Crosslink®

The Aerospace Corporation magazine of advances in aerospace technology

Summer 2002

Satellite Navigation

- Origins of GPS
- Overview and applications
- Constellation management
- Orbit determination
- Weapons delivery
- Antijamming for GPS
- Modernization and GPS III

Contents

Crosslink
Summer 2002 Vol. 3 No. 2

Departments

Cover: Karl Jacobs

6 Charting a Course Toward Global Navigation

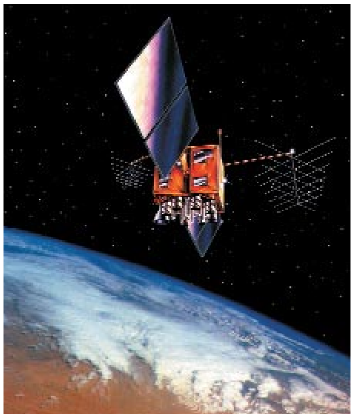
Steven R. Strom

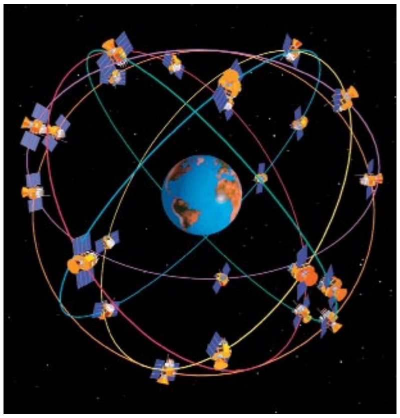
In the 1960s, the Global Positioning System emerged as a radical new way to provide precise navigation for U.S. armed forces across the globe. Early work at The Aerospace Corporation helped get the program off the ground.

12 Operation and Application of the Global Positioning System

Colleen H. Yinger

GPS was originally designed for defense operations, but civilian receivers now far outnumber military receivers. The number of operational receivers has increased exponentially over the last decade as the technology has moved in diverse and unexpected directions.





17 Optimizing Performance Through Constellation Management

Paul Massatt and Wayne Brady

Deciding where to put the GPS satellites is no easy task. Research at Aerospace has been instrumental in answering the fundamental questions of constellation management: how many, how high, how close, and how long.

22 Orbit Determination and Satellite Navigation

John Langer, Thomas Powell, and John Cox

The Global Positioning System is remarkably precise in determining a user's location. But before these satellites can help anyone else, they first need to know their own positions and movements. Orbit determination is the branch of space science that makes such knowledge possible.

30 GPS/Inertial Navigation for Precise Weapon Delivery

Anthony Abbott

For centuries, military planners have sought to place a weapon exactly on an intended target. Such accuracy not only helps ensure destruction of the target, it helps prevent collateral damage. While systems have improved throughout the years, the advent of GPS has brought a major advancement in precision weapon delivery.

36 Antijamming and GPS for Critical Military Applications

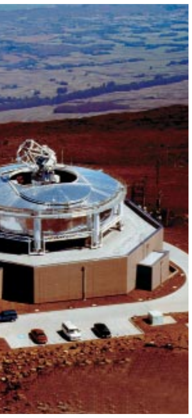
Anthony Abbott

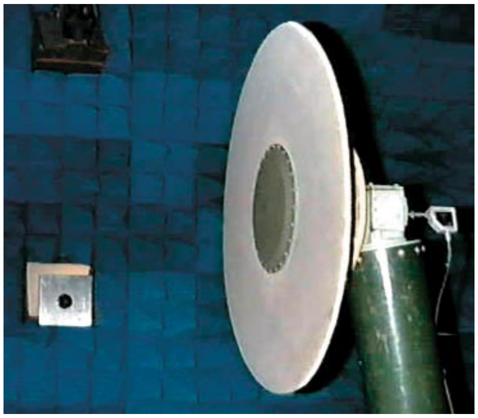
The Department of Defense is working hard to enhance the jam resistance of its GPS-based systems. Recent research at Aerospace has yielded promising results.

42 Modernization and the Move to GPS III

Steven Lazar

The numerous critical applications and infrastructures that have come to rely on GPS will require changes that cannot be accommodated by the system as originally conceived. Aerospace has been instrumental in defining a new system architecture that will ensure that military, civilian, and commercial needs are met far into the future.





From the Editors

Public appreciation of satellite-based navigation—as embodied in the Global Positioning System—has risen dramatically since the 1991 Gulf War and even more so during Operation Enduring Freedom. Yet the history of this revolutionary system extends back more than 40 years. Many organizations—including The Aerospace Corporation—helped define its earliest goals and capabilities by evaluating, integrating, and reconciling a host of competing ideas.

Like the Internet, GPS was originally intended for military applications, but it now boasts more civilian than military users. A major challenge, then, will be to keep GPS reliable enough for civilian use yet secure enough for critical defense needs. Indeed, the increase in civil and commercial applications has made protection against disruption more vital than ever before. Continued commercial development—not to mention government sponsorship—depends on keeping the system affordable, predictable, and responsive to user needs.

Aerospace played a central role in the evolution of the GPS architecture and continues to help guide its future course. For example, Aerospace models are used to optimize the constellation, determining the best configuration for a given set of user needs. Research into atomic standards, differential techniques, and augmentation schemes helped increase overall ranging accuracy. Studies of antijamming and hybrid navigational receivers have enhanced GPS support to military missions. Studies of signal propagation and frequency allocations have helped military and commercial developers share the system responsibly. Even ancillary work in GPS-supported orbit determination has produced tangible benefits for satellite operators.

A full account of The Aerospace Corporation's involvement in satellite-based navigation is beyond the scope of this single issue of *Crosslink*. Nonetheless, we hope this edition will serve as a useful introduction to the company's wide-ranging work in this field.

Headlines

For more news about Aerospace, visit www.aero.org/news/

Gabriel Spera

Galileo Goes Forward


European Space Agency

The European Union (EU) has decided to press forward with plans to develop Galileo, a European version of the Global Positioning System (GPS). The European Commission approved funding for the project despite resistance from the United States, which sees “no compelling need” for it, according to a U.S. State Department announcement.

The development phase of Galileo is expected to run from 2002 to 2005, allowing researchers to test the technology on orbit before implementing the complete 30-satellite constellation. A deployment phase will follow, leading to a full operational capability in 2008.

The Aerospace Corporation has been helping define U.S. position with respect to Galileo. For example, Aerospace analyzed potential interference to GPS from Galileo’s proposed navigation signal structure and assessed options for making the time and space reference frames interoperable. These reference frames define time and position calculations for system users. The navigation signals provide ranging signals, tied to the time and space reference frames, that allow a receiver to determine its position and time. The Aerospace work had two goals: to prevent GPS and Galileo from adopting signal designs that interfere with each other, and to identify opportunities for making the signals and reference frames interoperable. By making them interoperable, the United States and EU would enable manufacturers to build inexpensive receivers that can simultaneously use signals from both systems.

After identifying a range of approaches and assessing their technical and practical impact, Aerospace recommended that each system develop and maintain its own reference frames but provide users with the data needed to remove intersystem errors. Greater levels of coordination were viewed as technically desirable but would have required revisions of U.S. and EU policy. Aerospace also assessed several alternative Galileo signal designs in light of technical and national policy goals. The assessment identified candidate signals that would be compatible with existing GPS civil signals and that provide the opportunity for establishing a new common standard structure for future civil satellite navigation signals. These recommendations were provided to the GPS program office for eventual use by the Defense and State Departments.

The EU has pledged that Galileo will be a civil program under civil control, independent of, but interoperable with, the civil components of GPS. Although the initial funding approval freed up 4.5 million euros, the total system cost is estimated at 3.4 billion euros.

Air Force Approves Purchase of GPS IIF


The Boeing Company

The U.S. Air Force asked Boeing Space and Communications in March to proceed with production of the GPS IIF satellites. The Block IIF program will function as a bridge to eventual implementation of GPS III. The satellites will transmit new civilian and military codes with greater accuracy, integrity, availability, and antijam performance. They will also be compatible with the Evolved Expendable Launch Vehicle.

Aerospace has been assisting the Air Force throughout its GPS modernization efforts. For example, Aerospace reviewed Boeing’s system specification to ensure that it reflected the proper technical baseline. Based on Aerospace analyses, Boeing increased the satellite design life from 8 to 12 years, added more accurate rubidium frequency standards, and increased the L-band signal power with only modest cost growth.

Aerospace also influenced the selection of the solar array design. The choice came down to an expensive oversized two-panel design or a cheaper standard-sized three-panel design. The deciding factor was the reaction wheel required for critical maneuvers. Aerospace assessed reaction-wheel performance for both designs using customized deployment simulations. Based upon the Aerospace findings, the Air Force recommended the three-panel design, which Boeing subsequently adopted.

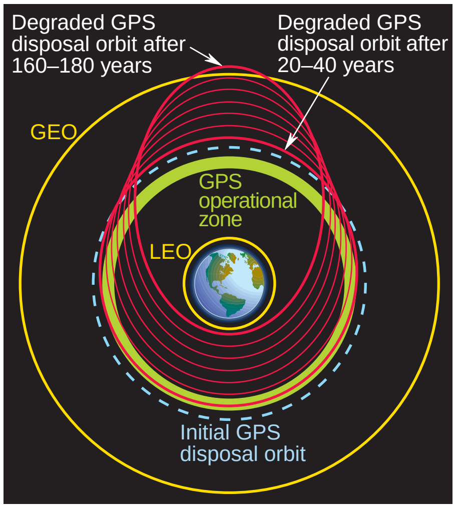
Aerospace recognized that the Block IIF program needed to achieve launch capability sooner than originally planned. By revising on-orbit satellite reliability estimates, Aerospace helped support a decision to move the first planned launch from January 2006 to October (or potentially March) 2005. In response to government concerns about the risk associated with early long-lead part procurement, Aerospace assessed alternatives with an eye toward constellation sustainment, technical feasibility, and translation of program needs into meaningful requirements. The effort resulted in a decision to proceed with an incremental long-lead approval option.

Collision Prevention for GPS

GPS satellites can help prevent collisions on Earth, but apparently, they need help preventing collisions in space.

In fact, GPS satellites placed in disposal orbits could collide with the primary operational constellation within 20 to 40 years, according to recent Aerospace studies. Revised procedures for decommissioning the old satellites are therefore needed to reduce the risk of collision.

The problem, explained Aerospace researcher Chia-Chun (George) Chao, is that the disposal orbits “start out circular but degrade over time into more eccentric orbits as a result of the resonance induced by sun/moon gravitational forces and the Earth oblateness effects.”



Besides jeopardizing the GPS constellation, these satellites could pose a threat to operational satellites in low Earth (LEO) and geosynchronous (GEO) orbits, Chao said. To reduce the probability of collisions, the decommissioned satellites must be inserted into disposal orbits at least 500 kilometers higher than the GPS constellation. Moreover, the initial eccentricity of the disposal orbit must be minimized as much as possible, and its perigee must be optimally oriented with respect to Earth’s equatorial plane.

The Aerospace report, commissioned by the Air Force, revealed other dangers as well. Future GPS satellites will be launched on the Evolved Expendable Launch Vehicle, which, unlike current GPS launch vehicles, may leave an upper stage near the constellation. Aerospace is participating in an Air Force study to develop a disposal procedure for these upper stages.

The Russian GLONASS navigation constellation, which already includes about 100 failed satellites, may also pose a collision risk in 40 years, the studies show. A similar problem applies to Galileo, the planned European navigation constellation.

The most recent study by Chao revealed that the newly recognized resonance effect is strongly dependent on orbit inclination and altitude. “The effect becomes more pronounced for Galileo orbits due to a higher altitude—3000 kilometers above GPS,” Chao explained. Understanding the dependence on initial inclination may help the designers of GPS III and Galileo systems select the proper inclination for minimizing the large eccentricity growth. “The maximum eccentricity growth for GPS and Galileo can be significantly reduced by selecting inclinations a few degrees from the current nominal values for both programs,” he said.

FCC Rules on Ultrawideband Devices

The Federal Communications Commission (FCC) has authorized the use of ultrawideband devices above 3.1 gigahertz and imposed strict technical limits on those below this frequency. The decision was intended to protect national security systems from frequency interference while allowing commercial deployment of new technologies.

Aerospace has taken an active role in U.S. evaluations of ultrawideband devices, recognizing that they could potentially interfere with GPS receivers if not properly regulated. Aerospace assisted the National Telecommunications and Information Administration (NTIA) in selecting operational scenarios to check and planning the appropriate tests. Aerospace also evaluated and critiqued NTIA documentation of the tests and inspected the testing site.

The Department of Defense supported the FCC decision, concluding that the technical restrictions on ultrawideband devices would be sufficient to protect spectrum-dependent military systems, including GPS. Such restrictions were the minimum required to avoid interference.

The Pentagon will monitor regulatory and market developments to ensure that national security is maintained and that ultrawideband devices, as deployed, do not jeopardize mission-critical operations supporting public safety, national security, and homeland defense.

Ultrawideband devices emit low-energy signals across very wide bandwidths. They are used for detection and surveillance as well as short-range communications.

A Fine System

The U.S. Department of Consumer Protection ordered a Connecticut car-rental agency in February to stop imposing speeding fines on its customers. The agency reportedly used GPS to track the speed of its customers and charged a $150 fine to their credit cards each time they drove more than 79 miles per hour for more than two minutes.

The consumer protection commission did not take issue with the use of GPS or the fine itself, but only with the agency’s failure to disclose the full details of its policy to renters.

The GPS component used in the cars is part of a system known as AirIQ OnBoard, which gathers ranging information about a host vehicle and transmits it wirelessly to a processing station—in this case, the rental company. The manufacturer of AirIQ OnBoard is a member of the Intelligent Transportation Society of America, a broad-based organization created by Congress in 1991 to coordinate the development of intelligent transport systems.

The rental agency plans to maintain its policy, but with better disclosure to its customers. Other agencies reportedly use AirIQ OnBoard—to locate lost or stolen cars, to provide driving directions, even to unlock car doors remotely for customers—but none imposes a surcharge for speeding. At least not yet.

Building Consensus from the Ground Up

Donna J. Born

As the first program director of Navstar/Global Positioning System, Bradford W. Parkinson led a group of military officers and a team of engineers to design GPS, the most revolutionary navigation tool since the invention of the chronometer.

Three concepts for navigation using space satellites had been developed by the early 1970s, the Navy's Transit and Timation systems and the Air Force's Program 621B. The Department of Defense wanted just one concept for a second-generation navigation system and formed a joint program office in 1973 to facilitate cooperation among the services toward that goal. Bradford Parkinson, an Air Force colonel in charge of Program 621B in the Air Force Space Division in El Segundo, was named the program office's first director and charged with the job of pulling together the three concepts into a new design.

Bradford W. Parkinson, GPS architect.

A major part of Parkinson's task was gaining consensus from the various services, who wanted to improve the concepts they had developed. After studying the competing concepts, he met with a group of military officers from the various services at the Pentagon during the Labor Day weekend in 1973 to come up with a design. What emerged from that four-day meeting was the blueprint for Navstar/Global Positioning System, which has since revolutionized navigation, bringing precise positioning capability to anyone anywhere for just the modest cost of a receiver (as low as $100).

"GPS has been a godsend to the military," Parkinson, who is today the chair of The Aerospace Corporation board of trustees, said at a recent interview. "It allows you to precisely do in all weather, day and night, what the military is supposed to be doing for the country. It made possible precision weapon delivery—the bomb hits what you think it's going to hit, and you don't have all this collateral damage. So I feel good about that. But it doesn't end there, you've got aircraft landings, ships at sea, farm tractors, automobiles, mining equipment, hikers …."

Parkinson said he is proud of leading the effort that brought about GPS, but he credits the work of many others: "a band of people who really believed in it. I led the synthesis, the definition of what GPS is, but the whole story includes the important work done by many persons from The Aerospace Corporation, the Air Force, the Naval Research Laboratory, and the Naval Surface Weapons Center. It's the culmination of a lot of technologies and support done by a lot of people."

For all his years of experience with GPS while it grew into a ubiquitous positioning tool, Parkinson still marvels at its capabilities. "This little beauty accesses all satellites in view," he said, holding up a small cellphone-size GPS receiver. "It gives you a baro-altimeter to a precision of a foot, gives you a magnetic compass, and allows you to wander around. I go out in the woods, looking for old hiking trails that have overgrown. As you move past a way point, the little compass comes up and gives you a black arrow that says the next point on the trail is a quarter mile that way. That's the culmination of GPS."

Parkinson has continued to be involved in some way with "the GPS adventure," as he fondly refers to it, throughout his career. He has written many papers on the topic, advised GPS doctoral students, worked on numerous national projects, and for a year was CEO and president of Trimble Navigation in San Jose, California, a company specializing in GPS technology. He said he's "right now in the middle of intense interaction on GPS." He considers GPS his greatest challenge, his most significant achievement, and the source of his work's most lasting influence. "Certainly GPS has been the highlight," Parkinson said.

His assignment to head the GPS joint effort was a logical confluence of Parkinson's background in navigation, demonstrated leadership, and experience in two branches of the military. At the U.S. Naval Academy, Parkinson majored in control engineering and learned about navigation and piloting. Just before graduation in 1957, he was selected from Naval Academy and West Point volunteers to become an officer in the newly formed "third service," and he graduated from the Naval Academy as a Second Lieutenant in the Air Force. In 1961 he earned an M.S. degree in aeronautics and astronautics from Massachusetts Institute of Technology, and in 1966, a Ph.D. in guidance, control, and navigation from Stanford University. He graduated with distinction from both the U.S.A.F. Air Command and Staff College and the Naval War College.

His first Air Force assignment after graduating from Stanford was as an instructor of astronauts and pilots at the Air Force Test Pilot School. By 1969 he had become chair of the astronautics and computer science department at the Air Force Academy, when a former classmate from the Naval Academy and MIT asked him to help develop a new form of a gunship, the AC/H130 or "Spectre," for use in Vietnam. The task sounded interesting and challenging to Parkinson, who said he was also drawn to the chance for new achievement. He was granted a leave from his teaching duties, and for the next year, he worked on the airplane and logged 170 hours of night combat in Vietnam, generally as the fire control officer, but twice as the mission commander. "It was the only weapon system that was effective in stopping infiltration through Laos of supplies for the North Vietnamese," Parkinson said. "I'm very proud of that ship. I love the C130." A photo of the "tough old four-engine airplane" has a prominent place on his office wall.


U.S. Air Force

Brad Parkinson (center) with Frank Butterfield of The Aerospace Corporation and Cdr. Bill Huston of the U.S. Navy in discussions about GPS in the early 1970s. A model of a phase-one GPS satellite is on the table at the far right.

Parkinson was director of the GPS Joint Program Office for six years. When by 1978, GPS had met its major goals, he decided to retire from the Air Force rather than move to an administrative position at the Pentagon in Washington, D.C. He returned to teaching, but after one year as professor of mechanical engineering at Colorado State University, his career took another turn—this time into the commercial business world. He became vice president of the Space Systems Group at Rockwell International, Inc., involved with the space shuttle, and a year later, vice president at Intermetrics, a software-development company in Cambridge, Massachusetts. In 1984, he accepted a research professorship at Stanford University, where he was later appointed a tenured professor and named to the endowed "Edward C. Wells" Chair of Aeronautics and Astronautics. He eventually became head of Stanford's GPS program and co-principal investigator for the NASA and Stanford Gravity Probe B gyroscope experiment to test two unverified predictions of Albert Einstein's general theory of relativity.

Chair of the Aerospace board of trustees since December 2000, Parkinson first joined the board in March 1997, bringing a technical background and experience that related well to the mission of the corporation. "I didn't hesitate to accept the appointment, in particular because Aerospace has a noble mission." The board's job, as Parkinson sees it, in addition to its important fiducial responsibility, is to give guidance to the company's president, William Ballhaus, while providing him the freedom to run the company. "I think you have a very, very competent president," Parkinson said. "And I'm a little proud of him because I led the search committee that found him."

Parkinson has served on the boards of several companies, is a fellow of many professional societies, and has been inducted into the NASA Hall of Fame. Numerous awards for his work include 1990 membership in the National Academy of Engineering, which carried the citation: "For technical leadership and innovative engineering management especially in gyroscopy and the global positioning system and for significant contribution to guidance and navigation." He is a fellow of England's Royal Institute of Navigation—Prince Philip presented him with the Gold Medal in 1983. "My dad came from England … so that tickled me and it tickled my dad." He considers his honorary degree from the University of Calgary to be quite an accolade.

Parkinson's vitality extends naturally into his private life. Among his many interests are sailing, skiing, snowshoeing, backpacking, and hiking in the woods, for all of which, not surprisingly, he relies on his GPS receiver. He is a history buff (President Lincoln and Admiral Nelson are two of his heroes) and delights in telling stories, which often reveal his sense of humor. For as long as he can remember, he wanted to be an engineer and is pleased with his achievements, yet humble before them. His wife, Ginny ("the joy of my life"), helps on that score. Driving with her one day recently, he was excited to show off "the wonderful things" he could do when he plugged a PC card with a GPS receiver into his laptop. "So," he recounts, "I'm getting ecstatic and I say: 'Look, it's got us right here on Los Altos Avenue.' She looks over at me with some disdain and says, 'Well, anyone can look out the window and see that.'" But she really does appreciate the GPS installed in her car, Parkinson continued, "You punch in the street, the address, and it takes you right there."

Although having "retired" from Stanford this year, Parkinson still carries an 80-percent research load. In addition to his board responsibilities at Aerospace, he contributes to many national efforts, most related to GPS, among them committees associated with GPS, NASA's Gravity Probe B, and the Federal Aviation Administration's Wide-Area Augmentation System—a GPS-based navigation and landing system that will provide precision guidance to aircraft. As to the future of GPS, Parkinson estimates today's 15 million users will grow to 50 million in 10 years. For that to happen, he said, GPS needs to be made more robust by increasing the current one civil signal to three, another achievement toward which he is working.

Charting a Course Toward Global Navigation

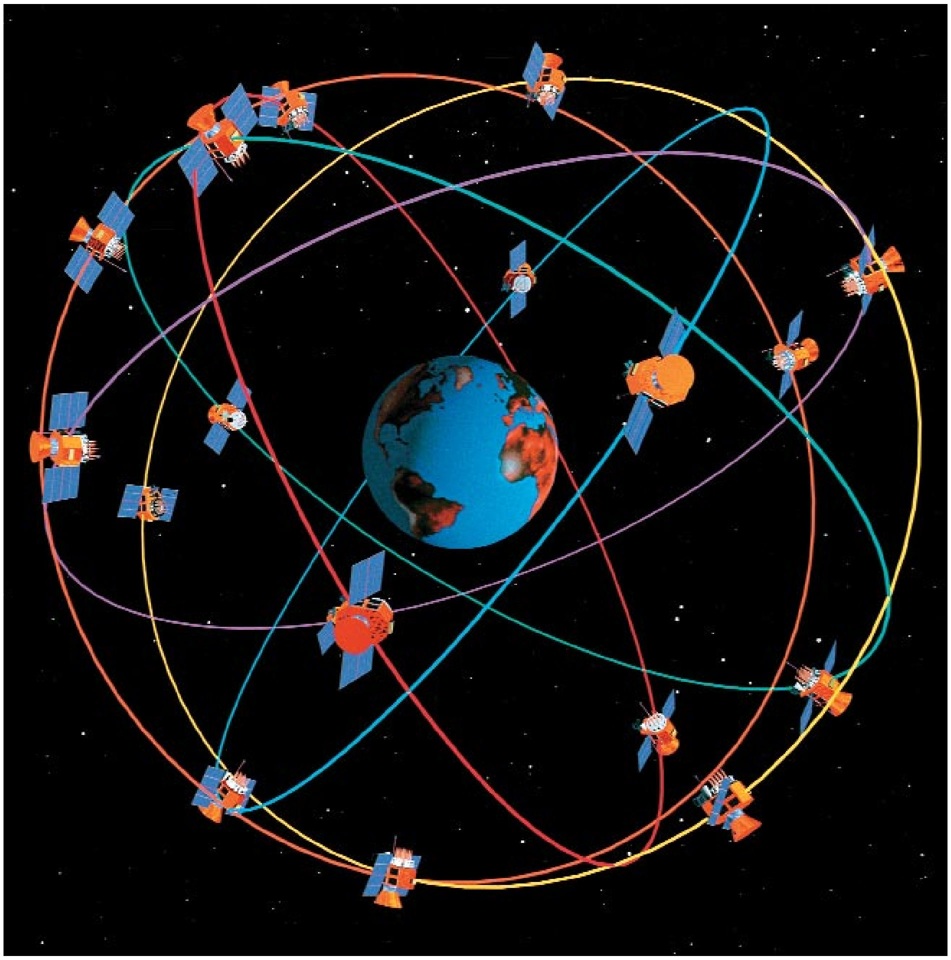
Steven R. Strom

In the 1960s, the Global Positioning System emerged as a radical new way to provide precise navigation for U.S. armed forces across the globe. Early work at The Aerospace Corporation helped get the program off the ground.

The recent conflict in Afghanistan has once more focused attention on the remarkable capabilities of the Global Positioning System (GPS), a satellite-based navigation system that allows users to pinpoint their location anywhere in the world. GPS first received widespread publicity during the Persian Gulf War of 1991. Though not fully operational at the time, the system had a significant impact on military operations, enabling allied forces to coordinate their movements in the featureless Iraqi desert and achieve a rapid victory with a minimum of casualties. Just over a decade later, GPS was used with similar success in the war in Afghanistan, a country renowned for its difficult terrain. Although the development of GPS can be traced back to the military demands of the Cold War era, it has gone far beyond its initial defense applications and now extends into the daily lives of millions of civilians, who use it for commercial, recreational, and educational purposes.

Many people are unaware that this revolutionary advance in navigational science was conceived, in part, through studies conducted at The Aerospace Corporation in the early 1960s. In addition, two of the men most responsible for its success have direct ties to Aerospace: Ivan Getting, the foremost initial advocate for GPS, was the corporation's founding president, and Bradford Parkinson, who headed the first GPS Joint Program Office, is chair of The Aerospace Corporation board of trustees. During the first half of the 20th century, researchers at various organizations were separately developing the technologies that would eventually be used to create GPS. By 1960, much of this work had coalesced in a manner that would place Aerospace at the heart of GPS research.

All images in this article are from The Aerospace Corporation archives



An early rendition of the Navstar/GPS constellation showing 18 satellites in orbit.

Precursors

Radio was the first modern technology applied to position finding. As early as 1912, Reginald Fessenden began conducting experiments on the coast of Massachusetts and devised a simple system of using radio waves to help ships determine their positions. The system was extremely inaccurate and geographically limited. The development of the first true all-weather position-finding system, LORAN A (Long Range Aid to Navigation), had to wait until World War II, when the destruction of Allied ships in the North Atlantic gave rise to a crash program to create such a system.

As the first president of Aerospace, Ivan Getting oversaw the development of Project 621B, the precursor to the Global Positioning System.

LORAN A was developed in Division Eleven of MIT's Radiation Laboratory. Coincidentally, in October 1940, a 28-year-old research physicist named Ivan Getting was beginning his tenure as head of Division Eight of the Radiation Laboratory. Although Getting's division did not do any work in navigation, as a member of the Radiation Laboratory Steering Division he "was very much aware of the remarkable success of LORAN." The Navstar/GPS system would later employ LORAN's method of using time difference in the arrival of radio signals to calculate position. During the postwar period, variations of LORAN A were developed, including the more accurate, high-frequency LORAN C and the low-frequency OMEGA system.

Many of the major scientific and technological advances of the mid-20th century were closely linked to the launching of the first artificial satellites. Indeed, the development of satellite technology was a crucial precursor for GPS, and the system's key navigational concept was discovered as a result of the Sputnik launch on October 4, 1957. Sputnik was little more than an orbiting radio transmitter, but it captured the attention of scientists across the globe. Two scientists at the Johns Hopkins University Applied Physics Laboratory (APL), George Wieffenbach and William Guier, realized as they listened to Sputnik's signal that they could determine its orbit from the Doppler frequency shift detected as it passed overhead. Their measurements were subsequently confirmed by findings from other tracking sites. From this observation, Frank T. McClure at APL reasoned that, conversely, if the orbit of a satellite were known, then Doppler-shift measurements could also be used to determine any ground position on Earth.

Pursuing this concept further, the Navy initiated studies for its first satellite navigation program, the two-dimensional Transit system, in 1958. Many scientists, engineers, and military leaders recognized from the beginning of the space race that satellites held great potential for navigation. In 1959, concurrent with the development of the Transit program, a staff report to the House Select Committee on Astronautics and Space Exploration predicted that during the next decade, "Satellites can, and will, become one of the principal aids to navigation for sea, air, and perhaps, space craft." The first Transit prototype satellite was launched in April 1960, demonstrating the feasibility of a satellite-based navigational guidance system. The development of Transit was important for the future of GPS, as elements of the program were eventually incorporated into the GPS architecture.

Another system used in early GPS studies was MOSAIC, a three-dimensional LORAN-type ballistic missile guidance system developed in the 1950s by the Missile Division of Raytheon, where Getting had gone to work in 1951 as vice president of engineering and research. MOSAIC (Mobile System for Accurate ICBM Control) was first proposed to the Air Force by Getting and his colleague Shep Arkin on May 11, 1960. The Air Force was worried about the potential vulnerability of America's land-based ICBMs, so the MOSAIC plan was to mount the Minuteman missiles on railroad cars and rotate their positions. In addition, MOSAIC provided for advanced control and guidance systems once the missiles were in flight. Just six

Brad Parkinson served as the first program manager of the GPS Joint Program Office, established in 1973.

Engineers from Aerospace and Grumman in 1972, testing a transmitter for the 621B Defense Navigation Satellite system at White Sands Missile Range, New Mexico.

weeks after Getting presented the MOSAIC proposal to the Air Force, he was invited to become the first president of the newly formed Aerospace Corporation. Getting's presidency began on August 1, 1960.

Project 621B

Only a few months after the formation of Aerospace in the summer of 1960, much of the knowledge base that was pivotal to the development of GPS was already taking shape. By necessity, Getting began his tenure with a rapid hiring campaign, attracting a large block of researchers and engineers from Space Technology Laboratories (STL). Several of the planners at STL had been briefed on the MOSAIC program, and although it was canceled in early 1961, they brought their expertise and knowledge to Aerospace. The principal mission of Aerospace was "to aid the United States Air Force in applying the full resources of modern science and technology to the problem of achieving those continuing advances in ballistic missiles and military space systems which are basic to national security." To that end, Aerospace initiated a series of studies in areas where the application of space systems might prove most valuable. One of the earliest of these studies dealt with navigation.

By the beginning of 1963, Aerospace had some 1463 scientists and engineers on staff. Two major studies were initiated that year. Project 75 attempted to define ballistic missile systems for the year 1975. Project 57 (the name was derived simply by inverting the numbers of Project 75) sought to clarify the areas where space systems could be successfully used for military applications. The Project 57 study was directed by Phillip Diamond of the Systems Planning Division, and, as Getting noted, it was "in this study that the GPS concept was born." In 1963, the Space Division of the Air Force began supporting this study, known as Project 621B, and requested that Aerospace continue its work on determining navigation coordinates from satellite signals. The Air Force placed a high priority on finding a better positioning system for its aircraft. The Transit system was too slow and too intermittent to keep up with the high speeds of airplanes, and the Air Force hoped to obtain an accuracy of 15 meters—much better than what Transit was providing for ships. According to Parkinson, Project 621B had "many of the attributes that you now see in GPS. It has probably never been given its due credit." Getting relates that the Aerospace navigation studies were "directed at meeting the Air Force requirements as we understood them: the system should be responsive to an unlimited number of users; the user equipment was to be passive (i.e., nonradiating); and it was to be as accurate as technology would permit."


An artist's rendering of a Navstar/GPS satellite.


B. P. (Pete) Leonard wears a Navstar backpack in this 1978 photo. Leonard, then vice president of Aerospace's Navstar program group, is flanked by Col. Don Henderson (left) of the Space and Missile Systems Organization (SAMSO) Navstar program office and Ed Lassiter (right), principal director of Aerospace's Satellite Navigation Systems Directorate.

From 1964 to 1966, several Aerospace team members made outstanding contributions to GPS studies within Diamond's division. These men included Peter W. Soule, James B. Woodford, Lawrence L. Hageman, Alfred Bogen, Richard Slocum, Robert Levinson, Arthur Shapiro,

Members of the Aerospace technical staff in 1980, discussing the space segment of GPS.

