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Engineering Achievements

The Global Positioning System (GPS): Creating Satellite Beacons in Space, Engineers Transformed Daily Life on Earth

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1. Prologue

In late 1990, war in the Persian Gulf loomed beyond a January deadline for Iraq to pull its invading forces back from Kuwait. On the front lines of the buildup leading to Operation Desert Storm, American troops began asking their families back home to shop local marine supply stores for commercial satellite navigation receivers and to mail the devices to them in the Middle East. A groundbreaking satellite constellation that the US military had been developing for decades to provide the nation's troops with global navigation data still lacked about a third of its full count of spacecraft. Nonetheless, enough of the satellites were orbiting and functional to broadcast position and time data that could greatly aid the US soldiers massing on and near the Arabian Peninsula to navigate the featureless desert terrain where they might soon be fighting. Unfortunately, almost none of them, nor their tanks, helicopters, or other vehicles, had been equipped with the military receivers needed to download the most precise data.

But the word was out. Less capable civilian receivers, already available in stores, could measure the satellite signals accurately enough to do the job. So, as packages of navigation gear made for fishermen and holiday boaters poured into military bases, encampments, and airfields, infantry soldiers stashed handheld units with their gear or secured larger ones to their Humvees (Fig. 1), soldiers in armored units attached them to their tanks, and helicopter pilots taped the instruments to the sides of their cockpits [1,2].

How prized and widely used the Global Positioning System (GPS) was before it was even finished perhaps gave a clue to the transformative impact the full system would soon have on human society and the central roles it plays today in the lives of Earth's human inhabitants. As the initial GPS constellation crept toward completion in the 1980s and early 1990s, people around the world with GPS receivers, for the first time in history, could instantly know exactly where they were and what the exact time was, even while jetting through the sky, scaling the planet's tallest peaks, or trimming their sails to ocean winds. Now, globally, throughout every second of every day, signals from the GPS satellites broadcast fine-resolution, highly accurate position and timing data that enables countless acts of precision navigation, measurement, vehicle control, and synchronization everywhere across the world.

2. Introduction

The GPS stands out among modern engineering achievements for being the first to provide to all who can access a suitable radio receiver the simple, fundamental, and immensely useful knowledge of their exact location. Throughout human existence, people have strived for reliable means to obtain this information—from features or markers in the landscape or seascape, from sightings on the stars or other celestial bodies, or from maps—but never until the GPS was a universal, global, portable, dependable, and highly accurate technology readily available that could provide that desired knowledge to anyone, nearly anywhere on the planet, instantly, and for free. Perhaps an equally important impact of GPS stems from the nanosecond-accuracy time signals it distributes worldwide. These signals synchronize vast flows of financial transactions, communications, electrical power, control signals, and myriad other data streams and measurements that have become globally essential for commerce, power grids, land, sea, air transportation and shipping, military maneuvers, Internet traffic, and many, many other activities and services.

This article recounts the history of the invention and development of the GPS, starting from the late 1950s, with the surprise launch by the then Soviet Union of the first artificial satellite, Sputnik 1. Prompted by this event, US space pioneers performed

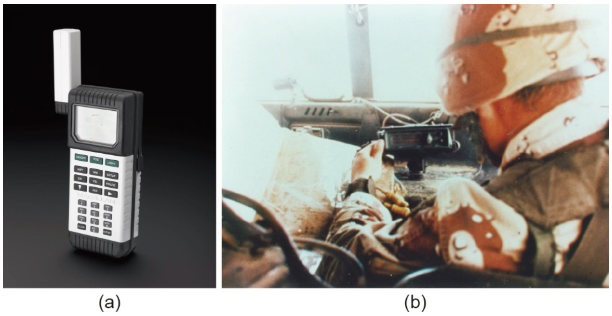
(a) (b)

Fig. 1. Sent to US troops in the Middle East by their families back home, GPS receivers made for civilian use, such as (a) the 1991 Magellan NAV 1000 and (b) the Trimble Trimpack mounted in a military vehicle, provided unprecedented navigation guidance in the Desert Storm campaign. Credits: The Science Museum (CC0); US Army (public domain).

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research that uncovered the potential for distance measurements to orbiting satellites with known positions in space to enable extremely accurate calculations of an observer's location on Earth. Prodded by engineers, scientists, and defense contractors, the initially reluctant US military worked to realize this locating ability, pursuing research and development programs in the US Navy (USN) and US Air Force (USAF). These efforts launched the world's first—albeit limited—global satellite navigation system, the USN's "Transit." GPS subsequently arose from a secret, later declassified, USAF program that extended the prior space advances of Transit and other programs, but also produced key innovations in ranging and communication signaling, space-worthy atomic clocks, satellite orbit prediction, spacecraft longevity, and user receivers.

After proving its military value in the 1991 Persian Gulf War, the GPS began full operation as a constellation of 24 satellites plus spares in 1995. A quarter century later, three additional global navigation satellite systems (GNSS)—one that became fully operational just last year (2020) and a second expected to become fully operational by 2022—have joined the GPS in space, all patterned on the GPS and capable of providing the same essential services. Since the early 1980s, the GPS has continued to play a leading role in enabling and sustaining pervasive and transformative technology, fueling the proliferation of a vast and still-growing array of civilian applications in navigation, transportation, communications, agriculture, industry, science, finance, and other areas upon which nearly every facet of modern society now depends [3]. Together with its sister constellations, this engineering achievement further provides an essential foundation for currently emerging technologies, such as 5G, that rely heavily on GNSS signals, and likely for other major innovations not yet imagined.

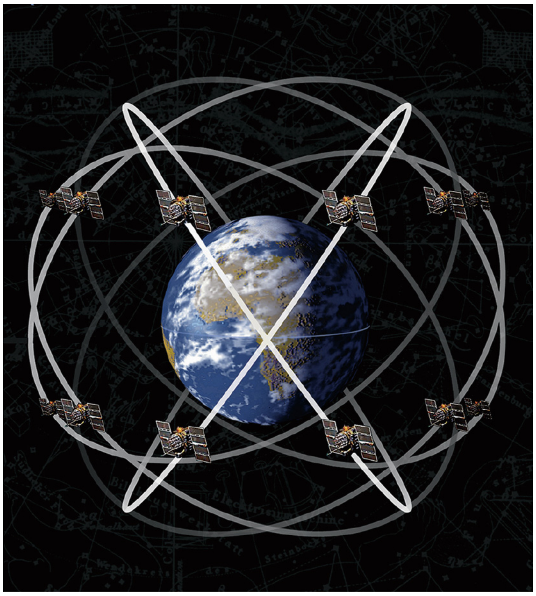


Fig. 2. The 24 (minimum) GPS satellites trace orbits designed to spread them evenly in space and time around the Earth, ensuring simultaneous sight lines to four or more of the spacecraft, 24/7, from everywhere on Earth. The system globally transmits position and timing data that enable precise measurements of location and nanosecond synchronization. Fully operational since 1995, GPS was the first GNSS to provide these capabilities; today, three more GNSS—largely modeled on GPS—have joined it in space. Credit: National Air and Space Museum, Smithsonian Institution (public domain).

3. Project overview

3.1. Coordinating humanity

As of January 2021, the current 31 operational satellites that officially comprise the GPS (seven more than the nominal, minimum constellation of 24, with additional "retired" satellites available to be turned back on) continuously circle Earth at an altitude of 20 200 km (Fig. 2) and beam their radio signals to the planet's surface below [4]. There, billions of receivers throughout the world in mobile phones and a multitude of other devices can lock on to signals from the GPS satellites and, increasingly, from the sister navigation constellations of Russia, China, and the European Union (EU). The acronym GNSS generically refers to any of these whole-Earth-spanning systems. India and Japan have fielded regional systems that supplement the coverage provided by the GNSS networks; together, all these systems constitute the world's satellite-based position, navigation, and time (PNT) infrastructure.

Accessible by radio receivers from nearly everywhere outdoors and from lightly shielded indoor locations as well, data from these PNT satellites facilitate and assure the correct operation of countless critical, computerized tools [2]. Phones and personal computers need the position data to use Google Maps or Waze, and the timing data to coordinate Weibo, Facebook, TikTok, and multitudes of other entertainment, e-payment, social media, gaming, banking, and other apps, as well as myriad websites, phone carriers, and Internet-enabled services. In addition to guiding and monitoring car drivers, fleets of trucks, aircraft pilots, and ship captains by the millions, the system makes it possible to continuously synchronize, route, and time-stamp (as needed) billions of daily data transfers throughout the world. Financial transactions, the distribution of power grid currents, mobile phone calls, and a vast array of other digitally driven sorts of human enterprise and activities could not occur without PNT signaling. Furthermore, reflecting the system's military origins, armed forces rely on PNT signals as they orchestrate maneuvers of soldiers and weaponry, precisely target artillery, bombs, and missile launches, and rescue downed comrades. Overall, the availability of GPS and other GNSS data—nonstop, instant, free, accurate, reliable, and ubiquitous—has become a routine and essential underpinning to the daily lives of an estimated half of Earth's almost eight billion people [5].

All this makes GPS a revolutionary technology, according to retired USAF Colonel Bradford W. Parkinson, PhD, who led the GPS program for its first six years (1972–1978). During that time period, the system's design crystallized, and Parkinson and his fellow engineers began to build and launch the current system's satellites. Parkinson, who served as the primary source for this article, describes GPS technology as "stealthy" in terms of how it has quietly enabled and driven so much dramatic change. Exact knowledge of where we are and what time it is has been hard to come by throughout most of human history. "But now we just pull out our cell phones and right away, we know where we are," Parkinson said. "Although, by and large, most people have no idea how GPS works."

