Insights into the Universe: Astronomy with Haystack's Radio Telescope

Alan R. Whitney, Colin J. Lonsdale, and Vincent L. Fish

MIT Haystack Observatory has been advancing radio astronomy and radio science for 50 years. Experiments and observations made using the radio systems developed and operated by Haystack Observatory have corroborated Einstein's general theory of relativity, pioneered the astronomical and geodetic use of very-long-baseline interferometry, and opened a new window for the study of black holes.

» **Haystack Observatory is an independent** research unit of the Massachusetts Institute of Technology (MIT) within the portfolio of the Vice President for Research. Its mission statement sets forth the observatory's ambitious research objective "to develop game-changing technology for radio science, and to apply it to the study of our planet, its space environment, and the structure of our galaxy and the larger universe." Another facet of the observatory's mission is educational outreach; programs that expose students and teachers from varying grade levels to Haystack's ongoing scientific research are a priority. In addition, both undergraduate and graduate students from area universities use the facilities at the observatory to further their own research projects.

The observatory is operated under an agreement with the Northeast Radio Observatory Corporation (NEROC), a consortium of educational institutions in New England, and its site encompasses roughly 1300 acres of MIT-owned woodlands within the towns of Groton, Tyngsborough, and Westford, Massachusetts. The site hosts a number of facilities, including the 37-meter Haystack antenna, the 46-meter steerable and 63-meter fixed ionospheric radar dishes with a 2 MW transmitter, the 18-meter Westford radio telescope, the Wallace Astrophysical Observatory, and several major Lincoln Laboratory installations. Haystack Observatory employs approximately 80 people and maintains a broad range of instrumentation and laboratory capabilities on site. Staff members conduct a vigorous, diverse basic research pro-

FIGURE 1. The Haystack antenna is the largest radome-enclosed antenna in the world. The radome protects the fragile antenna from wind and snow loading, and prevents distortion of the antenna surface caused by wind, snow, and sun. The radome does cause slight attenuation of the radio waves passing through it, but the stability and reliability that the radome ensures more than compensates for this slight downside.

gram in radio science, supported by a vibrant engineering infrastructure. Most of the observatory's science work is based on the in-house development of targeted enabling technologies, such as very-high-data-rate digital recorders and ultra-stable receiver systems.

Development of the field site began in the mid-1950s, and for the first dozen years, the site was a Lincoln Laboratory facility that included the iconic radome-enclosed Haystack telescope, completed in 1964 (Figure 1). Most of the funding for the development came from the U.S. Department of Defense (DoD), primarily the Air Force, which utilized the Haystack system for space surveillance. From the early days, the potential of the facility for basic scientific research was recognized and vigorously exploited. For example, studies of the upper atmosphere via the incoherent scatter technique using the site's 63-meter zenith-pointing dish at ultrahigh frequencies (UHF) began in the early 1960s. Such measurements have continued to the present day, yielding a unique, multidecade, uniform, consistent record of ionospheric conditions over the site.

By the mid to late 1960s, the Haystack radar had gained a reputation as a world-leading, high-precision, high-gain instrument, and its 37-meter dish was in high demand among regional radio astronomers. The combi-

nation of a very large and sensitive antenna outfitted with a wide-frequency range of available receivers provided these scientists with powerful tools to observe a wealth of molecular transitions and helped to give birth to the rich field of astrochemistry [1]. NEROC was formed in June 1967, originally with the aim of building a much bigger telescope, but more pragmatically to formalize and coordinate access to the Haystack dish for the community of interested universities in the Northeast. The leading members of NEROC were MIT and Harvard University, and the initial membership included 11 other universities.

In 1969, Senator Mike Mansfield, D-Mont., introduced an amendment to the Military Authorization Act, which prohibited the use of DoD funds "to carry out any research project or study unless such project or study has a direct and apparent relationship to a specific military function [2]." This amendment directly affected much of the research that was carried out at Haystack and funded by the DoD through Lincoln Laboratory. In order to preserve the burgeoning nondefense-related work at Haystack and yet sustain the mission of the Laboratory to conduct research specifically for national defense, it became necessary for MIT to split the nondefense component away from the Laboratory. In 1970, Haystack

Observatory was established as a separate entity of MIT. The antenna was transferred from Air Force to MIT ownership, and the field site was placed under the administration of the newly formed observatory. All Lincoln Laboratory activities were able to continue because of the creation of secure facilities across the site. Segregating the Laboratory's research and development work allowed the observatory to maintain an open-access environment consistent with a basic research mission funded primarily by civilian government agencies such as the National Science Foundation and National Aeronautics and Space Administration (NASA).

Haystack Observatory was born from a Lincoln Laboratory facility, and its original staff members were transferred from the Laboratory. The organizations share a deep bond and a long history of close cooperation on the site. Personnel are frequently shared between the two, and Lincoln Laboratory and observatory staff have worked shoulder to shoulder on many tasks for decades. Throughout its existence as first a Lincoln Laboratory and then an independent MIT facility, the observatory has engaged in astronomy, geodesy, atmospheric physics, and radio science. This article highlights some of that work.

Radar Maps of Lunar and Planetary Topography

As early as the late 1950s, scientists at Lincoln Laboratory used radar systems, including the original Millstone Hill 25-meter antenna, to make radar measurements of the Moon and Venus. These earlier efforts were primarily restricted to quasi-specular returns, although the Moon also showed weak diffuse returns, some with strong cross-polarization properties, that limited the inference of surface properties [3]. The completion of the Haystack 37-meter antenna in 1964, however, brought both lunar and planetary radar measurements to a new level.

By the mid-1960s, delay-Doppler radar measurements of the Moon with the Millstone Hill antenna and other systems in the U.S. and Canada had shown the predominance of a rather smooth undulating lunar surface with a small surface slope (which could not be reliably determined by optical measurements) [4]. This observation was an important assurance to the U.S. Apollo man-on-the-Moon program that surface topography would not likely be a hindrance if a reasonable landing area were chosen. Still, there remained significant questions about the detailed topography and surface characteristics of the

Moon: for example, "Would a lander sink into a sea of fine dust?" In addition, there was the nagging north-south ambiguity problem (from which hemisphere are Doppler echoes returning?) induced by Millstone's approximately 40-arcminute beam (25.6-meter diameter at 1295 MHz) covering both lunar hemispheres. The emergence of the powerful, high-frequency (X band, 8–12 GHz), narrow-beamwidth radar system at Haystack, as well as the development of "radar interferometry," proved to be key in helping settle these questions.

High-Resolution Lunar Radar Maps

One important new characteristic of the Haystack radar resulting from its large antenna size and high operating frequency was its beam footprint on the Moon that was only about one-eighth the diameter of the Moon. This characteristic resolved the north hemisphere–south hemisphere ambiguity (Figures 2a and 2b) that existed on previous radar systems, allowing the creation of unambiguous high-resolution (~1–2 km) topographic lunar maps over most of the visible surface (Figure 3) [5]. Additionally, analysis of cross-polarization returns allowed better characterization of the near-surface particle size distribution down to a depth of a meter or so, providing confidence to NASA that the Apollo lander would not sink into the lunar surface, as some pundits had speculated. Input from the Haystack radar results furnished important information to NASA when they were choosing potential Apollo landing sites. And, indeed, Stanley Zisk of Haystack Observatory, who was responsible for creating most of these high-resolution maps, was on hand in real time to advise astronauts on a landing site as they approached the Moon's surface.