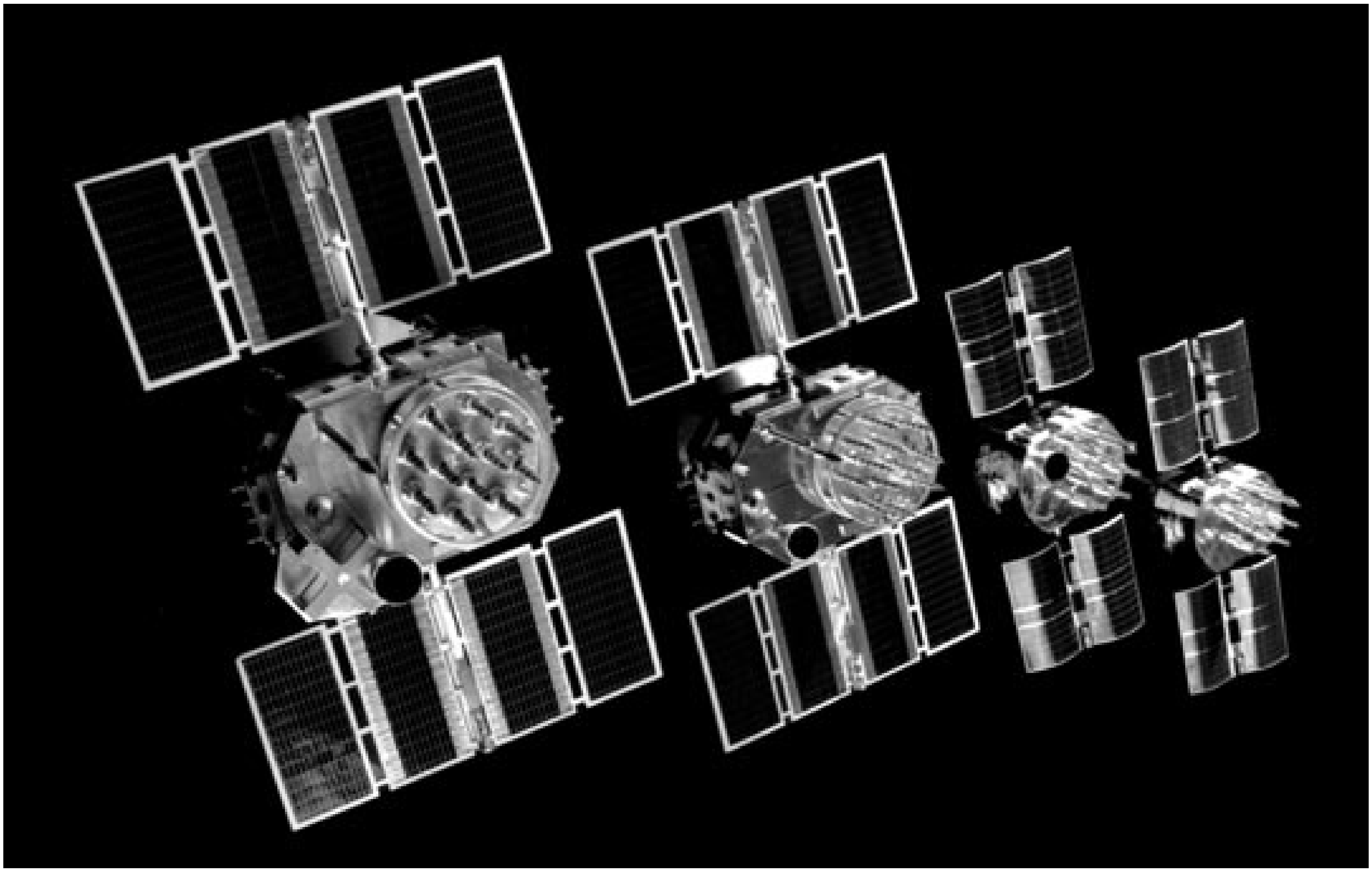
Howard F. Marx, and Hideyoshi Nakamura. It was Nakamura and some of his coworkers who suggested that range measurements for an aircraft should be calculated using signals from four satellites. The aircraft's crewmembers could then obtain a three-dimensional position by measuring four distinct differences in the signals' arrival times and then adding these to a clock connected to a quartz oscillator. Each satellite would also have its own clock, which would be updated continuously by ground signals. In essence, this was the operational concept that eventually led to GPS as it is known today. Woodford, who had joined the 621B team in 1965, conducted research on the characteristics of the signals that were transmitted from satellites to receivers. Following the conclusion of these studies in 1966 and briefings by Nakamura and Woodford, the Air Force awarded contracts to TRW Systems and Hughes Aircraft Company to begin design studies for the proposed system. Diamond and his team assisted with the design studies and continued research on other facets of GPS, including satellite deployment and the placement of onboard atomic clocks.

The ultimate implementation of GPS would not have been possible without concurrent advances in other fields. The 1960s witnessed remarkable leaps in the development of computers, solid-state microprocessors, atomic clocks, signal processing, and bandwidth utilization techniques. The advances in atomic clocks allowed Roger Easton of the Naval Research Laboratory's (NRL) Naval Center for Space Technology to develop an innovative satellite-based navigation system known as Timation (Time Navigation). Timation was conceived in 1964, and the first Timation satellite was launched in 1967, with a second following in 1969. These satellites each carried a high-quality crystal oscillator. The third satellite, launched in July 1974, was the first to fly an atomic clock. The Timation system was ultimately successful in providing three-dimensional location coverage. Meanwhile, Aerospace continued to conduct its own research for the 621B program. By the late 1960s, Aerospace recommended a concept design that employed 20 satellites placed in geosynchronous inclined orbits ranging 30 degrees north and south of the equator.

Compromise and Consensus

By this time, Getting and Diamond were actively working to obtain the full backing of the Department of Defense (DOD) for GPS. Air Force support for 621B continued, but any full-scale GPS effort would need support from DOD. It was becoming increasingly clear that some type of coordination was needed among the three competing ideas for a fully developed satellite-based navigation system: APL's Transit, NRL's Timation, and the Air Force's 621B. To coordinate these efforts, members of the Navy, Army, and Air Force formed NAVSEG (Navigation Satellite Executive Group) in 1968, but the committee had no real powers to enforce any decisions that it reached. In 1969, Getting asked President Nixon's science advisor, Lee Du Bridge, for help. Du Bridge had been Getting's boss at the MIT Radiation Laboratory. He advised Getting not to advocate a presidential commission to sell GPS, but to push his ideas through the military customers with

Weight and balance tests of the third prototype satellite in the Navstar/GPS constellation are conducted prior to its launch from Vandenberg Air Force Base.



Models of different versions of GPS in 1991.

the greatest needs for a navigation system. From that time on, Getting concentrated his efforts on the Air Force and the scientific elements of the Defense Department.

In November 1972, Air Force Col. Bradford Parkinson was assigned by Gen. Ken Schultz to manage the satellite navigation program. Parkinson's move from the Advanced Ballistic Missile Reentry System program to 621B marked the beginning of the first real progress in the eventual approval of GPS because he quickly realized that a synthesis of the three competing proposals would be necessary. Parkinson remembers that "I entered the picture when those three concepts were in a death struggle—none of them was going anywhere." Parkinson examined the competing concepts in great detail and came to the conclusion that some elements of all three systems would be needed in GPS if it was to prove successful.

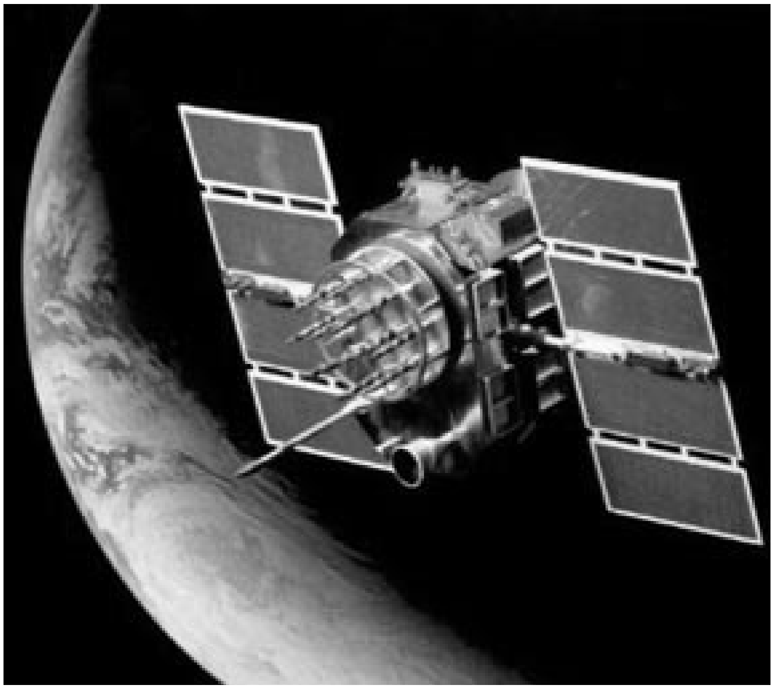
On April 17, 1973, DOD authorized the creation of a joint, three-service program office and selected the Air Force as the lead military service. Parkinson was appointed to be the first program manager of the newly created GPS Joint Program Office. The program's headquarters were located at the Los Angeles Air Force Station (as it was then known), the headquarters of the Space and Missile Systems Organization (SAMSO) in El Segundo, California. The Los Angeles Air Force Station was adjacent to The Aerospace Corporation, which established a GPS program office in July 1973 with Bruce L. Adams as its manager. He was succeeded by Edward Lassiter in 1974.

In August, Parkinson presented the 621B proposal to the Defense System Acquisition Review Council (DSARC), which promptly rejected it. But the council expressed likely support if the proposal could be expanded to address some of the ideas and requirements of the other armed services. Over the Labor Day weekend in 1973, Parkinson convened a meeting of about 12 military officers at the Pentagon to discuss such a multiservice system. It was at this meeting, he said, that "the real synthesis that became GPS was created." With program approval from Malcolm Currie in DOD Research and Engineering, Parkinson was able to convince all parties that the synthesized design was the proper one to select. The compromise system used atomic clocks in its satellites and orbits similar to those used for the Timation system, but with higher altitudes to provide a 12-hour period. The structure and frequencies of the digital signals were essentially the same as those used in 621B. The number of satellites proposed for the 1973 GPS system, 24, is the number in use today. As Parkinson would remark, "Basically our Labor Day system is still the current system."

As the program manager, Parkinson now had a unified development team for the hard work ahead, and with his new compromise in hand, he went back to DSARC and was granted approval to proceed with GPS work on December 22, 1973. Initial funding was about $150 million. The program was also renamed Navstar (which is not an acronym), but people still referred to it as Navstar/GPS, or simply GPS.

The ability to create the synthesis that became GPS and build the system remains Parkinson's outstanding achievement as program manager. As Getting would later remark in his autobiography, "The approval of the joint project, which became known as Navstar, would probably not have come about ... had not General

Schultz, commander of the Space Division, assigned Col. Brad Parkinson as program manager in November 1972.”



GPS Block II.

Rapid Development

Over the next 15 years, GPS development proceeded at a rapid pace. Much of the work in Phase I (concept validation) consisted of testing the many potential types of user equipment. Many of these experiments occurred at the Yuma Proving Ground in Arizona using ground-based transmitters in lieu of orbiting satellites. Extensive testing was also done with the position determination of a wide variety of vehicles, aircraft, and troops with GPS receivers. Between 1977 and 1979, more than 700 tests were conducted, and all of them confirmed the system’s extraordinary accuracy. On February 22, 1978, the first Block I developmental Navstar/GPS satellite was launched from Vandenberg Air Force Base, using an Atlas F booster. Three more satellites were launched in 1978. Ed Lassiter remembers that “Aerospace had a huge impact on the success of these first four launches and on the entire GPS program.”

The DOD approved Phase II of the program in 1979, the same year that Allan Boardman took over from Lassiter as GPS program director at Aerospace. This phase of GPS was intended to provide global two-dimensional coverage for a select group of users. In 1981, Jim Henry succeeded Boardman as principal director, and he remained in that position until 1992. Additional GPS satellites were launched in the early 1980s.

In 1985, Phase III (the production and development phase) began, and the first operational GPS Block II satellite was launched in February 1989. GPS was unexpectedly able to validate its worth following the Iraqi invasion of Kuwait in 1990, when the system provided invaluable navigational information to airborne, ground, and naval units of the allied forces. During and after the Persian Gulf War, the media’s coverage of GPS helped stimulate a surge of civilian interest. By the time GPS was declared fully operational in 1995, its future success was virtually guaranteed.

Conclusion

In 1992, as a member of the GPS team, Aerospace shared the nation’s most prestigious aeronautical award, the Collier Trophy. The citation accompanying the award called GPS “the most significant development for safe and efficient navigation and surveillance of air and spacecraft since the introduction of radio navigation 50 years ago.” The award was a capstone to three decades of difficult development work, remarkable innovation, and tireless advocacy by Aerospace personnel, often at a time when only a handful of people recognized the system’s enormous potential. As Getting would later note, “While the Collier Trophy was specifically directed at the GPS with principal recognition of The Aerospace Corporation, the Air Force, the Navy, and the associated contractor team, I look upon it as a recognition of Aerospace and all its programs and people.”

The Collier Trophy.

Further Reading

The Aerospace Corporation, *The Aerospace Corporation—Its Work: 1960–1980* (Times Mirror Press, Los Angeles, 1980).

The Aerospace Corporation Archives, Collier Trophy Collection, AC-124.

The Aerospace Corporation Archives, Ivan Getting Oral History Interview (March 17, 2001).

The Aerospace Corporation Archives, Ivan Alexander Getting Papers, Collection AC-036.

The Aerospace Corporation Archives, Office of Public Affairs Collection, AC-003.

I. Getting, *All in a Lifetime: Science in the Defense of Democracy* (Vantage Press, New York, 1989).

L. C. Larijani, *GPS for Everyone: How the Global Positioning System Can Work for You* (American Interface Corporation, New York, 1998).

B. W. Parkinson, interviewed by Michael N. Geselowitz, IEEE History Center, Rutgers University, New Brunswick, NJ (1999).

B. W. Parkinson, “Introduction and Heritage of NAVSTAR, the Global Positioning System,” *Progress in Aeronautics and Astronautics*, Vol. 163, 3–28.

B. W. Parkinson et al., “A History of Satellite Navigation,” *Navigation: Journal of the Institute of Navigation*, Vol. 42, No. 1, 109–164.

D. Sobel, *Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time* (Walker Publishing Company, Inc., New York, 1995).

Staff Report of the Select Committee on Astronautics and Space Exploration, House Document No. 115, *The Next Ten Years in Space: 1959–1969* (Government Printing Office, Washington, D.C., 1959).

J. E. D. Williams, *From Sails to Satellites: The Origin and Development of Navigational Science* (Oxford University Press, New York, 1992).

Colleen H. Yinger

Operation and Application of the Global Positioning System

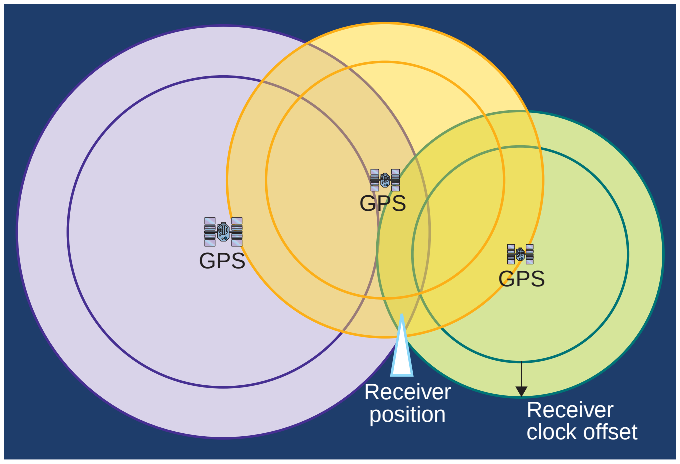
GPS was originally designed for defense operations, but civilian receivers now far outnumber military receivers. The number of operational receivers has increased exponentially over the last decade as the technology has moved in diverse and unexpected directions.

The Global Positioning System (GPS) provides timing and navigation for a wide range of applications, from intelligent transportation systems to power control grids. In the short time since its introduction, the technology has established itself as an indispensable component of daily life—even though most of its users know relatively little about it. When asked to describe the uses of GPS, many people mention its highly visible role in navigating airplanes or boats; but based on the number of receivers produced each year, the system's dominant roles are in intelligent transportation systems, telecommunications, and precision delivery of military munitions. Moreover, its use in supporting both critical civil infrastructure and military operations has received new attention since September 2001.

As principal advisor to the Air Force on space acquisitions, The Aerospace Corporation played a significant role in the development of GPS, providing proof-of-concept studies, constellation design and management studies, accuracy improvement initiatives, independent assessments, and operational assistance. With the modernized Block IIR and Block IIF satellites nearing launch—and the GPS III program now in its planning stages—the technology is poised to reach new levels of sophistication unimagined just a few years ago.

Concept Overview

GPS is designed to provide accurate three-dimensional navigation anywhere in the world, at any time, under all weather conditions. Each satellite is essentially an orbiting atomic clock with a radio-frequency transmitter that constantly broadcasts a signal. By comparing the signal received from the satellite with an internally generated signal, a receiver measures the time it takes for the signal to travel from the satellite to the user. Multiplying this time-delay measurement by the speed of light, the receiver calculates the user's *pseudorange* to the satellite (range plus user clock offset). Using such pseudorange measurements from four or more satellites, the receiver determines the user's three-dimensional position (latitude, longitude, and altitude) and time.



The position of the GPS receiver is where the ranges from a set of satellites intersect at a single measurement time. The range measurements are used together with satellite position estimates based on the precise orbital elements broadcast by each satellite. Four satellites can be used to determine three position dimensions as well as the offset between the receiver's inexpensive clock and a satellite's highly precise atomic clock. Computation of receiver clock offset is critical because a timing error of just 10 nanoseconds would produce 3 meters of ranging error (10 billionths of a second times the speed of light, 3×10^8 meters per second).

The GPS ranging signal is broadcast on two frequencies, 1575.42 megahertz (L1) and 1227.6 megahertz (L2). Each satellite transmits a unique code, enabling all satellites to use the same frequencies (a process known as code division multiple access). A short, unencrypted code (known as the C/A code) with a 1-millisecond period is broadcast on L1 and is generally used for civilian applications. Its short duration allows low-cost equipment to search its code phase quickly, enabling rapid acquisition and tracking. A longer, encrypted code (the P(Y) code) is broadcast on both L1 and L2 for so-called "authorized" users—generally U.S. government agencies and military allies. The P(Y) code provides more accurate ranging with lower risk of spoofing (reception of spurious signals that the receiver accepts as real) and better rejection of multipath (extraneous reflected) signals. Many authorized users initially acquire the C/A code, then transfer to P(Y).

Why are two frequencies needed? Earth's ionosphere delays the arrival of GPS signals, and this discrepancy must be corrected to achieve a precise position fix. Because signals at different frequencies propagate through the ionosphere at different speeds, users that receive both L1 and L2

Block IIA satellite.

signals can correct for ionospheric delays. Civil users can make less accurate corrections by using a mathematical model for the ionospheric delays. The parameters for the simple model are transmitted in the data message.

The Elements of GPS

The GPS system is made up of three segments—space, control, and user—all of which contribute to overall accuracy, reliability, and functionality.

Space Segment

The baseline GPS constellation consists of at least 24 satellites in six planes inclined at 55 degrees relative to the equatorial plane. The operational constellation includes additional satellites to ensure that maintenance and anomalies will have minimal impact on service. The satellites are positioned about 20,000 kilometers above Earth in approximately 12-hour orbits. With this configuration, almost every point on Earth can see at least five GPS satellites, and often many more.

The GPS satellites have solar panels to generate power and use shaped-beam antennas to provide nearly constant signal strength over Earth. Satellite lifetimes typically exceed ten years, thanks to a high degree of system redundancy.

Navigation performance is highly dependent on the stability of the cesium and rubidium atomic clocks. These high-quality space-qualified atomic clocks have stabilities of better than 1 part in 10^{13} over a period of one day, which translates to an error buildup of less than 10 nanoseconds (3 meters) per day. To keep accuracy high, Air Force Space Command computes and uploads clock corrections to the satellites, which in turn broadcast this information to the user as part of the data messages. The more stable the atomic clocks, the less frequent the satellite uploads need to be to maintain a desired ranging accuracy.

The first GPS satellite was launched in 1978. Initial operational capability was established in December 1993 when the full constellation of 24 satellites was completed. Final operational capability was announced the following year.

Control Segment

GPS employs a worldwide ground network to monitor the health of the satellites, keep them in their intended orbits, and update their clock and position data.

Five globally distributed monitor stations track the GPS satellites and send ranging data to a master control station in Colorado Springs. The master control station processes the ranging measurements in a Kalman filter every 15 minutes to determine satellite orbit and clock corrections. Periodically, roughly once per day for each satellite, the master control station predicts the orbits and clocks and forms a navigation message. The navigation message is sent to a ground antenna for upload to the satellite on an S-band data link and transmitted to the user on the GPS signal.

The navigation message is transmitted on both the L1 and L2 channels at a rate of 50 bits per second. The message has a 1500-bit frame (30-second duration) consisting of five 300-bit subframes (6 seconds each). Subframe 1 contains clock parameters. Subframes 2 and 3 contain orbit parameters. Subframes 4 and 5 contain almanac data (less accurate orbit data that is used only for signal acquisition), single-frequency ionosphere model parameters, and GPS-UTC (Coordinated Universal Time) offset data.

User Segment

A GPS receiver tracks selected satellites and computes user position. A receiver consists of an antenna (typically omnidirectional), filtering and amplification circuits, and signal-tracking components. Satellite positions are computed from navigation message data. The pseudorange measurements are corrected for satellite clock errors, Earth rotation, ionospheric delay, tropospheric delay, and relativistic effects. The corrected pseudorange data and satellite positions are used to compute user position, velocity, and time. The computation may be done using GPS alone or integrating data from other sensors such as altimeters, compasses, and inertial measurement units. Depending on the application, user position may be superimposed on a map, used to make corrections to a weapon in flight, or transmitted to a central processing facility.

Lockheed Martin Missiles & Space

Block IIR satellite.

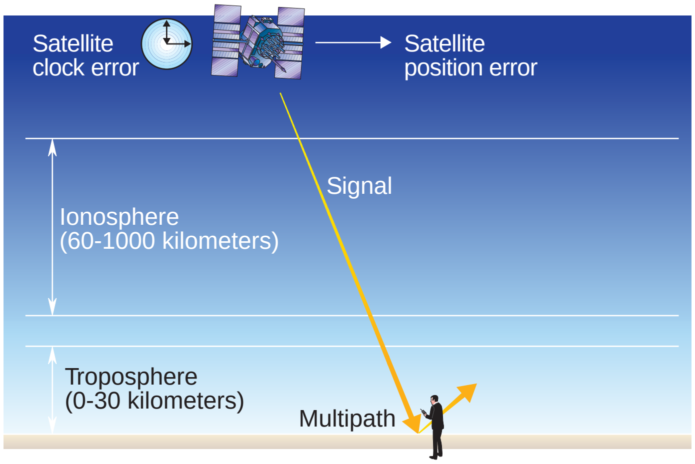
Continuous Development

The Aerospace Corporation has maintained a significant role in all of these system areas. For example, analysts at Aerospace helped define a constellation that would strike the right balance between user coverage and system cost. Aerospace continues to optimize the constellation for competing demands and to assess satellite replenishment strategies.

Aerospace participated in early proof-of-concept studies, algorithm development, and validation efforts to improve ground-station modeling and orbit calculations. Although most space programs need to predict the orbits of their satellites, the needs for GPS exceed those of other programs. Hence, GPS requires more detailed models and more accurate calculations. For example, Aerospace analysts were responsible for the adoption of a technique for modeling solar-radiation pressure, which removed a major impediment to GPS success by enhancing the estimation and prediction of the GPS orbits. Aerospace personnel have also been involved in algorithm enhancements, parameter selection, and similar initiatives that have significantly improved the accuracy of the system. The company remains active in the operations and modernization of the current ground control segment.

Aerospace has also developed new algorithms for jam-resistant receivers. For example, Aerospace is developing and promoting ultratight GPS/inertial coupling techniques that not only increase jamming protection but also improve accuracy, integrity monitoring, and detection and mitigation of multipath signals. Aerospace also played a key role in the development of the Combat Survivor/Evader Locator, a GPS-based rescue system for U.S. military forces.

Aerospace and the Naval Research Laboratory have supported the development of space-qualified atomic clocks for GPS applications since the early 1970s. Aerospace helped analyze and resolve numerous clock anomalies encountered during the early phases of the GPS program. Interestingly, the demand for highly stable clocks is diminishing, thanks to the success of the GPS program, so Aerospace is working with the Air Force to preserve the nation's industrial base for atomic clocks for GPS III and beyond.



GPS error sources include satellite clock and position errors, propagation errors, and user receiver errors such as noise and multipath signals. Military users can generally eliminate the ionospheric effect by using dual-frequency measurements. Civilians apply a single-frequency model that reduces ionospheric error. Multipath error is caused by reflection of GPS signals off nearby surfaces and depends on antenna-to-satellite geometry. Proper antenna design and placement can minimize multipath errors by eliminating reflected signals. Troposphere is modeled in the receiver.

Error Sources

GPS navigation performance is determined by the accuracy of the ranging signal and the quality of the user-satellite geometry. Sources of ranging-signal errors include signal-in-space errors (uncertainties in satellite position and clock data), signal propagation delays through the ionosphere and troposphere, and receiver errors. Satellite geometry determines how the ranging errors affect user navigation error. An ideal four-satellite geometry would have one satellite directly overhead and three satellites equally spaced around the user's horizon. In general, more satellites are better. Newer receivers generally implement "all-in-view" satellite selection, as opposed to "best-of-four" criteria, and 12-satellite civil receivers are common.

Navigation error is roughly the expected ranging error multiplied by the "position dilution of precision," an instantaneous measure of the geometric quality of the satellite configuration selected by the GPS receiver. Actual values typically range between about 2 and 3 for the operational constellation because most sites will see more than enough satellites, though their geometry will probably not be ideal. Locations and times with high position dilution of precision (often defined as greater than 6) produce less accurate navigation or a navigation "outage." The position dilution of precision concept provides a convenient way to predict user navigation performance, analyze alternate constellations, and study the impact of satellite failures.

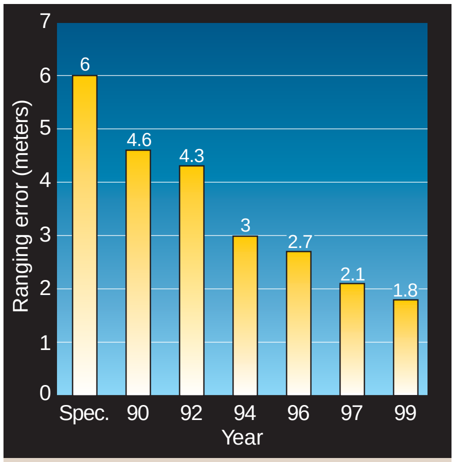
How Good Is It?

The original GPS specification called for a military three-dimensional position accuracy of 16 meters and a civilian horizontal accuracy of 100 meters (civilian accuracy was intentionally degraded—a protocol known as "selective availability"). Actual GPS navigation accuracy depends on the user's receiver, location, and dynamics. Military performance is now on the order of a few meters, constrained by signal-in-space errors and receiver performance. With selective availability set to zero in May 2000, stand-alone civilian systems can typically achieve performance in the 10–20 meter range, limited primarily by single-frequency ionospheric modeling constraints.

In addition to exceeding original accuracy expectations, GPS has also exhibited an impressive history of reliability, integrity, and availability. GPS satellites are outliving their specified mean mission life (six years) by a factor of nearly two. Aerospace studies of satellite reliability enabled the Air Force to revise its procurement schedules, thereby saving hundreds of millions of dollars without interrupting user coverage. In the eight years since full operational capability was declared, only one service failure occurred in which a satellite generated an unusually large error without either being declared unhealthy or being corrected immediately. The Air Force continues to look into ways to improve its responsiveness to the rare occurrence when a satellite inadvertently broadcasts incorrect information.

Augmentation

Applications requiring greater navigation accuracy can take advantage of a technique known as differential GPS. In this case, GPS satellites are tracked from one or more reference sites whose positions are precisely known, thereby determining the



Signal-in-Space Errors

Signal-in-space errors are errors in the clock corrections and orbit data broadcast by a satellite. Performance is driven by the stability of a satellite's atomic clock, the fidelity of the clock and orbit estimation and prediction, and the frequency of the navigation message uploads. Signal-in-space errors have been reduced from nearly 6 meters to about 1.7 meters over the past ten years as a result of constellation buildup, improved satellite clocks, enhanced ground algorithms and software tuning, and more frequent navigation message uploads. Aerospace provided enhanced algorithms and software tuning that helped achieve this nearly fourfold accuracy improvement.

The Boeing Company

Aerospace provided key technical guidance in the development of the Combat Survivor/Evader Locator (CSEL). This rescue radio uses GPS to communicate survivor position to rescue forces, enabling rapid rescue with minimal exposure to hostile conditions.

ranging errors to each satellite. The reference site transmits the ranging corrections to users in the vicinity in real time. Since the dominant error sources are common to the user and a nearby reference site, most errors can be eliminated. The accuracy of a differential system degrades with separation distance between the reference site and the user.

Numerous differential systems are currently operational or planned. The maritime differential GPS developed by the U.S. Coast Guard operates more than 50 differential sites around U.S. coastal areas, harbors, and rivers. The system provides better than 10-meter accuracy and was originally designed for harbor approach, vessel tracking, and buoy positioning.

Nationwide Differential GPS is a planned improvement and expansion of the maritime system to more than 120 sites to provide free differential corrections throughout the United States. Applications include train control, intelligent transportation systems, crop dusting, precision mining and farming, and snowplow management. For example, Nationwide Differential GPS—in conjunction with gyros, axle generator interfaces, track databases, and communication links—can help prevent train collisions and improve railroad track utilization. Several commercial differential systems are also available in the United States and internationally, some providing corrections via communication satellites.

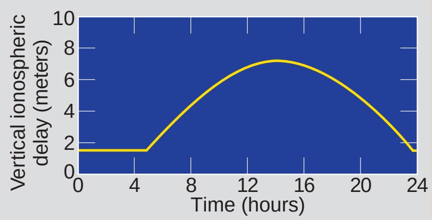
Surveyors and geologists studying plate tectonics achieve centimeter-level accuracy or better using a combination of differential techniques and carrier tracking. Carrier tracking uses the GPS radio-wave phase rather than standard code tracking to obtain ranging resolution that is a small fraction of the 19-centimeter wavelength (as small as 2 millimeters, or 1/100th of the wavelength). Carrier tracking is not appropriate for all users because it requires greater signal strength and resolution of the cycle ambiguity (i.e., which carrier cycle is being tracked). Also, it may be challenging for dynamic applications.

Aerospace was instrumental in the implementation and testing of a worldwide accuracy enhancement system for military users. By providing more frequent clock corrections in the GPS navigation message, this system reduces signal-in-space errors by 20–30 percent for suitably equipped military users. Aerospace demonstrated the potential of this method and other differential techniques to improve GPS navigation performance for several munitions, including the conventional air-launched cruise missile and the Joint Direct Attack Munition.

For the civilian aviation sector, the biggest navigation challenge is service integrity—that is, how does one guarantee that GPS is not broadcasting misleading information that could result in injuries or death? The Federal Aviation Administration Wide Area Augmentation System is being tested to meet the stringent requirements of the civilian aviation industry for accuracy, integrity, and system availability. The Wide Area Augmentation System processes tracking data from 25 reference stations throughout the United States to compute and disseminate GPS corrections and integrity information to aviation users via geostationary satellites. Since accuracy of civil users is generally constrained by

Signals Through the Ionosphere

The ionosphere, the layer of the atmosphere between about 60 and 1000 kilometers high, causes a frequency-dependent signal delay that can be a major source of GPS navigation error. The magnitude of this delay depends on user location (particularly latitude), time of day, time of year, and solar activity. For a satellite directly overhead, errors occurring during daytime hours typically range between 5 and 10 meters but can exhibit significant spatial and temporal variation.



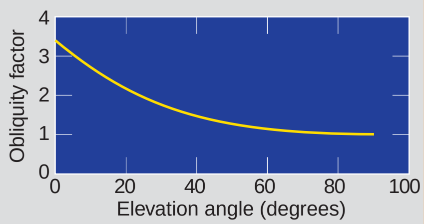
A typical vertical single-frequency ionospheric correction profile over the 24-hour day.

For a satellite located close to the horizon, the delay can be up to three times as great.

The dual-frequency GPS user can factor out ionospheric delays by using the time delays from the L1 and L2 pseudorange measurements.

Single-frequency receivers (primarily civilian) must use a model broadcast by the satellites to partially compensate for ionospheric effects. The vertical single-frequency correction is a cosine function with peak amplitude at 14:00 local time and a constant nighttime offset of 5 nanoseconds (which translates to roughly 1.5 meters). The amplitude and period of the model are computed from coefficients uploaded to the satellite daily by the control segment. An elevation-dependent obliquity factor converts the vertical correction to a slant correction. The single-frequency correction model typically reduces statistical ionospheric error by about 50–60 percent.

With the discontinuation of selective availability, ionospheric error has become the dominant error source for the single-frequency user. Modernized Block IIR satellites, to be launched beginning in 2003, will have a second civilian signal on L2, providing civilian users the opportunity to implement dual-frequency corrections, resulting in navigation and timing performance that approaches the level of the authorized user.



The elevation-dependent obliquity factor increases from 1.0 at vertical to about 3.0 at a 5-degree elevation.

GPS in Action

The potential applications for GPS systems go far beyond the initial project goals. Here are three diverse examples.

