The Global Positioning System

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Invited Paper

***Abstract*—The paper provides a top-level perspective on how the global positioning system works, how its services are used, and delves into the most important technical and geo-political factors affecting its long-term availability in an international setting.**

***Index Terms*—Global positioning system, GPS, navigation, satellite.**

I. Introduction

"Where am I," "Where are you," "How do I get there and how long will it take?"

UNCERTAINTIES in position and time have been vexing problems for all of mankind for millennia. In many cases, vexing has given way to life threatening, as humans have had to deal with challenges in navigation and synchronization where mistakes often have fatal consequences. Over the centuries, human ingenuity and necessity have led governments, companies, and individuals to construct a diverse mixture of technologies and mechanisms to provide answers. These run the gamut from sextants and mechanical clocks and watches measuring components of astronomical time to sophisticated radio signals (including radar) and highly precise clocks that measure time from transitions between quantum states in an atom.

I do not propose to detail that history, other than to note that it traces a centuries-long convergence of devices that manipulate physical measurement source locations and elapsed time into a single entity that uniquely enables continuous worldwide determination of highly precise three-dimensional position and time. That entity is the satellite-based global positioning system (GPS). My purpose herein is to give readers a top-level perspective on how GPS works and how we use its services and to provide insights into the most important technical and political factors affecting its long-term availability as the critical component in a dynamic international infrastructure.

The unheralded emergence of GPS is quietly, but effectively, revolutionizing the way modern society manages and uses the resources inherent in and related to position and time. In fact, the uniqueness of its integrating utility has stimulated the creation of a new word. Coined by Dr. Kirk Lewis of the Institute for Defense Analyses, the word "positime" (Pt) captures the essence of a marriage of three-dimensional position and time into a four-dimensional construct of immense usefulness in the future world of electronically enabled human endeavor. Further, the reality that its emergent contributions to international security and economic enterprise have already created dependencies that have gone largely unnoticed has led me to call GPS "the invisible infrastructure." I will address that invisible infrastructure from several perspectives: first, a brief description of how GPS operates, simple in concept, but complex in implementation; next, a summary of its myriad applications and some of the intricate technological relationships and dependencies that have already evolved; and finally, a brief overview of the complex political environment within which GPS is financed and operated by the U.S. government for its global multiplicity of benefits.

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II. An Elegant Convergence

GPS is a space-based positioning, navigation, and timing system developed by the U.S. Department of Defense (DoD). It emerged in the late 1960s and early 1970s as a merger of synergistic Navy and Air Force programs for timing and space-based navigation, respectively. The U.S. Air Force currently finances and operates the basic system of 24^{+} satellites and associated ground monitoring stations located around the world. GPS is widely characterized as a satellite navigation or a satellite positioning system, providing signals for geolocation and for safe and efficient movement, measurement, and tracking of people, vehicles, and other objects anywhere from the earth's surface to geosynchronous orbit in space. A less-known element omitted from many GPS descriptions is the embedded timing that serves an essential role in its navigation services. The precise time and stable frequency signals available from GPS are at least equal in importance to its navigation and velocity determination functions. They serve as synchronization sources for global communications, electronic transactions of all types, power-distribution networks, and innumerable other applications.

From its beginning, the GPS architecture was designed to minimize military navigation and timing vulnerability by moving the vital electronic processing and transmitting equipment into space to make them extremely difficult to reach. From there, GPS signals provide a multimission force multiplier service for an unlimited number of U.S. and allied military users. Though many believe civil applications only came along much later, in fact, GPS scope was expanded early in its development to include complementary civil capabilities as well.

