The Origins of

GPS

Stephen T. Powers, Brad Parkinson

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And the Pioneers Who Launched the System

The original system study, the key innovations, and the forgotten heroes of the world's first — and still greatest — global navigation satellite system. True history, told by the people who made it. Part One of a Two-Part Special Feature.

The stealth utility: over the past 30 years, a new entity has steadily and stealthily crept into the fabric of worldwide society, creating capabilities and dependencies that did not exist before. This utility is known as the Global Positioning System, or GPS. With more than a billion GPS receivers in use, this stunning achievement has truly revolutionized the way the world functions in the 21st century. Virtually every cell-phone system relies on GPS for timing. Almost every ship and aircraft carries multiple GPS receivers to provide positioning information. Other applications span military targeting, transportation, object tracking, and resource identification. Today, the loss of GPS signals would have catastrophic consequences.

How did GPS come into being? What technologies were essential to its success? Who developed those technologies? Recently a number of GPS histories have appeared that are very inaccurate on these subjects. Our purpose in writing this account is to set the record straight, and in so doing to give credit to many of the original developers of GPS whose contributions have somehow been forgotten. Throughout this article you will find their names highlighted. Space does not permit us to name the many other individuals who deserve enormous credit for the subsequent refinement and invention of new GPS applications.

Figure 1 gives a summary view of the history of U.S. satellite-based navigation, particularly GPS. Details of the Russian GLONASS and the European Galileo systems are not included as they arrived later, and generally mimicked the GPS development albeit with their own, locally developed detailed designs.

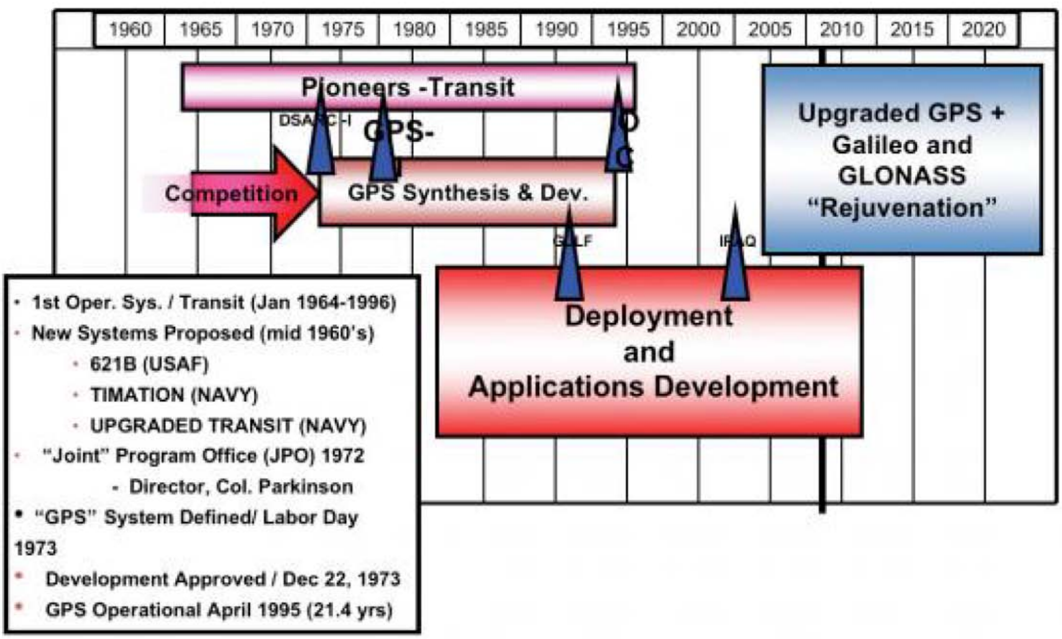


Figure 1. The eras of satellite navigation.

Dr. Richard Kershner, who led the development of Transit. On his left, young Col. Bradford Parkinson, who led the development of GPS.

This history focuses on the period up to about 1980, when GPS was approved for full-scale development. Between that time and the date that GPS was declared fully operational, April 27, 1995, many additional contributions were made. The system withstood several early attempts by the Air Force to cancel it entirely. Fortunately, those attempts did not succeed, and the Air Force now fully embraces GPS as an essential part of virtually every weapon system in the inventory.

We call this a tribute to the almost-forgotten people whose intellectual labor and skill initially developed GPS. As we unveil this story, we will point out the original — and critical — system study, the 1966 Woodford/Nakamura Report, that became the essential blueprint for GPS. Many people are unaware of this study since, in its original form, it was classified U.S. Department of Defense (DoD) Secret. It was not declassified until August 1979, more than a year after the first launch of a GPS operational satellite in February 1978.

We also intend to describe and justify the key innovation that enabled the system. This keystone technology is the GPS code-division multiple-access (CDMA) signal. While CDMA was necessary for GPS success, it was by no means sufficient.

We will also define and describe the five major original challenges that had to be met to achieve the success that GPS now enjoys; that will come in the second installment of this history, to appear in next month's issue.

Mathematician Bill Guier (l) and physicist George Weiffenbach (r), told APL Research Center director Frank T. McClure (c), about their success using Doppler tracking for satellites. "McClure's brain started going into fast forward," remembered John Dassoulas. "Knowing the navigational challenges the U.S. Navy faced, McClure said, 'Well, if you can find out where the satellite is, you ought to be able to turn that problem upside down and find out where you are.' "

GPS Predecessors: Transit

On October 4, 1957, the entire world was amazed by the launch of Russia's Sputnik satellite. The American public greeted this event with both apprehension and curiosity. Both the Army and Navy had been quietly working on satellite projects for some years. In an attempt to catch up, the United States had a spectacular failed launch when the Naval Research Laboratory's (NRL's) TV-3 crashed on December 6, 1957. On January 31, 1958, the United States Army launched a grapefruit-sized satellite, Explorer 1. The NRL then achieved success with the launch of TV-4, renamed Vanguard-1, on March 27, 1958.

In 1958, the Applied Physics Laboratory (APL) of Johns Hopkins University employed an extremely competent team of engineers and scientists. Two of those scientists, **Drs. William Guier** and **George Weiffenbach**, began to study the orbits of the new Sputnik satellites. The satellites were broadcasting a continuous tone signal. Their velocity relative to the ground created a Doppler shift of that signal that was unique. After some innovative work, Guier and Weiffenbach discovered they could determine the Sputnik's orbit with a single pass of the vehicle.

At that point **Frank McClure** of APL made a very creative suggestion: Why not turn the problem upside down? Using a known satellite position, a navigator could determine his location anywhere in the world after receiving and processing the satellite signal for 15 minutes. His insight became the basis for the Navy's Transit satellite program, also known as the Navy Navigation Satellite System (Figure 2).

This pioneering system was developed under the leadership of **Dr. Dick Kershner**, head of the Space Department of APL. Transit's main purpose was to provide position updates to the United States submarine ballistic-missile force then under development. These submarines were a major deterrent during the Cold War. Transit was first tested in 1960, and by 1964 the system was fully operational. Under Kershner, APL rapidly mastered the art of building long-life satellites. In fact, two of the vehicles continued operation for more than 20 years.

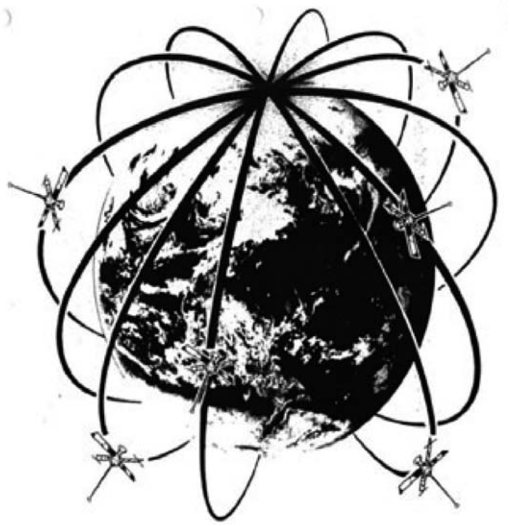


Figure 2. The Transit birdcage of operational orbits.

Transit was a relatively small satellite that initially used solar power and gravity-gradient stabilization (Figure 3). It provided a position fix every few hours; fixes took 10 to 16 minutes of exposure of the submarine's antenna on the surface. It achieved 25-meter accuracy, but only in two dimensions. Further, if the user was moving, accurate velocity measurement was critical: a 1-knot error would produce a 0.2-nautical mile position error.

All Navy ships could use the system, and in 1967 Transit was offered to the civilian community by Vice President Hubert Humphrey. Magnavox became the principal developer of civil user sets with **Tom Stansell** as an early expert in the technology.

Contributions to GPS. The Transit program developed a technique essential for GPS: the use of two frequencies to calibrate the time delay of the radio signal induced by the ionosphere. This dual-frequency technique was incorporated into GPS to attain the highest positioning accuracy. In addition, Transit also pioneered the accurate prediction of satellite orbits, another essential GPS technology. Orbit prediction will be highlighted later, as one of the five fundamental challenges that faced GPS system designers.

In 1974, Transit made a further contribution to GPS development that we discuss in that approximate timeframe.

Figure 3. A Transit satellite showing the gravity-gradient boom that kept the antennas pointing at the earth.

Program 621B

As early as 1962, **Dr. Ivan Getting**, president of the Aerospace Corporation, saw the need for a new satellite-based navigation system. He envisioned a more accurate positioning system that would be available in three dimensions, 24 hours a day, seven days a week. He had direct access to the highest levels of the Pentagon and was a tireless advocate for his vision.

Getting's energy and foresight in the early 1960s were essential to gaining Air Force support to study system alternatives. As a result, the Air Force formed a new satellite navigation program that was later named 621B. Getting's efforts were recognized in 2002 when he shared the Charles Stark Draper Prize of the National Academy of Engineering with Bradford Parkinson.

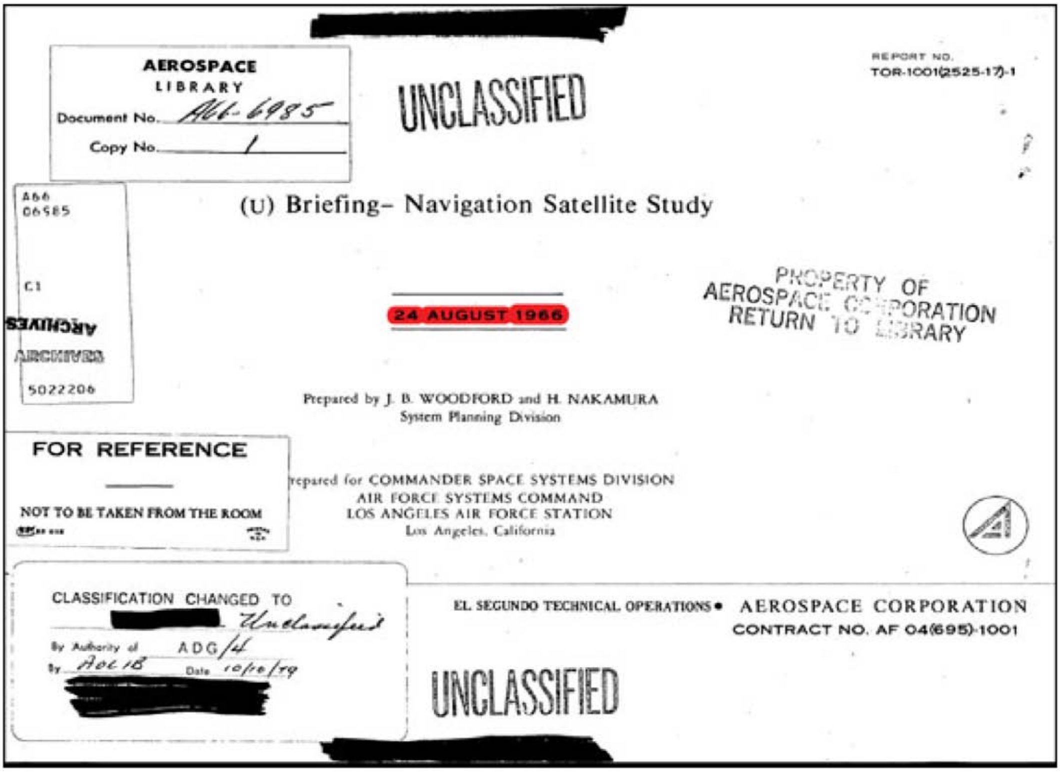
By 1962, engineers at Aerospace, under Air Force sponsorship, were heavily immersed in studying the system aspects of a new navigational satellite system. From 1964 to 1966, Aerospace carried out an extensive, formal system study whose principal authors were **James Woodford** and **Hideyoshi Nakamura**, both highly regarded space-systems engineers.