3.2. Groundbreaking

Given that the GPS was the first GNSS by decades, and the only PNT infrastructure enabling and supporting today's networked, data-immersed world, it is not surprising that it has won wide recognition as one of the most consequential modern engineering achievements. In 2003, the US National Academy of Engineering (NAE) bestowed the Charles Stark Draper Prize—considered by many in engineering to be the field's equivalent of the Nobel Prize—on Parkinson and on a fellow advocate of the pioneering system, the late Ivan Getting, former president of Aerospace Corporation, a defense contractor deeply involved in the invention and development of the GPS [6]. This groundbreaking technology and the hundreds of engineers and others who took part in its development have collectively received numerous other honors as well.

These accolades say much about the wide acceptance of GPS as a significant engineering achievement, but not as much about the motivations and dreams of its inventors, the struggles and challenges they overcame along the way, nor how they worked through those roadblocks. The honors also represent wise-in-hindsight responses that are very different from the skepticism and disinterest of most senior US military officers that the developers of GPS faced from the early 1960s until the partial system's first broad military use in the Gulf War conflict in 1991.

The idea of a satellite-based navigation system originated in the military: The USN and the Johns Hopkins University Applied Physics Laboratory (JHUAPL) near Baltimore, MD, designed and built Transit, the first global satellite navigation system. Although somewhat limited in its capabilities, Transit achieved great success. Nonetheless, notions of the feasibility and value—military and otherwise—of a faster, more accurate, universally accessible, and versatile system than Transit, which GPS eventually realized, scarcely existed among US military leaders. Throughout almost all of the development of the first GPS constellation, military commanders largely viewed the technology as an unnecessary and unwelcome competition for their budgets. ''If the Air Force had been left to their own devices, the program just would have died, from lack of budget,'' Parkinson said.

In the face of such political challenges through and beyond the decade of the Apollo missions, when the excitement and wonder about the dawning Space Age focused on the Moon, a group of visionary engineers took the first steps toward realizing this unproven space technology focused on the Earth. In doing so, they achieved a host of essential technical advances—from a scheme for encoding information from all of the system's satellites onto a single radiofrequency carrier to developing the world's first miniaturized atomic clocks that were robust enough in the face of radiation and temperature swings to survive in space. These and other advances ultimately resulted in a stealthy revolution that is easy to take for granted, but on which our increasingly digital world vitally depends.

3.3. Twin sparks

In the fall of 1957, twin sparks simultaneously and inadvertently ignited the single-minded pursuit of the vision of GPS by its inventors and builders. One was the launch of the world's first artificial satellite, the Soviet Union's Sputnik 1, which ushered in the Space Age. The other was informal experimentation at JHUAPL inspired by the debut of the Soviet spacecraft (Fig. 3).

Sputnik 1 launched into orbit on Friday, 4 October 1957. By the following Monday, two young JHUAPL physicists, William Guier and George Weiffenbach, had picked up the satellite's radio signal with a makeshift receiver setup. They began measuring the Doppler shifts of its 20 and 40 MHz radio transmission pulses as the satellite approached and then receded from them with each pass high overhead. They found that they could roughly gauge from those shifts the spacecraft's velocity and other orbital information, similar to how traffic police with radar guns measure the speeds of passing cars from changes in the frequencies of beams rebounding from the vehicles. For the next few months, the JHUAPL researchers and colleagues at other institutions worked to refine their estimates of Sputnik 1's orbital path.

As their approximation of the orbit grew increasingly exact, Frank McClure, the lab's director, asked a question that turned the impromptu project on its head. He wanted to know how accurately, assuming that the estimate of Sputnik's orbit was correct, the scientists could calculate their own position on Earth from their knowledge of that orbit and the frequencies of signals between the spacecraft and themselves. "The very first simulations indicated great accuracy—unbelievable accuracy!" Guier and Weiffenbach recalled years later [7]. McClure's question led to the essential realization underlying GPS: that human-made objects orbiting in space could be used to precisely determine locations on Earth.

3.4. First came Transit

More than just intellectual curiosity had prompted McClure's question. The USN was seeking a reliable way for its submarines in the nuclear-armed Polaris fleet to accurately fix their geographical positions. When McClure and mathematician Richard Kershner learned of Guier and Weiffenbach's accuracy results, they translated McClure's brainstorm into a design for the world's first navigation-satellite array. Kershner then founded a new Space Department at JHUAPL, which prototyped, tested, and built the system, called Transit, for the USN. When fully functioning, 5–8 satellites plus spares, all in transpolar orbits, provided global coverage (Fig. 4). Transit became operational in 1964; several years later, JHUAPL turned over the manufacturing of the last batch of Transit's production satellites to the Radio Corporation of America.

Using Transit, a submarine at the surface could locate itself with much better accuracy than leading ground-based, radio navigation systems of that era, such as Loran. Transit position fixes were

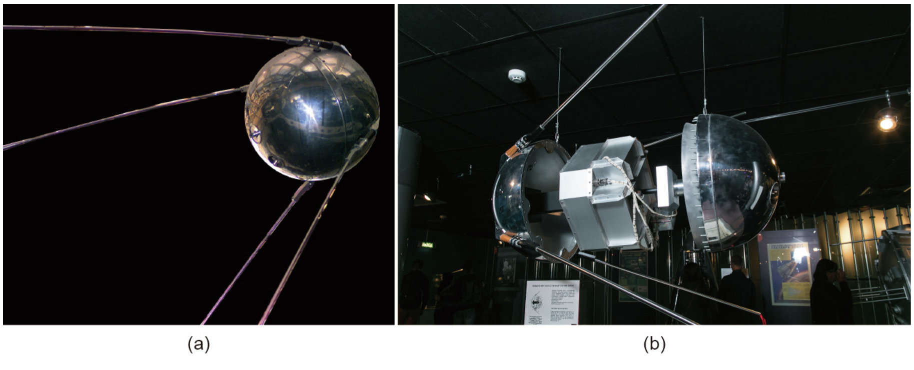

(a) (b)

Fig. 3. (a) A replica of Sputnik 1 displays the four swept-back antennae that enabled the Soviet Union's trailblazing spacecraft—the world's first artificial satellite—to broadcast radiofrequency pulses to nearly the entire inhabited Earth after its launch in October 1957. (b) The model shows the inside of the satellite, which travelled at ~29 000 km·h^{-1} (8100 m·s^{-1}), completing an orbit every 96 min. The satellite's radio pulses ceased when its batteries died after 21 days in space. Sputnik 1 burned up on 4 January 1958 while reentering Earth's atmosphere after three months in orbit. Credits: National Aeronautics and Space Administration (NASA; public domain); Wikimedia Commons (CC0 1.0).

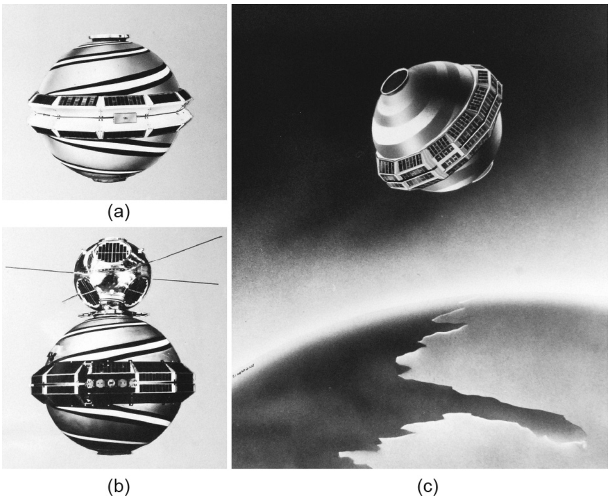


Fig. 4. An artist's illustration shows the first two satellites in the USN's Transit navigation system, (a) 1-B and (b) 2-A, the latter of which carried a US Naval Research Laboratory satellite into space on its top; (c) the third satellite, 3-A, is depicted orbiting Earth at an altitude of 800 km after its launch on 29 November 1960. The 0.91 m tall, roughly 90 kg 3-A launched carrying a similar hitchhiker as 2-A. Credits: Roger Simmons, National Archives (public domain).

derived by means of Doppler measurements on a single satellite and required 10–16 min after a wait of what could be hours until one of the constellation's satellites became detectable on a line of sight from a submarine's location. Among its limitations, Transit provided coordinates in only two dimensions, with no altitude information; furthermore, it could significantly mislocate a moving user unless the user's velocity was exactly specified. Still, the system provided 25 m fixes, which were highly accurate for that time, of any location throughout the world's oceans and successfully served as a navigation aid for USN vessels—as well as for civilian users from 1967 onward—for 32 years, until 1996.

Around 1962, while the USN and JHUAPL were creating Transit, the USAF inaugurated a secret program, called "621B," aimed at studying and testing concepts for a regional satellite navigation system centered on Southeast Asia. This program kicked off an interservice rivalry that confounded the development of GPS for many years. The USAF envisioned a far more capable system than Transit, one that could provide three-dimensional, almost instantaneous position fixes accurate to within a few meters. The next-generation system would also offer global time measurements synchronized to within 30 ns. That enhanced performance would make feasible rapid, recurrent, enroute position fixes for hypersonic military jets to guide precision airstrikes and other operations in Vietnam, where US military involvement was deepening. Although the system was originally meant to provide only regional coverage from satellites in geosynchronous orbits over Southeast Asia, its planners also viewed it as a possible first step toward the global satellite navigation network that was finally realized more than 30 years later by the GPS.

Starting in the early 1960s, Aerospace's Ivan Getting ardently advocated this concept of a faster, more sophisticated satellite navigation system that could provide users with three-dimensional position fixes to high-ranking Pentagon officials. Funded by the USAF, Aerospace conducted some 90 exploratory satellite navigation studies for 621B, including a 1964–1966 analysis by two of the company's top space-systems engineers, James Woodford and Hideyoshi Nakamura [8]. In this since-unclassified work, Woodford and Nakamura explored a dozen different system concepts that varied in type of communications, equipment for timekeeping and computing, and methodologies that might be employed by satellites, users, and ground stations.

