Calculating Times: Tracking Missiles, Testing Relativity[*]

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Introduction

A popular image persists of Albert Einstein as a loner, someone who avoided the hustle and bustle of everyday life in favor of quiet contemplation. Einstein did much to contribute to that image, famously telling a journalist, for example, that his ideal occupation would have been a lighthouse keeper—only then could he have achieved his sought-for isolation from society. Yet Einstein was deeply engaged with politics throughout his life. An outspoken socialist and pacifist, he bravely spoke out against the First World War and worked tirelessly for civil rights, civilian control of atomic energy, and to correct the abuses of domestic anti-communism after the Second. Indeed, he was so active politically that the U.S. Federal Bureau of Investigation kept him under surveillance for decades, compiling a 2000-page secret file on his political activities.[1]

Einstein's most enduring scientific legacy, the general theory of relativity—physicists' reigning explanation for gravity and the basis for nearly all current research about black holes, the big bang, and the shape and fate of the cosmos—has likewise been cast as an austere temple standing aloof from the all-too-human dramas of political history. In the late 1940s, physicist George Gamow captured this notion in one of his many cartoons. He sketched a "temple of relativity"—it bore more than passing resemblance to the Taj Mahal—gilded with Einstein's field equations. General relativity, Gamow tried to suggest, was the purest of the pure, separate even from the messiness of the rest of physics, let alone the grubby worlds of lucre and power. Relativity expert John

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Synge echoed the point in his 1960 textbook, writing that "of all physicists, the general relativist has the least social commitment. […] Let the relativist rejoice in the ivory tower where he has peace to seek understanding of Einstein's theory as long as the busy world is satisfied to do its jobs without him." Gravity might have exerted a pull on Newton's apple, these physicists asserted, but it avoided the lure of Eve's.[2]

The "ivory tower" construction fares no better when held up to historical scrutiny than does Einstein's self-depiction. General relativity had never been above, beyond, or outside of politics. Born in a time of war—Einstein completed his general theory late in 1915—the theory's earliest converts included a Russian mathematician interred in a German prisoner-of-war camp, a German astronomer interred in a Russian prisoner-of-war camp, and another German astronomer who passed his time while serving on the Russian front by finding the first exact solutions to Einstein's equations, only to succumb to a deadly disease a few weeks later.[3] The British astrophysicist-Quaker-pacifist-internationalist, Arthur Eddington, leaped on Einstein's relativity as a means of salvaging an international "brotherhood" of science, riven so starkly by the bitter wartime nationalisms. Eddington's ambitious eclipse expedition in 1919 sought to test a key prediction of Einstein's relativity, that a massive object like the sun could bend the path of starlight. His results, announced almost exactly one year after the Armistice, propelled Einstein and his general theory to instant fame.[4] Just one year later, some of the earliest converts to the Nazi cause targeted Einstein's now-famous theory to launch their *deutsche Physik* campaign against "Jewish physics."[5]

Despite the hoopla generated by Eddington's eclipse results—Einstein was greeted with a ticker-tape parade when he arrived in New York City not long after the eclipse results had been announced—general relativity suffered a curious fate during the middle decades of the twentieth century. In short, the topic all but vanished from the research agendas and teaching plans of most physicists. Einstein's achievement was a mathematical masterpiece, to be sure, but by the early 1930s the vast majority of physicists all over the world had turned away from the topic. Soon after consolidating their power, the Nazis formally banned the teaching of relativity throughout the Third Reich, squelching what had been the world's most active research communities on the topic and scattering many of its leading exponents around the globe.[6] Even beyond the Nazis' grip, physicists all over the world shifted their focus away from general relativity. Some complained that the theory lacked adequate experimental support; others chafed at the recondite mathematics; most felt the tug of quantum theory and soon nuclear physics. Through the 1950s and into the 1960s, graduate-level courses on general relativity could not be found in any of the major physics departments in the United States (and only rarely in Europe); problems on general relativity were absent from the nation's physics Ph.D. general examinations.[7]

During the 1960s, small pockets of interest in general relativity began to coalesce. On many physicists' telling, this "renaissance of relativity" sprang from a series of astronomical discoveries. Quasars, pulsars, and the cosmic microwave background radiation each seemed to require that physicists devote serious attention to subtle features of general relativity. The story has thus been cast in a familiar idiom of stubborn or surprising data forcing a new kind of theoretical engagement.[8] But where did those potent datapoints come from?

One of the most sensitive (and most heralded) tests of Einstein's general relativity to date was hatched at MIT in the 1960s—not on the Institute's Cambridge campus, but at Lincoln Laboratory, the Air Force-funded defense laboratory operated under MIT's auspices in the nearby suburbs. At Lincoln Laboratory a young researcher named Irwin I. Shapiro led a team of fellow physicists, astronomers, computer programmers, and radar gadgeteers in executing the test. Shapiro and coworkers used Lincoln Lab's powerful radar apparatus—designed, built, and paid for to enable the Air Force to track Soviet ballistic missiles, as well as to aid other military research in communications and surveillance—to bounce radar signals off of the planets Venus and Mercury, measuring the time required for the echoes to return to earth. In doing so, the defense lab scientists were able to test a relativistic prediction that such signals would be slowed down by the curvature of spacetime near the sun.

In the thick of the Cold War, using some of the country's most vital defense technologies, Shapiro and his collaborators verified Einstein's seemingly otherworldly theory to an impressive degree of accuracy. By exploring the origins and location of the so-called "time-delay test" within a key defense laboratory, we aim to unpack the roles played by Cold War priorities in the development of a seemingly pure and esoteric science. At the very least, the support of Air Force funding and the use of its hardware were indispensable to the success of Shapiro's time-delay test. But more than that, the methods that Lincoln Laboratory researchers pursued, the kinds of questions they asked, and the peculiar skills and attitudes they brought to the time-delay test were all deeply influenced by the technical and intellectual setting of their Air Force laboratory. In short, the time-delay test cannot be extracted cleanly from its overlapping contexts; its very shape, on virtually every level, was carved out by the exigencies of the postwar world. General relativity—ethereal and austere as it may often appear to be—was enmeshed in the political and technological environments of the Cold War.

Lincoln Laboratory and Ballistic Missile Defense

Radar and the Massachusetts Institute of Technology have had a long and close relationship, beginning with the decision by the National Defense Research Committee in October 1940 to create a laboratory at the Institute for the development of microwave radar technology. From its humble beginnings that autumn—when its entire staff consisted of twenty physicists, three security guards, two stockroom clerks, and a secretary—the Radiation Laboratory (or "Rad Lab") swelled by war's end to a sprawling complex with a staff of four thousand, managing industrial contracts totaling $1.5 billion (nearly $20 billion in 2014 dollars). In terms of overall spending and staff size, it grew even larger than the wartime Los Alamos laboratory, central node of the Manhattan Project.[9]

The impact of the Radiation Laboratory on MIT's postwar relationship with the U.S. military was profound. Near war's end, several MIT officials made plans to channel some of the Rad Lab's best personnel and equipment into a peacetime laboratory for advanced electronics research. With the Rad Lab's official demobilization at the end of 1945, the armed forces, too, jumped at the chance to extend their relationship with MIT, sponsoring its work on advanced electronics. The new Research Laboratory of Electronics (RLE), buoyed by $600,000 from the military's Joint Services Electronics Program (more than $7 million in 2014 dollars), initially employed seventeen MIT physics and electrical engineering faculty, along with several graduate students.[10] One of the earliest proposals involved consulting on a classified Navy air-to-air missile program called Project Meteor.[11] By 1950, as the Korean War re-intensified American efforts to mobilize its scientific and technological resources, RLE had assumed three major projects (including work on radar and communications systems) funded by each branch of the military.[12]

During the winter months of 1950-51, officials at MIT and the Air Force hammered out a contract to set up a new laboratory devoted to air defense research, known as Project Lincoln.[13] Its classified work—initially separated among five technical divisions, each working on a separate air defense system, such as "Communications and Components" and "Weapons"—grew out of and greatly exceeded that of RLE. By 1952, Project Lincoln had transformed almost seamlessly into Lincoln Laboratory, employing close to two thousand staff with a budget of nearly $12 million (more than $100 million in 2014 dollars); a year later, it was receiving more than $18 million from military coffers. In 1954, having outgrown its MIT campus home in Cambridge, Lincoln Lab departed for newly-constructed facilities at Hanscom Air Force Base in Boston's western suburbs, near the town of Lexington. Though Lincoln Laboratory's physical separation from MIT was complete, its intellectual and social ties remained strong, and it kept the Institute bound to the interests of the military as tightly as ever.[14]

In the early 1950s, air defense research at MIT concentrated on systems designed to counter nuclear attack delivered by aircraft. In the most plausible scenario, a Soviet bomber would approach the continental United States over its northern boundaries, flying low and fast, unnoticed by the United States's sparse array of World War II-era "Ground Control Intercept" radars (originally developed to detect large fleets of bombers in conventional formation).[15] Project Lincoln's earliest work was dedicated to developing a system to track and disable a Soviet nuclear bomber at any height in U.S. airspace. A second task soon emerged: to develop a system to provide early detection and warning of such an attack. These twin tasks led, respectively, to the Semi-Automatic Ground Environment (SAGE) and to the Distant Early Warning line (DEW). SAGE involved a nationwide network of radars and anti-aircraft weapons, coordinated by a high-speed digital computer, whose design was based on the "Whirlwind" machine under development at MIT.[16] The DEW line consisted of a series of radar installations dotted across the desolate Arctic expanse from Alaska to Greenland. The DEW line would give at least three hours' warning of a bomber attack from over the Pole; SAGE would take care of the rest.[17]

But as the technological characteristics and potency of the Soviet arsenal evolved, so too did American efforts to confront them. Despite the sophistication and the stream of human, material, and financial resources poured into both SAGE and DEW—SAGE alone cost some $8 billion, more than $70 billion in 2014 dollars—they were practically obsolete by the mid-1950s.[18] With the advent of the Intercontinental Ballistic Missile (ICBM), a nuclear warhead could be launched from well inside the Soviet Union and sent hurtling toward an American city, reaching its target in mere minutes rather than hours. Any hope of actually intercepting an ICBM (much less with a system like SAGE, designed to track and destroy targets that crept along at a snail's pace by comparison) was dashed. The severe calculus of Mutually Assured Destruction and the "launch on warning" policy required precision tracking of approaching enemy missiles—not only to provide a desperate last-minute warning to a doomed metropolitan area, but to arm and deploy the massive retaliatory nuclear assault that the United States would quickly unleash.[19]

The development of the so-called Ballistic Missile Early Warning System (BMEWS) began at Lincoln Laboratory in 1955. Each BMEWS station's "pencil-beam" missile-tracking radar was based on Lincoln Laboratory's prototype, built on Millstone Hill near Westford, Massachusetts (Figure 1). The Millstone radar—the first ever to use real-time digital data processing, firing its radar pulses with a single klystron transmitter operating with 60 kilowatts of average power—was complete in 1957, just in time to track Sputnik I.[20] In May 1960, the first BMEWS station (in scenic Thule, Greenland) welcomed reporters to watch as it "sent two radar beams, one atop the other, over the North Pole, 931 miles away, and across most of the Soviet Union." All quiet on the Eastern front, assured *The Washington Post*: "No rocket launchings were detected in the sweep," but should they ever be, "the electronic gear which is the brains of BMEWS instantaneously pinpoints both the launching site and the impact area, with eyelash accuracy."[21] By 1964, when the billion-dollar project was complete, three networked stations (in Greenland, Alaska, and Yorkshire, England) scanned the heavens round the clock.[22]

Figure 1: Lincoln Laboratory's Millstone Hill radar facility, a prototype missile-tracking radar for the Ballistic Missile Early Warning System (BMEWS). (Source: MIT Lincoln Laboratory.)