Radar Maps of Venus

Delay-Doppler radar images of Venus made by other telescopes as early as 1964 were created with single antennas whose beamwidth covered the entire surface of Venus, resulting in the same north-south ambiguity illustrated for the Moon in Figure 2a. When the Haystack radar capability became available in the mid-1960s, operating at the much shorter wavelength of 3.8 cm (~7.8 GHz), the single-antenna north-south ambiguity still existed. However, on the basis of his experience with astronomical radio interferometry, Alan Rogers of Haystack Observatory proposed using multiple receiving antennas in an
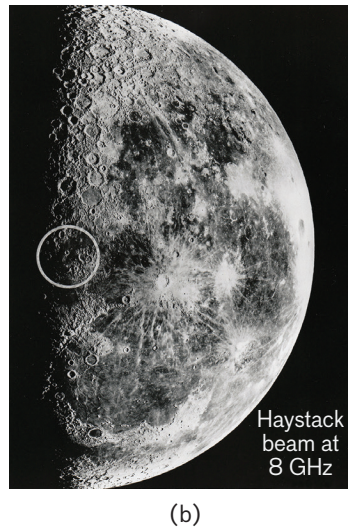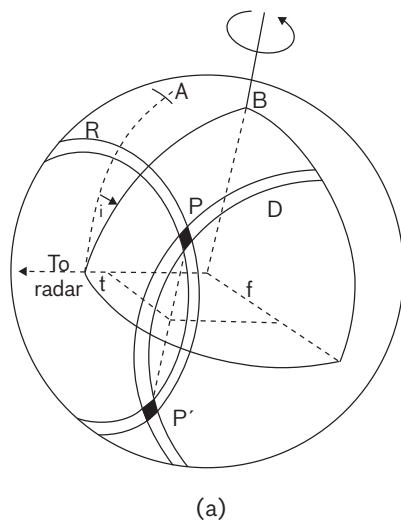
(a)

Haystack
beam at
8 GHz

(b)

FIGURE 2. (a) The illustration shows how symmetric areas north and south of the Moon's apparent equator (i.e., as viewed from Earth) share the same radar delay and Doppler shift, creating an ambiguity if the radar beam covers both areas. (b) The size of the Haystack radar beam on the Moon (white circle) is sufficiently small to remove this ambiguity except for a beam covering the apparent equator (i.e., as viewed from the Earth). Because the moon's orbit is inclined several degrees with respect to the Earth's rotation axis, the Moon's actual equator moves both north and south of the apparent equator during the course of a lunar orbit, allowing unambiguous mapping of areas near the actual lunar equator to be done by judicious choice of observing times.
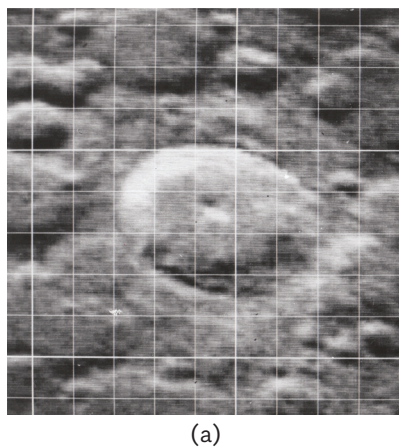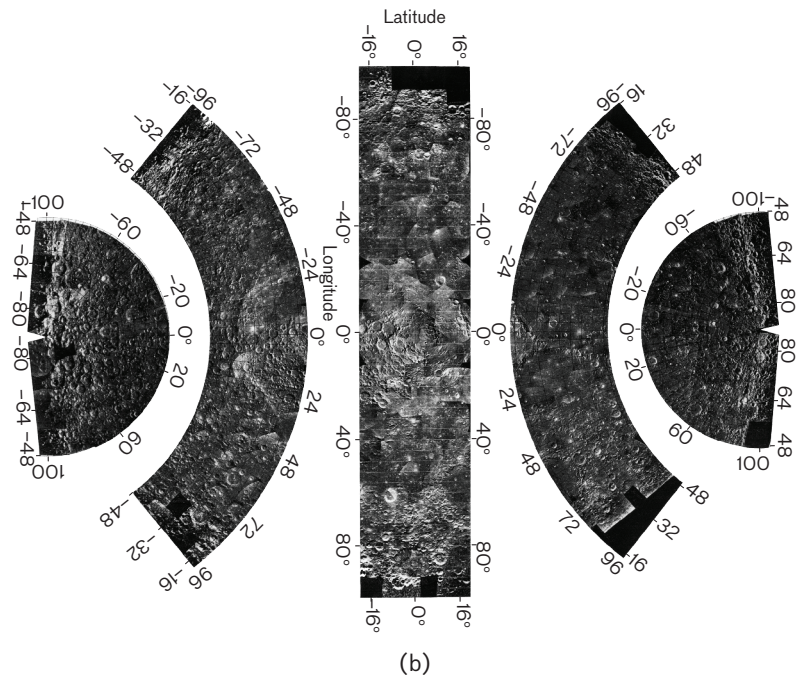

(a)

FIGURE 3. (a) This radar map of the lunar crater Tycho has resolution of 1 km; the grid lines are ~17 km apart. (b) This high-resolution radar map shows almost the entire visible surface of the Moon.

(b)

interferometric radar array to resolve this ambiguity. Linking Haystack's 37-meter antenna and the Westford Radio Telescope's 18-meter antenna, which are ~1.2 km apart, Rogers created a radar interferometer that, through clever data processing, was able to produce the first ambiguity-free radar map of Venus (Figure 4a) [6]. The radar-interferometry technique was subsequently adopted by the researchers at the Jet Propulsion Laboratory (JPL) in California and the Arecibo Observatory in Puerto Rico, and aided in the creation of the composite map of Venus shown in Figure 4b.

Subsequent space missions to the Moon and Venus have, of course, vastly improved the world's knowledge of those celestial bodies beyond the information provided by the early radar images, but the early observations nevertheless provided key information that supported the planning and execution of those space missions.
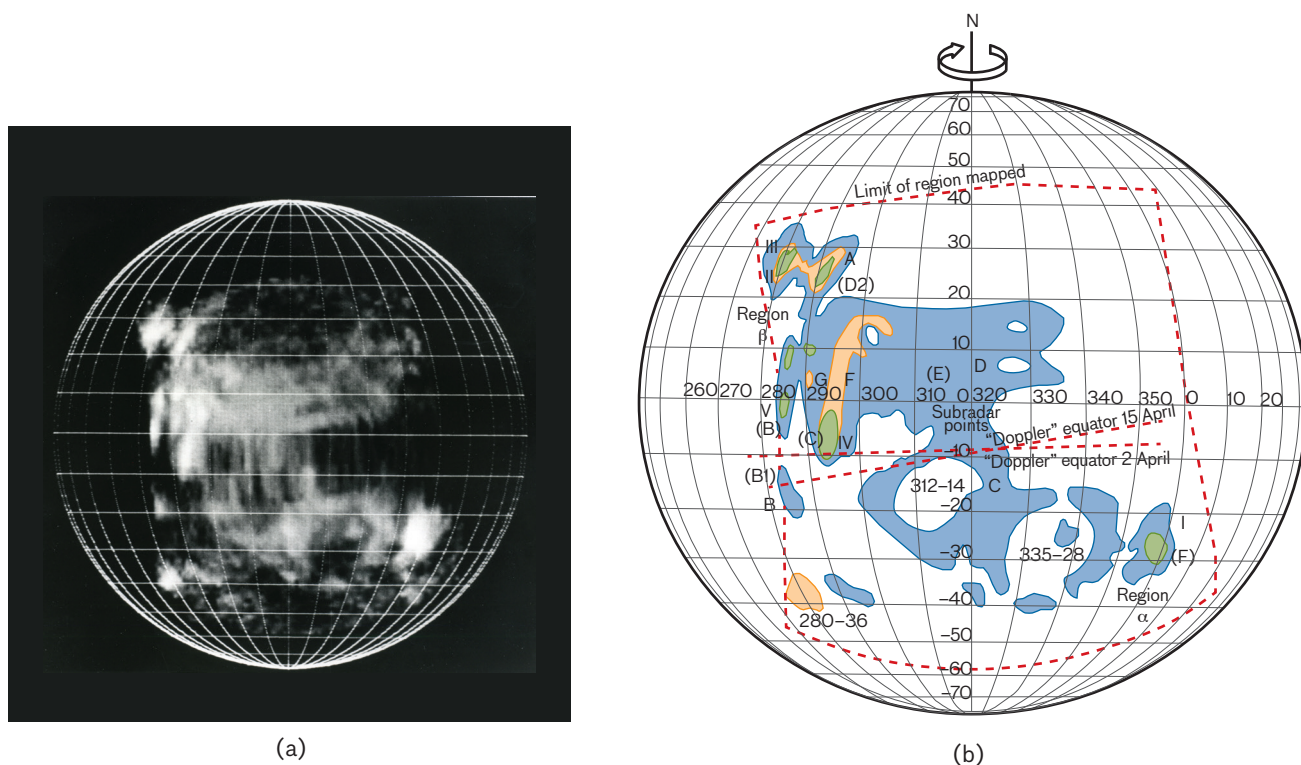
FIGURE 4. (a) This image is one of the first made with a radar interferometer (Haystack-Westford) in 1967; (b) The diagram of Venus's surface features is created from radar interferometry; features labeled with coordinate values (e.g., 335–28) are from the Haystack-Westford interferometer, and other features are from observations made by Richard Goldstein and Roland Carpenter of the Jet Propulsion Laboratory [7].