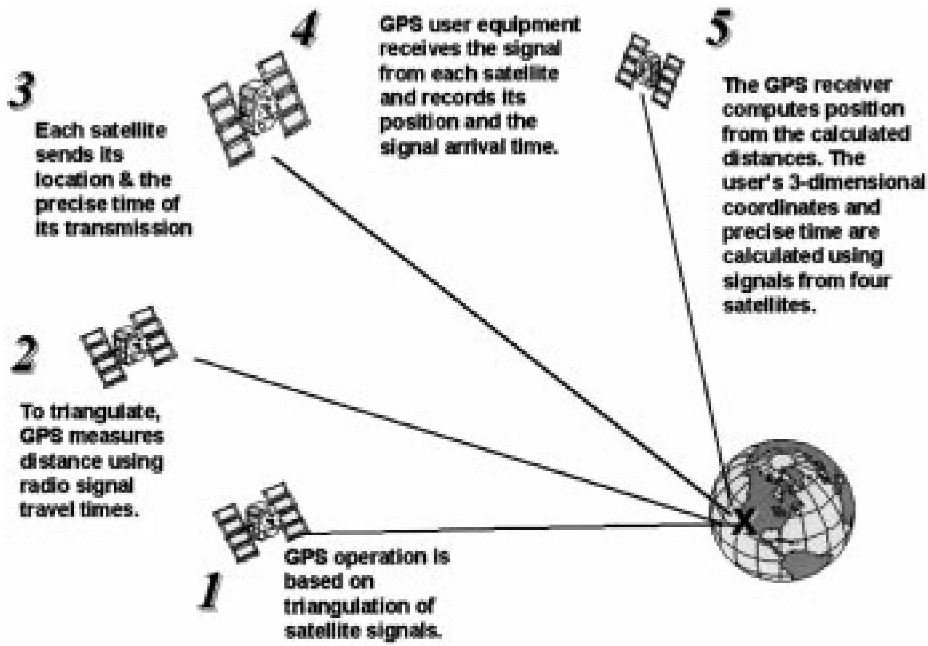

Fig. 1. How GPS works.

Simplistically, GPS implements a time-difference-of-arrival concept using precise satellite position and on-board atomic clocks to generate navigation messages that are continuously broadcast from each of the GPS satellites. These messages can be received and processed by users anywhere in the world to determine position and time accurate to within a few meters and a few nanoseconds, respectively (Fig. 1).

Each GPS satellite on-board computer and navigation message generator knows its own orbital location and system time very precisely. A global network of monitor stations carefully keeps track of these parameters. Corrections are uploaded to each satellite at least daily by the worldwide operational control system with Master Control Station at Schriever Air Force Base, Colorado Springs, CO. The uploads include orbit position projections for each satellite in the constellation, based on sophisticated models and effective for several weeks, as well as corrections to on-board satellite clocks. System time is maintained aboard each satellite by Cesium and Rubidium atomic frequency standards. In general, these on-board clocks are accurate to within a few nanoseconds of global coordinated time (UTC) as maintained by the Master Clock at the U.S. Naval Observatory (USNO) and are individually stable to a few parts in 10^{-13} or better. Early GPS satellites contain two Cesium and two Rubidium standards each, later versions have all Rubidium standards. Only one standard is operational aboard each satellite at any given time.

To produce accurate positions in three dimensions, a user must be able to see four GPS satellites, separated sufficiently and geometrically oriented in three-dimensional space so that processing will define a precise signal intersection. After much analysis, this basic requirement for simultaneous multisatellite global coverage resulted in a constellation design comprising 24 satellites at semisynchronous altitude (about 11 000 nautical miles) in six orbital planes, each of which is inclined at 55° (Fig. 2).

The GPS receiver uses the Pt information, broadcast in the navigation messages and traveling at the speed of light, to calculate approximate ranges to each of the satellites within line of sight to its antenna. These approximate ranges are called pseudoranges since biases in receiver clocks prevent the precise individual ranges from being determined directly. The pseudorange from each individual satellite defines a sphere on which a user may be located in three-dimensional space. The intersection of three spheres defines a point, though the intersection is imprecise due to the aforementioned biases in the receiver clock (which, in nearly all cases, is not an atomic clock) and to effects of ionosphere and atmosphere on the signal transit time. Addition of a pseudorange from a fourth satellite resolves the bias in the receiver clock and permits computation of the three physical dimensions of the precise intersection, as well as precise time. GPS operates within an Earth-Centered–Earth-Fixed (ECEF) reference frame so position determinations are essentially independent of the local topography, which must be accommodated by geodetic models within the GPS receivers. The baseline geodetic reference for GPS is World Geodetic Survey 1984 (WGS-84), though many other geodetic references are included in most GPS receivers.

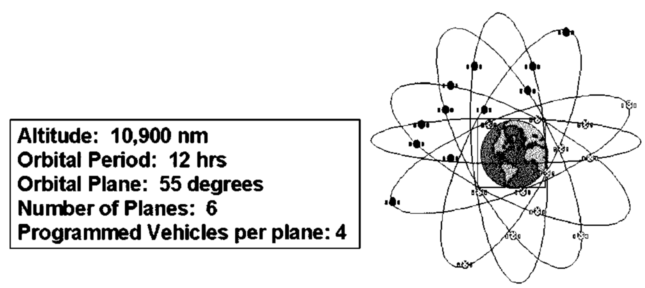

Fig. 2. GPS operational constellation.