Within Lincoln Lab's Radars and Weapons Division, Group 312 (Systems Research) was tasked with creating the design concept for the BMEWS radar configuration. The earliest classified report on the proposed system was written by Gordon Pettengill and Daniel Dustin.[23] Pettengill, an MIT graduate who wrote his Berkeley physics Ph.D. dissertation on the scattering of high-energy protons, was hired at Lincoln in 1954, excited by the chance to apply his lifelong interest in radio electronics to problems outside the overworked field of nuclear physics. Dustin, after graduating with a master's degree from MIT's Department of Business and Engineering Administration in 1949, worked at the Research and Development Board (the government's topmost advisory body for R&D spending) before being hired at Lincoln Lab in 1953.[24]

The two young researchers contemplated possible BMEWS radar configurations—the designs and spatial arrangements of radars that would maximize both the amount of warning time BMEWS could provide, and the accuracy of its missile trajectory predictions. Their recommendation was that the Air Force adopt a "pencil-beam scanning system" for BMEWS. "In the pencil-beam scanning type of system," they advised, "two or more observations separated in space and time provide data to allow prediction of the missile's path." Multiple narrow-beam radars separated by thousands of miles, each sweeping the horizon back and forth at fixed angles of elevation over the location of a possible launch site, would provide data about the range, velocity, and direction of a ballistic missile early in its flight. Depending on how steep or shallow the missile's orbital trajectory was, the configuration Pettengill and Dustin designed could provide anywhere from seven to more than thirty minutes of warning time, with accuracies ranging from "good" for steep trajectories to "fair" or "poor" for shallow ones.[25]

For a more precise account of how to predict missile trajectories from radar tracking data, Pettengill and Dustin turned to one of their colleagues, a recent physics Ph.D. named Irwin I. Shapiro. Shapiro had completed his undergraduate studies at Cornell in 1950 with a degree in mathematics and immediately entered graduate school in physics at Harvard. Hoping to avoid the draft, he took up a position at Lincoln Laboratory in June 1954, still a year away from finishing his doctoral thesis in theoretical nuclear physics. Shapiro was hired into Group 23, a radar development team in Division 2 (Aircraft Control and Warning), knowing "nothing whatever about radar at that time," as he later recalled. (See Figure 2.) Initially, Shapiro tackled theoretical problems related to the radar detection of objects in messy "clutter environments"—situations where the radar echoes from an object of interest (such as a satellite or a ballistic missile) were mixed in randomly with echoes from upper atmospheric phenomena, the surface of the earth itself, or nearby objects (such as the debris shed by a nuclear warhead's re-entry vehicle as it plummeted toward its target). Boiling the complex problem down analytically, Shapiro discovered that disentangling the interesting radar reflection signal from a jumble of uninteresting signals—by finely discriminating the frequency shifts or "Doppler signatures" of each individual reflection—could be accomplished with a simple mathematical scheme.[26]

Figure 2. Irwin I. Shapiro, 1950s. (Source: MIT Lincoln Laboratory.)

In the summer of 1955, just as work on BMEWS was gearing up, Shapiro narrowed in on a problem of critical importance: the calculation of ballistic missile trajectories (especially the coordinates of a missile's final destination) from radar tracking data. By 1956 he had joined the Systems Research group developing BMEWS, and he began to answer two key questions: what sort of information would be sufficient to determine where a ballistic missile would end up (and when), and how could that information be acquired from radar tracking signals?[27] Shapiro's final report was published early in 1957, and in its opening section he laid out succinctly the difficult problem before him. "In general, the totality of different radar measurements provides redundant data, i.e., provides more data than…necessary to dynamically specify a trajectory. For measurements corrupted by noise," as all radar signals inevitably were, "these data will be inconsistent," leading to "different dynamical trajectory predictions."[28] In other words, *many* possible missile trajectories could be gleaned from a *single* set of data. But a missile doesn't follow many trajectories—it follows one. The only way to choose the *real* trajectory—and fast—was to rely on a sophisticated, statistically-weighted decision-making algorithm. Shapiro used the remainder of his hefty report—175 pages filled with intricate calculations and technical diagrams—to develop just such a procedure.

Soon Shapiro's calculations were inscribed in Lincoln's ballistic missile-tracking computer systems by programmers in the Systems Research group. Algorithms like "Preliminary Estimation of Radar Trajectory" took in radar tracking data (encoded in binary format on magnetic tape) and spat out IBM punched cards, converted by an automatic plotter to graphs of the elevation and range of the tracked missile. In the end, a few computer printouts neatly summarized a detailed itinerary for nuclear obliteration.[29]

Irwin Shapiro and the Time-Delay Test

In the midst of his work on BMEWS, Shapiro attended a classified briefing on Air Force-funded research at MIT.[30] One of the speakers was George W. Stroke, a young electrical engineer at MIT's Research Laboratory of Electronics. In the late 1950s, Stroke had assisted in RLE's work on the Polaris project, the Navy's effort to develop a submarine-launched ballistic missile. Stroke helped perfect Polaris's optical alignment, orienting the missile's inertial guidance system with reference to the North Star (or "Polaris"). By 1959, he was starting up a new set of experiments at RLE, making high-precision interferometric measurements of the velocity of light.[31]

In the course of his light-velocity work, Stroke had stumbled across a curious prediction of general relativity, one that had long been recognized by cognoscenti but was not well-known outside the small community of relativity specialists. Gravity doesn't just alter the trajectory of a light ray, he reported at the military briefing; it alters its *speed*, too. "The velocity of light, measured by the same magnitude c independently of the state of motion of the frame in which the measurement is being carried out, should depend on the gravitational potential…of the field in which it is being measured," he wrote in a technical report in 1959. Gravity slowed light down. And though the effect would be far too small to measure even in the most sensitive laboratory experiment, the speed of light would be "smaller by 2 parts in a million on the [surface of the] sun, as compared with measurements on earth."[32]

Stroke's comments immediately struck Shapiro as completely surprising. He had acquired only a fleeting familiarity with general relativity during his graduate school days—Harvard did not offer a single course on the subject at the time.[33] It is no surprise that Shapiro had never heard about gravity's effects on light. More surprising is that Shapiro *did*, apparently, know about Einstein's famous explanation of the anomalous precession of Mercury's perihelion—one of the predictions that had won general relativity wide acclaim when it was first published. In 1959, it had occurred to Shapiro that perhaps Lincoln's radar techniques could be used to check Mercury's precession rate with better accuracy than traditional optical astronomy could achieve.[34] Soon after hearing Stroke's talk, Shapiro began to wonder whether radar might be used to measure the slowing down of light by gravity as well. After all, detecting and extracting minute radar signals from complicated backgrounds was what BMEWS had been designed to do.[35]

By the time Shapiro heard Stroke's classified briefing at MIT, his colleagues at Lincoln Laboratory were already hard at work on what came to be known as "planetary radar astronomy," using the world-class defense system to bounce radar signals off of other planets in the solar system to measure their location, range, and motion. Several factors converged during the spring and summer of 1957 to launch Lincoln Lab's venture into the new field.[36] An electrical engineer at the Lab, who was working on secure, un-jammable long-distance radio communication technology, had recently returned from a Fulbright fellowship to the University of Sydney in Australia, where he had studied with one of the world's first radio astronomy groups. Scribbling on napkins in the Lincoln Lab cafeteria, he and several colleagues from the BMEWS project estimated that the new Millstone radar at Lincoln might be able to bounce radar signals off of the planets

Mercury and Venus and detect the return echoes, after certain upgrades to the equipment had been implemented. Over the next two years, the group pursued their goal of detecting a radar bounce off the planet Venus, eventually publishing their results in *Science* magazine, for which President Eisenhower telegrammed his congratulations. That result turned out to have been awry—the team later concurred with competitors at other laboratories that their claimed detection was likely due to instrumental noise.[37]

Even so, the effort had hardly been wasted. Soon after the article appeared in *Science*, Lincoln Laboratory Director Carl Overhage had written to Lieutenant General Roscoe C. Wilson of the Air Force expressing his pride in the Lab's "achievement in long-range, interplanetary communication." (Wilson was Chair of the Joint Services Advisory Committee, and Overhage's immediate military overseer.) More than just an exercise in planetary astronomy, the experiment had important consequences for the Lab's work on defense technology, Overhage assured. In fact, the Venus-ranging test had "conclusively demonstrated" that radar detection and tracking measurements should be recorded on magnetic tape, and that digital computers were indispensable for processing such data. "This recording technique appears to be especially promising for those experiments in which *a priori* knowledge is lacking in several respects and only a brief period is available for observation."[38] The implications of Overhage's comments would not have been lost on Lieutenant General Wilson: the tracking of ballistic missiles and satellites were quintessential scenarios in which "*a priori* knowledge" of the tracked object's range and location was slim, and only a brief window of time was available to radar operators. Tracking the planets, in other words, provided essential target practice for the Laboratory's missile-detection mission, enabling the team to fine-tune and calibrate several components of the complicated radar system. And so the Lincoln group kept at it, completing their first successful, unambiguous real-time radar detection of Venus in spring 1961.[39]

In 1963 Shapiro was transferred to Group 37 (Space Physics) in Division 3 (Radio Physics). Now in the primary division responsible for developing the new field of planetary radar astronomy at Lincoln Lab, he began to work closely with the radar specialists who were continually perfecting their Venus tracking and ranging experiments.[40]

The time-delay test of general relativity developed naturally in Shapiro's newfound intellectual and technological environment. Perhaps, Shapiro would soon realize, the relativity experiment—which he had first dreamed up after hearing George Stroke's intriguing classified briefing—would now be possible with Lincoln's advanced radars. He would pass powerful radar signals through the intense gravitational field of the sun, bounce them off of Venus as his colleagues had done, and detect their echoes back at Lincoln. If Einstein and his general theory were right, the signals would take just a little too long to return home, compared to radar echoes sent when the sun was nowhere near the path to Venus. The strong gravitational field near the sun would delay them.[41]

But delay them by how much? Shapiro knew, from Stroke's briefing and a quick calculation, that the extra time-delay produced by a Venus reflection would be on the order of a few tens of microseconds. But he had never calculated the relativistic time-delay effect with any precision. For one, general relativity was outside Shapiro's expertise; the full calculation required considerable familiarity with the theory. More important, he had remained convinced—despite Millstone's success in contacting Venus, and despite the relative ease with which the Arecibo dish (an enormous structure carved into the Puerto Rican jungle) could be converted to radar operation—that no functioning radar facility was capable of detecting and timing the echo with an uncertainty of only a few microseconds. At the Symposium of the International Astronomical Union in Paris in May 1963, Shapiro described the outlines of his time-delay test and his preliminary findings: the experiment (and a more detailed calculation) would have to wait for a better radar.[42]

According to Shapiro, everything changed abruptly in the fall of 1964, when the construction of the most sensitive radar facility in the United States—the "Haystack"—was completed at Lincoln Laboratory. As Shapiro later claimed, it was during a cocktail party conversation with Stanley Deser, a general relativity specialist at nearby Brandeis University, that he experienced something close to an epiphany. "Suddenly it occurred to me, while I was talking, that Haystack was coming on line, and that Haystack might have enough capability to do the experiment….I went home and quickly did some back-of-the-envelope calculations which showed that we could do the experiment….Now it became something real, instead of purely theoretical."[43] With Peter Bergmann's classic general relativity text in hand, working feverishly for two days at a card table set up in his bedroom at home (while, incidentally, his wife was in the hospital, having just given birth to their son), Shapiro churned out the first rigorous calculation of the time-delay effect.[44]

There is little doubt that the opening of the Haystack facility was a decisive influence on Shapiro's thinking. As Laboratory Director William H. Radford would later explain to General Bernard A. Schriever of the Air Force, the design of the time-delay test was not only made *possible* by the development of hardware sophisticated enough to carry it out, but was actively *motivated* by it. "Prior to the existence of our new Haystack facility, this test was so far beyond the performance capability of any existing radar that it had not even seemed worthwhile to carry through the calculations on which the test is based," Radford wrote, echoing Shapiro's own version. "Thus the recognition and formulation of the test may be regarded as an unforeseen benefit from the Haystack development effort."[45] But other aspects of Shapiro's work at Lincoln Laboratory between 1963 and 1965 point to a somewhat earlier and more gradual development of his thoughts about the possibility of testing general relativity with radar. And they make especially clear the time-delay experiment's conceptual and technological debts to Shapiro's defense research.