Fourth Test of Einstein's General Theory of Relativity, 1964–1971

One of the three classical tests of general relativity originally proposed by Albert Einstein is the prediction of the deflection of starlight by the sun's gravitational field. Many experiments in the first half of the 20th century attempted to test this theory, mainly by measuring the deflection of starlight passing near the Sun; bending was observed, but the correspondence with Einstein's prediction could be measured only to about +/−20%, not sufficient to firmly distinguish Einstein's theory from other competing theories [8].

In 1964, Irwin Shapiro, a scientist then at Lincoln Laboratory, proposed a "fourth" test of general relativity—measuring the general-relativity prediction of "time dilation" or "excess delay" (independent of the deflection measured by earlier optical experiments) up to ~200 microseconds (μsec) for radio waves that travel very near the Sun. He suggested that radar measurements

of a planet near superior conjunction (Figure 5) should double the one-way time-dilation value; this value would be compared to the total round-trip time of up to ~1500 seconds. Mercury and Venus were the most suitable candidates for a planetary target [9].

Shapiro and colleagues first had to determine the orbits of Mercury and Venus to sufficient accuracy that orbit uncertainties would have a minor effect on the excess-delay measurements. Since the early 1960s, Shapiro, working with Michael Ash, had been using radar measurements from the Millstone Hill 25-meter radar, the Arecibo Observatory in Puerto Rico, and other observatories to accurately measure planetary distances as part of the Planetary Ephemeris Program that would make a precise ephemeris of the planets. After gathering and analyzing this information, they determined a model of the orbits of Mercury, Venus, Earth, and Mars with an uncertainty of ~30 km (light-travel time of ~100 microseconds), whereas prior opti-
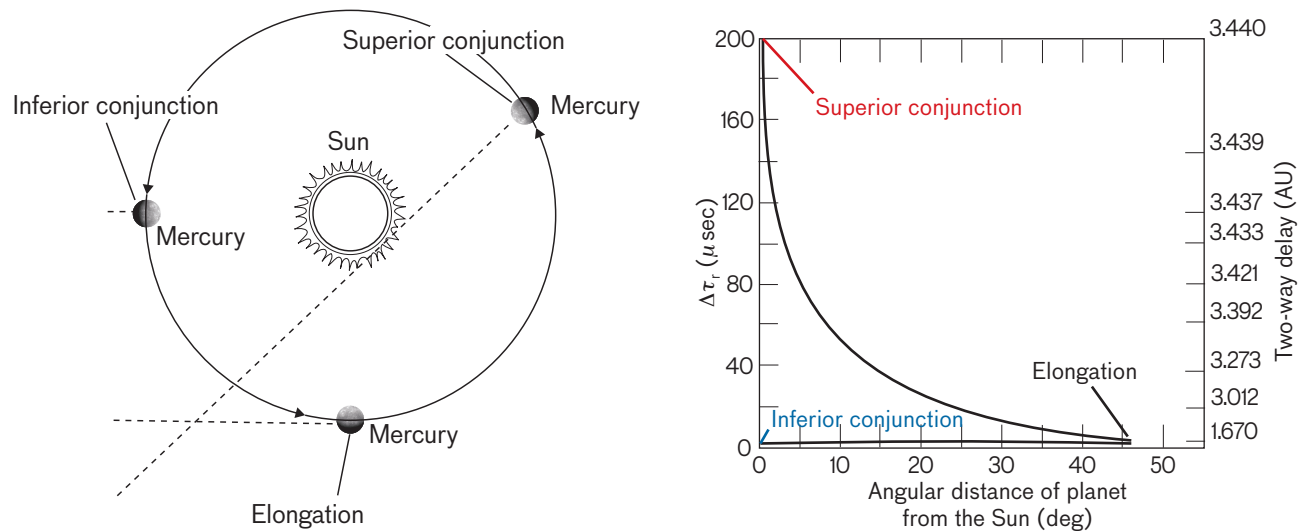
FIGURE 5. The Sun and Mercury geometry for the fourth test of general relativity is shown on the left; the plot on the right shows the predicted "excess delay" as a function of angular distance from the Sun.

cal measurements had uncertainties in the range of tens of thousands of kilometers [10].

The first results from a radar-echo excess-delay experiment were not obtained until 1967 [11], after an intensive program in early 1965 provided the Haystack antenna with a powerful new radar transmitter and receiver system operating at 7.84 GHz and controlled by a hydrogen-maser frequency standard that kept the 7.84 GHz signal coherent over intervals of 20 seconds. This transmit and receive system included a controller that could change the phase of the transmitted signal by 180 degrees every 60 μsec and was controlled by a 63-element shift-register code, resulting in a 3.78-millisecond code length. The autocorrelation function of the shift-register code enabled a strong peak with weak sidelobes (none greater than 35 dB below the peak) in order to unambiguously measure the round-trip delay of the return signal. When coupled to the basic sensitivity of the radar system, this new system yielded a round-trip return-time measurement accuracy of ~10 μsec near superior conjunction.

The 1967 results were obtained using Mercury as a target. The measurements, made on two successive orbits of Mercury, are shown in Figure 6, along with the predicted values. Analysis of the data showed a measured value of 0.8 ± 0.4 (expressed as a fraction of the effect predicted by

general relativity); this result was insufficiently precise to comfortably distinguish between competing theories [11].

By 1971, a substantial body of echo time-delay and (less importantly) Doppler data had been accumulated from radar observations of Mercury, Venus, and Mars made at Haystack Observatory, as well as from radar observations of Mercury and Venus made at the Arecibo Observatory at 430 MHz. The "crucial" measurements near superior conjunctions were obtained primarily at Haystack, but only for Mercury and Venus. The Arecibo measurements were of most use in refining the orbits of Earth and Venus, as well as in helping to remove systematic errors caused primarily by the solar corona, which has an effect inversely proportional to the square of radar frequency. With the combination of these measurements (Figure 7), the ratio of observed to predicted values was determined to be 1.03 ± 0.04 (formal error); this result was comfortably within what Einstein's theory predicted [12].

Researchers have subsequently made further improvements in the estimation of time-dilation values by employing transponders on planetary landers to make two-way measurements that eliminate any smearing of the radar-return signal caused by topographical features and that provide higher signal-to-noise measurements [13], as well as two-way measurements using the Cas-
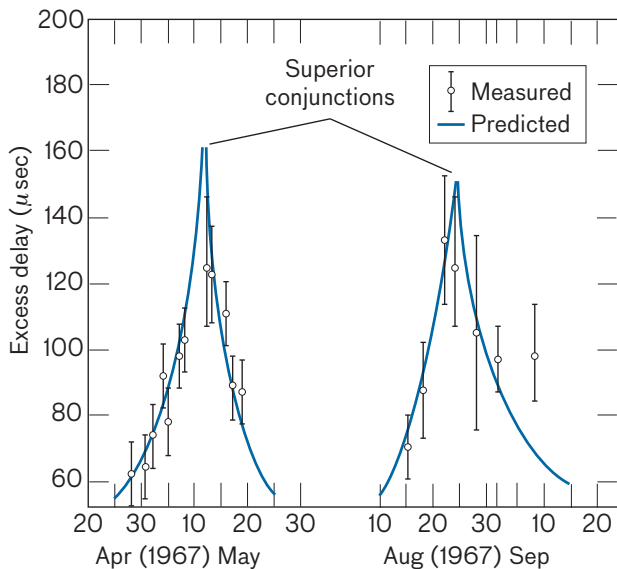
FIGURE 6. Comparison of the predicted and measured "excess delay" of Earth-Mercury round-trip due to general relativity; from 1967 data. These data were not sufficient to confirm the general theory of relativity.