Automated Collision Notification

GPS will play a major role in the enhanced 911 Phase II FCC mandate for cellular carriers, which will require automatic cell-phone location using network-based, receiver-based, or hybrid technology. GPS-based systems will be required to determine location to an accuracy of 50 meters (with 67 percent confidence) and 150 meters (with 95 percent confidence). Cellular carriers will deploy the capability over the next few years.

Some manufacturers are going a step further by developing automated systems for accident response. Some will use airbag deployment systems to detect crashes. Others will integrate sensors such as accelerometers to gather additional information about the severity of a crash. The cellular system would automatically transmit the data to an emergency center, enabling emergency crews to reach the crash site more quickly and with better preparation, even when the driver is unable to initiate the emergency call.

Maritime Navigation

The majority of commercial and recreational vessels now use GPS. Maritime applications include ship routing, traffic management, collision avoidance, and distress response. Differential GPS covers many coastlines and harbor entrances. In many cases, the accuracy of the GPS-based positioning system surpasses the accuracy of the nautical charts used by the mariners.

GPS has helped make onboard real-time ship routing a reality, enabling navigators to determine the optimal route based on the current weather, sea conditions, forecasts, and specific ship characteristics. The routine can be used to optimize a combination of travel time, fuel consumption, ship protection, and passenger comfort.

Some challenges remain—for example, the control of very large vessels in restricted waters and during berthing, especially in areas of strong tides or high winds. Integration of GPS with other devices such as underwater acoustic sensors may make these more challenging applications feasible.

Agriculture

Agricultural applications are naturally suited for GPS because open environments generally allow good satellite visibility. Already, GPS has been widely used in yield mapping, crop dusting, and assisted or automated steering of farm vehicles.

Yield mapping is a technique used to record the amount of crop harvested along with the real-time position of the harvesting machine. A two-dimensional yield map shows yield as a function of position, supporting decisions such as future fertilizer application rates.

An assisted steering system provides a display showing any deviation from a planned course, helping the tractor driver stay on track. An automated steering system completely relieves the driver of this task. Steering of machinery for planting, harvesting, fertilizing, and similar tasks typically requires accuracy on the order of 30 centimeters. This performance can be achieved with some differential systems or by integration of differential GPS with other sensors such as gyroscopes.

the accuracy of the GPS single-frequency ionospheric model, the Wide Area Augmentation System will transmit a more complex and accurate grid-based ionospheric model to its users. One of the most challenging technical areas is the accurate determination of this time-varying, geographically dependent ionospheric grid. Aerospace used its long-established ionosphere modeling expertise to test the ability of this algorithm to satisfy the Wide Area Augmentation System ionosphere correction requirements.

Applications above Earth

Although GPS was originally designed for terrestrial and airborne use, its applications now extend far above Earth. Aerospace has been active in many of these applications. A number of engineering studies by the company have supported the role of GPS on missiles and launch vehicles. As early as 1987, the Aerospace Range Systems Architecture Study recommended the "transition from radar to the Global Positioning System (GPS) as the primary source of tracking" at the Western and Eastern Space and Missile Centers. A 1999 Space-Based Range Feasibility Study reaffirmed GPS capabilities to meet most tracking requirements. Recent analysis has demonstrated GPS capabilities to satisfy launch vehicle tracking requirements for real-time range safety. All of these studies support increased use of GPS for range standardization to reduce operational expenses.

Flight experience has demonstrated GPS applicability on many satellites in orbits ranging from low Earth to geostationary. For example, Radcal—a radar calibration satellite launched by the Air Force in 1993—demonstrated a precision orbit determination capability using an inexpensive GPS receiver. Flight-data processing at Aerospace produced a postflight orbit accurate to 5 meters, satisfying requirements for the worldwide Department of Defense radar-calibration system.

Aerospace has also provided performance assessments for the more challenging mission of high-altitude spaceborne users. These users, well above the GPS constellation, receive some GPS signal spillover from the far side of Earth. Aerospace has shown that by using sophisticated orbit modeling and measurement processing, GPS can meet the orbit determination needs of many high-altitude space systems.

The Future of GPS

GPS is playing an increasingly important role in all aspects of military operations—from ground troop maneuvers to precision weapon delivery. But the role of GPS in civilian applications is expanding even faster. As navigation technology matures, the trend will continue toward embedded GPS applications integrated with communication systems and large databases. For example, integrated systems could provide immediate traffic information and route alternatives to rush-hour drivers or advertise a particular restaurant to potential customers in its vicinity as the dinner hour approached. In fact, given the emphasis on complete system integration, future users may not even be aware that satellite navigation technology will be at work in their daily lives.

Promising applications are abundant in the transportation arena: real-time traffic information, route guidance, fleet control, collision avoidance, automated accident reporting, and automated toll charges, to name just a few. Other uses—such as auto insurance pricing based on when, where, and how fast a car is driven—might not be so popular with the general public.

GPS has become an essential element in the global infrastructure and has exceeded the expectations of even its early developers. Aerospace played a prominent role in the development of this dual-use space system, and will continue to guide and support its future evolution.

Optimizing Performance Through Constellation Management

Paul Massatt and Wayne Brady

Deciding where to put the GPS satellites is no easy task. Research at Aerospace has been instrumental in answering the fundamental questions of constellation management: how many, how high, how close, and how long.

The configuration of the Global Positioning System (GPS) has always represented a compromise between user needs, budgetary constraints, and technical feasibility. The constellation has evolved to reflect changing requirements and program support, but the overriding management goal has never changed: to provide the most functional system for the broadest class of users, given a limited amount of resources. In pursuit of this goal, the GPS community must continually ask where to place satellites to best meet current and future needs. Research at The Aerospace Corporation has been essential in helping to answer that question.

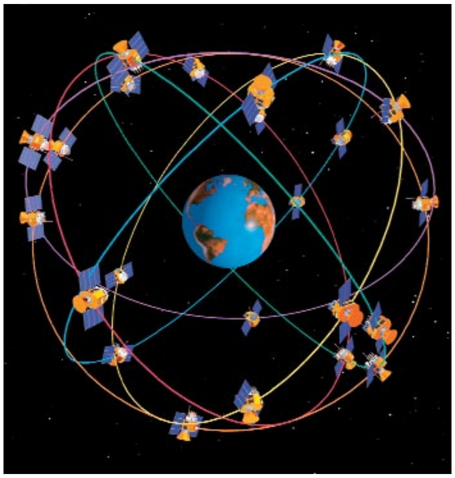
Initial Proposals

The 24 primary satellites in the GPS constellation orbit Earth at an altitude of roughly 20,000 kilometers, circling the planet twice a day with precisely repeating ground tracks. Each of the six orbital planes, inclined 55 degrees relative to the equator and evenly spaced around Earth, contains at least four satellites, and some contain an additional spare satellite.

A 24-satellite baseline constellation was first proposed in the late 1970s. Various studies indicated that three orbital planes each containing eight satellites uniformly spaced 45 degrees apart would meet initial requirements most efficiently. The inclination was set at 55 degrees, and the orbital period was set at 11 hours, 58 minutes (to support repeating ground tracks). The three orbital planes would be perpendicular to one another and equally spaced around the equator. The in-orbit phasing between adjacent planes would be offset by 30 degrees as measured from the point where they crossed the equator.

Highly symmetrical configurations such as this are known as uniform constellations. The satellites are evenly distributed within the orbital planes, and the orbital planes are equally offset from each other. Early GPS models focused on uniform constellations because they provide the most satellite visibility on a global scale; however, uniform constellations do not always provide the best geometry, which ultimately determines receiver accuracy.

Nonuniform constellations were also considered—particularly after funding cuts forced the GPS program to move from 24 planned satellites down to 18. Aerospace conducted extensive analyses of satellite failure effects and determined that a three-plane constellation would achieve the broadest coverage possible with the 18 budgeted satellites. In fact, this nonuniform three-plane constellation could provide greater coverage than a uniform three-plane constellation.



The baseline GPS constellation consists of 24 satellites in six inclined planes, providing continuous fourfold (or better) coverage across the globe.

Nonetheless, concern over the impact of satellite failures prompted a decision to support an 18-satellite, six-plane uniform constellation. Even this configuration, though, would result in a band of degraded accuracy that could last as long as one hour per day in the latitudes 30–40 degrees north and south of the equator.

Early Launches

Despite these planning efforts, no satellites were launched into any of these constellations. The first satellites were actually launched into two orbital planes with 120-degree separation at the equator. This arrangement was chosen because it could serve as the basis for either a three-plane or a six-plane constellation. Seven more Block I satellites were ultimately launched into a nonuniform constellation. The goal was to provide maximum coverage over Yuma, Arizona, where most of the early testing took place. The Block I satellites had a 63-degree inclination, which would provide better global coverage than a 55-degree inclination in case a six-plane constellation was adopted.

In the early 1980s, the United States decided to use the space shuttle as its principal launch source, and GPS was reconfigured for launch on this new platform. To accommodate new launch constraints, the inclination of the constellation was decreased to 55 degrees.

In early 1986, the space shuttle Challenger's solid rocket booster exploded during liftoff, prompting the GPS program to reassess its launch strategy. Consequently, the decision was made to switch from shuttle launches to Delta booster launches, and this switch caused a three-year delay in launching Block II satellites.

Shortly after the Challenger explosion, one of the Block I satellites failed. The Air Force was concerned that another satellite—the oldest on orbit—might also fail, eliminating any testing coverage at Yuma. Aerospace analysts examined the potential for moving different satellites to improve coverage. Researchers developed optimization techniques to determine the best arrangement for all satellites and the benefits that could be attained by moving only one or a few satellites.

The analysis revealed that one large maneuver would ensure three hours of daily testing coverage over Yuma even if the oldest satellite failed and five hours if it survived until the next block of satellites could be launched. This one large maneuver was coupled with a delay of station-keeping maneuvers for several other satellites to let them drift naturally into better locations. This event shows why simulations of coverage are often pessimistic: Most simulations assume that spares will only be moved within their existing slots when primary satellites fail. In actuality, if failures occur that are likely to have a long-term impact on GPS coverage, satellites will probably be moved wherever they're needed to improve the situation.

Spares and Pairs

While the GPS program office was transitioning to the initial 18-satellite target, Aerospace performed optimization studies to determine whether the three planned spares could be integrated more fully into the overall design to provide global coverage. Researchers began by studying the nature of the bands of degraded accuracy experienced with the 18-satellite, six-plane uniform constellation. Analysis showed that the degraded accuracy was produced at locations and times when only four satellites were visible. Moreover, it appeared that the high degree of symmetry inherent in the uniform constellation was in fact part of the problem. By carefully characterizing all of the regions of degraded accuracy, Aerospace determined that nonuniform fivefold coverage could be provided over the affected regions by substituting three satellites with three *pairs* of satellites. A small movement of two additional satellites enhanced the coverage even more.

While this strategy would prevent complete outages, it did not improve accuracy as much as desired; in fact, several regions would still experience substandard performance. Hence, Aerospace began searching for a way to optimize local performance.

Several obstacles had to be overcome before an optimization algorithm could be developed. For example, the methods generally used to evaluate coverage over the whole Earth throughout the course of a day relied on point-by-point evaluation over an extensive space-time grid. In addition, GPS receivers only locked onto four satellites at a time, so every combination of four satellites had to be examined individually. This method was cumbersome and slow. To optimize performance, one had to evaluate coverage over the large grid while also trying to determine how much to move the satellites, methodically repositioning each one and assessing its impact on performance. Moreover, the procedure required multiple iterations.

Researchers quickly realized that an optimum could not be achieved through traditional point-by-point grid evaluations. A breakthrough came when they applied new analytical methods using newly improved software. These changes considerably increased the efficiency of each objective function evaluation. They also allowed researchers to compute the effect of changing satellite locations more quickly. Rather than look at the effect of moving the satellites one at a time, they could track the satellites involved at the start and end of each period of degraded accuracy and analyze the effect of changing just those satellites. With these software efficiencies in place, optimization became much more feasible.

Gearing Up

The Aerospace analysis generated a nonuniform 21-satellite, six-plane constellation that had practically no degraded accuracy or severe drops in performance. The new constellation was also deemed more robust than the existing one, meaning it would perform better in case any satellites unexpectedly failed. Raising the inclination angle to 60 degrees or higher did not seem to impart any significant advantage, and considering that launch constraints made such a change difficult anyway, the inclination was preserved at 55 degrees. The Air Force approved the 21-satellite constellation as the new baseline and instructed the GPS Joint Program Office to implement it as soon as possible.

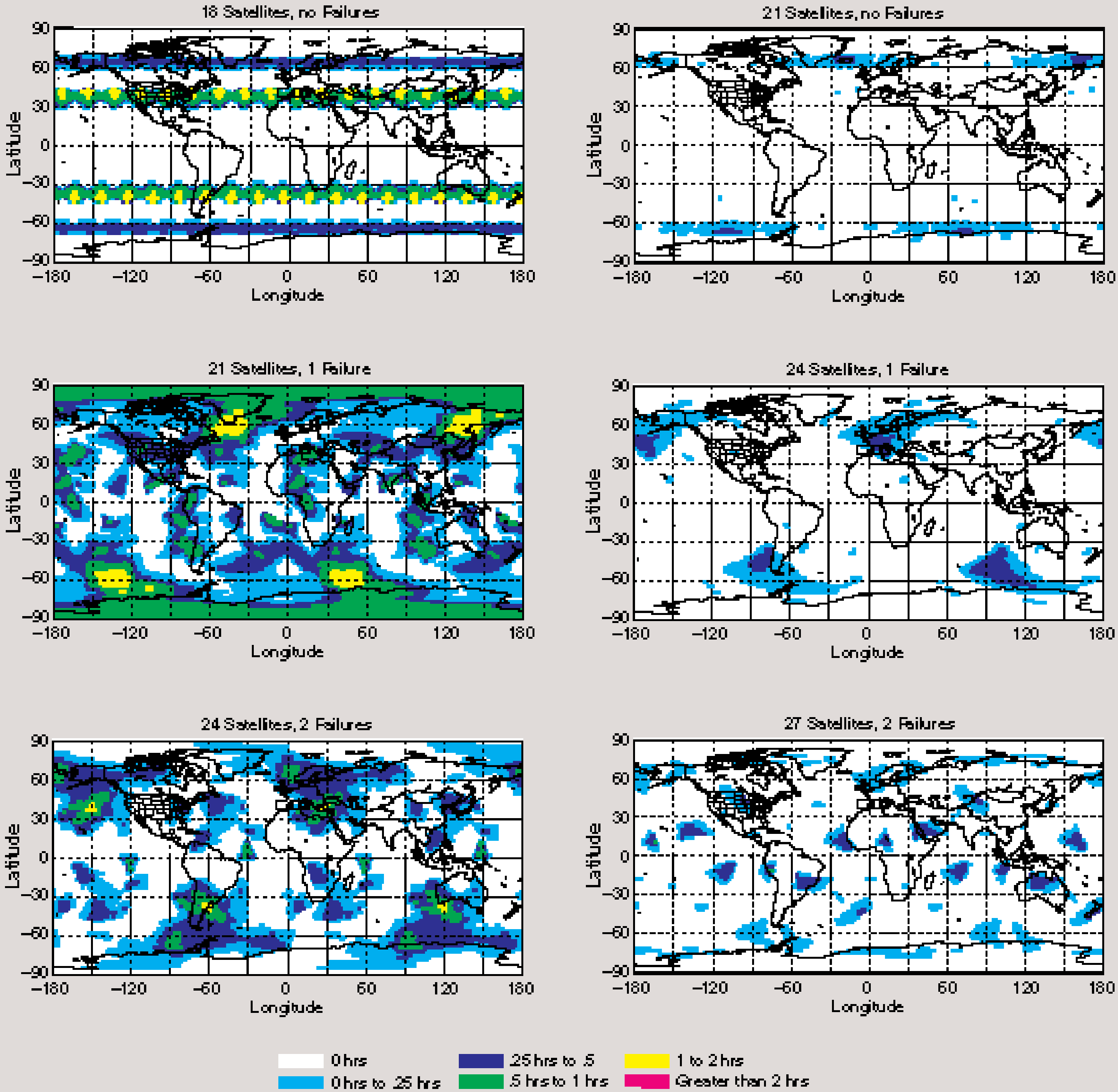
At the same time, the Air Force made clear that the ultimate goal for GPS was a 24-satellite constellation, and this was to be implemented as soon as funding permitted. Therefore, the program office needed to develop a 24-satellite constellation based on the 21-satellite plan. Fortunately, the program office had anticipated this need, and even before the Air Force authorized the 21-satellite constellation, Aerospace was already investigating the optimal 24-satellite constellation and developing a transition plan.

Computationally, this was not an easy task. The objective for the 24-satellite constellation was to maintain as much coverage as possible in the event of unexpected satellite failures. To find a local optimum, researchers would have to consider the failure of each of the 24 satellites individually. In addition, the larger constellation presented two to three times as many satellite combinations for each function evaluation.

Researchers tried to narrow their options as much as possible. For example, they decided to stick with the six-plane constellation because moving individual satellites from one orbital plane to another would require an extremely large amount of fuel. Also, they decided to focus on uniform constellations because the high degree of symmetry for such constellations favors strong global coverage. Still, these initial studies failed to provide a useful result. The best six-plane uniform constellation suffered significant losses of accuracy whenever a single satellite failed. In fact, coverage with a single satellite failure was not much better than that afforded by the 21-satellite constellation.

Aerospace analyzed the conditions that produced the poor accuracy and discovered that they all occurred with six satellites visible; however, the extremely regular and symmetric arrangement of the satellites actually prevented accurate ranging. It became clear that a uniform constellation might not be the best bet. While uniform constellations are effective at maximizing the number of satellites in view to users, they are not always effective at providing the best geometry to minimize position-estimate errors. Thus, unable to find a good six-plane uniform constellation, researchers began looking for a nonuniform alternative.

Several nonuniform arrangements were evaluated to see which one would provide the best coverage in case a number of satellites (up to three) failed. The best was a constellation based on the 18-satellite, six-plane uniform constellation—but in this case, certain satellites were replaced by pairs of satellites located close to each other (roughly 30 degrees apart on the same orbital plane). Once a robust initial configuration was found, Aerospace analysts migrated its modeling software to a



The coverage provided by the GPS constellation has grown more robust over time. These color contour plots show the cumulative amount of time per day that portions of the globe experience degraded accuracy (i.e., positioning error exceeding 9 meters or so). The first plot (top left) shows the amount of degraded accuracy for the full 18-satellite nonuniform constellation. The second plot (top right) shows that very few areas of degraded accuracy remain for the full 21-satellite nonuniform constellation. The third plot (middle left) shows that the 21-satellite constellation is sensitive to a single satellite failure. The fourth plot (middle right) shows that the 24-satellite constellation is less sensitive than the 21-satellite constellation to a single satellite failure. The fifth plot (bottom left) shows that the 24-satellite constellation is sensitive to a dual satellite failure. The sixth plot (bottom right) shows that the 27-satellite constellation is less sensitive than the 24-satellite constellation to a dual satellite failure. Hence, the ability of the constellation to withstand sudden satellite failures improves as the size of the nonuniform constellations increases. Moreover, the transition from one constellation to another generally involves only minor amounts of satellite repositioning.

Cray supercomputer, with modifications to take advantage of the Cray's pipeline processing capabilities.

Through this intensive modeling, the 24-satellite six-plane constellation was optimized to provide as much coverage as possible in the event of a single satellite failure. But although the optimization reduced the outages experienced with failures, it did not eliminate them all. The Air Force considered availability more important than small improvements in accuracy, so the constellation was optimized again to emphasize assured service over ultimate precision. With the redesigned constellation, the degradation in accuracy experienced during satellite failures was less severe. Moreover, overall performance after a satellite failure would not be significantly worse than with previous optimizations. As a matter of fact, the ranging error for the Block I satellites was less than half the initial specification, so the net accuracy provided by the new constellation was still better than the accuracy for which the system was originally built. In addition, the constellation showed little sensitivity to satellite drift.

Launch and Management

The GPS program office targeted initial Block II launches to enhance coverage over Yuma (to facilitate testing). After the success of the first few launches, remaining launches were targeted to improve global coverage as quickly as possible, with the exception that after Iraq invaded Kuwait, one launch was altered to provide better coverage over the Persian Gulf.

Midway through the buildup of the 21-satellite constellation, the Defense Department determined that GPS had the resources to support a 24-satellite constellation. This decision was based upon the strong performance shown by the Block I satellites (exceeding lifetime expectations by a factor of two) and the strong performance of the Delta launch booster. Realizing that many more satellites would have to be moved if the transition were conducted after full deployment, the program office began the transition to the 24-satellite constellation midway through the launch schedule. This action fulfilled the Air Force directive to implement a 24-satellite constellation as soon as funding permitted. The Pentagon reviewed the decision and consequently decided to support not only the 24-satellite constellation but also enough spares to ensure that the constellation size never fell below 24.

Spare satellites were not launched until the primary satellites had aged enough to present a strong probability of failure. When the risk of failure was deemed great enough, spares were launched into whichever orbital plane held the greatest risk of not maintaining four satellites. Each spare was positioned within the orbital plane in the location that provided the greatest increase to the robustness of the constellation. The availability of a large and robust constellation, coupled with the rarity of any satellite failure, allowed GPS to provide nearly continuous global coverage from the completion of the constellation in 1994 until the present.

All constellation design and management decisions were based on the need to achieve optimal performance within reasonable operational loads and cost constraints.

When the initial GPS constellation was deployed, it was managed without a specific coverage requirement. Consequently, all constellation design and management decisions were based on the need to achieve optimal performance within reasonable operational loads and cost constraints. Eventually, a requirement was imposed for global coverage 98 percent of the time with a reasonable level of accuracy. The requirement was based on the amount of coverage that could be maintained if a worst-case failure of two satellites occurred during conditions of the worst potential satellite drift. In actuality, most users would regard this coverage as unacceptable, so the requirement therefore did not change the management philosophy of striving to achieve the best coverage and robustness at all times within the stipulated budgetary constraints.

To date, users of GPS have not experienced the significant loss of coverage that was predicted in early failure and replacement models. Few failures have occurred, and the satellites have lasted much longer than originally expected. Still, the longevity of the GPS satellites has produced some unique problems. For example, in a few instances, when aging satellites failed, spare satellites were relocated to replace them. Afterward, engineers successfully revitalized the failed satellites, so the repositioned spares no longer contributed to the robustness of the constellation as strongly as they had earlier. In addition, the orbits of the aging satellites have migrated significantly from their ideal positions, which further erodes robustness.

Such migration within the orbital planes was expected, but the predicted impact was considered small compared to the predicted impact of complete satellite failures. In actuality, with satellites lasting much longer than expected, the impact has been greater than originally expected. Finally, the lack of satellite failures has created an unrealistic expectation by users that global coverage will continue at the same level that it has in the past—although this is like expecting an old car to experience no more mechanical problems than a new car.

Requirements and Demands

Recently, the aging of the constellation did permit a small outage lasting 15–20 minutes that repeated daily over portions of Texas and Oklahoma. While this outage was small compared to what one would expect under steady-state operation of the constellation (when failures and launches occur at roughly the same rate), the region that was affected did not consider it small at all. Concern over the outage and its impact on civil transportation systems prompted officials to reposition one of the older satellites and retarget a launch to ensure uninterrupted service over the affected area.

This incident clearly demonstrates the dichotomy that has developed between user expectations and design objectives. GPS was not designed to provide continuous, uninterrupted global coverage. While global coverage has always been an objective, it has been pursued only within the limits of budgetary constraints.

For example, the size of the constellation was adopted to balance user demands for maximum coverage against government demands to constrain cost. If global coverage were the only goal, then a larger constellation could have been built. The difference in expectations between the users and builders of GPS stems from the shift in the predominant user community from military to civilian. When GPS is tied to civilian requirements, any outages quickly become intolerable. The mushrooming demand for GPS is rapidly placing greater priority on the desire for guaranteed uninterrupted service; it remains to be seen whether future funding and improvements in constellation replenishment and management strategies will satisfy this desire.

The GPS satellites are growing old and more prone to failure. User expectations have been built upon the service provided by a very robust constellation of relatively young satellites. As satellites age, failures should occur roughly in proportion to their replenishment rate, approximately two to three times per year. Failures will also occur at nonuniform rates, with some years seeing no failures and some years seeing several. Maintaining coverage during the replenishment cycle will be challenging.

Consequently, Aerospace conducted a new study to determine whether a larger constellation with greater robustness could be implemented, using allocated spare satellites directly in its structure to decrease dependence upon replacements. From this study, Aerospace devised a 27-satellite constellation, and the program office has since repositioned certain satellites to facilitate the transition. The 27-satellite constellation has five satellites in every other orbital plane—two paired and one isolated. The constellation can be maintained so that the most critical slot in each orbital plane always contains a strong healthy satellite with low risk of failure.

This strategy should alleviate the need for quick replacement of satellite failures via on-orbit spares. It should also reduce the desire to deal with every potential failure by launching a spare, and thus help minimize replenishment costs. The new constellation was optimized for best coverage with failures using the same criteria applied to the existing constellation. It was also examined carefully for its performance with two failed satellites. The new constellation is not expected to redress all the issues regarding the imbalance between user expectations and program funding, but it should alleviate some of the problems.

New Studies and New Capabilities

GPS is currently reviewing all requirements, satellite designs, constellation designs, and constellation management strategies with the intent of providing a better system that can be launched between 2009 and 2020. Constellation management issues are especially important when one starts to compare different numbers of orbit planes. For example, in a six-plane constellation, it is better to fly a large constellation without spares rather than a small constellation with spares because failures are unpredictable and the number of spares required to cover all orbit planes is costly. Spares can be used to advantage in a three-plane constellation, however, if they can be equipped with the ability to rapidly replace failed satellites. A large constellation without spares reduces the sudden impact of failed satellites, while a small constellation with spares can restore full constellation service faster.

Comparisons of three- and six-plane constellations are difficult because they are managed differently. In addition, the likely cost of the long transition between constellations (roughly 12–15 years, or the lifetime of the satellites) must be carefully weighed along with an assessment of the transition's impact on performance. Many other issues need to be examined, such as the ability to expand the constellation to meet increasing user demands and the ability to defend against hostile threats. These analyses will require computation several orders of magnitude greater than before.

Aerospace is exploring other constellation management issues as well. For example, when is it better to preemptively reposition satellites to maintain healthy units in critical constellation slots? If a satellite fails and cannot be replaced quickly, does it make sense to move another satellite to improve the constellation's coverage or robustness? Should satellite drift be controlled by keeping satellites within specified tolerances, by assessing the impact to coverage, or by changing the altitude of the constellation? How do different constellations compare when appropriate management strategies for each are considered?

While increases in user requirements are likely to spur the demand for more satellites, the ability to meet that demand in a cost-constrained environment will require careful engineering. Fortunately, new hardware and software efficiencies are permitting Aerospace to achieve computational efficiency significantly better than before. This will greatly boost the ability to analyze new requirements and compare both constellations and constellation management schemes. Thus, the confluence of governmental budgetary constraints, user demand, and engineering capability should continue to determine the optimal configuration of the GPS constellation.

How High Should They Fly?

If GPS had been built for civilian instead of military use, it might have evolved as a regional U.S. system served by geosynchronous satellites, which would provide local coverage at a lower cost but would not support the nation's global defense capabilities. In actuality, the 24 primary and spare satellites orbit Earth at an altitude of 20,000 kilometers, circling the planet twice a day with precisely repeating ground tracks.

The altitude of the GPS constellation was influenced by two primary criteria: the need to support a system for detecting nuclear detonations, and the need to permit early testing of a small constellation with minimal risk. These criteria favored a semisynchronous orbit—but these criteria are no longer the primary drivers of constellation management.

Aerospace has been conducting studies to determine whether a new altitude would be preferable, but these studies consistently show a loss of efficiency in transitioning to a geosynchronous (or higher) orbit; from a cost-benefit perspective, the current altitude is still the most efficient.

One altitude change that may be beneficial, however, is a small boost that will allow the orbits to migrate from their repeating ground tracks. Currently, the ground track of each satellite crosses the equator at precisely the same longitude. As a result, each satellite experiences the same gravitational effects day after day. Thanks to the longitudinal variations in Earth's gravitational field, these gravitational effects eventually cause some satellites to speed up or slow down relative to each other. To preserve the beneficial satellite-to-user geometries, this acceleration or deceleration must be corrected every year or so with stationkeeping maneuvers—thrusts that counteract the gravity-induced motion. This thrusting action expends fuel and induces error into the satellite position that must be corrected over time by reestimating trajectories through postmaneuver monitoring and site observations. The satellite is marked unhealthy during this period and does not contribute to a user's navigation calculations. A small altitude change would move the satellites off their repeating ground tracks so that they would all experience the same cumulative gravitational field effects over time, eliminating the need for stationkeeping maneuvers.

Orbit Determination and Satellite Navigation

John Langer, Thomas Powell, and John Cox

The Global Positioning System is remarkably precise in determining a user's location. But before these satellites can help anyone else, they first need to know their own positions and movements. Orbit determination is the branch of space science that makes such knowledge possible.

For centuries, astronomers, physicists, and mathematicians have sought to predict the motion of celestial bodies. It was not until the late 1950s, however, with the launches of the Sputnik and Vanguard satellites, that the modern discipline of orbit determination was born. This new field differed from traditional astronomy in three essential ways. First, it typically tracked satellites via radiometric techniques, rather than via telescopes. Second, it focused on Earth-centered orbits, rather than orbits around the sun or distant planets. Third, it relied on intensive numerical calculations, rather than estimates and heuristics.

The science progressed quickly in its formative years, thanks to the rapid advances in computing technology that accompanied the early space race. Such developments finally made it possible to solve (in a reasonable amount of time) the computationally intensive equations that govern orbital motion. Much of the early work focused on generating better ephemerides—timetables of satellite speed and trajectory. Large computers would calculate the complex equations of motion to generate these tables, and the results would be compared with actual radio measurements from tracking stations. The comparison would reveal ways to improve the underlying algorithms, gradually increasing the precision of the orbital predictions.

Today, The Aerospace Corporation plays a prominent role in the science of orbit determination, along with the related fields of orbit reconstruction and orbit prediction. Techniques developed by the company continue to set the standard for researchers across the globe, and new advances promise to keep Aerospace at the forefront of the field.

U.S. Air Force

The Maui Space Surveillance Site, located at the summit of Mount Haleakala, Hawaii, is a state-of-the-art electro-optical facility supporting both the Air Force Maui Optical Station and a Ground-based Electro-optical Deep Space Surveillance (GEODSS) sensor suite. Data from this and other sites are used to compute the orbits of objects of foreign or unknown origin.

TRACE

Aerospace involvement in orbit determination extends back to 1961. The U.S. military space effort was well underway by this time, and the Air Force Satellite Control Network (AFSCN) already included a master control station in Sunnyvale, California, and nine S-band (1.7–2.3 gigahertz) tracking stations positioned across the globe. It was at this time that Aerospace engineers began developing an orbit determination and analysis program called TRACE.

TRACE was unique in that it was not designed for any one mission or application; rather, it provided a configurable, general scheme for modeling a wide array of orbits, orbital missions, and tracking networks—including AFSCN. It also possessed an error-analysis capability that enabled orbit planners to evaluate hypothetical scenarios and optimize tracking schedules accordingly.

TRACE became a standard tool in the industry and was used to prototype many early operational systems. In fact, TRACE-based analysis contributed to the orbit-determination design for most major U.S. military and intelligence satellite systems. The software has been under continuous development and enhancement for more than 40 years, and is still one of the few standards employed industrywide.

Traditional Approaches

Aerospace used its TRACE software to develop key concepts for the Defense Satellite Program (DSP), which provides military surveillance, and Milstar, which provides secure communications. The nature of these two constellations presented various challenges for planners and operators alike.

For example, researchers found that the accuracy of the DSP ephemeris could be enhanced by a reduction in the latency period of its distributed orbit-vector estimates. They achieved this by processing the tracking data and estimating the orbit in real time. In that way, the current orbit elements can be distributed at a frequency driven by the frequency of tracking data collection—nominally four to six times per day. Of course, a real-time orbit estimator presents a more difficult technical problem than the standard "least-squares" estimator. Noise and other unpredictable error sources can derail a real-time orbit estimator, and these need to be filtered out.

Aerospace developed a sequential filter that estimates the orbit of DSP satellites in real time. It's a prototype of a system that can provide accurate short-term predictive ephemerides on demand while also allowing autonomous orbit determination—meaning it can respond to changes in orbits or orbital measurements without human intervention. When proven, it will significantly reduce the operational cost of systems for generating highly accurate orbit estimations and ephemerides. The technology is also used to support launches of geosynchronous satellites, providing real-time estimates of launch-vehicle trajectory.

Milstar navigation requirements are based on the need for antenna maneuverability, signal timing accuracy, and system autonomy. To achieve system autonomy, Milstar uses its communication links to measure both range and satellite clock-time offsets relative to a master clock. The measured ranges from ground terminals and from other satellites are used to estimate a satellite's orbit using software based on TRACE.

Milstar's innovative use of communication links for orbit estimation and timekeeping required numerous analyses and continuous evaluation by Aerospace. The system performs well, and assuming a successful test of the recently launched Flight 5, will achieve global communications coverage.

Determining GPS Orbits

Navigation around the world has been dramatically changed by the Global Positioning System (GPS), and the power of this system is derived first and foremost from the orbit-determination process that drives it. After all, without a way to pinpoint the locations of the GPS satellites, users—who determine their positions relative to the GPS satellites—would quite literally be lost.

