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Secret Clocks: The US Military, Einstein's Relativity, and the Global Positioning System

ABSTRACT

For nearly a decade, beginning in the mid-1970s, a debate unfolded among physicists, engineers, and military officials over how best to include effects from Albert Einstein's theory of relativity within the new military technology, now known as the Global Positioning System (GPS). Although some exchanges were published in the open scientific literature, much of the debate played out behind the scenes, in memos, reports, and special review sessions arranged by the US military. Theoretical physicists, who had no relationship to the project, criticized early efforts to incorporate relativistic effects within GPS designs, complaining that significant information was not shared by military officials or defense contractors. Other experts in relativity, who consulted more closely with the US Air Force while GPS was under development, responded that the outside critics had little relevant experience with real-world engineering applications, and that their criticisms amounted to mathematical irrelevancies. Throughout the debate, few doubted that relativity—with its counterintuitive notions of space and time—needed to be taken seriously in the design and operation of GPS. Rather, they disagreed over how best to incorporate deep lessons from relativity in an engineering-relevant way, at a time when the stakes for the new military technology loomed large.

KEY WORDS: relativity, time dilation, gravitational redshift, GPS, navigation

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The following abbreviations are used: *CPAE*, Diana Kormos Buchwald *et al.*, eds., *The Collected Papers of Albert Einstein* (Princeton University Press, 1987–); CMW, personal papers of Clifford M. Will, in Prof. Will's possession, University of Florida, Gainesville.

Historical Studies in the Natural Sciences, Vol. 56, Number 3, pps. 210–251. ISSN 1939-1811, electronic ISSN 1939-182X. DOI: https://doi.org/10.1525/hsns.2026.56.3.210.

INTRODUCTION

Around 2:30 a.m. local time on January 17, 1991, two US Air Force helicopters led four Army Apache helicopters from an airbase in Saudi Arabia into Iraqi airspace. Army General Norman Schwarzkopf, commander of Coalition forces for what was dubbed "Operation Desert Storm," overcame longstanding rivalries between the two branches of the US military and authorized the Air Force aircraft to take the lead. The winning argument: The Air Force helicopters were equipped with Global Positioning System (GPS) receivers. The Air Force helicopters guided the Army ones to their targets, where they quickly destroyed Iraqi radar stations. The timing of the attack itself hinged on the operation of the new military navigation and targeting system. Whereas the US administration had issued an ultimatum to Iraq's leader, Saddam Hussein, to move troops out of Kuwait by a particular deadline, the US attack only began after engineers had been able to coax a malfunctioning satellite in the still-new GPS constellation back into operation. Over the next few hours and days, GPS-enabled B52 bombers launched GPS-guided cruise missiles against additional Iraqi targets. A new era of precision-guided weapons had begun.[1]

Today, GPS navigation is ubiquitous, well beyond war zones. The system is embedded in everything from commercial shipping and civil aviation to physics experiments on exotic particles, in addition to the phones on which billions of people stare at maps every day. In outline, the system relies upon a network of satellites, each of which constantly beams down radiofrequency messages to ground-based receivers. Those signals encode two critical pieces of information: the satellite's current location, and the time recorded by an onboard clock; in essence, "I am here, now." A user's receiver on the ground collects such signals from at least four GPS satellites. Since the radio signals each travel at a known speed—the speed of light—sophisticated software can quickly use the difference between the time stamp reported by a satellite's signal and the time registered by the receiver's own clock to calculate the distance between receiver and satellite. By repeating this process with the information from four satellites, the GPS receiver can pinpoint its own location in space and time.[2]

1. Michael Russell Rip and David P. Lusch, "The Precision Revolution: The Navstar Global Positioning System in the Second Gulf War," *Intelligence and National Security* 9, no. 2 (1994): 167–241, on 194–201; Greg Milner, *Pinpoint: How GPS Is Changing Technology, Culture, and Our Minds* (W. W. Norton, 2016), 63–8.

2. See esp. William Rankin, *After the Map: Cartography, Navigation, and the Transformation of Territory in the Twentieth Century* (University of Chicago Press, 2016), ch. 6. See also Bradford W.

Given the reliance of GPS upon clocks moving at high speeds at different elevations above the Earth, several physicists were quick to point out that corrections from Albert Einstein's relativity might be required in order to achieve sufficient accuracy. Indeed, physicists today often hail the fact that GPS relies upon several distinct relativistic corrections in order to operate reliably. If such relativistic effects were ignored, GPS positional accuracy would degrade by more than eleven kilometers *per day*—a far cry from the meter-scale accuracy that the system provides. The underlying physics is now so well understood that leading undergraduate textbooks on relativity include whole sections and homework problems related to relativity and GPS.[3]

Yet long before GPS became a widespread consumer technology, it was a secret military technology, under development by the US Department of Defense. For about a decade, between the mid-1970s and the mid-1980s, a debate simmered behind the scenes among physicists, engineers, and military officials over how to incorporate relativistic effects within GPS. The stakes seemed enormous—some raised the specter of nuclear war—amid bitter complaints about military secrecy, corporate special interests, and conflicting claims to relevant expertise. Throughout these debates, which unfolded in venues well beyond the academic cloisters within which experts in relativity usually lingered, few questioned whether Einstein's relativity would be critical to the successful operation of GPS. Rather, they sparred over who was getting the relativity *right*.

By tracing these debates over subtle relativistic effects in the context of worldly, high priority devices, we learn about the longer legacy of Einstein's crowning scientific achievement. Scholars have pored over the origins and early development of both special relativity and general relativity, as Einstein and a small circle of colleagues worked out their bizarre-sounding ideas during the early years of the twentieth century.[4] The efforts to incorporate relativistic

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Parkinson, Thomas Stansell, Ronald Beard, and Konstantine Gromov, "A History of Satellite Navigation," *Navigation: Journal of the Institute of Navigation* 42, no. 1 (1995): 109–64; and Paul E. Ceruzzi, *GPS* (MIT Press, 2018).

3. Clifford M. Will and Nicolás Yunes, *Is Einstein Still Right? Black Holes, Gravitational Waves, and the Quest to Verify Einstein's Greatest Creation* (Oxford University Press, 2020), 36–40; James B. Hartle, *Gravity: An Introduction to Einstein's General Relativity* (Addison-Wesley, 2003), 121–5, 132–3; Ta-Pei Cheng, *Relativity, Gravitation, and Cosmology: A Basic Introduction*, 2nd ed. (Oxford University Press, 2010), 80; Edwin F. Taylor, John A. Wheeler, and Edmund Bertschinger, *Exploring Black Holes: Introduction to General Relativity*, 2nd ed. (2017), ch. 4, https://eftaylor.com/exploringblackholes (accessed September 15, 2017).

4. For a recent overview, Michel Janssen and Christoph Lehner, eds., *The Cambridge Companion to Einstein* (Cambridge University Press, 2014).

effects within technologies like GPS, decades after theoretical physicists first began to grapple with special and general relativity, indicate how these now-canonical works became a fixture of modern physics, during what has been dubbed the "renaissance of relativity."[5]

At the same time, the heated debates over relativity and GPS illustrate the complicated roles of scientific expertise within the US national-security state during the Cold War.[6] Historians and sociologists of science have long drawn on scientific controversies—and the protracted means of achieving consensus—to probe subtle entanglements among competing epistemic claims and assertions of relevant expertise and authority, all embedded within a shifting landscape of institutions.[7] In the case of relativity and GPS, an arcane scientific controversy about coordinate systems and clock coordination quickly spilled well beyond a tightknit circle of specialists and the slow-grinding gears of academic peer review. Achieving closure required academic scientists, private-sector defense contractors, and military officials to navigate the subtleties of non-Euclidean geometry amid the high-stakes strictures of presidential directives, international relations, military classification, and trade secrecy.

CLOCKS IN MOTION

Since his teenage years, Albert Einstein had been fascinated by the propagation of light. He wondered in particular about its implications for how different people might describe the motion of objects through space and time—

5. On the "renaissance of relativity," see esp. Alexander S. Blum, Roberto Lalli, and Jürgen Renn, "The Reinvention of General Relativity: A Historiographical Framework for Assessing One Hundred Years of Curved Space-Time," *Isis* 16, no. 3 (2015), 598–620.

6. Jennifer Light, *From Warfare to Welfare: Defense Intellectuals and Urban Problems in Cold War America* (Johns Hopkins University Press, 2003); Zuoyue Wang, *In Sputnik's Shadow: The President's Science Advisory Committee and Cold War America* (Rutgers University Press, 2008); Audra J. Wolfe, *Competing with the Soviets: Science, Technology, and the State in Cold War America* (Johns Hopkins University Press, 2013); and Benjamin Wilson, *Strange Stability: How Cold War Scientists Set Out to Control the Arms Race and Ended Up Serving the Military-Industrial Complex* (Harvard University Press, 2025).

7. Karin Knorr-Cetina, *The Manufacture of Knowledge* (Pergamon, 1981); Steven Shapin and Simon Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life* (Princeton University Press, 1985); Harry Collins, *Changing Order: Replication and Induction in Scientific Practice*, 2nd ed. (University of Chicago Press, 1985 [1992]); Martin Rudwick, *The Great Devonian Controversy* (University of Chicago Press, 1985); Bruno Latour, *Science in Action: How to Follow Scientists and Engineers through Society* (Harvard University Press, 1987).

especially for people who were moving with respect to one another.[8] In his musings, he often returned to scenarios in which one person rode in a railway carriage at high speed while another person watched, feet firmly planted on the embankment. If each person carried identical clocks and rigid measuring rods, he wondered, would their measurements agree on how much time had elapsed between events, or on the distances between them?[9]

As he labored in fits and starts between 1905 and 1915 on what would become known as his special and general theories of relativity, Einstein identified several distinct ways in which different observers' measurements of time would depend on their own motion or location—either because of their large relative speeds as one zoomed past the other, or because of their different proximities to large celestial bodies like the Earth or the Sun. He and others also pondered the effects of rotating motion, contrasting the behavior of clocks held by passengers riding along the edge of a spinning carousel with those watching from the non-spinning center. The effect of large relative speeds became known as "time dilation"; the influence of large masses was dubbed "gravitational redshift"; and the impact of rotation was often referred to as the "Sagnac effect," after a clever experiment designed by French physicist Georges Sagnac in 1913.

Einstein first broached the notion of time dilation in his 1905 article, "On the Electrodynamics of Moving Bodies."[10] A few years later, he simplified his description by introducing the idea of a "light clock": "Two mirrors 1 cm away from each other may serve, for example, as a clock, where we count the number of times a light signal travels back and forth."[11] Since, according to Einstein's famous second postulate in his 1905 paper, the speed of light is a constant for all observers who move at constant speeds, one could use light to mark the passage of time. To an observer holding her light clock at rest on the railway embankment, with one mirror held firmly a height h directly above the other, each time the light ray bounced off the top mirror would be a "tick," followed some

8. Albrecht Fölsing, *Albert Einstein*, trans. Ewald Osers (Penguin,1997), 46.

9. See, e.g., Albert Einstein, "Zur Elektrodynamik bewegter Körper [On the Electrodynamics of Moving Bodies]," *Annalen der Physik* 17 (1905): 891–921, translated and reprinted in John Stachel, *Einstein's Miraculous Year: Five Papers That Changed the Face of Physics* (Princeton University Press, 1998), 123–60, on 125; and Albert Einstein, *Relativity: The Special and General Theory*, trans. Robert W. Lawson (Crown, 1961 [1916]), chs. 3–10.

10. Einstein, "Electrodynamics of Moving Bodies" (ref. 9), 138–9.

11. Albert Einstein, "Lichtgeschwindigkeit und Statik des Gravitationsfeldes [The Speed of Light and the Statics of the Gravitational Field]," *Annalen der Physik* 38 (1912): 355–69, as translated in *CPAE* vol. 4, doc. 3 (English translation supplement), 95–106, on 104.

time $\Delta t = h/c$ later, when the light ray returned to the bottom mirror, by a "tock." If her friend raced past on a fast-moving train at speed v, holding an identical pair of mirrors the same height h apart, the observer on the embankment would watch the light ray in her friend's clock follow a sawtooth pattern, zigzagging from bottom mirror to top and back again while the entire assembly whooshed along with the train. Using nothing more than the Pythagorean theorem, Einstein concluded: The observer on the embankment would measure the clock of her train-riding friend ($\Delta t'$) to run slowly compared to her own clock (Δt), with $\Delta t' = \Delta t/\sqrt{1-(v/c)^2}$. The effect would be perfectly symmetrical: The train-bound rider would watch her friend's clock on the embankment tick slowly compared to the clock on the train by the same proportion.