FIGURE 7. This typical sample of post-fit residuals for Earth-Venus excess-delay measurements is based on 1970 data. Note the dramatic improvement in accuracy compared to the 1967 data (Figure 6); the Arecibo measurements were the more useful ones for refining the orbits of Earth and Venus and for helping to remove systematic errors that were due mainly to the solar corona. Note that the Arecibo data in the above plot does not extend close to superior conjunction because of the large effect of the solar corona at Arecibo's lower operating frequency of 430 MHz.

sini spacecraft orbiting Saturn [14]. Nevertheless, the Haystack radar, along with its highly skilled teams of scientists and engineers (Figure 8), pioneered the way to the first measurements that confirmed an important prediction of Einstein's theory of general relativity.

First Very-Long-Baseline Interferometry Experiments

Ever since the birth of radio astronomy with the early work of Karl Jansky in 1933 [15], the need for improved angular resolution on the sky has been recognized. The long wavelengths of radio waves compared to optical wavelengths meant that even large single-aperture radio antennas could not compete with the resolution of even modest optical telescopes.

In the late 1940s, a "sea interferometer" constructed in Australia used a cliff-based seashore antenna to combine a direct observation of a celestial object with its reflection from the sea surface to create a crude, but intermittently workable, interferometer [16]. As early as 1953, radio astronomers were building arrays of antennas connected together with adjustable lengths of wires to implement a rudimentary form of interferometer-beam pointing. Into the 1960s, these "connected-ele-
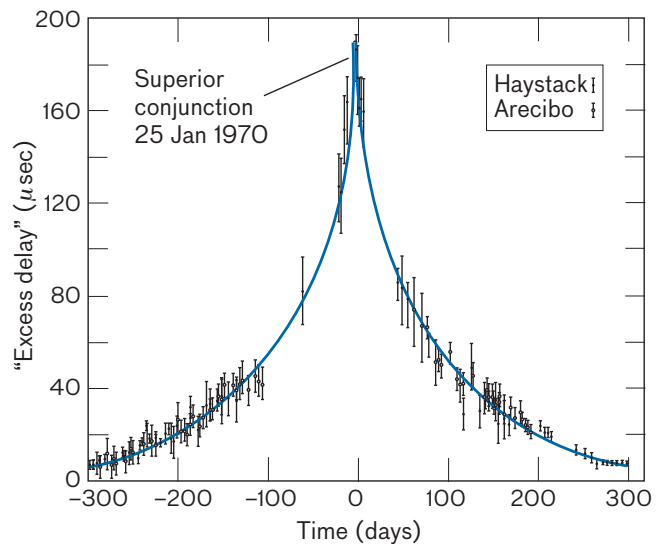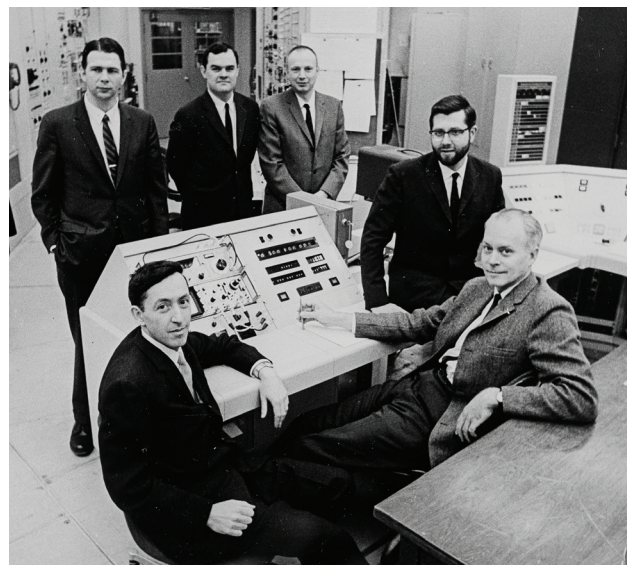

FIGURE 8. The radar team working in the Haystack antenna control room around 1967 included (seated, left to right) Irwin Shapiro and Gordon Pettengill; (back, left to right) Arnold Kaminski, Rich Brockelman, Richard Ingalls, and Michael Ash.
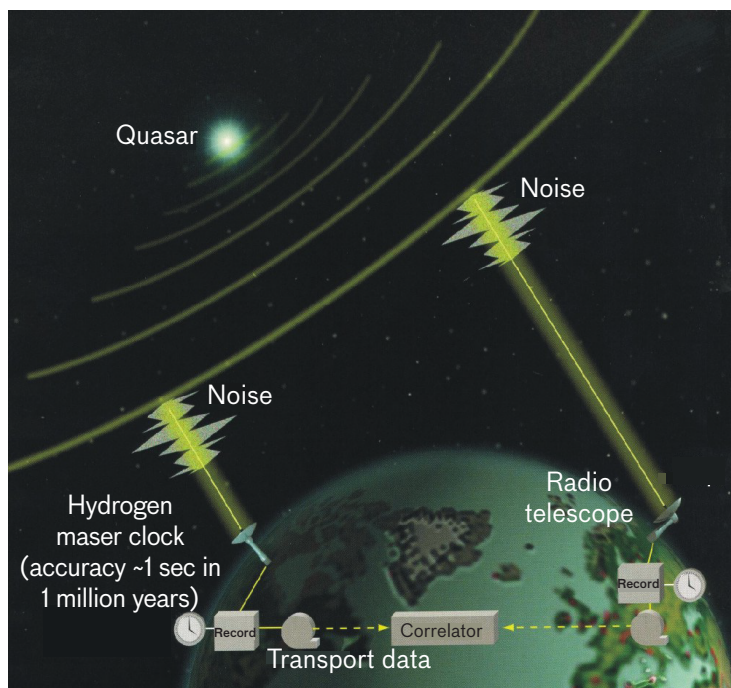
FIGURE 9. Schematic of a simple two-station very-long-baseline interferometry (VLBI) system. In practice, many VLBI observations include more than two stations simultaneously collecting data; some include as many of 20 stations scattered around the globe.

FIGURE 10. The Mark I VLBI recorder captured digitally sampled data at 720 kbps onto a standard 12-inch computer tape that filled in 3 minutes.

ment" interferometers became more sophisticated and useful, evolving into the beginnings of "aperture synthesis" arrays that could make limited "high-resolution" images of target sources [17]. But even these interferometers were constrained by the need for highly controlled real-time transmission of reference oscillators (to receivers), as well as received signals returned to a central location for cross-correlation between antennas, both typically done using coaxial cables.

In 1962, Leonid Matveyenko of the Lebedev Physical Institute of the Russian Academy of Sciences was the first of several scientists to recognize the possibility of building an interferometer with completely independent elements by using new high-stability frequency standards for oscillators and emergent recording technology (Figure 9) [18]. However, it was the Americans and Canadians who took up the challenge to demonstrate this new technique, christened very-long-baseline interferometry (VLBI).