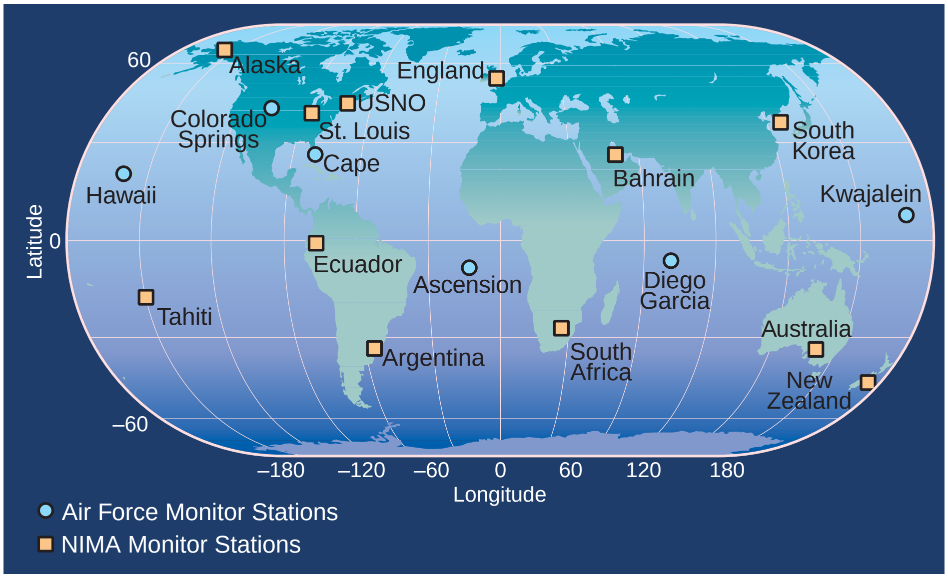
The GPS operational control segment collects tracking measurements at five (soon to be six) monitoring stations around the world. This information is transferred to a central processing facility in Colorado Springs. There, the data are processed via a Kalman filter, a device that estimates the GPS orbits and biases in the onboard atomic clocks. These estimates are then used to form "navigation messages," which are uploaded to the appropriate GPS satellites, which in turn transmit them to every GPS receiver in range. The navigation messages indicate where the satellites are so users can determine their position relative to them.

Aerospace was involved in the initial design, acquisition, and deployment of the GPS operational control segment, prototyping many of the algorithms in TRACE. Aerospace modeling and simulation led to a better understanding of GPS, and to numerous improvements.

For example, the fundamental performance metric for GPS is called user range error—a numerical value that describes errors in the estimates of GPS satellite position and onboard clock biases. Combined with information about the relative arrangement or geometry of the GPS satellites in view, user range error can help predict the accuracy of a GPS receiver's position, velocity, and time computation. In 1990, the specification for user range error was set at 6 meters. Continuous improvements to the GPS satellites and the operational control segment—made possible in part by Aerospace simulations—have effectively reduced the user range error from the initial target of 6 meters to approximately 2 meters today.

Improving GPS Orbits

The GPS operational control segment monitors the performance of the system, but has few resources for investigating and proposing improvements. This task is left to various GPS-related working groups. Acting in concert with these



Tracking data from six Air Force monitoring stations are used to compute GPS orbits. Additional NIMA tracking stations may be added to the GPS ground network in the future.

Sensor Systems for Satellite Tracking

Classical orbit determination has always relied on passive sensors such as telescopes. As technology has advanced, new ways of tracking objects in space have arisen, but passive sensors still play a role.

For example, the Space Surveillance Network of the Air Force Space Command has a system known as GEODSS (ground-based electro-optical deep-space surveillance sensors) that uses telescopes and television cameras. The telescopes scan an area of space at the same speed that distant stars appear to move, effectively keeping the stellar background static. The cameras take rapid snapshots of the area, and these are superimposed on the telescopic images to reveal any moving objects. Accuracy is excellent, but operation is restricted to night and fair weather conditions. The system offers other advantages. For example, GEODSS operators do not need to interact with any other country or program, which makes the system particularly useful for tracking objects of foreign or unknown origin. Technology of the sort used for GEODSS continues to advance. Scientists at Phillips Laboratory in New Mexico are developing a telescope that uses charge-coupled devices and advanced computer processing; Aerospace researchers are analyzing the orbit-determination accuracies possible with this new technology.

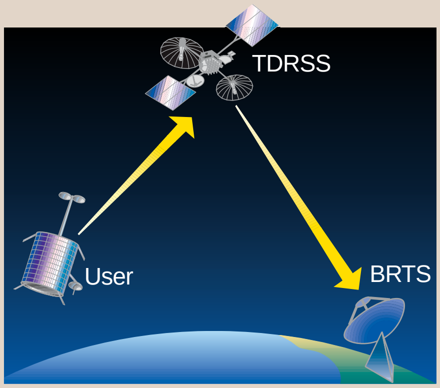
The Space Surveillance Network also uses radar to track satellites. In contrast to telescopes, which are essentially passive receivers, radar systems are considered active because they emit a microwave pulse toward a space object and measure the reflected energy.

All sensors used by the Space Surveillance Network, both passive and active, are considered noncooperative because they require no action on the part of the object being tracked. This feature permits tracking of objects that are not under U.S. control; it also enables tracking of space debris. In fact, the Space Surveillance Network is attempting to calculate the trajectories of every Earth-orbiting object bigger than a grapefruit.

Cooperative sensor systems require action by both the spacecraft and the ground station. One common example is the Space-Ground Link Subsystem, or SGLS, used by the Air Force Satellite Control Network. In this case, a pseudorandom numeric code can be imposed on an S-band carrier signal and uplinked to a spacecraft, which returns the signal after applying a frequency shift. The ground system correlates the received signal with a replica of the transmitted signal to generate a time-delay measurement. This measurement, when multiplied by the speed of light, provides an approximation of the round-trip distance. Accuracy can range from a few kilometers to a few meters, depending on the level of resources employed.

A somewhat more accurate and much more expensive technique is satellite laser ranging. In this case, a laser transmitter on the ground, combined with a telescopic/photometric receiver, bounces a precise laser pulse off a reflector on a spacecraft and computes the round-trip distance.

The ultimate cooperative technique is known as intersatellite crosslink ranging. In this technique, two satellites exploit special characteristics of a communication channel to extract ranging information. This has proved quite beneficial for both Milstar, a military communications system, and the Tracking and Data Relay Satellite System (TDRSS), primarily associated with NASA Earth-orbiting experiments. Both satellite systems are in geosynchronous orbits.



TDRSS satellites can take advantage of satellite-to-satellite ranging to obtain exceptionally precise orbit determination.

In the Milstar system, the crosslink ranging includes a mechanism for time transfer as well as relative distance measurements. Each satellite clock is autonomously referenced to a master clock, which is in turn synchronized to a reference cesium clock using time-offset measurements. These measurements also contain range information for estimating the orbits of each satellite. The resulting ephemerides and system time are accurate enough to permit communications and autonomy.

The orbits of the TDRSS satellites are determined from the Bilateral Ranging Transponder System (BRTS), which is similar to SGLS. In this case, however, operators can take advantage of satellite-to-satellite ranging and knowledge of the TDRSS orbits to perform their orbit estimations. For example, in processing data for Topex/Poseidon (a radar altimetry satellite), scientists found that the TDRSS ephemeris accuracy could be greatly enhanced by using TDRSS tracking from a satellite in a low Earth orbit. The Topex/Poseidon orbit was determined using satellite laser ranging and radiometric techniques. The orbits of the TDRSS satellites were then determined using one- and two-way TDRSS-Topex/Poseidon ranging. This technique reduced the TDRSS total position ephemeris error from 30 meters to less than 3 meters. Subsequently, the reduced ephemeris error improved the orbit estimations of satellites that used ranging to the TDRSS satellites in their calculations. These techniques demonstrated the benefits of satellite-to-satellite ranging for precise orbit determination.

Orbit determination for the GPS satellites is a curious mix of active and passive techniques. The GPS satellites actively radiate a radiometric signal similar to SGLS, while ground-based GPS receivers passively collect this information without providing direct feedback to the GPS satellites.

Orbit determination of other satellites *using* GPS moves this composite one step further. The client satellite passively collects the GPS signal, just as a ground-based receiver would; but the space-to-space measurements enjoy the geometric benefits associated with crosslinks. This added dimension allows the user satellite to apply the superior orbit determination underlying the GPS system to obtain highly accurate orbit determination for itself.

groups, Aerospace has played a key role in several initiatives:

Reduced Age-Of-Data. A major error source in the user range error is the "age" of the navigation message. Errors caused by orbital deviations tend to accumulate over time, so the GPS user will experience the greatest accuracy just after a navigation message upload, and the least accuracy just before. Originally, navigation messages were uploaded once per day, with additional uploads made whenever user range error was found to exceed its maximum allowable value. Over the years, however, error requirements have grown more stringent, necessitating better performance monitoring and more frequent uploads, particularly for "problem" GPS satellites deemed to have a higher risk or history of error. More frequent uploads, in turn, have significantly reduced the extent of user range errors.

Improved Satellite Clock Management. Aerospace has years of operational experience developing and managing atomic clocks for GPS satellites. Aerospace data helped show that it is better to decommission an anomalous GPS clock and activate a spare than to attempt to regulate the wayward clock.

Upgraded Station Surveys. Analysis at Aerospace showed that reducing the uncertainty in the GPS tracking station locations from 1.5 to 0.1 meters would significantly improve orbit and clock estimation. New surveys were performed to describe the locations more accurately, and the updated values were installed in 1994, enhancing overall performance.

Improved "Tuning" of the Kalman Filter. Aerospace and other research groups suggested a number of slight adjustments to some of the parameters used by the Kalman filter in the operational control segment. These adjustments were made in 1997, first to the parameters that control the estimation of the onboard clock biases, then to the parameters that control the estimation of the effect of solar wind on the GPS satellite trajectories. These enhancements, once validated by the various working groups, were implemented in the operational control segment and produced immediate and significant improvements in performance.

Aerospace continues to analyze the operational control segment with an eye toward improvement. Aerospace is also pushing to accelerate the Accuracy Improvement Initiative, a multipronged scheme that includes a major restructuring of the operational control segment estimation software, the addition of tracking data from a number of stations provided by the National Imaging and Mapping Agency, and other updates. Aerospace analysis indicates that these improvements will bring the user range error down to about 1.3 meters.

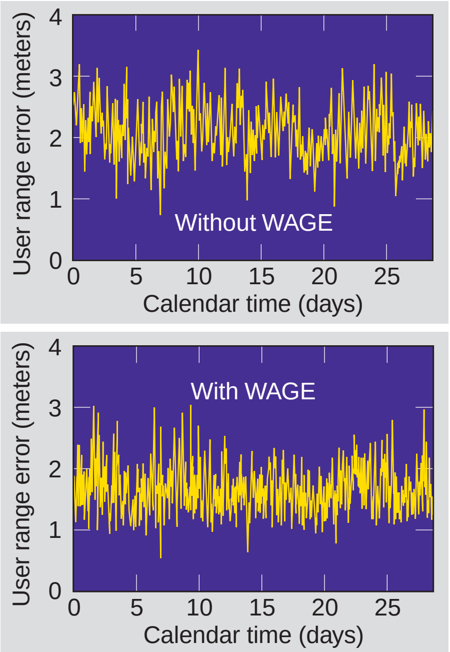
Continued Innovation

Aerospace was among the early proponents of the Wide Area GPS Enhancement (WAGE) initiative. This scheme, currently in operational testing, exploits the fact that a number of bits in the GPS navigation message broadcast are unused. These bits could be used to provide update information not only for the GPS satellite seen by the user, but for the entire GPS constellation. This clever trick of telemetry could reduce the user range error by 15–20 percent for a suitably equipped user.

Aerospace prototyped a system survivability mode for GPS, called Autonav, that enables the system to perform autonomously in case a disaster or other event renders the operational control segment unusable. The GPS satellites will perform intraconstellation ranging measurements via special crosslinks. Then, using onboard processing, each satellite will compute its own orbit and clock offsets. Not only does this approach provide security against catastrophes, but it could also help improve the performance of the constellation during normal operation. As the actual Autonav capability gets phased in, Aerospace will test the system to determine its potential benefits for regular performance.

GPS-Based Orbit Determination

Until the early 1990s, all orbit determination—even for GPS—relied on Earth-based tracking and processing. Typically, a network of tracking stations would monitor a constellation and transfer the tracking information to one or more "central" processing sites, where the actual orbits would be computed. With the maturation of GPS, certain satellites—particularly those in low Earth orbit—could carry GPS receivers and compute their own positions directly. The potential cost savings makes this approach very attractive: Ground stations might still be needed for tracking, telemetry, and control, but the resource-intensive processes of scheduling, collecting, and transferring ground-based tracking data could be avoided. In addition, the Department of Defense will dramatically reduce the use of S-band for satellite tracking, potentially freeing up a significant portion of this valuable spectrum band for other uses.



The Wide-Area GPS Enhancement initiative seeks to utilize unused bits in the GPS navigation message to provide update information for the GPS satellites. This technique of telemetry could reduce user range error by 15–20 percent for a suitably equipped user. The top graph shows user range error without enhancement, and the bottom graph shows the performance improvements possible through enhancement.

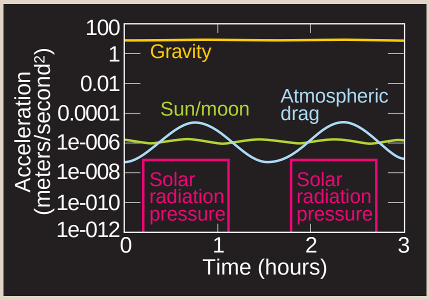
Aerospace helped develop the GPS-based orbit-determination scheme for Radcal, a radar calibration satellite deployed by the Air Force Space Test and Small Launch Vehicle program in 1993. Commissioned under an aggressive one-year contract-to-launch schedule, the satellite was chiefly designed to support calibration of the C-band radars used by the U.S. Space Launch Range. Unlike previous low-cost space missions, Radcal required precise orbit determination—accurate to 5 meters or less during radar calibration. To meet this requirement, Radcal carried a special Doppler beacon that could be tracked by a global network of tracking stations. It also carried two commercial-grade GPS receivers. These inexpensive devices were not equipped to decode the high-precision military signal known as the P(Y) code; rather, they were designed to receive the GPS Standard Positioning Service, which provided positioning accuracy on the order of 100 meters (because the signal was intentionally degraded at the time through a protocol known as selective availability).

Precision Modeling for Orbit Determination

High overhead, more than 20,000 kilometers above Earth, GPS satellites race by at speeds approaching 3800 meters per second. The movements of these spacecraft are generally described by the laws of planetary motion developed by Johannes Kepler almost 400 years ago—but they are by no means certain or simple. Each satellite must contend with diverse forces that constantly nudge and pull it from its desired orbit. Yet in spite of this, the positions of GPS satellites must be known at all times with exceptional accuracy. Modeling these orbits is a complex affair. Here are just a few of the many issues that must be considered.

Geopotential. Earth is not entirely spherical; in fact, it's roughly 20 kilometers greater in equatorial radius than in polar radius. It's also highly irregular in the distribution of its internal mass. As a result, Earth's gravitational field (or *geopotential*) is highly complex. Original models of this field were derived from surface measurements taken by gravity meters located throughout the world, combined with early measurements of orbiting spacecraft. Although these models gradually improved, they failed to remove gravitational effects as the principal error source in orbit determinations. The gravitational model established in 1996 incorporated a vast amount of highly precise GPS data together with laser tracking measurements and other data from Earth-orbiting satellites. The introduction of this model was a virtual watershed for orbit determination because, for the first time, gravity was no longer a major error source.

Dynamic Gravitational Effects. Earth's own gravitational field is only part of the picture. Earth's largest satellite—the moon—causes deformations of the planet known as tides. When people think of tides, they usually think of oceanic tides; but the situation is not so simple. Of much greater significance are the solid-earth tides, which, for example, can cause Los Angeles to rise as much as 40 centimeters in a given day. Earth's gaseous atmosphere can be similarly distorted. These shifts in mass must be accounted for in any precise calculation of Earth's gravitational field. Complicating matters, Earth's rotation is not constant; on any given day, the planet may spin faster or slower than the mean rotational rate that gives the typical 24-hour day. This effect cannot be predicted well and must be measured; orbit-determination systems must therefore receive regular updates and predictions from a scientific body known as the International Earth Rotation Service.



Accelerations for a polar low Earth orbit. Solar radiation pressure drops to zero when Earth blocks the sun.

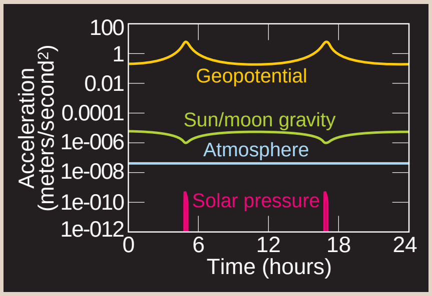
Coordinate Frames. The International Earth Rotation Service provides an additional measurement that's critical for precise orbit determination: the offset associated with "polar wander," a phenomenon caused by the movement of Earth's crust upon its molten core. The geographic North Pole and Earth's axis are offset from one another, and the offset changes from day to day. Somewhat more predictable are the precession and nutation of the Earth's spin axis, although orbit-determination experts must keep up with the latest theories concerning these variations in Earth's orientation.

Extraterrestrial Gravitation. All celestial bodies exert gravitational forces that can affect Earth-orbiting satellites. These forces are typically modeled via files from NASA's Jet Propulsion Laboratory, which provides ephemerides based on the latest astronomical observations.

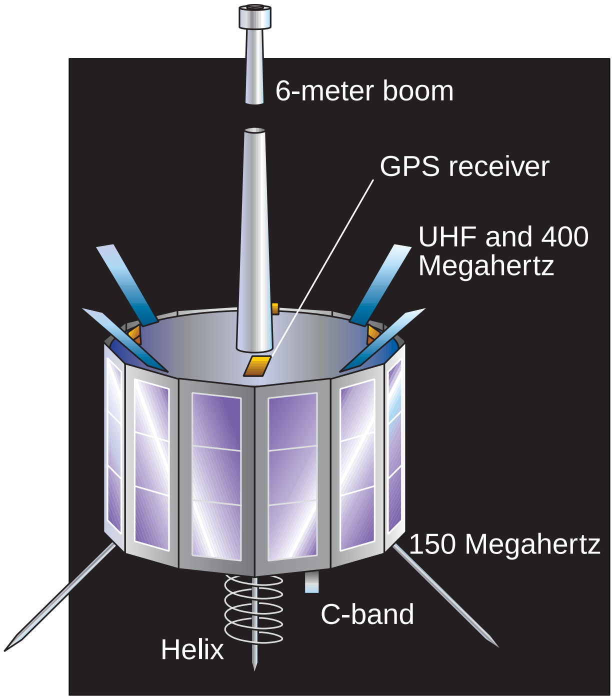
Solar Effects. The photons streaming from the sun exert a force on an Earth-orbiting spacecraft. Although this solar radiation pressure seems simple enough to compute, it in fact varies depending on the reflective capacity of the spacecraft surfaces and their orientation toward the sun. Depending on the orbit, the spacecraft may also be eclipsed, fully or partially, by either the moon or Earth. Moreover, sunlight may reflect off Earth and provide an additional source of photons—a measurable effect known as the albedo. Sunlight might also heat various parts of the spacecraft unevenly, and the heat radiation provides another source of acceleration. Modeling solar effects typically requires high-fidelity modeling of the spacecraft body itself and an understanding of its attitude regime.

Atmospheric Drag. There is no sharp boundary between Earth's atmosphere and the near vacuum of space. In fact, remnants of the atmosphere extend outwards for hundreds of miles. Satellites, particularly in low Earth orbits, fly through this thin atmosphere at high speeds, which induces enough drag to eventually bring them down. The modeling approach is similar to the one used for solar radiation pressure: The ballistic properties of the various surfaces are studied, and the orientation of the spacecraft is modeled. The drag-modeling problem is significantly harder, though, because the upper atmosphere is not well understood. Indeed, the best models of the day are accurate only to about 15 percent when employed under the best of postflight conditions.

Ionospheric Delay. In cases where radiometric measurements are employed, the effects of the dynamic ionosphere can lead to significant corruption of the signals—particularly for lower frequencies (such as the S-band associated with SGLS or the L-band associated with GPS). Moreover, during intervals of high solar activity, the ionosphere is prone to high scintillation or ionospheric storms. These are virtually impossible to predict and can only be measured.



Accelerations for a highly eccentric geosynchronous transfer orbit. Drag effects occur near the low perigee.



Radcal demonstrated that low-cost GPS equipment can be used to generate highly precise orbital data.

Data from the Standard Positioning Service can be augmented in various ways to obtain greater accuracy. To determine what methods would be both sufficient and cost-effective, Aerospace researchers built a complex simulation. At the heart of the simulation was Aerospace's TRACE program, used in one mode to generate the reference trajectories and orbital conditions and in another mode to support various estimation strategies.

The simulation showed that as the GPS data-collection interval expanded, the overall orbit error decreased. Still, the effects of selective availability remained too high to ensure the necessary precision. Thus, with the assent of the GPS Joint Program Office (JPO), the Radcal researchers asked a team from the Applied Research Laboratories at the University of Texas to develop a PC-based system that would remove the effects of selective availability. The output of this system was then fed into a TRACE-based estimator built by Aerospace to produce a final orbit.

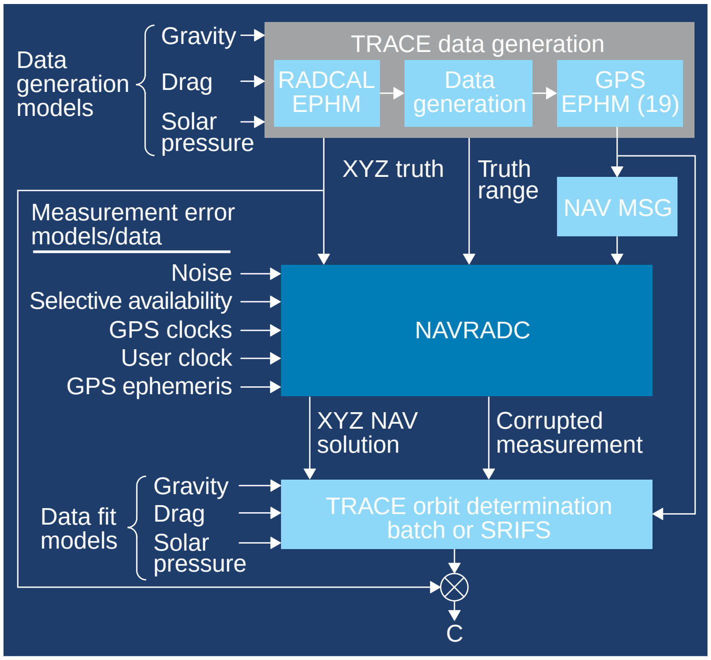
After Radcal was launched, the GPS data were collected and processed using TRACE. Orbits derived from these data were compared to orbits derived from the accurate but substantially more expensive Doppler scheme. The on-orbit results confirmed the earlier simulation analyses: with some additional processing, GPS measurements from an inexpensive commercial receiver could be used to produce precision orbits.

Radcal was significant as Aerospace's first involvement in precise low Earth orbit reconstruction via GPS data. The analysis tools and operational experience gained from this small program have subsequently provided significant benefit to a number of major low Earth orbit programs.

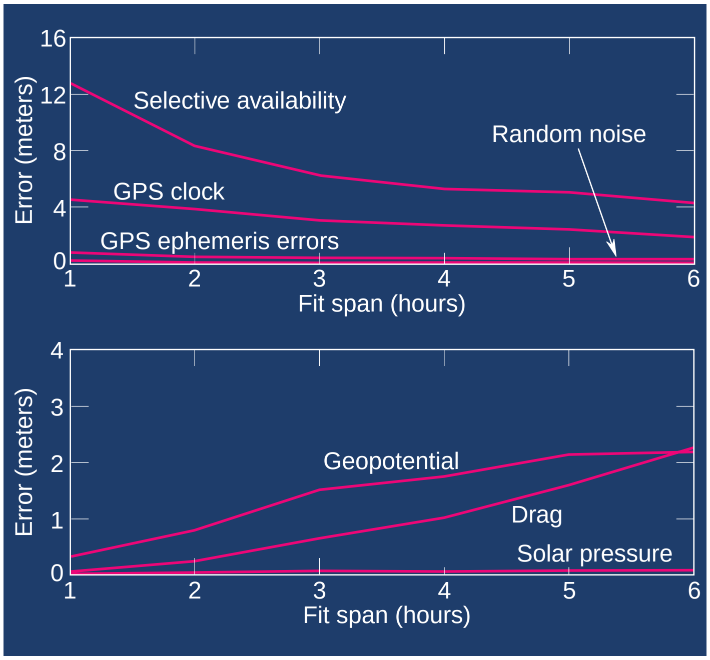
Geosynchronous Altitudes

Although GPS was designed primarily for users at or near Earth's surface, a new group of users have learned how to exploit the technology in ways that its early users probably didn't imagine. These new users take advantage of the fact that GPS satellite signals are directed toward Earth in a broadcast pattern that is slightly wider than the planet. Thus, a geosynchronous spacecraft on the opposite side of Earth can, with the proper equipment, receive and process the "spillover" GPS signals. Spacecraft operators recognized the potential to improve their navigation accuracy at a very early stage; however, the particulars of geosynchronous orbits present some unique challenges.

For example, geosynchronous spacecraft have historically been controlled from ground stations, as have most other spacecraft; however, a geosynchronous satellite has little or no relative motion with respect to Earth's surface, making the problem of geosynchronous orbit determination somewhat more difficult. Also, a single ground station can't always be located in the best spot for tracking a geosynchronous spacecraft, and this poor observation geometry adds another level of difficulty. GPS offers the potential for both improved geometry through multiple observation points and



Aerospace used a TRACE-based analysis tool to develop an optimal orbit-determination strategy for Radcal. The tool enabled analysts to simulate the effects of various measurement and force model errors. Aerospace used the same tool to develop the operational GPS-based orbit-determination system.



A key factor in Radcal processing was the "fit span," the length of the data interval used to compute the orbit. The effects of measurement errors decrease with a greater fit span, but the effects of force model errors increase. TRACE allowed analysts to select the optimal fit span.

The Kalman Filter: Applying the Scientific Method

Reconciling sensor data with astronomical models requires powerful computational resources. One such resource is the numerical algorithm known as the sequential state estimator. The most familiar example is the Kalman filter, which in one form or another is used in just about every computer-controlled device. The basic function is to estimate the "state" of a particular system based on measurements from appropriate sensors. The variables depend on the application, but typically include parameters such as position, velocity, temperature, pressure, and airspeed.

The mathematical derivation of the Kalman filter is quite complicated and requires preliminary knowledge of probability, control theory, and linear-system theory. However, for all this mathematical rigor, the Kalman filter can be described as simply a mathematical expression of the scientific method. In other words, the Kalman filter is an algorithm that describes the sequence of observation, experimentation, and deduction that is the heart of basic science.

The Kalman filter begins by creating a mathematical model that describes the dynamic nature of the system in question. It then guesses the values for relevant variables and quantifies the level of confidence in those guesses. Based on these guesses, the algorithm predicts the state of the system at some time in the future. It then makes observations and compares them to the predictions. If the observations agree with the predictions, then the model is assumed to be correct. If the predicted results disagree with the actual results, the model is adjusted to compensate for the discrepancy. The process can be repeated until the state estimate is consistent with the data.

The Kalman filter is used in several systems that maintain the orbits of artificial Earth satellites. For example, Canada uses a Kalman filter for orbit determination of the Telesat communications satellites. Also, the Air Force uses a Kalman filter to maintain the very accurate ephemerides of GPS satellites.

autonomous navigation of the satellite, without ground-based tracking.

Aerospace analysts began publishing studies on the problem of navigating geosynchronous satellites with GPS in the 1970s. Key issues included requirements for link closure, advantages over ground systems, autonomous navigation and control, and even formation flying at geosynchronous altitude.

While these studies and others were based on theoretical predictions and numerical simulations, there was little actual flight experience using GPS at geosynchronous altitudes until the Falcon Gold experiment of 1997. Sponsored by the U.S. Air Force Academy, the experiment captured GPS signals in a geosynchronous transfer orbit, which reaches geosynchronous altitude at its highest point. The Falcon Gold experiment consisted of a battery-powered sensor mounted on a Centaur upper stage, which captured small snapshots of radio energy around the GPS carrier frequencies and transmitted them to the ground. Aerospace assisted the Academy by processing this raw data with a special "software GPS receiver." The detection and characterization of several GPS signals in the Falcon Gold data both validated the low-cost hardware approach and verified that GPS signals could be used by spacecraft flying above the GPS constellation.

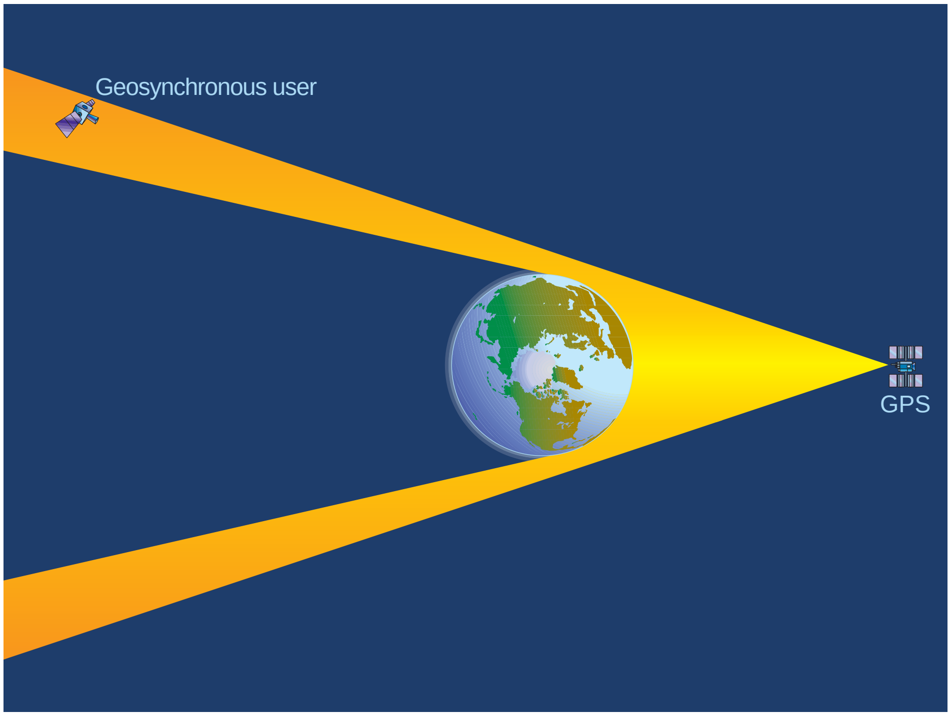
Introducing "Space Service"

In the past, spacecraft users of GPS—especially high-altitude spacecraft users—were not formally recognized as a class of GPS users. While the JPO was aware that many spacecraft were in fact using GPS in experimental or even operational capacities, it was unable to convince the operators of those systems to establish formal requirements like those identified for terrestrial and airborne users. Without this formal recognition from the JPO, spacecraft operators ran the risk that the JPO would modify the GPS signal in ways that would benefit terrestrial users but degrade the service to spacecraft users.

The volume of Aerospace analysis on spacecraft users of GPS, combined with the Falcon Gold results, led to the first formal recognition of spacecraft users in the Joint Requirements Oversight Council Operational Requirements Document for GPS, published in 1999. This formal recognition came with the addition of a "Space Service Volume" to the Operational Requirements Document, dedicated to high-altitude spacecraft users of GPS, which includes the region between low Earth and geosynchronous orbits.

Orbit Determination in the Future

The science of orbit determination has come a long way in 40 years. Starting from an offshoot of astronomy, it has developed



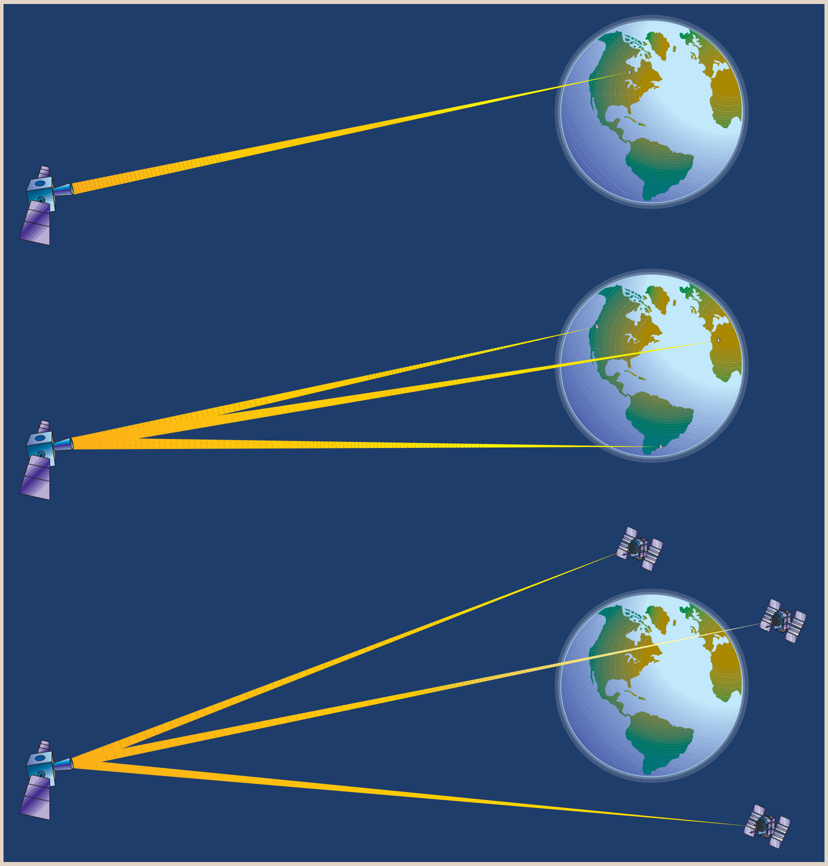
GPS satellite signals are directed toward Earth in a broadcast pattern that is slightly wider than the planet. Thus, a geosynchronous spacecraft on the opposite side of Earth can, with the proper equipment, receive and process the "spillover" GPS signals.