In 1907, while working on an invited review article, Einstein began to consider observers who might speed up or slow down—that is, accelerate—rather than only travel at constant speeds. In the midst of his writing, he had what he later called "the happiest thought of my life": an observer would not be able to distinguish between the effects of gravitation and acceleration. "*For an observer falling freely from the roof of a house there exists*—at least in his immediate surroundings—*no gravitational field*. Indeed, if the observer drops some bodies then these remain relative to him in a state of rest or uniform motion." He dubbed this interchangeability of gravity and acceleration the "equivalence principle."[12]

Near the end of his 1907 article, Einstein broached "the effect of the gravitational field on clocks."[13] He returned to this idea a few years later, providing a simpler derivation. He imagined a light ray with wavelength λ emitted from some height h, traveling down along the z axis. The light ray would take time $\Delta t = h/c$ to reach the origin. An observer accelerating upward at constant rate g would reach a speed $v = g\Delta t = gh/c$ with respect to the light source by the time the light ray reached the origin. To lowest order in v/c, the accelerating

12. Albert Einstein, "Grundgedanken und Methoden der Relativitätstheorie in ihrer Entwicklung dargestellt [Fundamental Ideas and Methods of the Theory of Relativity, Presented in their Development]," unpublished manuscript, Jan 1920, *CPAE* vol. 7, doc. 31, on p. 136 (English translation supplement), emphasis in original.

13. Albert Einstein, "Über das Relativitätsprinzip und die aus demselben gezogenen Folgerungen [On the Relativity Principle and the Conclusions Drawn from It]," *Jarbuch der Radioaktivität und Elekronik* 4 (1907): 411–62, in *CPAE* vol. 2, doc. 47, on p. 306 (English translation supplement).

observer would therefore measure the light ray to be Doppler-shifted: $\lambda' = \lambda\ (1 + v/c) = \lambda\ (1 + gh/c^2)$.[14]

Given the physical equivalence between acceleration and gravitation, Einstein argued, the same shift must occur for an observer at rest in a gravitational field. The difference in gravitational potential for observers in a gravitational field g separated by a height h was simply $\Phi = gh$, and hence $\lambda' = \lambda\ (1 + \Phi/c^2)$. To Einstein, the conclusion seemed clear: When propagating in a gravitational field, the wavelength of light would be stretched, shifting toward the red end of the spectrum. If the wavelength of light were affected, Einstein went on, then clocks would be, too. After all, one could use the frequency of light—which is just the number of wave crests that pass a given location per unit of time—to measure the passage of time. Einstein therefore suggested that the clock rates in a strong ($\Delta t'$) versus weak (Δt) gravitational field would be related as $\Delta t' = \Delta t\ (1 + \Phi/c^2)$: the stronger the gravitational field, the slower the clock. This effect became known as "gravitational redshift."[15]

In the midst of his thinking about gravitational redshift, Einstein wrote to his colleague Arnold Sommerfeld that he had begun wondering about a different sort of accelerated motion: uniformly rotating systems.[16] By 1912, Einstein had convinced himself that observers would disagree about basic geometrical quantities—such as the ratio of a circle's radius to its circumference—if one were riding along the edge of a fast-spinning carousel while the other sat still, without rotating, at its center. Given his equivalence principle, Einstein next suspected, similar disagreements about geometry should occur for observers in different gravitational fields. This insight led Einstein (grudgingly) to conclude that a proper description of gravitation would require non-Euclidean geometry—ironically, the subject of one of the many mathematics courses that Einstein had ignored as a university student. He reconnected with his close friend from student days, Marcel Grossmann, who by that time was a professor of mathematics in Zurich with a focus on non-Euclidean geometry. Together

14. Albert Einstein, "Über den Einfluß der Schwerkraft auf die Ausbreitung des Lichte [On the Influence of Gravitation on the Propagation of Light]," *Annalen der Physik* 35 (1911): 898–908, *CPAE* vol. 3, doc. 23, on 381–3 (English translation supplement). On Einstein's work at this time, see Michael D. Gordin, *Einstein in Bohemia* (Princeton University Press, 2020), ch. 2.

15. Einstein, "Über den Einfluß der Schwerkraft [On the influence of gravitation]," *CPAE* vol. 3, doc. 23, on p. 385 (English translation supplement).

16. Albert Einstein to Arnold Sommerfeld, 29 September 1909, in *CPAE* vol. 5, doc. 179.

they began collaborating on critical steps toward what would become the general theory of relativity.[17]

Meanwhile, an expert in experimental optics based in Paris, Georges Sagnac, had also become fascinated by effects of rotation on the propagation of light. Beginning in 1913, he mounted a device atop a meter-sized platform that he could spin at rates up to two revolutions per second. Shining light from a mercury lamp onto a half-silvered mirror, he split the beam so that one light ray traveled along the direction of the spinning platform, while the other ray traveled in the opposite direction. Sagnac could then measure shifts in the pattern of interference fringes once each light ray completed a lap around the device. Much like Albert Michelson's famous interferometer design, Sagnac's optical experiment was remarkably precise. In 1914, Sagnac reported measuring a relative shift of 0.07 fringes.[18]

Whereas Sagnac interpreted his results as proof that relativity itself must be abandoned—claiming that such interference shifts indicated that light did not travel at a fixed speed, independent of some light-bearing medium—several of Einstein's colleagues demonstrated, instead, that such an effect was exactly what one *should* expect if relativity were correct. In fact, Einstein's friend Max von Laue had derived such an effect in the context of relativity as early as 1911, prior to Sagnac's experiments, while Paul Langevin returned to the topic in 1921, explicitly demonstrating that Sagnac's results corroborated predictions from relativity.[19]

Von Laue's and Langevin's derivations were similar to Einstein's thought experiment about observers riding the rim of a spinning carousel versus sitting at its center. In this case, they imagined a network of observers riding along the edge, each equipped with a clock and a light source. The first observer could emit a light ray as soon as her clock struck noon; the next person along the

17. Albert Einstein, "Lichtgeschwindigkeit und Statik des Gravitationsfeldes [The Speed of Light and the Statics of the Gravitational Field]," *Annalen der Physik* 38 (1912): 355–69, in *CPAE* vol. 4, doc. 3.

18. Georges Sagnac, "Effet tourbillonnaire optique: La circulation de l'Éther lumineux dans une interférographie tournant [Optical Vortex Effect: The Circulation of the Luminiferous Ether in a Rotating Interferometer]," *Journal de Physique* 5th series, 4 (1914): 177–95. See also E. J. Post, "Sagnac Effect," *Reviews of Modern Physics* 39, no. 2 (1967): 475–93; and Gianni Pascoli, "The Sagnac Effect and Its Interpretation by Paul Langevin," *Comptes Rendus Physique* 18 (2017): 563–9.

19. Max von Laue, "Über einen Versuch zur Optik der bewegten Körper [On an Experiment on the Optics of Moving Bodies]," *Münchener Sitzungsberichte* (1911): 405–12; Paul Langevin, "Sur la théorie de la relativité et l'expérience de M. Sagnac [On the Theory of Relativity and the Experiments of M. Sagnac]," *Comptes Rendus* 173 (1921): 831–4; Pascoli, "Sagnac Effect" (ref. 18), 567–8.

circle would set her own clock to noon plus the time required for the light ray to reach her from her friend, then emit her own light ray announcing the time on her clock to the next observer along the track. The spinning observers would measure the complete trip to take $t = 2\pi R/c$, where R was the radius of the carousel. To the non-rotating observer sitting at the center, on the other hand, the first observer would move a distance $vt = \omega Rt$ while the light beams were in flight, where ω was the carousel's rotation rate. According to the non-spinning observer, therefore, a complete loop would require the light rays to traverse the added distance to meet back up with the first observer; hence, the complete loop would require some longer time, $t + \Delta t$. To lowest order in ω, the difference would be $\Delta t = 2\omega A/c^2$, where A was the area of the closed loop. The upshot: Relativity predicted that rotating versus non-rotating observers should display disagreement in their respective measurements of time intervals.[20]

In each of these scenarios—time dilation, gravitational redshift, and rotations—Einstein and his colleagues derived various effects of motion on clocks by elevating some postulate to a principle and then deducing consequences; none were inferred from observed phenomena at the time. Indeed, the predicted effects were tiny on everyday scales, and most eluded clear measurement for decades.

Consider time dilation. For a train traveling at 100 kilometers per hour—typical for passenger trains around 1900—the relativistic effect would be minuscule: a difference of just 4.3×10^{-15} in clock rates.[21] Little wonder that as late as 1920, the Dutch physicist Adriaan Fokker chided Einstein, his former teacher, "When are you going to invite an outstanding experimenter to demonstrate that moving clocks run more slowly than ones at rest . . . ? It really is almost insufferable that the theory of rel. still has to limp along on a single leg."[22] (The "single leg" which Fokker had in mind was length contraction, as inferred from the Michelson-Morley experiment.) About twenty more years elapsed before physicists produced compelling experimental evidence of time dilation.[23]

20. Von Laue, "Über einen Versuch" (ref. 19); Langevin, "Sur la théorie" (ref. 19); Pascoli, "Sagnac Effect" (ref. 18), 565–8.

21. On typical railway speeds at the time, see, e.g., John Droege, *Passenger Terminals and Trains* (McGraw-Hill, 1916), 284.

22. Adriaan D. Fokker to Albert Einstein, 2 June 1920, *CPAE* vol. 10, doc. 40.

23. Some of the first empirical evidence came in 1938 from the so-called Ives-Stilwell experiment. See H. E. Ives and G. R. Stilwell, "An Experimental Study of the Rate of a Moving Atomic

Even more time passed between prediction and test for gravitational redshift. In his 1911 paper, Einstein realized that his prediction might be tested by comparing the spectral lines of light near the surface of the Sun with those from Earthbound sources. Computing the difference in gravitational potential between the solar surface and local laboratories, Einstein suggested the redshift might amount to a few parts per million. Astronomers' efforts to measure such an effect remained notoriously difficult; indeed, astronomers in several countries traded bitter claims and counterclaims about alleged measurements of gravitational redshift well into the 1930s.[24] The first widely accepted measurement of the effect was performed by Robert Pound and Glen Rebka at Harvard University in 1959–60. Rather than try to measure solar spectral lines, they performed a test much closer to Einstein's original conception, exploiting then-new nuclear resonance phenomena to carefully measure the wavelength shift as light traversed a 22-meter tower within Harvard's physics building. The tiny shift was equivalent to a difference of just 2.4×10^{-15} in clock rates.[25]

In von Laue's first derivation of what came to be called the "Sagnac effect," regarding effects of rotation, he suggested that the disagreement in times required to complete a loop would be $\Delta t = 10^{-15}$ seconds for realistic interferometer experiments.[26] Sagnac's careful experiment in 1914 managed to measure just such a shift, though the interpretation of Sagnac's results remained controversial at least until Langevin's 1921 intervention.

By the time Einstein died in 1955, rockets and jet-powered aircraft had eclipsed the railway carriage and fairground carousel as the typical technologies of speed, while a new generation of timekeeping devices achieved parts-per-trillion

Clock," *Journal of the Optical Society of America* 28 (1938): 215–26; "An Experimental Study of the Rate of a Moving Atomic Clock, II," *Journal of the Optical Society of America* 31 (1941): 369–74; Roberto Lalli, "Anti-Relativity in Action: The Scientific Activity of Herbert E. Ives between 1937 and 1953," *Historical Studies in the Natural Sciences* 43, no. 1 (2013): 41–104.

24. Einstein, "Über den Einfluß der Schwerkraft [On the Influence of Gravitation]," *CPAE* vol. 3, doc. 23, on 384 (English translation supplement); Klaus Hentschel, "The Conversion of St. John: A Case Study on the Interplay of Theory and Experiment," *Science in Context* 6 (1993): 137–94; *The Einstein Tower: An Intertexture of Dynamic Construction, Relativity Theory, and Astronomy*, trans. Ann M. Hentschel (Stanford University Press, 1997), chs. 3–4; Jeffrey Crelinsten, *Einstein's Jury: The Race to Test Relativity* (Princeton University Press, 2006), chs. 5, 7.

25. R. V. Pound and G. A. Rebka, Jr., "Gravitational Red-Shift in Nuclear Resonance," *Physical Review Letters* 3 (1959): 439–41; "Apparent Weight of Photons," *Physical Review* Letters 4 (1960): 337–41. See also Klaus Hentschel, "Measurements of gravitational redshift between 1959 and 1971," *Annals of Science* 53 (1996): 269–95.

26. Von Laue, "Über einen Versuch" (ref. 19).

accuracy. In short order, what had begun as curious thought experiments became mission-critical design elements in a militarized space age.