Perhaps most important was the creation of a sophisticated computer program for calculating and refining the "ephemerides"—the positions in the sky, as a function of time—of the moon and planets. The "Planetary Ephemeris Program" (PEP) grew directly out of Shapiro's work on the prediction of ballistic missile trajectories. As input, PEP was designed to take a variety of radar and optical observations of an object's position in the sky, use them as initial conditions for the complicated set of differential equations (derived from classical celestial mechanics) that described the object's orbit, and then integrate them numerically. As output, it converted the stream of numbers produced by the integration into accurate tables of the object's ephemeris, which could then act as pointing instructions for the computers that aimed the Millstone and Haystack radars. The more observational input, the better. With more and more 'redundant' data telling PEP where an orbiting object was in the sky at a given point in time, the better the estimate that PEP could make of the object's position at earlier and later times. The statistical procedure behind PEP was exactly the kind that Shapiro had developed for his BMEWS ballistic-missile tracking project.[46]

Shapiro's text on ballistic missile tracking became a kind of recipe book for a major technical advance in astronomy: the generation of precise digital ephemerides. Shapiro later learned that when the Jet Propulsion Laboratory was developing its own ephemeris program in the early 1960s as it prepared for NASA's space missions, his book was required reading for members of the computer programming and radar tracking team.[47] As Lincoln Laboratory began to pursue its own radar astronomy program, Shapiro and a young researcher named Michael Ash started to develop the Planetary Ephemeris Program in earnest.

Ash was a recent Princeton mathematics Ph.D. and computer programming expert, first hired by the Laboratory in 1963 as an intern in the Space Physics Group, at that time concentrating on developing Lincoln's series of communications satellites. Under Shapiro's supervision, Ash began preparing the thousands of PEP Fortran statements that would be programmed on Lincoln's IBM 360 computer. Tables of optical ephemerides—published by the U.S. Naval Observatory and the Royal Greenwich Observatory, some from as early as the eighteenth century—had to be converted into machine-readable format as well.[48] Soon William Boyd Smith, an MIT-trained electrical engineer who had helped with the magnetic tape recording instrumentation for Lincoln's first Venus radar ranging tests, was enlisted to help Ash with the numerical integration routines. It "had to be exquisitely accurate," Smith recalled. "We had to do nine-body integrations of the Sun, Moon, and planets back to 1750, and we had to do it with an accuracy over that entire period of, say, a tenth of a second of arc."[49] The work continued at a heady pace through the spring of 1964, when Shapiro successfully convinced the Laboratory to hire several more staff to assist Ash in the development of the ephemeris program, even writing to Lincoln Steering Committee member (and future Assistant Secretary of Defense) Gerald Dinneen to help pay one programmer an extra two weeks' salary to finish coding his segment of the program.[50]

Shapiro's preparations for the time-delay test thus had begun long before the Haystack radar was up and running, and long before he had formally announced his intentions—either in publication, or to Lincoln Laboratory management. He and his colleagues had for many months been tweaking the computational apparatus needed to find a small target in distant space, aim and fire a radar signal at it, and listen carefully for the echo.

There was a crucial difference, however, between the experiment Shapiro was imagining in late 1964 and the Lincoln Venus echo tests of 1958-61. Instead of bouncing pulses off of the planet at inferior conjunction, when it lay directly between the sun and earth, Shapiro's test would ping Mercury or Venus at "superior conjunction," when either planet lay on the far side of the sun from earth. (Mercury was an attractive target because of its more frequent superior conjunctions, every three to four months. See Figure 3.) Because the signals would therefore pass closer to the sun, the spacetime through which they traversed would be more strongly curved by the sun's mass, and thus the time-delay effect would be much larger. But they would also have to be considerably more powerful than in previous experiments, and their echoes received with far greater sensitivity. Not only would the radar signals in Shapiro's proposed test travel a much longer distance (now roughly 520 million kilometers there and back in the case of Venus, requiring almost a half-hour of round-trip travel time). They would also have to pass through the fury of the solar corona—twice—without being hopelessly scattered or distorted.[51]

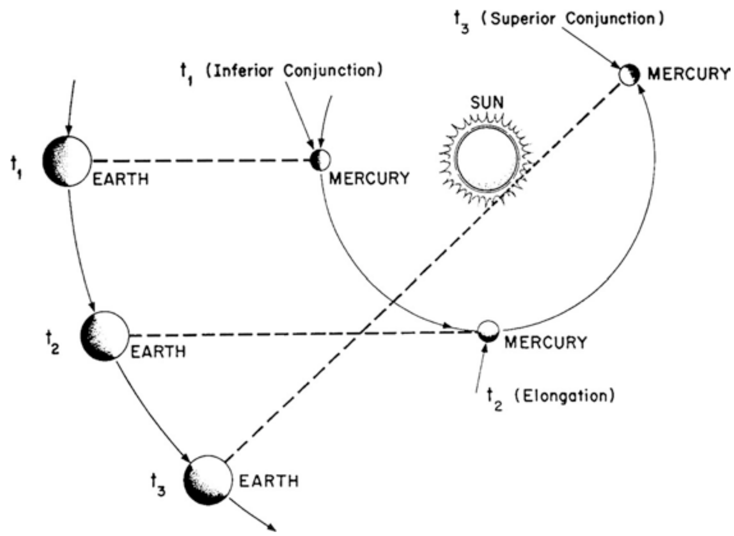

Figure 3: The solar system geometry of Irwin Shapiro's proposed time-delay test of general relativity, as it was represented in an internal report in 1965 by the head of Shapiro's division at Lincoln Laboratory. Reproduced from James W. Meyer, "Program Description—Radar Observations of the Planets," MIT Lincoln Laboratory Technical Note 1965-35 (9 July 1965), p. 24. (Source: MIT Lincoln Laboratory.)

Shapiro described his calculation and proposed experiment in a Lincoln Laboratory technical report published in mid-December 1964, casting it as the latest in a series of 'classical' tests of Einstein's general relativity. "Only three tests have been made since Einstein's theory was given its definitive form in 1916," he wrote, "all having been suggested in his original papers."[52] But the techniques of planetary radar astronomy, then being elevated to a high art at Lincoln Laboratory, would offer the means for a "fourth test":

> This test involves measuring the time delays between transmitting radar pulses toward either Venus or Mercury and detecting their echoes. These measurements must be taken at different relative orientations of the earth, the sun, and the target planet, with the most crucial ones being those near superior conjunction when the radar waves pass closest to the sun. For such configurations…predictions based on general relativity indicate that the time delays will be increased by as much as 200 [microseconds] because of the influence of the sun's gravitational field on the speed of radio wave propagation.[53]

Shapiro titled his internal Lincoln Lab technical report "Effects of General Relativity on Interplanetary Time-Delay Measurements," thus fitting his proposal squarely within the program of radar ranging experiments that had become a fixture of Laboratory life since 1958. Around the same time, he sent a very brief description of his proposed experiment to the prestigious journal, *Physical Review Letters*, where it was published at the end of December. In that short paper—and in the accompanying press release issued by Lincoln Laboratory—the BMEWS context remained tacit.[54]

The Haystack Radar

Shapiro's time-delay test of general relativity was not only nourished, but actively shaped from the start, by its defense-lab setting. The lines of force pointed in the opposite direction, as well. The experiment, through Shapiro's determined advocacy and the enthusiasm of his colleagues, had a deep impact on the activities and goals of Lincoln Laboratory's Radio Physics Division in the second half of the 1960s. These conduits of influence between the time-delay test and its laboratory embedding—linkages of money, materiel, and manpower—were nowhere more evident than in the development of the only instrument Shapiro argued was then capable of performing his experiment: Lincoln's Haystack radar facility.

As Shapiro observed in his original technical report, Haystack boasted two closely related design characteristics that would allow it to handle the time-delay test. Most important was the high electromagnetic frequency of its transmissions. Operating at around 8000 MHz (in the “X-band” of the microwave spectrum), Haystack’s radar signals could easily penetrate the solar corona—the sun’s intensely hot and violent atmosphere of electrons and ions—without being absorbed, distorted, or delayed. Other facilities, such as the Arecibo Ionospheric Observatory in Puerto Rico, operated at much lower frequencies (430 MHz). At those frequencies, the time-delay produced by rescattering of the radiation by the solar corona alone would be perhaps three times as large as the relativistic time-delay produced by the sun’s gravity. Because the exact amount of delay caused by the corona could only, in principle, be known with poor precision, the error in the corona-induced delay would make a careful measurement of the relativistic delay virtually impossible.[55]

Related to the frequency issue was the exceptional narrowness of Haystack’s “pencil-beam”—as with all radar propagation, the higher the frequency, the narrower the beam. With a focused beam, Haystack could pass its transmissions much closer to the edge of the sun (and therefore through a much stronger gravitational field) than rival antennas, thereby lengthening the measured relativistic time-delay. Arecibo, which could fire its beam within roughly one degree of the sun, was no match for Haystack, whose beam was no wider than a few hundredths of a degree.[56]

Shapiro made the case that Haystack seemed specially qualified for the proposed experiment, given both its raw transmitting power and minimal system noise. In a memo to Lincoln Laboratory’s upper management in November 1964—just as he was writing up his technical report and brief article for publication—he cut to the chase: if the Laboratory administration made a commitment to the experiment right away, one of Shapiro’s colleagues at Haystack had informed him “that the necessary instrumentation could be constructed in time for the next favorable planetary configuration…for Mercury on 12 June 1965.” Without mentioning whether upgrades to Haystack might be necessary, Shapiro assured his superiors that the time-delay test was feasible, on both technical and theoretical grounds.[57]

Shapiro's colleagues in Radio Physics would soon make it clear that Haystack *was* in need of significant—and costly—upgrades if it were going to precisely time radar echoes from Mercury or Venus as the planets raced around the far side of the sun. The source of funds for the upgrades was another matter: would the Air Force, which had funded Haystack's construction and paid for its maintenance, underwrite the radar's tune-up? Or would the Laboratory look to "outside support"? How would the upgrades be justified? (Was *general relativity* the kind of thing the Air Force was in the business of testing?) In any event, Lincoln's researchers understood a crucial point: Haystack, or, more specifically, its modular system of interchangeable transmitting and receiving electronics, could be tuned for one application (such as planetary radar astronomy) without permanently disabling the radar's other functions (missile and satellite tracking). It had been designed that way.[58]

The Haystack was conceived as a dual-use technology *par excellence*. Its design was first proposed in 1958, soon after the Millstone Hill radar came online as a prototype missile tracker for BMEWS. As described by Laboratory Director Carl Overhage in the summer of 1960, just a few months after Lincoln first began awarding procurement contracts to industrial firms for Haystack's construction, the new facility would enable researchers to improve knowledge of interplanetary distances, planetary rotation rates and surface characteristics, all in the name of improving defense: "These studies may have important consequences to the design of future radars for such purposes as missile discrimination or space-vehicle detection, where extremely high resolution and high effective radiated power are essential."[59] Tracking enemy missiles was the aim, and planetary radar astronomy served as a means toward that end.