At the time, it was unclear whether both the system's satellites and its users would need atomic clocks, which were big, heavy, and prohibitively expensive. In Woodford and Nakamura's most promising scenario, however, communications would go only from satellites to users, between sophisticated computers anchoring both ends, and the numbers and distribution of satellites would suffice to give every user simultaneous sight lines at all times to at least four of the satellites. For this round-the-clock, "four-in-view" condition to apply globally, at least 24 satellites would have to be in continuous operation. Only master control stations located on US-controlled soil would send any signals to the spacecraft, such as those for satellite position and time calibrations.

The engineers' work suggested that the payoffs could be great if such a system proved feasible. For one, users' receivers could, on their own and at virtually any time or place, almost instantly extract from satellites' continuous broadcasts the exact time and simultaneous distances to the requisite four satellites (or more for enhanced accuracy). This would be the only information needed by users to calculate precise, three-dimensional position fixes (Fig. 5). Secondly, the system would serve only "passive" users who, by design, would not need to transmit any electromagnetic signals that might lead enemies to them. Such a system could supply risk-free position and timing information 24/7 to all military assets, including combat soldiers, patrol boats, and tactical

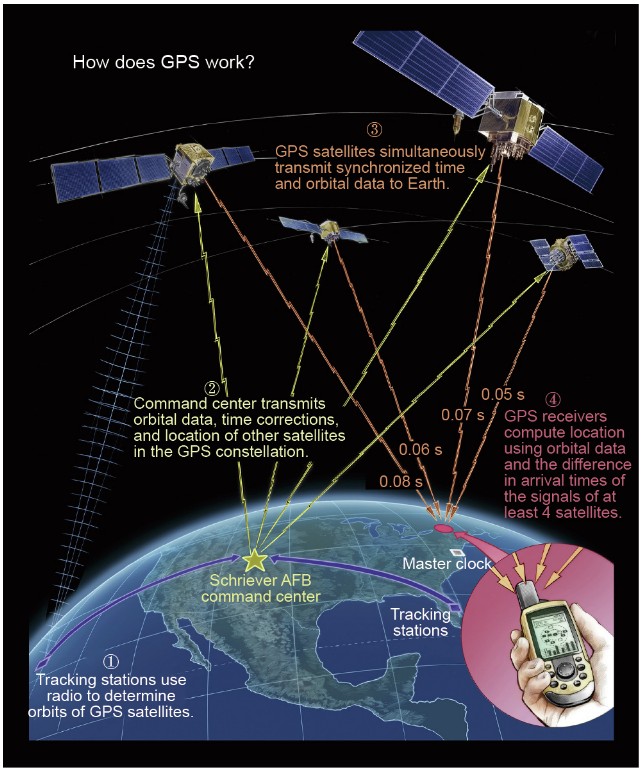


Fig. 5. How does GPS navigation work? A handheld receiver (bottom right) tracks the arrival times of signals from at least four satellites to determine the distances to those satellites. Combining those range calculations with precise satellite positioning and timing correction information also broadcast from those satellites allows the user device to calculate its position on Earth. The system includes tracking stations that observe satellite orbits to collect data for command centers that transmit essential updates and corrections to the constellation. These updates and corrections ensure that each satellite broadcasts precise system time and observation-verified, orbital positions, guaranteeing them as reference points in space for accurate user-position fixes on the ground Schriever AFB: Schriever Air Force Base. Credit: Bruce Morser, National Air and Space Museum, Smithsonian Institution (public domain).

bombers. When all users are passive, the number of simultaneous users becomes unlimited, so the service would be available to all.

Finally, although Woodford and Nakamura concluded that the satellites required atomic clocks on board (or accurate time, relayed from the ground) to achieve the desired timing and position accuracies, users' receivers would not need the advanced, bulky, and expensive timekeeping devices. The terrestrial instruments could ascertain position and the exact time thanks to the four-in-view satellites, with timepieces no more sophisticated than the small, inexpensive, quartz clocks that soon became widely used in digital electronics [9].

3.5. Technical hurdles

After the Transit system was fully under way at JHUAPL, engineers and scientists led by physicist Roger L. Easton at another nearby US military research and development institution, the Naval Research Laboratory (NRL) in Washington, DC, began building and testing prototype satellites for a space-based navigation system intended to surpass Transit. In addition to exact position fixes, the NRL concept, called Timation, was intended to offer users precise, universal time. According to Parkinson, NRL personnel were probably unaware of the details of the still-secret USAF 621B plan, which also intended to provide a highly accurate, reliable time signal. Although the NRL and 621B concepts differed in crucial ways, the two concepts had much in common.

By 1969, the second in a series of test satellites that the NRL built and launched to evaluate technologies for Timation had demonstrated ~60 m position accuracy for users at fixed (non-moving) locations, which was good but not yet better than Transit. Meanwhile, the USAF appointed a new director to its 621B program in 1972: Bradford Parkinson. At that time, Parkinson was a young colonel in charge of engineering for the USAF ballistic missile reentry program, and his qualifications had caught the attention of a general who wanted to shore up the beleaguered 621B program. Parkinson had flown combat missions in Vietnam, graduated from Stanford University with a doctorate in astronautical engineering, and chaired the USAF Academy's astronautics department. Prior to taking the engineering helm of the reentry program, he worked for three years in inertial navigation, and had studied inertial navigation for two years at Massachusetts Institute of Technology, in the laboratory of "Doc" Draper (namesake of the NAE's Draper Prize), who invented the first successful inertial navigation system.

As 621B's new leader, Parkinson ramped up the program's capabilities by recruiting a hand-picked cadre of about 25 USAF officers with advanced engineering degrees and work experience developing hardware for and testing guidance systems. Over discussions of the technical intricacies of his program's global navigation concept, Parkinson soon bonded with PhD physicist Malcolm Currie, a newly appointed, high-ranking civilian at the Pentagon. It was a fortuitous meeting of the minds for GPS. Currie had recently left Hughes Aircraft to become the Director of Defense Research and Engineering, the third most powerful position in the US Department of Defense (DoD). "I call him the Godfather," said Parkinson. "If anything was going wrong in the Pentagon, he would try to fix it for us."

Although the USAF and USN rivalry contributed to a few years of top-level indecision within the US military, in December 1973, a council of high-ranking officers from across the armed services, chaired by Currie, approved a 150 million USD, four-satellite, proof-of-principle demonstration of the 621B concept. As part of a then-new cooperative arrangement conceived by Currie, the satellite navigation effort became the first Joint Service Development Program in the DoD. The council established the GPS Joint Project Office (JPO) run by the USAF under Parkinson's leadership, placing the USN's Timation under its authority. Officers from other branches of the military—including the Navy, Army, Marine Corps, and Defense Mapping Agency—shared the administration of the project as deputy program managers.

To design, construct, launch, and validate its fledgling, four-satellite demonstration system (completed in 1979), which ultimately became a fully functional global constellation (completed in 1995) with its ground stations and essential user equipment, the JPO faced scores of technical hurdles. At the time these efforts began, satellites and rockets were still in their infancy, computers and other electronic devices were analog-based—clunky, slow, and power-hungry, and atomic clocks were both too large and too fragile to fly into space. To overcome the technical hurdles that needed to be addressed, five engineering advances were particularly key to the success of GPS: ① an accurate and reliable ranging signal from the satellites to user receivers on the ground; ② space-qualified atomic clocks; ③ robust, long-lived satellites; ④ precise prediction of satellite orbits; and ⑤ practical user receiver equipment [10].

4. Highlighted technology and innovations

4.1. Data delivery

Of all the advances, there seems to be general agreement among GPS pioneers that the groundbreaking ranging signal they devised for the system—which remains largely unchanged 25 years after the system was completed—contributed more than any other technical advance to its successful implementation and overall performance, versatility, and effectiveness. Woodford and Nakamura had set the stage with their assessment that passive users of a four-in-view constellation would not need bulky, expensive atomic clocks. Fleshing out the concept called for each satellite to broadcast not only its own orbital description and position coordinates, but also system time, the spacecraft's transmitter status, ionospheric delay models, and much more—even the orbital and position details for all other operational, sister satellites in the constellation.

Yet those continuous broadcasts could only transmit all of this information at a meager data rate to ensure that enough power was available for the critical ranging signals. Because of the restrictive GPS budget, the JPO had opted to save millions of dollars by initially using refurbished intercontinental ballistic missiles for its satellite launches. The thrust capability of those relatively low-cost, Atlas-F boosters limited the launch weight of each satellite, and hence the size of its solar array and, ultimately, the available transmitter power. The GPS developers could only reliably deliver a signal strength on Earth of a tenth of a millionth of a billionth of a watt. The system's specifications therefore guaranteed no more than this 10^{-16} W to receiver makers, and the satellites made do with their limited power by transmitting no faster than a mere 50 bits of data per second.

Each GPS satellite would relay its information by modulating two high-frequency carrier signals (1.2276 and 1.57542 GHz) that the constellation continuously beamed to users below. The JHUAPL designers and builders of the earlier Transit system had pioneered the use of this "dual frequency" means of directly measuring the frequency-dependent delays of satellite signals that passed through the ionosphere. "Fortunately, the delay is inversely proportional to the square of the carrier signal frequency," said Penny Axelrad, a GNSS expert and professor of aerospace engineering sciences at the University of Colorado, Boulder. "By receiving signals on two, or three, different frequencies, the GPS receiver can easily correct for this effect." The inexpensive GPS chips in today's smartphones can execute a similar solution. Transmitting at more frequencies costs satellites precious power, but the technique provides independent ranging signals and effectively enables users to calculate distances to constellation satellites exactly enough to fix their positions with great precision.

In the late 1960s and through the 1970s, electronic circuitry was transitioning from analog technology to lower power, compact, long-lived digital components. This evolved into the integrated circuits of today that have enabled massive improvements in computing. An inventive community of mathematicians and computer scientists discovered novel processing capabilities for digital signals and applied them to communications, sensing, control systems, and other fields. Within 621B, a hardware demonstration of these techniques for radio-ranging was already occurring in the New Mexico Desert (further described below), when approval for the initial four-satellite demonstration came through.