MILITARY ORIGINS OF GPS

The first stirrings of what would become GPS date to the Soviets' launch of *Sputnik 1* on October 4, 1957. Millions around the world breathlessly followed news of the tiny satellite. Two researchers at the Johns Hopkins Applied Physics Laboratory, William Guier and George Weiffenbach, did more than gape. Within days, they adapted a technique they had been working on at the lab for tracking guided missiles and applied it to tracking the *Sputnik* satellite across the sky. They recorded the Doppler shift of radio signals emitted by the satellite, jury-rigged a system to digitize the signals (a tricky task in the early days of electronic computing), and used that input to reconstruct the satellite's path. By the end of the month, as the satellite's batteries ran down and its telltale beeps faded to a whisper, Guier and Weiffenbach could predict its location about as accurately as elaborate tracking stations.[27]

The Applied Physics Laboratory, where Guier and Weiffenbach worked, had been set up in a hurry during in the spring of 1942, soon after the United States entered the Second World War. Much like more famous installations—the Radiation Laboratory at the Massachusetts Institute of Technology (MIT), which served as the hub for Allied efforts on radar, and the sprawling Manhattan Project that produced the first nuclear weapons—the Applied Physics Laboratory had originally focused on war-ready projects. Among its most impactful: the radar proximity fuse, a device that would detonate an explosive only once it was within range of its target. After the war, the US Navy negotiated with Johns Hopkins University to continue operating the lab as a defense contracting facility, and by the late 1940s much of the laboratory's effort focused on refining guided-missile technology for use on Navy ships.[28]

A few months after Guier and Weiffenbach had demonstrated that a receiving station on the ground could track a moving object in the sky by carefully analyzing the signals it beamed down, their supervisor at the lab, Frank McClure, called them into his office. His pitch to them: Could one reverse

27. Parkinson et al., "History of Satellite Navigation" (ref. 2), 111–12; Milner, *Pinpoint* (ref. 1), 36–7; Ceruzzi, *GPS* (ref. 2), 41–3.

28. Michael A. Dennis, "'Our first line of defense': Two University Laboratories in the Postwar American State," *Isis* 85, no. 3 (1994): 427–55.

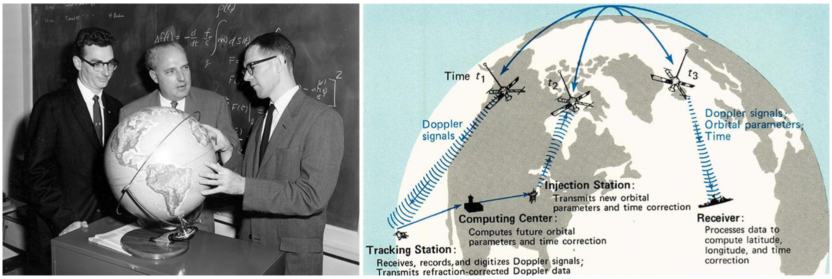

FIGURE 1. (Left) William Guier, Frank McClure, and George Weiffenbach at the Johns Hopkins University Applied Physics Laboratory, ca. 1958. (Right) Schematic of the US Navy "Transit" system, from Robert J. Danchik, "The Navy Navigation Satellite System (Transit)," *Johns Hopkins APL Technical Digest* 5, no. 4 (1984): 323–9, on 323. (Source: JHU/APL.)

the process, and use signals from a passing object whose position was known in order to identify one's own location on Earth? McClure had a specific objective in mind: the US Navy—still the lab's primary sponsor—needed some system for improved positioning accuracy for Polaris, its new system of ballistic missiles that could be launched from submarines. If shipboard monitors could passively receive signals from orbiting satellites, whose own paths were well known, then a given missile's guidance system could quickly establish its present location and calculate a path to its target (figure 1).[29]

Within weeks, the idea morphed from a brainstorming session into formal proposal. In less than a year, the lab took the lead on the new Navy "Transit" project: the first satellite-based radio navigation system. Major funding for the project came from the brand-new Advanced Research Projects Agency (ARPA), hastily stood up as part of the US government's frenzied response to *Sputnik*. (ARPA was later rebranded as DARPA, with the "D" for "Defense.") With lightning speed, the first Transit satellite was launched in April 1960, barely nine months after funding for the project had begun. The Navy Transit system became fully operational in 1964, and by 1967 a version was made available for civilian use. The luxury ocean liner *Queen Elizabeth 2* became one of the first commercial ships to adopt the navigation system, after its owners invested $65,000 for the special onboard receiver (more than $600,000 in 2026 currency).[30]

29. "Frank T. M'Clure, physicist, 57, dies," *New York Times*, 20 Oct 1973, 34; Parkinson et al., "History of Satellite Navigation" (ref. 2), 112–15; Milner, *Pinpoint* (ref. 1), 37–8; Ceruzzi, *GPS* (ref. 2), 38–41.

30. Rankin, *After the Map* (ref. 2), 258–61; Sharon Weinberger, *The Imagineers of War: The Untold Story of DARPA, the Pentagon Agency that Changed the World* (Knopf, 2017), 46, 66;

The Transit system could provide location accuracy to within around 400 meters for ships moving at sea. Around the time Transit became operational, a researcher at the US Naval Research Laboratory, Roger Easton, proposed a way to improve accuracy by about two orders of magnitude. The Transit system relied upon measuring the Doppler shift of signals from orbiting satellites. What if, instead, a network of satellites beamed down more specific information: reporting their own present location and the time registered by an onboard clock. This way, a receiver on the ground or at sea could receive such signals from several satellites. For each one, the receiver could compare the reported times at which the satellite signals were emitted with the local time when those signals were received, as reported by its own clock. Radio waves would travel at the speed of light, so the receiver could determine its distance from each of the satellites—a process called "range measuring"—and use the satellites' known positions to establish its own location. Easton dubbed this new technique "Timation," a combination of "time" and "navigation." Much like Transit, Timation would be passive: The receivers did not need to transmit their own signals, which would have made them vulnerable to detection by adversaries.[31]

To improve on the location accuracy compared to Transit, Easton focused on timekeeping. If the clocks on board the orbiting satellites were especially accurate and stable, that would remove a large source of positional uncertainty. His idea: Equip the satellites with atomic clocks.

Beginning in the late 1940s, researchers at centers like the National Physical Laboratory outside London and the National Bureau of Standards in Washington, DC, capitalized on surplus wartime microwave electronics—along with skills and knowledge gained on high-priority projects like radar—to produce atomic frequency standards, soon dubbed "atomic clocks." The devices took advantage of the quantized oscillation frequencies of electrons in atoms. When light whose frequency had been tuned to the atoms' resonant frequency was shone into a gas of those atoms, most atoms would absorb the incoming light and enter an excited state—exactly the kind of transition that physicists could measure with newfound accuracy using microwave cavities. If the frequency of the incoming light began to drift, fewer atoms would absorb the light, providing a fast indication that the light's frequency no longer matched the

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"Elizabeth 2 to Use Satellites in Space for Her Navigation," *New York Times*, 23 Dec 1968, 78; Lawrence Lessing, "Satellites to Steer By," *Fortune* 82, no. 2 (1970): 115–17, on 117.

31. Parkinson et al., "History of Satellite Navigation" (ref. 2), 119–26; Milner, *Pinpoint* (ref. 1), 40–41; Ceruzzi (ref. 2), *GPS*, 50–53.

intended one. With such feedback loops, researchers could coax the frequency standards to remain stable to parts per trillion. Such ultra-stable frequencies could then be converted into timekeepers by carefully recording the number of light-wave crests that passed a counter. By the mid-1950s, physicists at MIT, Harvard, and elsewhere had spun off commercial versions of these atomic clocks, typically exploiting a particular atomic transition in cesium atoms. (In 1967, delegates to the 13th General Conference on Weights and Measures redefined the second in terms of the 9,192,631,770 cycles associated with a specific energy-level transition in cesium-133 atoms.)[32]

Easton's idea of putting such special clocks aboard a network of satellites impressed some supervisors within the Naval Research Laboratory, but Timation had to compete for resources with the Navy's own higher-priority Transit system. Easton and his colleagues managed to launch a few test satellites during the late 1960s to conduct proof-of-principle measurements, but the system never achieved operational status akin to Transit.[33]

Around the time Easton first proposed Timation within the Navy, a separate group began to work on a secret project dubbed "Project 621B" for the US Air Force. Project 621B grew out of a collaboration between the Air Force Office of Scientific Research and the Aerospace Corporation. Founded in 1960 as a spin-off from the defense contractor TRW, the nonprofit Aerospace Corporation was chartered to "aid the US Air Force in applying the full resources of modern science and technology to the problem of achieving those continuing advances in ballistic missile and military space systems which are basic to national security." By autumn 1963, the Aerospace Corporation joined the Air Force's Space and Missile Systems Organization (SAMSO) to lead Project 621B.[34]

32. Paul Forman, "Atomichron: The Atomic Clock from Concept to Commercial Product," *Proceedings of the IEEE* 73, no. 7 (1985): 1181–204; "'Swords into ploughshares': Breaking New Ground with Radar Hardware and Technique in Physical Research after World War II," *Reviews of Modern Physics* 67, no. 2 (1995): 397–455; Jack S. Goldstein, *A Different Sort of Time: The Life of Jerrold R. Zacharias* (MIT Press, 1992), ch. 6; and Lisa Crystal, *Quantum Times: Physics, Philosophy, and Time in the Postwar United States* (PhD diss., Harvard University, 2013), ch. 1.

33. Milner, *Pinpoint* (ref. 1), 43–5; Ceruzzi (ref. 2), *GPS*, 52–7.

34. US Congressional Committee on Government Operations, *Air Force Ballistic Missile Management* (*Formation of Aerospace Corporation*) (Washington, DC: US Government Printing Office, 1961), on 18. See also 15–20; Parkinson et al., "History of Satellite Navigation" (ref. 2), 134–5, 156; and Air Force Research Laboratory, *Air Force Office of Scientific Research, 1951–Present* (US Air Force Office of Scientific Research, 2013), on p. 28. My thanks to Connemara Doran for bringing the latter document to my attention.

The main ideas for Project 621B were remarkably similar to Easton's Timation: launch a purpose-built network of satellites, each carrying an atomic clock, so that receivers could perform passive range measuring to establish their own locations. Whereas Easton had emphasized navigational uses, however, Project 621B focused on precision targeting. A classified briefing prepared by Aerospace Corporation researchers in August 1966 for the USAF Space Systems Division emphasized over and over again that their proposed system would support such missions as "tactical air strikes" by aiding "target identification and coordinate determination," with which navigation software aboard a fast-moving jet could determine the "bomb release point." They also advertised similar capabilities for "short range missile launch from aircraft" and direct input from satellites to the guidance systems for ballistic missiles.[35]

In their 1966 briefing, the Project 621B team noted that "cesium clock oscillators are now catalog items"—literally off-the-shelf technologies—which could be combined with recent advances in integrated circuits, so that the entire clock-plus-computer assembly would be "available in shoe box size," appropriate for a proposed fleet of small, space-ready satellites. They had even smaller units in mind as well, proposing a "manpack set," not to weigh more than 100 pounds, which could be used by individual soldiers on the ground for "target spotting." Such a system, the Aerospace Corporation team pitched, could provide location accuracy to within a few meters.[36]

Like the Navy Timation project, Project 621B never became a full-fledged, operational system. A classified review by an Air Force lieutenant colonel in 1970 concluded, "Do not immediately scrap your current equipment or organization" for navigation and targeting, "even though this equipment [as proposed in 621B] exists within the current technology." After all, he noted, "the question of program approval and funding still has to be answered."[37]

35. J. B. Woodford and H. Nakamura, "Briefing: Navigation Satellite Study," 24 Aug 1966, originally prepared as Aerospace Corporation classified report TOR-1001(1515-17)-1, quotations on 14 ("tactical air strikes"), 17 ("target identification," "bomb release point"), and 26 ("short range missile launch"). A declassified (and seemingly unredacted) version of this report is reproduced in Patrick J. O'Brien and John M. Griffin, "Global Positioning System Systems Engineering Case Study," Air Force Center for Systems Engineering, *Air Force Institute of Technology* document 34 (Wright-Patterson Air Force Base, 2007), https://scholar.afit.edu (accessed June 23, 2025), 73–122.

36. Woodford and Nakamura, "Briefing: Navigation Satellite Study," 46 ("catalog items," "show-box size"), 48–9 ("manpack set," "target spotting"). On projected accuracy, see 49, 70–71.

37. Lieutenant Colonel J. A. Fiebelkorn, "621B Satellite System" (1970), 14. Fiebelkorn's classified report from the US Air Force Policy and Plans Group was declassified in 1982 and is available from www.masterclock.com/masterclock-knowledge-center.html (accessed June 19, 2025).

