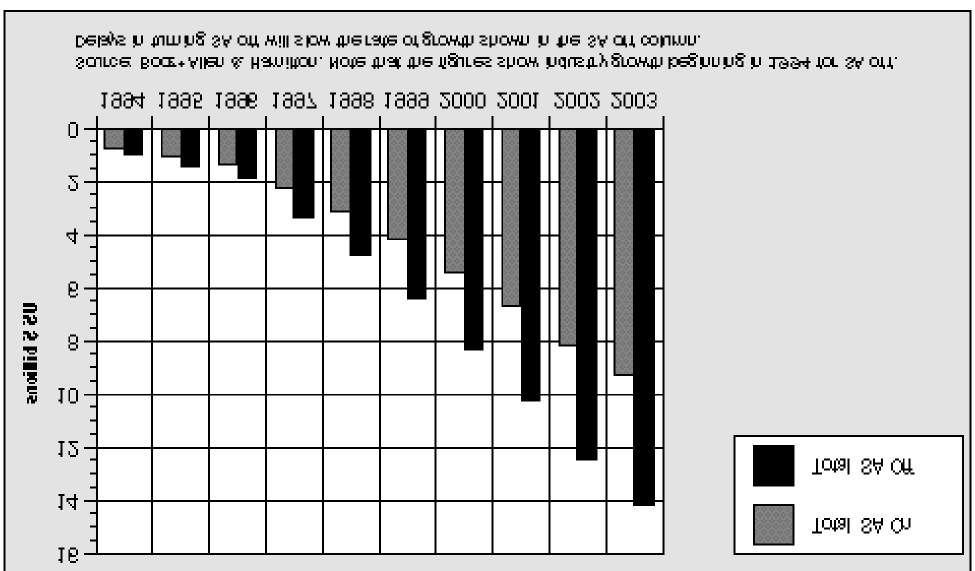


Figure 3: Estimates of Total North American GPS/DGPS Industry Size with SA On and SA Off: 1994–2003

MAKING GPS THE CORE OF A
GLOBAL POSITIONING AND
NAVIGATION NETWORK

Despite the rapid international diffusion of GPS technologies and the apparent willingness of many foreign users to rely upon the system, concerns continue to be expressed. The NAPA panel believes that such concerns should be addressed, consistent with U.S. national security interests, if GPS is to gain universal acceptance as the system at the core of a future international navigation system. These concerns include control of the system, participation in governance and funding of the system, and standards setting.

While some take U.S. dominance for granted, unresolved issues and concerns about control and national sovereignty nonetheless could lead to the development of a competing navigation satellite system similar to GPS, notwithstanding the worldwide availability of the GPS civil signal free of direct charge. A Russian system, GLONASS, has been partially fielded; Inmarsat, the International Marine Satellite Organization, may include a navigation capability in a future satellite network. The International Civil Aviation Organization is working on a Global Navigation Satellite System, with GPS and GLONASS as components. Whether these systems become complementary to or competitive with GPS depends on U.S. government actions.

GPS is becoming a *de facto* international utility, and it is in the U.S. interest to encourage the further diffusion and acceptance of GPS in this capacity. To the extent that the United States neglects the concerns and requirements of international GPS users, other nations would be more inclined to press on with plans to create alternative, stand-alone systems. Such a development would have a number of negative implications for the United States, in both the economic and the national security areas. It would be more difficult to maintain the military advantage accruing to the United States as the technological leader. It could also diminish the commercial advantages and the prospect of international contributions to GPS as well as impede the formation of an international navigation network.

The NAPA panel concluded that the United States needs to pay close attention to other countries and relevant international bodies. The panel finds that:

• Foreign interest and involvement in GPS are increasing rapidly as the system gains greater international acceptance as the navigation and positioning system of choice, despite some concerns among foreign governments and other users about the future reliability and availability of GPS, concerns that are heightened by the continued use of SA.

• Current, largely *ad hoc,* channels for foreign participation in GPS will, over time, likely be insufficient to meet other nations' demands for a stronger international voice in any global navigation system.

• Participation by international institutions, regional organizations, and foreign countries is appropriate in defining GPS requirements, monitoring the system's performance, and establishing compatible differential services, and this participation promotes GPS expansion worldwide.

• Foreign contributions to a worldwide navigation and positioning system based on GPS could reduce the costs of the system to the American taxpayer. However, such contributions would presumably be contingent upon greater international participation in the policy-making aspects of the system.

Opportunities exist for increased international involvement in GPS, including participation in both the definition of future requirements and financing of the system. The panel's recommendations are aimed at seeing that GPS is the basis for a truly global positioning and navigation system. They include the following:

n ***The United States should issue a clear and concise policy statement at the highest level that reasserts the U.S. commitment to provide permanent international access to the GPS signal and that states the U.S. intention to consider foreign interests in the future evolution of GPS.***

n ***The United States should formulate an explicit strategy to increase international acceptance and use of GPS that reassures foreign users of the reliability, credibility, and consistency of the United States as a provider.***

n ***The U.S. government should encourage and participate in developing and organizing a global navigation network with GPS as its foundation, and with appropriate arrangements for governance, management, and funding.***

MEETING NATIONAL SECURITY INTERESTS AND CONCERNS

GPS is an essential element of the U.S. national security posture. Already widely deployed in military units and systems, GPS is programmed, over the next decade, to become an integral part of all major weapon platforms (planes, ships, and land vehicles); a mainstay of troop and equipment maneuvering; and an embedded subsystem in an increasing number of so-called “smart” precision-guided munitions.

Balancing the commercial and societal advantages of widespread civilian access to reliable, accurate GPS positioning data and the national security interests has been a longstanding concern. The realization that a military adversary could use GPS technology against its creators led DOD first to separate military and civilian GPS signals and then intentionally to degrade the latter using SA when it proved more accurate than had been expected. The advantages and disadvantages of SA have been subjected to extensive debate as the importance of GPS to military and civilian users grows.

Military thinking about GPS has focused on securing the precision military GPS signal through encryption and on denying a highly accurate civilian signal to potential adversaries through SA. The security of the military signal is intact, but the difficulties with SA include:

• First, as the demand for and use of GPS grow, the military utility of using the civilian signal in wartime also grows. Many U.S. troops carried commercial receivers during the Gulf War and the 1994-1995 military operation in Haiti. In both cases, U.S. military commanders opted to turn SA to zero to improve signal accuracy for troops using such receivers. The anomalous situation thus exists of having SA to protect national security, yet turning it off in the very circumstances it was designed to serve.

• Second, DOD’s reliance on SA to degrade the civilian signal is quickly being undermined by the proliferation of inexpensive and robust differential systems.

• Finally, the political feasibility of denying or further degrading the civilian signal in response to military imperatives is eroding rapidly. The increasing integration of GPS technologies into the commercial and civil sectors ensures that denial or degradation would imperil public safety, adversely impact the economy, and impede the delivery of an increasing array of public and private services. Military commanders know that SA can be turned up to confound the enemy but may ignore the substantial commercial and international costs associated with such an action.

In addition, since most military receivers require the acquisition of the civilian signal prior to gaining access to the more accurate military signal, jamming of the civilian signal can currently affect the military’s access adversely. Techniques to prevent this effect are discussed in the NRC portion of this report.

The current level of SA (100 meters) is an inconvenience, an obstacle relatively easily overcome, rather than a significant deterrent to those who seek greater accuracy. But SA cuts both ways — a fact often forgotten in DOD — by encouraging ways such as differential GPS to get around it and leading to speculation on alternative stand-alone systems. The global diffusion of differential GPS, including to potential adversaries, is already well underway and accelerating rapidly. The United States cannot prevent the growth of such systems, aside from recourse to the politically untenable and economically ill-advised option of discontinuing or encrypting the civilian signal.

DOD is rightly concerned about the military implications of the increasing worldwide availability of high-quality, GPS-derived radionavigation data. But the existence of SA has distracted DOD from confronting this incipient problem head-on. For many in military commands, SA is a mental crutch that has slowed and inhibited the development of the capabilities required to address the problem directly: the ability to decrease accuracy to levels worse than 100 meters provides a superficially appealing, if unrealistic, answer to concerns about the availability of accurate navigation data.

SA will no longer be effective in denying potential adversaries the accuracies inherent in GPS and its augmentations; the NRC portion of this report addresses the technical considerations supporting this conclusion. The use of SA, and the uncertainty surrounding U.S. policy toward GPS, may be a temporary deterrent to foreign military (as well as civilian) users. But it is rapidly eroding as differential systems spread. In the longer term, the continuation of SA will be ineffective and could be counterproductive.

Nonetheless, the greater accuracy provided by GPS — with or without SA — and other augmentations of the civil signal poses an increased threat to U.S. and allied military forces. Even if, on balance, U.S. forces benefit more from GPS than do their adversaries, the advances in targeting and positioning that will arise from the increased availability of GPS signals pose an increasing threat and must be taken seriously. Memories of SCUD attacks on Riyadh and Tel Aviv are too recent to ignore the implications of this threat.