Their work was summarized as a DoD secret briefing in August 1966. As a result of the classification, it was unavailable to anyone outside the project until 13 years later, in 1979, when it was finally declassified (figure 4).

The Woodford/Nakamura Report was a complete system study that examined these issues:

- capabilities and limitations of then-current DoD navigation systems;
- tactical applications and utility of improved positioning accuracy;
- comprehensive analysis of alternative system configurations and techniques for positioning, using satellites.

The report concluded with a set of recommendations for advanced technology development for navigation satellite programs.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(U) Briefing– Navigation Satellite Study

24 AUGUST 1966

Prepared by J. B. WOODFORD and H. NAKAMURA
System Planning Division

Prepared for COMMANDER SPACE SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
LOS ANGELES AIR FORCE STATION
Los Angeles, California

CLASSIFICATION CHANGED TO
[redacted] Unclassified
By Authority of ADG/4
By Aoe 18 Date 10/10/79
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EL SEGUNDO TECHNICAL OPERATIONS • AEROSPACE CORPORATION
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Figure 4. Front page of the seminal GPS system study performed from 1964 to 1966 by USAF 621B Program. Originally classified secret, it was not declassified until after the initial GPS satellite had been launched. This was the essential foundation to the GPS System design.

The detailed analysis of possible passive navigation techniques was extremely important. It pointed out that the most capable passive-ranging design, called triple delta rho, would eliminate the need for an extremely stable clock in the user equipment and would provide three-dimensional positioning. (In this article we use clock, oscillator, and frequency standard interchangeably. The timing community makes some distinctions among these words, but for purposes of this history the distinctions are not particularly important.) This later was selected as the fundamental GPS system concept of ranging to four satellites simultaneously.

Key conclusions of the 1966 study advocated:

- passive ranging from the satellites (the issue was which ranging signal to use)
- atomic clocks in space, and a technology program to develop space hardened atomic clocks
- further system studies as well as experimental demonstrations.

Since the full survey of alternative system configurations was extremely important in selecting an optimum system configuration, we reproduce the summary in figure 5. Note that the “Computation Performed by User” is split into two columns. Focus on the columns of the one-way passive ranging techniques with the red outline. Inside, there are two “user boxes,” one with A and one with X. The A shows the user needs an atomic clock. The X shows the user needs only a crystal clock. The option later selected for GPS is designated as G. This technique is the 3Δρ (triple delta rho, or four satellites) that eliminated the need for the user atomic clock, and provided three-dimensional positioning (really four-dimensional since it also captured time).

In October 1970, more than four years after the completion of this study, Roger Easton of NRL applied for a patent on the two-satellite, ρ-ρ technique (option N) that required an atomic clock for the user and was only two-dimensional. The patent (U.S. 3,789,409) was granted in 1974, a year after the three-dimensional design of the GPS system had already been defined in the Lonely Halls Pentagon meeting to be described later.

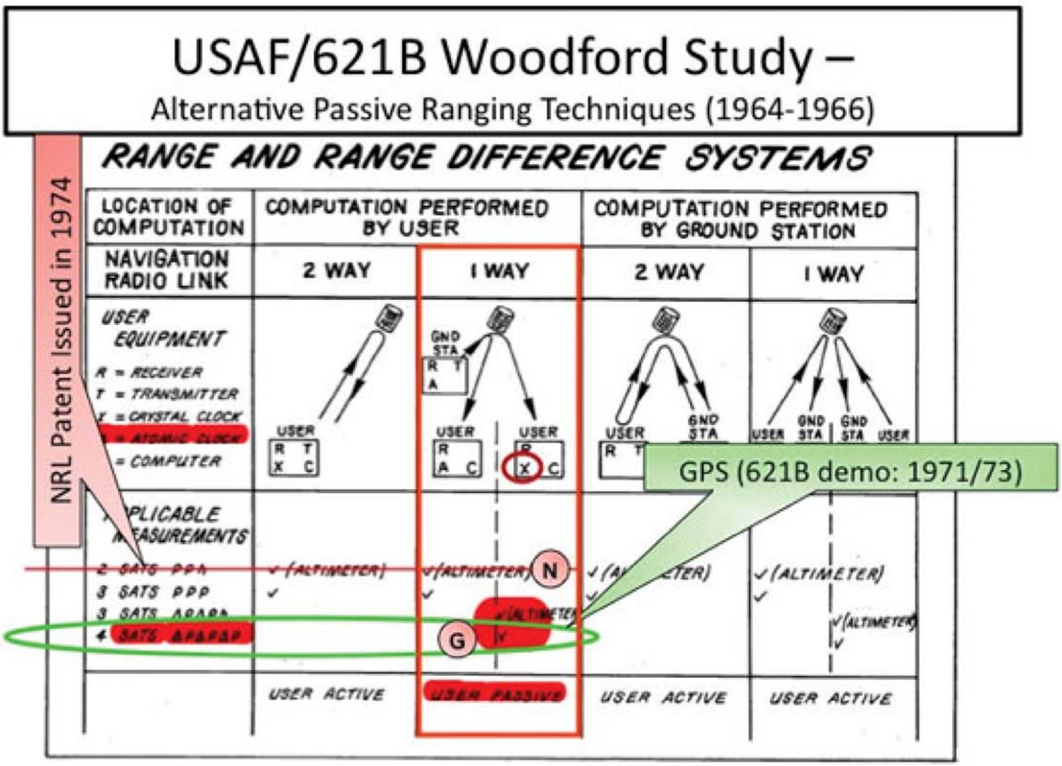


Figure 5. Summary of the alternative satellite-based navigation techniques from the1964–66 USAF/621B study. The most capable option, circled in green, became the basis for the White Sands prototyping and testing, and then evolved into GPS. NRL applied for a patent on the less capable technique (red line) four years after the Woodford/Nakamura Study was completed.

DR. IVAN GETTING, believed to be the earliest significant proponent for a new navigation system by 1962. He provided important support for GPS at the highest level of government.

HIDEYOSHI YAKAMURA, one of the authors of the key report on competing satellite navigation systems that identified the strengths of 621B for three-dimensional positioning.

JAMES WOODFORD, co-author of the report that advocated passive ranging, atomic clocks in space, and experimental demonstrations to prove the validity of nascent GPS concepts.

More 621B Studies. From 1966 to 1972, program 621B continued with trade-off studies including: signal modulation, user data processing techniques, orbital configuration, orbital prediction, receiver accuracy, error analysis, system cost, and comprehensive estimates of the tactical mission benefits. More than 90 reports completed by USAF/Aerospace during this period remain available in the Aerospace Corporation library.

PRN or CDMA Signal Structure. Of these studies, the most important were those aimed at selecting the best passive ranging technique for the navigation signal. By 1967, it appeared that the best technique was a variation of a new communications modulation known as CDMA. Pioneering this signal were several outstanding scientists, **Dr. Fran Natali** and **Dr. Jim Spilker** (both of Philco-Ford), and **Dr. Charlie Cahn** (of Magnavox).

Jim Spilker, one of the creative geniuses who helped develop the GPS signal structure. See his article on binary coded symbols on page 8 of this issue.

Charles Cahn, an important contricutor to GPS signal design. He advocated a C/A code length of 2047 chips, while Spilker wanted 511; Parkinson split the difference.

Robert Gold invented the technique that selected orthogonal modulation codes. This allows more than 50 satellites to broadcast on the same frequency.

Tom Stansell was a member of the Magnavox team that developed civil Transit receivers. He later became an advocate for GPS.

This signal has many names. In addition to CDMA, it is sometimes called spread spectrum, since the energy of the signal was spread over a wide range of radio frequencies. It is also sometimes called PRN or pseudorandom noise because the encoded (and repeated) sequence appears to be random transitions of +1 and -1.

The name code-division is used because each satellite is assigned its own coded signal. Each was a binary (digital) sequence selected to be uncorrelated with other signals and also uncorrelated with time shifts of the signal itself. The expected, powerful advantage of this technique was that all satellites would broadcast on exactly the same frequency. It would clearly lend itself to digital signal processing. Furthermore, and very important, any time-shifts induced by the receiver for the various satellite signals would be effectively eliminated.

However, several significant questions concerning CDMA still needed resolution. These included:

- Could such a signal be easily acquired in the face of time uncertainty and Doppler shifts?
- Was there a technique to encrypt the military signal so that unauthorized users could not gain access?
- How would the codes be easily selected to avoid a false lock and also allow additional satellites to be added without interfering with existing satellite signals?
- Would the anticipated complexity of the receiver drive costs to unacceptable levels?
- Was the signal resistant to accidental or deliberate interference?
- Could this signal accommodate communication capability for satellite location, satellite clock correction, and other parameters?

Fortunately, in 1967 a technique for selecting orthogonal codes was invented by an accomplished applied mathematician, **Dr. Robert Gold** of the Magnavox Corp. Naturally these are now known as the Gold codes. His solution resolved the third CDMA issue stated above.

White Sands Tests. To address the remaining issues, the 621B program developed two prototype versions of CDMA navigation receivers (Magnavox and Hazeltine) for testing at the White Sands Missile Range (WSMR). For these initial 1971 tests, 621B arranged four transmitters in a configuration known as the inverted range. (Interestingly, the more capable receiver was the MX-450 that was only on loan from Magnavox.) These transmitters broadcast CDMA signals from locations that were similar to a satellite configuration except that they were broadcast from the ground. For the simulation of satellite geometry, a balloon-based transmitter was also included for the aircraft-landing tests. **Al Gillogly** of Aerospace spent many hours installing and troubleshooting the test configuration.

Al Gillogly, Aerospace engineer (left), setting up the critical tests of prototype GPS receivers at WSMR in 1970.

By 1972, program 621B had successfully proven the effectiveness and accuracy of the CDMA signal by demonstrating that such a configuration would achieve 5-meter, 3-dimensional navigation accuracy. Much credit for the painstaking analysis of these results should go to **Bill Fees** of Aerospace who wrote the final detailed test report. These test results answered most of the remaining issues regarding the CDMA signal.

The tests also confirmed the power of the modulated signal by showing that all satellite signals could, indeed, be received simultaneously on the same frequency. These tests also corroborated the expectation that ranging to four satellites eliminated the need for a highly precise user atomic clock, while still supporting full, three-dimensional navigation. This became an extremely important feature of GPS. If each user had required an atomic-clock class frequency-standard, no inexpensive user equipment could have been produced within the technology horizon visible at that time. This is still true today.

All this evidence supported CDMA as the passive ranging signal of choice and was available to the Air Force's 621B team when the system configuration was selected at the September 1973 Pentagon meeting that will be discussed later.

621B Demo, Operational Differences. From the time of the 1966 Woodford/Nakamura study on, the Air Force and Aerospace advocated the use of atomic clocks in the operational satellites with the modulation also originating in the satellites. There were two significant risks to placing atomic clocks in the satellites: First, the technology readiness risk: no hardened atomic clocks had yet been designed and flown; and second, the political/budgeting risk associated with gaining approval for a development/demonstration program for the full capability. The Air Force developed a plan to reduce both risks.

In late 1968, the Air Force's NavSat program in the Plans Office (XR) at the Space and Missile Systems Organization (SAMSO) was redesignated as 621B. All of the various proposals that went forward from SAMSO to Headquarters came henceforth from the 621B office in XR. This included a proposal in early 1972 to deploy a four-satellite demonstration system. This proposal addressed both risks. It would reduce the technology readiness risk in the clocks by launching simple L-band transponders. At the same time, it would save substantial money, thereby reducing the political/budgeting risk.