The navigation messages are contained in two pseudorandom noise (PRN) code sequences (a Coarse Acquisition (C/A-code) 1023-bit-long sequence, repeating every millisecond, and an encrypted (Y-code) 6-trillion-bit-long sequence that repeats about every week), which contain information about individual satellite position and system time. The C/A-code is also commonly called the "civil signal" since it is unencrypted. Its frequent repetition permits rapid acquisition of GPS signals by all users. The GPS codes are transmitted from each satellite at two discrete L-band frequencies ($L1$ at 1575.42 MHz and $L2$ at 1227.60 MHz). Use of L-band frequencies minimizes effects of atmospheric phenomena on GPS signal transmissions. Further, transmitting the signals at two separate frequencies allows ionospheric effects to be determined and eliminated. The code sequences are different for each satellite, selected from a limited set of noninterfering codes called "Gold Codes," after their developer. Since all GPS satellites transmit at the same frequencies, the system uses Code Division Multiple Access (CDMA) to distinguish individual satellites by their unique code sequences. Within each GPS satellite, the C/A-code is clocked at 1.023 MHz and the Y-code is clocked at 10.23 MHz. The C/A- and Y-codes are used to phase shift-key (PSK) modulate the carriers, resulting in spread-spectrum signals of 2.046- and 20.46-MHz bandwidth, respectively. Use of spread-spectrum techniques permits the signals to be transmitted at very low signal strengths and recovered by receivers on or near the Earth's surface from below the noise floor. In fact, all the C/A and Y-code signals are received at the earth's surface at around -160 to -166 dBW. This has been popularly equated to viewing a 10-W light bulb from 1000 miles away. However, it reflects the power of spread-spectrum processing that makes the GPS resistant, but not invulnerable, to random, unintentional interference.

At present, only the $L1$ carrier is modulated by both codes, 90° out of phase with each other, and the $L2$ carrier is modulated only by the Y-code. However, within the next year or two (beginning with a replenishment satellite launch planned in 2003), modernization initiatives undertaken in 2000 by the U.S. government will create changes. First, a new civil signal, similar to, but more robust than the C/A-code at $L1$, will be added to the $L2$ carrier at 1227.6 MHz, joining the current Y-code. Next, another new civil code wider in bandwidth than the current C/A-code will be added at a new carrier frequency of 1176.45 MHz beginning with planned launches of the next generation of GPS satellites in late 2005.

All GPS signals are transmitted in relatively narrow portions of the L-band frequency spectrum that are internationally allocated for satellite navigation service use, and, as a result, may be protected from interference by adjacent higher power communications services. However, the extent of protection afforded by such allocations is questionable, as the finite resource of frequency spectrum is an increasingly valuable commodity, and initiatives to share spectrum are increasingly prevalent. At present, GPS military signals provide a slightly better level of precision and robustness than its civil signals, but, with system changes planned over the next several years, civil and military signals will be essentially equal in both precision and robustness.

III. Applications Beget Dependencies

The basic complement of GPS services has changed relatively little since program inception, and GPS has emerged as the quintessential dual-use system, which is of enormous benefit to myriad military, civil, commercial, and scientific users around the world. This multiplicity of uses pervades almost every aspect of GPS activity and provides the stimulus for its future improvement. Unfortunately, this diversity also acts against the system in its competition for resources, and I will summarize that situation later in this paper.

The fact of GPS success to date is unarguable. By any measure and definition, GPS is a stunning example of technological innovation and ingenuity. GPS remains the first and only global three-dimensional radionavigation and timing system providing continuous operational Pt service today. It has widely been called a "utility." In fact, GPS is a commodity service, provided as a public good by the U.S. Government (for safe navigation and other purposes) and freely available to all without direct cost or other encumbrance. It is not an overstatement to say that, in terms of application diversity, it is quite simply the most powerful positioning, navigation, timing, and synchronization technology ever conceived. This national technological resource has quietly, but quickly, become firmly established as an international utility supporting a variety of defined infrastructures.

Since the early 1990s, GPS has become a globally pervasive source of free and highly precise positioning and timing information. Its services (direct and derivative) are being increasingly incorporated into, and depended upon, by many of the critical national infrastructures supporting the defense and economic security of the U.S. These include telecommunications, electrical power distribution, banking and finance, transportation, emergency services, and military operations. Economically, as I will address later, GPS is a national asset whose applications return many times the investment in its development and implementation and considerably more than its annual sustainment cost. Militarily, GPS provides a constant worldwide source for highly precise position and time, both of which are essential to the safe and efficient conduct of military operations.

A general understanding of the full breadth of GPS services is essential to understanding the dependencies that grow from their ready accessibility. For many years, GPS was viewed with suspicion and skepticism by both its intended military customer base and by the federal civilian agencies through which it was intended to replace long-standing ground-based radionavigation aids. As the system reached operational status in the early 1990s, however, its consistent high-quality performance and low cost of use led to dramatic shifts in acceptance. Both the Coast Guard and Federal Aviation Administration (FAA) have initiated programs to augment GPS accuracy, and the FAA also sought to increase the assurance and availability of GPS-based services for aviation users. These and other initiatives will be discussed in detail below. The ubiquitous presence of GPS fosters its use as a generic utility that is enormously appealing to both government and commercial interests as a means of improving operating economy and efficiency in diverse infrastructures. To the maxim, "time is money," we can add the complementary phrase "and GPS is time." Taken together, the GPS Pt combination will drive fundamental changes in work processes and structures over the coming years.