The most obvious tactical change required to respond to these threats is to develop the capability to counter adverse use of GPS signals and other radionavigation signals, to acquire the necessary electronic warfare hardware, and to train U.S. military forces to use them. Military research and development should focus more on developing options to both deny the availability of accurate positioning from GPS should the need arise and to protect the availability of the military signal to U.S. and allied forces. U.S. military planning, doctrine, and operations should emphasize the denial of precision radionavigation data to adversaries in wartime. Technical approaches to limiting the availability of differential signals should also be investigated.

Accordingly, the NAPA panel recommends:

n ***U.S. military planning, research and development, doctrine, training, and operations should focus on denying the advantages of accurate positioning and navigation signals to adversaries in wartime through methods other than Selective Availability, including jamming.***

n ***The administration and the Congress should provide the resources required to develop and procure needed countermeasures and equipment as soon as possible.***

n ***Selective Availability should be turned to zero immediately and deactivated after three years. In the interim, the prerogative to reintroduce SA at its current level should be retained by the National Command Authority.*** (See also NRC committee recommendation on p. 22.)

GOVERNANCE AND MANAGEMENT: THE NEED FOR EVOLUTION

For the first two decades of GPS development, DOD carried out both the governance and management functions. DOD deserves great credit for its accomplishments. The Air Force, as DOD's executive agent, successfully developed and fielded the system and brought it to initial operational capability in December 1993. DOD also cooperated with civil agencies and the commercial sector as they explored and developed applications for a wide variety of civil government and private-sector users.

Recently, the Department of Transportation (DOT) has become more involved, and through it, the civil government sector. In the absence of clear and comprehensive policy guidance, participating organizations have been free to pursue their own agendas. Not surprisingly, DOD focuses on the attributes that best serve military needs; DOT's attention is focused on proposed differential systems for civil air and marine uses. This arrangement has led to conflicts, such as that between DOD and the Federal Aviation Administration (FAA) over the accuracy of FAA's proposed wide-area augmentation system (WAAS), which reflect the sometimes competing interests, in this case, civil air navigation needs versus concerns about national security. While not surprising, given the conflicting goals and viewpoints, such conflicts affect program implementation and costs, and slow realization of GPS's potential benefits to broad segments of society.

Although not an equal partner, DOT has taken some useful first steps to improve its interactions with DOD. The NAPA panel is concerned, however, that DOT has been slow in taking other needed actions, such as appointing a senior official with clear and continuing authority to oversee departmental initiatives, as well as coordinate all civil activities, on GPS. In addition, DOT is only minimally represented at the DOD operating levels and is only modestly representative of other civil users. With a DOT departmentwide reorganization in the offing, further delay is likely.

The NAPA panel is also concerned about the requirements-setting process and its implementation in DOD. Civil agency, commercial, and international input into the system is occurring in a more organized fashion but is still limited. This situation exists in large part as a reflection of the military requirements-setting process, which was not crafted to embrace the needs of civilian agencies or the private sector. In addition, various military commands have only recently become more aware of their own requirements for GPS as they continue to research and examine the potential applications of GPS.

The Air Force is limited by DOD guidance and funding to maintaining the system and responding only to defined military requirements. If a military command has requirements that exceed DOD guidance, the command is expected to provide the funds for meeting more demanding requirements. Any civil agency, private-sector, or international requirements in excess of military requirements are to be financed with non-DOD funds. The panel believes DOD needs to reexamine its procedures for identifying and funding research and development requirements for GPS improvements to better take into account the overall demands for GPS.

Several models of governance structures potentially relevant to GPS were explored during this study, including possible privatization. No alternative governance and management arrangement emerged as fundamentally superior to the current arrangement at this time. The panel believes that governance and management of GPS must evolve over time if they are to meet a rapidly changing and growing user environment. GPS must provide a quality of service second to none, and its governance must remain flexible, responsive, and able to accommodate international and commercial interests. A rigid or unresponsive governance and management structure would, in and of itself, provide an incentive for others to establish competing systems or technologies. A flexible structure is especially desirable in view of the likelihood that technological advances, and increasing international, commercial, and consumer applications, will continue to drive the evolution of GPS.

The panel took special note of the privatization option as requested in NAPA's charter for the study. Privatization is receiving increased attention in both the executive and legislative branches as they consider fundamental changes in the role, scope, and size of the federal government. Although this focus is not new, its intensity is.

GPS is essential to national security and, thus, its availability must be assured. Current arrangements provide for this access. As for civil use, GPS is user-passive and free. Its civil signal is unencrypted, making it readily available to anyone anywhere with a GPS receiver. Therefore, anyone can acquire and use the basic GPS signal with an off-the-shelf receiver. How then would a private firm offering the civil signal as a service cover its costs? Unlike a sovereign government, a private company cannot place a tax on receivers. Such a firm would have to market an encrypted signal; only then could it restrict and control the use of the signal and charge a fee for it. If the civilian signal were to be encrypted, the hundreds of thousands of civil receivers already in use would no longer work, violating a basic tenet of GPS operations that all system changes be “backward compatible.”

For this and other reasons, the NAPA panel concluded that privatizing GPS is not a satisfactory option. As interesting and provocative as the idea might be, outright sale of GPS would create serious problems and should be avoided.

Greater private-sector involvement could be achieved if the Air Force gave the GPS satellite contractor responsibility for future systems integration and operations, an approach proposed by one Air Force office. This approach also could improve system performance, economy, and efficiency.

The panel’s recommendations for governance and management take cognizance first and foremost of national security considerations. The best way to preserve the control needed for national security is for DOD to continue to manage and operate the basic system. Within this framework, the panel believes the United States should move toward a governance and management structure that pays greater attention to other nations and international bodies.

People and governments all over the world are increasingly dependent on GPS for many and varied uses; some relate directly to saving lives. The U.S. government has a primary responsibility to protect national security; it is also obligated to ensure the availability of this important and valuable resource to U.S. and international civilian users, consistent with national security.

The most important factor driving a decision by others to establish a competing system is the lack of confidence in a U.S.-provided basic GPS service perceived primarily as military-controlled and dominated. It follows that the most important actions the United States can take to enhance its position are to:

• Keep the civil GPS signal free of direct user charges and available to all;
• Turn Selective Availability to zero immediately and deactivate it after three years;
• Broaden civil agency participation in GPS governance; and
• Provide a forum for international parties to voice their needs, interests, and concerns.

These actions should increase international acceptance of GPS and forestall the day when competing satellite navigation systems are circling overhead. These actions are fully compatible and mutually reinforcing. Increased international cooperation provides the best opportunity for cost-sharing for GPS.

n ***The panel recommends that the President promulgate an executive order to set forth a national strategy and guidelines for GPS, establish a GPS Executive Board, reassert the policy of the United States to provide the civil GPS signal free of direct user charges worldwide, and announce that Selective Availability will be turned to zero immediately and deactivated after three years.***

Governance and policy leadership of GPS need a broader base and perspective. To achieve the national goals for GPS, the current governance and policy-making arrangement must be strengthened. Therefore, ***the GPS Executive Board should be created as soon as practicable.***

n ***The board, to be co-chaired by high-level designees of the secretaries of defense and transportation, should be responsible for governance oversight, highest level policy setting and policy guidance, and overall coordination for the entire GPS program, including augmentations.***

n ***The board's membership should extend beyond DOD and DOT to the Departments of Commerce, Interior, and State, so as to be more inclusive and representative of the broad spectrum of the domestic and worldwide GPS user.***
n ***The board should be directed to prepare an annual report for the President who, in turn, should forward it to the Congress.***
n ***The board also should be responsible for formulating a comprehensive strategy to increase international acceptance and use of GPS that reassures foreign users of the reliability and consistency of the United States as a provider.***
n ***The board should ensure that DOD's and the Air Force's requirements processes effectively accommodate military and civilian GPS requirements and that appropriate means are established to fund non-military requirements.***
n ***The board, acting through its co-chairs, should be responsible for resolving disputes arising over GPS program management, operations, and funding.***
The NAPA panel also recommends that:
n ***DOD retain responsibility for operation and maintenance of the basic GPS, and the Air Force continue to act as executive agent; DOD also should continue to be responsible for international military cooperative arrangements.***
n ***DOT should be strengthened and become a more assertive executive agent for all U.S. civil systems, oversee U.S. participation in international organizations and GPS-related systems, and make arrangements with DOD to satisfy civil requirements for positioning and navigation using the civil SPS signal.***
The executive order recommended above should provide a stronger charter for DOT's role, but effective leadership will be needed to carry it out. In this role, DOT should:
n ***Coordinate civil agency requirements for and use of GPS and actively represent the civilian GPS community (including private and commercial interests, both domestic and international).***
n ***Institutionalize its consolidated requirements identification process for all civil requirements for GPS and work with DOD to formalize the mechanisms for incorporating them, where appropriate, into the current military operational requirements process for GPS.***
n ***Work with DOD to better coordinate military and civilian research and development efforts.***
n ***Cooperate with the Air Force to monitor and report on the integrity of the civil GPS signal.***
Regarding use of the private sector for GPS differential services, the panel recommends that:
n ***As a general policy, the federal government should make use of the private sector for GPS augmentations beyond those specifically designed or required for public safety and national security.***

MAINTAINING STABLE FUNDING SOURCES

Based on available economic and financial evidence, the panel proposes a financing structure that relies on federal funds for maintenance of the basic system and augmentations vital to national security and public safety. In thinking about funding, it should be kept in mind that increasing private-sector activity will produce taxable income resulting in substantial revenue to the Treasury and foreign exchange from exports. With SA turned to zero, that income would increase. Indeed, continued federal support for GPS is essential to maintaining the system as a U.S.-operated military asset and is a good investment for the American taxpayer in that it stimulates economic growth. The panel reached six general conclusions about funding GPS.