By the mid-1960s, the critical developments of atomic frequency standards, coupled with rapidly developing recording and computer technology, led groups in the United States and Canada into a race to demonstrate the first successful VLBI observations. Three groups—one Canadian, another a collaboration between the National Radio Astronomy Observatory (NRAO) and Cornell University, and a third team at MIT and Haystack Observatory—worked feverishly to be the first to achieve successful VLBI observations. Both the Canadians and the Americans relied on available state-of-the-art rubidium atomic frequency standards for time and frequency stability. The U.S. teams adopted a fully digital sampling and recording system, sampling the 360 kHz observation bandwidth with 1-bit voltage samples at a rate of 720 kbps, then recording the results on then-standard 12-inch-diameter, open-reel digital recorder tapes common on early computer systems (Figure 10) [19, 20]; a single tape was filled in 3

Table 1. Awardees of 1971 Rumford Prize for Their Work in the Realization of VLBI

NRAO AND CORNELL	CANADA	MIT AND HAYSTACK
C.C. Bare	N.W. Broten	J.A. Ball
B.G. Clark	R.M. Chisholm	A.H. Barrett
M.H. Cohen	J.A. Galt	B.F. Burke
D.L. Jauncy	H.P. Gush	J.C. Carter
D.L. Kellermann	T.H. Legg	P.P. Crowther
	J.L. Locke	G.M. Hyde
	C.W. McLeish	J.M. Moran
	R.S. Richards	A.E.E. Rogers
	J.L. Yen	

minutes, requiring the recording of tens or hundreds of tapes. The Canadian group elected to use a 1 MHz analog bandwidth captured by a slightly modified analog television-industry video-recording system that also had timing pulses injected [21]. During cross-correlation processing, the speed of one tape was adjusted until correlation results came into view; for long baselines where the cross-correlation delay was changing rapidly because of the rotation of the Earth, the speed of one of the playback systems was adjusted to compensate. The difficulties of precisely and repeatably managing the playback process on these machines, especially for small correlation amplitudes, led eventually to the abandonment of analog recording machines in favor of fully digital systems on which data could be accurately time-tagged, as well as easily controlled and repeatably played back into a cross-correlation processing system.

During the pivotal year of 1967, no less than a dozen attempted VLBI experiments had varying degrees of success; in some cases, fringes were discovered only after a long period during which another group both recorded data and discovered fringes [19–21]. Additionally, during this period, both U.S. groups ended up collaborating to varying degrees, thereby muddying the waters in determining who was the winner of the race to successful VLBI. The 1971 American Academy of Arts and Sciences' Rumford Prize was fittingly awarded to members of all three groups (Table 1), with eight of the 22 awardees being from the MIT and Haystack Observatory team [22], four of whom (Bernard Burke, Joseph Carter, James Moran, and Alan Rogers) are still active after more than 45 years!

Today, VLBI is a global mainstay in the development and practice of high-resolution radio astronomy and high-precision geodetic VLBI, with many dozens of VLBI-capable antennas scattered worldwide. However, the Very Long Baseline Array, an array of 10 dedicated 25-meter-diameter antennas scattered across the United States from Hawaii to St. Croix, U.S. Virgin Islands, is the only existing dedicated VLBI array.

Since the first successful VLBI results in 1967, recording bandwidths have increased many orders of magnitude, while costs per unit of recorded data have dropped through the use of modern digital electronics (Figure 11); today, a state-of-the-art VLBI recording machine developed at Haystack Observatory can sustain a 16-gigabits/second (Gbps) data rate to an array of 32 removable hard disks for up to ~15 hours at a cost of approximately $20 thousand [23]. Although the bulk of VLBI data are still recorded and shipped to a correlator, it is increasingly practical to transmit data to the correlator via high-speed Internet (although more often by using after-the-fact copying of original recordings to a recorder at a remote correlator, and often at a lower speed than that at which the data were collected).

From the beginnings of VLBI research in 1967, Haystack Observatory has been deeply involved in the development and use of VLBI for both astronomical and high-precision geodetic observations, and is
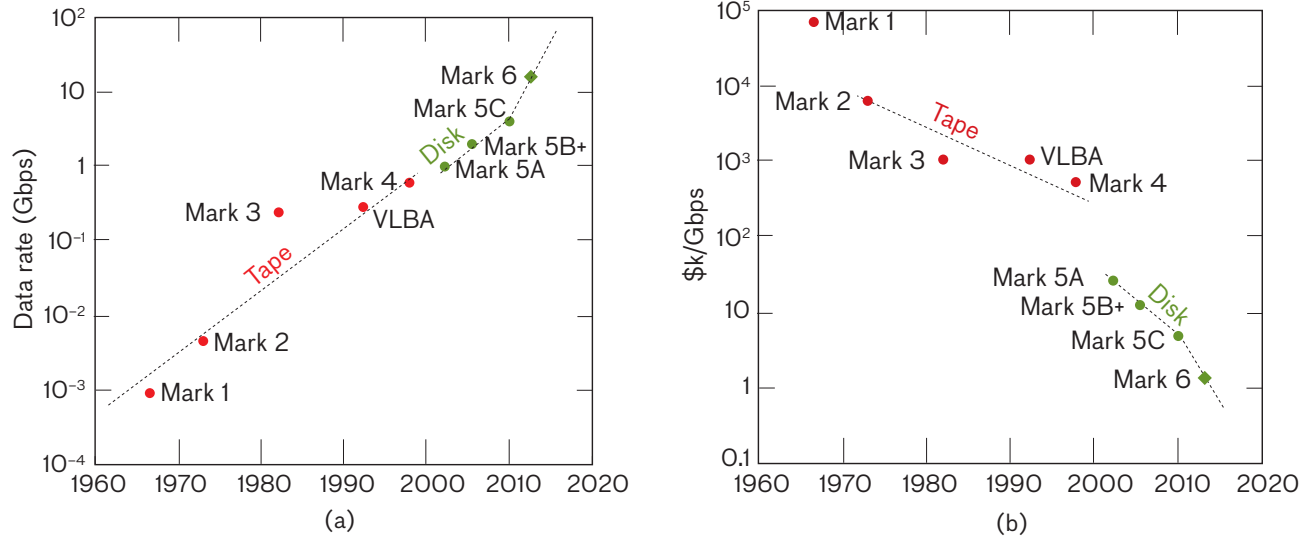
FIGURE 11. (a) Data-rate capability of VLBI recording systems has increased over time; Mark 3 and Mark 4 systems were developed at Haystack; Mark 5 and Mark 6 systems were developed in collaboration with Conduant Corporation. (b) Costs per unit of recorded data have correspondingly decreased because of modern digital electronics.

regarded as one of the world's premier laboratories for the development and practice of the VLBI technique.

Superluminal Motion Observed in Distant Quasars

In the few years following the first successful VLBI observations, the technique became more mature and the number of antennas equipped for VLBI expanded. Among them was the 70-meter-diameter NASA Deep Space Network antenna in the Mohave Desert of Southern California. In collaboration with NASA's Goddard Space Flight Center in Greenbelt, Maryland, Haystack Observatory established a Quasar Patrol project to take monthly to bimonthly observations of a set of approximately a dozen quasars* in order to better study their known time variations and their suspected, but not well-understood, spatial variations [24].

As part of the Quasar Patrol project, observations at 7.84 GHz were made of the well-known quasar 3C 279 in October 1970 and again in February 1971. Figure 12a shows that both sets of observations exhibited deep nulls

in "fringe amplitude" versus time, the nulls being interpreted as interfering spatially compact components at the apparent separation of an odd number of half-fringe spacings (fringe spacing equals wavelength/projected baseline length; projected baseline length continually changes as the Earth rotates). The fact that these nulls moved by about 45 minutes in the four months between observations (Figure 12a) is an indication that the apparent structure of the source changed significantly during that interval. Careful analysis showed that the data are consistent with, and most simply interpreted by, a model of two approximately equal-strength compact components moving apart by about 100 microarcseconds between the observation dates. Further observations continuing through April 1972 implied a nearly constant rate of separation of ~0.67 milliarcseconds per year at a constant position angle on the sky. Based on the distance to the quasar inferred from its measured redshift[‡] velocity of $Z = 0.538$, the separation velocity appears to be approximately 26 times the speed of light [Figure 12b] [25].

This startling result gained considerable attention

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*A quasar (an abbreviation of quasi-stellar radio source) is an extremely remote celestial object emitting huge amounts of energy. Quasars are believed to contain massive black holes and may represent a stage in the evolution of galaxies.