Tracking Geosynchronous Satellites with GPS

The traditional method of orbit determination for a geosynchronous spacecraft is to collect occasional range measurements from a tracking station on the ground. More than one station might be used, but never more than one at a time. Scientists have known this approach would be improved by adding more tracking stations and positioning them as far apart as possible along the circumference of Earth (as seen by the satellite). Unfortunately, many factors make this arrangement impossible. GPS offers a simpler solution.

Viewed from a geosynchronous spacecraft, GPS satellites (on the opposite side of Earth) are positioned somewhat beyond the edge of the planet—providing better tracking geometry than would be possible from any location on the ground. Moreover, the orbital configuration of the GPS constellation ensures that various satellites will be seen at comparatively wide distances from each other, further improving the tracking geometry. Also, in comparison to ground-based stations, GPS satellites exhibit greater relative motion with respect to the geosynchronous satellite.

Of course, a geosynchronous satellite will rarely, if ever, have four GPS satellites in view. Thus, it cannot employ GPS signals the way a user on Earth would. But geosynchronous satellites only use one station in their traditional method of orbit determination anyway, so an absence of more GPS signals is not a deficit.



Viewed from a geosynchronous spacecraft, GPS satellites on the opposite side of Earth are positioned somewhat beyond the edge of the planet—providing better tracking geometry than would be possible from any location on the ground.

into a robust, independent discipline that underlies today's most critical satellite and navigation technologies. Advances in orbit determination led to one of the most successful space programs of all time: the Global Positioning System. Interestingly, GPS itself is becoming the basis of orbit determination for a growing number of space systems—starting with the low Earth orbiting systems and extending even to the geosynchronous regime. With GPS receivers becoming ever more affordable, the odds are increasing that a GPS-based orbit-determination scheme will come along to rival or even supplant the traditional AFSCN-based approach. A global interest in freeing up portions of the valuable S-band spectrum further encourages a migration from AFSCN to GPS.

GPS isn't the only up-and-coming technology for orbit-determination. Laser tracking and optical schemes specifically for higher-altitude orbits are also drawing interest in the scientific community. These approaches promise higher accuracy, reliability, and autonomy for future space systems. Aerospace engineers continually track these emerging technologies, and the TRACE-led suite of Aerospace tools is continuously upgraded to model and analyze them. Thus, as the science of orbit determination continues to evolve, Aerospace will help set the pace and direction of further advances in the field.

Further Reading

F. H. Bauer, K. Hartmann, and E. G. Lightsey, "Spaceborne GPS: Current Status and Future Visions," *Proceedings of ION-GPS-98*, pp. 1493–1508 (Institute of Navigation, Nashville, September 15–18, 1999).

J. Cox, C. C. Chao, P. W. Stephens, and L. F. Warner, "Optical Tracker and S-Band Ranging Utility for Accurate Orbit Determination and Prediction," *Proceedings, AAS/AIAA Space Flight Mechanics Meeting*, Paper AAS 00-116 (January 23–26, 2000).

T. D. Powell, W. A. Feess, and M. D. Menn, "Evaluation of GPS Architecture for High Altitude Spaceborne Users," *Proceedings, Institute of Navigation 54th Annual Meeting*, pp. 157–165 (Denver, June 1–3, 1998).

T. D. Powell, P. D. Martzen, S. B. Sedlacek, C. C. Chao, R. Silva, A. Brown, and G. Belle, "GPS Signals in a Geosynchronous Transfer Orbit: 'Falcon Gold' Data Processing," *Proceedings of the 1999 Institute of Navigation National Technical Meeting*, pp. 575–585 (San Diego, January 25–27, 1999).

T. D. Powell, "The View from Above: GPS on High-Altitude Spacecraft," *GPS World*, pp. 54–64 (October 1999).

The Spaceborne GPS Information Site, http://gauss.gge.unb.ca/grads/sunil/sgps.htm, accessed May 16, 2002.

J. V. Langer, W. A. Feess, K. M. Harrington, M. R. Bacigalupi, R. G. Mach, P. A. M. Abusali, and M. A. Cardoza, "RADCAL: Precision Orbit Determination with a Commercial-Grade GPS Receiver," *Proceedings of the 1994 Institute of Navigation National Technical Meeting* (San Diego, January 1994).

GPS/Inertial Navigation for Precise Weapon Delivery

Anthony Abbott

For centuries, military planners have sought to place a weapon exactly on an intended target. Such accuracy not only helps ensure destruction of the target, it helps prevent collateral damage. While systems have improved throughout the years, the advent of the Global Positioning System has brought a major advancement in precision weapon delivery.

In trying to hit a target with a weapon, the most basic approach is to launch it with the correct initial trajectory and let physics do the rest. This approach, however, is fraught with errors. Even with modern technology, the ability to direct such a weapon is limited by the accuracy of the target coordinates, uncertainties concerning aerodynamics and mass, and many other factors. The process is difficult enough for a stationary launch platform and even more difficult for a moving launch platform, such as a fighter or bomber aircraft. The problem gets even worse if the weapon must be powered for a portion of its flight, as is the case with ballistic or cruise missiles.

The Boeing Company

Aerospace demonstrated potential GPS accuracy enhancement techniques for the Joint Direct Attack Munition (JDAM), widely used in recent military engagements. JDAM uses GPS combined with an inertial system for navigation. Once released, the bomb's INS/GPS will take over and guide the bomb to its target regardless of weather.

Navigation in Weapon Delivery

One of the early devices used to enhance missile accuracy is the Inertial Navigation System or INS. An INS calculates a vehicle's current position, velocity, and attitude by integrating the measurements from the system's inertial measurement unit—essentially a set of accelerometers and gyros. This information can then be used to steer the weapon toward the target. Although an INS improves weapon accuracy, the technique still leaves a significant margin of error, dominated by targeting errors and the buildup of instrument errors over time. Although many clever techniques have been invented to reduce these errors (including many developed at The Aerospace Corporation), the accuracy of weapon systems that rely solely on INS will always be limited.

During the 1960s and 1970s, Aerospace helped implement a new concept for navigation—the Global Positioning System (GPS). The system offers the user remarkable navigation accuracy simply through passive reception of satellite signals. The technology offers several advantages over INS in certain scenarios. For example, INS navigation errors tend to be cumulative, building up over time; but GPS errors tend to be bounded because the error sources (satellite position, velocity and signal propagation errors) are more easily modeled and mitigated. On the other hand, INS has good error performance in the short term, especially under high dynamics; GPS performs best with longer flight times and is less suitable for conditions of high dynamics. Not surprisingly, the two techniques are frequently combined to obtain robust, accurate navigation for demanding military applications.

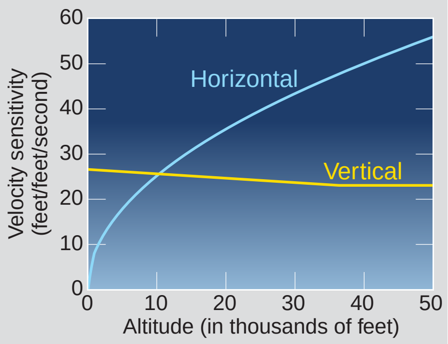
Dumb Bombs

Efforts to calculate the correct release condition for an unguided or "dumb" weapon began in the late 1960s and early 1970s. Again, the basic idea was to launch the missile with the correct trajectory from a moving platform and let physics do the rest. Although the mathematical equations were readily available, the algorithms for the continuously computed release point and continuously computed impact point only became feasible with the advent of microprocessors that were powerful enough to perform such calculations using data from the launch vehicle's navigation system. The first such system used inertial navigation outputs to compute the impact point and

Absolute Coordinates

With accurate real-time navigation information provided by a GPS/INS system, the ability to hit a target becomes limited primarily by inaccurate knowledge of its location. Even though numerous methods can identify the coordinates of a potential target, expressing its position in unambiguous terms had been a problem for decades. Before the advent of GPS, each part of the world had a different map reference that was based on its own Local Datum, which is a local representation of an ellipsoid that was thought to be appropriate for that part of the world. One can imagine the difficulty in determining the absolute target coordinates in a reference system without an accurate absolute definition. One of the first benefits that GPS provided was a method to tie all the maps of the world together in a common frame of reference.

Today, using GPS, one can accurately relate a point on a local map to an absolute reference system. In practical terms, this permits target location and strike functions to be performed in the same absolute coordinate system. Such a system significantly improves targeting accuracy; the small remaining targeting errors are now limited to targeting sensor errors and the variability of GPS errors between the targeting phase and the strike phase. GPS errors are becoming so small that the targeting sensor error will become the dominant remaining error in the future.



This chart shows the degree to which impact error is sensitive to errors in launch-vehicle velocity for dumb bombs without active guidance.

provided steering and release cues to the pilot.

GPS offered a better approach. One of the main objectives of the GPS Phase I program was the precise delivery of dumb bombs. In early tests, the continuously computed release and impact point algorithms were implemented using a four-channel GPS receiver that was integrated with the launch vehicle's inertial measurement unit. By integrating the navigation and weapon delivery functions in the same computer, the two processes could be synchronized, with the weapon delivery function using the current best estimate of navigation parameters (position, velocity, and attitude as well as wind speed and direction) for accurate impact point prediction.

The weapon delivery software was so sophisticated that it actually calculated the impact and release points based on the extrapolated position and velocity. The software would predict the impact point of the weapon if it were dropped at any given moment and compare it to the desired impact point. The impact error would be projected into along-track and cross-track components. The cross-track error drove a deviation display in the cockpit to help the pilot adjust the ground-track angle. The pilot's job was to steer the aircraft to drive the cross-track deviation to zero. At the same time, the along-track error was displayed. This allowed the pilot to judge how close the plane was to the correct release point. As the plane approached the release point, the pilot would arm the automatic release mechanism. The computer issued a release command when the along-track impact error reached zero.

The Phase I weapon delivery system was remarkably successful. The equations of motion for the bombs were fairly

U.S. Department of Defense

These bomb-damage assessment photos show a target in Afghanistan before (left) and after (right) a strike by a B-2 bomber using GATS/JDAM.

U.S. Department of Defense

GATS uses a synthetic aperture radar to determine relative target coordinates and downloads them to the JDAM prior to release.

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Bomb-damage assessment photos showing a target in Afghanistan before (left) and after (right) a strike by a B-2 bomber using GATS/JDAM (GPS-Aided Target System/Joint Direct Attack Munition). Today, thanks to GPS, multiple targets can be destroyed in one pass.

complete, and most error sources were either modeled or mitigated. The primary accuracy limitation was the wind: Although wind speed and direction could be determined at the release point, the wind could change as the weapon fell. Another error source that was difficult to mitigate was the variability in the aerodynamics and mass properties of each bomb. The predicted impact point algorithm had to use average values because it would be impractical to enter the values of each bomb into the operational software. Nonetheless, the program was considered a great success.

Smart Weapons

As impressive as the GPS Phase I weapon delivery test results were, they made clear that accuracy would remain inherently limited unless some intelligence were placed in the bomb itself. The first attempt to make dumb bombs into "smart" guided weapons used an INS and associated fin-actuation system in a tail kit that replaced the normal tail section of the bomb. At the time, GPS receivers were too big to fit in a tail kit. It was thought that with proper initialization from the host vehicle, the bomb's INS could sustain navigation accuracy from the release time to impact. This strategy worked well as long as the launch vehicle had a GPS receiver to initialize the bomb's INS prior to release. Without a GPS receiver on the launch vehicle, the handoff errors were too great for precision bombing, simply because the host vehicle's INS would accrue errors that would be handed off to the weapon during ingress.

The addition of GPS to the launch vehicle allowed it to initialize the bomb's INS with great accuracy. The navigation error buildup during the relatively short descent of the weapon was reasonably good as long as it was initialized properly. This approach, however, would not work well for a standoff weapon because the integrated instrument errors would grow to unacceptable levels during the longer weapon flight time.

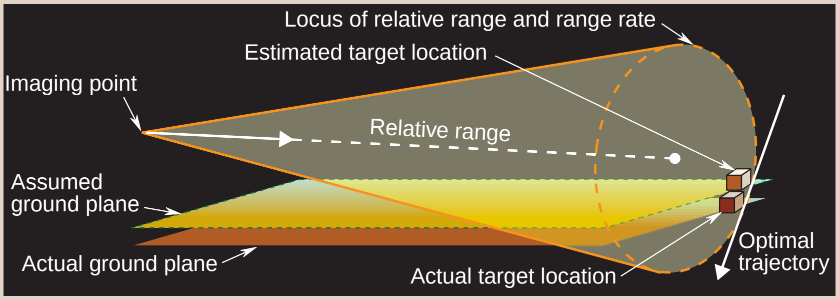
As GPS receivers became smaller, the prospect of placing one in the same tail kit with an inertial measurement unit became feasible. With this concept, as long as the

U.S. Department of Defense

U.S. Department of Defense

Bomb-damage assessment photos. The left photo shows Krivovo support base in Serbia. The strike was performed by a single B-2 at night in complete cloud cover after flying from Whiteman Air Force Base (midway between St. Louis and Kansas City) to Kosovo nonstop. Eight weapons, two per building, were deployed, with offsets in targeted points on each building to spread the damage. Synthetic aperture radar targeting was used just before launching the weapons. The photo to the right shows Shindand airfield in Afghanistan. The strike was carried out by a single B-2 at night after flying from Whiteman Air Force Base to the region nonstop.

Imaging Bias and Relative Targeting Errors



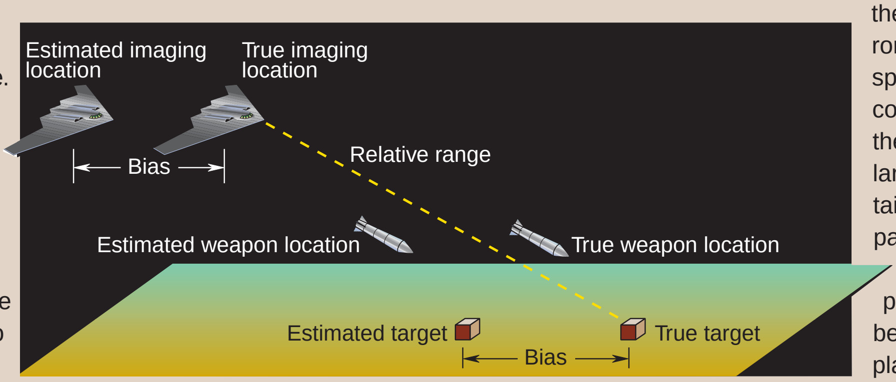
Synthetic aperture radar and the principles of relative targeting. In a typical airborne application, the system transmits microwave radiation and forms an image based on the relative range and range-rate of the reflected energy. When the operator selects a pixel in the image, it is a measure of the relative range and range rate to the target.

The synthetic aperture radar has become a popular targeting sensor in recent years, thanks in part to its ability to “see” through clouds and operate in daytime or night. In a typical airborne application, the system transmits microwave radiation and forms an image based on the relative range and range-rate of the reflected energy.

If this process is used to identify targets prior to a military strike, measures must be taken to prevent an unacceptable increase in target location error. If the targeting vehicle’s navigation system has a position bias, that same bias will affect the estimate of the target coordinates because the range and range-rate measurements are relative to the estimated position of the radar’s antenna at imaging time. Velocity errors will also produce targeting errors. The key to managing navigation errors for targeting is to keep the position error as constant as possible and the velocity error as close to zero as possible during imaging. This will produce an error in the target position estimate that is very close to the position error of the targeting vehicle at imaging time.

Such control of position and velocity errors is possible with GPS, assuming proper satellite selection before and during the imaging period. If the satellite selection is frozen to the same four satellites during imaging, the range error would stay roughly the same because the satellite geometry would not appreciably change during that time. Because the position error is nearly constant, the velocity errors approach zero. Proper filtering of the GPS measurements and the use of a high-quality INS achieves extremely stable position errors and velocity errors almost too small to measure.

One of the benefits of using synthetic aperture radar in conjunction with GPS/INS guidance is that the weapon can be made to approach the target from a preferred direction to minimize any residual targeting errors. In fact, one can predict the three-dimensional targeting error ellipsoid by knowing the location and velocity vector of the targeting vehicle at each synthetic aperture radar imaging time. One direction usually has a larger targeting error uncertainty due to the projection of synthetic aperture radar errors into the targeting space. If the weapon is controlled to approach the target along this largest direction of uncertainty, the resulting impact error can be minimized. This error projection property can be very useful in mission planning if the target requires a preferred approach angle—such as a tunnel entrance.



Since the synthetic aperture radar measures the relative range and range rate to the target, it will have a bias in the target coordinate estimate. The weapon can be forced to incur the same bias by suitable satellite selection.

target coordinates could be determined using GPS, the impact error could be driven quite low. The impact error would be dominated by the targeting error and the GPS error during the weapon’s flight time. The error buildup of the INS would be essentially removed—which is particularly attractive for standoff weapons with long flight times.

Of course, if the weapon uses a GPS receiver, the launch vehicle must provide the necessary GPS handoff information (in addition to the INS transfer alignment information). This handoff information usually consists of initial position, time, and velocity, as well as the GPS satellite orbital data. This information is especially critical for a weapon with a short flight time because it must obtain a GPS fix well in advance of ground impact to steer out the residual INS error buildup. Typically, the weapon requires enough information from the launch vehicle to acquire and track the GPS satellites within several seconds after release.

For older weapons, the GPS receiver uses the coarse acquisition (C/A) code to acquire the signal and then switches to the military P(Y) code. Although the C/A code provides the easiest way to acquire the GPS signals, it is also more vulnerable to jamming. Most modern weapons use (or will use) direct P(Y) code acquisition for better antijam protection. Direct P(Y) acquisition requires more careful host-vehicle integration because the weapon must have knowledge of time to within several milliseconds in order to search the range and range-rate uncertainties through its direct-acquisition application-specific integrated circuit chip. A time transfer from the host vehicle’s GPS receiver to the weapon’s GPS receiver via the flight management and the weapons management subsystems usually accommodates this time initialization.

The conventional air-launched cruise missile is guided by GPS. GPS accuracy can be improved using a variety of augmentation systems, such as differential GPS and wide-area differential enhancement.

U.S. Air Force

The difficulty in accurate time transfer to the weapon is more a matter of economics than technology. Without an appropriate direct-acquisition chip in the GPS receiver, direct P(Y) acquisition requires initial knowledge of time to an accuracy on the order of tens of microseconds. To send a time pulse with this accuracy requires a high-bandwidth line to each weapon. This can be expensive to install. On the other hand, if the weapon has a direct-acquisition chip, the receiver can tolerate a time uncertainty on the order of a few milliseconds for direct acquisition of the P(Y) code. Accuracy on this level can be accomplished with a standard serial interface, if care is taken during the design of the software message protocol. Hence, many contractors have chosen not to install the high-bandwidth line in favor of using a weapon with a direct acquisition capability. As integrated circuits improve, the time accuracy requirement should diminish further without sacrificing antijam performance.

Integrated Systems

As long as the targeting function is performed independently of the strike function, the associated error contributions from each of these functions will be additive. Moreover, the GPS contribution to the targeting error could be different than the GPS contribution to the strike system error if the time delay between targeting and strike is more than 10 or 20 minutes. With proper systems engineering, however, such concerns can be minimized.

For example, a complete system can be designed more optimally than a series of optimally designed individual subsystems all functioning together. Weapon delivery is no exception. In the case of GPS/INS weapons, integration of the targeting and strike functions at the system level enables certain design choices that are not possible when each subsystem is independently conceived.

Designers have known for years that errors in the GPS measurements are temporally and spatially correlated—partly due to the design of GPS, and partly due to errors in signal propagation through the ionosphere and troposphere. This error correlation could be exploited through a system-level design that uses the same satellites in the targeting and strike functions.

Thanks to the very long distance from the navigator to each of the GPS satellites, the relative geometry of all GPS navigators in the same vicinity (such as a vehicle on the ground and an airplane flying above it) is similar. Hence, they will all experience essentially the same range measurement errors. The correlation is especially high if all navigators use the same four satellites. In fact, even some of the atmospheric errors, such as ionospheric propagation delay, are spatially correlated over significant distances. Hence, using the same satellites in the targeting function and the strike function offers error correlations that can be exploited to improve accuracy.

The temporal correlation of errors becomes important when the targeting and strike phases must remain separate. Again, the property of the GPS ephemeris errors is such that, except for ephemeris updates, the range error from an imperfect ephemeris is highly time correlated. This temporal correlation can be exploited to minimize errors if the time from the targeting phase to the strike phase is on the order of several minutes. The temporal correlation of atmospheric propagation errors also works in the favor of accuracy if their correlation properties are exploited.

Without a systems approach to the entire problem, targeting errors would be a major contributor to the weapon's overall impact error budget. Proper integration of the targeting function and the weapon navigation function is ultimately responsible for complete system accuracy. The key to achieving very small weapon impact error is to force the weapon's navigation system to incur nearly the same errors as the targeting vehicle. This is one of the few instances in life where two wrongs make a right.

The techniques used to ensure that the weapon makes the same errors are straightforward, but many practical design choices must be made to ensure this behavior under all circumstances. The first step is to force the weapon to use the same four satellites that the targeting vehicle used. The weapon should also use the same ephemerides and ionospheric compensation calculations as the targeting vehicle. Given these design choices, the weapon will achieve the same position biases as the targeting vehicle, and the impact error will be dictated by other error sources that are more random in character.

As weapons are reduced in lethality, the accuracy of the impact point must become even greater to ensure target kill.

Future Trends

Although GPS-based relative navigation systems are capable of impressive accuracy even with substantial GPS position biases, there's still room for improvement. In the future, absolute navigation using GPS will probably be so accurate that relative navigation will no longer be required. Future conflicts will probably rely on smaller munitions (250 to 500 pounds) to minimize collateral damage. As weapons are reduced in lethality, the accuracy of the impact point must become even greater to ensure target kill.

GPS/INS-guided weapons are very effective against stationary targets, but many adversaries have adopted defensive strategies that involve constant movement. This challenge is being addressed by numerous studies, which have shown that GPS/INS delivery techniques can still work if some adjustments are made—specifically in terms of calculating the revised target coordinates and transmitting them to the weapon in flight. Several methods could be used to send updated coordinates to the weapon—for example, updated target coordinates could be sent to the weapon with a new signal. This approach would allow the weapon to receive and decode the updated target coordinates and send them to the guidance function within the weapon's computer. Aerospace is studying possibilities such as this.

Aerospace is also investigating a number of methods for detecting moving targets and estimating their coordinates. Some types of synthetic-aperture radar are already capable of indicating moving targets on the ground. Current methods cannot yet establish an unambiguous target track with high confidence and accuracy, but considerable research is under way to perfect this capability.

One of the most stringent requirements associated with moving targets is the latency of the updated targeting data. If the target is traveling in a predictable path—along a straight line or a digitally mapped road, for example—this problem can be resolved with a more relaxed latency requirement by using track filtering and prediction algorithms. If the target is in an open area and is capable of "jinking" maneuvers, the latency requirement becomes far more demanding. Hence, the need for frequent updates in the targeting data may drive the system architecture. For example, the same vehicle that launched the weapon might have to perform the targeting update function and send the data directly to the missile over a radio link.

Summary

GPS and INS technology work extremely well together to provide the high accuracy and robustness needed for modern weapon delivery systems. As targeting technology improves, the integration of the targeting function into the weapon delivery system should result in spectacular accuracy not only for stationary targets but for moving targets as well. By properly integrating timely, accurate targeting information with the postlaunch guidance and navigation functions, a major advance in future weapon delivery capabilities will be possible.

GPS for Stealth Bombing

Although separate vehicles can be used for targeting and strike functions, a single vehicle can often do the job more efficiently and reliably.

The B-2, for example, has several unique attributes that are particularly useful for integrated targeting and delivery of GPS/INS-guided bombs. The first is its long range and large payload capacity. One B-2 can take off from the continental United States with sixteen 2000-pound bombs and deliver them halfway around the world on sixteen different target points or all on the same target point. (In fact, the B-2 dropped two bombs on the same point during a test drop from an altitude of over 12 kilometers in April 1998.)

The second noteworthy attribute is its stealth. The craft can perform targeting during ingress, reach the target without detection by enemy radar, and perform "launch and leave" weapon drops during day or night even under complete cloud cover.

These features—together with the highly accurate stellar-inertial navigation system, synthetic-aperture radar, and weapon delivery subsystem—contributed to the success of the B-2 in missions over Kosovo and Afghanistan.

Although 2000-pound bombs can be used on most targets, there are some hardened targets—such as deeply buried bunkers—that require special weaponry. All the concepts and features relating to conventional munitions can also be applied to "bunker busting." If the tail kit assembly used on a bunker buster has enough control authority (in terms of fin actuator torque and fin surface area), a bunker-buster bomb can not only pinpoint a target, but also penetrate the ground to a prescribed depth before detonating its explosive charge. Obviously, accuracy is critical for a bunker-buster bomb. With GPS-based radar targeting and a GPS/INS navigation tail kit, the accuracy can be assured along with a high confidence of no collateral damage.

Antijamming and GPS for Critical Military Applications

Anthony Abbott

The Department of Defense is working hard to enhance the jam resistance of its GPS-based systems. Recent research at Aerospace has yielded promising results.

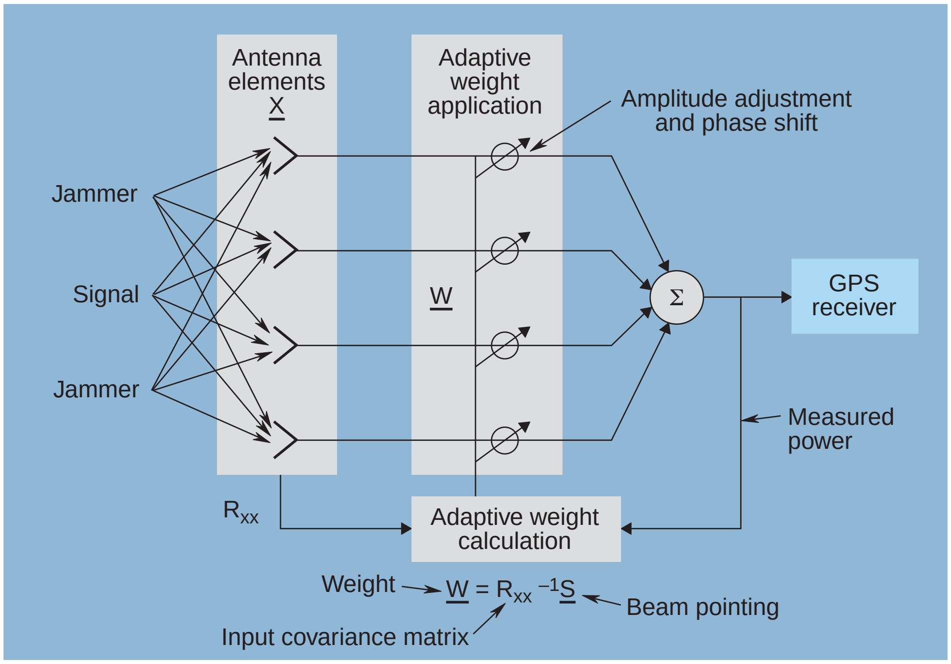
The Global Positioning System (GPS) has become an essential part of the military infrastructure. For that reason, it presents a target for adversaries wishing to undermine the ability of the United States and its allies to conduct military operations. Although the GPS spread-spectrum signal offers some inherent antijam protection, an adversary who is determined to negate a GPS system need only generate a jamming signal with enough power and suitable temporal/spectral signature to deny the use of GPS throughout a given threat area. The reason for this problem is clear: GPS satellites produce low-power signals that must travel great distances to reach the receiver. A jammer, on the other hand, can produce a stronger signal much closer to the receiver, and since signal power diminishes as the square of the distance traveled, the jammer has a distinct advantage.

This vulnerability has been identified as a high priority within the Department of Defense (DOD), and numerous programs have been established to develop near-term solutions for today's potential threats and more extensive long-term solutions for projected future threats. The Aerospace Corporation has been spearheading many of these development efforts.

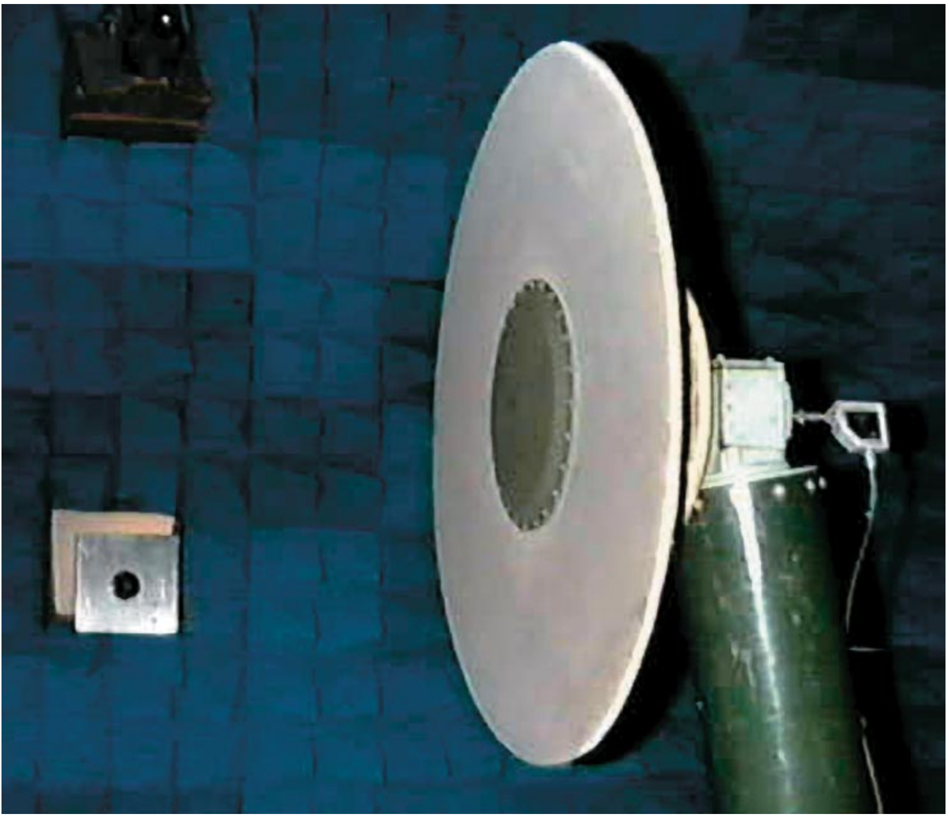
Traditional Approaches

The first system developed to increase GPS antijam capability for users on the ground or in the air was the controlled reception pattern antenna. This device consists of an array of six antenna elements arranged in a hexagon around a central reference element. The elements are all connected to an electronics box that controls the phase and gain (or *complex weights*) of each element's output and combines the seven elements into a single output. This signal processing produces an adaptive gain pattern that can be manipulated to place a null in the direction of an undesired signal source. The underlying principle is fairly straightforward: Received GPS signals are rather weak and cannot be detected or measured without a signal-correlation process; therefore, the processing algorithm assumes that any measurable energy above the ambient noise must be a jamming signal, and so it computes the necessary weights to null the source.

Aerospace has been at the forefront of improving the performance and robustness of the adaptive processing algorithms for three decades. Still, certain factors limit the usefulness of these antennas for some vehicles. Controlled reception pattern antenna arrays are physically quite large (on the order of 35 centimeters in diameter) and generally cannot be used, for example, on small missiles that lack the necessary mounting space. In addition, a controlled reception pattern antenna can only counter a limited number of jammers, as it eventually runs out of "degrees of freedom" or antijamming options when the number of spatially distributed jammers grows too great. This is because the array must use at least two elements to null one jammer. Hence, as a rule of thumb, *n* elements can



A generic adaptive-array processing scheme. Signals from the antenna array are prioritized or "weighted" before being combined and processed by the GPS receiver.



Air Force Research Laboratory

A jam-resistant GPS antenna undergoes testing at the Air Force Research Laboratory.