To meet the needs of the evolving GPS effort, in-house engineers and digital-signal-processing experts from industry had focused on a communications protocol known as Code Division Multiple Access (CDMA). By assigning a mathematically distinct code to each satellite, the CDMA protocol made it possible for all satellites to broadcast on the same frequency, without mutual interference or data loss. At the same time, all user receivers could simultaneously range to each satellite by accurately measuring the arrival time from each of four or more satellites in view.

In field tests of the CDMA-based scheme conducted in 1971–1973 at the White Sands Missile Range in New Mexico, the 621B team deployed two types of prototype CDMA receivers built by electronics industry companies on contract to the program. These receivers detected and processed the signals emanating from four “pseudolites,” ground-based transmitters that simulated the broadcasts of GPS satellites. Engineers then compared the computed position fixes with the instruments’ actual locations measured with lasers installed on the testing range. The calculated and laser-pinpointed locations were within 5 m (circular error probable) of each other in three dimensions. These findings helped gain approval for the four-satellite demonstration, resolving the doubts of some in the Pentagon and confirming that a global system of real satellites with four-in-view accessibility and CDMA could deliver the unprecedented level of position accuracy the JPO had claimed was feasible.

4.2. Orbiting atomic clocks

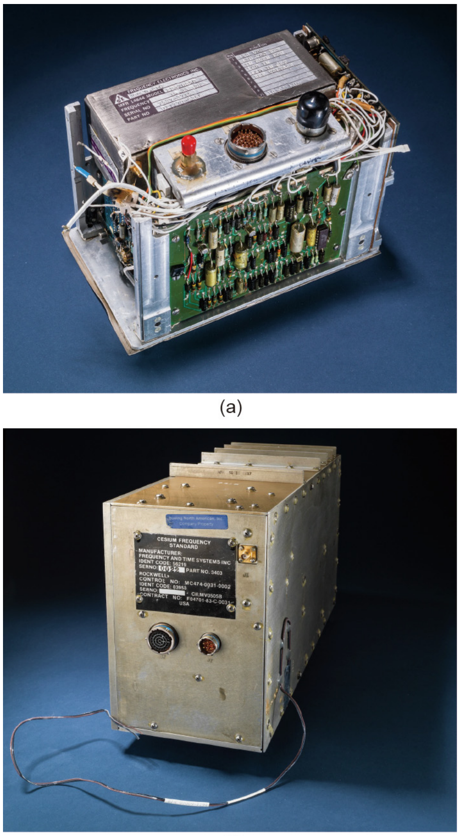
As the project’s engineers prepared for the crucial, four-satellite tests in the late 1970s, the clock technology needed by the GPS did not yet exist. While the four-in-view satellite condition eliminated the need for an atomic clock in each GPS receiver, this benefit came at a price. The entire constellation needed to synchronize its signals to nanoseconds—a few billionths of a second. Although this could be achieved with a continuous signal from a GPS ground control network, a better solution would be to install very stable clocks to “flywheel” time aboard each GPS satellite, with calibration occurring once or twice a day.

Commercial atomic clocks using beams of cesium atoms, which were first developed in the 1950s, could meet the GPS timing specifications. Unfortunately, the temperature swings of spaceflight would harm the accuracy of those clocks, which were built for laboratory use. Furthermore, intense ionospheric radiation in the region where the GPS was to orbit, which could kill an unshielded human in less than a minute, would also rapidly destroy the clocks. Moreover, these sophisticated instruments took up too much room and weighed too much to meet satellite volume and weight limitations. The GPS needed much smaller clocks that were highly stable and well protected from the extreme environment of space.

Whereas Woodford and Nakamura’s 1966 report encouraged the USAF to initiate a clock development program aimed at such goals, Easton’s group in the USN had already begun this work. Aboard the test satellites the NRL used to assess potential position accuracy and other aspects of its envisioned Timation system, the lab included experiments on simple quartz clocks; on novel, miniaturized, rubidium atomic clocks made by the small firm Efratom Elektronik GmbH of Munich, Germany (which later opened an office Munich, Germany (which later opened an office in California); and on compact cesium-beam atomic clocks crafted by the small contractor Frequency and Time Systems, Inc. (FTS) of Danvers, MA (Fig. 6).

During a decade of in-space clock trials by the NRL that began in 1967, instabilities in the satellites’ three-dimensional orientations (attitude) plagued the tests. Variability in where, from what angle, and when sunlight would most strongly strike the spacecraft made internal temperatures changeable, causing the quartz clocks’ frequencies to change as well, even with onboard temperature compensation. The results of these trials made it clear that simple quartz devices would not suffice for GPS. Regarding the atomic clocks, however, which were yet to be hardened against the extremes of temperature, radiation, or mechanical stress, the unsteady conditions mainly rendered the tests inconclusive.

A typical rubidium atomic clock made at that time by a large company would be ~30 cm tall and 48 cm wide, designed for mounting on an industrial electronics rack. In contrast, each lightweight, compact, low-power, Efratom rubidium clock was contained in a 10 cm cube, which encapsulated a vapor of rubidium atoms and other gases as its timing source. By the time a 1974



(a)

(b)

Fig. 6. (a) Designed by the German firm Efratom in partnership with Rockwell International, lightweight, compact, low-power rubidium atomic clocks like the one shown here enabled the first four GPS satellites to achieve the demonstration project’s milestones. (b) The fifth GPS satellite carried a compact, space-hardened cesium-beam atomic clock like this one, built by the Danvers, MA, contractor FTS. Credit (both): Dane A. Penland, National Air and Space Museum, Smithsonian Institution (public domain).

NRL field evaluation of a pair of rubidium clocks returned ambiguous results, the four-satellite demonstration project had been approved, and the JPO had hired Rockwell International of Seal Beach, CA, to build the first GPS satellites. With the launch date planned for 1978, Rockwell partnered directly with Efratom to produce space-hardened versions of their promising rubidium clocks. In the meantime, FTS was developing a prototype space-hardened, cesium-beam clock that the NRL tested on another satellite launched in 1977, again with indeterminate results, with the exception of one clock that apparently worked well until its power supply failed just 12 h into the evaluation.

Nonetheless, the miniature, space-hardened, Efratom/Rockwell rubidium clocks met the stability and robustness requirements, allowing the first four GPS satellites to achieve the demonstration milestones. "An atomic clock, a small atomic clock, is just as much of a world-changer as GPS is," said Hugo Fruehauf, who was Rockwell's GPS chief engineer at the time [1]. Fluent in German, Fruehauf had worked closely with the clock's Efratom co-developers. On the fifth GPS satellite, launched in 1980, a space-hardened FTS cesium clock finally succeeded in space, the first of a series of space-worthy cesium clocks that proved to be at least as stable as the rubidium clocks that initially enabled GPS to meet all of its design objectives [9,11].

Despite the extraordinary accuracy and stability of its newly achieved atomic clocks, the satellite system still had to compensate for an unavoidable timing discrepancy due to relativistic effects. As general relativity predicts, space clocks run faster than terrestrial clocks in control stations and in user receivers on Earth because of the weaker gravitational field at the orbiting clocks' altitude of 22 200 km. If nothing were done about this rate difference, the satellites' clocks would get ahead of ground clocks by ~45 $\mu s \cdot d^{-1}$. In addition, in accordance with special relativity, the rapid velocities of the space clocks stretch out the time intervals they are measuring, slowing down their "ticking" in comparison with ground-based timepieces. This lessens the timing mismatch to ~38.6 $\mu s \cdot d^{-1}$. To eliminate that remaining difference, GPS operators slightly reduce, by about 0.006 Hz, the roughly 10 MHz frequencies of the on-satellite, atomic clocks prior to launch. Without this adjustment, GPS-determined positions would be thrown off by ~10 $km \cdot d^{-1}$, a debilitating error that would only grow with time.

4.3. Long-lived satellites

Short-lived satellites can bankrupt a space program because of the high cost of constructing and launching replacements. For example, the satellites in the first, then Soviet Union, GLONASS constellation lasted only 2–3 years on average. This lifespan translated into 8–12 new satellites and launches needed per year to keep the GLONASS 24-satellite constellation fully operational.

Aiming for long GPS satellite lifetimes from the start, Rockwell International adopted quality-control measures, including redundancy of the most failure-prone components, painstaking practices for parts selection that downgraded bad performers, extensive component monitoring in flight, and follow-up analyses of equipment failures. These efforts paid off, with the first ten GPS satellites lasting an average of 7.6 years (Fig. 7). During the GPS II generation era, satellite mean lifespan reached 10–12 years, which required 2–3 replacement launches annually. The latest GPS III satellites, which began launching in late 2018, are intended to have a 15-year lifespan, with four of these satellites in one orbit as of November 2020.

4.4. Precise predictions

The engineers and scientists who devised the Transit system had pioneered advanced capabilities for predicting the orbital trajectories of its satellites. This was a critical need for Transit, and the goals for the GPS had even more stringent requirements. For example, the planet-circling paths of navigation satellites can take them out of sight for hours from active ground stations that upload the updated coordinates to the constellation. In the case of Transit, as its roster of orbiting satellites filled up, Guier and fellow JHUAPL scientists used observations of the spacecraft's trajectories to refine gravitational models of Earth. They then fed the improved data into satellite-orbit and terrestrial-position calculations. Whereas the early Transit system's position accuracy was off by up to 1 km, the error margin dropped to 99 m as the models improved—significantly better than the project's stated goal of 185 m accuracy. As the program matured, the static horizontal errors decreased to 25 m (Transit did not provide vertical position) [12].

Fig. 7. Engineers testing the third prototype GPS satellite before its launch in 1978. Credit: The Aerospace Corporation (public domain).