‡ Redshift is a (Doppler) shift of the spectral lines emitted by a celestial object moving away from the Earth toward longer wavelengths (toward the red end of the spectrum).
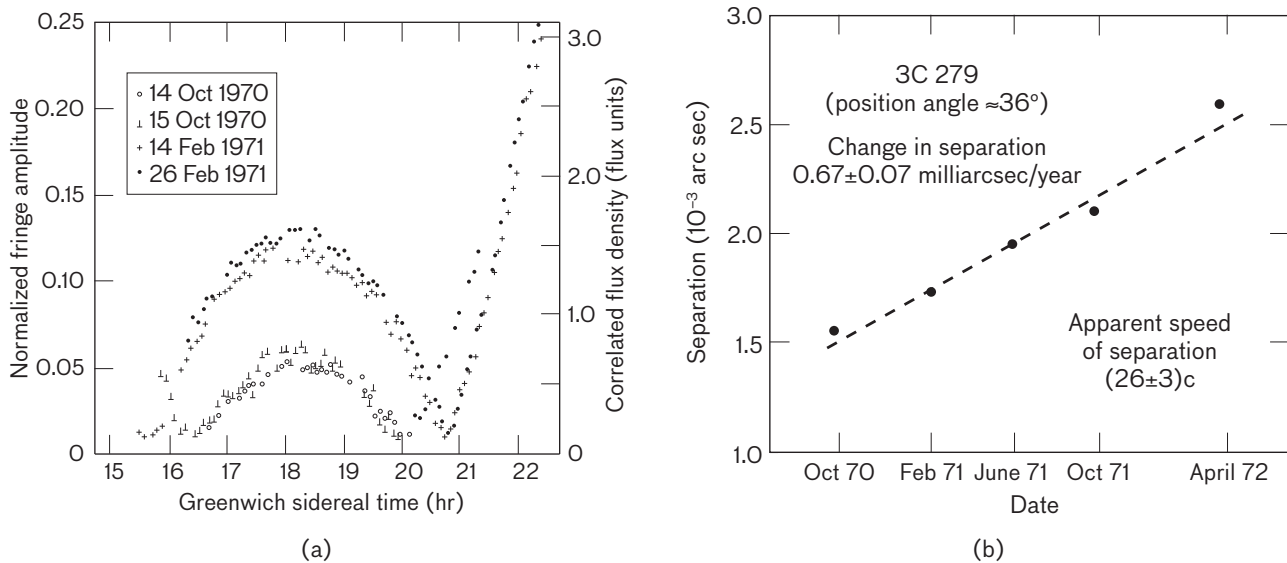
FIGURE 12. (a) The plot of fringe amplitude versus time of quasar 3C 279 shows movement of deep nulls between October 1970 and February 1971, indicating increasing separation of two approximately equal-strength components between those dates. (b) The apparent separation of source components is based on observations from October 1970 through April 1972, and the apparent speed of separation of ~26 times the speed of light is based on the redshift distance to the quasar.
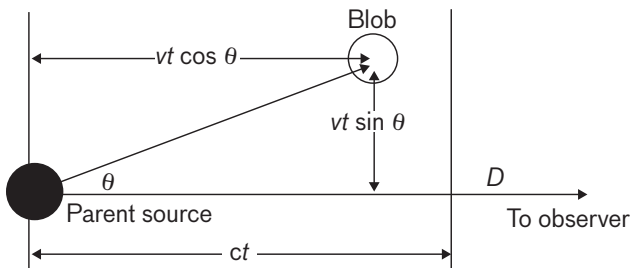

FIGURE 13. The geometry of the simple calculation shows how the illusion of faster-than-speed-of-light motion can be explained.

while a search for explanations began. Might there be three fixed sources in a line whose brightnesses changed to mimic the observed apparent motion? Or could the apparent speed of separation correspond to a phase velocity rather than a group velocity? Or might it be some sort of multipath phenomenon as, for example, a moving, inhomogeneous refractive medium interposed between a single source and an observer that might lead to a double image with relative positions varying in time?

In the end, the most likely explanation is the simplest. Suppose we assume the simple geometry of Figure 13 showing a parent source and a radiating blob that has

been ejected at velocity v at an angle θ with respect to the distant observer's line of sight. A simple geometric calculation of the ratio of the transverse displacement of the blob from the line of sight divided by the time difference observed for the displacement to occur shows that the apparent blob transverse velocity is given by

$$v_{\text{apparent-transverse}} = v\sin\theta/(1 - v/c * \cos\theta), \qquad (1)$$

where v is the actual blob velocity with respect to the parent, c is the speed of light, and θ is the angle between the observer's line of sight to the object and the trajectory of the blob [26]. If θ is a small angle (i.e., within a few degrees to the line of sight) and v is near c, it is clear from Equation (1) that the apparent blob transverse velocity can be many times the speed of light. In simple terms, if the blob is traveling near the speed of light and constantly emitting, the radio waves emitted "pile up" behind the blob and reach a distant observer over a period of time much shorter than the actual interval over which they were emitted, giving the illusion that the transverse velocity is much higher than the actual velocity.

The publication of this result in *Science* in 1971 provided the first hard observational evidence of so-called superluminal motion [25] and caused rather a sensation

in the few months before the simple geometric explanation above was realized. Since then, many other examples of superluminal motion have been discovered in distant extragalactic objects.

Following the publication of the 1971 *Science* paper, some VLBI experimenters took a look at earlier data on 3C 279, which suggested, on occasion, that fringes simply seemed to disappear between one observing session and another. Since VLBI is a very complicated technique, observation failures of one sort or another were not uncommon, and the dots were not connected until the observations detailed above gave virtual proof that there was a least an appearance of superrelativistic motion. Following the discovery that a prediction had been published several years earlier by Rees to explain the data shown above [26], some of the earlier "no-fringe" data were later reinterpreted to offer additional support for Rees's model. Today, many so-called superluminal quasars have been observed.

Birth and Development of Geodetic Very-Long-Baseline Interferometry

In 1967, the first experiments in VLBI were primarily aimed at making high-resolution maps of distant radio sources and/or placing upper bounds on their angular sizes that could not be determined by other means. Radio astronomers soon realized that VLBI was also a tool that could be used to make precision measurements of Earth and its orientation in space relative to the distant quasars [27, 28]. Unlike astronomical VLBI, geodetic VLBI, as it came to be known, would depend upon many precision measurements of wavefront time-of-arrival differences (to within a few picoseconds) made between many pairs of antennas in a globally scattered array over a period of 24 hours. By combining the results of such measurements, scientists could determine and track the precise three-dimensional relative positions of the participating antennas with a precision of a few millimeters, as well as precisely establish the Earth's rotation rate and the orientation of its rotation axis in space, all tied to a coordinate system established by an array of extragalactic quasars.

Late in 1967, researchers at Haystack Observatory, led by Alan Rogers, took up the challenge to develop a VLBI system to make these precise measurements. Rogers conceived the idea of "frequency-switched" (i.e., frequency-hopped) VLBI able to create a "synthe-

sized bandwidth" of a few hundred MHz (large for that time) that would allow high-precision measurements of group-delay between pairs of participating antennas [29]. Receivers operating simultaneously at X band and L band (1–2 GHz) would enable the determination of the signal frequency dispersion through the ionosphere, and hence the ionosphere's radio "thickness" as a function of frequency; this determination would, in turn, allow the effects of the ionosphere to be removed from the measurements. Precise calibration systems were also developed to measure and track (to a small fraction of a nanosecond) cable-length changes caused by temperature variations and antenna motion, as well as to measure the local-oscillator phase differences between the frequency-switched bands. Newly available hydrogen-maser frequency standards provided frequency stability of nanoseconds over time scales from minutes to tens of hours. These new frequency standards were far better than the rubidium frequency standards used in most earlier astronomical VLBI experiments and provided the necessary frequency and time-base stability to undertake these measurements. The radio signals received at each telescope were digitally sampled and accurately time-stamped before being recorded on standard 12-inch-diameter open-reel computer tapes common in that era. Cross-correlation of recorded data was done on the CDC 3300 computer at Haystack Observatory. Preliminary experiments in 1968 and 1969 led to the determination of the relative positions of antennas in Massachusetts, California, and West Virginia to within a few meters, which was remarkable at that time [30].