In many circles, this proposal was erroneously thought of as 621B because it came from that office, but in fact, the operational concept for 621B never contemplated or advocated using transponders in the final operational system. Transponders had been rejected for the operational system because they could be easily jammed from the ground. Such a jamming signal would overpower the transponder and steal all of the transmitted energy away from the transponded navigational signal. This enemy jamming would shut down the entire system, clearly an unacceptable risk.

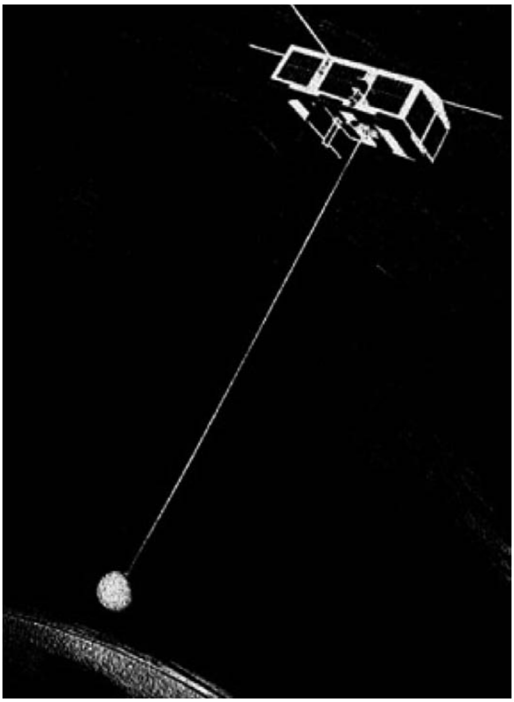
Figure 6. The Japanese QZSS has a similar constellation to an early proposal for GPS under 621B.

Proposed Initial Constellation. To demonstrate four-satellite, passive ranging capability, 621B had studied a number of orbital configurations, including geo-synchronous and lower inclined orbits. The program proposed to place a constellation of three or four synchronous satellites in orbits over the United States. This array would allow extended periods of four-satellite testing without committing to a full global employment. If this demonstration were successful, the next step would have been to add three more longitudinal sectors, each with its own array. Again, the principal redeeming feature of this approach was that there was some hope of it being funded. The Air Force in the Pentagon placed enormous pressure on the 621B program to come up with the absolutely cheapest way to demonstrate the four-satellite approach.

This proposed constellation design was a reasonable compromise, given the boundary conditions of a four-satellite demonstration and absolutely minimal cost. It is interesting that the Japanese, with a requirement to supplement GPS with satellite signals to improve coverage in urban areas (where there are high shading angles), have designed a very similar constellation. The Japanese configuration is intended to improve coverage restricted to their longitudinal sector of the globe. The new system is called Quasi-Zenith Satellite System (QZSS), and the Japanese appear to be well on the way to fielding it.

Timation and NRL

In 1964, the U.S. Navy initiated a second satellite program, named Timation, under the direction of **Roger L. Easton,** Sr., a long-time member of the NRL staff. The NRL's Timation project was aimed at exploring techniques for passive ranging to satellites, as well as time transfer between various timing centers around the world. This project ran parallel to, and was in competition with, the Air Force Program. It subsequently developed a number of experimental satellites, the first of which was called Timation 1. This small satellite, weighing 85 pounds and producing 6 watts of power, was launched on May 27, 1967.

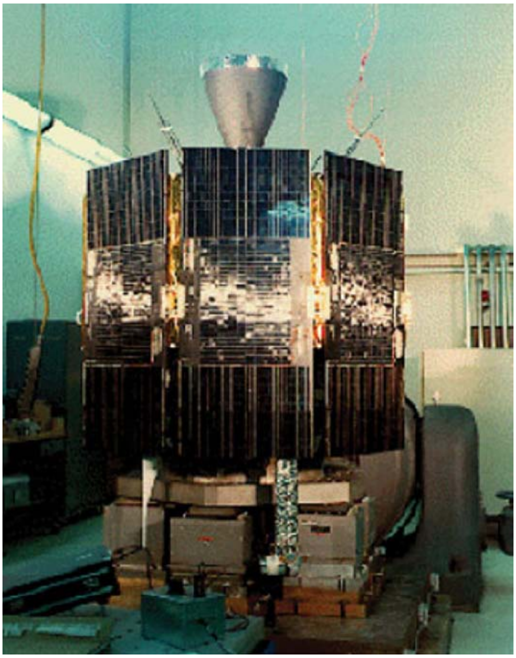


Timation 1, developed by NRL, was a miniaturized, innovative design. The quartz clock was less stable than expected, apparently due to temperature and cosmic-ray effects.

The key feature of Timation 1 was that it included a very stable quartz clock. The fundamental ranging technique was to synchronize a clock at the user's location with the clock on the satellite and use a passive-ranging signal structure called side-tone ranging. By 1968, NRL demonstrated single-satellite position fixes, accurate to about 0.3 nautical miles, that required about 15 minutes of data collection (Global Positioning System, Volume 1, chapter "Navigation Technology Program," R.L. Easton, p.16). NRL engineers encountered two significant problems during their testing: solar radiation caused shifts in the clock's frequency, and ionospheric group delay created ranging errors.

The NRL launched a second satellite, Timation 2, into a 500-mile orbit on September 30, 1969. To calibrate ionospheric group delay, the satellite broadcast on two frequencies very similar to the technique pioneered by the Transit program. Its quartz oscillator was expected to be somewhat more stable, about one part in 1011. Again, a large frequency shift was observed in the clocks that was finally traced to a solar proton storm. NRL was able to demonstrate ranging accuracies of approximately 200 feet to a fixed location.

Timation NTS-1. The last satellite in the original Timation series was launched in July 1974. By that time the Timation program had been placed under the GPS Joint Program Office in Los Angeles, reporting through the Navy Deputy, **Cdr. Bill Huston,** to the Program Director Col. Bradford Parkinson. The JPO had renamed the satellite as Navigation Technology Satellite (NTS-1). The gross weight had been increased to 650 pounds with a power requirement of 125 watts. This satellite, developed by **Pete Wilhelm** of NRL, was placed at an orbital altitude of 7,500 nautical miles.



Timation NTS-1 carried two slightly modified commercial rubidium clocks.
Unfortunately, attitude-stabilization problems induced temperature variations that masked any quantitative performance evalulation.
The atomic clocks were not useful as prototypes for GPS.

The NTS satellites were strictly technology-testing satellites. For many reasons, they had no role in the development of the operational satellites by the JPO and Rockwell. The latter were operational satellites and were called NDS, for Navigation Development Satellites. They were the only ones used in the operational testing during phase I of GPS.

NTS-1 included two small, lightweight rubidium oscillators as clocks. A German commercial company called Efratom had independently developed these models. Amazing at the time, they only consumed about 13 watts of power and weighed some four pounds each. Further Efratom involvement will be pointed out later. While NRL made some electronic modifications, the modified clocks were not in any sense able to withstand the radiation of the GPS orbits. The NTS-1 clocks were certainly not prototypes for the Rockwell clocks that were developed directly for the JPO and flown on the first block of GPS satellites.

NRL tests showed that the modified rubidium clocks had an unacceptable level of sensitivity to temperature variations. **Al Bartholemew** of the NRL later wrote that "the lack of attitude stabilization system on NTS-1 resulted in large temperature variations which ultimately masked any quantitative evaluation of rubidium standard performance." (Global Positioning System, volume 1, chapter "Satellite Frequency Standards," C.A. Bartholomew, p. 25.) This apparently occurred because the satellite used a two-axis gravity gradient stabilization system that does not function well at these altitudes. The Navigation Development Satellites (NDS) satellites, later developed by the JPO, avoided this by developing a new, full three-axis, attitude-control system. NTS-1 carried other space technology demonstrations including highly efficient solar cells.

Later, NRL developed a second (and last) satellite (NTS-II) for the GPS Program Office, after the Pentagon had approved the project in December 1973. The vehicle included two modified cesium beam oscillators developed by Frequency and Time Systems Inc. (FTS) of Danvers Massachusetts. The key atomic clock developer was the engineer and creative entrepreneur **Robert Kern.** This clock showed great initial promise but it was not yet a space prototype in terms of radiation hardening and parts life. In addition, the JPO provided a Rockwell-developed navigation payload for NTS-II that the JPO had developed for the operational GPS satellites. This would allow the NRL satellite to broadcast the GPS CDMA signal.

Bob Kern, who founded FTS and Kernco. Superb engineer and creative entrepreneur. He designed and built the first operational space-borne Cesium clock that was verified on the fifth GPS vehicle.

Bill Fees wrote the final test report detailing 621B's effectiveness and accuracy with a CDMA signal.

Lt. Gen. Ken Schultz appointed Col. Brad Parkinson as 621B Program Director (later GPS). His strong support, particularly in recruiting talent for the JPO, was essential in creating the competence and skills of the GPS Program.

NTS-II was launched on June 23, 1977, from Vandenberg Air Force Base. Originally it was hoped that NTS-II would be a part of the initial GPS test constellation. It could then have supplemented the satellites being developed by Rockwell, providing another passive ranging signal for the user equipment tests at Yuma Proving Ground. Unfortunately, the NRL ranging transmitter in NTS-II failed prior to the launch of the first JPO NDS satellites, rendering the NRL satellite unusable for the Yuma Proving Ground testing. "Of the two experimental cesium standards carried on NTS-II," **Ron Beard** of NRL wrote, "one experienced a power supply failure after a period of satisfactory operation." It is known that the other cesium clock continued to operate for over a year, but quantitative drift rates on orbit were never available. As a result of these failures, the cesium clock tests were inconclusive. (Proceedings of the IEEE 43rd Annual Symposium on Frequency Control, 1989, R.L. Beard, p. 276.) Only tests with the first four JPO/Rockwell satellites were available to support the full-scale development approval on June 5, 1979.

For the next step, NRL defined a radiation-hardening program and contracted with FTS to develop a hardened cesium clock. This new clock was flown on the fourth operational GPS satellite (NDS 4, launched December 10, 1978). Unfortunately, the clock suffered a premature failure of the power supply after only 12 hours of operation. FTS soon found the root cause and fixed the design. Beginning with NDS 5, the on-board cesium clocks performed well and were equal or better in stability to the Rockwell rubidium oscillators.

Competition, Lonely Halls

By 1972, a few Pentagon authorities had recognized that a new satellite-based navigation system would be a valuable asset with multiple military applications. Literally hundreds of positioning and navigation systems in use by the DoD were expensive to maintain and upgrade. Obviously, a single replacement system offered significant cost savings. Unfortunately, the two competing concepts from 621B and NRL apparently confused the decision-makers. Discussions grew very acrimonious at times. As a result of this inter-service competition and a reluctance to commit the necessary monies, the Pentagon put off making any decision.

In November of 1972, Col. Bradford Parkinson was the director of engineering for the Advanced Ballistic ReEntry Systems Program (ABRES) at SAMSO. **Brig. Gen. Bill Dunn,** who led the advance planning group (XR), identified Parkinson as a potential candidate to head the floundering 621B program. At Dunn's behest, **Lt. Gen. Kenneth Schultz,** commander of SAMSO, asked Parkinson if he would like to be assigned to the 621B program. Parkinson had a very relevant background in navigation, guidance, and control that included a Ph.D. from Stanford in astronautical engineering. He had been chair of the Astronautics Department at the U.S. Air Force Academy, spent three years as a guidance analyst at the Central Inertial Guidance Test Facility, and was operationally oriented with 26 combat missions in AC-130 gunships.

The background was a match, but Parkinson expressed an unwillingness to volunteer for the assignment if he were not assured that he would be the program director. Schultz said he could not yet make that promise. However, immediately after Parkinson left his office, the general reassigned him to the 621B program and effectively made him the director.

Beginning in December, immediately after he assumed control of 621B, Parkinson instituted a series of 7 a.m. educational meetings. At these gatherings, the program staff reexamined every aspect of the proposed 621B program, including alternatives. This educational process was a key to having everyone in the Program Office completely understand the technical issues they faced.