First, any policy change in the funding structure for GPS must take into account the fact that the United States has a profound stake in maintaining GPS for military use alone, quite independent of any other uses or developments. As a vital military asset, GPS needs a solid and reliable funding base; its funding should not be placed in any jeopardy through experiments with other funding structures and mechanisms.

Second, the basic GPS program is a public good.[6] The investment of public funds for its primarily military purposes has already been made. The system is currently available, no charge is made for its commercial use, and it is not feasible to charge directly for individual use of the signal. In addition, the last three administrations have committed to making the civil signal available free of direct charges to users. Those who want accuracy beyond that available from the basic civil signal can purchase differential services or use augmentations provided by the federal government.

Third, the existing GPS program, even without augmentation, is already stimulating significant growth in important industries, especially those that have high potential for generating jobs and raising standards of living, such as the knowledge and electronics industries. Imposing user fees or taxes could slow that growth and delay important new uses of GPS. Fees and taxes could also reduce the taxable income from GPS-related activities. Furthermore, it is impossible to calculate the amount of an "equitable" user charge, given current and likely available data; it is not even technically possible to determine who uses the GPS signal or how much they use it. It would be possible to tax individual users or impose user charges in the United States in some fashion, but it would not be possible to tax users overseas in the same fashion or on the same basis, if at all.

Fourth, the greatest economic effect of GPS, and thus the program's most likely method of paying for itself, is reflected in the revenues generated through the existing tax structure. This revenue can be enhanced by turning SA to zero, which will stimulate additional revenue-producing activity in the private sector. The benefits that GPS provides the economy, and the national policy of encouraging the growth of the information and communications infrastructure, outweigh the potential revenue that might be generated by a direct tax on vendors or users.

Fifth, many augmentations of GPS now in operation or in the planning stage are privately funded and will generate economic growth and additional revenue at no direct cost to the federal government. Federally funded augmentations of GPS, such as the FAA's WAAS and the Coast Guard's differential system, support traditional functions of the federal government that serve vital public safety purposes; as such, it would be inappropriate to charge additional user fees or impose taxes for them.

Sixth, the United States should be prepared to seek cash and in-kind contributions to maintain and enhance a global navigation network with GPS at its heart. This approach also supports the panel's earlier recommendations that the United States explore international funding in support of GPS and that a forum be provided for international voice in GPS as a global navigation network based on it evolves.

Therefore, the NAPA panel recommends that:

n ***Congress and the administration treat the current basic GPS as a public good, paid for through general revenues.***

n ***Congress and the administration refrain from imposing a receiver tax and impose no special fee or tax on private differential systems.***

n ***The costs of the Coast Guard's and FAA's augmentations of GPS and related systems should be covered by the appropriate trust funds without raising fees.***

SUMMING UP

GPS is much more than a satellite system for positioning and navigation. It represents a stunning technological achievement that is becoming a global utility with immense benefits for the U.S. military, civil government, and commercial users and consumers worldwide.

Civilian navigational applications were expected from the outset of GPS. Unanticipated innovative applications have grown exponentially in recent years, going far beyond the basic uses originally envisaged for the system. GPS technologies have been applied in fields such as aircraft approach and landing, surveying and mapping, oil prospecting, geological research, telecommunications network synchronization, and even automobile navigation, thus replacing older, inferior, and more expensive technologies and providing capabilities where none previously existed.

Management and funding challenges exist, but they do not raise serious questions about the established management and funding of the basic GPS system. In part, they are symptomatic of the complexities involved in any dual-governance arrangement involving organizations with different cultures and missions. More fundamentally, they represent the clash between the demands for improved accuracy and integrity by civil users, both domestic and international, and DOD concerns about the impact of these trends on the U.S. national security posture.

Evolution, rather than revolution, in governance, management, and funding is needed for the United States to maintain its leadership in this vital technology and to encourage commercial and international reliance on GPS.

[1] Accuracies for GPS are usually expressed in terms of 95 percent probability.

[2] PPS accuracy, as specified here in 95 percent probability, is usually specified in spherical error probable (SEP) of 16 meters (50 percent probability).

[4] GPS provides an internationally available service, similar in many respects to a public utility. The system requires a substantial up-front capital investment, has decreasing average costs, is generally available to anyone, and therefore is a natural monopoly; that is, it is more efficient to have one instead of many providers.

[5] *Accuracy* is the degree of conformity between the estimated or measured position or velocity of a platform at a given time and its true position and velocity. *Integrity* is the ability of a system to provide timely warnings to users when the system should not be used for navigation. *Availability* of a navigation system is the percentage of time that the services are usable, for example, an indication of the ability of the system to provide usable service within the specified coverage area.

[6] A public good has two major characteristics: first, once the public good has been paid for and is available, an additional user imposes no cost on the system and does not diminish its availability to others; second, it is impossible or very expensive to prevent anyone from using it. In addition, a public good usually benefits a large segment of the citizenry.

[7] SA is a purposeful degradation in GPS navigation and timing accuracy that is accomplished by intentionally varying the precise time of the clocks on board the satellites, which introduces errors into the GPS signal. With SA, the civilian signal on which the Coarse Acquisition (C/A) code is transmitted, is limited to an accuracy of 100 meters, 95 percent probability. Military

receivers with the appropriate encryption keys can eliminate the effects of SA and obtain an accuracy of approximately 21 meters (95 percent probability).

[8] The Coarse Acquisition (C/A) code is broadcast on the L-band carrier signal known as L_1, which is centered at 1575.42 MHz.

9 DGPS is based upon knowledge of the highly accurate, geodetically surveyed location of a GPS reference station, which observes GPS signals in real time and compares their ranging information to the ranges expected to be observed at its fixed point. The differences between observed ranges and predicted ranges are used to compute corrections to GPS parameters, error sources, and/or resultant positions. These differential corrections are then transmitted to GPS users, who apply the corrections to their received GPS signals or computed position.

[10] GLObal Navigation Satellite System or GLONASS is a space-based radionavigation system also consisting of three segments just as GPS does. GLONASS is operated and managed by the military of the former Soviet Union. The GLONASS space segment also is designed to consist of 24 satellites arranged in three orbital planes. The full GLONASS constellation is currently scheduled to be completed in 1995. GLONASS does not degrade the accuracy of its civilian signal by SA or similar techniques.

11 Recent measurements with SA turned to zero have ranged from 5 meters to 10 meters (95 percent probability). However, the accuracy without SA greatly depends on the condition of the ionosphere at the time of observation and user equipment capabilities.

[12] Anti-Spoofing (A-S) is the encryption process used to deny unauthorized access to the military Y-code. It also significantly improves a receiver’s ability to resist locking onto mimicked GPS signals, which could potentially provide incorrect positioning information to a GPS user.

[13] Wide-Area Augmentation System (WAAS) is a wide-area DGPS concept planned by the FAA to improve the accuracy, integrity, and availability of GPS to levels that support flight operations in the National Airspace System from en route navigation through Category I precision approaches. WAAS will consist of a ground-based communications network and several geosynchronous satellites to provide nationwide coverage. The ground-based communications network will consist of 24 wide-area reference stations, two wide-area master stations, and two satellite uplink sites. Differential corrections and integrity data derived from the ground-based network, as well as additional ranging data, will be broadcast to users from the geostationary satellites using an “L_1-like” signal.

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[16] A preliminary analysis of the L-band spectrum allocation that was conducted by Mr. Melvin Barmat, Jansky/Barmat Telecommunications Inc., Washington D.C., January 1994.

Issues Addressed by NRC

In response to a request from Congress, a joint study on the Department of Defense's Global Positioning System (GPS) was conducted by the National Academy of Sciences and the National Academy of Public Administration. The National Academy of Sciences was asked to recommend technical improvements and augmentations that could enhance military, civilian, and commercial use of the system. The National Academy of Public Administration was asked to address GPS management and funding issues, including commercialization, governance, and international participation. To conduct its part of the study, the National Academy of Sciences established an expert committee, through the National Research Council (NRC), the operating arm of the National Academy of Sciences and the National Academy of Engineering. Specifically, the National Academy of Sciences was asked to address the following three technical questions:

(1) Based on presentations by the Department of Defense (DOD) and the intelligence community on threats, countermeasures, and safeguards, what are the implications of such security-related safeguards and countermeasures for the various classes of civilian GPS users and for future management of GPS? In addition, are the Selective Availability and Anti-Spoofing capabilities of the GPS system meeting their intended purpose?