Each of these rival programs limped along in parallel until April 1973, when the US Deputy Secretary of Defense issued a memorandum stipulating that the separate Navy and Air Force efforts be integrated into a single project, soon labeled the "Navstar Global Positioning System," or GPS. By autumn 1973, the Pentagon had established a new GPS Joint Program Office at the Los Angeles Air Force Base in El Segundo, California, under the leadership of Air Force Colonel Brad Parkinson, a veteran of Project 621B. The new Joint Program Office was charged with managing efforts across the military branches, all in close coordination with the Aerospace Corporation—which had already been established in El Segundo back in its earliest days, as part of the Ramo-Wooldridge contractor, to be close to the Air Force ballistic missile program (figure 2).[38]

The group launched the first purpose-built GPS satellite, dubbed NTS-2, from the Vandenberg Air Force Base in California in June 1977. (The acronym stood for "Navigation Technology Satellite"; NTS-1 had been the last of the Timation test satellites.) By February 1978, target test runs had begun at the Army's Yuma Proving Grounds in Arizona (figure 3). To keep the new recruits focused on their main task, Colonel Parkinson posted signs in the GPS Joint Program Office which 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.[39]

Around that same time, the US Comptroller General reported to Congress with a similar message, albeit in a more bureaucratic tone: "All military services are interested in using GPS" for such "operational objectives" as "precision weapon delivery" and "terminal navigation and landing."[40]

Scientists and engineers in the Soviet Union followed a similar trajectory. Their "Tsikada" ("Cicada") program, which launched in the late 1960s, relied upon passive processing of Doppler shifts from orbiting satellites for naval navigation, much like the US Navy's Transit system.[41] The Soviets'

38. Robert F. Keller, Acting Comptroller General, *Report to the Congress: Status of the NAVSTAR Global Positioning System* (Government Printing Office, 1977), 1. See also Milner, *Pinpoint* (ref. 1), 54–7; Ceruzzi (ref. 2), *GPS*, 57–61; and Wilson, *Strange Stability* (ref. 6), ch. 4.

39. Milner, *Pinpoint* (ref. 1), 58–60, on 58. See also Parkinson et al., "History of Satellite Navigation" (ref. 2), 138. On NTS-1, see Ceruzzi (ref. 2), *GPS*, 56–7.

40. Keller, *Status of the NAVSTAR* (ref. 38), 12.

41. Parkinson et al., "History of Satellite Navigation," 118–19; Milner, *Pinpoint* (ref. 1), 44.

FIGURE 2. US Air Force Colonel Brad Parkinson (center) poses with Frank Butterfield of the Aerospace Corporation (left) and Navy Commander Bill Huston (right) at the new GPS Joint Program Office, early 1970s. (Source: Aerospace Corporation.)

FIGURE 3. US Senator Barry Goldwater (R.–AZ, left) listens to a soldier's GPS "manpack" during testing at the US Army Proving Grounds in Yuma, Arizona, 1981. (Source: US Army.)

GLONASS program, meanwhile, began in earnest in the mid-1970s, soon after the GPS Joint Program Office was established in the United States. The first GLONASS satellites were launched in October 1982, about four years after the launch of NTS-2, and systemwide testing began about six years later.[42]

DUELING RELATIVISTS

On a human scale, the speed of light is fast: Light travels 30 centimeters in a nanosecond. For a system like GPS to achieve location accuracy of around one meter, the network of clocks on orbiting satellites must remain synchronized to within just three nanoseconds. By the mid-1960s, as atomic clocks became more readily available and placing satellites in orbit came to seem routine, some researchers began to ask whether one had to worry about relativity when designing such a system. Within a few years the question had shifted: It became not whether to include relativity, but how to adjudicate when experts in relativity arrived at different conclusions—while the stakes for the military targeting system seemed so high.

Hardcoding Relativity

Among the first to address the question of relativistic effects for clock coordination was W. J. Cocke, a civilian contractor at the Aerospace Corporation. In 1966—not yet three years after the Aerospace Corporation had begun working on the Air Force's Project 621B—Cocke published a short paper that "consider[ed] the relativistic effects for which one must eventually compensate" in such a system.[43] Cocke had recently begun working for the Aerospace Corporation, soon after completing his PhD in astrophysics at Cornell University. Even after joining Aerospace, he did not have access to all the relevant classified information. Without revealing too much, a colleague in the company's Tracking and Radar Department asked Cocke to consider possible relativistic effects on satellite-borne clocks.[44]

42. Parkinson et al., "History of Satellite Navigation," 156–60 (ref. 2); Ceruzzi, *GPS* (ref. 2), 157–62.

43. W. J. Cocke, "Relativistic Corrections for Terrestrial Clock Synchronization," *Physical Review Letters* 16 (1966): 662–4.

44. W. J. Cocke, "Can GPS Test Gravity's Speed of Propagation?," *Physics Today* 55, no. 11 (2002): 98.

Cocke wrote a classified technical report for the Aerospace Corporation and prepared a brief, unclassified version, which was published in the leading physics journal, *Physical Review Letters*. In his open article, Cocke made no mention of the military project that had prompted these questions. Instead, he calculated the effects of time dilation and gravitational redshift for a pair of clocks on Earth, one at sea level and the other atop Mount Everest. He found that even such an Earthbound example would yield a measurable difference in clock rates—about one part in a trillion, comparable to the sensitivity of the latest atomic clocks. Rather than rely on Einstein's authority or take the recent Pound-Rebka experimental results on gravitational redshift at face value, however, Cocke ended on a more cautious note: "There is no plethora of verifications of the equivalence principle, and thus we await with interest the development of more refined techniques in chronometry."[45]

Cocke's calculation could easily be applied to the nascent GPS scheme. Physicist Carroll Alley, who consulted for the Air Force on the GPS project, ran the numbers. Designs at the time called for each satellite in the GPS network to travel in twelve-hour orbits at an altitude of around 20,000 kilometers. To an observer on the ground, the satellites would appear to zip by at over three kilometers per second—and hence a ground-based observer should measure the moving clocks on each satellite to tick slowly due to time dilation. On the other hand, the magnitude of the gravitational potential of the Earth at the satellites' altitude would be considerably weaker than at the Earth's surface—so the orbiting clocks would be slowed down by gravitational redshift much less than those on the ground. Combining these two relativistic effects suggested that the orbiting clocks would tick at a rate 445 trillionths faster than otherwise-identical clocks on the ground. If left uncorrected, this tiny difference would surpass the error budget for GPS's navigational accuracy within a few seconds.[46]

The numbers seemed clear enough to physicists like Alley, but he quickly found "considerable uncertainty among the Air Force and contractor personnel" as to whether such "effects were real." Some project engineers remained skeptical that *any* esoteric effects from relativity could be relevant for a real-world system such as GPS. Others tried to incorporate relativity, but

45. Cocke, "Relativistic Corrections" (ref. 43), 664. Cocke's article in *Physical Review Letters* noted that it was a revision of Aerospace Corporation Report No. TR-669(6260-20)-1, which had been prepared under a US Air Force contract.

46. Carroll O. Alley, "Proper Time Experiments in Gravitational Fields with Atomic Clocks, Aircraft, and Laser Light Pulses," in *Quantum Optics, Experimental Gravitation, and Measurement Theory*, ed. Pierre Meystre and Marlan O. Scully, 363–427 (Plenum, 1983), 421–3.

wound up double-counting some of the corrections—thinking, for example, that they needed to account *both* for gravitational redshift *and* for a Doppler shift of the electromagnetic waves as they traveled from sky to ground (which, in Einstein's calculation, were just two ways of calculating the same effect). Alley counseled patience: "We should not be surprised at such lack of understanding of some of the fundamental concepts of General Relativity since the subject is almost never taught to engineers and rarely even to physicists." Indeed, he continued, even "among eminent physicists," confusion lingered over many of the implications of Einstein's work.[47]

The project engineers came around soon enough. The first GPS program satellite, NTS-2, launched in June 1977, carried a cesium frequency standard stable to about one part per ten trillion. The onboard computer ran software to transmit signals encoding the output from the clock, which could then be measured at various ground stations and compared with identical reference clocks. Rather than trust the physicists' prediction that relativistic effects would cause a difference in clock rates between satellite and ground, the engineers compromised and included a switch. Controllers on the ground could send a command to the satellite's onboard computer to change its reported clock rate by a specific amount, in order to absorb the calculated effects of time dilation and gravitational redshift. If the relativistic corrections failed to show up, the engineers could simply send a second command to the satellite, resetting its software to default mode.[48]

A few months later, a team from the Naval Research Laboratory reported the results at a symposium organized by the US Army Electronics Research and Development Command. During the first two hundred days after launch, the measured clock rates on NTS-2 and at the ground stations did indeed drift, with the satellite's clock consistently ticking more quickly than the ground-based controls by 442.5 parts per trillion—a remarkable match, to within just 0.56%, of the relativistic prediction. (Indeed, although the engineers did not pause to note the fact in their presentation, their measurements constituted one of the most precise tests of general relativity up to that time.) Next, the ground crew sent the

47. Alley, 423–4. On engineers' skepticism, see also Galison, *Einstein's Clocks, Poincaré's Maps: Empires of Time* (W. W. Norton, 2003), 288–9. On the dearth of coursework on general relativity within US physics departments at the time, see David Kaiser, "A psi is just a psi? Practice, pedagogy, and the reconstitution of general relativity, 1942–1975," *Studies in History and Philosophy of Modern Physics* 29, no. 3 (1998): 321–88, on 321–3.

48. Thomas McCaskill, Joseph White, Sarah Stebbins, and James Buisson, "NTS-2 Cesium Frequency Stability Results," *Proceedings of the 32nd Annual Symposium on Frequency Control* (US Army Electronics Research and Development Command, 1978), 560–66.

command for the onboard computer to modify the time stamps it reported, adjusting the actual clock rate by the preset amount—and immediately the *reported* rates of the satellite and ground clocks fell into sync.[49]

This empirical test quieted the skeptics. Following the NTS-2 report, physicist Carroll Alley, along with several other experts working on GPS, issued a one page memorandum to GPS contractors, under the auspices of the Air Force Space and Missile Systems Organization (SAMSO). Item one stated simply, "To meet its design goals, GPS requires the consideration of relativistic effects. These effects are best described by the theory of General Relativity . . . [which] is supported by the small amount of experimental data at an adequate level. Therefore the effects can and must be accounted for to the necessary levels of accuracy." The committee next noted that several recent technical documents prepared by GPS contractors (such as the General Dynamics Electronics Division), which purported to calculate various relativistic corrections, contained errors that needed to be corrected. More generally, the group concluded, "The designers of GPS user equipment in particular should have available adequate and proper documentation so that the appropriate relativistic corrections can be included."[50]

Soon after the memo was circulated, GPS project personnel began preparing the onboard satellite computers with a factory offset prior to launch, which adjusted the rate at which the time measured by the onboard clocks would be reported in the outgoing signals. The effects of time dilation and gravitational redshift were coded directly into the chips that ran the onboard computers, with comparable corrections coded into the ground-based receivers. Even this adjustment did not always go as planned. A few years later, a physicist at the National Bureau of Standards had to send a memorandum to colleagues throughout the GPS project. The latest round of chips for the ground-based receivers "had a 'bug' in it," he explained. "The net of the problem was that the relativistic 'red' shift equation was essentially there, but the 'bug' prevented its implementation." Enclosed with the letter were new EPROM chips with the error corrected, plus a hand-drawn figure to clarify how to access and replace the offending chips. "If you wouldn't mind sending the old EPROM back to us we would appreciate it. We apologize for this inconvenience and faux pas."[51]

49. McCaskill, et al., 560–61 and Figs. 11–12.

50. David W. Allan, Carroll O. Alley, Neil Ashby, M. D. Harkins, R. F. C. Vessot, and G. M. R. Winkler, "Report of SAMSO/NAVSTAR-GPS Relativity Seminar, National Bureau of Standards, Boulder, Colorado, 8–9 March 1979," CMW, folder "Global Positioning System."

51. Memo from David W. Allan (Time and Frequency Division, National Bureau of Standards), 5 Feb 1985, CMW, folder "Global Positioning System."

Occasional implementation errors aside, relativistic effects had become hard-coded into the GPS infrastructure.

Outside Critics and the Question of Rotation

So much for time dilation and gravitational redshift. What about effects of rotation? Neither Cocke's 1966 article nor the single-satellite NTS-2 test concerned coordinating clocks among a *network* of satellites, each rotating with respect to observers on the ground. Several other physicists, who had no connection to the GPS program, began to study possible effects of rotation on clock coordination. Coincidentally, their first paper on the topic arrived at *Physical Review Letters* one day after the launch of NTS-2 in June 1977.[52]

Jeffrey Cohen and Harry Moses proposed a "new test of the synchronization procedure in noninertial systems." They began by reminding readers of Einstein's 1905 proposal for synchronizing clocks using light signals. Next, they noted that Einstein's scheme could be extended to "a set of clocks lying along a curve in a noninertial frame," such as a collection of clocks on multiple satellites orbiting around the Earth. Such a test would be feasible, they wrote, since such "satellites containing clocks are already in orbit"—though they made no reference to the classified GPS program. Instead, their calculation had been prompted by discussion with other experts in general relativity.[53]

To begin their calculation, Cohen and Moses turned to the classic textbook on general relativity by the Soviet theorists Lev Landau and Evgeny Lifshiftz, first translated into English in 1951. Landau and Lifshitz had included a section on "Rotation," concluding that "clocks on the rotating body cannot be uniquely synchronized at all points." Rather, if one began by sending a light signal from clock A to clock B and so on around a closed loop, the total offset Δt would depend on the light ray's integrated path through the curved spacetime. For simple scenarios, working to lowest order in the rotation speed, Landau and Lifshitz recovered Sagnac's result from the 1910s.[54] When Cohen and Moses applied these results to the case of clocks on satellites in geosynchronous orbits above the Earth,

52. Jeffrey M. Cohen and Harry E. Moses, "New Test of the Synchronization Procedure in Noninertial Systems," *Physical Review Letters* 39, no. 26 (1977): 1641–3. The article was received at the journal on 24 Jun 1977.