During this period Gen. Schultz supported the program in every way that he could. In particular, Parkinson was allowed to recruit Air Force officers whose background and experience were aligned with the needs of the fledgling program. All had advanced engineering degrees from the very best universities in the country including MIT, Michigan, and Stanford. In addition, virtually every officer had experience in developing real hardware or in testing inertial guidance systems. The first officer Parkinson brought aboard was Air Force **Major Gaylord Green,** who had worked for him on ABRES. Green's creativity, focused on satellites and orbits, had an extremely important impact on the success of GPS.

The result of Parkinson's hunting license was a cadre of about 25 of the best and brightest people that the Air Force had to offer.

In addition there was a small, carefully-selected group of Aerospace technical support personnel (led by **Walt Melton** from 1970 to 1972). This fine group of Aerospace engineers and scientists was experienced in an all technical aspects of space navigation programs and particularly skilled at issues relating to signal modulation, satellite position prediction, and building long-life satellites. Many of their names will be highlighted in Part Two of this story. The Aerospace contingent continued to enjoy the strong support of the president of the Aerospace Corporation, Ivan Getting.

Replacing Melton early in Phase One was **Ed Lassiter,** who had extensive space-flight experience and was a mainstay of the early GPS development.

Major Gaylord Green. His innovations included design of the modified orbits that ensured daily test time at the instrumented Yurna range.

Walter Melton, early leader of the Aerospace Program, a creative engineer who later led a group at General Dynamics that developed the GPS Ground Control System.

Ed Lassiter was the Aerospace program manager under Brad Parkinson for the latter stages of Phase 1. A skilled engineer with much flight experience, he was especially skilled at early identification and solution to program risks.

Dr. Malcolm Currie. As the number 3 man in the Pentagon, his support was essential to overcoming resistance from the Air Force.

During early spring of 1973, the director of Defense Research and Engineering (DDR&E), **Dr. Malcolm Currie,** formerly of Hughes Aircraft, who had just been appointed to the number three position in the DoD, found himself flying between Washington, D.C. and Los Angeles on most weekends. His secondary purpose was to oversee the relocation of his family, but he needed an official reason to travel to Los Angeles. So, each Friday afternoon he would visit SAMSO in Los Angeles for a presentation. After a few weeks, his host Gen. Schultz ran out of subjects to present, and instead invited Currie to spend an afternoon with his new program director, Col. Parkinson.

Schultz's invitation led to an astonishing meeting, because a newly-promoted colonel does not usually have the opportunity to confer with the number three person in the DoD over an uninterrupted three- or four-hour period. This informal meeting was held in private, in a very small cubicle within the JPO offices. With a Ph.D. in physics, Currie was a very quick study, so the interaction was lively and deep, delving into every aspect of the 621B proposal. After that meeting, Currie became a good friend to and a sponsor of the new satellite-based navigation program. He later played a critical role in ensuring DoD support, particularly in light of the Air Force's attempts to cancel the infant program.

DSARC 1. On August 17, 1973, Parkinson was invited to the Defense Systems Acquisition Review Council meeting to make a presentation on 621B. The meeting's purpose was to determine whether to proceed with the concept demonstration program. It was held at the Pentagon, and attended by senior officers of all services, with Mal Currie presiding. At the meeting's conclusion, the Council voted against approving the 612B program. Currie immediately invited Parkinson into his private office to tell him he wanted a new system proposal developed that would incorporate the best features of all the technical alternatives. He emphasized the need for a joint program involving all services.

Lonely Halls Meeting. Parkinson immediately called a meeting in the Pentagon over Labor Day weekend, September 1973. Over that weekend, the world's largest office building appeared to be a series of poorly-lit, uninhabited tunnels because everyone was away on vacation. The light at end of those tunnels, both figuratively and literally, came from a small conference room on the top floor, seating about a dozen attendees, all Air Force officers except for three Aerospace Corporation engineers. The purpose of the meeting was to define modifications to the 621B proposal that would meet Currie's directive. Parkinson wanted the isolation to ensure unfettered creativity in defining the new proposal.

Leading to this, the Analytical Sciences Corporation (TASC) under the guidance of Gaylord Green had completed a new systems study, a review and update of the earlier systems study directed by Jim Woodford and Hideyoshi Nakamura for project 621B in 1964–66.

After much deliberation, over that weekend the JPO defined the GPS with ten facets:

- The fundamental 621B concept of simultaneous passive ranging to four satellites would be the underlying principle of the new system proposal, ensuring that user equipment would not require a synchronized atomic clock.
- The signal structure would be the 621B CDMA modulation. It would include both a clear, acquisition modulation (C/A) and a precision military modulation (P/Y). The C/A modulation was to be freely available to civil users throughout the world.
- There would be two GPS broadcast frequencies in the L band, using the same dual-frequency technique that Transit had employed to correct for ionospheric group delay, as well as providing redundancy.
- Based on the progress that NRL had made in satellite clocks, the program committed to space-hardened atomic clocks on the first operational/demonstration GPS satellites (called Navigation Development Satellites, or NDS). At the Lonely Halls meeting, Parkinson concluded that the NRL technology was relatively low-risk, obviating the need to use the ground-relay, experimental demonstration scheme that 621B had previously proposed. It later turned out that the clock development was not as mature as it appeared, but the JPO backup clock development by Rockwell was available in time for the first launch.

- The orbits for the satellites were to be inclined at 62° and not geosynchronous. Green proposed 11-hour, 58-minute (sidereal synchronous) orbits that gave about two hours of testing over the same United States test area each day. NRL had advocated similar 8- or 12-hour inclined orbits. Because of the need for an extensive testing program on an instrumented range, exact 8- or 12-hour orbits would have been unsatisfactory, because they would continuously shift relative to the Earth. While these orbits resembled those advocated by NRL, Green's modification was critical to the success of the testing program.
- Orbit prediction would be handled with modifications to the Transit-developed orbit-prediction programs called Celeste.
- The initial test constellation would include four operational satellites, competitively procured, one of which would be a refurbished qualification model. They would be launched on refurbished Atlas-F rockets, which minimized cost, but also limited the number of solar panels that could be carried because of weight.
- A family of user equipment prototypes would be procured competitively. This equipment would span all normal military uses, and also include a low-cost set that would prototype civilian use. Where affordable, competitive contracts would be let. Particular attention would be devoted to user equipment integration with inertial navigation units and demonstration of anti-jam capabilities.
- The master control station and its backup would be on U.S. soil, but monitor stations would be placed around the world.
- The testing would be principally performed at the Army's Yuma test range with accuracy measured from a tri-lateration laser configuration. Using three laser ranging devices at the same time would ensure that all test vehicles could be measured to about a meter of positioning error. It was expected (and later proven) that this technique could even calibrate Air Force or Navy fighter aircraft flying close to Mach 1. Testing would make use of the inverted range concept, with satellites replacing each range transmitter as each newly launched GPS satellite became operational on orbit.

Dual Use. One aspect should be strongly pointed out. Contrary to some versions of GPS history, from the very beginning, GPS was configured to be a dual-use system. Civilian users were to be given free access to the signal specification and were expected to use the so-called clear acquisition signal for navigation and other purposes. In fact, Parkinson highlighted civilian use when he testified before Congress on the proposed new system.

GPS Approval. That Labor Day weekend of September 1973 had been a very busy three days. With help from the Air Staff Program Element Monitor (PEM) **Lt. Col. Paul Martin,** the Lonely Halls gathering developed a seven-page Decision Coordinating Paper (DCP) and a presentation of the new concept. Over the next two-and-a-half months there was a flurry of activity as Parkinson made presentations and defended the concept before all those who could block the proposal in the Pentagon. This effort was culminated with the approval to proceed on December 14, 1973. There were no significant modifications to the proposal that had been developed during the Lonely Halls meeting in the Pentagon.

During the whole Phase I development, Parkinson resolved to avoid any conflict with the other original competitors to build a satellite-based navigation system. He deliberately ignored dubious claims of invention and statements regarding the origins of GPS technology. Until quite recently, he has overlooked these false claims by those who did not directly participate in determining the GPS architecture and did not participate in the specific GPS design and deployment. He felt the real purpose was to build the system, not to fight over credit.

Recently an article appeared that implied that the GPS design was essentially the same as Timation. (“In what ways did GPS improve on Timation?” Easton: “I can’t think of any ways in which GPS improved on Timation. Essentially, they are the same system.” Interview in High Frontier magazine.)

Aware that this incorrect statement denigrated the people who had first analyzed, advocated, and demonstrated the fundamental concept, as well as built the system, Parkinson resolved to correct the record, and highlight the names of those who deserve credit. This is a major purpose of this article. This article has been reviewed and approved for veracity by virtually all the key figures (still alive) who actually designed, built, and tested GPS.

GPS Phase I program approval meant that the real work could begin. The conclusion of a two-part history, told by the people who made it.

With Gaylord Green, Hugo Fruehauf, Brock Strom, Steve Gilbert, Walt Melton, Bill Huston, Ed Martin, James Spilker, Fran Natali, Joe Strada, Burt Glazer, Dick Schwartz, Len Jacobson, AJ Van Dierendonck, and others.

By January 1974, the GPS program at the Joint Program Office (JPO) was well underway. With only about 30 officers, the workload was enormous. Fortunately, the Aerospace cadre of about 25 also made extraordinary contributions. In a flurry of activity, the team developed requests for proposals, made top-level specifications, and published initial interface control documents. The work of converting viewgraphs into real hardware, as many know, is an exacting and sometimes painful process.

Of course there were many challenges, but five of them, principally engineering, stand out as particularly daunting. These were:

- Defining the specific details of the GPS CDMA signal structure;
- Developing space-hardened, long-life, atomic clocks;
- Achieving rapid and accurate satellite orbit prediction;
- Ensuring and demonstrating spacecraft longevity approaching ten years;
- Developing a full family of GPS user equipment.

We discuss each challenge in detail, including the names of those most instrumental in meeting them. The first appearances of their names are **highlighted,** although if they appeared in Part One of this story (May 2010 issue), their names are not highlighted.

Early GPS manpack worn by JPO Army deputy Lt. Col. Paul Weber. This photo graced the cover of the first-ever GPS brochure.

Challenge 1. *Defining the specific details of the GPS CDMA signal structure (coherence, acquisition, spreading, communication protocol, structure, error correction, message structure, and so on).*

The selection of the GPS signal structure was broadly confirmed with the tests that were run by program 621B at the White Sands Missile Range with the help of **Joe Clifford,** Bill Fees, and **Larry Hagerman,** all from the Aerospace Corporation.

While the fundamental decision to select CDMA had been made during the Lonely Halls meeting, a vast number of details had yet to be worked out. Fortunately, there were many earlier studies of the signal. Dr. Jim Spilker (then of Philco Ford), who had also written the major reference book on digital communications, authored one of the studies. Dr. Charles Cahn, Nat Natali, **Burt Glazer, Ed Martin,** and Dr. Robert Gold of Magnavox all made significant contributions. One of the most important details was the decision that the carrier, code, and data of the GPS signal would all be phase-coherent (Figure 1). As discussed later, this decision enabled much of the precision that we now see in advanced GPS receivers.

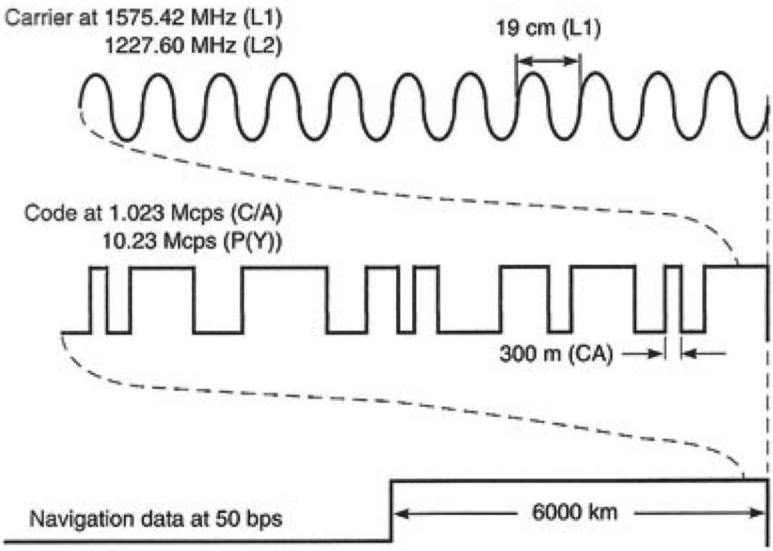


Figure 1. GPS signals were designed to be all aligned as transmitted, that is, coherent. (Courtesy Misra and Enge, Global Positioning System).