(2) What augmentations and technical improvements to the GPS itself are feasible and could enhance military, civilian, and commercial use of the system?

(3) In order to preserve and promote U.S. industry leadership in this field, how can communication, navigation, and computing technology be integrated to support and enhance the utility of GPS in all transportation sectors, in scientific and engineering applications beyond transportation, and in other civilian applications identified by the study in the context of national security considerations?

In its interpretation of Task 1, the NRC committee decided not only to determine whether Selective Availability (SA) and Anti-Spoofing (A-S) were meeting their intended purpose, but also to determine the broad ramifications of the use of these techniques and to make specific recommendations for each. In response to Task 2, the committee made recommendations for technical improvements because it believed that only identification of technical improvements would be of little value without an accompanying recommendation. In response to Task 3, the NRC committee considered "U.S. industry leadership" to mean technical preeminence focused on meeting the demands of a growing number of user applications, while maintaining a technical advantage for the DOD.

TASK 1: SELECTIVE AVAILABILITY AND ANTI-SPOOFING

Based on presentations by the DOD and the intelligence community on threats, countermeasures, and safeguards, what are the implications of such security-related safeguards and countermeasures for the various classes of civilian GPS users and for future management of GPS? In addition, are the Selective Availability and Anti-Spoofing capabilities of the GPS system meeting their intended purpose?

The DOD has stated that SA[7] is an important security feature because it prevents a potential enemy from directly obtaining positioning and navigation accuracy of 30 meters (95 percent probability) or better from the C/A-code.[8] Since the military has access to a specified accuracy of

21 meters (95 percent probability), they believe U.S. forces have a distinct strategic and tactical advantage. With SA at its current level, a potential enemy has access only to the C/A-code signal with a degraded accuracy of only 100 meters (95 percent probability). The DOD believes that obtaining accuracies better than 100 meters (95 percent probability) requires a substantial amount of effort on the part of an unauthorized user. Further, DOD representatives have expressed their belief that our adversaries are much more likely to exploit the GPS C/A-code rather than differential GPS (DGPS), because its use requires less effort and technical sophistication than is required to use DGPS.[9] In addition, some DOD representatives contend that local-area DGPS broadcasts do not diminish the military advantage of SA because they could be rendered inoperative, if warranted, through detection and destruction or by jamming.

It is opinion of the NRC committee, however, that any enemy of the United States sophisticated enough to operate GPS-guided weapons will be sophisticated enough to acquire and operate differential systems. Enemies could potentially take advantage either of the existing, commercial systems available worldwide or install a local DGPS system, which could be designed and operated in a manner that would be difficult to detect. These systems can have the capability to provide velocity and position corrections to cruise and ballistic missiles with accuracies that are equal to or superior to those available from an undegraded C/A-code. It should be noted that with both GPS- and DGPS-guided weapons, accurate knowledge of the target location is a prerequisite for weapon accuracy. Even if the level of SA is increased, DGPS methods could still be used to provide an enemy with accurate signals. Thus, the NRC committee concluded that the existence and widespread proliferation of DGPS augmentations have significantly undermined the effectiveness of SA in denying accurate radionavigation signals to our adversaries. In addition, the Russian GLONASS system broadcasts unencrypted signals with an accuracy comparable to an undegraded GPS C/A-code, which further erodes the effectiveness of SA.[10]

The unencrypted C/A-code, which is degraded by SA, still provides our adversaries with an accuracy of 100 meters (95 percent probability). With SA set at zero, the stand-alone accuracy improves to around 30 meters (95 percent probability).[11] While this improvement enhances the ability of an adversary to successfully attack high-value point targets, significant damage also can be inflicted with accuracies of 100 meters, (95 percent probability). Therefore, in either case (30-meter or 100-meter accuracy) the risk is sufficiently high to justify denial of the L_1 signal by jamming. The jamming strategy has the additional benefit of denying an adversary all radionavigation capability, including the even more accurate DGPS threat.

The NRC committee strongly believes that preservation of our military advantage with regard to radionavigation systems should focus on electronic *denial* of all useful signals to an opponent, for example, by jamming and spoofing, while improving the ability of civil and friendly military users to employ GPS in a jamming and spoofing environment. Continued effort to deny the accuracy of GPS to all users except the U.S. military via SA appears to be a strategy that ultimately will fail. Thus, the NRC committee recommends that the military employ denial techniques in a theater of conflict to prevent enemy use of GPS or other radionavigation systems.

The NRC committee believes that the principal shortcoming in a denial strategy, regardless of the level of SA, is the difficulty that military GPS receivers currently have in acquiring the Y-code during periods when the C/A-code is unavailable due to jamming of the L_1 signal. The implementation of direct Y-code acquisition capability would provide the optimal solution to this problem. The technology for developing direct Y-code receivers is available today. The committee believes that a focused, high-priority effort by the DOD to develop and deploy direct Y-code user equipment, backed by forceful political will from both the legislative and executive branches, can bring about the desired result in a relatively short period of time. In the interim before direct Y-code receivers can be fielded by the military, various operating disciplines can be used to minimize the impact of L_1 C/A-code jamming on the ability to acquire the Y-code directly.

From the onset of the study, the NRC committee agreed that national security was of paramount importance and, without exception, the U.S. military advantage should be maintained. As outlined above, the committee determined that the military effectiveness of SA is greatly diminished because of the widespread proliferation of DGPS and the existence of GLONASS. In addition, the NRC committee compiled the following findings related to the effects of SA and A-S[12] on the various classes of civilian users:

• The presence of SA and A-S increases the cost and complexity of Federal Aviation Administration's Wide Area Augmentation System (WAAS)[13] and limits the effectiveness of Receiver Autonomous Integrity Monitoring (RAIM).[14]

• The presence of SA affects the acceptance of GPS by some commercial users and limits the ability of the Coast Guard's DGPS service to provide important safety-related information to its users.

• GPS-based automobile navigation systems, which require accuracies in the 5- to 20-meter range, would no longer require DGPS if SA was eliminated and further improvements were made to the basic GPS. The elimination of SA would also improve the performance of those DGPS systems required for higher-accuracy applications, such as collision avoidance, that are important to the future Intelligent Transportation System.

• Most mapping, surveying, and geodetic applications would be enhanced by cost savings from quicker acquisition of data. The elimination of SA and the ability to track code on two frequencies can improve acquisition time.

• Post-processing can eliminate the effects of SA for most Earth science applications, but the presence of A-S increases the cost and limits the performance of many techniques.

• Although GPS currently meets all accuracy requirements for both GPS time transfer and time synchronization using direct GPS time, many telecommunications companies are still hesitant to utilize GPS because of concerns about system reliability and the presence of SA.

• SA has little or no effect on the ability to use GPS for spacecraft orbit or attitude determination, but A-S limits the performance of orbit determination for spacecraft that rely on dual-frequency codeless measurements. A-S may also contribute to limitations on achievable attitude determination accuracy.

The six most important findings of the NRC committee regarding the impact of SA on the various classes of civilian users and on meeting its intended purpose are

(1) The military effectiveness of SA is significantly undermined by the existence and widespread proliferation of DGPS augmentations as well as the potential availability of GLONASS signals.

(2) Turning SA to zero would have an immediate positive impact on civil GPS users. Without SA, the use of DGPS would no longer be necessary for many applications. System modifications that would further improve civilian accuracy also would be possible without SA.

(3) Deactivation of SA would likely be viewed as a good faith gesture by the civil community and could substantially improve international acceptance and potentially forestall the development of rival satellite navigation systems. Without SA, the committee believes that the number of GPS and DGPS users in North America would increase substantially.[15]

(4) It is the opinion of the committee that the military should be able to develop doctrine, establish procedures, and train troops to operate in an L_1 jamming environment in less than three

years.
(5) The technology for developing direct Y-code receivers is currently available and the development and initial deployment of these receivers could be accomplished in a short period of time if adequately funded.
(6) The FAA's WAAS, the Coast Guard's differential system, and GLONASS are expected to be fully operational in the next 1 to 3 years. The Coast Guard's DGPS network and the WAAS will provide accuracies greater than that available from GPS with SA turned to zero and GLONASS provides accuracies that are comparable to GPS without SA. At the same time, other local DGPS capabilities are likely to continue to proliferate.

n ***Selective Availability should be turned to zero immediately and deactivated after three years. In the interim, the prerogative to reintroduce SA at its current level should be retained by the National Command Authority.***

Although many civil users could benefit if A-S is turned off as noted above, the NRC committee found that A-S remains critically important to the military because it forces potential adversaries to use the C/A-code on L_1, which can be jammed if necessary without inhibiting the U.S. military's use of the encrypted Y-code on L_2. Further, encryption provides resistance to spoofing of the military code. The NRC committee determined, however, that the current method of manual distribution of Y-code decryption keys is laborious and time consuming. The DOD has recognized this problem and has ongoing efforts to distribute keys electronically. The NRC committee believes that an electronic key distribution capability would greatly enhance the use of the encrypted L_2 Y-code. The committee also believes that technology is available to upgrade the current encryption method and suggests that the Air Force should explore the necessity of utilizing this technology. Modifications to the Block IIR satellites and the Block IIF request for proposal may be required if upgraded encryption methods are necessary. Changes to military receivers also will be required.

n ***A-S should remain on and the electronic distribution of keys should be implemented at the earliest possible date. In addition, the Air Force should explore the necessity of upgrading the current encryption method. Required receiver enhancements should be incorporated in future planned upgrades.***

TASK 2: TECHNICALIMPROVEMENTS

What augmentations and technical improvements to the GPS itself are feasible and could enhance military, civilian, and commercial use of the system?