53. Cohen and Moses, 1641. The authors thanked relativists Peter Havas and Banesh Hoffmann for comments on their draft.

54. L. D. Landau and E. M. Lifshitz, *The Classical Theory of* Fields, 4th ed., trans. Morton Hamermesh (1951; Pergamon, 1975), 254–5.

they found a substantial effect: "Δt is surprisingly large: $\Delta t = 9$ μsec [microseconds] and is thus easily measurable by atomic or even good quartz clocks." They suggested trying to measure such an effect with real-world orbiting clocks.[55]

A potential mismatch of nine microseconds seemed like an interesting curiosity to Cohen and Moses at first, and a feasible way to test predictions of Einstein's theory. Yet they soon became alarmed when they learned about the still-secret GPS program, non-classified details about which appeared from time to time in the open literature.[56] As far as Cohen and Moses were concerned, the effects of rotation meant that a network of clocks on GPS satellites could never remain synchronized to requisite accuracy, because they would each be undergoing accelerations due to rotation—and the effect from rotation, which they had just calculated, appeared to dwarf the error budget required for GPS navigation. Their result (nine microseconds) was *three thousand times greater* than the GPS operational requirement of three nanoseconds.

Cohen and Moses quickly began working with two other colleagues, Arnold Rosenblum and Angelo Skalafuris. Members of this quartet shared several characteristics: Each had been trained in general relativity, most worked in the Philadelphia area, and none had any connection with the GPS program. Cohen was on the faculty in the physics department at the University of Pennsylvania, following a postdoctoral fellowship at the prestigious Institute for Advanced Study in Princeton. His 1966 dissertation at Yale had been on "Rotating Masses and Their Effect on Inertial Frames"—exactly the topic that now loomed so large. Moses was on the faculty at the University of Massachusetts, Lowell, having completed his PhD at Columbia University in 1950. By the time he and Cohen began working on effects of rotation on clocks, Moses had worked extensively as an atmospheric scientist in centers like the Argonne National Laboratory and the Air Force Cambridge Research Laboratories, with a focus on analyzing radio-transmitted data from balloon-borne instruments. He had been elected a Fellow

55. Cohen and Moses, "New Test" (ref. 52) 1641–2. Cohen and Moses began by rewriting the line-element for a general stationary metric, $ds^2 = g_{00} (dx^0)^2 + 2g_{0i}\, dx^0\, dx^i + g_{ij}\, dx^i\, dx^j$, as $ds^2 = g_{00} (dt + g_{00}{}^{-1}\, g_{0i}\, dx^i)^2 + (g_{ij} - g_{00}{}^{-1}\, g_{0i}\, g_{0j})\, dx^i\, dx^j$. The term proportional to $dx^i\, dx^j$ defined the metric on spatial surfaces; the orthogonal (timelike) direction was therefore governed by the "time differential" $d\tau = dt + g_{00}{}^{-1}\, g_{0i}\, dx^i$. Although $d\tau$ would vanish on the spatial surface, the *integral* of $d\tau$ over a closed contour would *not* vanish, in general, yielding a *global* difference in measured times for clocks distributed along the rotating hypersurface.

56. See, e.g., "In the News: Navstar," *SpaceWorld* (1968): 49; Lessing, "Satellites" (ref. 30); "Rockwell to Develop Navstar Satellites," *Aviation Week and Space Technology*, 1 Jul 1974, 52; "Satellites for Navstar System," *SpaceWorld* (1975): 30; A. J. van Dierendonck, S. S. Russell, E. R. Kopitzke, and M. Birnbaum, "The GPS Navigation Message," *Navigation* 25, no. 2 (1978): 147–65.

of both the American Physical Society and the New York Academy of Sciences. Rosenblum had completed his master's degree at Penn and his doctoral studies at Temple University in Philadelphia in 1970, working with the accomplished relativity expert Peter Havas, while Skalafuris was a longtime visiting faculty member in the physics department at Penn, having completed his PhD in astrophysics at Brandeis in 1963. Skalafuris also held a research-staff appointment at the Naval Research Laboratory.[57]

Beginning in the late 1970s, this outsider quartet began devoting more of their attention to clock synchronization and possible implications for GPS. They published follow-up articles in venues like *Physical Review Letters* and the brand-new specialist journal *Classical and Quantum Gravity*.[58] They also began a behind-the-scenes campaign.

At the time, the theoretical framework for incorporating relativistic corrections within GPS had largely been worked out by physicists Neil Ashby, a Harvard-trained physics professor at the University of Colorado, Boulder, and David W. Allan, chief of the Time and Frequency Coordination Group at the nearby National Bureau of Standards laboratory in Boulder. (In his 1965 master's thesis at the University of Colorado, Boulder, Allan had introduced what came to be known as "Allan variance," a now-standard method for measuring the stability of atomic clocks amid frequency-dependent noise.[59]) Ashby wrote a lengthy report, "An Earth-Based Coordinate Clock Network," in April 1975; Ashby and Allan published a detailed article in 1979 on "Practical Implications of Relativity for a Global Coordinate Time Scale" in the

57. Jeffrey M. Cohen, *Rotating Masses and their Effect on Inertial Frames* (PhD diss., Yale University, 1966); "Moses, Harry Elecks," in *American Men and Women of Science*, ed. Katherine H. Nemeh, Pamela M. Kalte, and Noah Schusterbauer, 22nd ed. (Gale, 2005), vol. 5, 527; Jeffrey M. Cohen, Peter Havas, and V. Gordon Lind, "Arnold Rosenblum" (obituary), *Physics Today* 45, no. 3 (1992): 81; Angelo J. Skalafuris, *Structure and Stability of Stellar Shocks* (PhD diss., Brandeis University, 1963). See also, e.g., Harry E. Moses, "Helicity representations of the coordinate, momentum, and angular momentum operators," Report AFCRL-70-0015, Aeronomy Laboratory, Air Force Cambridge Research Laboratories (United States Air Force, Office of Aerospace Research, 1970). I am grateful to Ben Wilson for bringing this report to my attention.

58. Jeffrey M. Cohen, Harry E. Moses, and Arnold Rosenblum, "Clock-Transport Synchronization in Noninertial Frames and Gravitational Fields," *Physical Review Letters* 51, no. 17 (1983): 1501–2; Jeffrey M. Cohen, Harry E. Moses, and Arnold Rosenblum, "Electromagnetic Synchronisation of Clocks with Finite Separation in a Rotating System," *Classical and Quantum Gravity* 1 (1984): L57–9; Angelo J. Skalafuris, "Current Theoretical Attempts toward Synchronization of a Global Satellite Network," *Radio Science* 20, no. 6 (1985): 1529–36.

59. David W. Allan, "Statistics of Atomic Frequency Standards," *Proceedings of the IEEE* 52, no. 2 (1966): 221–30.

engineering journal *Radio Science*; and Ashby prepared an unpublished "tutorial" on "special and general relativistic effects in the global positioning system" in June 1983, as part of his Air Force contract.[60]

None of these materials were readily available to researchers like Cohen, Moses, Rosenblum, and Skalafuris. Ashby's 1975 report circulated as a technical report of the US Department of Commerce, which housed the National Bureau of Standards—unclassified, but unlikely to be stocked in typical university libraries. Ashby's and Allan's 1979 article in *Radio Science* had appeared in a peer-reviewed journal, though one that shared almost no overlap in readership with venues such as *Physical Review Letters*. And Ashby's 1983 "tutorial" did not circulate beyond fellow Air Force staff and contractors.

Once they happened upon Ashby and Allan's 1979 article in *Radio Science*, the outsider quartet did something remarkable: They sent copies of the article—which had already undergone peer review prior to publication in the engineering journal—to several colleagues, soliciting their own post-publication peer reviews from experts in general relativity.

What came back confirmed their suspicions. From Prof. Hans-Jürgen Seifert, a mathematical physicist in Hamburg, West Germany, they received a scathing assessment. In his opening paragraph, Seifert observed that "Unfortunately [the article] seems to present neither correct results nor a clear description of the problem." For starters, Seifert huffed, the paper used "prerelativistic language in which the beautiful and simple Einstein's theory occurs as [a] vast set of somehow arbitrary corrections. In fact, the fundamental equation (1) [in Ashby and Allan's paper], on which the rest of the paper is based, obviously does not take some important effects into consideration. . . . The (dominating!) effect of the rotation of the reference system, treated correctly in the beginning, is lost during the calculation." By the end of his first page, Seifert declared simply that "the results as they stand cannot be used"—followed by another full page of detailed critique.[61]

60. Neil Ashby, *An Earth-Based Coordinate Clock Network* (Washington, DC: US Department of Commerce, April 1975); Neil Ashby and David W. Allan, "Practical Implications of Relativity for a Global Coordinate Time Scale," *Radio Science* 14, no. 4 (1979): 649–69; Neil Ashby, "Special and General Relativistic Effects in the Global Positioning System: A Tutorial," unpublished final report to the US Air Force (Jun 1983), CMW, folder "Relativistic Effects in Time Transfer."

61. H.-J. Seifert, "Remarks on the Paper 'Practical Implication of Relativity for a Global Coordinate Time Scale' by Ashby and Allan," 27 Jan 1984, CMW, folder "AJS Materials."

The response from Professor Christopher J. S. Clarke of the Mathematics Department at the University of York in Britain was similarly blunt. “I find the above paper quite unacceptable as a basis for a theory of measurement within general relativity, because of the underlying assumptions which are incompatible with relativity theory.” Among the demerits: “the authors ignore the dynamical effects of the earth’s rotation: the metric they use is a static metric transformed into rotating coordinates, which does not include the effect whereby the rotation of the earth produces a non-static metric,” a fundamental relativistic effect known as “frame-dragging” (or the Lense-Thirring effect). In closing, Clarke was clear: “I recommend that no reliance be placed on these authors’ results unless they can be obtained by other means.”[62]

Seeing their concerns confirmed with such vigor, members of the outsider quartet decided to offer their own services to the Air Force. In early December 1983, Cohen and Skalafuris sent an unsolicited grant proposal to USAF Lieutenant Colonel James Sheerer. It began by telling Air Force readers what they already knew: “Although described as a navigational system, the NAVSTAR GPS constellation of 24 satellites will greatly benefit the Defense Department. . . . Present day use of cruise, ballistic and precision strike systems demand target locators of high accuracy, within a meter.” In order to achieve such accuracy, they continued, “it would be necessary to synchronize navigational clocks to 3 nanoseconds accuracy.” Yet the calculation by Cohen and Moses, published in *Physical Review Letters* in 1977, “showed that an error of 9 microseconds can arise from general relativistic effects associated with the earth’s rotation.”[63]

Since Cohen and Moses published their calculation, moreover, new information seemed to corroborate their predictions. Cohen and Skalafuris noted in their proposal that a Japanese research group had recently experimented with clock coordination between a satellite in geosynchronous orbit and a ship at sea, and measured a discrepancy of 9.42 microseconds, which the Japanese team attributed to “error of synchronization in a rotating coordinate system.”[64]

62. C. J. S. Clarke to Arnold Rosenblum, 21 Nov 1983, CMW, folder “AJS Materials.” Seifert and Clarke were well-known to the outsider group. As recently as July 1983, Rosenblum had co-organized a NATO Advanced Research Workshop with Seifert and Clarke in Hamburg.

63. Jeffrey M. Cohen and Angelo J. Skalafuris, “Proposal for Synchronization of a Global Satellite Network,” grant proposal to the US Air Force (1983), 2. The proposal was sent as an enclosure in Angelo J. Skalafuris to Lt. Col. James Sheerer, 2 Dec 1983, CMW, folder “AJS Materials.”

64. Yoshikazu Saburi, Minoru Yamamoto, and Kikuo Harada, “High-Precision Time Comparison via Satellite and Observed Discrepancy of Synchronization,” *IEEE Transactions on Instrumentation and Measurement* IM25, no. 4 (1976): 473–7, on 475.