Building on Transit's success, GPS developers created enhanced orbital models for predicting ephemerides (trajectories) that accounted for the planet's gravitational field and tides; solar and Earth radiation; and the wandering position of the planet's spin axis, which can vary by up to around 15 m. In addition, the space-hardened clocks developed for GPS satellite time synchronization enabled further improvements in orbital prediction accuracy. For GPS to consistently deliver its intended position accuracy, the models underlying its satellites' orbit predictions could add no more than a few meters to the receivers' satellite ranging errors during 1.45×10^8 m of orbital travel [11]. Because GPS also needed to recalculate its models quicker than the Transit system, its development team had to devise a novel mathematical approach capable of generating expected orbital paths in near real time.

4.5. Empowering users

A heartbreaking tragedy and, later, the first Iraq war enabled the GPS enterprise to meet the last of the five key engineering challenges: developing inexpensive user equipment to provide rapid access to PNT data. This advance would ultimately drive the technology's acceptance and adoption by both the military and civilians worldwide.

The tragedy struck in 1983, when the Soviet Union mistook the off-course Korean Airlines passenger flight 007 for a spy plane and shot it down, killing all 269 people aboard. In response, US President Ronald Reagan guaranteed the GPS civilian signal for global use; although the specifications for using the GPS civilian signal had been freely available from the start, they had not been guaranteed. The early GPS system had implemented "selective availability," meaning that it broadcast two distinct signals, one for the military and the second for civilian use. Whereas anyone could access the less accurate civilian signal, only the US military could access the signal with best accuracy (to ensure its advantage in battle). Nevertheless, the civilian signal would suffice to avoid gross navigation errors like the one that led to flight 007's deadly mistake. Reagan also pledged to give no less than ten years notice of the system shutting down. Significantly, Reagan's guarantee and this pledge reassured electronics companies about the future prospects for GPS. Firms started developing and manufacturing GPS receivers in greater numbers, although these devices were initially expensive specialty items, especially those designed for the military, which slowed their adoption.

The JPO had tried to seed the military demand by issuing contracts to create a family of demonstration military receivers designed to meet a range of different goals, sizes, and prices. The nine varieties of user instruments that the program designed and built in limited quantities tended to be bulky and heavy, with large power demands (Fig. 8). The largest device was a massive military console taller than a person, which was meant for permanent installation in a large aircraft; it was outfitted with five channels and seated two operators in front of a bank of electronics racks as wide as five people standing side by side. This device demonstrated that GPS could operate undeterred by a 1 kW enemy jammer just a few thousand feet below it. Smaller units, each with a fat rod antenna, included an 11 kg "manpack" to sling on a soldier's back, another version to mount on a military jeep, and a civilian prototype about the size of a clock radio.

Lacking military-grade receivers in its inventory just prior to the start of Operation Desert Storm, the DoD itself started ordering civilian receivers in large quantities, which supplemented the ones sent to the Middle East by the family and friends of savvy soldiers. The USAF operators of GPS also temporarily shut off the selective availability that degraded the civilian signal, permitting troops to use the civilian gear with full accuracy. Ultimately, nearly 90% of the receivers that the US armed forces used in Desert Storm were civilian ones; the DoD had purchased 10 000 from Trimble Navigation and 3000 more from Magellan Systems [2].

When combat began in mid-January 1991, television viewers saw astonishing weapon delivery accuracy that wiped out the Iraq Air Force. Widespread use of GPS also enabled the US Army to navigate effectively through the featureless desert and target enemy artillery with unprecedented and devastating accuracy. These striking demonstrations of the PNT capability promised by the developers of GPS finally convinced the military services—which had long been reluctant participants in its creation—of the system's enormous value.

4.6. Speed bumps

Until Desert Storm, however, misgivings and misunderstandings about satellite navigation and skepticism about its military value had persisted after the June 1979 approval for building the full satellite constellation. In fact, the Office of the Secretary of Defense eliminated the GPS budget for 1980 through 1982. Although the budget was soon reinstated, it was slashed by 30%, or 500 million USD, for the fiscal years 1981–1986. This cut decreased the targeted constellation size by a quarter, to 18 satellites plus three spares. It also slowed the development of the more advanced, next-generation "Block II" satellites. By 1988, due to concerns that an 18-satellite system would underperform, the DoD restored the constellation's satellite number to 24, including three spares. Plans for Block II satellites were also reinstated [2].

Nonetheless, budget issues continued to slow the development of GPS, impose new and unexpected technical and management hurdles, and stretch out the construction timeline of the complete GPS system. "We developed the new, full system, as Mal Currie requested, with the same budget as intended for the test program. Money was always an issue," recalled now-retired USAF Colonel Gaylord Green, a guidance and navigation engineer who played major roles in all phases of GPS development [1]. Parkinson originally knew Green as a fellow graduate student at Stanford who later worked for him in the USAF reentry vehicle program; when Parkinson took the reins of 621B, he invited Green to join the satellite navigation project. Green later served as director of the GPS program from 1985 to 1988.

Still, some setbacks to the GPS occurred independently of the rivalries and budget ups and downs within the US military. The fiery Challenger shuttle launch disaster in 1986 halted GPS satellite launches, which had been assigned to the space shuttle fleet in 1979. It took two years for launches to recommence using Delta II rockets. Nevertheless, the project benefited when other military programs saw opportunities to use GPS to support their own goals and bolstered the navigation system's budget. When the USN needed a way to track tests of Trident missiles launched in broad ocean regions, Parkinson and James Spilker, a digital communications pioneer and major contributor to the design of GPS, proposed a way to use GPS signals to do the job. The DoD's acceptance of that proposal boosted the number of GPS satellites in the four-satellite demonstration phase of the project by two, transferring 66 million USD from the USN to the USAF program.

The US nuclear disarmament program also provided a GPS budget increase by adding nuclear detonation sensors to the satellites. Intended to help assess nuclear strikes, the sensors also monitored compliance with the 1968 Nuclear Non-Proliferation Treaty. According to Green, adding these sensors did more than just provide needed funding. Before the full GPS system was given final approval, the budget analysis had concluded that it failed to pro-

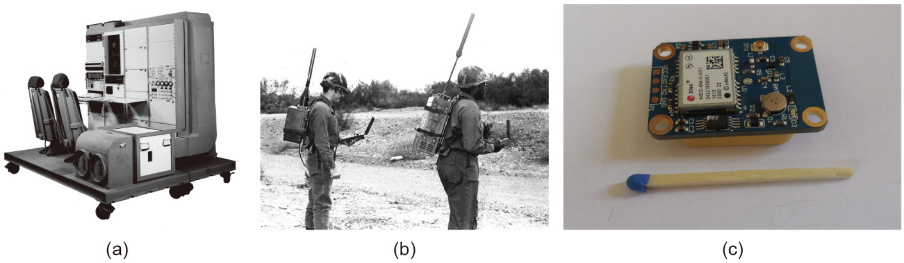

(a) (b) (c)

Fig. 8. (a) The first military GPS five-channel receiver built in 1977 by the company now known as Rockwell Collins was intended for use in an airplane. Weighing more than 120 kg, the device was mounted on a USAF equipment flight test pallet. (b) Two soldiers test early models of the ~11 kg GPS "manpack" receivers in 1978, each with a fat rod antenna. (c) A state-of-the-art GPS chip in 2017. Credits: Rockwell Collins (public domain); USAF (public domain); Wikimedia Commons (CC0 1.0).

vide enough military utility, said Green. “The nuclear detonation detection system gave us enough military utility to get the program approved.”

4.7. Up and running

In July 1995, just a few years after Desert Storm, the USAF announced the full operation of GPS—some 22 years after the 1973 approval for the four-satellite demonstration of the concept [13]. In the same year, the independent nation of Russia, to which the GLONASS satellite system had passed with the collapse of the Soviet Union, declared the 24-satellite array fully operational, for military use only. But the constellation quickly fell into disrepair, shrinking to seven satellites by 2002 and triggering a Russian restoration that has enabled the system to again become fully operational [14]. Now, after 25 years of operation, GPS has other company besides GLONASS. China recently completed its GNSS, called BeiDou, with a launch on 23 June 2020 that increased the constellation’s size to its full complement of satellites. The EU’s Galileo system is nearly complete and expected to become fully operational with 24 active satellites plus six spares by 2022. “The Chinese system and Galileo are comparable to GPS, but GLONASS has never been a competitor to GPS in terms of quality of signals or positioning.” said Todd Humphreys, a GNSS expert and associate professor of Aerospace Engineering and Engineering Mechanics at the University of Texas at Austin, who directs the university’s Radionavigation Laboratory.

In hindsight, if the USAF had fully welcomed satellite navigation and supported the GPS project, the system could have been completed closer to 1985 than 1995, said Parkinson, who retired from the USAF in 1978. He entered civilian life as a professor at Colorado State University in Ft. Collins, CO, then became a vice president at Rockwell, and next a group vice president at Intermetrics in Cambridge, MA. With GPS still in his blood, he dreamt up civilian applications for the satellite system that continued to slowly take shape within the reluctant military establishment, turning many of those ideas into sketches (Fig. 9).

In 1984, Parkinson returned to Stanford University as a full professor of aeronautics and astronautics. Through the 1990s, among other achievements, he led a research group that devised a host of high-precision civilian uses for GPS (as did hundreds of engineers at many other academic institutions and private companies). For example, whereas ordinary GPS signals provide sufficient accuracy to aid long-range navigation for airlines and other civil aviation carriers, guiding aircraft onto runways in darkness or inclement weather requires much higher integrity and accuracy. Before GPS, many airports provided this guidance with complex and expensive Instrument Landing Systems. Sponsored by the US Federal Aviation Administration (FAA), Parkinson, faculty colleagues, and students helped develop the Wide Area Augmentation System (WAAS) that is now used throughout the United States, Canada, and Mexico (other nations have deployed similar systems in other regions). Broadcasting a message that ensures integrity of the signal and provides small corrections to natural errors, WAAS notifies users of faulty satellite signals within 6 s; its corrections additionally support positioning accuracies of a few meters [15].