IV. Telecommunications

Over the past decade, global timing and communications infrastructures have quietly adopted GPS as the primary distribution mechanism for time and frequency synchronization. The USNO serves as the nation's timekeeper and is by far the major contributor to the global timing standard Universal Coordinated Time (UTC). As a part of its mission, the USNO maintains its Alternate Master Clock at the GPS Master Control Station and provides the data necessary to steer GPS time directly to the USNO standard. As a result, the timing signal from the GPS satellite constellation [called UTC(GPS)] is being used internationally as a direct and globally available source of UTC. Since such satellite-based timing establishes a totally new means of distributing precise time around the world, actions are underway within the International Telecommunications Union to permit formal adoption of such time transfer by the international timing community. At the same time, major national and international telecommunications service providers, including both wireless and wireline technologies, have recognized the value of using the freely accessible GPS timing signals derived from the highly stable suites of atomic frequency standards aboard each GPS satellite. Beginning in the late 1980s, many have largely replaced their complements of ground-based atomic frequency standards in favor of receiving continuous (and free) precise time and frequency signals from GPS. With its signals providing a principal source of timing synchronization and frequency syntonization at the Stratum 1 (Primary Reference Source) level, GPS has become an essential component in the flow of digital data between multiple service providers, as one encounters in internet operations and in diversified telecommunications networks. Also, because of its accessibility, GPS has become an essential, but largely unknown, enabling technology for the economical operation of cellular telephone and other wireless media nationwide and around the world.

V. Electrical Power Distribution

Nationwide, many electric power companies have begun to use GPS timing and frequency services to improve the economy and efficiency of their operations. They primarily use GPS signals for monitoring stability of line frequencies, frequency synchronizing, or "syntonizing" services with adjacent power company networks, and isolating faults in their own transmission networks. The fidelity of service provided by GPS far exceeds the routine needs of power companies, but its ready free availability makes it very appealing, and the precise timing signal is useful in isolating damage in remote lines to within a single tower span. In addition, as electrical service deregulation and competition increase across the country, the interoperability dependencies between individual service providers will only heighten the importance of syntonization provided by GPS as companies must respond to widespread load variations and to system surges created by environmental effects such as solar storms.

VI. Electronic Commerce and Finance

Many banking and financial firms employ GPS timing for synchronization of their encrypted computer networks, though this function is, in most cases, hidden within contracted telecommunications services. Also, computer transactions are routinely time tagged, and with the advent of Internet trading, the precise timing of transactions is becoming more important. Presently, both the USNO and the National Institute of Standards and Technology (NIST) (part of the Commerce Department) are legally certified time stamping services for the purpose of determining financial transaction sequences. The mechanism for distribution of the precise timing signals across the Internet is GPS. As e-commerce and e-trading expand in the U.S. and internationally, the importance of precise time stamping will increase. Additionally, with recent interest by state and local jurisdictions in taxing Internet transactions, there is growing interest in use of legally authenticated GPS locations as a vehicle for assigning sales taxes to Internet purchases that currently are "locationless." Innovative applications of GPS signals have already been patented that use the combination of constantly varying GPS signals and precise time to create a "location signature" that is harder to forge than a written signature and harder to compromise than a password. These GPS-derived Pt signatures may well become essential complements to passwords and encryption as means of enabling and protecting all types of electronic commerce including communications, entertainment and high value financial transactions. As reliance on such innovations becomes embedded in the electronic financial infrastructure, it will further underline the importance of GPS signal continuity and the unambiguous combination of instantaneous position and time.

VII. Transportation

For many years during its implementation, GPS was viewed with some skepticism by the civilian transportation agencies through which it was intended to replace long-standing ground-based radionavigation aids. As it reached operational status in the early 1990s, however, its consistently high-quality performance and low cost of use created a dramatic shift in planning, as reflected in the Federal Radionavigation Plan. Two U.S. Department of Transportation (DoT) modal agencies, the U.S. Coast Guard and the FAA, initiated programs to augment GPS accuracy. The Coast Guard initially began with an differential augmentation service to provide sub-10-m accuracy around the contiguous U.S. (Maine–Texas and California–Alaska), the Great Lakes and St. Lawrence Seaway, and the Mississippi and Missouri River watersheds using marine radiobeacons. That service is now fully operational and actually operates at a precision of 1–2 m. In the aftermath of the Exxon Valdez accident, it has been officially (Act of Congress and Coast Guard regulation) added to the carriage requirements for oil tankers operating in proximity to land. The service has also been expanded to interior land applications in the last couple of years in a cooperative venture with the Federal Railroad Administration and the Air Force called Nationwide Differential GPS (NDGPS). NDGPS will transmit augmentation signals to provide 1-m accuracy to rail and other land users across the U.S. using low-frequency signals from the old Air Force Ground Wave Emergency Network, which is otherwise being dismantled. This service is specifically intended to support positive train control, but obviously has service implications far beyond railways.