Cohen and Skalafuris heralded such independent confirmation "by a group working at the other end of the globe," which had been published "almost simultaneously with Cohen and Moses, so that neither was apparently aware of the other's result." Likewise, Cohen and Skalafuris continued, a colleague at the Canadian Institute for Theoretical Astrophysics had informed them that the Canadian satellite ANIC1 "is relaying the microsecond discrepancy in accordance with Cohen and Moses' predictions."[65]

To clarify whether relativistic effects from rotation would really cripple GPS, Cohen and Skalafuris explained that one would need to understand precisely how such effects were incorporated within the GPS system. And yet:

> the mechanism by which such corrections are carried out does not seem to be available to inquiries let alone published in either the open or classified literature, according to telephone conversations with personnel at [GPS contractor firms] IBM, Magnavox and the Aerospace Corporation, from whom this synopsis was obtained. The only reference quoted over the telephone from GPS contractors was N. Ashby and D. W. Allan (Radio Science v14, 4, 649–669, July 1979), and in which a great deal, if not a sole reliance, has been placed for the design of the GPS system. Unfortunately that manuscript would be considered erroneous by the physics profession in its language as well as in the formulae used.[66]

As evidence for their last observation, Cohen and Skalafuris included some of the external feedback they had solicited.[67]

Cohen and Skalafuris requested three years of funding to support the research efforts of a five-person team, to be based in Cohen's and Rosenblum's home departments at Penn and Temple. In addition to theoretical studies, the group proposed conducting a series of experimental tests of atomic clocks in motion "with associated electronics designed to correct for the kinematic and gravitational effects along the flight path."[68]

65. Cohen and Skalafuris, "Proposal for synchronization" (ref. 63), 2–3. Cohen and Skalafuris cited Saburi, Yamamoto, and Harada, "High-Precision Time Comparison" (ref. 64) and (regarding the Canadian satellite ANIC1) personal communication from R. N. Hendriksen.

66. Cohen and Skalafuris, "Proposal for Synchronization" (ref. 63), 4.

67. In his cover letter of 2 Dec 1983, Skalafuris referred to enclosed reports on the Ashby and Allan paper by Clarke and by Helmut Rumpf ("a reviewer for European physics journals in relativity theory"); the letter from Seifert, dated 27 Jan 1984, had not yet arrived. Rumpf's letter is not extant in Clifford Will's files.

68. Cohen and Skalafuris, "Proposal for Synchronization" (ref. 63), 7–8.

In his cover letter to Sheerer, Skalafuris tried to put the unsolicited proposal in context. "In addition to being a physicist," he wrote, "I am a licensed and examined professional engineer in several states and therefore can appreciate an engineering approach to a problem." He and his colleagues were not (yet) certain that all was wrong with the GPS program; rather, he complained, their efforts to understand key details had been hampered by corporate obfuscation and military classification. Hence Cohen and Skalafuris urged Sheerer and his colleagues to seek "once and for all, [a] legitimate and neutral opinion." "As far as I can discern," Skalafuris closed, "there is no disagreement among the members of the professional physics community in theoretical general relativity, but only between them and the GPS contractors who cannot be said to voice a neutral opinion over their own economic interests."[69]

Having received no response by mid-January 1984, Skalafuris wrote to Sheerer: "You understand that we are sever[e]ly handicapped by the unwarrented [*sic*] secrecy which accompanies the physical and mathematical thinking of those who have designed the [GPS] system. Therefore all we can do is speculate on how someone with intelligence yet without training in general relativity would attempt to solve the problem at hand"—and as far as they could tell from the outside, those attempts were on a bad track. A few weeks later, Skalafuris complained to Sheerer of "simple protectionist policies of contractors who stand to profit by the silence" regarding the critiques that the outsider physicists had raised.[70]

Still dissatisfied with the lack of response, Skalafuris wrote to Dr. Nicholas Yannoni, head of the Signal Processing and Timing Devices section at Hanscomb Air Force Base in the Boston suburbs. Skalafuris forwarded the as-yet unanswered grant proposal as well as the outside letters by Seifert and Clarke, which he suggested would be "enough material to start a discussion." Skalafuris's sense of urgency stemmed from quite worldly concerns, which he ticked off by number.[71]

First, "accuracy in ballistic and intercontinental missiles implies smaller payloads could be sufficient," for both conventional warheads and nuclear weapons. Given "the acknowledged worldwide deleterious consequences to both sides of excessive nuclear arms encounters," the United States would gain

69. Angelo J. Skalafuris to Lt. Col. James Sheerer, 2 Dec 1983, CMW, folder "AJS Materials."

70. Angelo J. Skalafuris to Lt. Col. James Sheerer, 13 Jan 1984 ("we are sever[e]ly handicapped"); Skalafuris to Sheerer, 22 Feb 1984 ("simple protectionist policies"), CMW, folder "AJS Materials."

71. Angelo J. Skalafuris to Nicholas Yannoni, 3 Feb 1984, CMW, folder "AJS Materials."

a tactical advantage if it could target and deliver conventional weapons with the kind of accuracy promised by promoters of GPS.[72]

But there was a catch, which Skalafuris listed second: US authorities were presumably undertaking arms-reduction negotiations with the Soviets, under the assumption that the US military would soon have the advantage of improved targeting accuracy from operational GPS. Such negotiations "may be compromised by the current representations of accuracy being advertised by GPS contractors," which appear to be "scientifically untenable." Since Soviet researchers were likely to see such claims as empty—after all, Landau and Lifshitz had trained a generation of world-class experts in general relativity within the Soviet Union—the GPS contractors' unearned bragging "may well be an inspiration to the opposing side to negotiate while our position remains unwittingly compromised."

And third: NATO allies may lose faith in the United States, since "concerns by NATO scientific affiliates"—including, presumably, Hans-J. Seifert, whom Skalafuris identified in his letter as "Dean of the West German Military Institute"—had been raised that reliance upon US defense systems "may rest upon insecure grounds."[73]

In just one page, Skalafuris elevated the stakes from a narrow controversy over relativistic effects to geopolitical meltdown. Getting the relativity wrong, he warned, might trigger nuclear Armageddon.

Expert Reviews

A week after receiving the materials from Skalafuris, Yannoni (the section chief at Hanscomb Air Force Base) forwarded them to his colleague Dr. Bernard Kulp, Chief Scientist for the US Air Force Systems Command, based at Andrews Air Force Base near Washington, DC. Yannoni explained that he had read the materials that Skalafuris had sent, "but not being conversant with gravitational theory/effects at this level, I'm unable to take a position." After talking by phone with Skalafuris and reviewing the written materials, Yannoni agreed that "the recommendation for impartial, third-party review is logical," not least because "the notes of Seifert and Clarke cannot be ignored." From Kulp the materials moved still further up the chain of command, until Air

72. On the interplay between assessments of targeting accuracy and necessary warhead size at the time, see Donald MacKenzie, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance* (MIT Press, 1993).

73. Skalarufis to Yannoni, 3 Feb 1984.

Force Brigadier General Philippe Bouchard directed the Air Force Studies Board, in conjunction with the National Research Council, to convene an expert review panel.[74]

In short order, the Air Force Studies Board established a "Committee on Accuracy of Time Transfer in Satellite Systems" (CATTISS), chaired by academic physicist Clifford Will. Will had completed his PhD at Caltech in 1971 with renowned relativist (and later Nobel laureate) Kip Thorne, then served as an Enrico Fermi Postdoctoral Fellow at the University of Chicago and as a young faculty member at Stanford University. In 1981 he published the influential monograph, *Theory and Experiment in Gravitational Physics*, hailed by reviewers at the time as a "concise and meaty book" and a "masterly survey" that would be "invaluable to researchers in gravitation." That same year, he joined the faculty at Washington University in St. Louis, Missouri as a tenured professor.[75]

Nine other reviewers joined Will on CATTISS. Several, like Will, held faculty appointments at prestigious universities and were accomplished researchers in general relativity (including Richard Matzner, Douglas Eardley, and William Hamilton). Others were based at major research centers like the US Naval Observatory (Gernot Winkler) and the Harvard-Smithsonian Center for Astrophysics (Robert Vessot). Still others were based at private firms with long experience in defense contracting, such as Bell Labs (Brockway McMillan) and the Aerospace Corporation (Jurn-Sun Leung); of course, the Aerospace Corporation had been involved with GPS since the 1960s. Nicholas Yannoni, from Hanscomb Air Force Base, served as the Air Force liaison.[76]

As Will learned upon joining the new committee, his group was not alone. Another soon-to-be member of CATTISS, Robert Vessot, had begun asking colleagues what they knew about the concerns being raised by Cohen, Moses, Rosenblum, and Skalafuris about GPS. "In an effort to gain some understanding of the problem and how it could best be resolved," Vessot explained to an Air Force Studies Board representative in April 1984, he had spoken with Irwin

74. Brig. Gen. Philippe O. Bouchard to Julian Davidson (chair, Air Force Studies Board), 23 Mar 1984, CMW, folder "AJS Materials."

75. Career details available at https://www.phys.ufl.edu/~cmw/biosketch.html (accessed 30 Jun 2025). See also Joseph H. Taylor, "Tests of Gravity," *Nature* 299 (16 Sep 1982): 284 ("concise and meaty book"); and David H. Douglass and Mark Bocko, "Gravitation," *Science* 216, no. 4549 (28 May 1982): 979 ("masterly survey," "invaluable to researchers").

76. On CATTISS membership, see the correspondence in CMW, folder "CATTISS–Organization."

Shapiro, director of the Harvard-Smithsonian Center for Astrophysics where Vessot was based, and also a JASON member.[77] DARPA's JASON group had been founded in 1960 as a division of the Institute for Defense Analysis, under contract to DARPA, to provide expert consulting on classified military projects. By the 1980s, the group often provided a version of peer review for military projects that otherwise might not face the critical scrutiny that journal peer reviewing was meant to provide (at least in principle) for unclassified research.[78]

Shapiro, in turn, had skimmed the fast-growing thicket of materials from Cohen and Skalafuris and declined to take the bait. Confident that the outsiders' critique did not pose a serious threat to the eventual operation of GPS, Shapiro had concluded it best not to engage further. As he explained to another veteran of many DARPA reviews, "The rhetoric used, especially by Skalafuris, in the documents of complaint, smacked so much of zealotry that I felt sober discussion of the merits of the case would prove unavailing. I had a similar experience years ago with [Immanuel] Velikovsky from which I learned the futility of tangling with the convinced."[79] While Shapiro bowed out, other members of the JASON group took up the charge, including a dazzling roster of leading academic physicists: Freeman Dyson (Institute for Advanced Study), Paul Horowitz (Harvard), William Press (Harvard), Malvin Ruderman (Columbia), and Sam Treiman (Princeton). Douglas Eardley, a leading expert in general relativity at the University of California, Santa Barbara, did double duty: He chaired the JASON study group while also serving on the Air Force CATTISS review committee.[80]

77. Robert F. Vessot to Julian Davidson (chair, Air Force Studies Board), 23 Apr 1984, CMW, folder "CATTISS–Organization."

78. On the JASON group, see esp. Finn Aaserud, "Sputnik and the 'Princeton Three': The national security laboratory that was not to be," *Historical Studies in the Physical and Biological Sciences* 25, no. 2 (1995): 185–239; Ann K. Finkbeiner, *The JASONs: The Secret History of Science's Postwar Elite* (Viking, 2006); Wilson, *Strange Stability* (ref. 6), ch. 5.

79. Irwin Shapiro to Don LeVine (Mitre Corporation), 28 Feb 1985, CMW, folder "AJS Materials." On Immanuel Velikovsky's heterodox theories of the Solar System—which drew enthusiastic attention from "New Age" undergraduates during the 1970s—see esp. Michael D. Gordin, *The Pseudoscience Wars: Immanuel Velikovsky and the Birth of the Modern Fringe* (University of Chicago Press, 2012).

80. Douglas Eardley et al., "Relativistic Effects in the Global Positioning System," Report JSR-84–104, May 1985. Originally unclassified; copy available from the US Defense Technical Information Center at https://apps.dtic.mil/sti/citations/ADA158720 (accessed March 4, 2023).

CATTISS and JASON proceeded in parallel, though some important differences emerged. Members of the JASON group all had security clearance and could make use of classified materials. The CATTISS group, on the other hand, would only engage with unclassified materials. Even with this separation, things did not always go smoothly. Clifford Will later recalled an "awkward moment" several months into his group's work, when a staff person from the Air Force Studies Board asked Will when he had become a naturalized US citizen. When Will replied that he was a Canadian, working in the United States on a permanent-resident green card—"a fact evidently overlooked on the c.v." that Will had submitted to the Air Force—the staffer blanched. "This was a problem," Will recounted, "because by AFSB rules all studies are initially classified, even if they do not actually deal with classified material," as was the case for CATTISS. "After some urgent phone calls the staffer managed to get a general to declassify the study retroactively," so that Will could continue to serve on the committee he had already been chairing for the better part of a year.[81]

Both CATTISS and the JASON study group began operations in late spring 1984. Eardley invited Cohen, Skalafuris, and their colleagues to meet in person with the JASON group in La Jolla, California in July 1984. Skalafuris wrote afterward to thank Eardley for sharing (unclassified) information about GPS, and for sketching out key points at a blackboard. In particular, Eardley had emphasized, the GPS framework did not rely on synchronizing the orbiting clocks and ground-based observers within a single reference frame—which, indeed, would not be consistent with relativity. He also shared with them a preprint of a short follow-up paper that Ashby and Allan had submitted to *Physical Review Letters*, which explicitly addressed the published critiques by Cohen, Moses, and Rosenblum.[82]

A few weeks later, Skalafuris wrote to Eardley again. "We have been rediscussing the GPS problem in view of the new information transmitted to us in La Jolla," and the outsider group was more convinced than ever that problems still lurked within GPS. For starters, it seemed that the latest paper by Ashby and

81. Will and Yunes, *Is Einstein Still Right?* (ref. 3), 39. See also the forms and correspondence from Sep and Nov 1984 in CMW, folders "CATTISS-Organization" and "AFSB Meeting November 1984."