The exact Gold codes family had to be selected from the original family, since Dr. Gold's technique did not include the natural Doppler shifts. The data message was integrated into both the civil (C/A) and military (P/Y) signals through inversion of their codes every 20 milliseconds.

To work out the details of the data message, the JPO had a strong team including **Major Mel Birnbaum, Col. Brock Strom,** and **Capt. Bob Rennard.** Outside contractors making major contributions included Dr. Fran Natali, **Dr. A. J. Van Dierendonck,** and others. Van Dierendonck played a particularly effective role in helping define "GPS time." This sounds rather mundane, but had some very interesting complexity. Jim Spilker recommended the 1023-bit message length to avoid a correlation problem associated with Doppler shifts (this recommendation was incorrectly attributed in the last issue).

The data stream came down at 50 bits per second. Through this tiny pipe of information, all the precision of GPS had to pass. It included the space-vehicle orbit-position information (ephemerides), system time, space-vehicle clock-prediction data, transmitter status information, and C/A signal handover time to the P/Y code. Also as a part of the message, ionospheric-propagation delay models were incorporated for the single-frequency user. Further, to aid rapid acquisition of new satellites just rising over the horizon, the ephemerides of all other satellites in the full constellation had to be included. Each digital word had to be defined in terms of scaling, bias offset, and precision in terms of the number of bits transmitted.

About 95 percent of the GPS message has endured with no changes needed at all. In a few cases, because the newer user equipment is more accurate, greater precision is desirable. It is a great tribute to the brilliant engineers and scientists who designed the signal structure in 1975 that it has endured for 35 years with so little need for modification.

Some of the JPO Heroes at a "dining-in," a recognition dinner. From left, Major Mel Birnbaum (made many important contributions. He was famous for marathon code reviews that could last 18 hours straight. He hated to miss schedules!); Col. Don Henderson (later Maj. Gen.) second Air Force deputy; Major Ralph Tourino (later Maj. Gen.), Program Control; Lt. Col. Ken Juvette. director of procurement; and LCdr. Joe Strada, a key leader in the extensive test program.

▲ **A.J. VAN DIERENDONCK** helped define "GPS Time."

▲ **ED MARTIN,** one of the key systems engineers at Magnavox.

▲ **ERNST JECHART (LEFT) AND GERHARD HUEBNER,** developers of the commercial rubidium clock. They later teamed with Rockwell to develop the first successful GPS clock, the only working clock on the first four GPS vehicles.

▲ **HUGO FRUEHAUF,** chief engineer for the design and development of the first GPS satellites. His oversight was essential to produce the first GPS atomic clocks.

▲ **RON BEARD** of NRL, a staunch supporter of GPS over many years.

Challenge 2. *Developing space-hardened, long-life, atomic clocks (qualified for the upper Van Allen Belt, with 4- to 5-year lifetime requirement for individual clocks).*

In 1966, both the Air Force and the Navy recognized that developing a precise, stable time-base for generating the one-way (passive) navigation ranging signal in the satellite was essential. Cesium atomic clocks had been invented, demonstrated, and offered for commercial sale by the middle of the 1950s, before the Space Age. The major commercial issues with these clocks were that they tended to be bulky, power-hungry, and not hardened against space radiation. To address that problem, rubidium atomic clocks, noteworthy for their small size and low power requirements, were developed. Still, the issues of mechanical and radiation hardening as well as temperature sensitivity had to be resolved before they could be used in space.

The 621B/Woodford/Nakamura study of 1964/66 called for atomic clocks in the satellites in at least seven places. The study advocated a technology program to space-harden existing clock technology. Unfortunately, the Air Force chose not to pursue a space atomic-clock technology program.

However, the Naval Research Laboratory (NRL) did institute a program in 1964. It pursued the technology for stable clocks with a series of satellites that have already been discussed. The first Timation satellite, launched in May 1967, carried a quartz clock. Not surprisingly, the frequency varied substantially with satellite temperature. The second Timation satellite also contained a quartz clock as well as a temperature controller and showed improved operation, but the results still fell short of those necessary for a GPS satellite. The third satellite in the series had not been launched before the Pentagon approved GPS development in December 1973. In any case, Timation III was designed to carry two slightly upgraded, off-the-shelf commercial rubidium clocks.

Qualification Model of the first GPS atomic clock, built by Rockwell International working directly with Efratom, a small German company.

Based on the progress that NRL had made, during the Lonely Halls meeting the JPO decided to commit to atomic clocks in the first operational GPS satellites. This third Timation satellite was renamed NTS-I and came under the newly formed Joint Program Office for GPS. The satellite was launched on July 14, 1974, as a part of the GPS program. However, the ineffective attitude-stabilization system caused varying sun angles and hence, significantly varying temperatures, masking any careful evaluation of the rubidium performance.

The GPS space-based rubidium atomic clock technology was derived from a unit produced by Efratom, a small company initially based in Germany. The geniuses behind this creative device were **Ernst Jechart** and **Gerhard Huebner.**

By the summer of 1974, a satellite contractor, Rockwell International (RI), had been selected to build the GPS operational satellites. Included in the program direction by the JPO was a separate development of rubidium clocks for the satellites as an alternative to the NRL cesium clock effort, in case the NRL effort faltered. **Hugo Fruehauf** of Rockwell had independently discovered and contacted Efratom, the company that NRL was working with, although his interaction was totally independent of that of the NRL. In addition, Fruehauf's relationship with Efratom was simplified because of his fluency in German, since Jechart did not speak English, and Efratom had just established an office in Southern California near the Rockwell developers. Figure 2, a page from the original Rockwell proposal, shows the excellent ground test data at both 1000 seconds and at 24 hours.

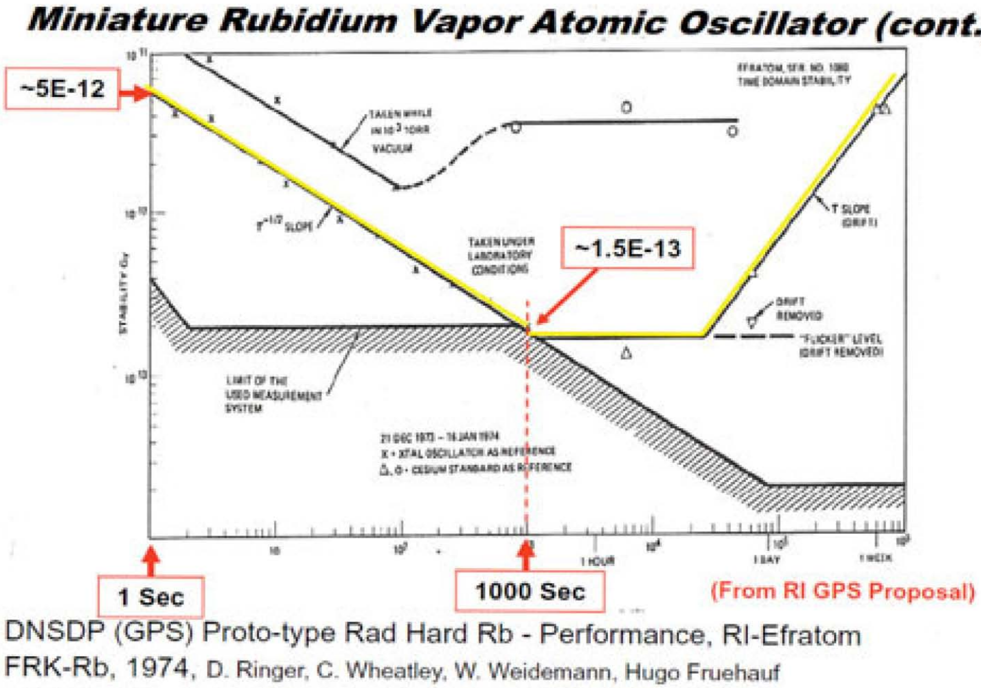


Figure 2. Test results for the Rockwell proposed GPS space-hardened prototype atomic (rubidium) clock, based on the Efratom commercial clocks.

On realizing that the small Efratom company would be incapable of producing a radiation-hardened, space-qualified rubidium oscillator, RI's GPS satellite program manager Richard Schwartz created a teaming relationship with them, which included his chief engineer, Hugo Fruehauf, plus Dale Ringer, Dr. Chuck Wheatley of Rockwell's Autonetics Division, and Efratom's Werner Weidemann. With heroic efforts, this team built a space-qualified clock in time for the first GPS launch in February 1978.

Meanwhile, the NRL-sponsored development of a cesium clock by FTS ran somewhat behind schedule. Their cesium clock was not available for the first three GPS satellite launches. The first NRL hardened clock was included on the fourth GPS satellite; unfortunately that unit failed after 12 hours of operation because of a power-supply problem. As a result, the only operating clocks on the first four GPS satellites were those developed by the Joint Program Office through its contractor Rockwell International. The decision to proceed to full-scale development for GPS, called DSARC 2, was made before any NRL-developed clocks had become operational.

That said, the NRL-sponsored FTS cesium clocks were available for later satellites, and performed extremely well. Later Block II GPS satellites carried two rubidium-frequency standards made by Rockwell and two cesium-frequency standards (primary source, Frequency and Time Systems; secondary sources, Kernco and Frequency Electronics Inc., on selected vehicles). Figure 3 summarizes the early clock program.

Program / (Service)	Dates	# of Sats / Nav Method	Nav Dim	Clocks	Ops Status
NNSS (Transit); (Navy-JHU/APL)	1964 to ~1990	(7) Doppler Signals	2D	(1) Quartz Oscillator	Was fully operational
Timation I & II; (Navy-NRL)	1967 and 1969	(2) Side-tone Ranging	2D	(1) Quartz Oscillator	Experimental. Very sensitive to thermal variations and Proton bombardment.
Navigation Technology Satellite-1 (NTS-1) (Navy- NRL)	Launch July 1974	(1) Hazeltine 621B Transm., No Data; + (2) Ranging Tones	2D	(2) Efratom Com'l Rb's, modified by NRL to perform in space, +(1) Quartz	Experimental: (1) Rb operated for more than one year– no quantitative data; (1) Rb failed early
NTS-2; (Navy-NRL); USAF/JPO provided Nav. Payload	Launch July 1977	(1) Rockwell-ITT PRN Nav. Pkg. provided by USAF-JPO; + (2) Side-Tone Ranging Signals	2D	(2) Proto space qualified FTS Cs + (2) Quartz Osc's	Good initial performance from Cesiums. Although intended to be part of the initial (4) Satellite Nav testing, NTS-2 failed before GPS nav testing began.
GPS Operational Prototypes, awarded to Rockwell in 1974 by USAF-JPO.	Devel'mt 1973-75; Rockwell Block-I launches began Feb.1978	(4) / ITT PRN Nav. Pkg's. each satellite	3D	(3) RI-Efratom Rb's on the 1st (3) DNS Sats; 4th Sat & up, (3) RI-Efratom Rb's + (1) 2nd gen. FTS Cs**. 1st Cs on NDS 4 failed after 12 hrs, but fixed for NDS-5	GPS Constellation of (4) Rockwell Block-I GPS Satellites for the initial Navigation Test Program. Only Rockwell Rb clocks available for testing at YUMA for GPS.

Figure 3. Earliest satellite-clock technology developments, culminating in the last row: four Rockwell satellites with Rockwell-developed rubidium clocks.

In spite of NRL's development difficulties, GPS users owe a debt to the lab for its pursuit of this technology. Clearly GPS would not have performed so well without space-hardened atomic clocks. It was the apparent NRL progress that strengthened the argument. The support of Ron Beard of NRL in this joint effort has been invaluable to the program over many years. More than 450 atomic frequency standards have now flown in space. By far the greatest user has been GPS.