Beginning in 1969, Haystack Observatory began a collaboration with NASA's Goddard Space Flight Center to develop a state-of-the-art, two-station, geodetic-VLBI observing system, and in 1980, the first regular observations began with antennas in Texas and Massachusetts to monitor Earth's rotation. Through the 1980s, several additional geodetic-VLBI stations were set up in Europe. Subsequently, a number of years of data collection and analysis led to the first precision measurement of the evolution of the baseline length between the U.S. and Europe [31]. Figure 14 shows the smoothness of the measured relative motion between the Westford antenna at Haystack Observatory and an antenna in Germany. In the early 1990s, the first high-precision global map of tectonic motion was created (Figure 15) [32] and fur-
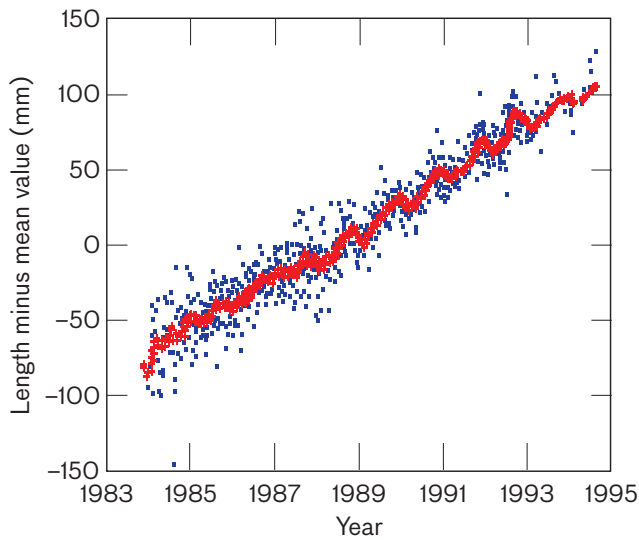
FIGURE 14. The plot shows details of length-of-baseline measurements between an antenna in Westford, Massachusetts, and an antenna in Wettzell, Germany; the data provided evidence of the gradual opening of the Atlantic Ocean floor. The red line is a running average of the data showing a rate of separation of ~17 mm/yr.

ther suggested that the tectonic plates move fluidly over the Earth (except, of course, at their boundaries, where they collide, separate, or slide against each other to create earthquakes, mountains, volcanoes, or deep ocean trenches).

The same geodetic-VLBI technique was also used to make the first extended set of high-precision measurements of the rotation period of Earth that reveals variations of more than a millisecond over periods of weeks to months (Figure 16). Interestingly, comparison of this Earth-rotation-period data with the measured total angular momentum in Earth's atmosphere (from Earth and satellite-based global wind measurements) shows a very strong correlation, as also seen in Figure 16. These results established for the first time that the largest driver of variations in Earth's rotation rate is atmospheric winds, i.e., solid Earth and its atmosphere exchange angular momentum to keep the total angular momentum of the Earth/atmosphere system constant [33].

Other geodetic measurement techniques, such as satellite laser ranging (SLR) and the Global Positioning System (GPS), can also make various measurements of the Earth. SLR measures round-trip delay to a set of satellites equipped with corner-cube reflectors [34]. The SLR data have the unique ability to accurately locate the center of mass of the Earth, which VLBI is unable to do. GPS, which can make few-millimeter-accuracy measurements

FIGURE 15. Tectonic plate motions were measured with geodetic VLBI; for reference, the Hawaii vector (labeled Kokee) is approximately 8 cm/yr. In this plot, the sum of the tectonic motion vectors is constrained to be zero in order to maintain a net-zero gross rotation rate change. A VLBI antenna is located at the foot of each vector.

over distances less than a few hundred kilometers, does an excellent job of measuring local motion across plate boundaries, but cannot match VLBI for global measurements, and neither SLR nor GPS is able to accurately define overall global scale, a capability that is intrinsic to VLBI. Furthermore, only VLBI can measure Earth orientation in the near-inertial reference frame defined by distant quasars. Accurate daily VLBI measurements of Earth's rotation, along with periodic VLBI measurements of the axis-of-rotation orientation, are used to calibrate the orbits of GPS satellites with respect to Earth's surface, allowing GPS ephemeris data to be regularly updated to provide GPS users with accurate surface-location solutions.

Haystack Observatory, with NASA support, is currently developing the next generation of VLBI instrumentation for 1-millimeter global position measurements and 0.1 millimeter/year rate movements. Dubbed VGOS (for VLBI Global Observing System) [35], this new observing system includes a highly calibrated and stable broadband receiver that operates over a full instantaneous 2–14 GHz frequency range, recording data at a minimum of 8 gigabits per second. The system's new 12-meter antennas are designed to move rapidly around the sky so that no two antenna-pointing positions are more than about 20 seconds apart, allowing rapid measurements over the entire visible sky, a capability required to accurately calibrate, measure, and remove the effects of the rapidly changing characteristics of the lower atmosphere. Prototype systems are now being tested at the Westford Observatory and at NASA's Goddard Space Flight Center. Following the completion of testing, NASA plans to build many such stations around the world over the next few years as part of a larger international Global Geodetic Observing System that includes GPS and SLR.

Black Holes and the Event Horizon Telescope

As the most extreme objects predicted by general relativity, black holes have long fascinated both astronomers and the public at large. Small black holes are formed from the collapse of massive stars. Even larger black holes, with masses millions or billions of times that of the Sun, are found at the center of most galaxies, including our own, the Milky Way. These supermassive black holes often drive powerful jets that carry matter and energy out to scales larger than the host galaxy itself [36, 37].
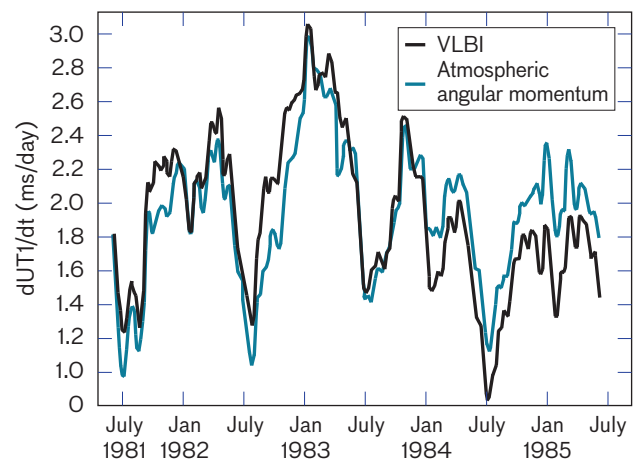

FIGURE 16. The VLBI-measured length-of-day variations are overlaid by atmospheric angular momentum over the same period, illustrating the angular-momentum exchange between the atmosphere and solid Earth, conserving the total angular momentum of the Earth/atmosphere system.

Black-hole candidate sources are regularly observed across the electromagnetic spectrum, but spatially resolving the emission to get a detailed glimpse of the material in the highly relativistic space-time continuum around the black hole has proven challenging. Black holes are small; the Schwarzschild radius, which is the size of the event horizon around a nonrotating black hole, is approximately 3 km per solar mass [38]. For stellar-mass black holes, the Schwarzschild radius corresponds to an angular size that is much too small to resolve with current arrays. In contrast, the supermassive black holes in the center of our galaxy (Sagittarius A*, or Sgr A* for short) and the nearby giant elliptical galaxy Messier 87 (M87, also known as Virgo A) have Schwarzschild radii of about 10 microarcseconds. While these radii are incredibly small, they can be resolved with VLBI at submillimeter wavelengths [39]. Existing VLBI arrays, including the Very Long Baseline Array and the Global 3-Millimeter-VLBI Array, which do not observe shortward of 3.5-millimeter wavelength, are unsuitable because they cannot peer through the optically thick synchrotron emission far from the black hole. Additionally, the emission from Sgr A* is strongly blurred because of scattering from free electrons in the inner galaxy, an effect that is proportional to the square of the observing wavelength [40].