Haystack was a technological marvel—an embodiment of the hulking "big science" mode of postwar research.[60] Its huge, 120-foot diameter reflector dish was made of an extremely thin aluminum sheet, laid over a pattern of aluminum bars forming 96 honeycomb-shaped panels. The aluminum skin was stretched over its frame so tightly that at any point, the reflector surface deviated from a perfect paraboloid by less than a tenth of an inch, the measure of its so-called “surface tolerance.” The radar’s antenna structure—the reflectors and the trusses on which they were mounted, as well as the nearly 7000-pound “plug-in equipment box” containing the complicated electronics required to send and receive the powerful radar signals—was encased within a 150-foot-diameter radome to shield the entire system from the weather. (The sun’s heat might warp the reflector’s aluminum surface, and even the smallest accumulation of ice and snow on the dish during the harsh New England winter would render the antenna inoperable at X-band frequencies, where exceptional surface tolerances were necessary.) The radome, originally procured by the Air Force for an Arctic radar station and designed to withstand 130 mile-per-hour winds, was made of a frame of interlocking steel beams forming the triangular panels of a geodesic sphere. Each of the 930 panels was covered by a sheet of white fiberglass, less than a tenth of an inch thick, chosen for its transparency to X-band microwave radiation. The result resembled nothing so much as the famous “Spaceship Earth” exhibit, later built at Disney’s Epcot Center; see Figure 4. Most important for tracking experiments, the Haystack antenna could be steered digitally. The whole apparatus rested on a bearing and control system weighing almost nineteen tons, floating on a nearly frictionless film of oil 0.005 inches thick, allowing the dish to be rotated smoothly around its central vertical axis, as well as tilted up or down to face targets higher or lower in the sky, all to accuracies of a fraction of a degree.[61] Construction began in the autumn of 1960, and the facility was dedicated in early October 1964.[62]

Figure 4: Lincoln Laboratory's Haystack radar facility, completed in 1964. (Source: MIT Lincoln Laboratory.)

The construction and subsequent upgrades to Haystack signal larger shifts in national priorities, especially at the nexus of defense projects and scientific research. The Haystack facility had been designed and built during the boom years of defense spending after Sputnik. Upgrades to Haystack, on the other hand—prerequisite to fulfilling Shapiro's longed-for test—were negotiated in a fast-changing political environment. As early as January 1965, the Pentagon announced major job cuts at the Lawrence Livermore defense laboratory in California. The following year, the Department of Defense released its first report from "Project Hindsight," an in-house accounting of the benefits to military priorities and preparedness that had accrued over two decades of spending on basic science. For the first time since World War II, military bureaucrats began to second-guess the Cold War template of funding non-mission-oriented research in hopes of advancing military goals.[63] Military planners' own concerns about the effectiveness of defense spending for basic research were soon amplified by nationwide campus protests against the Vietnam War, in which calls rang out for the Pentagon to get out of the higher education business.[64] Lincoln Laboratory, having depended on Air

Force money from the beginning, was especially sensitive to possible fluctuations in its funding stream. Laboratory administrators quickly needed to adapt their strategies to appeal to civilian as well as military sponsors. Suddenly the presence of Shapiro's time-delay test on the laboratory's roster assumed a brand-new significance.

In January 1965, less than a month after Shapiro had first published his "fourth test" technical report and article, Paul Sebring (the leader of the Surveillance Techniques group and manager of the Haystack facility) wrote to James W. Meyer, Head of Lincoln's Radio Physics Division, on the subject of NASA funding for both Millstone and Haystack radars. Though designed and built for missile defense, the huge radar facilities could also benefit civilian agencies like NASA—which might be induced to begin sharing the costs.[65]

Against that backdrop, Shapiro's esoteric experiment quickly became the keynote of the Laboratory's efforts to diversify its sources of funding. While Sebring diligently outlined a host of NASA-relevant tasks that an upgraded Haystack radar could accomplish—mapping structural features and surface characteristics of the moon in fine detail, mapping the surface of Venus and determining the composition of its atmosphere, performing similar measurements on Mercury and Mars and refining the orbital parameters of the planets—the key reason for the upgrades, he admitted, was Shapiro's time-delay test. The trick was wording the proposal to NASA in a way that brought everything together. Sebring advised Meyer that "while the most important result of a 10-db increase in Haystack capability will be the ability to perform the fourth test of general relativity made against Venus or Mercury at superior conjunction," it was surely worth emphasizing the "many other experiments that will be greatly improved in quality."[66]

Shapiro made his own plug for NASA sponsorship the next day. He provided Lincoln's Radio Physics Divison head James Meyer with a list of scientific experiments (including most prominently his time-delay test) that could only be conducted if Haystack received its expensive upgrades.[67] Meyer, in turn, prepared a draft proposal and budget estimate for “Deep Space Radar Measurements” for NASA. The new plug-in radar equipment box alone, including the 500-kilowatt transmitter (a significant improvement over the existing 100-kilowatt transmitter), would initially cost $675,000 (about $5.1 million in 2014 dollars); an upgrade to the radar-computer interface would set NASA back an extra $10,000; and various architectural upgrades to the antenna structure would cost some $45,000. Not only that, in 1966, before the upgrades were complete, an additional $300,000 would be needed to get the whole thing properly calibrated and tested. “The staff and their support…will be provided by our General Research Program supported by the United States Air Force. The funds requested here are only those required to procure the necessary instrumentation to carry out the experiments described.”[68] Meyer quickly followed up with a formal proposal to NASA for “Radar Observations of the Planets,” again listing “the conduct of a 4th test of general relativity” as the first item of business.[69]

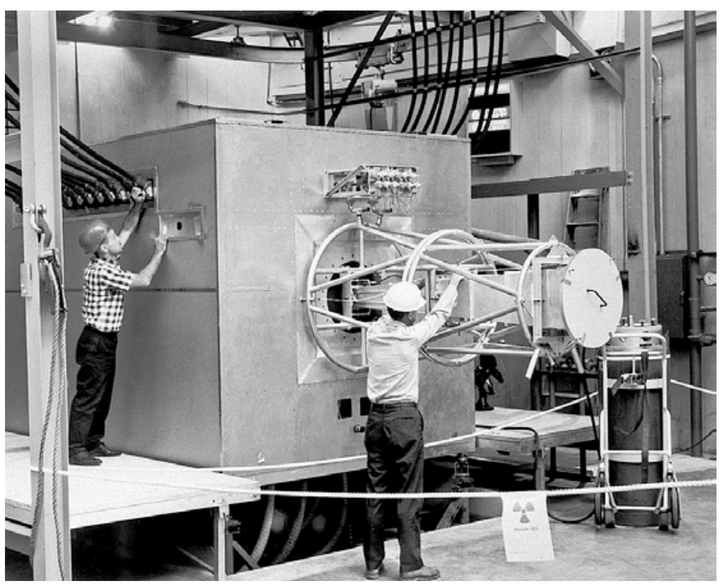

Figure 5: One of Haystack’s modular plug-in equipment boxes, including the radar’s powerful transmitter. (Source: MIT Lincoln Laboratory.)

Despite some expressions of interest, the NASA money never materialized—at least not in time for the first iterations of the time-delay test in 1966 and 1967. As the proposals bumped higher and higher up Lincoln's and NASA's respective chains of command, NASA officials began to balk at the price tag. They expressed regret that neither the agency's Space Science and Applications division nor its Planetary Astronomy division had funds of such magnitude to spare (unlike, for example, NASA's Manned Space Flight division).[70]

At the eleventh hour, the Air Force stepped in with money to improve the Haystack radar. It remains unclear why exactly it did so. Shapiro and other scientist-participants would later recall that their arguments about the inherent scientific value of radar astronomy and the "fourth test" were compelling, setting off a chain of persuasion upwards through Laboratory and Air Force command.[71] Of course, the Air Force might well have had its own reasons for seeking improved transmitter power: as Laboratory staff and management had consistently argued for both Millstone and Haystack radars, improved performance for tracking the moon and the planets implied improved performance for tracking missiles and satellites; all along, the planetary radar efforts had served as effective target practice, enabling engineers and technicians to fine-tune the instruments for their primary mission of spotting incoming ICBMs. Though Shapiro and his Lincoln colleagues had to sweat through the uncertainties that spring, by August 1965, with the new Air Force funding in hand, Lincoln could begin awarding contracts to outside companies to start working on the massive upgrades to Haystack. [72]

The Time-Delay Test and the Fate of the Haystack Radar

The announcement of plans to conduct the "fourth test" of Einstein's general relativity made waves far beyond Lincoln Laboratory. Enthusiastic letters began to arrive at Shapiro's office from all corners of the United States. For one eager inquirer from Norfolk, Virginia, Shapiro suggested grabbing a copy of Peter Bergmann's general relativity text to get a better handle on the subject. To another would-be relativity researcher from Quincy, Massachusetts, who wrote up his own “theory and proposed test” for Shapiro’s approval, Shapiro was sorry to report that “you did not analyze your experiment in sufficient detail,” and that “your analysis of Einstein’s predictions are seriously in error.” Shapiro regretted that a Chicago high school student’s “request that I explain the entire theory of relativity to you in a letter is not possible to fulfill.” And to one resident of Boston’s tony Beacon Hill neighborhood, who had pulled out her own checkbook in support of the “fourth test” upgrades, Shapiro assured that although he was unable to accept her generous donation, “every effort is being made to carry out the relativity experiment as soon as possible.”[73]

A few of Shapiro’s physics colleagues also expressed interest in the upcoming test, but not always with the same degree of enthusiasm. Some pressed him to clarify details of his calculation; his 1964 article in *Physical Review Letters* had been much more abbreviated than the lengthy treatment in his Lincoln Laboratory technical report—which, though unclassified, enjoyed a much smaller circulation.[74] Others granted the importance of the proposed test, but disagreed that it should be counted the “fourth test”; Stanford’s Leonard Schiff, for example, had proposed a distinct experimental test of general relativity a few years earlier.[75] Still others engaged Shapiro in a priority dispute. Duane Muhleman of Caltech’s Jet Propulsion Laboratory had written up his own proposal for a time-delay test slightly before Shapiro’s was in print but after Shapiro had discussed his idea at an international astronomy conference that both had attended. A crucial difference between the rival proposals, as Shapiro pointed out to his JPL colleague in increasingly heated correspondence, was that Muhleman’s version involved radar propagation during a planet’s inferior, rather than superior, conjunction—for which the predicted gravitational effect would almost certainly be undetectable.[76]

While trying to keep up with all the correspondence, Shapiro and Michael Ash were frantically working to complete their Planetary Ephemeris Program, incorporating more and more radar and optical observations of Mercury and Venus (away from superior conjunction) to make the program's orbital predictions more accurate. "Good news: The program ran successfully," Shapiro happily announced to Gordon Pettengill in fall 1965; still, there was more work to do debugging "parts of the program, statement by statement."[77] Shapiro badgered the Jet Propulsion Laboratory's Richard Goldstein to publish his Venus ranging data. "More than four and a half years have elapsed since JPL first made radar contact with Venus, yet no data at all has been published." Shapiro would not be delayed. If Goldstein's supervisor wouldn't allow him the time to prepare data tables, Shapiro would be happy to write a letter demanding the raw data himself.[78] Michael Ash, Shapiro's right-hand-programmer, continued to pester the U.S. Naval Observatory with letter after letter requesting optical ephemeris data for the sun, moon and planets on punched cards to be fed into the IBM 360.[79]

By the summer of 1966, Shapiro was complaining to the Lincoln personnel department that it had become "quite clear that we are severely programmer limited in our attempt to analyze the interplanetary radar observations for the new test of general relativity." PEP's calculations had to be so incredibly accurate that even precise optical observations of the *outer* planets were needed to account for their slight gravitational perturbations on the orbits of the earth, Mercury and Venus. The need for manpower was dire. Though Shapiro expected to be able to complete at least a "semiquantitative test" of Einstein's theory to an error of perhaps 35 percent, "our results may fall almost an order of magnitude lower in test accuracy simply because of our inability to handle the programmer chores."[80] To Haystack director Paul Sebring he wrote that Haystack had "the potential to provide the most accurate tests yet made of Einstein's predictions" and that nailing down the orbital parameters of Mercury and Venus was absolutely crucial: "general relativity literally hangs on it." But the researchers needed help finishing the computer work, including "approximately $5,000 to finish putting all of these [optical ephemeris] data on punched cards. The laboratory's card-punch operators have been shown to be incapable of handling this work on finite time scale."[81] Nearly forty separate tasks remained before PEP would be ready for the "fourth test," he explained in a separate memo.[82] Exhausted but still pushing hard, Shapiro wrote to an MIT colleague in early 1966 that preparing for the time-delay test was occupying an "inordinate fraction" of his time.[83]

