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Permanent Link to Part 2: The Origins of GPS, Fighting to Survive

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Five Challenges, One Key Technology, the Political Battlefield — and a GPS Mafia Part 2 of a Two-Part Story. Read Part 1 here. By Bradford W. Parkinson and Stephen T. Powers, 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. 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. 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 1 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! (Credit: Bradford W. Parkinson and Stephen T. Powers) 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. (Credit: Bradford W. Parkinson and Stephen T. Powers)

Credit: Bradford W. Parkinson and Stephen T. Powers 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 3 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. (Credit: Bradford W. Parkinson and Stephen T. Powers) 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. (Credit: Bradford W. Parkinson and Stephen T. Powers) 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. Figure 3. Earliest satellite-clock technology developments, culminating in the last row: four Rockwell satellites with Rockwell-developed rubidium clocks. (Credit: Bradford W. Parkinson and Stephen T. Powers) 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). (Credit: Bradford W. Parkinson and Stephen T. Powers) 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. (Credit: Bradford W. Parkinson and Stephen T. Powers) 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 initially 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: Data: Bradford W. Parkinson and Stephen T. Powers 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) receiver, 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. (Credit: Bradford W. Parkinson and Stephen T. Powers) 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. Left: 1978 single-channel (sequential) Manpacks, two types by Magnavox and Texas Instruments. Batteries alone weighed much more than current military handsets. Right: The second JPO deputy, Col. Don Henderson (left), and Aerospace program manager Ed Lassiter (right). Bottom: A modern 12-channel (parallel) Atheros chip receiver with more capability. (Credit: Bradford W. Parkinson and Stephen T. Powers)" width="550" height="302" />Left: 1978 single-channel (sequential) Manpacks, two types by Magnavox and Texas Instruments. Batteries alone weighed much more than current military handsets. Right: The second JPO deputy, Col. Don Henderson (left), and Aerospace program manager Ed Lassiter (right). Bottom: A modern 12-channel (parallel) Atheros chip receiver with more capability. (Credit: Bradford W. Parkinson and Stephen T. Powers) 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. 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/Eschbach 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. (Credit: Bradford W. Parkinson and Stephen T. Powers) 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. (Credit: Bradford W. Parkinson and Stephen T. Powers) 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. (Credit: Bradford W. Parkinson and Stephen T. Powers) 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. Credit: Bradford W. Parkinson and Stephen T. Powers 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. (Credit: Bradford W. Parkinson and Stephen T. Powers) 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 development. 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). Figure 8. Refurbished Atlas-F booster characteristics. Col. Parkinson and Maj. Green brought this concept from previous use on the USAF ABRES program. (Credit: Bradford W. Parkinson and Stephen T. Powers) 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. (Credit: Bradford W. Parkinson and Stephen T. Powers) 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.

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2021-06-03

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