82. Angelo J. Skalafuris to Douglas E[a]rdl[e]y, 25 Jul 1984, CMW, folder "AJS Materials." The paper in question was Neil Ashby and David W. Allan, "Coordinate Time on and near the Earth," *Physical Review Letters* 53, no. 19 (1984): 1858. The article was received at the journal on 14 Nov 1983 but not published until Nov 1984.

Allan—albeit "an improvement in thought," which now "approaches the concept as CMR [Cohen, Moses, and Rosenblum] have laid it down"—nonetheless still missed their main point. The timing discrepancy that the outsider physicists had identified was a *global* quantity: "the magnitude is zero at every point except for a jump discontinuity upon completing any closed path," since it arose as the *integral* of a particular quantity. In their follow up work, on the other hand, Ashby and Allan had discussed the Sagnac effect, but did not distinguish between local discrepancies (which would arise moment by moment) and global ones associated with closed paths. Beyond these subtleties, Skalafuris shared more frustrations: "Over the past 8 years that I have followed this controversy, I have seen at each stage official reports revised to come into coincidence with the Cohen-Moses declaration. . . . I get the same impression from this new paper by Ashby. It is not clear that this method of continual revision based on external prompting will lead to a solution of the problem in a finite amount of time."[83] Skalafuris expanded upon these concerns—citing unpublished communications from Eardley at the JASON summer meeting—in a long article in *Radio Science*, the same engineering journal in which Ashby and Allan's 1979 paper had appeared.[84]

The JASON group focused intensively on the GPS question that summer, when members gathered in La Jolla, and completed their report in May 1985. The Air Force CATTISS group had a broader remit—not only to review the specific critiques raised by Cohen, Skalafuris, and their colleagues and recommend changes to existing GPS protocols as needed, but also to help the Air Force anticipate how to implement relativistic corrections for future missions, which might require even greater accuracy. CATTISS began meeting in May 1984 and held six two-day meetings over the next year and a half, before filing their detailed report in August 1986.[85]

The CATTISS committee's efforts culminated in a briefing that committee chair Clifford Will delivered to US Air Force General Lawrence Skantze, Commander of Air Force Systems Command. Will faced a daunting task: Boil down arcane features of relativity for high-ranking officers regarding a high-

83. Angelo J. Skalafuris to Douglas E[a]rdl[e]y, 13 Aug 1984, CMW, folder "AJS Materials."

84. Angelo J. Skalafuris, "Current Theoretical Attempts toward Synchronization of a Global Satellite network," *Radio Science* 20, no. 6 (1985): 1529–36.

85. Julian Davidson (chair, Air Force Studies Board) to Clifford Will, 9 May 1984, CMW, folder "CATTISS–Organization" (on the committee charge); on the group's meeting schedule, see Appendix B, "Committee Activities," in Air Force Studies Board, Committee on Accuracy of Time Transfer in Satellite Systems, *Accuracy of Time Transfer in Satellite Systems* (National Academy Press, 1986), 49.

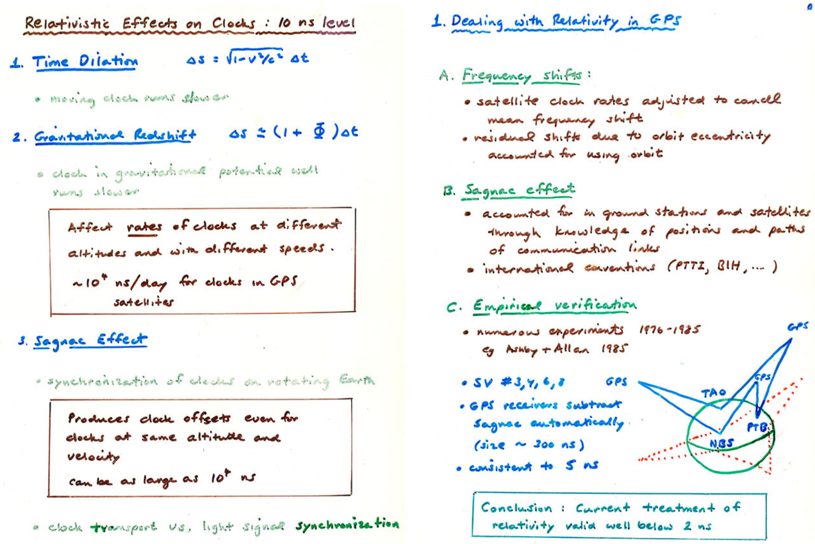

FIGURE 4. Clifford Will's handwritten overhead transparencies for his briefing to US Air Force General Lawrence Skantze in 1986, summarizing the findings of the Air Force Studies Board review of relativistic effects in GPS. (Source: C. M. Will.)

stakes program. He began with hand-drawn overhead transparencies, sketching "relativistic effects on clocks: 10 ns [nanosecond] level."[86] (figure 4.) (As Will later recalled, General Skantze fell asleep during Will's presentation, but his aide took careful notes.[87])

Both the JASON group and the CATTISS committee arrived at the same conclusions: The Ashby-Allan framework had been adequate all along. "It is true that the [Ashby-Allan] paper is not written in language similar to that of most textbooks in relativity theory," the CATTISS report noted, and indeed, "some of the underlying assumptions and connections to fundamental theory are not spelled out as clearly as some theoretical physicists might hope. This is not surprising because most relativity textbooks are at most tangentially concerned with real world measurements and systems."[88]

Meanwhile, the CATTISS committee continued, timing discrepancies from rotations were real, but not a threat to the system. "The effects treated by

86. Will's handwritten overhead transparencies are available CMW, folder "AFSB Briefing, November 1986."

87. Will and Yunes, *Is Einstein Still Right?* (ref. 3), 39–40.

88. Air Force Studies Board, *Accuracy of Time Transfer* (ref. 85), 17.

Cohen and Moses (1977) and those by Cohen, Moses, and Rosenblum (1983) are not new. . . . [Those papers] appear correct, but they contain nothing new for the purpose of time synchronization of satellite systems such as GPS." In identical wording that appeared in the JASON and CATTISS reports, both groups emphasized that such effects from rotation were "*not* uncontrollable errors." Rather they were "completely computable corrections," since the orbits of the GPS satellites were consistently monitored to high precision, and updates were regularly transmitted to each satellite. Will emphasized the distinction in his presentation: Whereas both time dilation and gravitational redshift "affect [the] *rates* of clocks at different altitudes and with different speeds," effects from rotation produce "*offsets* even for clocks at [the] same altitude and velocity." In essence, the effects of rotation identified by Cohen, Moses, and their colleagues would mean that observers on the ground and on the satellites would disagree on when "12 noon" struck, but—unlike the effects of time dilation and gravitational redshift—the effects of rotation would not affect the *rate* at which each observer measured the second hand of a clock move from 12:00:00 to 12:00:01.[89]

Operational procedures for addressing such offsets among rotating clocks had been hammered out, scrutinized, and standardized by researchers in a *different* expert community—far from the study of relativity—and codified by groups like the Bureau International des Poids et Mesures. For physicists who worked directly on GPS, based at institutions like the US Bureau of Standards, it was part of their day job to stay cognizant of such esoteric developments in the field of "time transfer." Indeed, Neil Ashby and David Allan had recently led teams that demonstrated that the international conventions for addressing timing offsets among rotating clocks were sufficiently accurate even for the GPS system. Their results were shared in venues such as the International Union of Radio Science Symposium on Time and Frequency and published in the *IEEE Transactions on Instrumentation and Measurement*, rather than in journals such as

89. Air Force Studies Board, *Accuracy of Time Transfer* (ref. 85), 16 and Eardley et al., "Relativistic effects" (ref. 80), 8 ("The effects," "not uncontrollable errors"); Will's transparencies CMW, folder "AFSB Briefing, November 1986" ("affect [the] *rates*"). Several other physicists also argued that the Cohen-Moses effect was identical to the familiar Sagnac effect: D. B. Lichtenberg and R. G. Newton, "Comment on 'New Test of the Synchronization Procedure in Noninertial Systems," *Physical Review* D 19, no. 4 (1979): 1268–70; F. Curtis Michel, "'New' Synchronization Procedure in Nonertial Systems," *Physical Review D* 19, no. 4 (1979): 1271–2. See also the reply in Jeffrey M. Cohen, Christ Ftaclas, and Harry E. Moses, "Clock Synchronization in a Rotating Frame," *Physical Review D* 19, no. 4 (1979): 1273–4.

Physical Review Letters or *Classical and Quantum Gravity*.[90] Academic physicists on the Air Force Study Board review committee, such as Clifford Will, had help getting up to speed on such material from fellow panelists who hailed from this distinct expert community. Will's files from his time chairing the CATTISS committee include more than three hundred pages of clippings and reprints on "time transfer," nearly all of them by researchers based at the US Naval Observatory, the US Bureau of Standards, the Jet Propulsion Laboratory, the Aerospace Corporation, and comparable facilities in other countries.[91]

What about the other critiques that Cohen and Skalafuris had raised in their December 1983 proposal? Regarding the Japanese test that had reported a 9.4 microsecond discrepancy between atomic clocks on a moving satellite and on a ship at sea, the outsider physicists (according to the Air Force reviewers) had misinterpreted the experimental report. The Japanese group had reported an offset between the two clocks, not a difference in measured clock rates, and "offsets are accidents of history for clocks."[92] (Essentially, the clocks had been set to the equivalent of "12 noon" slightly differently.) The numerical coincidence with the relativistic effect that Cohen and Moses had calculated in 1977 was just that—a meaningless coincidence. The JASON report was more blunt on this point: Cohen and Skalafuris had been "completely wrong" about the Japanese experiment and had committed "an elementary misunderstanding of procedures for precise time transfer."[93]

The critiques raised by relativity experts Seifert (in West Germany) and Clarke (in Britain), which had helped to convince USAF General Bouchard to convene the Air Force Studies Board review, warranted more careful assessment. Both CATTISS and the JASON group agreed that Seifert and Clarke were "two respected relativity theorists who have done distinguished work in mathematical relativity." Yet Seifert and Clarke (according to both reports) "have little or no research experience with experimental tests of relativity theory, actual measurements in relativity, or in particular with time transfer." That difference in training and experience, both review panels concluded,

90. See, e.g., David W. Allan et al., "Accuracy of International Time and Frequency Comparisons via Global Positioning System Satellites in Common-View," *IEEE Transactions on Instrumentation and Measurement*, IM-34, no. 2 (1985): 118–25. Compare with earlier international efforts on time standardization, as described in Galison, *Einstein's Clocks* (ref. 47).

91. See CMW, folders "Time Transfer–General" and "Relativistic Effects in Time Transfer."

92. Air Force Studies Board, *Accuracy of Time Transfer* (ref. 85), 17.

93. Eardley *et al.*, "Relativistic effects" (ref. 80), 8.

yielded understandable but—in the end—harmless misunderstandings when it came to the operation of an applied project like GPS.[94]

In the 1979 paper by Ashby and Allan—which the outsider critics had sent to Seifert and Clarke—Ashby and Allan had acknowledged that they were constructing an *approximate* description of the spacetime appropriate for rotating observers near the Earth, ignoring relativistic effects that would enter at higher orders in perturbation theory.[95] Hence the opening equation of their paper—which Seifert and Clarke had dismissed as erroneous—was consistent with the framework laid out in Clifford Will's own monograph, *Theory and Experiment in Gravitational Physics*, when considering realistic scenarios near the Earth. (Both reports cited Will's monograph on this point.) Relativistic effects such as frame dragging, which Clarke had highlighted as missing in the Ashby-Allan treatment, *would* affect the rates at which clocks ticked and not only yield an offset due to rotations. But such effects were about one hundred times smaller than those of time dilation and gravitational redshift for specific systems like GPS, and hence could safely be ignored. Whereas the CATTISS group confirmed this point with an explicit calculation in an appendix, the JASON group simply noted, with evident sarcasm, that "we do not live on a neutron star or a black hole," so naturally such tiny effects could be neglected.[96]

In the end, the expert reviews hinged on subtleties over how to handle different coordinate systems. One of the deep lessons of relativity was that researchers could use *any* coordinate system and rely upon Einstein's equations to relate quantities as observers would measure them in any other coordinate system. The Ashby-Allan framework took advantage of this freedom to construct an Earth-centered inertial reference frame whose origin coincided with the Earth's center of mass, but which did not rotate. Coordinate time t in this reference frame represented what an atomic clock *would* measure if it were at rest with respect to the origin and positioned arbitrarily far above the Earth's north pole, so that gravitational redshift would remain negligible. By design, this coordinate time was different from the proper time τ measured by any particular moving clock on or near the Earth.[97]

94. Identical wording appears in Air Force Studies Board, *Accuracy of Time Transfer* (ref. 85), 18, and in Eardley *et al.*, "Relativistic effects" (ref. 80), 9.