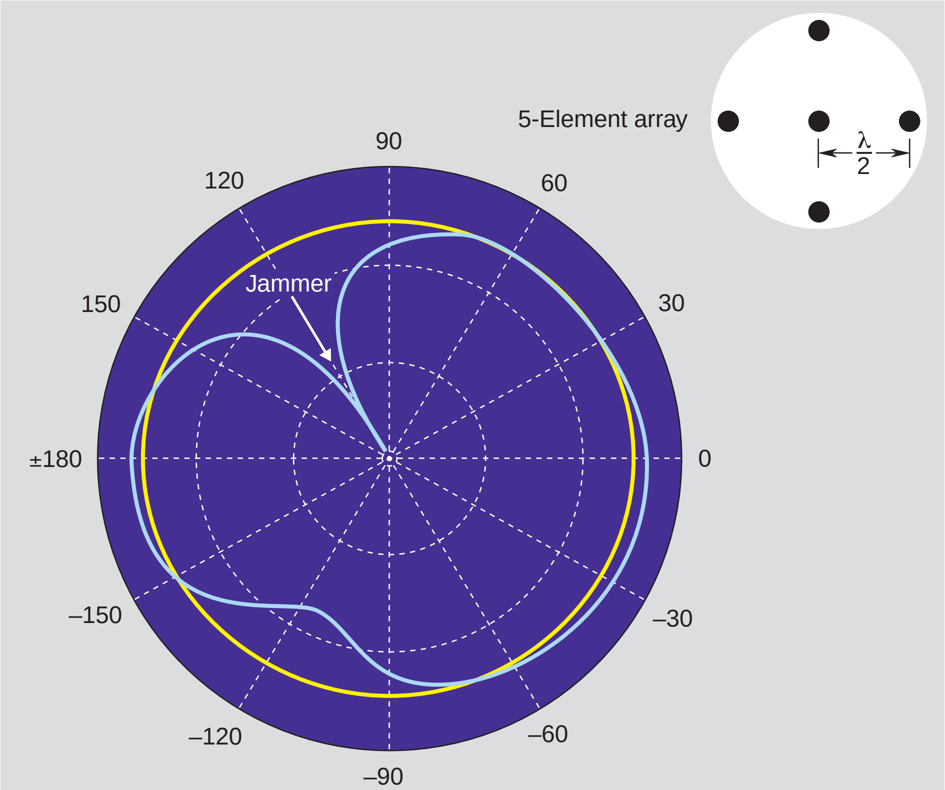
null $n-1$ jammers. Moreover, the antenna must devote a degree of freedom to a jammer regardless of the jammer type (broadband or narrowband). This approach is less effective than other, more advanced processing techniques that can attack a broadband jammer with spatial resources and a narrowband jammer with time/frequency resources.

Various alternatives are being researched as part of the GPS Modernization and Navwar programs. Aerospace is working closely with the GPS Joint Program Office, other federally funded research and development organizations, and the various DOD laboratories to identify several mutually synergistic antijam techniques to meet current and projected threats. The most obvious approach to increase antijam performance is to increase the transmitted power from the GPS satellites. Although the GPS Modernization program will increase satellite power, this approach alone will not provide the entire antijam performance that is required. It is therefore necessary to provide additional antijam capability from the user equipment. Basically, these user equipment techniques fall into two categories: those that reduce the jammer power while retaining or amplifying the GPS signal and those that increase the signal-to-noise ratio through advanced signal processing in the receiver (i.e., processing gain).

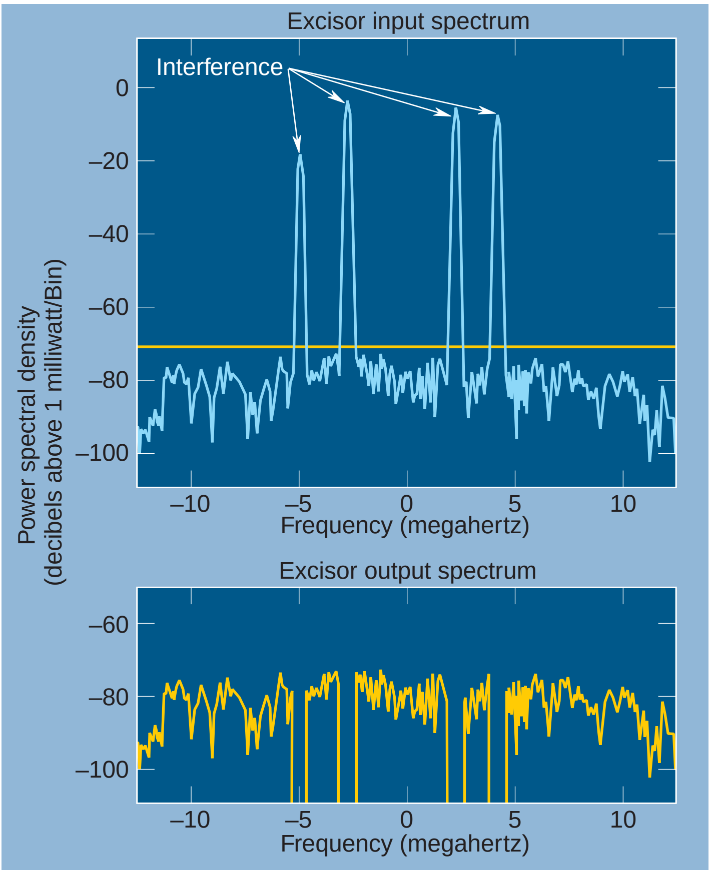
No one method is right for all circumstances because each application presents its own unique requirements and constraints. Moreover, a given technique may be effective against a particular class of threats, but may not necessarily address all threats. For example, an adaptive narrowband filter is effective against a jammer that has some repetitive or predictable signal structure, but is ineffective against a broadband noise jammer, whose signal cannot be predicted from previous samples. Likewise, spatial adaptive antenna arrays are effective against a limited number of broadband noise and structured signal jammers, but eventually run out of degrees of freedom as the number of jammers increases.

Jammer Signal Power Reduction

Among the advanced techniques for reducing jammer power, the most promising employs a technology that was originally

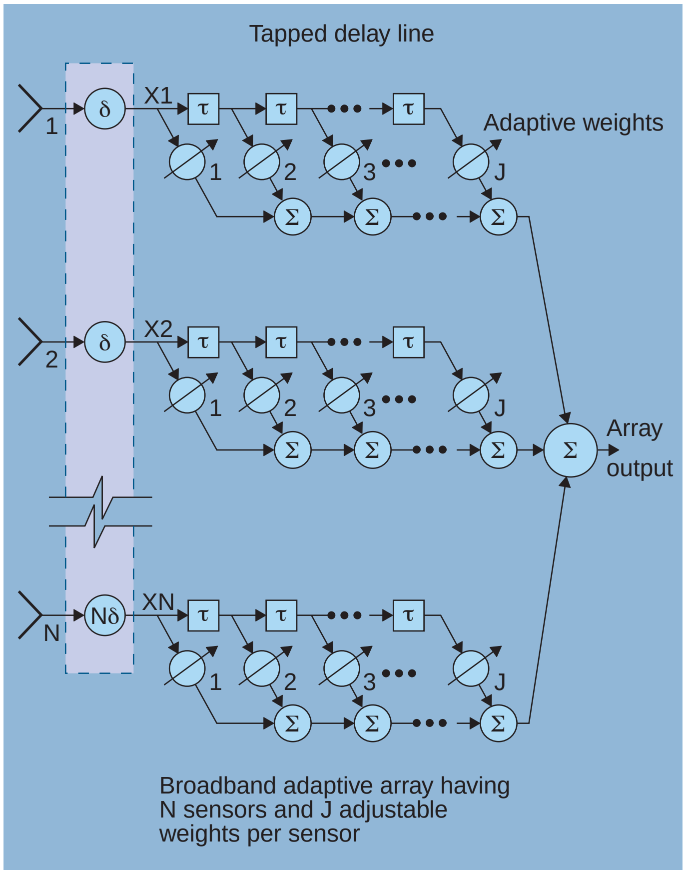


In a power-inversion array antenna, the individual elements are geometrically arranged with an interelement spacing of one-half a GPS carrier wavelength. This arrangement is useful for applications where the desired signal is weak and the interference is strong.



The MITRE Corporation

Structured interference signals can be removed via time- or frequency-domain processing techniques. The top figure shows the input power spectrum of a GPS signal with four continuous-wave jammers present. The bottom figure shows the output power spectrum of a frequency excision filter developed at MITRE. This processing can be implemented in real time.



Space-time adaptive processing can be effective in combatting multiple jammers. In this technique, the output of each element in a phased array is delayed slightly longer than the one that preceded it. The output of each is available as a separate signal, and each can be processed with a unique weight and combined into a composite signal.

developed for radar, called space-time adaptive processing. With this technique, the output of each antenna array element is delayed using a series of tapped delay lines, each stage of which outputs a version of the input signal slightly later than the previous stage. The output of each tap is available as a separate signal, and each can be processed with a unique complex weight and combined into a composite signal. A close variant of this technique, called space-frequency adaptive processing, performs equivalent processing in the frequency domain.

These techniques show promise because they optimally attack multiple jammers with a coordinated use of spatial and temporal resources. Although space-time adaptive processing and space-frequency adaptive processing can also run out of degrees of freedom, they can counteract many more jammers of various types before reaching their limits because there are $n \times m$ choices of weights, where n is the number of elements and m is the number of taps on each element.

A very similar antijamming technique—actually a subset of space-time and space-frequency adaptive processsing—is known as adaptive narrowband filtering. Adaptive narrowband filters work with a single antenna element, so they are typically used in applications that lack sufficient space for a spatial antenna array. They are effective against structured interference signals, such as continuous (e.g., sine) waves or pulsed signals, but they are ineffective against broadband interference, which does not have an identifying signature that can be tracked and eliminated. Adaptive narrowband filters can operate in the frequency domain, time domain, or amplitude domain.

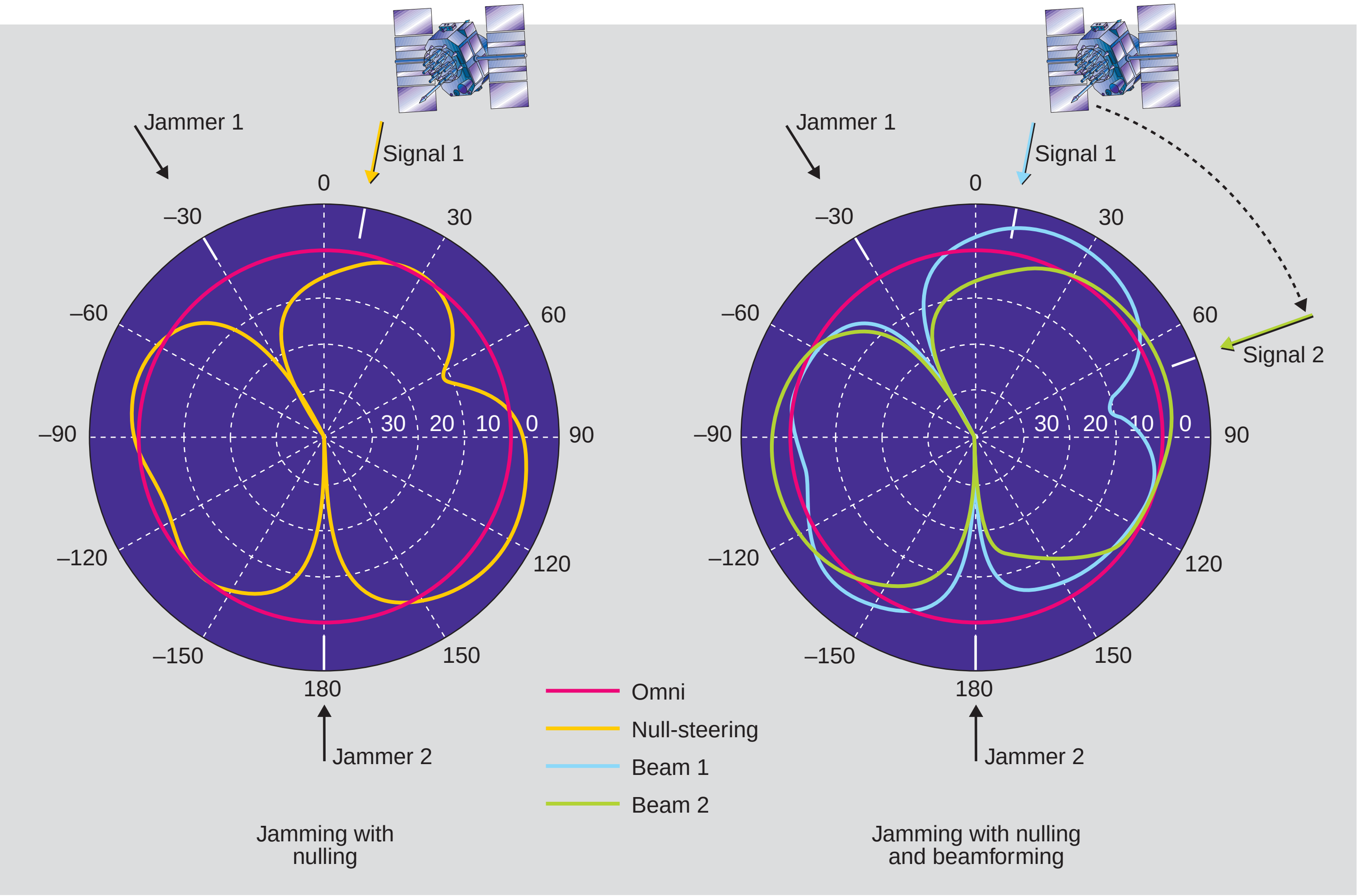
As with the controlled reception pattern antenna, conventional space-time and space-frequency adaptive processing systems attempt to minimize measured power under the assumption that any measured power must be a jamming signal. The weakness in that strategy is that the GPS signal may also be attenuated if the processing algorithm does not consider the direction from which the GPS signal arrives. This weakness can be overcome through additional beam steering or beamforming. Although these two techniques attempt to accomplish the same result, they do so by completely different strategies.

Beam steering uses the direction to the desired satellite as an additional constraint on the complex weight applied to each tap output. To perform these calculations, the processor needs to know the direction to the desired GPS satellite and the position and attitude of the host vehicle.

Beam steering is a “precorrelation” technique, meaning it does not require GPS signal detection to compute the phase and gain for each tap on each array element. Beamforming, on the other hand, is a “postcorrelation” technique, meaning it attempts to maximize the signal-to-noise ratio after signal capture. Both techniques maximize the GPS signal while simultaneously minimizing the jammer power for multiple jammers of various types.

Processing Gain

The second major antijamming strategy involves processing gain improvement. The



Raytheon Company

Beamforming improves antenna gain in the direction of the GPS satellite. The image to the left shows how adaptive nulling can neutralize jamming signals. The image to the right shows how beamforming works with the nuller to neutralize jammer signals while strengthening satellite signals.

GPS spread-spectrum signal derives some inherent jam protection from the "despreading" process, which converts it from a 20-megahertz bandwidth to a narrower bandwidth. Signal power grows stronger as bandwidth is reduced, so for maximum antijam performance, the narrowest possible bandwidth should be used in the despreading process.

Just how narrow the bandwidth can be depends in part on the design of the code and carrier tracking loops used by the GPS receiver and the dynamic operating environment. Recall that a GPS receiver gets a signal from a satellite, generates a local copy, and compares the two to derive range and range-rate measurements. The tracking loops try to maintain a "lock" on the satellite signal by driving the difference in the signals (as measured by the signal correlator) to zero.

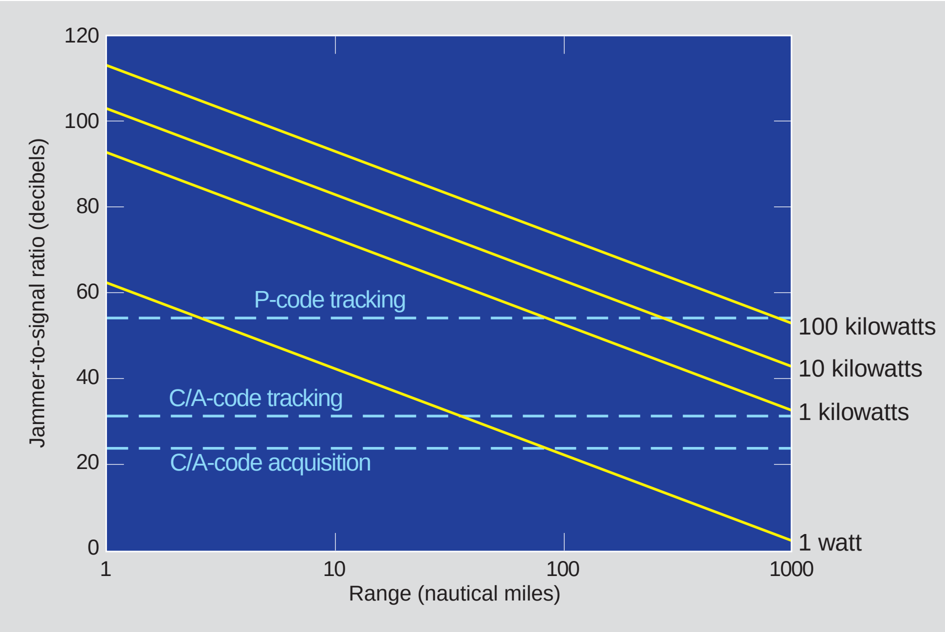
In general, greater antijam performance can be achieved by narrowing the bandwidth of these code and carrier tracking loops. Unfortunately, narrow tracking-loop bandwidths imply sluggish response time, and if a vehicle is undergoing high acceleration, the narrow-bandwidth tracking loop cannot keep pace. If the tracking-loop bandwidth were widened, it would be more responsive to high acceleration, but it would not filter the noise as effectively.

One solution is to aid the tracking loops by supplying information about the vehicle's acceleration and the motion of the satellite to be tracked. This information could be supplied, for example, by an inertial navigation system and the GPS satellite almanac. With this supplemental information, the receiver's tracking loops can anticipate the dynamics along the line-of-sight to the satellite and use a narrow-bandwidth filter to process the fresh outputs from the signal correlators. If the aiding information is reasonably accurate, the bandwidth of the tracking loop can be narrowed because it will only need to track the errors in the aiding information (which vary slowly over time), rather than the absolute motion of the antenna.

The aided tracking loop, with its narrower bandwidth, provides more processing gain and more protection against jamming; however, it's still not enough to thwart a very strong jammer that may be close to the GPS navigation set. The limitations of aided tracking loops are more practical than theoretical: In actual implementation, the aiding information will contain numerous errors.

The most notable errors arise from two sources: imperfect implementation of the aiding data interface, and the inconsistency of the motion between the aiding sensor and the GPS antenna or "lever arm." (In most vehicles, the antenna and the aiding sensors are in different locations, and "lever-arm" compensation must be provided because the GPS antenna is not sensing the same motion as the aiding sensors.)

The first error source, the data interface, exists because traditional receivers are designed to use whatever inertial measurement unit is present on the host vehicle. (An inertial measurement unit—or IMU—is a set of gyros and accelerometers that feed the inertial navigation system in an



This graph shows the effects of jamming on unprotected GPS performance. For example, at a jammer-to-signal ratio of about 55 decibels, a jammer located about 100 nautical miles from the receiver could jam the GPS signal through a 1-kilowatt signal. At 1000 nautical miles, 100 kilowatts would be required.

aircraft or missile.) The GPS receiver and the host vehicle communicate over an asynchronous serial bus, and the designer of the GPS receiver usually does not accept the IMU data without “deweighting” it in some manner. This deweighting process can limit the achieved bandwidth reduction below theoretical levels and hence limit the antijam performance.

The second error source, lever-arm compensation, is unavoidable if the GPS antenna is not located with the IMU. Unfortunately, many factors—such as vehicle attitude, vehicle rotation, and body flexure—prevent perfect lever-arm compensation, even when the IMU *is* situated in the same box as the receiver. Hence, the bandwidth of the tracking loops must be wide enough to maintain GPS signal lock despite these factors—and this limits the antijam performance. In some applications, such as small weapons, the antenna is naturally close to the IMU and the body is rigid, so the lever-arm compensation is not as significant an error source as it is in avionics applications.

New Approaches

To meet the future challenge of GPS applications that must operate in projected jamming environments, the GPS Joint Program Office is pursuing several promising technologies and a future GPS set architecture that will yield further improvements in antijam performance. Aerospace is actively involved in defining advanced architectures and technologies that will economically provide better antijam performance. Two approaches in particular are generating considerable interest in the field.

Microelectromechanics

With the recent advances in microelectromechanical systems, new architecture concepts that were unimaginable five years ago have now come within reach. One such technology, the microelectromechanical IMU, will have a significant impact on the future design of user navigation sets.

As noted, the best way to reduce the bandwidth of the tracking loops (and thus improve antijam performance) is to keep the GPS antenna and the IMU together, thereby forcing the lever arm to zero. This placement eliminates the need for the lever-arm correction and its associated errors. Of course, when IMUs were first invented, they were very large, and although they’ve become smaller over the years, they remain large enough to require special attention concerning their placement in a host vehicle or missile. The ability to place an IMU in the same box with the GPS receiver was viewed as a significant step forward. But until recently, no one considered the possibility of embedding the IMU in the antenna itself.

That is precisely the thinking now being pursued under the leadership of Aerospace. The cost, size, and performance of microelectromechanical IMUs are improving to the point where they’ll soon be good enough to embed in a GPS antenna. This new architecture overcomes many of the factors that prevented the narrowing of tracking-loop bandwidths in older systems. For example, because the IMU would be dedicated to the GPS set, a synchronous interface between the two could be designed with proper attention to interface errors and data latency. In addition, the placement of the IMU with the GPS antenna would make both sensors experience the same motion, so there would be no need for lever-arm compensation with its associated errors.

Although the accuracy of microelectromechanical IMUs cannot compete with more traditional technologies (such as those that use ring-laser gyros), accuracy is reaching a level that is adequate for aiding GPS. Extremely high accuracy is not required if the IMU error sources are reasonably stable because the navigation processing algorithm constantly estimates these low-bandwidth error sources and compensates accordingly.

In other words, it’s the short-term stability of these instrument error sources that’s important for aiding GPS. And although short-term stability errors can be sensitive to temperature and acceleration, compensation models whose coefficients are calibrated prior to operation can usually mitigate their effects. So, for short periods of time, errors in the microelectromechanical IMU approach acceptable levels for aiding GPS.

It should be noted that the microelectromechanical IMU is not meant to replace the IMU that may be present in the host vehicle. If there is a need for inertial navigation accuracy without GPS, then the microelectromechanical IMU would probably not satisfy that requirement. The microelectromechanical IMU is intended as part of the GPS navigation set (notice that the word “receiver” has not been used), and is present in the GPS antenna regardless of whether there is a need for an IMU by the host vehicle.

Ultratight GPS/Inertial Coupling

Another technology has recently emerged to address the need for antijam performance. This new technique, called ultratight GPS/inertial coupling, is a different method to jointly process GPS and IMU data. Several organizations throughout the United States have been performing research in this area, either through independent research and development funds or DOD research contracts. Although each approach is unique in its implementation, they all share certain common traits. For example, they all eliminate the code and carrier tracking operations, which are susceptible to jamming even when aided. All use estimated navigation parameters to generate the local replica signal needed to track the satellite signal. All directly use the correlator outputs (i.e., comparisons of the local and satellite signals) to compute the range and range-rate errors for the navigation processing algorithm.

Aerospace is an industry leader in ultratight coupling. Four years ago, Aerospace began to develop its formulation of ultratight coupling and filed for a U.S. patent. About the same time, Aerospace became aware of similar research being conducted at other companies and other patents that were pending. When the antijam potential of this processing approach was determined, Aerospace was instrumental in obtaining interest at the various DOD research laboratories to fund development programs.

Today, virtually all GPS vendors to DOD have contracts to pursue some sort of ultratight coupling. A milestone was reached in November 2001 when the first official government-sponsored test of an ultratight coupling formulation was conducted at Eglin Air Force Base. The antijam performance was slightly better than predicted. The test results essentially confirmed the performance that had been predicted at Aerospace using simulations. Currently, the Aerospace formulation is being implemented in a real-time computer. One GPS vendor has asked to license the Aerospace formulation, and many other companies are using it for studies.

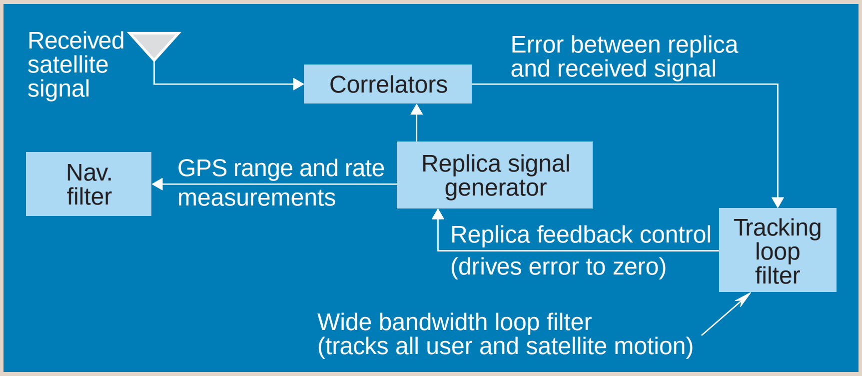
Summary

Future GPS systems—particularly for weapon delivery—will benefit from the optimal integration of GPS receivers with inertial measurement units and the use of adaptive processing algorithms and antennas that reject unwanted signal interference while maximizing the power of the desired satellite signal. The combination of all these technologies and the associated system architecture will be the blueprint for DOD GPS sets for the next several decades.

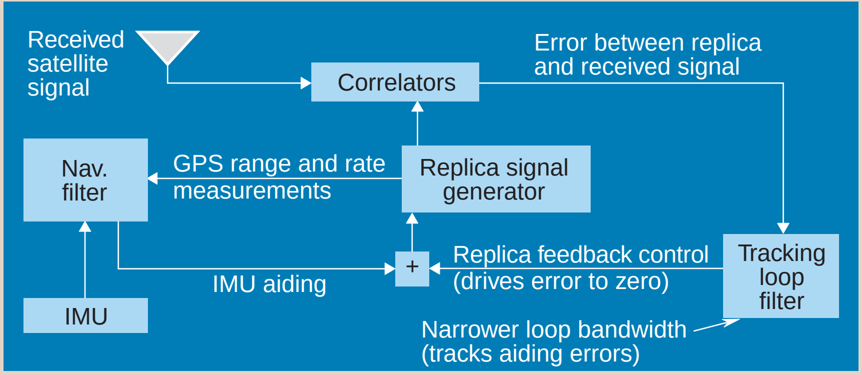
Many of the GPS antijam techniques and architectures that will be used in future equipment have roots at Aerospace, which has been the technical conscience of the program since its inception.

GPS/Inertial Coupling

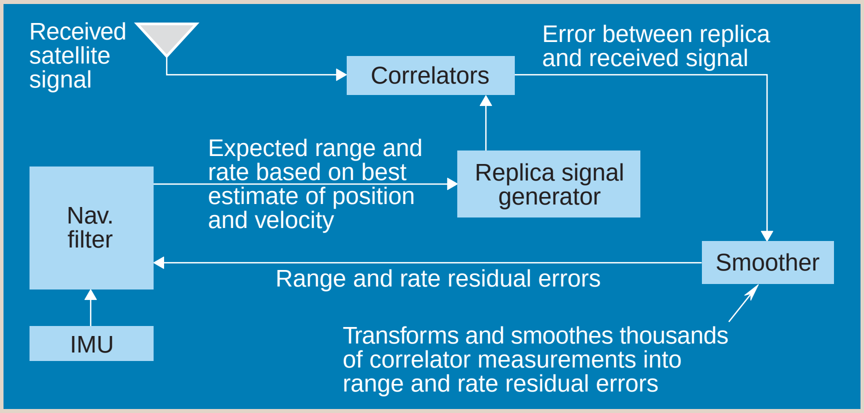
Unaided



Aided with tight GPS/IMU coupling



Aided with ultratight coupling



Ultratight coupling is an effective way of integrating raw GPS measurements with raw inertial measurement unit (IMU) measurements. The technique eliminates conventional code and carrier tracking loops and many of their associated limitations. Instead, navigation measurements are obtained directly from the raw received GPS signals. Long measurement-smoothing times can reduce the effective bandwidth of the processing, thereby improving antijam performance and accuracy. With conventional unaided tracking loops (top), the wide bandwidth loop filter tracks all user and satellite motion. In a tightly coupled GPS/IMU tracking loop (middle), a narrower loop bandwidth is used to track errors in IMU, providing more noise rejection (and jam suppression). With ultratight coupling (bottom), a smoother transforms and smoothes thousands of correlator measurements into range and rate residual errors.

Modernization and the Move to GPS III

Steven Lazar

The numerous critical applications and infrastructures that have come to rely on GPS will require changes that cannot be accommodated by the system as originally conceived. Aerospace has been instrumental in defining a new system architecture that will assure that military, civilian, and commercial needs are met far into the future.

Enhancements to the Global Positioning System (GPS) have historically been driven both by technological advances and by user demand. The atomic frequency standard in the navigation payload has improved over the years, yielding a nearly threefold increase in ranging accuracy over original specifications. Hardware and software upgrades to the operational control segment have steadily reduced the positioning and timing errors attributable to satellite orbit determination. Rapid growth in the civilian market has spurred remarkable improvements in the performance, size, and cost of user equipment. Whole industries have sprung up to provide augmentation services to niche markets that will eventually include commercial aviation and maritime administration.

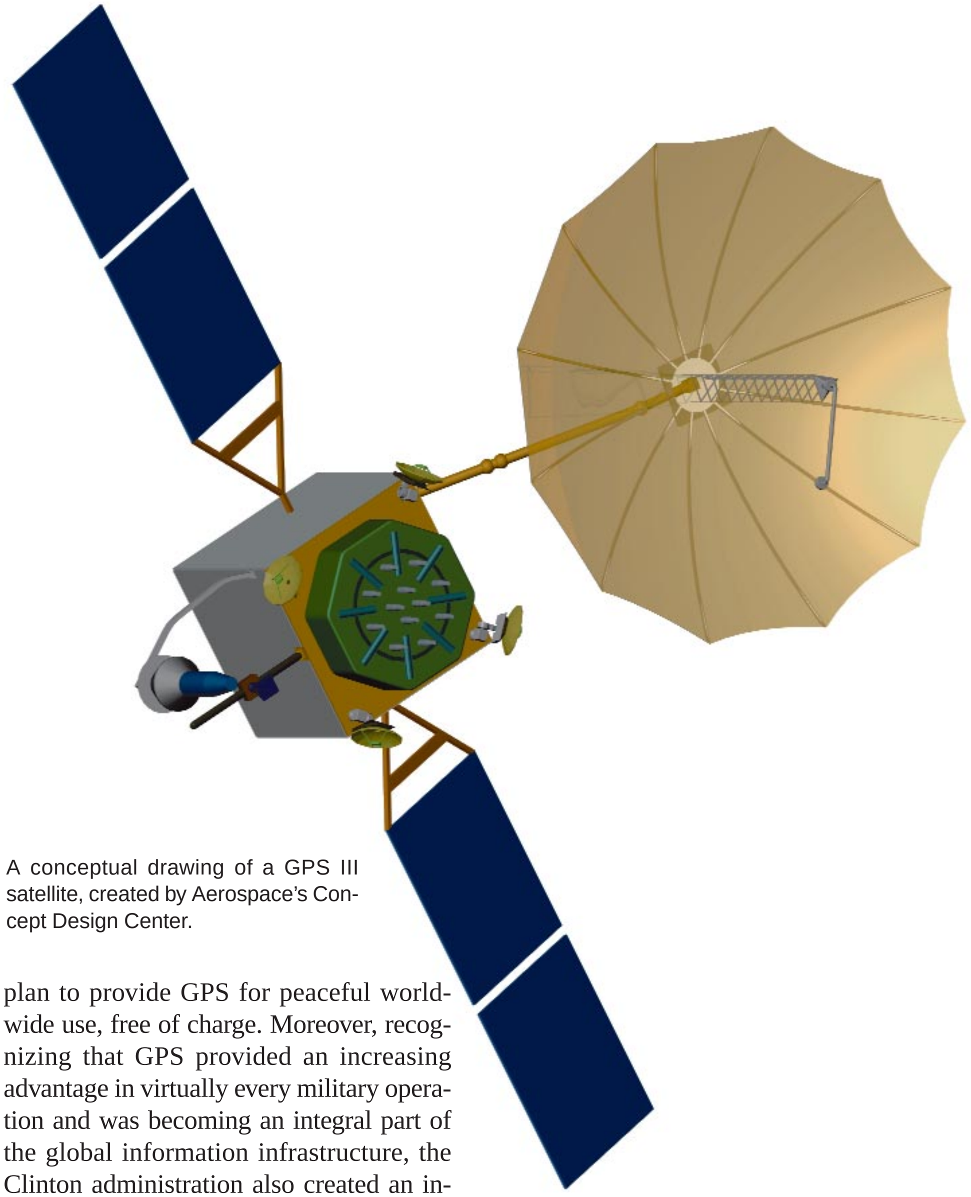
Nevertheless, the numerous critical applications that have come to rely on GPS will require changes that cannot be accommodated by the system as originally defined. For instance, efforts to modernize the second-generation (Block II) system focused on enhancing the space and control segments through retrofits to the original design, but these initiatives do not go far enough; rather, a substantially different approach will be needed to keep pace with the exponential growth in civil and commercial applications that rely on GPS balanced with the increasingly rigorous demands on the military side.