In another collaboration with Parkinson’s Stanford research group, the FAA funded a 1992 loan of a Boeing 737 from United Airlines to the team for landing experiments. The advanced, GPS-based, position-sensing technique known as differential GPS enabled the aircraft to measure its own position with centimeter accuracy and its attitude to one degree or better [11]. Using GPS-only measurements, Parkinson’s team demonstrated 110 “blind” landings (executed by autopilot alone under instrument

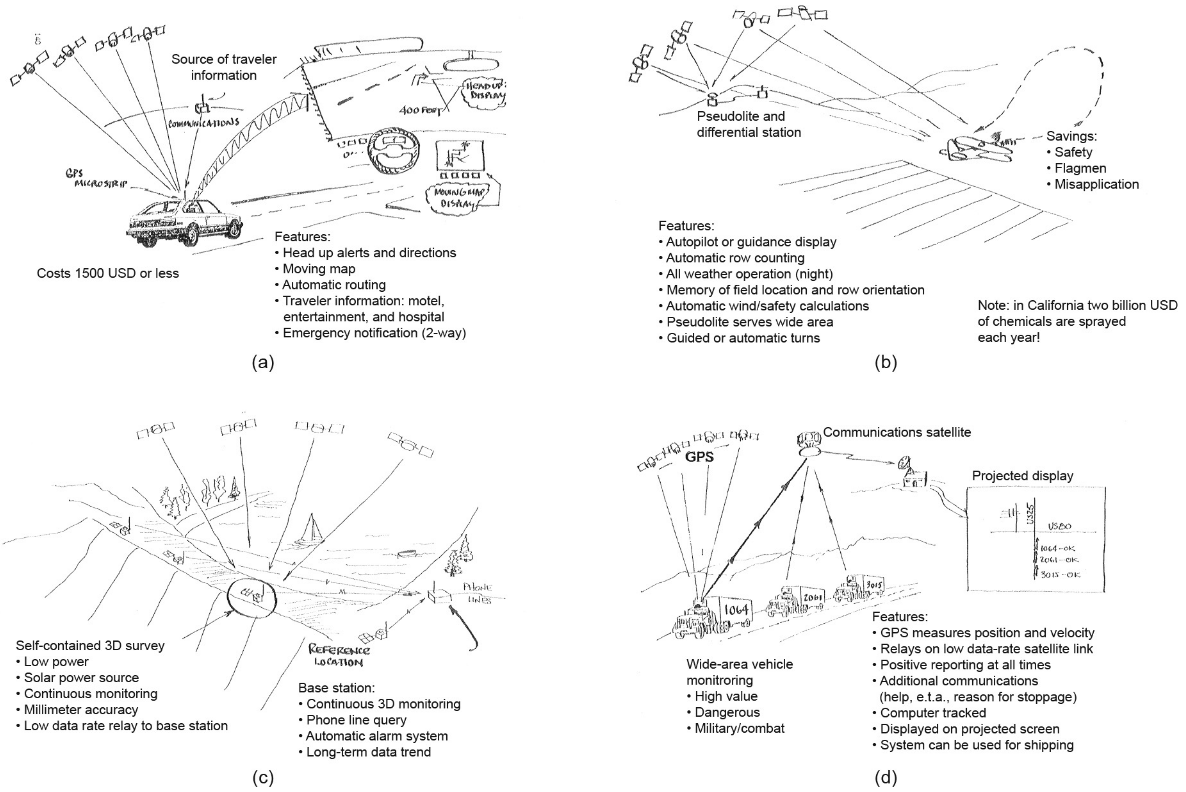


Fig. 9. (a) Automobile navigation system; (b) semi-automatic crop dusting; (c) automatic dam fault monitoring; (d) wide-area vehicle monitoring. These sketches were created in 1980 and 1981 by Professor Bradford Parkinson, who led the advocacy, design, and development of GPS as the first director of the GPS program from 1972 to 1978. The sketches outline civilian applications Parkinson envisioned at the time for GPS, including the now ubiquitous GPS navigation systems for automobiles and other vehicles, today run from cell phones, that have rendered printed road maps largely obsolete. e.t.a.: estimated time of arrival. Credit: Bradford Parkinson, with permission.

guidance and monitored by a human pilot ready to retake control if needed) [16]. Today, the FAA is in the process of authorizing the use of GPS for less automated (Category I) precision landings and has committed to developing specifications for GPS-only, Category III landings, which are "blind" through touchdown. The agency has also made determining aircraft positions via satellite navigation a central element of its ongoing modernization of the US air traffic control system, called NextGen. That massive upgrade began in the early 2000s and is scheduled to continue until at least 2025.

Pursuing another, purely terrestrial, high-precision application of GPS, also in the 1990s, Parkinson's Stanford program received financial support and a tractor from the American agricultural equipment company John Deere. The student research team modified the tractor, adding GPS-based guidance and control to create the world's first fully robotic farm tractor in 1996. The control system achieved driverless steering to 2.54 cm at a tractor speed of 5 $\mathrm{m{\cdot}s^{-1}}$ and attitude measurement of the vehicle to a single degree in each dimension. This research has led to the wide adoption of GPS-guided precise positioning in farming, which helps farmers meet the challenge of increasing crop yields and lowering costs with faster and more efficient planting and harvesting (Fig. 10). The pinpoint application of fertilizers and pesticides can also reduce the environmental impact of raising crops. Annual worldwide sales of the GPS-based, auto-farming industry have surpassed 1 billion USD [17].

Among the first GPS users to find ways to exceed the system's nominal positioning accuracy, scientists and surveyors developed novel measurement techniques that require more time and more complex setups but can take measurements using GPS with millimeter accuracy, a thousand-fold more precise than normal GPS position fixes. Such exacting GPS measurements are aiding scientific investigations [18] in fields from seismology, landslide motion, and plate tectonics to atmospheric and other environmental studies (Fig. 11). Precision GNSS measurements and guidance have also spread to mining and to the control of rapidly proliferating drones. Meanwhile, the expanding applications of ordinary GPS now encompass emergency response and rescues of all sorts, wildlife tracking, border enforcement, fishing regulation, weather forecasting, and innumerable other uses.

A huge boost to the usefulness of GPS for ordinary people worldwide occurred in 2000. Acceding to long-voiced pleas from the commercial sector, US President Bill Clinton ordered the permanent cessation of selective availability, ending degradation of the civil signal (Fig. 12). With this decision and the application of WAAS corrections, mobile phones could attain 2–3 m accuracy under a clear sky, making possible the street-level navigation these phones now routinely provide. In fact, "selective availability was an aggravation, but denied no one full accuracy," Parkinson said. "Ironically, the US Coast Guard was operating a nationwide system that broadcast corrections to remove the deliberate errors applied by the DoD."


(a) (b)

Fig. 10. (a) A Starfire(D) GPS receiver installed at the canopy front of this John Deere 8345 RT tractor guides its satellite-assisted steering system. (b) Guided by precision GPS, Precision Mazes (Lee's Summit, Mo, USA) created this corn maze in Sunderland, MA, USA. Credits: bdk, Wikimedia Commons (CC BY-SA 3.0); Precision Mazes (public domain).


(a) (b)

Fig. 11. (a) A Smithsonian Institution researcher uses a high-precision GPS device to survey a sand dune in 2005 at Ibex Dunes in Death Valley National Park in California, USA. (b) A US Geological Survey (USGS) team sets up a portable "spider" instrumentation package containing high-precision GPS units to monitor movement in a March 2014 landslide in northwest Washington, USA. Credits: Jim Zimbelman, National Air and Space Museum, Smithsonian Institution (public domain); Jonathan Godt, USGS (public domain).

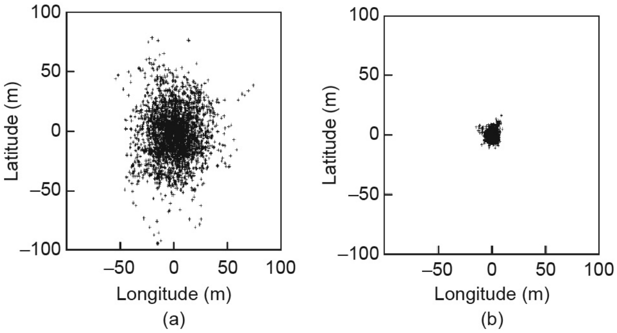


Fig. 12. These two figures compare the accuracy of GPS with and without selective availability (SA), each plotting 24 h of GPS data, (a) on the day before and (b) the day after SA was discontinued on 2 May 2000. The plot on the left with SA shows accuracy to within a radius of ~45 m; the plot on the right without SA shows accuracy to within a radius of ~6 m. Credit: Ashley Hornish, National Air and Space Museum, Smithsonian Institution (public domain).

A dramatic decrease in the size, weight, power use, and cost of GPS receivers also spurred the huge leap in their use. Technicians had assembled the early, bulky instruments from discrete components, according to the state of the art at that time, as compact, lighter, integrated-circuit technology was still in its infancy. But starting a decade or so later, the novel circuit-making approach had matured enough to set off a fast transformation to smaller, more energy efficient, and much less expensive GPS receivers with far greater capabilities. Whereas the first GPS receivers, although intended to be relatively user-friendly in price and portability, cost more than 100 000 USD and weighed ~50 kg, today's manufacturers buy the tiny GPS chips used in smart phones for less than 2 USD apiece.

After the success of GPS in Desert Storm and subsequent military operations in Somalia, Bosnia, and elsewhere, the US military finally embraced its satellite navigation system. "Suddenly, the Air Force got religion. They realized what they had," said Parkinson. From then on, the brainchild of the "space weenies," as the astronautical engineers who developed GPS were derisively known, became an essential component of DoD weapons systems, missions, and maneuvers. For the fiscal year 2020, the annual US federal appropriation for military and civilian uses of GPS totaled nearly 1.8 billion USD [19].