At the same time, the FAA has also begun a multihundred million (now multibillion) dollar program called the Wide-Area Augmentation System (WAAS) to increase the accuracy, reliability, and availability of GPS-based services for aviation users by transmitting special augmentation signals over satellite communications links. The FAA WAAS is also a model for international civil aviation ventures called EGNOS (Europe) and MSAS (Japan) to provide seamless global augmentation to GPS. In addition to all this activity, foreign differential GPS services, mostly (but not all) government-sponsored, are widely available to serve a diverse range of positioning (Geographic Information Systems) and transportation needs.

Together, these international activities reflect an unparalleled commitment to satellite navigation services, and specifically to GPS. A common thread through all this activity is that each represents an augmentation to the core service provided by the GPS satellites—and none will operate on its own without the presence of the basic GPS signals. In most cases, the augmentations serve as checks on the quality of the basic signals, but together, they will soon represent an absolutely critical component of transportation economy and public safety.

VIII. Emergency Services

Closely related to GPS contributions to both communications and transportation are its contributions to the emergency services infrastructure of police, fire, and ambulance providers. Use of GPS is growing significantly among regional ambulance providers as a means of managing fleets of emergency vehicles. As its use increases in automobiles, it is becoming a significant factor in 911-type situations, where emergency vehicles are dispatched to accident locations by activation of a GPS location keyed to activation of an air bag. Further, GPS-derived positions are now being included in planning for E-911 capabilities required by legislation from cellular telephone service providers. GPS has also proven its value to fire departments operating in devastated parts of the California hills after the Oakland fire of several years ago, to the diverse government emergency response teams dealing with the aftermath of Hurricane Andrew in south Florida and with flooding in the midwest. While GPS use is growing rapidly in this sector, it has not yet reached the point of reliance, though incorporation in E-911 situations will dramatically increase its importance in the future.

One historical impediment to widespread adoption of GPS that is currently being addressed is the difficulty people in general have had in finding paper map products (even those printed from digital sources) that can be used with GPS equipment. Up to now, those paper maps that have grids printed on them can use any of several grid systems to identify locations. Many of the commercially proprietary grids do not permit precise locations to be determined, and virtually none work with GPS equipment. However, the U.S. Federal Geographic Data Committee in December 2001 approved a new standard grid for such applications that will eliminate this “Beta–VHS” confusion. Called the U.S. National Grid (USNG), this standard will permit easy depiction of positions to 10 m or less anywhere in the U.S. using a set of letters and numbers about the size of a telephone number. Since the USNG is based on the global standard grid called Universal Transverse Mercator, it is also nonproprietary and globally extendable. With a primary initial objective of reducing incident location uncertainty to speed up emergency response, USNG will also improve the effectiveness of GPS employment for a wide range of public and private applications.

IX. Military

Militarily, GPS provides an unparalleled force-enhancement tool. It is unique in its ability to establish an unambiguous correlation in four dimensions between a target and a dynamic weapon system aimed at that target—all the time, anywhere on the earth, and under any conditions of light, weather, or other source of target obscuration. Further, since it requires no electronic transmissions for access, it enables safe, efficient, and precise operations in situations where complete radio silence is required. Due to those performance features, both the DoD and Congress have mandated GPS for military operations. Its functionality is being installed and integrated into virtually every significant operational warfighting and support vehicle operated by the DoD and in extensive portable configurations as well. Its timing signal is also incorporated into many military communications nets in ways similar to commercial telecommunications networks.

Beginning with Desert Storm and continuing through the conflicts in Kosovo and today’s war on terrorism, U.S. military experience highlighted the importance of GPS to warfare in situations where collateral damage must be minimized and in which visibility is limited—regardless of cause. General Les Lyles, a former Air Force Vice Chief of Staff, spoke to the importance of GPS to the Kosovo operation, calling it “indispensable.” A review of any military planning document indicates that virtually all future operational concepts will require use of GPS military signals if they are to be affordably implemented. The DoD is now undertaking an initiative to incorporate several hundred million dollars of improvements into the system to increase its robustness and to separate military and civil signals in the frequency spectrum in order to facilitate localized tactical denial of GPS civil signals and prevent their use by hostile forces. The importance of these measures was significantly increased with the removal of selective availability accuracy degradation from GPS signal transmissions on May 2, 2000.