Meanwhile, Shapiro's Lincoln Laboratory coworkers were engaged in an all-hands-on-deck effort to get Haystack and its planetary radar equipment box ready as soon as possible. Managers at the Laboratory in both the Haystack operations division and the Radio Physics Division pushed their teams around the clock—even reassigning shop foremen and encouraging technicians to work overtime on the weekends—to be ready when Venus would next be in the opportune position of its orbit.[84] The time-delay experiment, Sebring reminded Division 3, "is of the greatest scientific interest and seems certain to attract wide attention to Lincoln Laboratory…if it succeeds." Only an intense effort would ensure Lincoln's "being first to make the proposed test." November 9th, when Venus would slip briefly behind the sun, was quickly approaching.[85]

The hard work paid off: Haystack was ready just in time. Data was successfully collected during Venus's November 1966 superior conjunction, as well as the superior conjunctions of Mercury in January, May, and August 1967. Early in March 1968, Shapiro made the first public release of preliminary "fourth test" results at the meeting of the American Physical Society in Boston. The experiment, he announced, had confirmed general relativity—even if only within fairly generous margins of error. Less than a week later, he sent off a paper to *Physical Review Letters*.[86] Published in May, the paper explained that the experiment had been made possible by an "intensive program" to outfit Haystack with a new transmitter and receiver. Considering each experimental run separately, Shapiro and his coauthors (including Pettengill, computer programmers Ash and Smith, and three of the Haystack engineers who had instrumented its upgrades) concluded that the "most reliable of these data agree, on average, with the excess-delay predictions of general relativity to well within the experimental uncertainty of ±20%."[87]

Later that month, Shapiro formally presented Lincoln Laboratory Director Milton U. Clauser with the first preprint. "Although the accuracy attained was not as high as we had hoped"—20% uncertainty hardly amounted to razor-sharp scrutiny or conclusive confirmation of Einstein's theory—"it nonetheless represents a substantial achievement in a very difficult experiment." Moreover, "despite the unfortunate predilection of the popular press to present the result as a one-man show, the experiment was successful only because of the skill and spirit of a large number of Lincoln personnel." With understated admiration for his coworkers, Shapiro reminded Clauser that the design and construction of the new plug-in equipment box for Haystack had been a "massive effort." The grueling pace of work during May 1967 ("unbroken except for Mother's Day"), when Haystack tracked Mercury through superior conjunction daily from 4:30am to 7pm, "served to demonstrate poignantly the dedication of the staff."[88]

No eye-catching headline heralded the findings as they had after Arthur Eddington's announcement in 1919, even though the news was the same: Einstein's relativity had held up. Instead, the scientific success was bittersweet. Before Shapiro had finished writing up his "fourth test" results in 1968, ever clearer signs of a massive shift in the U.S. military support of basic science could be detected throughout Lincoln Laboratory. For at least a year, high-level officials in the Department of Defense, the Air Force, and administrators at Lincoln and MIT had asked searching questions about the Laboratory's future; Lincoln, it had become clear, occupied precarious territory between the Pentagon, Capitol Hill, and the Great Dome of MIT's Cambridge campus. As the Vietnam War raged, critics called ever more loudly for the bond between the national security state and America's universities—held together by the clasp of the Cold War for more than twenty years—to be severed. The Lab was caught in the center of the debate.

And the Haystack radar would be among the first vestiges of Lincoln's military-academic mission to be amputated by severe federal budget readjustments.[89]

In late summer 1967, Secretary of Defense Robert McNamara, MIT President Howard Johnson, and former MIT administrators and Presidential Science Advisors James Killian and Jerome Wiesner held a telephone conference addressing "long-range questions affecting Lincoln Laboratory in its service to the country, specifically the Department of Defense," and its "continuing operation as a part of M.I.T." In a letter to McNamara after the conversation, Johnson summed up Lincoln's dual orientation. Its mission-oriented work was "aimed at assisting the military establishment in finding technical solutions to…problems in ballistic missile penetration and ballistic missile defense, in space communications," and other areas. More basic research—buoyed by the General Research Program, which had fostered the construction of the Haystack radar—allowed "the Laboratory to look beyond its immediate tasks." However, Johnson continued, recent Congressional budget cuts to Federal Contract Research Centers (FCRCs, of which Lincoln was a prominent example) had "opened the question of how M.I.T. should plan for the future operation of Lincoln."[90]

Just as Johnson was writing to McNamara, a Defense Science Board task force commissioned by the Director of Defense Research and Engineering had recommended that each of the Defense Department's FCRCs provide a statement of "their interpretation of the primary purposes and current technical objectives" of their work.[91] Lincoln was being asked to explicitly justify its research pursuits to the Department of Defense—and this only a month after the latest round of data collection for Shapiro's relativity experiment had taken place at Haystack. MIT President Johnson's official statement to the Assistant Secretary of the Air Force included a tidy list of the Lab's accomplishments in radar and communications. But he was "deeply concerned" about Defense Department budget cuts and Lincoln's "unfortunate" classification as an FCRC. Lincoln had "no financial cushioning and relies almost completely on annual appropriations from the Air

Force" and the Pentagon's Advanced Research Projects Agency. Budget cutbacks didn't only curtail military work at Lincoln: its "general research effort" had suffered deeply for years as well. Of what continuing value would the Laboratory be to the Institute, if its personal and material assets were so easily buffeted by the changing winds of national defense?[92]

However the Institute, Lincoln Lab, and the Air Force might choose to handle them, the changes issued from Washington were sweeping and rapid. In 1969 Senate Majority Leader Mike Mansfield successfully tacked a rider (the so-called "Mansfield Amendment") onto the military authorization bill requiring all Defense Department-funded research to have a "direct or apparent relationship" to military operations.[93] In November that year, Lincoln Laboratory Director Milton Clauser told MIT President Johnson that staff reductions and the "additional unplanned deletion of $450,000 from our budget for rising overhead costs [nearly $3 million in 2014 dollars] [would] be difficult to accommodate." Only one week after violent clashes between student protesters and riot police in front of MIT's military-funded Instrumentation Laboratory, Clauser wondered in frustration whether it was "inappropriate to suggest that the activities on the campus contributing to the rising overhead be given some scrutiny?"[94]

Just a few days later, Haystack director Paul Sebring notified Clauser that negotiations for the transfer of the Haystack facility from the Air Force to civilian control were now proceeding at top speed. A year before, the Northeast Radio Observatory Corporation (NEROC), a nonprofit consortium of New England research institutions, had submitted a proposal to the National Science Foundation for a phased-in, three-year transfer of Haystack control from the Air Force. An advisory panel of prominent astrophysicists led by Princeton's Robert Dicke recommended that NSF approve the request (though, in Sebring's opinion, the panel had underappreciated Haystack's special "sophistication and broad application").[95] As the NSF delayed its final decision and NEROC made a parallel funding pitch to NASA, the Air Force forcibly set its own timeline. In February 1970 Assistant Secretary of the Air Force for R&D Grant Hansen warned Lincoln that by the following July, if Haystack had not been adopted by another government agency, it would be declared surplus and its computer apparatus scavenged for other military uses.[96]

After last-minute guarantees from the NSF and NASA to help absorb Haystack's $1.5 million-per-year operating costs (more than $9 million per year in 2014 dollars), the Air Force handed Haystack over lock, stock, and barrel to MIT and NEROC that summer. When Haystack's transmitter proceeded to fail several times in the early 1970s, NASA (no longer in need of lunar radar maps for its Apollo missions) was unwilling, all over again, to fund replacements. Haystack's last radar transmission—a ranging signal to Mercury—was sent in March 1974.[97]

Conclusion

For the past thirty years, scholars have interrogated the interplay of scientists and military patrons during the Cold War. Debate has raged over who set scientists' intellectual agendas. What effects, if any, did the firehose of military spending have on the range of topics pursued or the styles of scientific inquiry? Some commentators have argued that the hothouse environment of the Cold War produced dangerous distortions from proper scientific efforts.[98] Others have countered that scientists have never existed outside of society; Galileo navigated patronage relationships no less complicated than those of the American physicists in the nuclear age.[99] Still other scholars have tilted the debate slightly skew to the budgetary axis, focusing on the entanglement of personnel, training, instruments, and foreign relations. Yet even these cases have focused overwhelmingly on examples of science and technology that were of obvious military interest, from nuclear physics to materials science, electronics, and computing, or the geosciences crucial to navigation, communication, and submarine detection.[100]

Episodes like the general-relativistic time-delay test expand the pattern, exemplifying just how extensively the new template had reached. Despite the frequent portrayal of Einstein's general relativity as an austere and otherworldly temple, physicists' Cold War engagement with Einstein's work bore most of the marks we have come to expect of the era: seemingly limitless funding (at least for a time), sprawling machinery, soaring technological hubris, and a close mapping of personnel, tools, techniques, and skills between scientific practice and military priorities.[101] The long duration of the time-delay test, from conception in the late 1950s to completion in the early 1970s, further allows us to map the rocky transition from post-Sputnik boom to stagflation bust. "Cold War science" was no more a static entity than the planet Venus; both became moving targets.

For much of 1969 (when Haystack was still a military instrument), until nearly the end of 1970 (when it was officially a tool of civilian science), Haystack once again bounced radar echoes off of Venus for roughly 300 days on either side of superior conjunction. Incorporating data taken at the Arecibo facility (far from superior conjunction), Shapiro's group combined a total of roughly 1700 time-delay measurements to shave down their earlier uncertainty estimates from 20% to less than 5%. Einstein was still right, and the Haystack team had now completed the most sensitive test of general relativity to date. The paper published in *Physical Review Letters* in May 1971 was the culmination of work by Shapiro and colleagues to test relativity with the techniques of planetary radar astronomy. With little mention of the instruments involved, the group cast its "new radar result" as simply the latest refinement of a series of tests of Einstein's theory. By itself, the paper seemed the purest of pure science—an otherworldly theory, subject to a rather esoteric experiment.[102]

The original 1968 paper, however, was far more evocative of the time-delay experiment's deep and tangled roots in Cold War defense priorities. The bulk of the article was given, as the authors put it, "to a more detailed discussion of…the novel experimental techniques" demanded by their test, including everything from the technical features of Haystack's transmitter to various methods of computer-aided signal processing. At times, they recounted, the radar echo had been "as small as 10^{-21} [watts], i.e., about 10^{27} times weaker than the transmitted signal power"; only clever design and exquisite instrumentation had made the experiment possible.[103] To produce, detect, and meaningfully interpret so magnificently tiny a return signal, Lincoln Laboratory's staff had drawn on resources that were unavailable, even unimaginable, beyond the walls of their defense lab home.

Amid the *Sturm und Drang* surrounding whether MIT should divest its Air Force laboratory at Lincoln or spin off the Haystack radar to civilian overseers, MIT President Howard Johnson pointedly reminded the Air Force Director of Laboratories that "the new test of Einstein's theory of general relativity [had] evolved from the Laboratory's intensive efforts in advanced radar technology."[104] Indeed it had. With technical and intellectual skills shaped by years of work on radar communications and satellite- and ballistic missile-tracking projects, and equipped with multi-million-dollar Air Force-funded hardware, the Laboratory's researchers had put an extraordinarily subtle physical effect—and Einstein's most celebrated theory—to the test. Neither "pure" nor "applied," the relativistic time-delay test was Cold War science through and through.

Notes

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Abbreviations: MITA, Institute Archives, Massachusetts Institute of Technology; MITLL, Lincoln Laboratory, Massachusetts Institute of Technology. Per Lincoln Laboratory's request, we will cite archival materials from Lincoln's collections without specifying box and folder numbers.