95. Ashby and Allan, "Practical implications of relativity," Appendix A.

96. Air Force Studies Board, *Accuracy of Time Transfer* (ref. 85), 18 and Appendix E; Eardley et al., "Relativistic effects" (ref. 80), 4 ("we do not live on a neutron star"). See also Will, *Theory and Experiment in Gravitational Physics*, ch. 4.

97. Air Force Studies Board, *Accuracy of Time Transfer* (ref. 85), 9–11.

The GPS software performed all "primary calculations" involving the locations and movements of clocks, and of the light signals traded between them, within this non-rotating, inertial reference frame—even though this convenient frame did not coincide with those of any of the GPS satellites or of the observers on the ground. Hence there was never a need for the ground observers to achieve perfect synchronization with the overhead satellites—rather, *all* of those clocks would be treated within the imagined Earth-centered non-rotating frame. Relativistic effects like time dilation, gravitational redshift, and the Sagnac effect were computed for each clock (on the ground and in the sky) within this single reference frame.

As a last step, the system software then transformed the final answers for any given receiver's location to an Earth-fixed rotating reference frame. At no point did anyone need to synchronize the clocks among the orbiting satellites with observers on the ground—and hence no discontinuous jumps arose, of the sort that Cohen, Moses, and Rosenblum had calculated, whenever a given satellite completed a closed loop around some particular spot on the ground. In real-world systems like GPS, each of these coordinate transformations induced some errors, but all remained within the few-nanoseconds error budget for GPS. As Will concluded for the Air Force leadership—putting his takeaway message in a box for added emphasis—"Current treatment of relativity [is] valid well below 2 ns" (Figure 4).[98]

CONCLUSION

By the time Clifford Will briefed Air Force leadership on his committee's findings in 1986, the GPS Joint Program Office had successfully launched ten satellites. Just two years later—despite delays caused by the Space Shuttle *Challenger* explosion in January 1986, which halted delivery of additional GPS satellites via shuttle—US Strategic Air Command added GPS-enabled cruise missiles to its nuclear arsenal.[99] That milestone, together with the dramatic deployment of GPS-enabled craft and munitions during the Gulf War in 1991, capped a four-decade effort within the United States to develop a system of satellite-borne clocks for military navigation and targeting.

98. Will's transparencies CMW, folder "AFSB Briefing, November 1986" ("current treatment").

99. Milner, *Pinpoint* (ref. 1), 61–2.

Midway through that development, a handful of academic researchers and defense consultants began to assert that systems like GPS could only operate successfully if designers took Einstein's relativity seriously. Several distinct effects seemed relevant: time dilation from rapid relative speeds, gravitational redshift from stark differences in elevation, and the Sagnac effect from rotations. By the late 1970s, the question had shifted from whether one needed to incorporate relativity to a thornier one: Were the relativistic effects being implemented correctly? That conceptual question became entangled with social and institutional ones: Who among the jumble of defense contractors, military overseers, and civilian scientists could be trusted to sort it all out?

Throughout this episode, the boundaries between "pure" and "applied" research in the physical sciences—so often blurred during the Cold War—became nearly unrecognizable.[100] Critics with PhDs in theoretical physics and extensive experience with engineering projects at government facilities sparred with university faculty from elite institutions, who worked alongside researchers from industrial firms, all on behalf of the US Air Force. The experts charged with reaching consensus on the question of relativistic effects in GPS were hampered by different notation, terminology, and communication patterns among mathematical physicists and time-transfer engineers, all exacerbated by military and contractor secrecy. At the end of their report, the JASON study group recommended that "as a result of these apparent confusions by highly respected researchers," there was a clear need for "a pedagogical article that will explain time transfer and GPS, not in the practical terms in which they have been expounded up to now, but in the careful language of theoretical relativity."[101] Such articles exist today, but dueling experts had no such documents to pore over while the high-stakes debate played out.[102]

100. Compare with the classic discussions in Paul Forman, "Behind Quantum Electronics: National Security as Basis for Physical Research in the United States, 1940–1960," *Historical Studies in the Physical and Biological Sciences* 18, no. 1 (1987): 149–229; and Daniel J. Kevles, "Cold War and Hot Physics: Science, Security, and the American State, 1945–56," *Historical Studies in the Physical and Biological Sciences* 20, no. 2 (1990): 239–64.

101. Eardley et al., "Relativistic effects" (ref. 80), 9.

102. See, e.g., Neil Ashby, "Relativity and the Global Positioning System," *Physics Today* 55, no. 5 (2002): 41–7; "Relativity in the Global Positioning System," *Living Reviews in Relativity* 6 (2003), 1, https://doi.org/10.12942/lrr-2003-1. The Soviet (now Russian) GLONASS system shares many design similarities with GPS, and also relies upon incorporation of the same relativistic effects to maintain accurate operation. A Russian-language review article from 2010 identifies time dilation, gravitational redshift, and the Sagnac effect in formalism that is easily relatable to present-day US descriptions for GPS, though I have not been able to discern how and when such corrections were

None of the members of the outsider quartet—Jeffrey Cohen, Harry Moses, Arnold Rosenblum, and Angelo Skalafuris—were present for the closed-door briefing when Clifford Will updated Air Force leadership about his committee's findings. Nor is it clear if or when the critics received word of the expert panel's conclusions. The outsider group did not publish any responses to either the JASON report or to the CATTISS study, the latter of which was published as a standalone booklet in conjunction with the US National Academy of Sciences. Like the 1975 report by GPS advisor Neil Ashby, which circulated as a "gray literature" report under the auspices of the Commerce Department, the CATTISS report was unclassified but also unlikely to be available in most university libraries.[103]

Jeffrey Cohen and Arnold Rosenblum returned only once more to the question of clocks on orbiting satellites, in a brief article published in *Physics Letters A* in 1988. Setting up their calculation in much the same way as the group's first articles from 1977, Cohen and Rosenblum suggested that a distinct relativistic effect due to rotation, known as "frame dragging," *could* be measurable with a network of orbiting satellites, *if* the accuracy of the onboard clocks could be improved by about a factor of one million compared to the routine parts-per-trillion accuracy of the atomic clocks that were (by the late 1980s) routinely available. On this point, Cohen, Rosenblum, and the authors of the JASON and CATTISS reports likely would have agreed—each review panel had also acknowledged that the Ashby-Allan approximation had neglected frame dragging, since (the reviewers concluded) such effects were so minuscule that they could be ignored for practical GPS functioning. To conduct such a test, Cohen and Rosenblum proposed, one would "send up clocks in satellites both in geosynchronous and anti-geosynchronous orbits. Because of the proposed G.P.S. system, this is certainly not out of the question"—so long as clock technology could make a fantastic leap in the interim.[104] In effect, Cohen and Rosenblum had tacitly turned from using

first identified and implemented within the Soviet system. I am grateful to Asif Siddiqi for finding and translating appropriate sections of A. I. Perov, V. N. Kharisov, eds., *GLONASS: Printsipy postroeniia i funktsionirovaniia*, 4th ed. (Radiotekhnika, 2010), 284–7.

103. For example, a record of the 1986 CATTISS report does appear in the extensive database known as the Astrophysics Data Sytem (ADS), maintained by NASA and the Smithsonian Astrophysical Observatory, available at https://ui.adsabs.harvard.edu. Yet as of Feb 2026, this database records *zero* citations to the report among its collection of 28 million records.

104. Jeffrey M. Cohen, Arnold Rosenblum, and Yeaton Clifton, "On the Use of Clocks in Satellites for the Testing of Dragging of Inertial Frames in Einstein's General Relativity," *Physics Letters A* 131, no. 3 (1988): 163–4. The first successful measurement of relativistic frame-dragging

relativity to critique satellite networks like GPS to using such networks as tools to test *other* features of relativity. Neither Moses nor Skalafuris, meanwhile, ever published on the question of clock coordination after their group's articles that had helped to trigger the Air Force review.

Tragically, the 1988 article by Cohen and Rosenblum was among the last that either researcher published on relativity altogether, let alone on effects of rotation or subtleties of timekeeping metrology. Jeffrey Cohen had been diagnosed with amyotrophic lateral sclerosis (ALS) in 1977, around the time of his first publications on relativistic effects on rotating clocks. Ten years later, his condition had worsened so badly that he required full-time care. Arnold Rosenblum, meanwhile, suffered a grand mal seizure on New Year's day in 1991 and died at age 47.[105] After Harry Moses's papers with Cohen and Rosenblum on relativistic effects of rotation between 1977 and 1984, he appears to have devoted more attention to other topics in mathematical physics and teaching, and less on applied projects; Angelo Skalafuris published one additional peer-reviewed research article in 1987 (on using satellite imagery for improved geodesy), and then turned his efforts to private engineering contracting.[106]

In the meantime, the GPS system underwent a halting transition from military tool to civilian resource. On September 1, 1983, Korean Air Lines flight 007 was shot down over Soviet airspace; it had drifted off its intended course from Alaska to Seoul. About two weeks later, the Reagan administration announced that GPS would be made available for civilian use once the system became operational, several years down the road. But there was a catch. To protect US military advantage, the GPS system would operate under a regime dubbed "selective availability": the satellites would broadcast two separate signals. An encrypted signal, strictly accessible by military devices, would enable receivers to achieve meter-scale accuracy, while a second signal, purposely degraded, would restrict civilian devices to accuracies about one hundred times worse.[107]

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near Earth—using a different technique than that proposed by Cohen, Rosenblum, and Clifton—was reported in Francis Everitt et al., "Gravity Probe B: Final Results of a Space Experiment to Test General Relativity," *Physical Review Letters* 106, no. 22 (2011): 221101.

105. Jaclyn LaPlaca, "Former Professor Deals with Handicap," *The Daily Pennsylvanian*, 3 July 1996; Marion Cohen, *Dirty Details: The Days and Nights of a Well Spouse* (Temple University Press, 1996); Cohen, Havas, and Lind, "Arnold Rosenblum" (obituary) (ref. 57).

106. Based on searches for publications by Harry E. Moses and by Angelo Skalafuris in such databases as Web of Science and the NASA ADS system.

107. Milner, *Pinpoint* (ref. 1), 81–3; Ceruzzi, *GPS* (ref. 2), 85–7, 95–103.

In spring 2000, after reassessing the comparative military risk and civilian-market opportunity, the Clinton administration ended selective availability. Much like the "relativity switch" that had been built into the NTS-2 satellite's system software, the Clinton administration's policy change required a simple software update. Early in the morning of May 2, 2000, ground controllers uploaded new instructions to the computers onboard each GPS satellite, overwriting the software patch that had directed the satellites to transmit coarse-grained position information over the unencrypted channels. With that software update, average errors in location accuracy for civilian devices instantly fell by a factor of one hundred.[108]

Less than a decade later, so-called "smartphones" began to saturate the civilian market, equipped with GPS receivers. Since then, Einstein's relativity has helped billions of people find their place in the world, every single day.

ACKNOWLEDGEMENTS

I am grateful to Marc Aidinoff, Edmund Bertschinger, Alexander Blum, Jaco de Swart, Connemara Doran, Michael Gordin, Cyrus Mody, Matthew Stanley, Luca Thanei, Benjamin Wilson, and Nicolàs Yunes for detailed and constructive comments on an earlier draft of this paper, and to Clifford Will for sharing materials from his personal files.

108. Memorandum from Samuel Berger [National Security Advisor] and Neal Lane [Director, White House Office of Science and Technology Policy] to President William J. Clinton, 28 April 2000 (declassified on 11 May 2018), Clinton Presidential Records, NSC Records Management (GPS), OA/box 4088, William J. Clinton Presidential Library (my thanks to Marc Aidinoff for providing this document); Office of the Press Secretary, "Statement by the President regarding the United States' decision to stop degrading Global Positioning System accuracy," 1 May 2000, available at https://clintonwhitehouse3.archives.gov/WH/EOP/OSTP/html/0053_2.html (accessed July 25, 2025); Christophe Adrados, Irène Girard, Jean-Paul Gendner, and Georges Janeau, "Global Positioning System (GPS) Location Accuracy Improvement Due to Selective Availability Removal," *Comptes Rendues Biologies* 325 (2002): 165–70.