X. Practical Realities Intrude

Until very recently, this fundamental life-changing technology and our constantly growing dependence on it have largely escaped the notice of the mass media and popular scientific community (except for anecdotal reporting), yet, as we have seen, it directly affects the lives of millions on a daily basis. Consequently, the full extent of its contributions to the global infrastructure is understood by only a small segment of the technical population. The very fact that the far-reaching contributions of GPS are not well known to most people is both a reason for its success to date and a source of concern for its viability in the future. During its implementation, its relative lack of notoriety helped protect it from most political infighting as its underlying technological concepts were proven and its user bases became established. However, now that the nation has become reliant on its diverse benefits, its quiet emergence presents a problem. As an infrastructure enabling technology managed and operated with little fanfare by the government, it has not generated widespread awareness of the important role it plays in our national security and economy. This is particularly true among the members of Congress on whom it ultimately depends for financing. The myriad factors that have led to reliance on GPS—its multiple uses, incredibly successful performance, and the diverse constituencies it supports—create a political dilemma that raises concern for the future of the system in the hours of its initial triumph. The dilemma stems from the seemingly significant investments necessary to sustain and improve GPS services for all users. The budget to maintain and improve GPS and to develop and maintain civil augmentation services runs roughly between 800-million to 1-billion dollars per year. The majority of that funding is provided at present by congressional appropriations to the Defense Department, following earlier unsuccessful attempts to finance the system from a combination of military and civil accounts. That annual cost seems like a lot of money; however, it pales in comparison to the multisector economic benefits that GPS delivers through improvements in safety, efficiency, and economy of operations. A Commerce Department study undertaken in 1998 forecasted the annual worldwide market for GPS applications alone at 10-billion dollars by 2001 and surpassing 16-billion dollars by 2003.

XI. Financing and Politics

We might expect that these market projections, along with the technology base and infrastructure dependencies already identified, would be sufficient to stimulate long-term policy and financial support from the U.S. government. However, now that GPS has achieved its initial quiet success, its stewards must now contend with the relatively thankless, but critical, long-term struggle of maintaining and improving the system as a component of the national utility infrastructure. As such, GPS must compete continually for resources with glamorous new technologies that promise equally revolutionary results. At question is whether the framework that stimulated its initial success will be sufficiently robust to sustain and strengthen the evolution of the GPS utility into the future. Unfortunately, despite its tremendously successful implementation, funding for GPS activities has been haphazard and marginal in recent years. In the absence of broad-based public and commercial awareness of GPS contributions to public safety, economy, and comfort, and sharing of that awareness with elected representatives, the prospects for the situation improving are not assured. This awareness, however, is essential to ensure the continuity of financing necessary to maintain and modernize the system.

GPS was built to meet the *specific* requirements of the military and the largely *inferred* requirements of diverse civil users. To date, the military requirements have largely driven the best system performance, but the removal of the selective availability feature in May 2000 and the planned addition of more civil signals are bringing that same level of performance to global civil users.

Now that the diverse benefits promised by GPS during its development are being realized, the institutional situation, both domestic and international, has shifted dramatically. Many civil requirements for signal fidelity and availability have come to exceed military operational needs, and federal civil agencies have decided that separate individually financed augmentations to GPS would be the most effective way to meet those more stringent requirements. Experience has shown, however, that augmentations can be costly and suffer from their own competition for resources. Further, there are significant variations in augmentation cost and effectiveness, and changes to the basic system could mitigate the need for some augmentations entirely. The political ramifications of this changing situation stress the ability of the government to manage and finance this system-of-systems through existing institutional arrangements. Unfortunately, effective structural incentives do not exist in the government's program-execution process to promote multiagency coordination leading toward common objectives for the "national good." Consequently, this remains a continuing area of concern for those interested in systematic evolution of the technology.

Despite its financing issues, GPS has been characterized over the last two decades by stable and consistent service policies. While all the policies may not have been popular with all users, the consistency of their application has been highlighted by the U.S. GPS Industry Council as a crucial contributor to the growth of GPS-related business activity worldwide. A Presidential Decision Directive (PDD) was issued in March 1996 that redefined GPS policy management, but left most of the underlying policies regarding GPS services in place.

To manage GPS, the PDD created a formal Interagency GPS Executive Board (IGEB), jointly chaired by the DoD and DoT and involving other agencies as appropriate. It also assigned specific agency responsibilities to the DoD for sustaining and operating the basic satellite constellation, to the DoT as lead agency for civil interests and for civil augmentations to GPS and to the State Department for international outreach. However, it did not directly establish a process or mechanism for resolving disagreements resulting from shared budget responsibilities, which we have already seen is a troublesome reality of multiagency management situations.