[1] Fred Jerome, *The Einstein File: J. Edgar Hoover's Secret War Against the World's Most Famous Scientist* (New York: St. Martin's Press, 2002); David E. Rowe and Robert Schulmann, eds., *Einstein on Politics: His Private Thoughts and Public Stands on Nationalism, Zionism, War, Peace, and the Bomb* (Princeton: Princeton University Press, 2007).

[2] George Gamow, *One, Two Three…Infinity* (New York, Viking, 1947), chap. 5; J. L. Synge, *Relativity: The General Theory* (New York: Interscience, 1960), vii. Synge is also quoted in Jean Eisenstaedt, *The Curious History of Relativity: How Einstein's Theory of Gravity was Lost and Found Again*, trans. Arturo Sangalli (Princeton: Princeton University Press, 2006 [2003]), 252.

[3] Klaus Hentschel, *The Einstein Tower: An Intertexture of Dynamic Construction, Relativity Theory, and Astronomy*, trans. Ann M. Hentschel (Stanford: Stanford University Press, 1997), 23; David Rowe, "Making mathematics in an oral culture: Göttingen in the era of Klein and Hilbert," *Science in Context* 17 (2004): 85-129, on 114-115; and Leo Corry, *David Hilbert and the Axiomatization of Physics* (Boston: Kluwer, 2004), 322, 364.

[4] John Earman and Clark Glymour, "Relativity and eclipses: The British eclipse expeditions of 1919 and their predecessors," *Historical Studies in the Physical Sciences* 11 (1980): 49-85; Alistair Sponsel, "Constructing a 'revolution in science': The campaign to promote a favourable reception for the 1919 solar eclipse experiments," *British Journal for the History of Science* 35 (2002): 439-467; Matthew Stanley, "'An expedition to heal the wounds of war': The 1919 eclipse expedition and Eddington as Quaker adventurer," *Isis* 94 (2003): 57-89; Matthew Stanley, *Practical Mystic: Religion, Science, and A. S. Eddington* (Chicago: University of Chicago Press, 2007), chaps. 3-4.

[5] Hubert Goenner, "The reaction to relativity theory, I: The anti-Einstein campaign in Germany in 1920," *Science in Context* 6 (1993): 107-133; Jeroen van Dongen, "Reactionaries and Einstein's fame: 'German scientists for the preservation of pure science,' relativity and the Bad Nauheim conference," *Physics in Perspective* 9 (2007): 212-230; Milena Wazeck, *Einstein's Opponents: The Public Controversy about the Theory of Relativity in the 1920s*, trans. Geoffrey S. Koby (New York: Cambridge University Press, 2014 [2009]).

[6] Alan Beyerchen, *Scientists Under Hitler: Politics and the Physics Community in the Third Reich* (New Haven: Yale University Press, 1977); Mark Walker, *Nazi Science: Myth, Truth, and the German Atomic Bomb* (New York: Perseus, 1995).

[7] Jean Einstaedt, "The low water mark of general relativity, 1925-1955," in *Einstein and the History of General Relativity*, ed. Don Howard and John Stachel (Boston: Birkhäuser, 1989), 277-292; David Kaiser, "A psi is just a psi? Pedagogy, practice, and the reconstitution of general relativity, 1942-1975," *Studies in History and Philosophy of Modern Physics* 29 (1998): 321-338; Eisenstaedt, *The Curious History of Relativity*.

[8] See esp. Clifford Will, *Was Einstein Right? Putting General Relativity to the Test* (New York: Basic Books, 1986). See also Kip Thorne, *Black Holes and Time Warps: Einstein's Outrageous Legacy* (New York: W. W. Norton, 1994).

[9] David Kaiser, "Introduction: Moments of decision," in *Becoming MIT: Moments of Decision*, ed. David Kaiser (Cambridge: MIT Press, 2010), 1-13, on 8. See also Stuart W. Leslie, *The Cold War and American Science: The Military-Industrial-Academic Complex at MIT and Stanford* (New York: Columbia University Press, 1993), especially 20-25; Michael Aaron Dennis, "'Our first line of defense': Two university laboratories in the postwar American state," *Isis* 85 (1994): 427-455; and Deborah Douglas, "MIT and War," in Kaiser, *Becoming MIT*, 81-102.

[10] Leslie, *Cold War and American Science*, 25.

[11] Leslie, *Cold War and American Science*, 27.

[12] Leslie, *Cold War and American Science*, 31.

[13] Leslie, *Cold War and American Science*, 32-35; Eva Freeman, ed., *MIT Lincoln Laboratory: Technology in the National Interest* (Lexington, MA: MIT Lincoln Laboratory, 1995), 6; and David Kaiser, "Elephant on the Charles: Postwar growing pains," in Kaiser, *Becoming MIT*, 103-121, on 108-109.

[14] See Leslie, *Cold War and American Science*, 32-41; Freeman, *MIT Lincoln Laboratory*, 7-13; and Rebecca Slayton, "From a 'dead albatross' to Lincoln Labs: Applied research and the making of a normal Cold War university," *Historical Studies in the Natural Sciences* 42 (2012): 255-282.

[15] Freeman, *MIT Lincoln Laboratory*, 3.

[16] On the history of Project Whirlwind and SAGE see, e.g., Freeman, *MIT Lincoln Laboratory*, 15-33; Paul N. Edwards, *The Closed World: Computers and the Politics of Discourse in Cold War America* (Cambridge: MIT Press, 1996), chap. 3; and Atsushi Akera, *Calculating a Natural World: Scientists, Engineers, and Computers During the Rise of U.S. Cold War Research* (Cambridge: MIT Press, 2007), chap. 5. See also Donald L. Clark, "Early advances in radar technology for aircraft detection," *Lincoln Laboratory Journal* 12, no. 2 (2000): 167-180, especially 167-168.

[17] Freeman, *MIT Lincoln Laboratory*, 35-36.

[18] Leslie, *Cold War and American Science*, 35.

[19] See, e.g., General Bernard A. Schriever of the Air Force (later chief military custodian of Lincoln Laboratory) to Secrety of the Air Force Eugene Zuckert, 13 August 1962, in Library of Congress, Papers of General Curtis LeMay, Box 141, Air Force Systems Command (AFSC) 1962. This and similar documents related to the history of early missile-detection and the policy of "launch on warning" may be found at the website of George Washington University's National Security Archives: "Launch on warning: The development of U.S. capabilities, 1959-1979," accessed 14 April 2010. Available at http://www.gwu.edu/~nsarchiv/NSAEBB/NSAEBB43/. See also Donald MacKenzie, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance* (Cambridge: MIT Press, 1990); Rebecca Slayton, *Arguments that Count: Physics, Computing, and Missile Defense, 1949-2012* (Cambridge: MIT Press, 2013); and Benjamin Wilson, "Insiders and outsiders: Nuclear arms control experts in Cold War America" (Ph.D. dissertation, MIT, 2014).

[20] Freeman, *MIT Lincoln Laboratory*, 47-49.

[21] Warren Rogers Jr., "U.S. tries huge radar on Russia," *The Washington Post* (17 May 1960), A6.

[22] Leslie, *Cold War and American Science*, 35; Freeman, *MIT Lincoln Laboratory*, 49.

[23] G.H. Pettengill and D.E. Dustin, "A comparison of selected ICBM early-warning radar configurations," MIT Lincoln Laboratory Technical Report #127, 13 August 1956.

[24] For background on Pettengill, see the citation for the 1997 Whitten Medal of the American Geophysical Union: "Pettengill receives the Whitten Medal," *Eos, Transactions, American Geophysical Union* 78, no. 39 (1997), 419-420. On Dustin, see his obituary in the online edition of *Bates Magazine*: "Obituaries," accessed 18 June 2013. Available at http://www.bates.edu/magazine/back-issues/y2008/summer08/departments/vital-statistics/obituaries-2/. Dustin's master's thesis (titled "An investigation of the environment for scientific research in industry, in the university, and in government") is located in the collection of MIT's Hayden Library.

[25] Pettengill and Dustin, "Comparison," 13-15.

[26] Irwin I. Shapiro, interview conducted by Andrew J. Butrica, 30 September 1993. (All oral history interviews conducted by Andrew J. Butrica cited in this paper are courtesy of the NASA History Office.) See also "Interview With Irwin Shapiro," p. 5, MITLL. On radar in clutter environments, see for example Donald L. Clark, "Early advances," 172-174.

[27] In an interview, Shapiro summarized the problem as follows: "You have this radar in, say, Alaska, and a missile comes over the pole. Where is it going? Is it going to New York? Is it going to San Francisco? Is it going to Chicago? Grand Forks, North Dakota? Where is it going?" See Irwin I. Shapiro, interview conducted by Andrew J. Butrica, 4 May 1994, pp. 1-2. Shapiro's group leader, David Falkoff, had earlier written a brief report summarizing the basic properties of ballistic trajectories. Shapiro's work expanded this simple theoretical framework to the context of radar observation. See D.L. Falkoff and E.C. Lerner, "Characteristics of trajectories," MIT Lincoln Laboratory Group Report No. 47.3 (January 1956), GR-47-3, MITLL; and Shapiro interview by Butrica, 30 September 1993, p. 2.

[28] I.I. Shapiro, "The prediction of ballistic missile trajectories from radar observations," MIT Lincoln Laboratory Technical Report #129 (27 February 1957), 1.

[29] Irwin I. Shapiro, *The Prediction of Ballistic Missile Trajectories from Radar Observations* (New York: McGraw-Hill, 1958); Kent Kresa and Peter A. Willmann, "Three degrees-of-freedom trajectory analysis program," MIT Lincoln Laboratory Group Report 312G-5 (1962); Kent Kresa and Menasha Tausner, "Programs for calculating a predicted radar trajectory," MIT Lincoln Laboratory Group Report 312G-13 (8 August 1962).

[30] Irwin I. Shapiro, interview conducted by Andrew J. Butrica, 1 October 1993, p. 7.

[31] On Stroke's background at the RLE, see "George Wilhelm Stroke: An Interview Conducted by William Aspray," IEEE History Center, 3 July 1993, accessed 3 March 2010. Available at http://www.ieeeghn.org/wiki/index.php/Oral-History:George_Wilhelm_Stroke.

[32] The quotation is from George W. Stroke, "Light," MIT Research Laboratory of Electronics Technical Report #348, 9 January 1959, p. 19. Most experts on general relativity at the time agreed that gravity should affect the speed (and not just the direction and frequency) of light's propagation; see, e.g., Albert Einstein, "Die Grundlage der allgemeinen Relativitätstheorie," *Annalen der Physik* 49 (1916): 769-822, as translated and reprinted in Albert Einstein et al., *The Principle of Relativity*, trans. W. Perrett and G. B. Jeffery (New York: Methuen, 1923), 109-164, on 114-115, 162-163; Albert Einstein, *Relativity: The Special and General Theory*, trans. Robert W. Lawson (New York: Henry Holt, 1920), 111; Albert Einstein, *The Meaning of Relativity* (Princeton: Princeton University Press, 1956 [1922]), 92-93; Wolfgang Pauli, *Theory of Relativity*, trans. G. Field (New York: Dover, 1958 [1921]), 143-144, 154, 160; Hermann Weyl, *Space-Time-Matter*, trans. Henry L. Brose (New York: Dover, 1922), 224, 252-255; A. S. Eddington, *The Mathematical Theory of Relativity*, 2nd ed. (Cambridge: Cambridge University Press, 1924), 93-94; Max Born, *Einstein's Theory of Relativity* (New York: Dover, 1962 [1924]), 356-358. Even a modern textbook analyzes Shapiro's time-delay test in terms of variable speed of light: M. V. Berry, *Principles of Cosmology and Gravitation* (Philadelphia: Adam Hilger, 1989), 88-90. Physicists today often describe the effect differently: all *local* measurements of the speed of light conducted by freely-falling (inertial) observers will agree, and hence one may conclude that the speed of light is constant even in general relativity. On the other hand, measurements of speed presuppose the establishment of a coordinate system. Having established a coordinate system extended in spacetime beyond one's infinitesimally small region, even freely-falling observers would see the speed of a light ray vary as it traveled through a large region of gravitationally warped spacetime. That is, in any given coordinate system, the speed of propagation along a null geodesic, dr/dt, will depend on the spacetime curvature.