Today GPS is a true dual-use system. Although it was originally designed to provide a military advantage for U.S. forces, the number of civilian users now exceeds the number of military users. During the course of the study, the NRC committee examined various technologies and augmentations applicable to GPS. It determined that several improvements could be made to the system that would enhance its use for civilian, commercial, and military users without compromising national security. Some of the improvements could be made immediately; others could be incorporated on some of the Block IIR spacecraft that are currently being built and included in the specification requirements for the next generation Block IIF spacecraft. The committee's recommendations are listed below. Although the approximate cost of each improvement is given when available, potential funding mechanisms for each improvement are not discussed. In general, the issue of GPS funding is addressed by the National Academy of Public Administration.

Recommendations That Enhance GPS Performance for Civil and Commercial Users

The NRC committee found that the most prominent need for commercial and civil users is greater stand-alone accuracy, availability, and integrity. With improved performance of the basic GPS signal, many users would no longer require augmentations to obtain the data they require. Any additional system enhancements and modifications to improve stand-alone positioning accuracy for civilian users are relatively ineffective in the presence of SA. However, if the recommendation to deactivate SA is implemented, the committee has identified several enhancements that could provide significant improvement for both civilian and military users. With SA removed, the major enhancement that would greatly increase accuracy for civilian users is the addition of a new, unencrypted signal that allows for corrections of errors introduced by the ionosphere.[16] While very important for civil users, this feature will provide minimal additional capability to military users because they already have this capability through use of their encrypted signals.

n ***Immediate steps should be taken to obtain authorization to use an L-band frequency for an additional GPS signal, and the new signal should be added to GPS Block IIR satellites at the earliest opportunity.***

Recomendations That Enhance GPS Performance for Military Users

As stated above, GPS was originally designed to provide our forces with a military advantage. In the past, DOD has depended on a strategy of global signal degradation, through SA, to reduce the GPS signal accuracy to civilian and unauthorized users, while providing a more accurate, encrypted signal to authorized users. However, as stated above, the committee believes that the military usefulness of SA is severely diminished and that it is urgent that the DOD focus its attention on *denial* of all useful signals to an opponent, for example, through jamming and spoofing techniques, including jamming of the unencrypted C/A-code, rather than relying on SA. The NRC committee therefore recommends several military receiver enhancements that would support such a strategy.

n ***The development of receivers that can rapidly lock onto the Y-coded signals in the absence of the C/A-code should be completed. The deployment of direct Y-code receivers should be given high priority by the DOD.***

n ***Nulling antennas and antenna electronics should be employed whenever feasible and cost effective. Research and development focused on reducing the size and cost of this hardware should actively be supported.***

n ***The development of low-cost, solid-state, tightly-coupled integrated inertial navigation system/GPS receivers to improve immunity to jamming and spoofing should be accelerated.***

n ***The development and operational use of GPS receivers with improved integration of signal processing and navigation functions for enhanced performance in jamming and spoofing should be accelerated.***

n ***Military receivers should be developed that compensate for ionospheric errors when L_1 is jammed, by improved software modeling and use of local-area ionospheric corrections.***

In the interim time before such enhancements can be fielded by the military, various operating disciplines can be used to minimize the impact of C/A-code jamming on the ability to acquire the Y-code directly.

Recommendations that Enhance GPS Performance for All Users (Civil, Commercial, and Military)

In view of the rapidly expanding use of GPS, the NRC committee believes that GPS must be capable of continuous operation in all foreseeable contingencies. This capability is critical. The one area where the NRC committee found limited redundancy was in the operational control segment (OCS). Although the NRC committee determined that the Air Force has several experiments planned to improve the system, it believes there are some additional improvements that can be made to the OCS that would increase stand-alone accuracy, availability, and integrity; improve the overall reliability of the system; or simplify day-to-day operations. Recommendations that would result in greater stand-alone GPS accuracy and integrity include uploading more current clock and orbit information to all satellites, increasing the number of monitor sites, reducing the clock and ephemeris errors, and improving Block IIR and Block IIF integrity monitoring capability. In addition, the NRC committee found a need for (1) a simulator to test software and train personnel, (2) modern receivers at the monitor stations, and (3) a permanent, backup master control station. Specifically, the NRC committee recommends:

n ***Additional GPS monitoring stations should be added to the existing operational control segment. Comparison studies between cost and location should be completed to determine if Defense Mapping Agency or Air Force sites should be used.***

n ***The operational control segment Kalman Filter should be improved to solve for all GPS satellites' clock and ephemeris errors simultaneously through the elimination of partitioning, and the inclusion of more accurate dynamic models. These changes should be implemented in the 1995 OCS upgrade request for proposal.***

n ***Procurements for the replacement of the monitor station receivers, computers, and software should be carefully coordinated. The new receivers should be capable of tracking all satellites in view and providing C/A-code, Y-code, and*** L_1, ***and*** L_2 ***carrier observables to the OCS. Upgradability to track a new*** L_4 ***signal also should be considered. OCS software also should be made capable of processing this additional data.***

n ***Firm plans should be made to ensure the continuous availability of a backup master control station.***

n ***A simulator for the space and ground segment should be provided as soon as possible to test software and train personnel.***

n ***The operational control segment software should be updated using modern software engineering methods in order to permit easy and cost-effective updating of the system and to enhance system integrity. This should be specified in the 1995 OCS upgrade request for proposal.***

n ***The planned Block IIR operation should be reexamined and compared to the accuracy advantages gained by incorporating inter-satellite ranging data in the ground-based Kalman Filter and uploading data at some optimal time interval, such as every hour, to all GPS satellites.***

n ***Block IIR satellite communication crosslinks should be used to the extent possible with the existing crosslink data rate to support on-board satellite health monitoring for improved reliability and availability and in order to permit a more rapid response time by the operational control segment.***

n ***The Block IIR inter-satellite communication crosslinks should be used to relay integrity information determined through ground-based monitoring.***

n ***The DOD's more frequent satellite navigation correction update strategy should be fully implemented as soon as possible following the successful test demonstration of its effectiveness. In addition, the current security classification policy should be examined to***

determine the feasibility of relaxing the 48-hour embargo on the clock and ephemeris parameters to civilian users.

As shown in Figure 4, if the above recommendations are implemented, the NRC committee believes that the overall GPS performance and reliability will be greatly enhanced and that a stand-alone horizontal accuracy of the basic GPS signal approaching 5 meters (95 percent probability) could be achieved for both civilian and military users.

Improvement Implementation Strategy

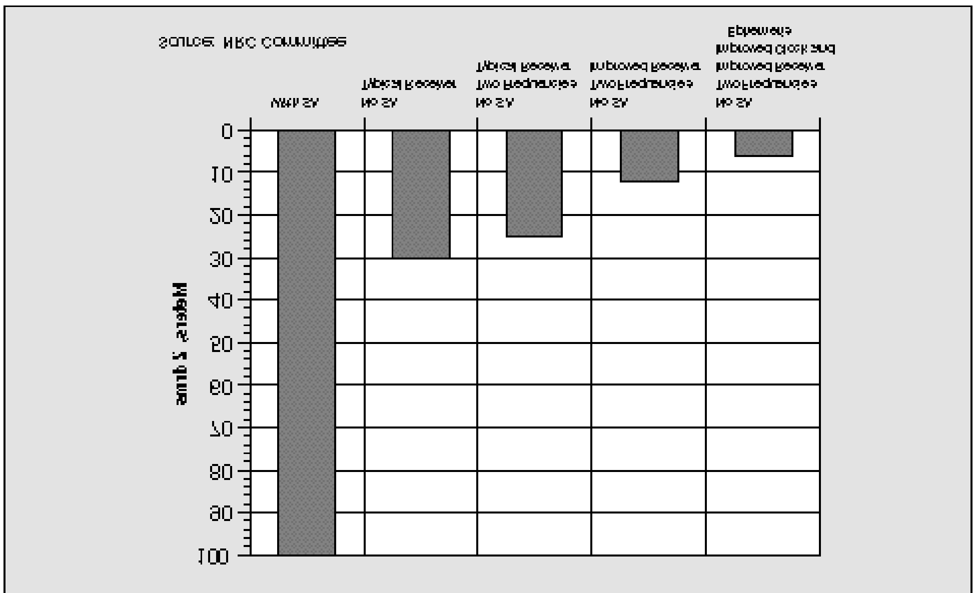

Figure 4: Stand-Alone Horizontal SPS Accuracy Resulting from Recommended Improvements and Enhancements

Because of the relatively long life time of GPS satellites (5 to 10 years) and the length of time required to replace the total constellation of 24 satellites, opportunities for introducing enhancements and technology improvements to the system are limited.