Block IIR satellite. The first launch in this series took place on July 22, 1997. Of the 21 planned satellites, 6 healthy units are in orbit, 1 suffered a launch failure, and 14 have not yet been launched. The first “modernized” Block IIR is scheduled to launch in 2003.

History of Modernization

The shift in GPS from an essentially military application to a dual-use system can be traced back to 1983, when Soviet fighter jets shot down a civilian passenger plane that had strayed into Soviet airspace. In response, President Reagan declared that GPS should be available for worldwide civilian use to prevent such catastrophes in the future. The specifics of civil use were established in a Memorandum of Agreement between the Department of Defense (DOD) and the Federal Aviation Administration (FAA) in 1992. As time went on, the disparity in quality between the new civil service and the legacy military service became apparent. In a report published in 1995, the National Research Council called for a second civil signal that would provide service equivalent to that previously enjoyed only by the military. This second signal would permit greater accuracy (by facilitating correction of ionospheric effects), provide a backup link in case of local interference, and allow more precise ranging measurements through its wider-bandwidth signal. On the military side, the National Research Council and other groups expressed concern over the ease with which an adversary could jam the relatively weak GPS signals. In addition, given the effectiveness of GPS in Operation Desert Storm, some analysts predicted that hostile entities would begin using it before too long.

America’s GPS policy was firmly set forth in a 1996 Presidential Decision Directive that gave consent to the DOD/FAA



A conceptual drawing of a GPS III satellite, created by Aerospace's Concept Design Center.

plan to provide GPS for peaceful worldwide use, free of charge. Moreover, recognizing that GPS provided an increasing advantage in virtually every military operation and was becoming an integral part of the global information infrastructure, the Clinton administration also created an interagency board for the management of GPS. Still, there was no clear plan detailing what changes could be made most effectively and what part of the system should deal with the increasing service demands.

The Air Force initiated studies to evaluate the trade-offs between performance and cost among various alternatives for dealing with postulated threats to the system. The studies concluded that the signal-in-space used by the military had to be boosted by a significant amount to provide an operational advantage to the greatest array of users. Additionally, the need to prevent unauthorized use while preserving U.S. and allied use spurred studies to identify separate signals and spectrum allocations for military, civilian, and aviation use. At the request of DOD, The Aerospace Corporation led a study that looked for ways to separate the military signal without having to secure additional spectrum in the already crowded radio-frequency bands. The study concluded that frequency reuse within the existing bands would allow for a new military signal (with higher power) in the lesser-used outer portions of the currently registered bands. Thus, the existing civil signal at the primary frequency and the proposed new civil signal at the secondary frequency would remain unaffected by the new military signals, which came to be called the M code.

A vice presidential announcement in 1998 heralded the changes to the original L1 and L2 signals under the GPS modernization program. The new signal for aviation use (called L5) was announced in a subsequent White House release. The discontinuation of selective availability in 2000 was the easiest but most concrete portent of the changes that would come. As a result, the Block IIR program (already in production at the time) and the Block IIF program (in preliminary design) were modified to include gradual additions to the signals and power levels. Of course, these programs could not be significantly altered because of the maturity of the designs and the need to sustain the GPS constellation with regularly scheduled launches. Modernization of the control segment also got underway with the addition of new monitoring stations and processing techniques to reduce errors in positioning and timing.

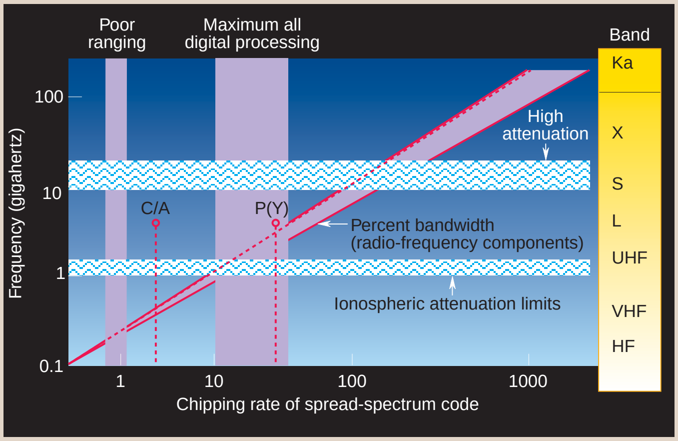
Researchers from Aerospace confirmed that the most efficient means to generate the high-power M-code signal would entail a departure from full-Earth coverage, characteristic of all the user downlink signals up until that point. Instead, a high-gain antenna would be used to produce a directional spot beam (several hundred kilometers in diameter). As a result, the necessary power could be directed specifically toward areas of interest, reducing the amount of amplifier power needed on a satellite and limiting potential interference on the ground. Originally, this proposal was considered as a retrofit to the planned Block IIF satellites. Upon closer inspection, program managers realized that the addition of a large deployable antenna, combined with the changes that would be needed in the operational control segment, presented too great a challenge for the existing system design. As a result, the focus shifted from a modification of this existing contract to a new start program. That new start was granted by Congress in 2000 and came to be called GPS III.

Assured Delivery

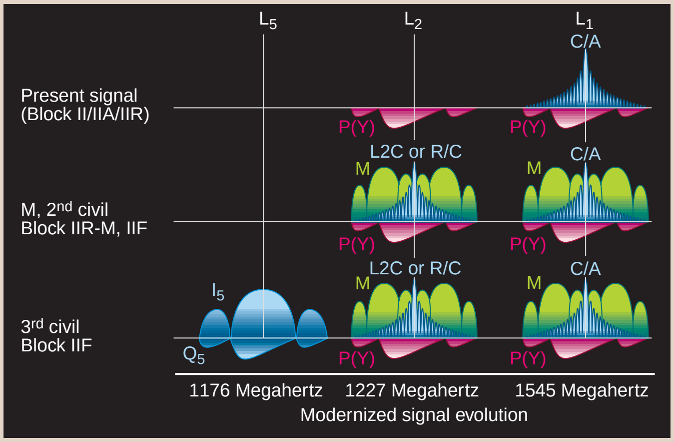
The suggested target levels for GPS III accuracy and signal availability were found to be incremental improvements over what could possibly be achieved by a fully modernized Block II constellation and updated control segment. What is needed most from GPS III is the *assurance* of such performance in the face of both deliberate attack and normal degradation of the system components. Such assurance can be attained in part through a more robust operations center as well as more secure ground-to-space and space-to-space links. As for the high-power spot-beam, assured service is not just a matter of delivering the enhanced signal on the ground; rather, it implies the ability of the system to respond to changing signal requirements in an operationally timely manner. The spot-beam signal must be designed to allow users to acquire the signal with the requisite accuracy, along with ancillary products such as

Frequency Reuse and Signal Modernization

Aerospace was part of a team established to analyze the various alternatives for a new military GPS frequency. The researchers faced no restrictions in terms of the candidate frequencies or bandwidth, but their initial examination quickly ruled out all frequencies except for a narrow band around the current two GPS frequencies. For ranging to a satellite the way a GPS receiver does, narrow bandwidth modulation (below approximately 1 megahertz) does not provide usable positioning. Lower frequencies do not penetrate the ionosphere but are reflected, resulting in the phenomenon called "skip," which makes the atmosphere opaque to radio transmissions. Higher frequencies are heavily attenuated by moisture in the atmosphere, especially at low grazing angles. On the other hand, components of transmitters and receivers can reasonably accommodate percentage bandwidths of below a few percent without introducing serious distortion or undue expense. Therefore, the candidate choices for this military frequency were right around the L or S bands. Not surprisingly, these are exactly where most satellite systems are vying for spectrum. At a loss for additional frequencies, Aerospace suggested a different approach. Applying the concept of spectrum reuse, whereby niche frequency bands are sometimes filled within allocations of different services, the unused portion of the GPS registered frequencies were identified. While the C/A and P(Y) codes are centered on the L1 and L2 carriers, the outer edges of the band are virtually unused. An Aerospace-patented application of biphase modulation was suggested to "split" the new military signal, allowing it to straddle the center of the band. Thus, the M code was born.



The current GPS constellation has signals on two frequencies (L1 and L2) with P(Y) code modulation dedicated to military use. L1 also has the C/A coded signal that is the primary signal for civil GPS users. Among the factors considered in selecting the optimal frequency and bandwidth for a space-to-Earth signal suitable for high-accuracy ranging are attenuation through the ionosphere, rain attenuation, code rate for accuracy, and limits of digital circuitry and radio-frequency components. As part of the GPS modernization efforts, Aerospace reexamined these tradeoffs and found that the current C/A and P(Y) codes at the L1 and L2 frequencies are in fact optimal choices.



The first phase of the modernization of the Block II system will provide two additional signals, designated as the M code, on L1 and L2 for military use. The M code signals are designed to use the edges of the band with only minor signal overlap with the preexisting C/A and P(Y) signals. A second dedicated civil signal on L2 will be added to give civil users full dual-frequency service. In the next phase of modernization, another frequency (L5) with a new modulation type will be dedicated to high-accuracy use, fundamentally for aviation. The two components of the signal have been designated as I_5 and Q_5.

updated navigation messages. Meeting these needs may entail additional infrastructure, control elements, and communication networks.

Assurance also means the ability to respond quickly to service anomalies and unanticipated disruptions. This type of assurance is known as integrity. For the civil user, integrity means that the system can be trusted in safety-of-life applications such as vehicle surveillance and guidance. In the near term, this level of integrity will be added as an external overlay to GPS by the FAA's Wide Area Augmentation System, a network of ground reference stations that correct for GPS signal errors and provide information regarding the health of each satellite. Potential performance and cost benefits can be achieved by integrating these functions in one navigation system.

For the military user, integrity might mean that a GPS-guided weapon can be trusted to complete its mission with an acceptably low likelihood of collateral damage. Toward this end, a goal for GPS III may be a high degree of self-monitoring, both within the space vehicle and within the constellation. This layered integrity approach, which may also include ground monitoring and a custom integrity signal provided by FAA for civil and commercial aviation, has the potential to meet dual-use needs. The same safety features may efficiently meet civil needs for safety-of-life services and military needs for guiding weapons to their targets reliably and effectively.

Spectrum Challenges

Of the various design challenges driving the specific enhancements planned for GPS III, spectrum considerations are among the most important. The high-power M-code military signal is particularly sensitive and will have to be added judiciously. At the upper primary frequency (L1), the signals from a GPS satellite compete with other GPS signals that share this band as well as with signals from the Wide Area Augmentation System and various European augmentation systems. At the secondary frequency (L2), signals must coexist with surveillance radar systems, and Aerospace has supported studies to determine the degree to which current and future signals can do so.

Although the higher-power signal will have sufficient bandwidth within the registered frequency, it may still prove difficult to prevent the total signal from spilling over the occupied bandwidth.

Spectrum issues affect the uplink, downlink, and crosslink frequencies as well. The uplink and downlink bands used for telemetry, tracking, and control (TT&C) are subject to reallocation to permit increased commercialization of government bands for emerging mobile-satellite systems. The directional crosslinks, used for satellite-to-satellite communication and potentially for intersatellite ranging, represent a significant departure from the current ultrahigh-frequency implementation, which is essentially nondirectional. The current crosslink signal is not situated in a properly allocated band and can suffer from occasional interference as a result of the broad satellite-antenna coverage at that frequency. While modernization of the Block II serves as a first step in addressing some of these issues, the fundamental design changes that can truly deal with the changeover in frequency bands are beyond the scope of the existing programs and configurations.


U.S. Air Force

Garmin

Garmin

The early GPS receivers were quite bulky—and in fact had to be worn like a backpack. In contrast, today's receivers are extremely compact and easy to integrate with other portable electronic devices. Shown here are the Street Pilot III (top right) and eTrex Summit (bottom right) from Garmin.

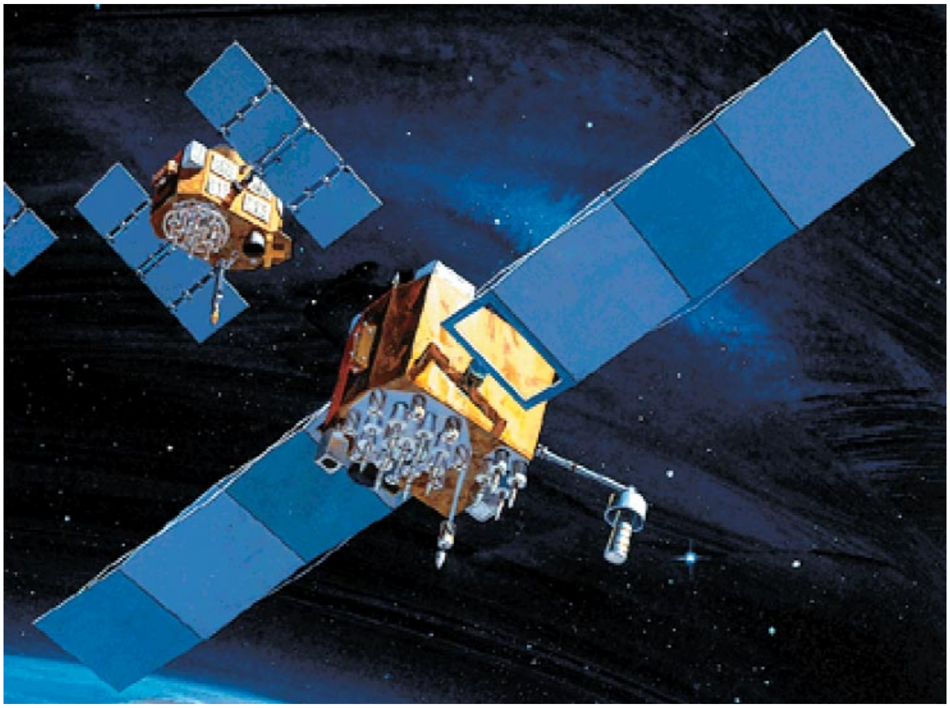
Integrated Dual Use

GPS III offers the opportunity to depart from previous designs, rather than simply add to them. The FAA Wide Area Augmentation System, Coast Guard National Differential GPS, and numerous global monitoring networks operate independently of the main GPS infrastructure, and the operational control segment does not fully benefit from the superior availability and orbit determination capability of these civil networks. A potential innovation in GPS III would be to incorporate the products of such civil networks (with the appropriate safeguards) into its operational database. International concerns could also be met by incorporating monitoring and integrity information from other countries and regions. The use of host country messages in a local area can satisfy the need for sovereign countries to maintain control over their regional radio navigation aids within the context of a service carried on GPS.

As for the increasing crowding of the electromagnetic spectrum, some of the proposals identified in GPS III make it possible to meet the growing operational need within the confines of protected national and international frequency allocations. In the case of the high-power military signal, the use of a highly directional spot beam and better spectral and geographical tailoring of the signals could allow the system to satisfy this goal. High-frequency ground-to-space and space-to-space communication links have been recommended by the research and contractor teams to create a survivable network for the command and maintenance of the system under variously challenging conditions.

Acquisition Innovation

Not all of the innovations in the GPS program have been purely technical. As a departure from the traditional way in which the Air Force acquires space systems, GPS III was designated as a "pathfinder" for a new process. In the past, similar acquisition programs had to endure numerous meetings of separate process teams to gain acceptance of the acquisition strategy. In contrast, GPS III will undergo a review by a single body, the Independent Program Assessment team, under the aegis of the Air Force's Space and Missile Systems Center. The Independent Program Assessment team will gauge the readiness of the program to pass the respective milestones and report to the milestone authority. Composed of representatives from numerous other programs, the Independent Program Assessment team brings diverse viewpoints and expertise from numerous quarters and prepares other program offices to transition to this new way of doing business.


U.S. Air Force

Artist's rendition of a Block IIF satellite. The first unit is scheduled to launch in 2005.

The Aerospace Corporation has been instrumental in conducting trade studies among a host of proposed architectural elements for the Block II modernization and GPS III design efforts. Aerospace researchers working with the corporation's Concept Design Center have been analyzing constellation size, number of planes, spacecraft design, and ground-segment configuration in regard to performance and total life-cycle cost. This capability has been used to independently validate the results of contractor studies and to create a government technical baseline. The baseline helps refine requirements that will serve to specify what GPS III should be and allow the Air Force to estimate the program's cost and funding cycle going into the next phase of the acquisition.

With the help of DOD's Center For Systems Acquisition Development, Aerospace has also conducted critical risk assessments at various stages of the acquisition program. More recently, the potential risk of some of the new features for GPS (although they are not new in other space programs) such as the large spot-beam antenna and higher-frequency crosslinks have been examined more closely. The interdisciplinary Aerospace research team has used its database to alleviate some concerns and to help formulate prudent development and production schedules for planning and cost estimation.

The transition of the operational control segment has also been identified as a focus area, and Aerospace has been assisting in concept development and advanced planning. The safe transition from the control of the current constellation to the more advanced and networked operations for the future satellites is a key focus area for architecture explorations and risk reduction.

Flexibility and Growth

One of the chief lessons learned from the modernization program is that the process of getting design changes developed, tested, and phased into the operational system is both deliberate and slow. The remarkable longevity of the GPS satellites has meant that for large and economical satellite acquisitions, new requirements and technology updates take a long time to implement. When designed in from the beginning, flexible elements can be readily accommodated in the architecture. Furthermore, planning for future growth with a margin of flexibility in processor capacity, memory, power, mass, and thermal capacity can allow for improved or even new payloads and missions to be accommodated quickly and economically.

The American GPS is not without competitors. In fact, in the 1980s, the Soviet Union launched its own version called GLONASS, although this system has fallen into disrepair since the breakup of the Soviet Union. More recently, the European Union has decided to develop another global navigation satellite system, called Galileo. U.S. policy is still evolving with regard to Galileo, but the question of whether to be competitive, complementary, or fully interoperable with foreign systems like Galileo underscores the need for flexibility as well as improved services for future GPS manifestations.

Indeed, the international competition to create the preeminent global navigation satellite system may be decided by the ease with which a system can either establish or adopt service standards. Given that the frequencies, signal structures, and protocols of the various potential services in Galileo have not been fully defined, timely decisions on the part of the United States with respect to GPS III may set the pace in establishing these standards. Accelerating the program, maximizing the civil benefits, and including provisions for international cooperation in the operation of GPS III can build confidence on the part of equipment manufacturers and local certifying agencies. Most important, providing the technical and operational backing for the political assurances of superlative and reliable service will allow the United States to make sure that GPS remains the leader in the global navigation satellite arena.

Conclusion

It would be presumptuous to try to predict all the ways that GPS will evolve in the next 30 years; however, it's safe to say that GPS will continue to play both a visible and supporting role in virtually all commercial, civil, and military enterprises. The modernization of Block II will achieve noticeable performance improvements, and augmentation systems will provide an added dimension of safety for applications such as air travel and marine navigation. GPS III promises to consolidate these and further advances. With more capable and efficient design and management, the future GPS will help the military achieve its objectives reliably and discriminately while safeguarding the trust of all of its users.

Bookmarks Recent Publications and Patents by the Technical Staff

Publications

P. M. Adams and G. Radhakrishnan, "Microstructure of Pulsed-Laser Deposited Titanium Carbide Thin Films Grown for Tribological Applications," *Microscopy and Microanalysis Proceedings* (Long Beach, CA, Aug. 5–9, 2001), Vol. 2, Supp. 2, pp. 1238–1239.

P. Anderson et al., "Multisatellite Observations of Rapid Subauroral Ion Drifts (SAID)," *Journal of Geophysical Research A: Space Physics*, Vol. 106, No. A12, pp. 29,585–29,599 (Dec. 2001).

P. C. Anderson et al., "Statistical Patterns in X-ray and UV Auroral Emissions and Energetic Electron Precipitation," *Journal of Geophysical Research*, Vol. 106, No. A4, pp. 5907–5911 (Apr. 2001).

P. C. Anderson, S. M. Petrinec, and K. Liou, "Statistical Patterns in X-ray and UV Auroral Emissions and Energetic Electron Precipitation," *Journal of Geophysical Research*, Vol. 106, No. A4, pp. 5907–5911 (Apr. 2001).

J. M. Baer, V. J. Ang, and W. C. Hwang, "90-Ampere-Hour Nickel-Hydrogen Dependent Pressure Vessel (DPV) Low Earth Orbit (LEO) Life Test Evaluation," *Proceedings of the 17th Annual Battery Conference on Applications and Advances* (Long Beach, CA, Jan. 15–18, 2002), pp. 35–40.

D. N. Baker, C. A. Barth, K. E. Mankoff, S. G. Kanekal, S. M. Bailey, G. M. J. Mason, and J. E. Mazur, "Relationships Between Precipitating Auroral Zone Electrons and Lower Thermospheric Nitric Oxide Densities," *Journal of Geophysical Research*, Vol. 106, No. A11, pp. 24,465–24,480 (Nov. 1, 2001).

R. A. Basheer, S. Jodeh, and A. R. Hopkins, "Properties of Blends of Sulfonic Acids Doped Polyaniline and Polyester-Polyether Block Copolymer," *Materials Research Innovations*, Vol. 4, pp. 144–147 (2001).

E. J. Beiting and J. E. Pollard, "Electromagnetic Emissions from a BHT-200 Hall Thruster," *27th International Electric Propulsion Conference* (Pasadena, CA, Oct. 15–19, 2001). IEPC Paper 01-342.

K. L. Bellman and C. Landauer, "Virtual Worlds as Meeting Places for Formal Systems," *Applied Mathematics and Computation*, Vol. 120, Nos. 1–3, pp. 165–173 (May 2001).

J. Betser, "The Challenge of Creating Productive Collaborating Information Assurance Communities via Internet Research and Standards," *Proceedings of the 20th IEEE Symposium on Reliable Distributed Systems* (New Orleans, LA, Oct. 2001), pp. 70–71.

J. Betser, A. Walther, M. Erlinger, T. Buchheim, B. Feinstein, G. Matthews, R. Pollock, and K. Levitt, "GlobalGuard: Creating the IETF-IDWG Intrusion Alert Protocol (IAP)," *Proceedings of the DARPA Information Survivability Conference and Exposition II* (Anaheim, CA, June 12–14, 2001), Vol. 1, pp. 22–34.

B. Blake et al., "The Evolution of the Anomalous Cosmic Ray Oxygen Spectra from 1995 to 1998—Ulysses Observations," *Space Science Reviews*, Vol. 97, Nos. 1–4, pp. 363–366 (July 2001).

J. Blake et al., "Lightning-Induced Energetic Electron Flux Enhancements in the Drift Loss Cone," *Journal of Geophysical Research A: Space Physics*, Vol. 106, No. A12, pp. 29,733–29,744 (Dec. 2001).

J. B. Blake, J. E. Mazur, et al., "Solar-Proton Polar-Cap Intensity Structures as a Test of Magnetic Field Models," *Validation of Magnetospheric Models: Proceedings of the Symposium of COSPAR Scientific Commission D* (Warsaw, Poland, July 16–23, 2000), pp. 1753–1757.

I. D. Boyd and M. W. Crofton, "Grid Erosion Analysis of the T5 Ion Thruster," *37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit* (Salt Lake City, UT, July 8–11, 2001). AIAA Paper 2001–3781.

L. W. Brownlow, G. A. Dorn, and T. J. Mosher, "A Proposal for Detailed Mapping of Martian Aquifers Using Penetrators," *Conference on the Geophysical Detection of Subsurface Water on Mars, Proceedings* (Houston, TX, Aug. 6–10, 2001).

J. Camparo, "Precision Measurements with an Atomic Candle," *Proceedings of the 2001 IEEE International Frequency Control Symposium and PDA Exhibition* (Seattle, WA, June 6–8, 2001), pp. 111–116.

L. A. Campbell, "Characteristic Values of the Jacobian Matrix and Global Invertibility," *Annales Math. Polonci*, Vol. 76, Nos. 1–2, pp. 11–20 (2001).

K. Chan, "Analytical Expressions for Computing Spacecraft Collision Probabilities," *Proceedings of the 11th Annual AAS/AIAA Space Flight Mechanics Meeting* (Santa Barbara, CA, Feb. 11–15, 2001), pp. 305–320. AAS Paper 01-119.

C. C. Chao, J. Cox, and R. Burns, "Ground Tracking and Control of GEO Cluster Satellites Using the Raven Telescope," *Proceedings of the 11th Annual AAS/AIAA Space Flight Mechanics Meeting* (Santa Barbara, CA, Feb. 11–15, 2001), pp. 901–912. AAS Paper 01-165.

M. W. Chen and M. Schultz, "Simulations of Storm Time Diffuse Aurora with Plasmasheet Electrons in Strong Pitch Angle Diffusion," *Journal of Geophysical Research*, Vol. 106, No. A2, pp. 1873–1886 (Feb. 2001).

M. W. Chen et al., "Modeling the Quiet Time Inner Plasma Sheet Protons," *Journal of Geophysical Research*, Vol. 106, No. A4, pp. 6161–6178 (Apr. 2001).

J. G. Coffer, M. Anderson, and J. C. Camparo, "Collisional Dephasing and the Reduction of Laser Phase-Noise to Amplitude-Noise Conversion in a Resonant Atomic Vapor," *Physical Review A: Atomic, Molecular, and Optical Physics*, Vol. 65, No. 3, pp. 033807/1–9 (Mar. 2002).

S. H. Crain, J. E. Mazur, R. B. Katz, R. Koga, M. D. Looper, and K. R. Lorentzen, "Analog and Digital Single-Event Effects Experiments in Space," *IEEE Transactions on Nuclear Science*, Vol. 48, No. 6, pp. 1841–1848 (Dec. 2001).

M. W. Crofton, "New Laser Applications for Electric Propulsion," *27th International Electric Propulsion Conference* (Pasadena, CA, Oct. 15–19, 2001). IEPC Paper 01-305.

M. W. Crofton and I. D. Boyd, "Origins of Accelerator Grid Current—Analysis of T5 Grid Test Results," *Journal of Propulsion and Power*, Vol. 17, No. 1, pp. 203–211 (Jan. 2001).

M. W. Crofton et al., "Near-field Measurement and Modeling Results for Flight-Type Arcjet—NH Molecule," *Journal of Spacecraft and Rockets*, Vol. 38, No. 1, pp. 79–86 (Feb. 2001).

P. R. Dahl, "Dynamic Hysteresis Model Application to Stiction Type Problems," Advances in the Astronautical Sciences, *Proceedings of the Annual AAS Rocky Mountain Guidance and Control Conference* (Breckenridge, CO, Jan. 31–Feb. 4, 2001), pp. 95–111.

M. I. Desai, G. M. Mason, J. R. Dwyer, J. E. Mazur, C. W. Smith, and R. M. Skoug, "Acceleration of He-3 Nuclei at Interplanetary Shocks," *Astrophysics Journal*, Vol. 553, Nos. 1–2, pp. L89–L92 (May 20, 2001).

S. J. DiMaggio, Z. H. Duron, and S. Rubin, "Accelerometer Spiking Under Cryogenic Conditions," *Experimental Mechanics*, Vol. 41, No. 2, pp. 174–181 (June 2001).

S. J. DiMaggio, S. Rubin, and B. H. Sako, "Gear Fault Detection in Rocket Engine Turbomachinery," *Journal of Propulsion and Power*, Vol. 17, No. 2, pp. 225–231 (Apr. 2001).

S. J. DiMaggio and B. H. Sako, "Basic System Identification for Condition Monitoring of Turbopumps (Rocket Engines)," *2001 IEEE Aerospace Conference Proceedings* (Big Sky, MT, March 10–17, 2001), p. 7-3200.

K. W. Dotson, "Transient Coupling of Launch Vehicle Bending Responses with Aerodynamic Flow State Variations," *Journal of Spacecraft and Rockets*, Vol. 38, No. 1, pp. 97–104 (Feb. 2001).

K. W. Dotson, R. L. Baker, and B. H. Sako, "Semiempirical Analysis of Limit Cycle Oscillation from Transonic Flow-State Changes at Angle of Attack," *42nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit* (Seattle, WA, Apr. 16–19, 2001). AIAA Paper 2001–1288.

K. W. Dotson, J. M. Womack, and P. J. Grosserode, "Structural Dynamic Analysis of Solid Rocket Motor Resonant Burning," *Journal of Propulsion and Power*, Vol. 17, No. 2, pp. 347–354 (Apr. 2001).

P. Duggan, S. Sampson, R. Burnell, R. Koga, P. Yu, S. H. Crain, S. McEndree, J. Tausch, D. Sleeter, and D. Alexander, "Comparative Testing of ADSP-21020 Digital Signal Processors from Multiple Vendors," *IEEE Radiation*

Effects Data Workshop Record (Vancouver, BC, July 16–20, 2001), pp. 19–25.

J. L. Emdee, "A Survey of Development Test Programs for Hydrogen Oxygen Rocket Engines," *39th AIAA, Aerospace Sciences Meeting and Exhibit* (Reno, NV, Jan. 8–11, 2001). AIAA Paper 2001–0749.

J. L. Emdee, "A Survey of Development Test Programs for LOX/Kerosene Rocket Engines," *37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit* (Salt Lake City, UT, July 8–11, 2001). AIAA Paper 2001-3985.

W. A. Engblom, M. A. Weaver, and E. D. Ndefo, "Numerical Study of Vehicle/Pad Configuration Effects on Launch Ignition Transients," *39th AIAA, Aerospace Sciences Meeting and Exhibit* (Reno, NV, Jan. 8–11, 2001). AIAA Paper 2001-0802.

F. Fatemi, K. M. Jones, H. Wang, I. Walmsley, and P. D. Lett, "Dynamics of Photoinduced Collisions of Cold Atoms Probed with Picosecond Laser Pulses," *Physical Review A*, Vol. 64, Paper 33421.

J. F. Fennell, J. Roeder, et al., "Ring Current Ion Composition During Solar Minimum and Rising Solar Activity—Polar/CAMMICE/MICS Results," *Journal of Geophysical Research*, Vol. 106, No. A9, pp. 19131–19147 (Sep. 2001).

S. Goldstein et al., "Computational Aspects of Transfer Trajectories to Halo Orbits," *Journal of Guidance, Control, and Dynamics*, Vol. 24, No. 4, pp. 796–804 (Aug. 2001).

C. W. Gray, "Star Tracker/IRU Attitude Determination Filters," *Advances in the Astronautical Sciences, Proceedings of the Annual AAS Rocky Mountain Guidance and Control Conference* (Breckenridge, CO, Jan. 31–Feb. 4, 2001), pp. 459–476.

D. F. Hall et al., "MSX Contamination Environment During the Fourth Orbital Year," *39th AIAA, Aerospace Sciences Meeting and Exhibit* (Reno, NV, Jan. 8–11, 2001). AIAA Paper 2001–0096.

J. H. Hecht, R. L. Walterscheid, M. P. Hickey, and S. J. Franke, "Climatology and Modeling of Quasi-monochromatic Atmospheric Gravity Waves Observed over Urbana, Illinois," *Journal of Geophysical Research*, Vol. 106, No. D6, pp. 5181–5195 (Mar. 2001).

J. H. Hecht, R. L. Walterscheid, and R. A. Vincent, "Airglow Observations of Dynamical (Wind Shear-Induced) Instabilities over Adelaide, Australia, Associated with Atmospheric Gravity Waves," *Journal of Geophysical Research*, Vol. 106, No. D22, pp. 28,189–28,197 (Nov. 2001).

H. Helvajian, "3D Microengineering Via Laser Direct-Write Processing Approaches," chap. 14 in *Direct-Write Technologies for Rapid Prototyping Applications* (New York, Academic Press, 2002).

L. K. Herman, C. M. Heatwole, and G. M. Manke, "Attitude Determination for the STEX Spacecraft Using Virtual Gyros," *Guidance and Control 2001: Proceedings of the Annual AAS Rocky Mountain Conference* (Breckenridge, CO, Jan. 31–Feb. 4, 2001), pp. 113–132. AAS Paper 01-008.

K. C. Herr, "Thermal Infrared Spectral Band Detection Limits for Unidentified Surface Materials," *Applied Optics*, Vol. 40, No. 27, pp. 4852–4862 (Sep. 20, 2001).

D. Hinkley and E. J. Simburger, "A Multifunctional Flexure Hinge for Deploying Omnidirectional Solar Arrays," *42nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit* (Seattle, WA, Apr. 16–19, 2001). AIAA Paper 2001-1260.

A. Jackson, R. Das, and T. Jackson, "Finding Answers to Space Industry's Top 10 Reliability Problems," *Annual Reliability and Maintainability Symposium 2001 Proceedings: International Symposium on Product Quality and Integrity* (Philadelphia, PA, Jan. 22–25, 2001), pp. 333–338.

S. W. Janson, "Nanotechnology—Tools for the Satellite World," *6th ISU Annual International Symposium: Smaller Satellites, Bigger Business?* (Strasbourg, France, May 21–23, 2001).

A. B. Jenkin and R. A. Gick, "Analysis of the Collision Risk Associated with GPS Disposal Orbit Instability," *Proceedings of the 11th Annual AAS/AIAA Space Flight Mechanics Meeting* (Santa Barbara, CA, Feb. 11–15, 2001), pp. 223–242. AAS Paper 01-115.