As a further indication of national solidarity and resolve regarding the GPS resource, the Congress passed into law in Fall 1997 a measure complementing the PDD and amplifying some of its provisions. Together, the PDD and legislation provided bipartisan government-wide endorsement of the importance of GPS to the nation. They highlighted several areas of national interest, including GPS importance to national security, promoting broad acceptance of GPS services as standards for international use, facilitating use of GPS and augmenting its services for civil purposes, and encouraging international cooperation in GPS markets and use of GPS for peaceful purposes.

XII. Frequency Spectrum and Politics

The radio-frequency spectrum access issues facing GPS are both technically and politically complicated. By design, GPS operates at extremely low power, making it susceptible to certain kinds of interference if frequency spectrum use is not carefully controlled. GPS signals are transmitted in portions of the RF spectrum that are also very popular and in high demand for satellite communications services that generally produce the kind of interference most harmful to GPS.

Although GPS and communications services are quite synergistic in their applications, they are incompatible in their use of spectrum. GPS suffers from a tremendous disadvantage because of its low signal power. Some satellite communications service providers have already sought approval through the national and international regulatory processes for their signals to encroach on the GPS spectrum allocation, placing the viability and utility of GPS signals at serious risk. For technical reasons, moving the GPS signals or significantly boosting power from the satellites are *not* options.

As a result of this experience, Congress included statutory language in two bills passed in the fall of 1998 that further highlighted the importance of GPS to the national interest, stressing the need to efficiently use the spectrum in which GPS operates and to protect it from disruption and interference.

Complicating the situation are recent initiatives from a new technology called ultrawide-band. The emergent ultrawide-band industry seeks to produce equipment whose signals spread across all the frequencies where GPS operates, which could exacerbate this situation further. The additive effects of all these diverse transmissions on GPS are not well understood, and yet, commercial pressure for sharing of valuable spectrum places the viability of this national infrastructure component at increased risk in the face of competing interests that seek to overturn the concept of restricted frequency bands.

The financial burdens of conducting technical analyses, performing tests, publishing results, and internationally advocating support for preservation of the GPS spectrum create a major source of complication for the U.S. government. In contrast to the commercial satellite communications providers, the government has difficulties sharing costs among agencies, particularly in cases where unanticipated costs conflict with current-year budgets. In most of these cases, government agencies are unwilling to redirect funds from other activities, relying instead on GPS equipment manufacturers to provide data and test results or otherwise work out the problems in the marketplace. These bureaucratic realities complicate development of a coherent and deliberate GPS spectrum strategy, placing the system at a disadvantage *vis-a-vis* competing communications interests. At present, no effective structural solution to this dilemma has been identified, and the burden of proof to mount both technical and policy defenses against spectrum encroachment falls on in-place technologies such as GPS more so than on prospective new occupants of the spectrum. A partial solution may yet come from the congressional language that specifically admonished the DoD to take a leadership role in efficiently using and protecting GPS spectrum, but no substantive action has yet been taken. With the assurance of increasing demands for bandwidth and claims of "interference-free" sharing technologies, innovative approaches are necessary to more effectively manage this finite resource. Unfortunately, there is no "free" spectrum, and a reenergized multijurisdictional "band management" structure may be necessary to ensure control of the existing background noise floor. Since GPS signals already operate below the noise floor, signal aggregations that tend to raise the floor translate directly into reduced signal availability—an especially crucial concern for all safety-of-life services that depend on the interference protection afforded by restricted bands.

XIII. International Initiatives and Politics

The picture is somewhat brighter for U.S. government initiatives directed at building international awareness and acceptance of GPS services as world standards while supporting open-market competition in GPS equipment and applications. A Joint Statement on GPS has been in place between the U.S. and Japan since 1999. Talks to further U.S./Japanese cooperation in the commercial and scientific, transportation, and policy and public safety uses of GPS have taken place.

Discussions with the European Union (EU) are also underway. While no bilateral agreement has been reached, the U.S. initiative for an Open System Architecture has apparently struck a responsive chord with European agencies and officials. In February 1999, the EU announced a preliminary decision to undertake a European satellite navigation system called Galileo, advertised as being compatible with the GPS signal standard, even though it is planned as a separate system. Galileo has been in development within the EU since its announcement. Many details such as work sharing, financing, technical implementation, and cost recovery are still being worked out, but the overall strategy represents a promising approach toward international integration of a civil Global Navigation Satellite System (GNSS).