Figure 5 shows the current plan for satellite replacements. According to the GPS Joint Program Office, current plans for the Block IIF contract include 6 short-term and 45 long-term “sustainment” satellites. As currently planned, the Block IIF satellites will be designed to essentially the same specifications as the Block IIR satellites. The current program and schedule make it possible for another country to put up a technically superior system that uses currently available technology before the United States can do so. Under the current planning and in the absence of a preplanned product improvement (P^3I) program, the earliest opportunity for an infusion of new technology in the GPS space segment would be after Block IIF, probably sometime after the year 2020.

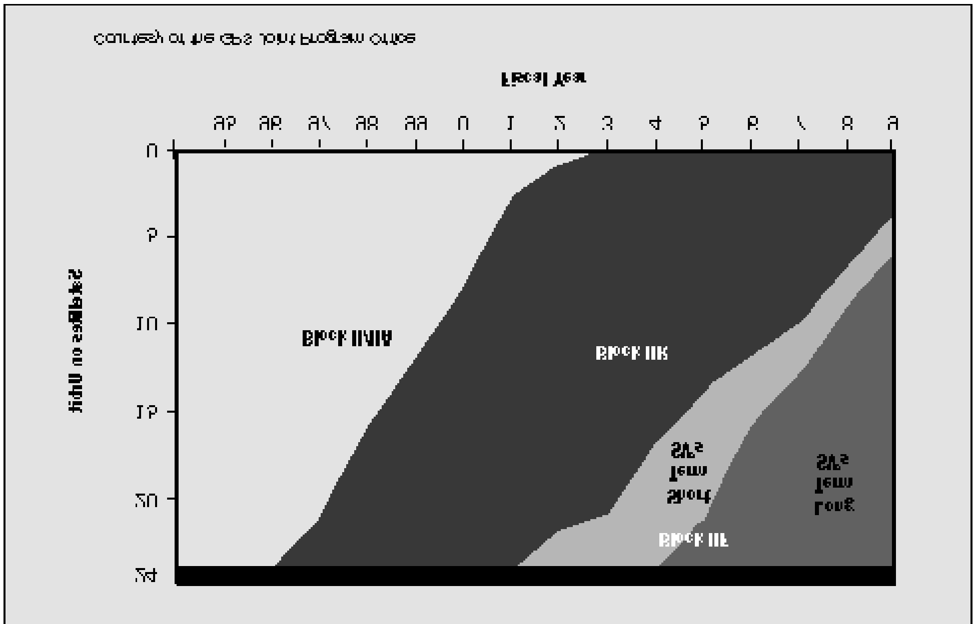

Figure 5: Current Plan for Satellite Replacement

The NRC committee believes that there are significant improvements that could be made to the system much earlier than post-Block IIF that would not only enhance its performance for civilian and military use but also make it more acceptable and competitive internationally. One method to incorporate technology in an efficient and timely manner is through a P^3I program beginning as early as possible in Block IIR. With this type of approach, planned changes and improvements could be intentionally designed into the production of the satellites at specific time intervals.

Assuming that the first improvements suggested in this report are incorporated in the later half of the Block IIR satellites, additional funding might be required to incorporate changes for the already completed Block IIR satellites. However, the NRC committee believes that the timely improvement in system performance is adequate justification for the additional cost.

In addition to the specific recommendations given in this report, the NRC committee also discussed several enhancements that it believes have particular merit and should be seriously considered for future incorporation. Although a few enhancements could be included on the Block IIR spacecraft, especially if a P^3I program were implemented, most of the enhancements would have to be incorporated in the Block IIF spacecraft design.

TASK 3: Technology Integration

In order to preserve and promote U.S. industry leadership in this field, how can communication, navigation, and computing technology be integrated to support and enhance the utility of GPS in all transportation sectors, in scientific and engineering applications beyond transportation, and in other civilian applications identified by the study in the context of national security considerations?

The NRC committee found that civil, commercial, and military GPS users are making rapid progress in developing and utilizing systems that integrate GPS with other technologies. For many navigation and position location applications, GPS is being combined with one or more of the following: radar; inertial navigation systems; dead reckoning systems; aircraft avionics and flight management systems; digital maps; computers and computer databases; and communication datalinks. For timing applications, GPS can be combined with reference clocks and digital communication networks. Surveying and mapping users have combined GPS with computer databases, inertial navigation systems, digital imaging systems, and laser measuring systems. Earth science users have integrated GPS with radar altimeters, precision accelerometers, synthetic aperture radar, computer databases and workstations, and communications datalinks. By integrating GPS with other technologies, highly accurate positioning and timing information can be obtained at a very modest cost, which provides a large incentive to system designers to develop integrated GPS products. For example, with the large market potential for ground vehicle position location and guidance systems, there is considerable motivation for the vigorous commercially funded research and development activity that is underway. The NRC committee believes that the U.S. user equipment industry's intensive focus on research and development is sufficient to ensure that its technical competitiveness will be maintained.

During its deliberations, the committee found that some user communities had a limited number of very specific issues related to the integrated use of GPS with other technologies that may require government action. Examples include the need to modernize the air traffic management system to take advantage of the full capabilities of GPS-based navigation and surveillance and the need to speed up the process of providing up-to-date digital hydrographic data for use in Electronic Chart Display Information Systems (ECDIS). In general, however, the GPS industry is meeting most user demands by continuously improving integrated user equipment and services and is limited only by the need to augment and enhance the characteristics of the basic GPS constellation. Therefore, it is the opinion of the NRC committee that the *most important* government action required is to improve the performance of the basic GPS satellite system to provide the highest levels of position accuracy, signal integrity, and signal availability that can be technologically achieved at reasonable cost without negatively impacting national security. The committee believes that the performance improvements summarized in response to Task 2 above meet these criteria.

[1] Accuracies for GPS are usually expressed in terms of 95 percent probability.

[2] PPS accuracy, as specified here in 95 percent probability, is usually specified in spherical error probable (SEP) of 16 meters (50 percent probability).

[4] GPS provides an internationally available service, similar in many respects to a public utility. The system requires a substantial up-front capital investment, has decreasing average costs, is generally available to anyone, and therefore is a natural monopoly; that is, it is more efficient to have one instead of many providers.

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APPENDIX A
Legislation Authorizing the Study

Conference Report - National Defense Authorization Act FY 1994

SEC. 152. GLOBAL POSITIONING SYSTEM

(a)PROGRAM STUDY REQUIRED.-

(1) The Secretary of Defense shall provide for an independent study to be conducted on the management and funding of the Global Positioning System program for the future.

(2) With the agreement of the National Academy of Sciences and the National Academy of Public Administration, the study shall be conducted jointly by those organizations.

(3) Of the amounts authorized to be appropriated to the Department of Defense for fiscal year 1994 and made available for procurement of Global Positioning System user equipment, for procurement of spacecraft, or for operations and maintenance, up to $3,000,000 may be used for carrying out the study required by paragraph (1).

APPENDIX B
Biographic Sketches of NAPA Panel and Staff

NAPA PANEL

JAMES R. SCHLESINGER, Panel Chair - Chairman, Mitre Corporation. Former Secretary, U.S. Department of Energy; Assistant to the President; U.S. Secretary of Defense; Director, Central Intelligence Agency.

CARL O. BOSTROM * - Physicist. Former Director, Johns Hopkins University Applied Physics Laboratory; Member, Defense Intelligence Agency; Scientific Advisory Board, 1983-present (Chairman 1987-1992); Former member, Air Force Scientific Advisory Board; Former Ex Officio member, Defense Science Board.

CHARLES W. COOK * - Consultant. Former Deputy Assistant Secretary, U.S. Air Force and Executive Secretary, Defense Space Operations Committee; Deputy Under Secretary, U.S. Air Force; Assistant Director, Defense Research and Engineering, Office of the Secretary of Defense; Deputy Division Chief & Chairman, Space Operations Requirements Subcommittee, Central Intelligence Agency; Corporate Director, North American Aviation.

HAROLD B. FINGER - Consultant. Former President and CEO, U.S. Council for Energy Awareness; Manager for Strategic Planning and Development Operations, and General Manager, Center for Energy Systems, General Electric Company; Assistant Secretary for Research and Technology, U.S. Department of Housing and Urban Development; Associate Administrator for Organization and Management, and Director, Space Power and Nuclear Systems, National Aeronautics and Space Administration.