Challenge 3. *Achieving rapid and accurate satellite orbit prediction, to within a few meters of user ranging error (URE) after 90,000 miles of travel.*

Since the GPS system architecture had upload stations only on U.S. soil, the satellites were out of sight for many hours, making accurate prediction of their orbits essential. To achieve the expected positioning accuracy, the orbit prediction had to contribute less than a few meters of ranging error after 90,000 miles of travel. Achieving this standard was a major challenge in the early days of GPS. Such a prediction must account for the complications of Earth pole wander, Earth tides, general and special relativity, the noon turn maneuver of the satellite, solar and Earth radiation, and the reference station's location. Figure 4 gives an example of the problems of polar wander. With roughly a 400-day period, this effect had an amplitude of many tens of feet. While this wander has to be included in the GPS orbit-prediction model, fortunately GPS is the major technique to measure it.

Another, usually unrecognized feature is that the monitor stations only use the GPS signal for ranging. In other words, they are passive, rather than using the usual technique of that era, two-way ranging. The reference receivers were of a special design, developed by Jim Spilker's company, STI. They successfully received the first signal from the Rockwell/ITT satellite (NDS-1) on March 5, 1978, after its launch on February 22, 1978.

Fortunately, the Transit program had pioneered precise orbit prediction and had taken these effects into account. Its Astro/Celeste program, developed by **Bob Hill** and **Dick Anderle** at the Naval Surface Weapons Center in Dahlgren, Virginia, batch-processed the measurements taken by the reference stations. Unfortunately, this processing would take too long to provide the most up-to-date predictions.

A new scheme was devised that included partial derivatives of prediction relative to reference-station measurements. A.J. Van Dierendonck applied his knowledge of filters to help lead development of these calculations, which allowed a modified (linearized) Kalman filter to be used for near-real-time optimal prediction. Bill Fees of Aerospace, Walt Melton of General Dynamics, and **Sherm Francisco** of IBM, among others, implemented these techniques. The initial master control and upload stations were located at Vandenberg Air Force Base, since moved to Schriever Air Force Station; a backup master control station has been re-established at Vandenberg.

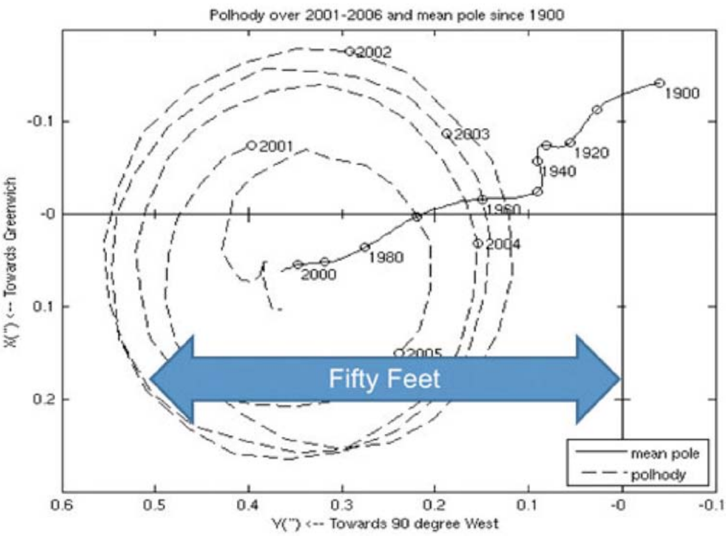


Figure 4. Motion of the Earth's spin axis must be included in the measurement parameters for GPS satellite location. The broadcast ephemeris is adjusted to include this effect, so the user need not make further adjustments. (Courtesy of International Earth Rotation and Reference Service).

Challenge 4. *Ensuring and demonstrating spacecraft longevity approaching 10 years (the issue was GPS affordability).*

The issue was simply that sustaining a constellation of 24 satellites would be prohibitively expensive if the satellites did not have long lives. Again, the Air Force/621B study by Woodford and Nakamura in 1966 focused on the problem: "The most specific change in satellite technology is the increase of mean time before failure (MTBF). MTBFs on the order of 3 to 5 years can now be considered feasible."

The problem is easily illustrated in Figure 5. The light blue line shows the trade-off between average satellite lifetime, L, and the required number of satellites per year for a 24-satellite constellation. GLONASS, the Russian system competing with GPS, has the experience shown in the upper white box. With satellite lifetimes averaging two to three years (or less), GLONASS has a corresponding requirement for eight to 12 satellite launches per year. Only a very wealthy country can sustain such a launch program.

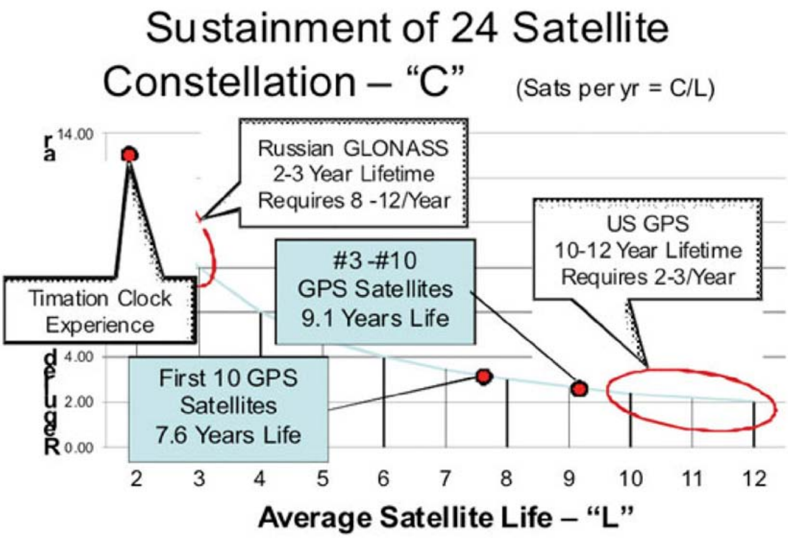


Figure 5. The imperative for long satellite lifetimes.

The red oblong illustrates the U.S. GPS experience, which requires only two to three launches per year. Also shown is the initial experience of GPS during Phase I. The first 10 GPS satellites reached an average age of 7.6 years, with #3 and #10 exceeding 9 years. This is an enormous credit to Rockwell International and in particular the program manager Richard Schwartz. He had excellent system engineering support from **Andy Codik.** The JPO satellite division was intially led by Major Gaylord Green and later by **Maj. Doug Smith,** with help from **Capt. Jack Henry.**

Three factors are key to long-lived satellites:

- Designs with carefully selected redundancy (for example, clocks, power amplifiers),
- Enforcing a rigorous part-selection program including the de-rating of parts (must be class S. or equivalent),
- Testing as you fly and insisting on a detailed analysis of all failures.

Figure 5 also illustrates why the Timation clocks could not be used as prototypes for the GPS program. In general, their maximum lifetimes were approximately one year. Clearly their designs needed greater maturation.

The demonstrated lifetimes were essential to passing the next milestone, DSARC II, which allowed GPS to proceed to full-scale development.

Challenge 5. *Developing a full family of GPS user equipment that capitalized on the digital signal (leading to inexpensive digital implementation) and spanned most fundamental military uses, as well as demonstrating civilian cost feasibility.*

The last, but certainly equally difficult of these five engineering challenges, was the development of nine different types of GPS user equipment. Recognize that a major part of the challenge was to stuff the real-time digital software processing into the relatively primitive digital computers of that era. Table 1 summarizes the development of user equipment:

User Equipment Set	Description	Manufacturer
X Unaided	Four-channel, high-performance, military	Magnavox
X Aided	Four-channel, inertially-aided, military	Magnavox
Y Unaided	Single-channel, sequential, military	Magnavox
Y Aided	Single-channel, sequential, inertially-aided, military	Magnavox
HDUE-High Dynamic	Five-channel, high-performance, military	Texas Instruments
MVUE-Manpack Vehicular	Single-channel manpack/ground vehicle military	Texas Instruments
GDM-Generalized Development Model	Five-channel, high anti-jam military	Collins Radio Group of Rockwell International
MP-Manpack	Single-channel manpack/ground vehicle military included concept for determining azimuth	Magnavox
Z (ARN 132)	Single-channel, low-cost civil prototype	Magnavox

▲ **TABLE 1** User equipment.

All of the sets performed well within specification. They were characterized, however, by large size and heavy power demands. Magnavox, under the technical direction of **Vito Calbi,** produced the largest variety of user equipment. It was a subcontractor to General Dynamics, who reported directly to the JPO. At Aerospace, **Frank Butterfield** was a gifted contributor, particularly skilled at practical antenna design.

The Generalized Development Model (GDM) reciever, developed by Rockwell Collins Group, was the largest of the sets, created for a specific purpose: to demonstrate the ultimate jam resistance for GPS user equipment. It attained performance better than 100 db jamming-to-signals ratio (J./S) in actual flight test. The GDM receiver achieved this by integration with inertial components, directional antennas, and shading with the aircraft body. Such a receiver can fly directly over a 1 kW jammer at 4,000 feet and not be affected. The original GDM program manager at the USAF Avionics Lab was **Maj. Roger Brandt.**

The Rockwell Collins Generalized Development Receiver (GDM). This advanced receiver achieved more than 100 dB of anti-jam in actual flight tests.

The single-channel manpacks were large and clumsy, but they operated very well. The payoff created by the CDMA signal is illustrated with the 12-channel, single-chip modern implementation, shown in the bottom picture. This contemporary chip's accuracy is much better than any of the equipment produced during Phase I.

Developing test environment and analysis setup was almost as challenging as the user equipment. Lt. Col. Val Denninger, Maj. Darwin Abbey, and Lt. Cdr. Joe Strada led this very successful effort. While most testing took place at Yuma Proving Ground, test sites were also located in San Diego and elsewhere.

1978 single-channel (sequential) Manpacks, two types by Magnavox and Texas instruments. Batteries alone weighed much more than current military handsets.
Righthand photo, the second JPO deputy, Col. Don Henderson (left), and Aerospace program manger Ed Lassiter (right). Bottom, a modern 12-channel (parallel) Atheros chip receiver with more capability.

The Most Fundamental GPS Innovation

The CDMA (spread-spectrum or PRN) modulation used for passive ranging is clearly the most fundamental innovation of GPS. This signal enabled four-dimensional positioning for the user without requiring an atomic clock in the user equipment. The Russian GLONASS (the other, partially-operational global navigation satellite system) also used spread-spectrum passive ranging, but resorted to a frequency-separation scheme (FDMA, frequency-division multiple-access) that has proven inferior in actual use.

▲ **GOOD OL' COUNTRY BOYS.** "I was making very frequent trips to D.C. and elsewhere. Accompanying me I usually had the excellent support of **Captain Fergus Henderson** (who was studying to be a lawyer, and had a master's from MIT), and **Major Harry Hughes** (USMA, 1959). Occasionally my AF Deputy, Steve Gilbert, would also help me. When we got on the airplane to go home, we would somehow end up humming 'Country roads, take me home' as a sort of lament and blues song. As a result, 'Country Roads' became the Program's song. Steve Gilbert was a very accomplished banjo player. I was a struggling banjo player. We would sing the song in two-part harmony, as here at a dining-in, and everyone pretended to like it. On one memorable trip, Steve broke out his banjo in the air and we had a whole section of a DC-10 involved in a sing-along."

The innovative design of this CDMA signal has enabled all of today's precision applications for GPS. It is currently common for inexpensive GPS receivers to simultaneously receive signals from more than 10 satellites, yet all of these signals are being broadcast on exactly the same frequency. In fact, the number of signals that can be received is virtually unlimited using the spread-spectrum CDMA approach. Using a routine processing algorithm, the user, receiving more than four signals, has an instantaneous position that is more accurate than that using four satellites alone. This robustness includes a technique to ensure integrity of the GPS solution. The method, called receiver-autonomous integrity monitoring (RAIM), isolates a rogue satellite that is not operating properly, to ensure integrity of the GPS solution.