Possible limiting factors in the future integration of these systems into a seamless global service include issues related to the fundamental timing reference and to frequency spectrum/signal structure choices. Also, as is frequently the case in this arena, these technical issues can have significant policy and political implications. The selection and management of a timing reference is critical to the ability of these space-based services to continue providing a global source of time and frequency synchronization for faster and more complex international digital communications. As networked technologies continue to demand seamless service at increasingly higher data rates, the requirement for precision is likely to tighten beyond what is required for navigation. This will stress not only the source and management of the system timing function(s), but also the basic relativistic models that are embedded in the GPS control infrastructure and have sustained its operations to date. The selection and population of frequency spectrum with new signals by new entrants is equally important. As we saw in the previous section, new signals in the band must be carefully designed and implemented in the available spectrum to avoid interference or disruption to the existing low-power services already in place. Compatibility between GPS and a future Galileo or other system is the desired end state. Technical design choices that promote compatibility will provide benefits to both international security and economic enterprises because additional, easily accessible signal sources of comparable fidelity to GPS will improve service availability and performance for all. Conversely, design choices that undermine compatibility or interoperability with GPS could signal international policy shifts that will quickly transcend the technical arena and become a source of political and diplomatic conflict.

XIV. The Way Forward

For over 20 years, the GPS has benefited from service policies consistently set forth and applied that enabled its flourishing worldwide exploitation. With such a stable policy foundation in place, including assured continuity of separate military and civil signal resources available free of direct user fees, several key objectives for GPS services suggest themselves. Working to satisfy these objectives will promote continued growth in satellite-based Pt services, while expanding the myriad uses and international economic benefits derived from application of those services.

In order of priority, these objectives are as follows.

- Justifying use of and preserving adequate frequency spectrum for GPS, its augmentations, and complementary space-based services, so they may operate free of unintentional disruption and interference on a global basis.
- Continuing to improve the effectiveness and robustness of civil GPS as a commodity service operated for the public good.
- Capitalizing on the technology investment by continuing to evolve national security, economic, and scientific applications of the technology for the benefit of U.S. and global infrastructures.
- Consistently applying a customer-oriented service philosophy along with a policy of open signal availability to encourage international acceptance of civil GPS and its augmentations as international standards, while promoting open-market competition in GPS equipment and applications.

These suggestions represent essential elements for the continued successful evolution of this critical technology. Toward that end, national leaders must recognize and acknowledge the broader benefits this technology can make available to humanity and elevate GPS above the narrow interests of any particular department or constituency. Achieving that goal requires cultural change as well as executive and legislative commitment at the highest levels. The technology and vital infrastructure represented by satellite positioning and timing deserve that level of attention.

That the GPS record to date has been successful is unquestionable. It took about 25 years to turn an intriguing concept into an operational reality. That seems a long time in today's rapidly changing environment. However, when one realizes that the operational reality is a revolutionary global life-changing technology, the 25 years spent getting here become inconsequential. Now, the question is, how can that revolutionary capability be sustained, nurtured, protected, and improved to continue delivering its promise for future decades and the billions who will benefit from it?

XV. Information Sources

Additional general information, as well as more detailed information, is available from the following representative sources. [Online]. Available: http://gps.losangeles.af.mil/ (GPS Joint Program Office); http://www.navcen.uscg.gov/ (U.S. Coast Guard Navigation Center); http://www.ion.org (Institute of Navigation); http://www.gpsworld.com (GPS World Magazine); http://www.trimble.com (GPS equipment manufacturer); http://www.garmin.com/aboutGPS/ (GPS equipment manufacturer); books: *Understanding GPS: Principles & Applications* by Elliott D. Kaplan; GPS "*Red Books*" available through publications of the Institute of Navigation.

Jules G. McNeff received the B.S. degree in electrical engineering from the U.S. Air Force Academy, Colorado Springs, CO, in 1972, and the MBA degree from Harvard Business School, Harvard University, Cambridge, MA, in 1982.

His professional experience includes the following: Space and Defense Group, Science Applications International Corporation (SAIC); Executive Director, Military Issues, U.S. Global Positioning System Industry Council; Director, Public X-Y Mapping Project; Editorial Advisory Board, GPS World Magazine. He is involved with the advancement of GPS commercial interests broadly within SAIC and supports contractual efforts with the National Security Space Architect, which is involved in planning the evolution and use of space-based positioning, navigation and timing systems, and services of the future within the overall national space architecture. He possesses over 25 years experience in DoD systems development and acquisition, including over 15 years with the GPS. He has established numerous programmatic, acquisition, and security policies that the DoD have followed in acquiring and operating GPS. He has represented the DoD in all major system studies and policy deliberations affecting GPS from 1989 to 1996. He has negotiated domestic and international agreements for use of the military capabilities of GPS by U.S. Federal civil agencies, by the NATO nations, and by other allied and friendly countries. He has chaired the DoD team supporting a Joint DoD/DOT Task Force on Management and Operation of GPS, which produced the management framework that has now been institutionalized by the President and Congress for dual military/civil use of the system. He has represented the DoD on an Interagency Working Group responsible for preparation of a PDD on GPS.

Mr. McNeff was the recipient of a 1996 Stellar Award, selected by the Rotary National Award for Space Achievement Foundation based on his long-term efforts on behalf of the GPS program.