EDWIN L. HARPER - President and Chief Executive Officer, Association of American Railroads. Former Senior Vice President and Chief Financial Officer, Campbell Soup Company. Executive Vice President, Dallas Corporation; assistant to the President for Policy Development, the White House; Deputy Director, U.S. Office of Management and Budget.

RAY KLINE - Former President, National Academy of Public Administration; Deputy Administrator and Acting Administrator, U.S. General Services Administration; Associate Administrator for Management Operations, National Aeronautics and Space Administration.

WILLIAM Y. SMITH - Former President, Institute for Defense Analyses; Fellow, Woodrow Wilson International Center for Scholars; Deputy Commander-in-Chief, United States European Command; Chief of Staff, Supreme Headquarters, Allied Powers, Europe; Assistant to the Chairman, Joint Chiefs of Staff; General, U.S. Air Force, Ret.

MILTON J. SOCOLAR - Former positions with the General Accounting Office: Special Assistant to the Comptroller General of the U.S.; Acting Comptroller General of the U.S.; General Counsel and Deputy General Counsel.

JOHN G. STEWART - Executive Director, Consortium of Research Institutions. Former Vice President, Resource Development, Manager of Corporate Administration, and Manager of Planning and Budget, Tennessee Valley Authority (TVA); Member, Aerospace Safety Advisory Panel, NASA; Staff Director, Subcommittee on Science, Technology and Space, U.S. Senate; Staff Director, Subcommittee on Energy, Joint Economic Committee, U.S. Congress; Executive Assistant to the Vice President of the United States.

TERENCE A. TODMAN - Consultant. Retired, U.S. Department of State Foreign Service: Career Ambassador to Argentina; Ambassador to Denmark; Ambassador to Spain; Assistant Secretary of State for Inter-American Affairs; Ambassador to Costa Rica; Ambassador to Guinea; Ambassador to Chad.

NAPA STAFF

Arnold E. Donahue, Project Director - Executive Vice President, Pacific Trade Associates; Former Senior Executive Service, Chief, Command, Control, Communications and Intelligence (C^3I), Office of Management and Budget; Intelligence officer and economist, Central Intelligence Agency.

Roger L. Sperry, Co-Project Director - Director of Management Studies, National Academy of Public Administration. Former Professional Staff Member, U.S. Senate Committee on Governmental Affairs; Senior Group Director and Special Assistant to Comptroller General, U.S. General Accounting Office.

Ronald S. Boster, Senior Research Associate, Governance and Management - Former Chief of

Staff to three Members of Congress; Sr. Economist, Deputy Staff Director, and Executive Director of House Budget Committee (minority staff); research economist at USDI and USDA; Adjunct Professor, Center for Public Policy and Administration, Virginia Polytechnic Institute and State University.

Benita C. Carr, Administrative Assistant; project and administrative support, including word processing and logistics for standing panels and related NAPA projects.

C. Clayton Durr, Senior Research Associate - Commercial - Management consultant, business executive and entrepreneur - Co-founder Telegen Corporation; Executive Advisor, Strategic Insight Inc.; aerospace industry manager and consultant.

Julie A. Everitt, Research/Administrative Assistant - Former Staff Assistant, Senator Tom Harkin; Intern, Alliance for Redesigning Government.

Jeffrey S. Fitzpatrick, Project Coordinator/ Research Associate - Former Policy Analyst, U.S. Advisory Commission on Intergovernmental Relations.

Michael J. Full, Research Associate - Supervisory Geodesist, Department of Geodesy and Geophysics, Defense Mapping Agency Aerospace Center (DMAAC); fourteen years of experience working on TRANSIT and GPS programs as tracking station operator, monitor station network manager, GPS program manager and precise ephemeris production supervisor.

Henry R. Hertzfeld, Senior Research Associate, Funding - Senior Research Associate, the Center for International Science and Technology Policy, George Washington University. Senior Economist at the National Science Foundation; Senior Economist, NASA Headquarters.

Albert J. Kliman, Issue Area Leader, Funding - Independent consultant in the fields of government organization, budgeting, and financial management. Former Budget Officer, Department of Housing and Urban Development. President of the American Association for Budget and Program Analysis.

Emerson Markham, Senior Research Associate, Funding - Former Budget Director, Veterans Administration, ACTION, and Airways Modernization Board; has held a variety of financial management and planning positions in eight federal agencies over a 34-year period; Project Director on NAPA projects, including projects with the Administrative Office of the U.S. Courts, Department of Veterans Affairs, General Accounting Office, Office of Personnel Management, and Treasury Department.

Carole M. P. Neves, Issue Area Leader, International - Project Director, National Academy of Public Administration. Former Project Director, Urban Systems Research and Engineering Inc.; Technical Staff, the Mitre Corporation; Adjunct Professor, Center for Public Policy and Administration, Virginia Polytechnic Institute and State University.

Leslie D. Smolin, Issue Area Leader, Governance and Management - Founder and President, E & D Associates; Former Director, Booz•Allen Health Care Inc.; Former Managing Director, DataFocus Inc. (a subsidiary of Convergent Solutions Inc.); Director of the Pyramid Group, Adia Information Technologies Inc.; Senior Manager, Booz•Allen & Hamilton, Inc.; Supervisory Analyst, U.S. General Accounting Office.

APPENDIX C

Abbreviated NRC Committee Biographies

LAURENCE J. ADAMS (NAE) is the retired President and Chief Operating Officer of the Martin Marietta Corporation. He joined Martin Marietta in 1948 after receiving a bachelors degree in aerospace engineering from the University of Minnesota. Mr. Adams has held over a dozen engineering, management, and senior leadership positions in the company, and was President of the aerospace division before becoming President and Chief Operating Officer. He is an expert in many areas of space and missile engineering, including propulsion, materials structures and dynamics, safety, reliability, and systems effectiveness. Mr. Adams has been a member of United States Air Force committees and panels, and USAF Scientific Advisory Board studies and panels. Mr. Adams has served as chair of several NRC committees, including the Committee on Advanced Space Technology and the Panel on Small Spacecraft Technology, and is a former president of the American Institute of Aeronautics and Astronautics.

PENINA AXELRAD is an assistant professor in the Aerospace Engineering Sciences at the University of Colorado at Boulder. Prior to joining the faculty of the University of Colorado, she was a lecturer in the Department of Aeronautics and Astronautics at Stanford University, where she received her Ph.D. in 1991. Dr. Axelrad received her B.S and M.S. in aeronautical and astronautical engineering from the Massachusetts Institute of Technology. Her professional experience with GPS includes prior employment as a GPS program manager and lead systems engineer for Stanford Telecommunications and as a GPS consultant for various companies. Dr. Axelrad has published a number of papers in the GPS field and she is the 1994-1995 Western Region Vice President of the Institute of Navigation. She also is an associate editor of *NAVIGATION*, The Journal of the Institute of Navigation.

JOHN D. BOSSLER is the director of Center for Mapping at the Ohio State University and a professor in the Department of Geodetic Science and Surveying. Dr. Bossler was the Director of Charting and Geodetic Services at NOAA and is a retired Rear Admiral in the NOAA Commissioned Corps. Dr. Bossler is knowledgeable of GPS and has experience in ocean and land mapping, geodesy, global change research, land and ocean surveying, and high accuracy uses of GPS. Dr. Bossler is past president of AM/FM International, the American Congress on Surveying and Mapping, the Geodesy Section of the American Geophysical Union, and is president of the University Consortium of Geographic Information Science. Dr. Bossler received his civil engineering degree from the University of Pittsburgh, and his M. S. and Ph.D. in geodetic science from the Ohio State University. Dr. Bossler has served and chaired several NRC committees.

RONALD BRAFF is a Principal Engineer at the Center for Advanced Aviation System Development (CAASD) at The MITRE Corporation. Mr. Braff is an expert in navigation technology, a technical advisor for the FAA concerning the application of GPS in the National Airspace System, and the test director for the FAA's Local Area Augmentation System (LAAS) for GPS. While at MITRE, his past activities included management and technical contributions in the following areas for the FAA: applications of satellites to communications, navigation, and surveillance, operational research of the FAA's field maintenance system, and analysis of air traffic control automation. Mr. Braff is the editor of the peer reviewed quarterly, *NAVIGATION*, The Journal of The Institute of Navigation. He recently served on the NRC's Committee on Advances in Navigation and Piloting.

A. RAY CHAMBERLAIN has been Vice President of the American Trucking Associations, Inc. since 1984. In 1987, Dr. Chamberlain was appointed as Executive Director of the State of Colorado Department of Highways and later its successor, the Colorado Department of Transportation. He has served one term as president of the American Association of State Highway and Transportation Officials; and has served as chair of the National Research Council's Transportation Research Board and the National Association of State University and Land Grant Colleges. He has also served as Chief Executive Officer of Chemagnetics, Inc.; Executive Vice President of Simons, Li & Associates, Inc.; and President of Mitchell & Co., Inc. From 1969 to 1980, he was President of Colorado State University, where he held a variety of positions, including Dean of Engineering, Executive Vice President and Treasurer of the Governing Board. He is a member of the American Society of Civil Engineers. Dr. Chamberlain is on the Board of Directors for, Fort Collins Chamber of Commerce, the Food Production Foundation, and Synergetics International. He has served on several NRC committees and chaired the NRC's Transportation Research Board's Strategic Transportation Research Study on Highway Safety. Dr. Chamberlain obtained his B.S. in engineering from Michigan State University and his Ph.D. in engineering from Colorado State University. Dr. Chamberlain possesses a broad knowledge of surface transportation issues, including state and local issues as well as the freight industry.