[33] Kaiser, "A psi is just a psi?" 322.

[34] Shapiro interview by Butrica, 1 October 1993, p. 7.

[35] Shapiro interview by Butrica, 1 October 1993, pp. 7-8.

[36] For an account of the Venus detection experiment, see Andrew J. Butrica, "In conjunction with Venus," *IEEE Spectrum* 34 (December 1997): 31-38; and Andrew J. Butrica, *To See the Unseen: A History of Planetary Radar Astronomy* (Washington, D.C.: NASA History Office, 1996), 27-36.

[37] Butrica, "In conjunction with Venus," 32; and Butrica, *To See the Unseen*, 44-46. For the published report, see R. Price, P.E. Green, Jr., T.J. Goblick, Jr., R.H. Kingston, L.G. Kraft, G.H. Pettengill, R. Silver, and W.B. Smith, "Radar echoes from Venus," *Science* 129 (20 March 1959): 751-753.

[38] Carl F.J. Overhage to Lieutenant General Roscoe C. Wilson, 24 March 1959, Box 76, Folder "Lincoln Laboratory" 4/4, AC134, MITA.

[39] Butrica, *To See the Unseen*, 30-46. A team at JPL succeeded in detecting Venus with radar in March 1961, followed closely by RCA's Missile and Surface Radar Division in Moorestown, New Jersey (the prime contractor for the BMEWS missile-tracker radars) in March and April 1961. Around the same time, researchers at Jodrell Bank in the UK and a Soviet team under Vladimir Kotelnikov at the Long-Distance Space Communication Center in the Crimea also succeeded in detecting Venus with radar.

[40] Shapiro interview by Butrica, 30 September 1993, pp. 4-5.

[41] Shapiro interview by Butrica, 1 October 1993, pp. 7-8.

[42] Shapiro interview by Butrica, 1 October 1993, pp. 8-9; J Kovalevsky, ed., *The System of Astronomical Constants: International Astronomical Union Symposium 21* (Paris: Gauthier-Villars, 1963); Irwin Shapiro to Joseph Weber, 22 April 1965, MITLL. Shapiro informed Weber that he had first done "the necessary rough calculations in the summer of 1962."

[43] Shapiro interview by Butrica, 1 October 1993, pp. 9-10.

[44] Peter G. Bergmann, *Introduction to the Theory of Relativity* (Englewood Cliffs, NJ: Prentice-Hall, 1942); Shapiro interview by Butrica, 1 October 1993, pp. 9-10.

[45] W.H. Radford to General B.A. Schriever, 1 March 1965, Box 75, Folder "Lincoln Laboratory" 1/4, AC134, MITA.

[46] M.E. Ash, "Generation of planetary ephemerides on an electronic computer," MIT Lincoln Laboratory Technical Report #391 (2 June 1965), 1-3; M.E. Ash, "Generation of the lunar ephemeris on an electronic computer," MIT Lincoln Laboratory Technical Report #400 (24 August 1965), 1-2. Shapiro discussed the basic outlines of the Planetary Ephemeris Program in his oral history interview conducted by Andrew J. Butrica, 30 September 1993, pp. 19-21. Butrica also discusses the program in *To See the Unseen*, 123-26. In one of his oral history interviews, Shapiro made the connection between his calculations of ballistic missile trajectories and the design of the Planetary Ephemeris Program even more explicit: "Because I had worked on that ballistic missile problem, I was approached by those people at Lincoln Laboratory who were planning the first Venus radar experiment. They felt that they needed some expertise in celestial mechanics. That is how I first became involved in radar astronomy, and that led to PEP. It was that chain of events." See Irwin I. Shapiro, interview conducted by Andrew J. Butrica, 4 May 1994, p. 3.

[47] Shapiro interview by Butrica, 4 May 1994, p.3.

[48] On Ash's background, see the Shapiro interview by Butrica, 30 September 1993, p. 19. Shapiro and Ash made written requests to several observatories around the world, including some in Japan and South Africa, for tables of centuries-old optical ephemerides. See, e.g., Irwin I. Shapiro to Dr. R. L. Duncombe, U.S. Naval Observatory, 17 June 1965, MITLL; and Irwin I. Shapiro to Astronomer Royal, Royal Greenwich Observatory, 16 August 1965, MITLL.

[49] William Boyd Smith, interview conducted by Andrew J. Butrica, 29 September 1993, pp. 1-2 and pp. 13-16.

[50] Shapiro to G.P. Dinneen, 24 November 1964, MITLL; and Shapiro interview by Butrica, 30 September 1993, p. 19. On Dinneen's career, see *The Global Agenda for American Engineering: Proceedings of a Symposium Held in Honor of Gerald P. Dinneen* (Washington, D.C.: National Academy Press, 1996), 1-3.

[51] Shapiro interview by Butrica, 1 October 1993, pp. 9-10.

[52] I.I. Shapiro, "Effects of general relativity on interplanetary time-delay measurements," MIT Lincoln Laboratory Technical Report #368 (18 December 1964), 1. As Shapiro (and most other physicists) viewed the history of gravity research, three essentially distinct kinds of experimental tests of general relativity had been proposed before his time-delay experiment. These 'classical' tests included the bending of starlight by the sun (as first observed by Eddington in 1919), the observation of the anomalous precession of Mercury's perihelion (well-known among astronomers since Urbain Le Verrier first observed it in the mid-nineteenth century), and the "redshift," or decrease in frequency, of light as it travels from regions of stronger gravitational field to regions of weaker gravitational field (measured precisely in atomic experiments at Harvard University by Robert Pound and Glen Rebka in 1959). Shapiro's proposed test of general relativity was thus the "fourth" in a series. On the equivalence principle and the history of 'classical' tests of general relativity, see Will, *Was Einstein Right?*, chaps. 3-5.

[53] Shapiro, "Effects of general relativity," 1.

[54] Irwin I. Shapiro, "Fourth test of general relativity," *Physical Review Letters* 13 (28 December 1964): 789-791; Allen S. Richmond to Julius A. Stratton, 22 December 1964, Box 76, Folder "Lincoln Laboratory" 2/4, AC134, MITA. Cf. "New test proposed for Einstein theory," *New York Times* (28 December 1964), 26.

[55] Shapiro, "Effects of general relativity," 21-22. "Mcps" is a measure of frequency in "megacycles per second," or millions of cycles per second. In the International System of Units (commonly called "SI"), frequency is measured in units of "hertz," abbreviated "Hz," with 1 Hz equivalent to one cycle per second. Thus, 1000 MHz (megahertz) is equivalent to 1000 Mcps.

[56] Shapiro, "Effects of general relativity," 21; and Herbert G. Weiss, "The Haystack experimental facility," MIT Lincoln Laboratory Technical Report #365 (15 September 1964), iii.

[57] Shapiro to J. Arthur, W. Davenport, B. Lax, J. Meyer, and P. Sebring, 10 November 1964, MITLL.

[58] The Air Force did fund research on general relativity at the time, but almost exclusively small projects in theoretical physics, rather than major equipment upgrades, as in the case of Haystack. See

Joshua N. Goldberg, "US Air Force support of general relativity: 1956-1972," in *Studies in the History of General Relativity*, ed. Jean Eisenstaedt and A. J. Kox (Boston: Birkhäuser, 1992), 89-102.

[59] Carl F.J. Overhage to Lieutenant General Roscoe C. Wilson, 30 August 1960, 76:1, AC134, MITA. A Lincoln Laboratory information pamphlet similarly played up Haystack's unrivaled resolving power, noting that it was "designed to detect a one-square-meter target at a range of 20,000 nautical miles, and a target only 0.0001 square meter in cross-section at 2,000 miles." Pamphlet located in Box 76, "Lincoln Laboratory" Folder 2/4, AC134, MITA.

[60] See esp. Peter Galison and Bruce Hevly, eds., *Big Science: The Growth of Large-Scale Research* (Stanford: Stanford University Press, 1992); and Cyrus Mody, "How I learned to stop worrying and love the bomb, the nuclear reactor, the computer, ham radio, and recombinant DNA," *Historical Studies in the Natural Sciences* 38 (2008): 451-461.

[61] Weiss, "Haystack," esp. 1-6. Information on the radome construction is included on the back cover of *Technology Review* 64 (January 1962), Box 76, Folder "Lincoln Laboratory" 3/4, AC134, MITA. The thickness of the "bearing and control" system's oil film is mentioned in Weiss, "Haystack," 11.

[62] Carl F.J. Overhage to Lieutenant General Roscoe C. Wilson, 21 November 1960, Box 76, Folder "Lincoln Laboratory" 4/4, AC134, MITA; Lincoln Laboratory Procurement Information, Serial No. 301, Purchase Order No. B-00375, 1 May 1964 (North American Aviation, Inc.); and Serial No. 252, Purchase Order No. BB-112, 18 June 1963 (Univac Division, Sperry Rand Corporation), MITLL; "Haystack facility dedication ceremony," Box 76, Folder "Lincoln Laboratory" 2/4, AC134, MITA.

[63] Anon., "1,000 atomic workers face loss of jobs," *Los Angeles Times* (7 January 1965): 16; C. W. Sherwin and R. S. Isenson, *First Interim Report on Project Hindsight* (Washington, DC: Office of the Director of Defense Research and Engineering, June 1966). See also Karl Kreilkamp, "*Hindsight* and the real world of science policy," *Science Studies* 1 (1971): 43-66.

[64] Cf. Daniel Kevles, *The Physicists: The History of a Scientific Community in Modern America*, 3rd ed. (Cambridge: Harvard University Press, 1995 [1978]), chaps. 24-25; Roger Geiger, *Research and Relevant Knowledge: American Research Universities since World War II* (New York: Oxford University Press, 1993), chaps. 8-9; Leslie, *Cold War and American Science*, chap. 9; Matthew Wisnioski, "Inside 'the System': Engineers, scientists, and the boundaries of social protest in the long 1960s," *History and Technology* 19 (2003): 313-333; and Kelly Moore, *Disrupting Science: Social Movements, American Scientists, and the Politics of the Military, 1945-1975* (Princeton: Princeton University Press, 2008), chaps. 5-6.

[65] P.B. Sebring to J.W. Meyer, 12 January 1965, MITLL.

[66] Sebring to Meyer, 12 January 1965, MITLL.

[67] I.I. Shapiro to J. Meyer, 13 January 1965, MITLL.

[68] J.W. Meyer, "Work statement and budget estimate for deep space radar measurements," 27 January 1965, MITLL.

[69] J.W. Meyer, Editor, "Program description: Radar observations of the planets," 25 January 1965, MITLL. Meyer's proposal was also published in an internal Lincoln Laboratory Technical Note: see J.W. Meyer, "Program description—Radar observations of the planets," MIT Lincoln Laboratory Technical Note 1965-35 (9 July 1965). For cost estimates, see "Table V" ("Personnel, costs, & time, preparation for 4th test of general relativity") in "Budgetary memorandum," (undated), likely prepared by Paul B. Sebring for James W. Meyer, MITLL.

[70] Homer E. Newell to Dr. W.H. Radford, 1 March 1965; Paul B. Sebring to Dr. William Brunk, 20 April 1965; and J.W. Meyer to W.H. Radford, 24 May 1965, all in MITLL.

[71] Pettengill described the unusual funding situation at Haystack in the mid-1960s as follows: "We had money from NASA to do some lunar work, and we had special money that came in a peculiar way to support the fourth test of General Relativity. That money paid for the transmitter, which became the backbone of the Haystack radar facility." See Pettengill interview by Butrica, 28 September 1993, p. 42. Pettengill also recalled that radar astronomy at Lincoln Laboratory, more generally, had always been regarded as perfectly consistent with (and fostered by) military work: "At Millstone [in contrast to the Arecibo facility in Puerto Rico], radar astronomy was never considered the prime mission. It was an allowable activity. It was even encouraged. It was certainly funded, but you did not hire people specifically to do that work. It was to be kept in its proper place. It was never put that way, but you knew it. Your prime involvement was with the military work, the classified work. You could never let that lapse. However, as long as you did your homework, you could do this other work, which was more fun. It was okay, but it was

never a prime objective. It was tolerated." See Pettengill interview by Butrica, 28 September 1993, pp. 31-32.