A. B. Jenkin et al., "Orbital Debris Hazard Assessment Methodologies for Satellite Constellations," Journal of Spacecraft and Rockets, Vol. 38, No. 1, pp. 120–125 (Feb. 2001).

H. A. Katzman, O. O. Esquivel, J. Calder, and B. Sullivan, "Infrared Thermal Imaging During Simulation of Electronic Thermal Plane Performance," *25th Annual Conference on Composites, Materials, and Structures* (Cocoa Beach, FL, Jan. 22–26, 2001).

D. E. Keenan, "A Formation Flying Strategy for CloudSat/Picasso-Cena," *2001 IEEE Aerospace Conference Proceedings* (Big Sky, MT, March 10–17, 2001), pp. 2/535–552.

J. Knauf, L. Drake, and P. Portanova, "Evolved Expendable Launch Vehicle System—The Next Step in Affordable Space Transportation," *52nd International Astronautical Congress* (Toulouse, France, Oct. 1–5, 2001). IAF Paper 01-V104.

R. Koga, S. H. Crain, P. Yu, and K. B. Crawford, "SEE Sensitivity Determination of High-Density DRAMs with Limited-Range Heavy Ions," *2001 IEEE Radiation Effects Data Workshop and IEEE Nuclear and Space Radiation Effects Conference, Workshop Record* (Vancouver, BC, July 16–20, 2001), pp. 182–189.

R. Koga, P. Yu, K. B. Crawford, S. H. Crain, and V. T. Tran, "Permanent Single Event Functional Interrupts (SEFIs) in 128- and 256-Megabit Synchronous Dynamic Random Access Memories (SDRAMs)," *2001 IEEE Radiation Effects Data Workshop and IEEE Nuclear and Space Radiation Effects Conference, Workshop Record* (Vancouver, BC, July 16–20, 2001), pp. 6–13.

R. C. Lacoe, J. V. Osborn, D. C. Mayer, S. Brown, and J. Gambles, "Total-Dose Tolerance of the Commercial Taiwan Semiconductor Manufacturing Company (TSMC) 0.35-mu m CMOS Process," *2001 IEEE Radiation Effects Data Workshop and IEEE Nuclear and Space Radiation Effects Conference, Workshop Record* (Vancouver, BC, July 16–20, 2001), pp. 72–76.

C. Landauer, "Simulation Spectrum and Stability Models," *Proceedings of the 35th Annual Hawaii International Conference on System Sciences* (Hawaii, HI, Jan. 7–10, 2002), pp. 1559–1568.

C. Landauer and K. L. Bellman, "Computational Infrastructure for Experiments in Cognitive Leverage," *Cognitive Technology: Instruments of Mind, 4th International Conference, Proceedings* (Coventry, UK, Aug. 6–9, 2001), pp. 490–519.

C. Landauer and K. L. Bellman, "Modeling Current Events," *Proceedings of the 35th Annual Hawaii International Conference on System Sciences* (Hawaii, HI, Jan. 7–10, 2002), pp. 1503–1512.

C. Landauer and K. L. Bellman, "Wrappings for One-of-a-Kind Software Development," *Proceedings of the 35th Annual Hawaii International Conference on System Sciences* (Hawaii, HI, Jan. 7–10, 2002), pp. 3987–3995.

C. Lee, E. Coe, J. M. Clark, J. Stepanek, C. Raghavendra, and K. Bellman, "Time Management in Active Networks," *Proceedings Third Annual International Workshop on Active Middleware Services* (San Francisco, CA, Aug. 6, 2001), pp. 51–64.

M. S. Leung and G. W. Stupian, "Magnetic Properties of Fe Microstructures with Focused Ion Beam-Fabrication Nano-Constructions," *IEEE Transactions on Magnetics*, Vol. 37, No. 4, pp. 2101–2103 (July 2001).

N. S. Lewis and A. R. Hopkins, "Detection and Classification Characteristics of Arrays of Carbon Black/Organic Polymer Composite Chemiresistive Vapor Detectors for the Nerve Agent Simulants DMMP and DIMP," *Analytical Chemistry*, Vol. 73, No. 5, pp. 884–892 (Mar. 1, 2001).

J. R. Lince and P. P. Frantz, "Anisotropic Oxidation of MoS_2 Crystallites Studied by Angle-Resolved X-ray Photoelectron Spectroscopy," *Tribology Letters*, Vol. 9, Nos. 3–4, pp. 211–218 (2001).

S. Lindsey and C. S. Raghavendra, "Energy Efficient Broadcasting for Situation Awareness in Ad Hoc Networks," *Proceedings International Conference on Parallel Processing* (Valencia, Spain, Sep. 3–7, 2001), pp. 149–155.

K. R. Lorentzen, J. B. Blake, U. S. Inan, and J. Bortnik, "Observations of Relativistic Electron Microbursts in Association with VLF Chorus," *Journal of Geophysical Research*, Vol. 106, No. A4, pp. 6017–6027 (April 2001).

D. K. Lynch, R. J. Rudy, C. C. Venturini, S. Mazuk, and R.C. Puetter, "Near-Infrared (0.8–2.5 micron) Spectroscopy of Nova Sagittarius1998 = V4633 Sagittarii," *Astronomical Journal*, Vol. 122, No. 4, pp. 2013–2016.

D. K. Lynch, R. W. Russell, and M. L. Sitko, "3–14 Micron Spectroscopy of Nova V445 Puppis," *Astronomical Journal*, Vol. 122, No. 6, pp. 3313–3316 (Dec. 2001).

A. Mathur, T. M. Nguyen, and G. Goo, "Rain Attenuation Model Assessment for Wideband Gapfiller Satellite Communications Link," *MILCOM 2001 Conference Proceedings* (Tysons Corner, VA, Oct. 28–31, 2001).

J. E. Mazur, G. M. Mason, and R. A. Mewaldt, "Charge States of Energetic Particles from Corotating Interaction Regions as Constraints on Their Source," *Astrophysical Journal*, Vol. 566, No. 1, pp. 555–561 (Feb. 10, 2002).

H. H. Nguyen and T. M. Nguyen, "Beamforming When Direction of Arrival is Random with Applications to Space Diversity Processing," *ICC 2001: IEEE International Conference on Communications Conference Record* (Helsinki, Finland, June 11–14, 2001), pp. 2620–2624.

T. M. Nguyen and C. C. Wang, "On the Link Budget Calculation for CDMA Systems," *2001 IEEE Aerospace Conference Proceedings* (Big Sky, MT, Mar. 10–17, 2001), pp. 2/909–913.

J. R. Nolan, "Comparison of Commercial High-Resolution Satellite Imagery," *2001 IEEE Aerospace Conference Proceedings* (Big Sky, MT, Mar. 10–17, 2001), pp. 2/925–930.

T. W. Nuteson and G. S. Mitchell, "Digital Beamforming for Smart Antennas," *2001 IEEE MTT-S International Microwave Symposium Digest* (Phoenix, AZ, May 20–25, 2001), Vol. 1, pp. 125–128.

N. Ogamba, "Effectiveness of Analysis of Electrical Test Data of Defective Ceramic Capacitors," *21st Capacitor and Resistor Technology Symposium* (St. Petersburg, FL, Mar. 2001), pp. 226–230.

R. P. Patera, "A Method for Calculating Collision Probability Between a Satellite and a Space Tether," *Proceedings of the 11th Annual AAS/AIAA Space Flight Mechanics Meeting* (Santa Barbara, CA, Feb. 11–15, 2001), pp. 243–258. AAS Paper 01-116.

R. P. Patera, "General Method for Calculating Satellite Collision Probability," *Journal of Guidance, Control, and Dynamics*, Vol. 24, No. 4, pp. 716–722 (Aug. 2001).

E. L. Petersen, R. P. Welle, M. J., Traum, E. D. Abbey, and M. Rickard, "A New Shock-Tube Facility for Studying Combustion Phenomena in Mixtures Containing Condensed Species," *35th National Heat Transfer Conference* (Anaheim, CA, June 10–12, 2001).

G. E. Peterson, R. G. Gist, and D. L. Oltrogge, "Covariance Generation for Space Objects Using Public Data," *Proceedings of the 11th Annual AAS/AIAA Space Flight Mechanics Meeting* (Santa Barbara, CA, Feb. 11–15, 2001), pp. 201–214. AAS Paper 01-113.

A. Quan, R. Crawford, H. Shao, K. Knudtzon, A. Schuler, D. Scott, S. Hayati, R. Higginbotham Jr., and R. Abbott, "Automated Threat Response Using Intelligent Agents (ATRIA)," *2001 IEEE Aerospace Conference Proceedings* (Big Sky, MT, Mar. 10–17, 2001), pp. 2721–2730.

M. V. Quinzio, G. To, and A. H. Zimmerman, "Scanning Porosimetry for Characterization of Porous Electrode Structures," *Proceedings of the 17th Annual Battery Conference on Applications and Advances* (Long Beach, CA, Jan. 15–18, 2002), pp. 291–295.

M. V. Quinzio and A. H. Zimmerman, "Dynamic Calorimetry for Thermal Characterization of Battery Cells," *Proceedings of the 17th Annual Battery Conference on Applications and Advances* (Long Beach, CA, Jan. 15–18, 2002), pp. 279–284.

T. S. Rose, D. Gunn, and G. C. Valley, "Gamma and Proton Radiation Effects in Erbium-Doped Fiber Amplifiers: Active and Passive Measurements," *Journal of Lightwave Technology*, Vol. 19, No. 12, pp. 1918–1923 (Dec. 2001).

R. J. Rudy, D. K. Lynch, S. Mazuk, C. C. Venturini, R. C. Puetter, and F. Hamann, "Markarian 478: a Second Seyfert Galaxy with 1 Micron Fe II Emission Lines," *Publications of the Astronomical Society of the Pacific*, Vol. 113, No. 786, pp. 916–919 (Aug. 2001).

R. J. Rudy, D. K. Lynch, S. Mazuk, C. C. Venturini, R. C. Puetter, and P. Hoflich, "Early-Time Infrared Spectra of the Type Ia Supernova 2000cx," *Astrophysical Journal*, Vol. 565, No. 1, pp. 413–418.

L. W. Schumann and T. S. Lomheim, "Infrared Hyperspectral Imaging Fourier Transform and Dispersive Spectrometers—Comparison of Signal-to-Noise-Based Performance," *Imaging Spectrometry VII, Proceedings of the Conference* (San Diego, CA, Aug. 1–3, 2001), pp. 1–14.

R. Selesnick et al., "Mapping Jupiter's Outer Radiation Belt," *Journal of Geophysical Research A: Space Physics*, Vol. 106, No. A12, pp. 29,859–29,869 (Dec. 2001).

R. S. Selesnick, "Simulation of the Anomalous Cosmic Ray Radiation Belt with Atmospheric Production and Decay," *Geophysical Research Letters*, Vol. 28, No. 17, pp. 3417–3420.

R. S. Selesnick, C. M. S. Cohen, and K. K. Khurana, "Energetic Ion Dynamics in Jupiter's Plasma Sheet," *Journal of Geophysical Research*, Vol. 106, No. A9, pp. 18,895–18,905.

S. S. Shen et al., "New Hyperspectral Compression Options in JPEG-2000 and Their Effects on Exploitation," *Imaging Spectrometry VII; Proceedings of the Conference* (San Diego, CA, Aug. 1–3, 2001), pp. 154–165.

C. P. Silva, A. A. Moulthrop, M. S. Muha, and C. J. Clark, "Application of Polyspectral Techniques to Nonlinear Modeling and Compensation," *2001 IEEE MTT-S International Microwave Symposium Digest* (Phoenix, AZ, May 20–25, 2001), Vol. 1, pp. 13–16.

E. J. Simburger, J. Matsumoto, D. Hinkley, D. Gilmore, T. W. Giants, and J. Ross, "Multifunctional Structures for the PowerSphere Concept," *42nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit* (Seattle, WA, Apr. 16–19, 2001). AIAA Paper 2001–1343.

K. Siri and K. A. Conner, "Parallel-Connected Converters with Maximum Power Tracking," *Proceedings of APEC 2002: 17th Annual IEEE Applied Power Electronics Conference and Exposition* (Dallas, TX, Mar. 10–14, 2002), Vol. 1, pp. 419–425.

G. W. Stupian, N. Ives, N. Marquez, and B. A. Morgan, "Application of Lead Isotope Analysis to Bullet Individualization in Two Homicides," *Journal of Forensic Science*, pp. 1342–1351 (Nov. 2001).

T. Swan-Wood, J. G. Coffer, and J. C. Camparo, "Precision Measurements of Absorption and Refractive-Index Using an Atomic Candle," *IEEE Transactions on Instrumentation and Measurement*, Vol. 50, No. 5, pp. 1229–1233 (Oct. 2001).

S. R. Turner, "Active Browsing," *Proceedings of the IASTED International Conference Internet and Multimedia Systems and Applications* (Honolulu, HI, Aug. 13–16, 2001), pp. 181–186.

G. C. Valley, "Modeling Cladding-Pumped Er/Yb Fiber Amplifiers," *Optical Fiber Technology: Materials, Devices and Systems*, Vol. 7, No. 1, pp. 21–44 (Jan. 2001).

R. L. Walterscheid, "Gravity Wave Transports and Their Effects on the Large-Scale Circulation of the Upper Mesosphere and Lower Thermosphere," *Advances in Space Research*, Vol. 27, No. 10, pp. 1713–1721 (May 2001).

R. L. Walterscheid and M. Hickey, "One-Gas Models With Height-Dependent Mean Molecular Weight—Effects on Gravity Wave Propagation (Thermosphere Models)," *Journal of Geophysical Research. A. Space Physics*, Vol. 106, No. A12, pp. 28,831–28,839 (Dec. 2001).

R. L. Walterscheid, G. Schubert, and D. G. Brinkman, "Small-Scale Gravity Waves in the Upper Mesosphere and Lower Thermosphere Generated by Deep Tropical Convection," *Journal of Geophysical Research D: Atmospheres*, Vol. 106, No. D23, pp. 31,825–31,835 (Dec. 16, 2001).

H. G. Yeh, C. C. Wang, and A. H. Yamada, "Performance of the FFT-Based SDPSK Receiver in Fading Channels," *2001 IEEE Aerospace Conference Proceedings* (Big Sky, MT, Mar. 10–17, 2001), pp. 3/1385–1389.

R. J. Zaldivar, R. W. Kobayashi, and T. J. Dickinson, "Exposure of Polycyanurate and Epoxy Matrix Composites to Hypergolic Rocket Fuel Components," *Journal of Spacecraft and Rockets*, Vol. 39, No. 1, pp. 99–105 (Jan. 2001).

Patents

S. J. Curry, D. M. Schwartz, J. F. Collins, “Convolutional Despreading Method for Rapid Code Phase Determination of Chipping Codes of Spread Spectrum Systems,” U.S. Patent No. 6,345,073, Feb. 2002.

This signal-processing technique is designed for use in radio communication systems that employ chip-spreading codes and that therefore require code-phase determination for rapid acquisition of direct-sequence spread-spectrum signals. Taking advantage of the algebraic structure of the spreading code, this despreading method applies convolutional decoding to received signal-chip symbols. Modeled reduced-state structures with branchword transitions reduce metric computations while providing additional constraints for modifying convolutional sequential metric searches. These features improve the speed of code-phase determination. The method works best with a modified convolutional sequential search algorithm, such as a modified Fano Tree or Viterbi trellis convolutional sequential search. The method can also directly determine a modulated data stream, when present, to provide demodulated data without necessarily performing conventional cross-correlation despreading.

M. M. Gorlick, “Wearable Electronics Conductive Garment Strap and System,” U.S. Patent No. 6,350,129, Feb. 2002.

An electrically conductive strap can communicate power and signals between batteries and electronic devices attached to it. The strap can be embedded in blouses, pants, belts, and similar articles of clothing, allowing personal electronic devices to be comfortably worn. Ordinary conductive snaps made from common materials provide reliable connection between the strap and the electronic devices. The strap is made of woven materials such as a conductive webbing that incorporates at least two durable electrical conductors directly into the conductive strap.

G. F. Hawkins, E. C. Johnson, J. P. Nokes, “Wheeled Large Surface Thermographic Inspection Heating Apparatus with Uniform Heating,” U.S. Patent No. 6,400,898, June 2002.

Designed for thermographic inspection of large structures, a heater radiates a uniform amount of heat upon a large surface in a short period of time. The surface can then be imaged by a handheld infrared camera for quick detection of subsurface flaws. Easy to manipulate, the portable device is well suited for inspecting composite-overwrapped concrete bridges and buildings where debonding of the composite-concrete interface is a concern. Motor-controlled wheels translate an array of several equally spaced heating elements at a constant rate. The highly uniform heating eliminates the need for postprocessing of the data and enables the operator to detect flaws or defects at the time of inspection. The handheld equipment can be used in various sites without the difficult and lengthy setup associated with other types of heating equipment.

T. M. Nguyen, J. Yoh, A. S. Parker, D. M. Johnson, “High Power Amplifier Linearization Method Using Modified Linear-Log Model Predistortion,” U.S. Patent No. 6,307,435, Oct. 2001.

Using a modified linear-log model, this predistortion technique linearizes the output of high-power amplifiers used in digital communication systems. The technique is specifically intended for nonlinear high-power amplifiers that suffer distortion when converting an amplitude-modulated input signal to a phase-modulated or amplitude-modulated output signal. A complex baseband linearizer provides predistortion at baseband, thereby reducing spectral regrowth and improving bit-error performance. The predistortion effects are matched to the amplifier distortions to cancel them out. The modified linear-log model reduces the clipping effects through the peak operating point for a specified output-power loss with minimum distortion.

E. J. Simburger, “PowerSphere Deployment Method,” U.S. Patent No. 6,318,674, Nov. 2001.

This patent describes a method of deploying multiple flat panels interconnected by rotating hinges to achieve a predetermined curved shape, such as a sphere. The method is primarily intended to create a spherical enclosure known as a PowerSphere for use as an attitude-insensitive solar panel on a miniature satellite; however, the technique can also be used to create any similarly curved structure—for example, a curved geodetic tent for terrestrial use. Internal supporting struts and interconnecting panel frames and hinges are inflated during unfurling to automatically form the curved surface.

E. J. Simburger, A. Prater, P. J. Carian, “Power Distribution System,” U.S. Patent No. 6,396,167, May 2002.

Particularly useful for microsatellites and nanosatellites, a power-distribution system delivers energy from multiple dc power sources and storage devices (such as solar cells and batteries) connected in parallel to a regulated power bus. The parallel connection is accomplished through microelectronic dc-dc regulators attached to each individual cell or battery, eliminating the need for serial connections. When total power from power sources exceeds system needs, the excess current is used to charge the dc storage devices. The regulators will continue to provide sufficient coupled power to the bus even if one or more of the power sources or storage devices fails. When used in conjunction with a spherical solar-cell array, the power-distribution system can ensure adequate electrical power to a satellite regardless of its orientation toward the sun.

K. Siri, “Maximum Power Tracking Solar Power System,” U.S. Patent No. 6,369,462, Apr. 2002.

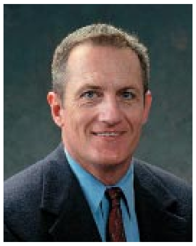
This power-tracking system ensures the delivery of maximum power from a source (such as a solar-cell array) to a load (such as a satellite payload). The system determines a proper control direction toward the source maximum-power point in one out of three possible controlling states: increasing, decreasing, or steady. These states are controlled by an array-voltage set-point command modulated by a dither signal, enabling regular power tracking (or system output voltage regulation) when load-demand is below the source peak power and maximum power tracking (or system solar array voltage regulation) when load-demand is above the source peak power. The system can deliver power to constant or pulsating loads and storage cells. When configured for a constant-power or pulsating load, the system uses both damped input-filter and damped output-filter capacitors or bus stabilizers coupled across the input and the load, respectively, to stabilize the input and output voltages around the selected dither frequency. At frequencies above the center frequency of the bus stabilizers, the system creates sufficient damping effects to ensure both input and output voltage stability without undesirable oscillation. The maximum-power tracking system can support existing commercial-off-the-shelf dc-dc converters that use current-mode control in an innermost control loop. Multiple sets of paralleled converters and their respective maximum power trackers can be distributively connected to their respective array sources while their converter outputs are coupled in parallel using shared bus control signals for fault-tolerant equalized power conversion.

A. M. Young, S. S. Osofsky, “Active Feedback Pulsed Measurement Method,” U.S. Patent No. 6,396,298, May 2002.

This active feedback circuit minimizes voltage transients during pulsed measurements of a semiconductor device such as a high-power field-effect transistor (FET). The method uses three bias tees: an input-gate bias tee for applying an accurately shaped pulsed input; a sensing bias tee for sensing terminal voltages (such as drain voltages for an FET); and a drive bias tee for coupling in a feedback signal from an active feedback circuit. The feedback circuit receives an ac coupled input-error signal for the dc terminal voltage and provides a drive signal as an error signal to maintain the applied dc test voltages at stable levels. A pulsed I-V (current and voltage) or pulsed S-parameter (scattering parameter) measurement can be accomplished within 1 microsecond of the leading edge of the gate pulse with reduced drain-voltage transients. When the I-V measurements are made quickly after the rising edge of the gate pulse, self-heating and trap effects will be minimized. The resulting model will closely match the measured performance of the device.

Contributors

Charting a Course Toward Global Navigation



Steven R. Strom is the corporate archivist for Aerospace. He holds an M.A. in American history from Boston College and has completed all of the work toward his Ph.D. in history at Rice University except for his dissertation. He is the author of "A Perfect Start to the Operation: The Aerospace Corporation and Project Mercury," which appeared in the Summer 2001 issue of *Crosslink* (steven.r.strom@aero.org).

Operation and Application of the Global Positioning System

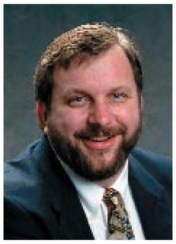
Colleen H. Yinger, Senior Engineering Specialist, Navigation and Geopositioning Systems Department, has more than 15 years of experience in GPS performance and applications. She has supported the GPS Joint Program Office in the areas of architecture analysis, control-segment enhancements, atmospheric compensation, augmentation systems, military and space applications, and precise timing. She joined Aerospace in 1978. She holds an M.S. in mechanical engineering from the University of California, Los Angeles (colleen.h.yinger@aero.org).

Optimizing Performance Through Constellation Management

Paul D. Massatt is Senior Engineering Specialist in the Navigation and Geopositioning Systems Department. He began analyzing GPS constellation performance when he joined Aerospace in 1985 and subsequently developed the nonuniform 24-satellite constellation that defines GPS nominal orbits today. His analyses of constellation buildup, launch placement, anomaly resolution, and system innovations have defined most of the orbital positions of the GPS satellites since the 1980s and have helped the Air Force manage the constellation and define future system requirements and architectures. He holds a Ph.D. in applied mathematics from Brown University (paul.d.massatt@aero.org).

Wayne Brady joined Aerospace in 1979. Until his retirement, he served as Director of the Mission Modeling and Simulation Office. He holds M.S. degrees in mechanical engineering and management science from the University of Southern California. He lives in Oregon.

Orbit Determination and Satellite Navigation



John Langer, Senior Project Leader, Global Positioning System, has been with Aerospace for more than 15 years. He specializes in orbit determination and GPS, with particular focus on space applications of GPS. Before joining the GPS program office, he managed the Orbit Determination Section of the Navigation and Geopositioning Systems Department. He holds an M.S. in mathematics from the University of Washington (john.v.langer@aero.org).

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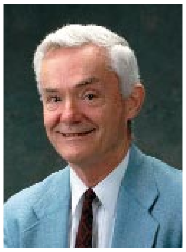

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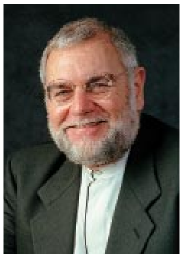
GPS/Inertial Navigation for Precise Weapon Delivery

Antijamming and GPS for Critical Military Applications



Anthony Abbott is Principal Engineer in the GPS III and Military Applications Directorate, supporting the GPS Joint Program Office in advanced antijam technology and user equipment architecture. He joined Aerospace in 1968, and helped develop the conceptual definition of System 621B, the predecessor to GPS. He also contributed to the design and analysis of numerous satellite programs, including Phase I GPS, while a section manager in the Controls Department. He left Aerospace in 1976 to join Magnavox as a senior staff engineer for GPS Phase I user equipment, participating in the design, integration, and field testing of the first unaided and INS-aided GPS sets, including the first weapon-delivery system fully integrated with GPS. In 1982, he joined Northrop Grumman as the chief analyst on the B-2 navigation system and later on the B-2 GPS-Aided Targeting System and GPS-Aided Munition. He returned to Aerospace in 1997. He has an M.S.E.E. from the University of Southern California in system science and holds three U.S. patents (with two more pending) and one international patent. He received the Engineers' Council Merit Award in 1997 for participation in the B-2 GPS-Aided Targeting System (anthony.s.abbott@aero.org).

Modernization and the Move to GPS III

Steven Lazar is Systems Director for GPS III in the Weather and Navigation Division. He has more than 21 years of experience in radio-frequency and antenna applications in space and ground systems, signal design and test for radio-navigation systems, and spectrum management. He has been in the GPS program office since 1989. He has an M.S. in electrical engineering from the University of California, Los Angeles. He received The Aerospace Corporation President's Award in 1998 for his work in helping to invent a new signal structure for GPS. He is the author of more than 20 papers and holds one U.S. patent (steven.lazar@aero.org).

The Back Page

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A Brief History of Human Navigation

Commerce and conquest—perhaps the two greatest drivers of human civilization—have always depended on accurate navigation. Helen of Troy, through her beauty, may have launched a thousand ships, but the Greeks needed something more reliable to guide them to the battle. Fortunately for them (less so for the Trojans), the science of navigation was already well established by the time they set off across the wine-dark sea.

Indeed, the history of human navigation goes back thousands of years. With the rise of mercantilism in the ancient world, traders found that boats provided the easiest and most efficient means of transporting goods. As early as 5500 years ago, merchants in Mesopotamia and Egypt were building vessels large enough to carry goods on a commercial scale. Egyptian sea voyages are even recorded in hieroglyphs dating back to about 3200 BCE. The beginnings of navigation, as an organized study, can be traced to this period.

The mariners who steered these trading vessels needed accurate navigation to get to the next port safely. Typically, they remained close to shore and used geographic landmarks to guide them—a technique known as *piloting*. If they needed to venture out into the open water, they could make crude approximations of time and latitude by observing the height of the sun. When they traveled at night (which was uncommon), they used the moon, stars, and planets as celestial guides—assuming the sky was clear.

The Greeks and Phoenicians made great strides in navigation and developed techniques that remained in use for thousands of years. By some accounts, the Phoenicians were the first to use the Pole star for maritime navigation and the first to circumnavigate Africa. The Pole star, which remains fixed above the North Pole, was critical for early navigation because it allowed navigators in the Northern Hemisphere to gauge their latitude by measuring its height. The Greeks and Phoenicians also lit bonfires along shorelines at key locations, facilitating travel by night.

About the same time the Phoenicians were charting the Mediterranean, other seafaring cultures were exploring the vast expanses of the South Pacific. Like Western mariners, the Pacific Islanders used stars, currents, and migratory seabirds to find their way. Their star maps were particularly sophisticated, as evidenced by the remarkable distances—literally thousands of miles of open seas—that they successfully traversed.

Map courtesy of Dr. Seymour Schwartz

Mediterranean mariners also learned to keep records of a ship's direction, speed, and travel time to determine position—a technique known as *dead reckoning*. Starting from a known point, such as a port, the navigator would measure the heading and distance traveled in one day and mark that position on a chart. Each day's ending position would be the starting point for the next day's measurements. The system was notoriously inaccurate. Speed was estimated by watching seaweed or driftwood float by the ship, and travel time was measured by an hourglass.

Beneath overcast skies, navigators relied on guesswork and intuition to determine a ship's heading. A better method arose around 1100 CE, when the Chinese created the first magnetized needle compass. Eight or nine decades later, this invention would appear in Europe, too.

Indeed, the 12th and 13th centuries brought several navigational advances to Europe, including the lead line for determining sounding depths. This period also saw a florescence in the creation of nautical charts and celestial almanacs. Seafarers also rediscovered tools used by the ancient Greeks—most notably the astrolabe and the cross-staff. These devices were used to measure the elevation of the sun or stars above the horizon. To find the latitude of a ship at sea, the navigator would measure the height of the noon sun or a star of known declination and consult an almanac to find out what latitude corresponded to the data for that date.

A similar device was the Arabian *kamal*, a rectangular plate with a string attached in the center. Before leaving port, the navigator would hold the plate out until its upper and lower edges touched the North Star and the horizon and tie a knot in the string to mark the distance from nose to plate. To return to port from an unknown position at sea, the navigator would sail north or south until the plate again touched the North Star and horizon when held out at the distance marked by the knot, and then sail along that latitude toward port. Most kamals would have several knots to indicate the latitudes of frequently visited ports.

In the 15th and 16th centuries, trade with the Far East and exploration of the Americas intensified, fostering a renewed interest in navigational techniques. Merchants and their backers could not afford to lose even a single ship laden with spices or precious gold. Nonetheless, explorers such as Columbus still relied on dead reckoning and similarly unreliable techniques. Clearly, new methods and instruments were needed.

One such instrument, developed around the turn of the 17th century, was the *quadrant*, essentially a quarter of a circle with a plumb bob suspended from its apex. To determine latitude, the user would site the sun or a star along one vertice, letting the plumb line fall across the curved 90-degree scale, indicating the angle of elevation. Of course, staring directly at the sun is not without its drawbacks. Thus, a variation of the quadrant, known as the back-staff, soon gained preference, as it allowed the user to face away from the sun to make the necessary measurements.

Subsequent advances in optics led to the invention of the *sextant* in 1731. This instrument uses mirrors to generate images of the sun and horizon. To determine the height of the sun, the user would tilt one mirror using a calibrated dial until the image of the sun was precisely superimposed upon the image of the horizon. Not only was the instrument more precise, it was easier to use on a rolling deck.

Of course, sailors on the high seas were not the only ones who needed to know their position; explorers and cartographers traveling through the wilderness also needed such information. The sextant, however, was essentially unusable when the horizon was obscured by mountains or forests. To compensate, instrument makers began developing devices with artificial horizons. These advances would later play an important role in the development of the airplane and the submarine, which operate above and below the horizon.

Still, while latitude measurement improved, longitude measurement remained out of reach. Precise timekeeping seemed the logical approach, but the best clocks of the day lacked the precision or robustness to withstand choppy seas.

The “longitude problem” was so vexing that England established a Board of Longitude in 1714 and offered 20,000 pounds sterling to whoever could resolve it. Some of the greatest minds of Europe joined the race for a solution. Some believed that variations in Earth’s magnetic field held the key, while others insisted on celestial techniques. John Harrison trumped them all by building a chronometer that lost less than one second per day during long sea voyages. Still, the board was reluctant to confer the award on someone who was not a member of the established scientific academy, and Harrison—greatly embittered—had to wait until 1763 to collect his prize.

Harrison’s chronometer gradually gained favor, and the pace of navigational advancement slowed during the industrial era. Still, the ability to move and communicate over long distances by telegraph and railroad spurred the need for civil and military time coordination. Thus, in 1884, at the height of the British Empire, Greenwich, England, was established as the world’s Prime Meridian. Previously, each major nation established its own prime meridian and local time; the promulgation of Greenwich Mean Time did away with these, and standardized navigational readings throughout the globe.

After a period of relative quiescence, the 20th century brought an unprecedented wave of navigational advances. The century opened with the first transatlantic radio transmission by Marconi in 1901, followed by the first airplane flight by the Wright Brothers in 1903. These two events would soon become closely linked, in navigational terms. The rapid acceptance of the airplane necessitated navigational improvements, as pilots were essentially in the same boat as mariners centuries before. As a result, many navigational advances of the 20th century focused on aeronautical and astronautical techniques, although ships and ground vehicles also benefited from this work.

By the 1920s, the development of radio navigation was underway. By 1935, England had conducted a successful trial of the first radar system. By 1939, a chain of working radar stations was in place along the south and east coasts of England—and this system proved critical in the Battle of Britain the next year.

Radio direction finding thus became the standard for aircraft navigation, eliminating the need for celestial techniques. Radio in turn gave way to inertial guidance—which is essentially a highly sophisticated form of dead reckoning.

The Global Positioning System, of course, brought a revolution as great as any in the history of navigation. With the advent of GPS, users anywhere in the world could easily (and cheaply) determine their position with remarkable accuracy by passive reception of satellite signals.

But the story is far from over. As civilization reaches farther into space—where terms such as “horizontal” and “vertical” hold little meaning—new navigational techniques will be required. The earliest space flights used special sextants that measured the angle between the edges of Earth or celestial bodies to determine position. These sextants have since been replaced by electronic devices. Even geosynchronous satellites have begun using GPS signals for orbit determination.

As space vessels venture out beyond the reaches of the inner solar system, they will encounter new navigational challenges. Some of these will be met through techniques that resemble those used by the first sailors thousands of years ago. Others may require a whole new way of thinking about location and time.

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Summer 2002 Vol. 3 No. 2

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