RUTH M. DAVIS (NAE) is President and CEO of the Pymatuning Group, Inc. in Arlington, Virginia and a member of the National Academy of Engineering. Her research interests include automation, electronics, computers, and energy. Dr. Davis received her Ph.D. in mathematics from the University of Maryland in 1955. She joined the David Taylor Model Basin in 1955 and was head of the Operations Research Division there from 1957 to 1961. She has worked for the National Library of Medicine, the National Bureau of Standards, and was Deputy Undersecretary for Research and Engineering for the Department of Defense and an Assistant Secretary in the Department of Energy. Since 1981, she has been President of the Pymatuning Group, and an Adjunct Professor in the School of Engineering at the University of Pittsburgh. Dr. Davis is currently the chairman of the Aerospace Corporation, and is on the board of seven Fortune 500 Companies. She is also a member the NRC's Aeronautics and Space Engineering Board and the Naval Studies Board. She is serving on the Committee on the Space Station, and the Panel for the Cooperation on Applied Science and Technology Program. Dr. Davis has received the Department of Commerce Gold Medal and the Ada Augusta Lovelace Award.

JOHN V. EVANS (NAE) is President and Director of COMSAT Laboratories, which is the largest research center devoted entirely to satellite communications research. Prior to his current position, Dr. Evans was Assistant Director of the MIT Lincoln Laboratory. Dr. Evans is the co-editor of *Radar Astronomy* and has published over a hundred papers on the topics of radar reflection and high-power radar studies of the upper atmosphere and ionosphere. Dr. Evans has served on several NRC committees and chaired the Committee on Solar Terrestrial Research. Dr. Evans has served on the U. S. National Committee of the International Union of Radar Science since 1968. While he was chair in 1978, Dr. Evans led a delegation of over 150 U. S. scientists to the General Assembly in Helsinki, Finland.

JOHN S. FOSTER, Jr. (NAE) is the retired Vice President of the Science and Technology Department at TRW Inc. He joined TRW in 1973 as head of the company's energy research and development programs. Prior to his employment at TRW, Dr. Foster served in two Presidential Administrations as Director of Defense Research and Engineering (DDR&E) within the Department of Defense. In this position he instituted new policies and procedures for the management of technology and systems acquisition, and personally contributed to the successful development of many advanced defense systems, including GPS. Dr. Foster received a bachelor's degree in mathematics and physics at McGill University in Montreal, and earned a Ph.D. in physics from the University of California at Berkeley. He joined the staff of the Lawrence Berkeley National Laboratory while he was still a student, and helped to establish the Lawrence Livermore National Laboratory in 1952. He later served as Director of the Laboratory. Dr. Foster holds several patents, and is the author of many publications in the fields of high-energy physics, defense technology, and electronic systems. He has served on several NRC committees, including the Study of Presidentially Appointed Scientists and Engineers, and the Panel on the Impact of National Security Controls on International Technology Transfer.

EMANUEL J. FTHENAKIS is the retired Chief Executive Officer and Chairman of the Board of Fairchild Industries. Previously, he had the position of Executive Vice President in charge of the company's Communications, Electronics, and Space Group. Mr. Fthenakis joined Fairchild in 1971 as Director of Information Systems at the Space and Electronics Division, and was founder and Chief Executive of American Satellite Company during its formative years. A native of Greece, and a naturalized U.S. citizen, Mr. Fthenakis graduated from the National Polytechnic University of Greece and from Columbia University in New York. He was a member of the technical staff at Bell Laboratories and later joined General Electric Company's Space Division as Director of Engineering, where he was involved in the development of strategic reentry vehicles and other missile programs. Between 1962 and 1969, Mr. Fthenakis founded, organized, and directed the Ford Space Division and was responsible for developing the first U.S. military communications satellite system. In 1982 he received a presidential appointment to serve on the National Security Telecommunications Advisory Council.

J. FREEMAN GILBERT (NAS) is with the Institute of Geophysics and Planetary Physics at the University of California, San Diego. He received his Ph.D. in 1956 from the Massachusetts Institute of Technology, and is widely published in the field of geophysics. Dr. Gilbert has served on a number of NRC committees and has served as a board member for the Computer Sciences and Telecommunications board, and the Earth Sciences and Resources Board, which he currently chairs.

RALPH H. JACOBSON is the President and Chief Executive Officer of The Charles Stark Draper Laboratory. Prior to holding this position, Mr. Jacobson served in the U.S. Air Force for 31 years, and retired at the rank of Major General. His career included tours as a tactical airlift pilot, a project officer for the Titan-II inertial guidance system, and a number of assignments in the U.S. Space Program. As a Brigadier General, Mr. Jacobson was assigned to the Space Shuttle Program Office at NASA Headquarters, and later was the Air Staff Officer responsible for the budget of the Air Force's space program. His last position was Director of Special Projects within the Office of the Secretary of the Air Force. Mr. Jacobson received a B.S. from the U.S.

Naval Academy, an M.S. in astronautics from the Air Force Institute of Technology, and an M.S. in business administration from the George Washington University. He is a member of several boards, committees, and advisory groups in the national security and aerospace fields, and is a former member of the NRC Committee on the Enhanced, Lower Cost Air Force Space Systems.

IRENE C. PEDEN (NAE) is a professor of electrical engineering at the University of Washington. She joined the faculty of the University of Washington in 1961 after receiving her Ph.D. from Stanford University, and after holding a number of professional positions in industry. From 1991 to 1993 Dr. Peden served in the National Science Foundation as the Director of the Electrical & Communications Systems Division and the Director of the Engineering Infrastructure Development Division. Her expertise includes electrical engineering and radio science, and she has published a number of professional papers on these subjects. Dr. Peden has served as a board member and chair for dozens of professional and honorary societies, and has served on several NRC committees.

KEITH D. MCDONALD is President of Sat Tech Systems and Technical Director for Navtech Seminars, Inc. Previously, Mr. McDonald directed the FAA's Aeronautical Satellite Division, and managed the satellite applications and technology program. He was also the Scientific Director of the DOD's Navigation Satellite Program during the formative stages of the GPS program. Mr. McDonald has been active in RTCA, preparing guidelines for the use of satellite systems in aviation, and has received the RTCA Citation for Outstanding Service. He also has received the Institute of Navigation's (ION) Norman P. Hays Award for outstanding contributions to the advancement of navigation, and served as the 1990 ION President.

JAMES W. SENNOTT is a professor of electrical and computer engineering at Bradley University. He is an expert in navigation and positioning systems, estimation theory, multiple access, spread-spectrum communications, image processing, software design and microprocessor architectures. In addition to his work at Bradley University, Dr. Sennott has worked with the Department of Transportation; NASA Goddard Space Flight Center; Caterpillar Tractor, Co.; Sat Tech Systems, Inc.; Delco Electronics; Interstate Electronics; Track Recorders; COMSAT Laboratory; and the MITRE Corporation. Dr. Sennott has been the principal investigator on contracts funded by the FAA; the U. S. Coast Guard; Caterpillar Tractor, Inc.; and the U. S. Maritime Administration. In his work for the U. S. Coast Guard, Dr. Sennott assisted in the development and application of GPS methods, including DGPS. Dr. Sennott received his B.S. in electrical engineering from the University of Delaware in 1963 and his M.S. and Ph.D. from Carnegie-Mellon University.

JOSEPH W. SPALDING is Project Manager of the Advanced GPS Project at the United States Coast Guard Research and Development Center in Groton, CT. Mr. Spalding has been conducting research in GPS and DGPS for nine years, and has published a dozen technical reports on these subjects. His current projects at the Research and Development Center include systems that measure the integrity of GPS and DGPS performance both on-board ships and as static monitors for the Coast Guard DGPS service and vessel attitude determination by using an array of GPS antenna/receiver combinations. Mr. Spalding holds a B.S. in electrical engineering from the State University of New York Maritime College and an M.S. in computer science from the University of New Haven. He is also a licensed Merchant Marine officer holding a rating of

Third Mate of Oceans.

LAWRENCE E. YOUNG is a technical group supervisor developing high precision radiometric systems for geoscience and spacecraft applications at Caltech’s Jet Propulsion Laboratory (JPL). The last twelve years of this work have concentrated on the development of high-accuracy GPS technology including digital receivers, multipath reduction, nanosecond-level clock synchronization, and the use of GPS for kinematic platforms and satellite applications. Dr. Young has published a number of papers related to GPS receiver and antenna research. He received a B.A. in physics from Johns Hopkins University, and a Ph.D. in nuclear physics from the State University of New York at Stony Brook.