[72] Lincoln Laboratory Procurement Information, Serial No. 413, Purchase Order No. BB-232, 24 August 1965 (Lehigh Design Company), MITLL.

[73] Shapiro to Wilbert F. Buie, 25 January 1965; Shapiro to Emory Ladner, 26 February 1965; Shapiro to Robert N. White, 7 December 1966; and Shapiro to Cordelia Galt, undated, MITLL.

[74] Shapiro to George H. Brigman, 26 February 1965; Shapiro to Steven Weinberg, 4 March 1965; Shapiro to Joseph Weber, 22 April 1965; Shapiro to B. Bertotti, 21 December 1965; and Shapiro to James C.W. Scott, 22 August 1967, MITLL.

[75] P.G. Bergmann, review of "Fourth test of general relativity" by Irwin I. Shapiro, *Mathematical Reviews* 30 (December 1965); Irwin I. Shapiro to P.G. Bergmann, 12 January 1966; Shapiro to L.I. Schiff, 14 May 1965, 21 July 1965, 29 October 1965, and 12 November 1965, all in MITLL. Leonard Schiff's proposal was first published as Schiff, "Possible new experimental test of general relativity theory," *Physical Review Letters* 4 (1 March 1960): 215-217. Schiff teamed up with Stanford experimentalists William Fairbank and Robert Cannon, experts on low-temperature physics and sensitive gyroscopic instrumentation, to propose an orbiting gyroscope experiment to NASA in 1961. (A similar calculation and experiment had been outlined by MIT scientist George Pugh in 1959, while working for the Pentagon's Weapons Systems Evaluation Group.) Though the proposal received initial funding, the challenging experiment would fail to get off the ground in time for Schiff to see actual results (he passed away in 1971). A more recent incarnation of the gyroscope experiment—NASA's "Gravity Probe B"—was flown during 2004-5, and data analysis is still ongoing. See Will, *Was Einstein Right*, chap. 11; and for the later history of (and latest news on) the gyroscope test, see Stanford's Gravity Probe B website: "Gravity Probe B: Testing Einstein's Universe," accessed 18 April 2010. Available at http://einstein.stanford.edu/.

[76] Duane O. Muhleman and Paul Reichley, "Effects of general relativity on planetary radar distance measurements," *Jet Propulsion Laboratory Space Programs Summary* 4, no. 37-29 (31 October 1964): 239-241; D.O. Muhleman and I.D. Johnston, "Radio propagation in the solar gravitational field," *Physical Review Letters* 17 (22 August 1968): 455-458. See also Shapiro to Duane O. Muhleman, 17 December 1964, 14 May 1965, 2 September 1966, and 26 September 1966, MITLL. Shapiro would later call the episode "one of the major annoyances of my professional life." "I felt he had taken my idea, and he didn't give me any credit for it….He would never admit it. He would never admit it." See Shapiro interview by Butrica, 1 October 1993, pp. 12-16.

[77] Shapiro to Pettengill, 13 September 1965, MITLL.

[78] Irwin I. Shapiro to R.M. Goldstein, 17 November 1965, MITLL. Still sore from the ordeal with Muhleman, Shapiro aimed a quick shot at the rival laboratory: "From experience I know that JPL people don't like to write letters, but I would really appreciate your answer."

[79] See, e.g., Michael E. Ash to A.N. Adams, 26 November 1965; Michael E. Ash to Superintendent, U.S. Naval Observatory, 6 December 1965; and Michael E. Ash to R.L. Duncombe, 15 March 1966, MITLL. See also Michael E. Ash to R.L. Duncombe, 5 August 1966, MITLL; and Michael E. Ash to Superintendent, U.S. Naval Observatory, 28 April 1967, MITLL.

[80] I. Shapiro to H. Sherman, 22 July 1966, MITLL.

[81] I.I. Shapiro to P.B. Sebring, 3 March 1967, MITLL.

[82] Irwin I. Shapiro, "Schedule for program completion and checkout for planetary ephemerides," 7 April 1966, MITLL.

[83] Irwin I. Shapiro to Reginald E. Newell, 16 February 1966, MITLL.

[84] See J.S. Arthur to S.H. Dodd et al., 4 March 1966, MITLL; G.H. Pettengill to P.B. Sebring, 8 March 1966, MITLL; P.B. Sebring to J.S. Arthur et al., 9 March 1966, 1966, MITLL; and P.B. Sebring to J.S. Arthur et al., 17 May 1966, MITLL.

[85] P.B. Sebring to J.S. Arthur et al., 9 March 1966, MITLL. Our reconstruction of the experiment is inspired by similar close studies of the usually unseen labor behind laboratory work. See, e.g., Steven Shapin, "The invisible technician," *American Scientist* 77 (Nov-Dec 1989), 554-563; Peter Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago: University of Chicago Press, 1997); and Harry Collins, *Gravity's Shadow: The Search for Gravitational Waves* (Chicago: University of Chicago Press, 2004).

[86] Irwin I. Shapiro to Samuel Goudsmit, 7 March 1968, MITLL. Leonard Schiff acted as referee for the paper. See Irwin Shapiro to Leonard I. Schiff, 29 May 1968; and Irwin I. Shapiro to Leonard I. Schiff, 10 July 1968, MITLL.

[87] Irwin I. Shapiro, Gordon H. Pettengill, Michael E. Ash, Melvin L. Stone, William B. Smith, Richard P. Ingalls, and Richard A. Brockelman, "Fourth test of general relativity: Preliminary results," *Physical Review Letters* 20 (27 May 1968): 1265-69, on 1265.

[88] I.I. Shapiro to M.U. Clauser, 19 March 1968, MITLL.

[89] On the dramatic transformations in the science-state relationship in the late 1960s, see, e.g., Kevles, *The Physicists*, 406-415; Leslie, *Cold War and American Science*, chap. 9; and Moore, *Disrupting Science*, chap. 5.

[90] Howard W. Johnson to Robert S. McNamara, 22 September 1967, Box 203, Folder 13, AC118, MITA.

[91] Frank R. Haggerty to Milton U. Clauser, 26 September 1967, Box 203, Folder 12, AC118, MITA.

[92] Howard W. Johnson to Alexander H. Flax, 31 October 1967, Box 203, Folder 12, AC118, MITA.

[93] As Daniel Kevles notes, although the amendment was removed the following year, "its statement of congressional intent had a lasting impact, especially in the defense bureaucracy's interpretation of its latitude in research funding." See Kevles, *The Physicists*, esp. 414-415. Part of the amendment is quoted in Butrica, *To See the Unseen*, 80.

[94] Milton U. Clauser to Howard W. Johnson, 13 November 1969, Box 203, Folder 12, AC118, MITA. Johnson mentioned the news coverage of campus protests at MIT to Brigadier General Raymond A. Gilbert of the Air Force Systems Command, assuring him that the "events as reported by the news media have seldom been presented in the proper perspective." That said, Johnson admitted, the 1969 "period of critical self-examination as to the basic nature and purpose of the Institute" would have fundamental consequences for the way MIT balanced "advancing knowledge" with "rendering service to the community and nation." See Howard W. Johnson to Raymond A. Gilbert, 13 February 1970, Box 203, Folder 12, AC118, MITA. On the impact of anti-Vietnam War protests at MIT, see Kenneth Hoffman et al., *Creative Renewal in a Time of Crisis: Report of the Commission on MIT Education* (Cambridge: MIT Press, 1970); Dorothy Nelkin, *The University and Military Research: Moral Politics at MIT* (Ithaca, NY: Cornell University Press, 1972); David Kaiser, "Elephant on the Charles: Postwar growing pains," in Kaiser, *Becoming MIT*, 102-121; and Stuart W. Leslie, "'Time of troubles' for the special laboratories," in Kaiser, *Becoming MIT*, 123-143.

[95] P.B. Sebring to M.U. Clauser, 21 November 1969, contained as an attachment to Milton U. Clauser to Jerome B. Wiesner and Edward M. Purcell, 25 November 1969, Box 203, Folder 12, AC118, MITA.

[96] Howard W. Johnson to Robert C. Seamans, Jr., 21 May 1970, Box 203, Folder 11, AC118, MITA.

[97] Howard Johnson attributed the transfer of Haystack directly to "the constraints imposed by Section 203 of the Fiscal Year 1970 Military Procurement Authorization Act" (the Mansfield Amendment) in a letter to Secretary of the Air Force Robert Seamans, Jr. See Howard W. Johnson to Robert C. Seamans, Jr., 21 May 1970, Box 203, Folder 11, AC118, MITA. The yearly operating cost estimate for Haystack is found in P.B. Sebring to M.U. Clauser, 21 November 1969, contained as an attachment to Milton U. Clauser to Jerome B. Wiesner and Edward M. Purcell, 25 November 1969, Box 203, Folder 12, AC118, MITA. Andrew Butrica reports the last Haystack radar transmission recorded in the logbooks of Haystack engineers Richard Ingalls and Alan Rogers, in *To See the Unseen*, 83.

[98] See esp. Paul Forman, "Behind quantum electronics: National security as basis for physical research in the United States, 1940-1960," *Historical Studies in the Physical Sciences* 18 (1987): 149-229; Leslie, *Cold War and American Science*.

[99] See esp. Daniel Kevles, "Cold war and hot physics: Science, security, and the American state, 1945-1956," *Historical Studies in the Physical Sciences* 20 (1990): 239-264.

[100] See esp. Forman, "Behind quantum electronics"; Leslie, *The Cold War and American Science*; Galison, *Image and Logic*; Spencer Weart, "Global warming, Cold War, and the evolution of research plans," *Historical Studies in the Physical and Biological Sciences* 27 (1997): 319-356; Edward Jones-Imhotep, "Disciplining technology: Electronic reliability, Cold-War military culture, and the topside

ionogram," *History and Technology* 17 (2001): 125-175; David Kaiser, "Cold War requisitions, scientific manpower, and the production of American physicists after World War II," *Historical Studies in the Physical and Biological Sciences* 33 (2002): 131-159; Naomi Oreskes, "A context of motivation: US Navy oceanographic research and the discovery of sea-floor hydrothermal vents," *Social Studies of Science* 33 (2003): 697-742; Jacob Hamblin, *Oceanographers and the Cold War: Disciples of Marine Science* (Seattle: University of Washington Press, 2005); John Krige, *American Hegemony and the Postwar Reconstruction of Science in Europe* (Cambridge: MIT Press, 2006); and Akera, *Calculating a Natural World*.

[101] Cf. Mody, "How I learned to stop worrying," 451-461.

[102] Irwin I. Shapiro, Michael E. Ash, Richard P. Ingalls, William B. Smith, Donald B. Campbell, Rolf B. Dyce, Raymond F. Jurgens, and Gordon H. Pettengill, "Fourth test of general relativity: New radar result," *Physical Review Letters* 26 (3 May 1971): 1132-1135. In the years following the Lincoln Laboratory efforts, other researchers capitalized on artificial spacecraft, including the Viking and Voyager probes, to repeat the Shapiro time-delay test and shrink the error bars even further. To date, the time-delay tests have confirmed predictions of general relativity to 1 part in 100,000. See Clifford M. Will, "The confrontation between general relativity and experiment," *Living Reviews in Relativity* 9 (2006), 38-42. Online article, available at http://www.livingreviews.org/lrr-2006-3.

[103] Irwin I. Shapiro et al., "Fourth test of general relativity: Preliminary results," 1265.

[104] Howard W. Johnson to General Raymond A. Gilbert, 18 November 1968, Box 203, Folder 12, AC118, MITA.