Another technique, called carrier tracking, is enabled with the coherence of the code and the carrier broadcast in this signal. When coupled with some form of differential GPS operation, the result is relative positioning accuracy that is unprecedented — frequently better than a millimeter. For example, surveyors can now routinely resolve three-dimensional position to this accuracy. Even common user equipment can make use of the coherence of the signal. The receiver accomplishes this by employing the so-called Hatch/Eschenbach filter that uses the reconstructed carrier signal to smooth the code-transition measurement that greatly decreases the noise of the raw code measurement.

The processing gain in the GPS CDMA signal has been enhanced by deep integration with inertial navigation components. This has enabled the demonstrations of very high interference rejection by such receivers. **Dale Klein** and **Ed Copps** of Intermetrics Corp. were major contributors to the integration of GPS with inertial measurement units for the Magnavox high-performance military receivers.

Side-Tone Ranging. The competing side-tone ranging signal structure offered by NRL in the 1970 Easton patent had a fundamental flaw. If the signals were broadcast at the same frequency, they would interfere with each other. On the other hand, if they were broadcast on different frequencies, the user equipment would require a separate analog front end and tracking loops for each signal. In addition, each channel would have its own time-delay bias that would probably vary with temperature of the user equipment. A study by Magnavox also noted that the side-tone ranging signal could be easily spoofed; it was not clear how to encrypt such a signal. The final problem was that the signal was fundamentally an analog type and would have not been able to take advantage of modern digital signal processing. As a result, the receivers would be more complex and expensive.

The Air Force 621B/Aerospace and Magnavox studied the CDMA signal structure extensively after the 621B Woodford/Nakamura study was completed in 1966. Bob Gold of Magnavox had, in 1967, invented the technique to select acquisition codes that were mathematically guaranteed to not look alike (were uncorrelated). Early in the program, the JPO hired Dr. Jim Spilker, a recognized worldwide authority on digital signal processing, to contribute to this effort. Another worldwide expert, Charlie Cahn of Magnavox, was also a major contributor to the signal design. As mentioned previously, the details of the signal required the efforts of many people.

By 1969, the CDMA signal was being used in many communication applications. Adapting this signal for navigation raised the questions that were posed in an earlier section. It is hard to believe today the issues surrounding its use had to be addressed in 1970. It is to the great credit of Program 621B that it built the receivers and ran the series of tests at White Sands Missile Range that had earlier resolved all the major issues surrounding the signal structure. This irrefutable evidence allowed the JPO team to confidently choose this signal during the Lonely Halls meeting in September 1973. Great credit must go to Bill Feess who worked tirelessly to complete the analysis that demonstrated 5-meter accuracy in those White Sands tests.

CDMA-Enabled Applications

The distinction between the Timation side-tone ranging and the 621B CDMA signal is critical to understanding the origins of GPS. The Air Force CDMA signal was different in essential and fundamental ways from the Easton side-tone ranging modulation. Three examples of precise three-dimensional applications, not achievable with side-tone ranging, illustrate the subsequent success of the 621B digital CDMA signal.

Aircraft Blind Landing. In 1992, the Federal Aviation Administration (FAA) sponsored Stanford's development and demonstration of the first Category III (blind landing) system in a commercial aircraft; the effort was led by **Clark Cohen** and developed by a group of Stanford students under the supervision of Brad Parkinson. The only sensor for both position and attitude was GPS. The carrier-tracking receiver was a derivative of a Trimble receiver; it relied on the CDMA signal structure for both accuracy and integrity. (See Figure 6.)

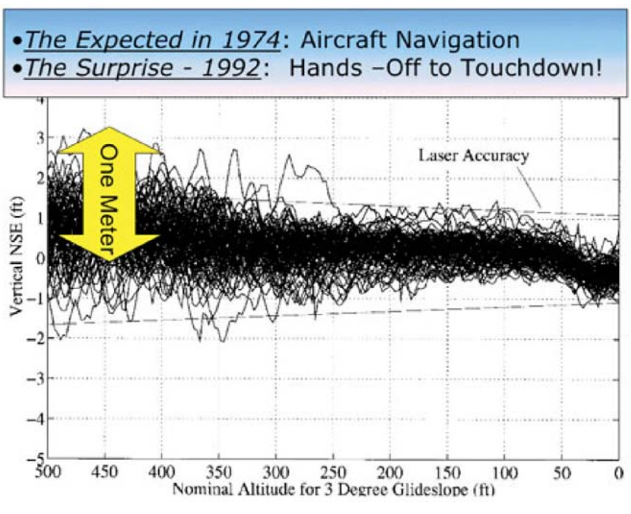
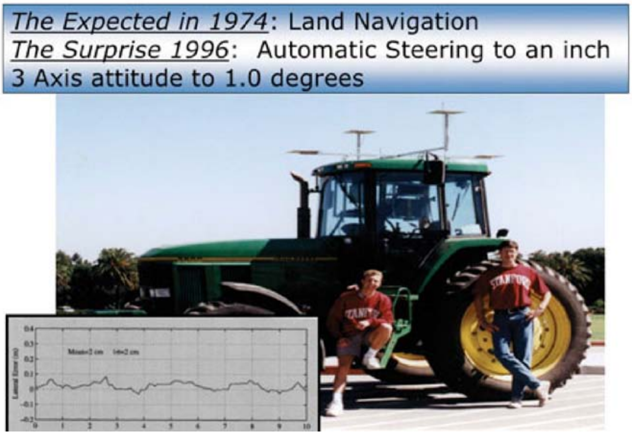


Figure 6. Results of first blind landing tests using GPS alone, 110 landings with a commercial Boeing 737.

Robotic Farm Tractor. Using similar technology, a different group of Stanford students in the same lab demonstrated the first precision GPS-controlled robotic farm tracker. Again, the capability was enabled by the GPS CDMA signal. The John Deere Company sponsored this effort, which has now expanded into a worldwide market of more than $400 million per year.



Robotic farm tractor developed at Stanford with support from John Deere company.
Student leader Mike O'Connor and colleague Tom BeLl shown. Tracking test at 5 meters/second, with worst error around 3 inches!
Now a $400M/year market.

Earth Crustal Monitoring. A third example of the power of the CDMA signal is precise survey, focused on Earth movement and crustal tracking (Figure 7). The original GPS surveying receivers were pioneered by Phil Ward at Texas Instruments and Charlie Trimble at Trimble Navigation, among others.

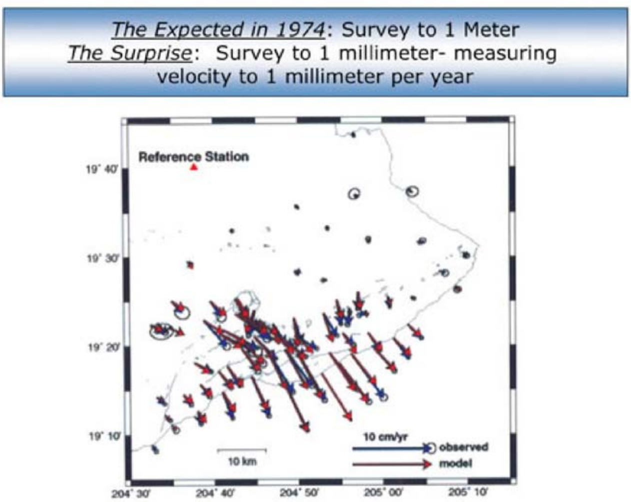


Figure 7. Continuous observation of earth crustal motion with a precision of better than a millimeter: distributed slip on Kilauea volcano, Hawaii.

Summary. Many technologies came together to make GPS operational, none more revolutionary than the signal structure demonstrated by 621B at White Sands, and selected by Parkinson during the Lonely Halls meeting. Virtually all high-precision uses of GPS depend on the characteristics of this signal.

▲ **DICK SCHWARTZ**, GPS satellite development manager and VP at Rockwell International. His skill ensured the success of the first GPS constellation of 4 RI satellites.

▲ **MAJOR WALT LARKIN**, one of the keys to satellite long life. Larkin, Irv Rezepnik of Aerospace, and the Rockwell GPS spacecraft developers insisted on rigorous selection and testing of all spacecraft components.

▲ **SHERM FRANCISCO** of IBM did key work in orbit prediction.

▲ **PHIL WARD** developed the TI-140, an early commercial high-precision receiver.

▲ **CHARLIE TRIMBLE** produced early surveying receivers.

▲ **LT. COL. (LATER COL.) STEVE GILBERT** fought the successful battle in the Pentagon that allowed GPS to survive threatened funding cuts in the early 1980s.

More on GPS Origins

The fundamental basis for the GPS design was clearly the Woodford/Nakamura and subsequent studies undertaken by 621B, not the system outlined by NRL in the Easton patent. More than 500 million current users have overwhelmingly confirmed the value of the selected technique using a minimum of four-satellite passive ranges and the CDMA signal. If each GPS user had to employ an atomic clock, the price of most GPS receivers would be prohibitive. The value of a four-dimensional solution for users has also been irrefutable. Had GPS followed the blueprint of the NRL patent, it is reasonable to say that almost all system uses, military as well as civilian, would have been fatally compromised. Further, had the Easton side-tone ranging signal been selected, broadcasting 30 satellites on the same frequency, as GPS does today, would have created an undecipherable electromagnetic jumble.

Summarizing Easton's Patent. We earlier mentioned the NRL/Easton patent for the Timation design. It is important to summarize that invention and its relationship to the actual GPS design. A few people have written that Roger Easton "invented" GPS. As stated, Easton did have a competing concept that he had developed at NRL. In October 1970, four years after the completion of the secret, seminal system study by Woodford and Nakamura, Easton applied for a patent, "Navigation System Using Satellites and Passive Ranging Techniques," that was granted on January 29, 1974 (U.S. 3,789,409). A careful reading of the patent, available on the web, reveals the following:

- The technique described by Easton clearly calls for a synchronized "extremely stable oscillator" at the user station. Elsewhere he states: "would typically be controlled by an atomic clock." This less-capable method of navigating was examined in the Woodford/Nakamura study, four years before Easton's patent application, and is definitely not the technique chosen by GPS.
- The patent advocates the use of a passive ranging technique, whose description occupies most of the patent, with multiple frequency tones, not the CDMA technique of GPS that had already been studied by 621B. Before the patent was issued, 621B had already built prototype GPS CDMA receivers, flown them at the White Sands range, and demonstrated three-dimensional accuracies of about 5 meters. The Easton passive-ranging technique, commonly called side-tone ranging (STR), had been included in a 621B analysis of alternatives. STR was rejected because of poor resistance to interference or spoofing, and the inability to broadcast all satellites at the same frequency without destructive self-interference.
- Both the description and the accompanying diagram in the patent clearly refer to two-dimensional navigation, using lines of position. To extend this to three or four dimensions was not mentioned. Such extension would probably only be possible if the satellites all broadcast on different frequencies, which would have made extremely high-precision positioning (as attained by the actual GPS design) infeasible.

Thus, it is correct to state that the Easton patent did not, in any way, represent the actual GPS design in at least these three fundamental aspects.

Further Transit Contribution. In 1974, after the first phase of GPS had been approved, the Transit program requested funds to upgrade the Transit signal structure to the same passive ranging technique (CDMA) being planned for GPS. The program's purpose was to use Transit signals to track Trident missile testing launches in broad ocean areas. Air Force Col. Bradford Parkinson (director of the GPS Program), Dr. James Spilker (Stanford Telecommunications Inc.), and **Jack Klobuchar** (Air Force Cambridge Research Laboratory) responded with a technique for substituting GPS signals, with a translated frequency relayed to the ground to track those missile tests.

After three Pentagon briefings on the proposed alternative technique, **Dr. Bob Cooper** of the DoD concluded that the GPS signal would be used. Included was a decision to add two more satellites to the Phase I development of GPS to accommodate the Trident launch window. As a result, $66 million was transferred from the Navy to the USAF GPS program. The benefit to the fledgling GPS program was enormous. This greatly expanded the test time for GPS, and also reduced the risk, since no spare satellites had been approved for the program. While the Trident program was somewhat unhappy with the loss of funds and control, it immediately unleashed the creativity of Johns Hopkins University Applied Physics Laboratory and successfully met the Trident missile test tracking requirements.