5. Closing observations

5.1. Indispensable

Regular funding for maintenance and improvements has allowed the GPS to keep pace with rapid technological change.

The United States has continuously replaced satellites from the constellation with upgraded ones as old satellites are retired (Fig. 13). The USAF launched the system's fourth GPS III Space Vehicle 04 on 5 November 2020 (Fig. 14). The second ("II")-generation satellites that these newest space vehicles are superseding include sub-generations of satellites that were launched in five distinct and successively more advanced series from 1989 to 2016. Improvements have included greater size and power, newer electronics and ranging codes, and a greater number and variety of transmitted frequencies.

However, as the system's value and the number of critical applications have increased, GPS has undergone increasingly frequent and ingenious attacks, categorized as spoofing or jamming [20]. While spoofers trick users by sending their GPS receivers false signals with misleading data, jammers drown out legitimate signals with powerful, meaningless ones in the same frequency range. To counter such threats, the USAF has modernized GPS with additional ranging signals and frequencies, and the manufacturers of receivers and their antennae have also implemented more robust technology to detect spoofing and resist jamming.

Concerns have also been raised over the increasing reliance of so many of the world's critical activities on the GNSS infrastructure. A recent study sponsored by the US government estimated that the United States gained 1.4 trillion USD from GPS from 1984 to 2017 [21,22]. The study further details the many dire effects that are likely to result from a 30-day outage of the system, assuming that a hypothetical breakdown would also affect the other GNSS networks—a prospect that Parkinson considers to be highly unlikely. In any case, the report states that losing GPS services for a month could create widespread upheaval due to collapsing telecommunications networks. US crop production would be disrupted because American farmers have widely embraced automated tractors, harvesters, and other equipment that rely on GPS data to execute precision movements. Together with the failures of other GPS-enabled services, these effects and their consequences would take an economic toll of 30–45 billion USD on just the United States alone during that brief, 30-day period. While congressional acts and directives from past presidential administrations in the United States have called for the implementation of terrestrial PNT services to back up GPS/GNSS since at least 2004, no such general system yet exists. For air transportation, however, the FAA plans to continue the operation of a minimal set of terrestrial radionavigation ground stations throughout the United States to ensure backup flightpath and landing guidance, albeit with less accuracy and altitude information than GPS and other GNSS provide. A US presidential executive order issued on 12 February 2020 again required government agencies to develop plans for fallback, non-GNSS-based PNT services [23].

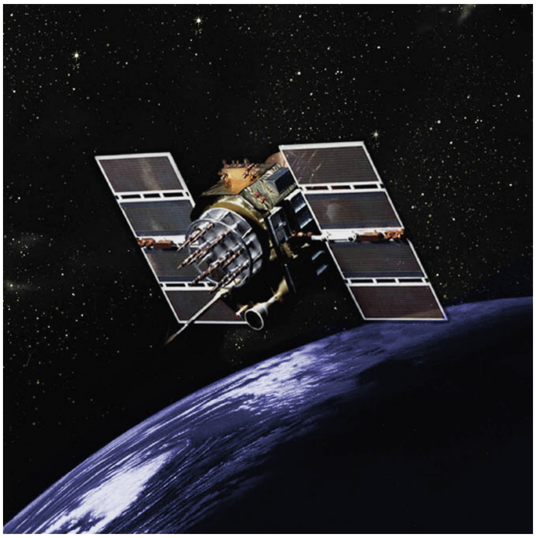


Fig. 13. Artist's illustration of a second-generation, GPS Block IIA satellite; these satellites, launched from 1989 to 1997, are now all retired, with the last one decommissioned in 2019. Most of the current GPS constellation consists of more recent series of second-generation GPS satellites, with 29 (10 IIR, 7 IIR-M, and 12 IIF) remaining operational as of August 2020. Credit: GPS.gov (public domain).

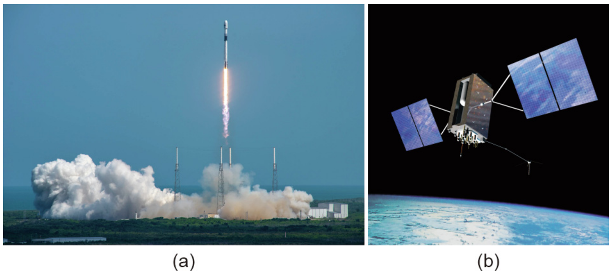


Fig. 14. As of November 2020, four third-generation (GPS III) satellites had joined the GPS constellation since 2018. (a) A SpaceX Falcon 9 rocket carrying the third GPS III satellite, SV 03, lifts off from Cape Canaveral Air Force Station, FL, in June 2020. (b) Artist's illustration of a GPS III satellite; these latest generation satellites are engineered for a 15-year lifespan. Credits: SpaceX (public domain); GPS.gov (public domain).

Fortunately, the proliferation of GNSS constellations, and all their backup satellites, greatly decreases the likelihood of a global—or even partial—PNT failure. It also often boosts both position accuracy and integrity by measuring the range to many more than four satellites. Parkinson commented that, on a recent hike to a small peak in the California mountains near his home, he looked at his phone and found that it was gathering data from 11 satellites. Although the US Federal Communications Commission only recently authorized the use of EU's Galileo, GNSS chip manufacturers had already incorporated all global constellations, as well as all regional augmentations, into their latest generation of chips.

In the coming decades, the GPS and its sister GNSS are expected to remain as vital infrastructure for the networks and precision services that they helped create, as well as for new connectivity, services, and capabilities that are pending or beyond the immediate horizon. As a case in point, no fewer than 34 nations as of February 2020 had already begun to deploy 5G, the next generation of wireless communications. This much-anticipated new architecture permits data downloads at up to 20 GB per second—hundreds of times faster than with 4G—and will be critical for new technologies including autonomous vehicles and so-called "smart cities" [24]. These new 5G-based technologies are ever more highly dependent upon the PNT signaling provided by the GNSS constellations.

5.2. Timeline

Table 1 provides an overview of the development landmarks for GPS and the current global GNSS infrastructure, from the October 1957 launch of Sputnik 1 to the 2020 completion of the third global system, China's BeiDou, and the pending completion of EU's Galileo.

5.3. Continuing to serve

GPS continues to serve the global population with no signs of becoming obsolete or irrelevant. With regard to the design of GPS signals that are broadcast day in and day out, as of 2010 "about 95% of the GPS message has endured with no changes needed at all," wrote Parkinson, as the first author of a two-part series about the origins of GPS that appeared in the May and June

Table 1
Timeline of GPS development landmarks.

Date	Landmark	Brief description
October 1957	Launch of Sputnik 1	First artificial satellite rockets into orbit from Soviet Union
March 1958	Satellite navigation concept proposed	Sputnik orbital research inspires JHUAPL director Frank McClure
October 1961	Apollo program, first flight	Start of US Moon landing/exploration program, 12 astronauts ultimately reach lunar surface
1962	USAF inaugurates classified "621B" program	Research initiated to explore potential satellite navigation system to support US military operations in Vietnam
1964	USN's Transit becomes operational	First global satellite navigation system, created to serve US nuclear-armed Polaris submarine fleet
August 1966	Woodford/Nakamura classified report	Secret analysis of advanced navigation system options shapes GPS design; work was declassified in 1979
July 1969	Apollo 11 mission	First humans—Neil Armstrong, and Edwin "Buzz" Aldrin—land and walk on Moon
1971–1973	White Sands Missile Range Experiments	Ground instruments simulating four-satellite array achieve 5 m, 3D position accuracy
December 1972	Final Apollo Moon landing	Harrison Schmidt, 1st scientist on Moon, and Eugene Cernan set up scientific experiments, take photos, collect samples
1972–1973	USAF Colonel Parkinson helms 621B, then JPO	621B satellite demonstration project approved, GPS becomes a joint forces project led by USAF
1978–1979	First four GPS satellites launched	Successful 4-satellite test with Efratom/Rockwell atomic clocks, Pentagon approves full-scale GPS buildout
February 1980	First operational cesium atomic clock	Fifth GPS satellite carries space-hardened, cesium-beam clock to orbit
1981–1986	GPS budget setback	30% cut trims satellites' heft, upgrades, and system size; partly reinstated by 1988
September 1983	Soviets down Korean Air Flight 007	Tragic killing of all 269 people on off-course airliner prompts US to guarantee GPS civilian signal globally for at least ten years
January 1986	Space Shuttle Challenger disaster	Cancels two years of planned satellite launches; lift-offs resume in 1988 on Delta II rockets
February 1989	Start of GPS II deployment	Second generation satellites launched until 2016; mean design lifespans increase to 12 years
January 1991	Operation Desert Storm begins	GPS navigation and precision weapon guidance strongly aids US and allied armed forces
1992	Boeing 737 "blind" landings	Stanford program under Professor (retired Colonel) Parkinson lands airliner solely under GPS control
July 1995	GPS announced as fully operational	USAF completes 24-satellite system, meeting all performance requirements
Late 1995	Russia declares GLONASS operational	Military-only system; disintegration shrinks constellation to seven satellites in 2002, when restoration begins
1996	USN decommissions Transit	System no longer needed for navigation, satellites subsequently used for ionospheric research
1996	Agricultural equipment automation via GPS	Robo-tractor engineered by Parkinson's Stanford group steers to 2.5 cm precision and controls 3D attitude to 1°
May 2000	Selective availability ends	GPS precision previously accessible only to US military becomes universally available
February 2003	Top engineering prize awarded to GPS pioneers	Bradford Parkinson and Ivan Getting share 2003 Charles Stark Draper Prize
June 2008	First GPS chip added to an iPhone	Launch of iPhone 3 begins era in which GPS navigation becomes ubiquitous feature of mobile phones
December 2018	First GPS III satellite launch	Third generation GPS satellites with mean design lifespans of 15 years start joining constellation
June 2020	China GNSS BeiDou complete	With June launch, China's constellation attains planned size with 30 satellites
2022	EU GNSS Galileo complete	Galileo's constellation of 24 satellites plus six spares becomes fully operational

2010 issues of the trade publication *GPS World* [9,11]. "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" [9,11]. "Make that 45 years today," Parkinson said in August 2020.