GPS JPO Innovations

GPS was the first DoD program directed to be managed as a Joint Service Development Program. This new approach, conceived by Dr. Currie, led the GPS program to be designated a JPO or Joint Program Office. As a result, there were deputy program managers assigned from the Navy (**Cdr. Bill Huston**), Army (**Lt. Col. Paul Weber**), Marine Corps (**Lt. Col. Jack Barry**), and Defense Mapping Agency (**Paul Frey**), as well as the customary Air Force deputy (initially **Lt. Col. Steve Gilbert,** later **Lt. Col. Don Henderson**). Rather than use these well-qualified people from other services simply as liaisons, they were each assigned specific programmatic responsibilities.

At the first major program review at Andrews Air Force Base, Parkinson called the convening general's attention to the fact that he was leading a joint program, and with the general's indulgence he had invited his deputies from the other services to attend. Since attendance by other services at Air Force program reviews was unheard of, this drew a gasp from the roughly 200 Air Force officers attending. The JPO approach truly broke new ground in intra-service cooperation.

At the JPO. Frank Butterfield of Aerospace, Col. Parkinson, and Cdr. Bill Huston, deputy JPO director from the U.S. Navy, in the early 1970s. A model of a Phase I GPS satellite stands on the table between the latter two.

Parkinson had entreated the Federal Aviation Administration to also send a deputy. The public response by the FAA deputy administrator for development was: "We don't want GPS, we don't need GPS, and if it is ever deployed, we will never use it." Throughout this period, **Glen Gilbert** (sometimes called "the father of air traffic control") was a strong and early advocate for FAA use of GPS. It took many years for the FAA to accept his views. Obviously times change; the current relationship between the FAA and the GPS Program Office is excellent, fostered by Col. Dave Madden and his FAA counterpart Leo Eldredge.

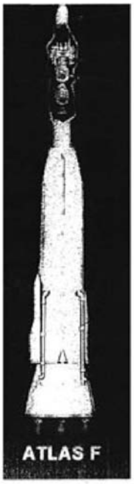
JPO as Prime Contractor. The JPO cadre served as the prime or integrating activity for the whole program. Gen. Schultz almost fired Parkinson when he proposed this. The general had expected him to hire a separate commercial integrating contractor. After Parkinson explained that the major interfaces between the three segments — satellite, ground control, and user equipment — were the signals, Gen. Schultz acceded to the plan. This pioneering aspect was critical because it ensured that all aspects of the system would be under the direct purview and control of the JPO.

Award and Incentive Fees. The use of innovative procurement awards for the contractors was very new in DoD in 1974. Beginning with the satellite contract, the JPO made extensive use of new forms of positive rewards for the contractor, including incentives for on-orbit performance. Gaylord Green pioneered this activity with skills developed as a project officer in the Advanced Ballistic ReEntry Systems Program (ABRES) program office. Incentives were applied to virtually all the other contracts as well, and seemed to have a very positive effect.

Normally the Space and Missile Systems Organization (SAMSO) procurement office, which was independent of the JPO, would have been reluctant to approve such radical new ideas. Fortunately, Parkinson carpooled with another colonel who was head of SAMSO procurement and a breath of fresh air. This attitude was exemplified by a sign at eye level as you left the procurement director's office: "Nothing would be done at all if a man waited until he could do it so well that no one could find fault with it." (It turns out this came from remarks by Cardinal John Henry Newman.) With that attitude, the SAMSO office approved almost all of the JPO's "wild" procurement innovations. Many of these innovations are now routine.

Changes. The Air Force provided a high-level spec for the satellite that defined the signal structure, the power on the ground, the frequencies, the orbit, and the amount of weight the booster could put into that orbit at apogee. The JPO left it up to the contractor to design a satellite that could meet those requirements. The key point is the JPO never changed the requirements, which kept GPS on course with minimum cost increases for the devlopment.

Refurbished Atlas F Booster. Today, up to half the cost of a satellite on-orbit is the cost of the booster to place it there. While the costs were perhaps not proportionally so large in 1977, they still could consume large pieces of a program's budget. Luckily, the United States had mothballed much of its liquid-fuel ballistic missile force during that period. The JPO chose to use refurbished Atlas Fs as boosters, saving many millions of dollars. Some have suggested this idea originated with NRL. While NRL may have also been using them, both Parkinson and Green came from the ABRES program where refurbished Atlas Fs were already employed. Thus, the decision made in the Lonely Halls meeting was based on knowledge the JPO already had, which included additional steps the ABRES had taken to improve the reliability of the booster. (See Figure 8).



Refurbished Atlas F ICBM	
Configuration	**Weight (lb)**
Atlas F at Lift -off	270,934
Navstar Payload at Booster Separation	1636
Payload at final orbit	982

Figure 8. Refurbished Atlas-F booster characteristics. Col. Parkinson and Maj. Green brought this concept from previous use on the USAF ABRES program.

A Motto. Emblazoned on a prominent wall in the JPO was a sign that read:

"The mission of this Program Office is to

- Drop 5 bombs in the same hole
- and build a cheap set that navigates
- and don't you forget it!"

By distilling the JPO mission into one succinct motto, the program intended to provide a guide for all its actions. If a decision fundamentally helped achieve that mission, it was probably the right one.

The Political Battlefield. Political battles in the Pentagon are often brutal and unforgiving. The fundamental reason is that the budget is always viewed as a zero-sum game. One program's money comes at another program's expense. GPS was a system that sprang from the space development community ("the Space Weenies") and had virtually no champions from the operational components. Unlike current DoD satellite programs, there were no explicit formal requirements for the new system and hence little official status. Parkinson spent many trips to the operating forces to explain the value of precision weapon delivery. Between skepticism and deafness, GPS survival was always extremely uncertain. The Air Force generally opposed its deployment, even after the extensive tests of 1978–80 had clearly demonstrated that GPS was, by far, the best blind-bombing system ever conceived.

Fortunately, there were some key supporters of GPS who overcame that resistance. They were affectionately called the **GPS Mafia.** The most important member of this unchartered group was Malcolm Currie, whose efforts were discussed earlier. His powerful number-three position at the Pentagon gave him the authority to force funding decisions on the uniformed military. At least one general officer was extremely upset with Parkinson over his relationship with Dr. Currie, and gave him a public tongue-lashing over the issue during a chance encounter in a Pentagon corridor. **Dr. Johnny Foster,** whom Mal Currie replaced, was another early supporter of the program.

USAF Col. Steve Gilbert, the original deputy program manager for GPS in Los Angeles, was a tireless, heroic contributor. Later on he played a critical role, fighting the battles within the Pentagon as the Air Force Program Element Monitor (PEM). His next position was as the GPS representative in the Office of the Secretary of Defense. While there, Steve fought back repeated challenges that would have canceled GPS in the early 1980s. Without his efforts, GPS almost certainly would never have happened. Other members of the GPS Mafia were Lt. Col. Paul Martin (the original GPS Program Element Monitor), **Brig. Gen. Hank Stelling** (RDS in Pentagon), and **Cols. Brent Brentnall** and **Emmitt DeAvies** (DDR&E representatives).

The users of GPS owe all of these supporters a real vote of thanks. As the Duke of Wellington said about the battle of Waterloo, "It was a near-run thing."

Fortunately, GPS supporters prevailed, and the two Iraq wars have made all branches of the military believers in the value of the system, although they sometimes regard it as magic. A combat Army colonel in Iraq was reportedly asked what he thought of satellite systems to help him fight. His response:

"I don't need any (expletive) space systems. My GPS and my Iridium comm give us everything we need."

GPS really is a stealth utility.

Thoughts on the Future

There are now many additional or improved satellite systems on the horizon. American GPS has heretofore only offered a single, clear navigation signal for civil users. That is rapidly changing. Two more frequencies and a number of additional signals will be available from the next two generations of U.S. satellites. Other countries are also working hard to follow the GPS lead. Figure 9 depicts some of these new systems.

Figure 9. Upgrades of GPS (only current operational civil signal; next generation, four new civil signals at two new frequencies), GLONASS (next generation, four new civil signals at two new frequencies) and new international navigation satellite systems (Galileo, four new civil signals to appear at two new frequencies; finally, Compass) are on the near horizon. The plethora of signals will enable improved accuracy and integrity. This will lead to new applications.

An international common navigation signal called L1C has been accepted and almost completely defined. It will broadcast on the same 1575 MHz frequency as the current GPS civil signal. It will be of the same type (CDMA) as the original GPS signal, although it will have significant enhancements to increase precision and accuracy. If the engineering is done properly, this signal should be interchangeable for all GNSS systems that support civilian use. The positioning, navigation, and timing (PNT) community will benefit enormously by having all of these signals available. Again, the key enabling decision was the CDMA signal structure defined by 621B and tested at White Sands.

We will mention one CDMA-enabled application with a large market potential. This is the use of multiple GNSSs (up to 50 satellites) in automobiles for lane guidance and car separation. During times of low visibility, freeways are notorious for multi-vehicle collisions. We believe the technology will be in hand to greatly reduce these tragedies. The new application would involve cooperative navigation with cars in the vicinity all tied together in a communication grid. GPS-measured velocity is almost a forgotten aspect of the system, yet it can be accurate to much better than 0.1 meters per second. If two cars in the vicinity of each other can know both relative position and relative velocity, collision probabilities can be easily assessed and avoidance actions quickly and automatically recommended.

This is just a glimpse of the future. We believe many other new or improved applications will be enabled by future deployments.

Summary

Just as a building is not invented, GPS was not the product of any single invention. GPS as a system was an innovation enabled by many antecedent technologies and concepts. Some were brand new in application, or had to be adapted to their role in GPS, for example the CDMA signal technique. In making those system selections, the final design was the product of the entire JPO team, whose roots went back to many of the greatest institutional sources of innovation in the country.

The two most critical foundations were:

- The comprehensive study done by Jim Woodford and Hideyoshi Nakamura for USAF/621B in 1964/66, exploring virtually all alternative ranging techniques from satellites, both active and passive, and calling for atomic clocks in the satellites. In particular, the four-dimensional 621B concept of using "four in view" was analyzed and became the bedrock of the GPS design, ensuring that the user could make do with a simple crystal clock.
- The selection and demonstration of the CDMA passive ranging signal by 621B at White Sands. These tests confirmed four-satellite, single-frequency operation and proved that such operation obviates the need for an atomic clock in each GPS user set.

These directly led to the systems architecture decisions made in the Lonely Halls meeting. Also essential were finding workable solutions to the five critical challenges:

- Defining the specific details of the GPS CDMA signal structure
- Developing space-hardened, long-life, atomic clocks
- Achieving rapid and accurate satellite orbit prediction
- Ensuring and demonstrating spacecraft longevity
- Developing a full family of GPS user equipment.

In tracing the origins, the first navigation satellite program, the Transit program of APL, should be singled out. Working under contract to the Navy's Nuclear Submarine Program, APL pioneered the dual-frequency technique to calibrate ionospheric delay errors as well as the painstaking development of an accurate orbit-prediction program. Both early efforts were essential to the ultimate success of GPS.

Also important was NRL's push to harden frequency standards for use in satellites. While the JPO rejected Easton's navigation technique, NRL's apparent clock progress, by 1973, convinced the decisionmakers at the Lonely Halls meeting to commit to including atomic clocks in the first prototype, Rockwell-built GPS satellites. While it is ironic that no clock with NRL heritage was operational on the first four GPS satellites, the NRL's persistence finally paid off with the introduction of its cesium beam clocks on an equal footing with the Efratom/Rockwell-designed rubidium clocks later, during GPS Phase II.

Throughout this article, many of the contributors to the early definition, development, and testing of GPS have been named. Certainly many others have also been inadvertently left out. In closing we would like to sincerely thank the scores of engineers who assembled the first-of-a-kind demonstration system.

As a stealth utility, one pervasive accolade is that GPS is now taken for granted. People throughout the world now expect to know exactly where they are and what time it is.