GPS has provided a foundational infrastructure for many of the currently dominant technologies of the world, which its unprecedentedly exact position and timing information often made possible. The constellation's configuration and the basic ways in which it works have fundamentally enabled our increasingly complex digital world. In particular, the ability of GPS to simultaneously broadcast to a limitless number of receivers allows unbounded growth in both applications and users. This engineering achievement, modernized and updated but largely unchanged, functions as a core component of countless advanced applications in navigation, communications, computer networking, weaponry, scientific research, finance, transportation, and many other fields [25].

"The revolution continues," said Parkinson, in a talk he gave at Google in Mountain View, CA, in January 2020. "The engine that has driven GPS is engineering. Electrical engineering and computer science were really at the heart of it, but all disciplines of engineering were involved."

5.4. The revolutionist: Bradford W. Parkinson

USAF Colonel Parkinson took command of the then-classified GPS program in late 1972, leading an early and crucial stage of its design and implementation (Fig. 15). Now a recalled emeritus professor of aeronautics and astronautics at Stanford University in Palo Alto, CA, Parkinson remains highly active in the position, navigation, and timing field. After retiring from the USAF in 1978, Parkinson worked in academia and industry for several years before joining the faculty at Stanford, where he led a research group focusing on the development of an ever-expanding array of GPS applications.

Here, the self-described "revolutionist" Parkinson responds to questions about this major engineering achievement, more than 25 years after it became fully operational.

WEISS: In 1962, US President John F. Kennedy made a famous speech about plans for the civilian space agency, the National Aeronautics and Space Administration (NASA), to land humans on the Moon in that decade. The US military was already, in relative obscurity, designing and building the first satellite navigation systems. These two efforts defined the dawn of the Space Age for the United States—was there interaction between the two programs?

PARKINSON: The focus of the NASA Moon effort was manned space. NASA had their own set of engineers, companies that worked with them, and the Draper laboratory at the Massachusetts Institute of Technology that did the guidance for the Apollo program. Doc Draper, who I knew personally, was almost religious in his fervor against satellite navigation. Because it was a signal in space, not self-contained, he would say, "What man can produce, man can destroy or disrupt." While NASA has never been involved in the development, management, or technology of GPS, there is a subtle exception. Our GPS satellites were built by Rockwell International. Rockwell was also building the space shuttle, the immediate successor to Apollo. There were separate divisions

(a) (b)

Fig. 15. (a) In this 1970s photograph, USAF Colonel Bradford Parkinson (center), Director of the JPO, discusses GPS with engineer Frank Butterfield (left) of The Aerospace Corporation and USN Commander Bill Huston (right). (b) Bradford Parkinson in 2016 at Stanford University in California, USA, where he remains on the faculty as a recalled professor emeritus of aeronautics and astronautics. Credits: The Aerospace Corporation (public domain); Courtesy of Brad Parkinson.

for the space shuttle and GPS, but if GPS needed engineers to work on an aerodynamic, thermodynamic, or heat-transfer problem, it could draw on Rockwell's vast army of engineers, not for their knowledge of the shuttle specifically, but rather for their raw knowledge of technologies in general.

WEISS: Many senior American military officers, even in the USAF that ran the GPS project, did not want a satellite navigation system. How did GPS survive that opposition?

PARKINSON: Dr. Malcolm Currie, a civilian with a doctorate in physics, was in charge of all of the research and development money for the whole US DoD. In 1972, Currie was visiting Los Angeles, where I was stationed. A general who was trying to entertain Currie thought, "I know how to occupy about three hours. I will send him down to Parkinson. He talks a lot." At the end of our discussion, something magic happened. Dr. Currie became the champion of our program, and a direct, informal line of communication began between the two of us. In 1978, when extensive tests of our four-satellite demonstration system proved that we met all the global objectives, the Air Force still did not want to fund it. But the civilian leadership in the Pentagon—Dr. Currie, in fact—intervened and, in essence, forced the Air Force to fund it. But for the Air Force go-slow on our budget, full operational capability of GPS might have occurred at least ten years earlier than 1995.

WEISS: Given the military's opposition to GPS, what enabled you to keep going?

PARKINSON: The atmosphere was one of desperation. I quickly developed a severe stomachache because I was working such long hours and drinking too much coffee. As the program's new leader in 1972, I ended up swapping out nearly all the people I had inherited, not because they were bad, but the project needed a bunch of dedicated, indomitable, selfless people. And that is what we were. All of these people I recruited hated to lose. We would not tolerate not doing this. But we were all alone in that regard. Besides Dr. Currie, we did not have a lot of friends. The camaraderie was extreme. You were not going to let the team down, whatever it took.

By about 11:30 each morning, I would have an overwhelming number of problems in my in-basket. My solution was to go running at noon every day, at least four miles. On Fridays, it was always ten miles. I would go out and come back refreshed, positive, and with a set of action items. I was always a runner, but not like this. I even became a marathoner, and at least a dozen of my guys also became marathoners. It was our way of coping.

In addition, every Friday evening, we all went to the officers' club and drank beer together. There were jokes and camaraderie, but also technical discussions in which a lot of problems were hacked out. When I was in combat, we would get together at the officers' club after six hours of getting shot at. It was a bunch of guys talking about what we should have done, what the tactics were, what the result was. And also joking and enjoying mutual respect. The atmosphere of the GPS team's Friday beer calls was similar. The running and the Friday beer calls were a therapy that was frankly essential for what we were doing. My stomach problem, which I had never had before in my life, went away.

WEISS: What prompted the military to offer civilian use?

PARKINSON: Before we launched the first satellite, I gave testimony to Congress that we were going to have a civil signal available, although not guaranteed, and that I would publish how to use it. Then everyone asked me, "How did you make that decision?" I just made it. I did not ask anyone. If I had asked, there would have been a lot of people trying to tell me no. So, instead, I decided this is the way it would be. The first civil set that locked on GPS, to my knowledge, was built by students in England at the University of Leeds under Professor Peter Daly. They showed that we had, indeed, provided specifications that allowed non-military users to completely define and navigate with the system.

WEISS: You have said that you were struck by the vast differences in speed with which civilian applications of GPS have been adopted.

PARKINSON: In terms of rapid adoption, the market pull on agricultural uses of GPS has been enormous. In 1996, students in my program at Stanford devised the very first, GPS-guided, robotic tractor, retrofitting a commercial model to automatically navigate crop fields with extraordinary precision by means of satellite signals. Although the farm-equipment manufacturer John Deere deserves credit for providing a tractor and a lot of funding, they doubted at the time that farmers would want this. They were wrong. In less than 15 years, the market for robotic farm equipment reached 400 million USD. It has more than doubled since then.

At the slow end of adoption is fully GPS-controlled aircraft landings. In 1992, thanks to United Airlines and the US Federal Aviation Agency loaning us a Boeing 737, we demonstrated 110 straight "blind" landings right down to touch down. It worked perfectly. But getting to full FAA certification for these "Category 3" landings has been a terribly slow process. They are edging into it. You have got to prove that the system will not fail in more than one in ten million landings. It has been 28 years since we demonstrated those first blind landings. That is almost a person's career.

WEISS: What has surprised you?

PARKINSON: Recently, I have been dazzled by the pressing into areas I did not think were feasible, like using GPS to locate spacecraft. For orbits lower than those of the GPS satellites, it is a slam dunk. But, at least on paper so far, some have already pressed this out to geosynchronous orbits above the GPS orbits. The next step could be a real *tour de force*. An upcoming experiment will attempt to do navigation for a vehicle orbiting the Moon using remnant energy from GPS satellites that sprays past our planet from the constellation's broadcasts to the Earth's surface below. Also surprising is how people studying tectonic plates are measuring relative motion on either side of the plate boundary to accuracies of better than 1 mm in three dimensions. The velocity might be 10 $\text{cm}\cdot\text{a}^{-1}$, but they are measuring that speed with accuracy on the order of millimeters per year.

In hindsight, automobile navigation is the application I should have made my fortune on. It was one of a half-dozen potential applications I sketched concepts for around 1980 (Fig. 9). My concept had a moving map on a heads-up display, a little voice telling you when to take the next turn, and a communications link. I thought it was all pretty slick, but we did not do more on it back then, not having anticipated the advent of ubiquitous mobile phones.

WEISS: The potential for attacks and hacks against GPS and the other GNSS has raised increasing concern for their safety and reliability. What is your perspective?

PARKINSON: Congress and the DoD have been wringing their hands about jamming and spoofing of GPS, all heated up that this is a big problem. It really is not—we know how to make GPS receivers that are near immune to these attacks. These receivers are much more complicated than the ones in our cell phones, but they can withstand powerful jamming and totally isolate any spoofing.

We demonstrated countermeasures to both jamming and spoofing when I ran the program in 1978, using a substantial part of our budget to put together a great receiver. Guess what? Commercial airplanes do not have them, partly because we have laws against exporting technology. Commercial avionics manufacturers could build such receivers, but they could not put them in the airplanes sold to certain countries. Everyone knows how to build such secure receivers. They may not understand how well you can do it, but if you have critical, safety-of-life applications or a large ship, you can get a receiver that works despite even 10 000 W of jamming. Compared with what is in a cell phone, such a receiver is expensive, perhaps 100 000 USD. But compared to the cost of a modern oil tanker, that is nothing. Jamming and spoofing is more a political problem, not a technical one.

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