Star Formation Studies at Haystack Observatory

by Philip C. Myers, Harvard-Smithsonian Center for Astrophysics

For more than 20 years, the 37-meter antenna of Haystack Observatory was used to identify and study dense cores, the condensations that form low-mass stars like the Sun. Spectroscopic observations of molecular line emission were made at a 1 cm wavelength (especially in rotation-inversion lines of ammonia) to identify cores and to study their sizes, temperatures, and internal motions. Finer-resolution observations of lines at a 3 mm wavelength, primarily from molecules of carbon monosulfide (CS) and diazenylium (N_2H^+), identified cores that are contracting or gaining mass from their surrounding gas. These studies contributed to our current understanding of the central role of dense gas in forming stars.

In 1975, Haystack Observatory began to offer radio astronomers a low-noise maser receiver at 1.3 cm wavelength and a 1024-channel digital correlator spectrometer. These improvements made it possible to observe lines of interstellar ammonia with much better sensitivity and spectral resolution than before. Ammonia lines were expected to be good probes of dense star-forming gas. Groups from the University of California–Berkeley, led by Charlie Townes, and from MIT, led by Alan Barrett, were eager to observe the star-forming sky with improved vision. At one of the first targets, the Kleinmann-Low Nebula in Orion, the MIT team found evidence of unusually broad lines [a]. Such high velocities would soon be understood to trace the powerful outflows that arise from massive protostars.

With Priscilla Benson and others at MIT, I began to observe ammonia in spots of high extinction in nearby dark cloud complexes. These regions in Taurus, Perseus, and Ophiuchus were known to harbor young low-mass stars. Regions of massive star formation like Orion had brighter lines, but they were too rare and diverse to study as a group. In contrast, nearby dark clouds promised many more star-forming condensations to detect and study. Haystack gave us the necessary sensitivity, resolution, and observing support.

We found that ammonia is readily detected in spots of high extinction and is detected more often in spots that are close to young low-mass stars (Figure A1).

Through systematic surveys and follow-up studies, we were able to build up a picture of the initial conditions of low-mass star formation, as arising from self-gravitating condensations of about one solar mass extending about 0.1 parsec[†], supported mainly by their internal thermal motions at a temperature of about 10 K [b, c]. The role of dense cores in forming stars was confirmed by observations with the Infrared Astronomical Satellite (IRAS). Many of the cores found with our Haystack surveys proved to harbor previously unknown IRAS protostars [d]. The core properties we identified also matched theoretical models of gravitational collapse and star formation [e].

After the Haystack antenna upgrade in 1993, our group used line observations at 3-millimeter wavelength to study the motions in and around cores. With Chang Won Lee and others, we found that the densest cores present line shapes whose blue-skewed asymmetry indicates inward motions at about half the sound speed. These motions may be
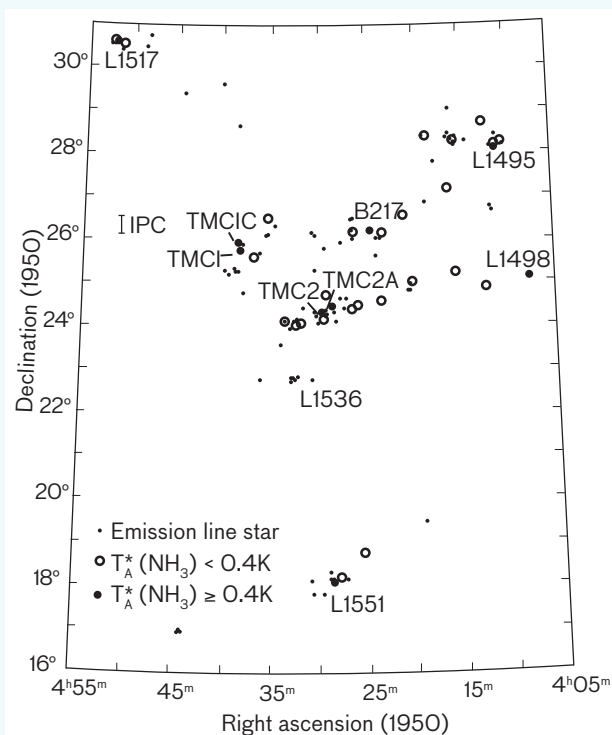
FIGURE A1. The figure gives a comparison of the positions of emission-line stars in Taurus-Auriga (small filled circles) with positions where dense cores were sought and found (large filled circles) or sought and not found (large open circles). Dense cores were found more frequently in groups of emission-line stars (9 out of 20) than away from groups of emission-line stars (1 out of 8); adapted from Figure 4 of Myers and Benson [b].

due to the processes of core formation and gravitational contraction [f, g].

This research produced more than 20 papers describing Haystack observations, and numerous additional analysis and follow-up papers. Together these papers have received more than 4000 citations in refereed journals. I am grateful to Joe Salah and to many other Haystack Observatory staff members for their outstanding support.

† parsec is an astronomical unit of length equal to about 31 trillion km or 3.26 light years.

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Philip C. Myers is a senior astrophysicist at the Smithsonian Astrophysical Observatory, which is a member of the Harvard-Smithsonian Center for Astrophysics. He studies star formation and molecular clouds with observations at radio, millimeter, and infrared wavelengths, and with theoretical models. His research has focused on properties of dense cores, protostar evolution, the role of magnetic fields in star formation, the structure and contraction motions of star-forming clouds, young clusters, and the initial mass function of stars. He has published more than 250 papers in refereed journals. As a radio astronomer at Haystack Observatory, he has helped to develop receivers, carried out numerous observational programs, and served on the Committee on Operations and Plans.

Leveraging its extensive experience in the development of instrumentation for VLBI, Haystack Observatory has led the formation of the Event Horizon Telescope (EHT), a project to create a system of existing submillimeter telescopes as VLBI stations for observing supermassive black holes (Figure 17). Twelve institutions began the collaboration with Haystack Observatory to develop the EHT: Arizona Radio Observatory at the University of Arizona; Harvard-Smithsonian Center for Astrophysics in Massachusetts; Radio Astronomy Laboratory at the University of California–Berkeley; Joint Astronomy Centre–James Clerk Maxwell Telescope on Mauna Kea, Hawaii; California Institute of Technology Submillimeter Observatory; Combined Array for Research in Millimeter-wave Astronomy in California; Max Planck Institute for Radio Astronomy in Germany; National Astronomical Observatory of Japan; Institut de Radioastronomie Millimétrique in France; National Radio Astronomy Observatory; Academia Sinica Institute for Astronomy and Astrophysics in Taiwan; and Large Millimeter Telescope in Mexico.

The EHT is made possible by the digital revolution. Detecting small-scale structures around supermassive black holes requires very sensitive VLBI stations. Existing submillimeter telescopes are being outfitted with modern digital back ends and recording systems, which can process much wider bandwidths much more cheaply than can analog systems. The EHT uses digital beamformers to sum the collecting area of interferometers into single VLBI elements with an equivalently large aperture. Haystack Observatory is leading an international team to produce a beamformer for the Atacama Large Millimeter/submillimeter Array in Chile, which, when completed, will be the most sensitive submillimeter VLBI station on the planet [41].

Observations made by the EHT in recent years have produced high-profile scientific results. Observations of Sgr A* have made a compelling case that the black hole must have an event horizon. The extremely compact emission that has been detected, most likely from a very hot accretion disk that is inclined to the line of sight, has allowed strong constraints to be placed on the black-hole spin vector (Figure 18) [42–44]. Detections of the similarly compact emission around the black hole in the M87 galaxy have shown that the prominent jet is fed by winds from the inner edge of an accretion disk in prograde rotation around a rapidly spinning black hole [45].
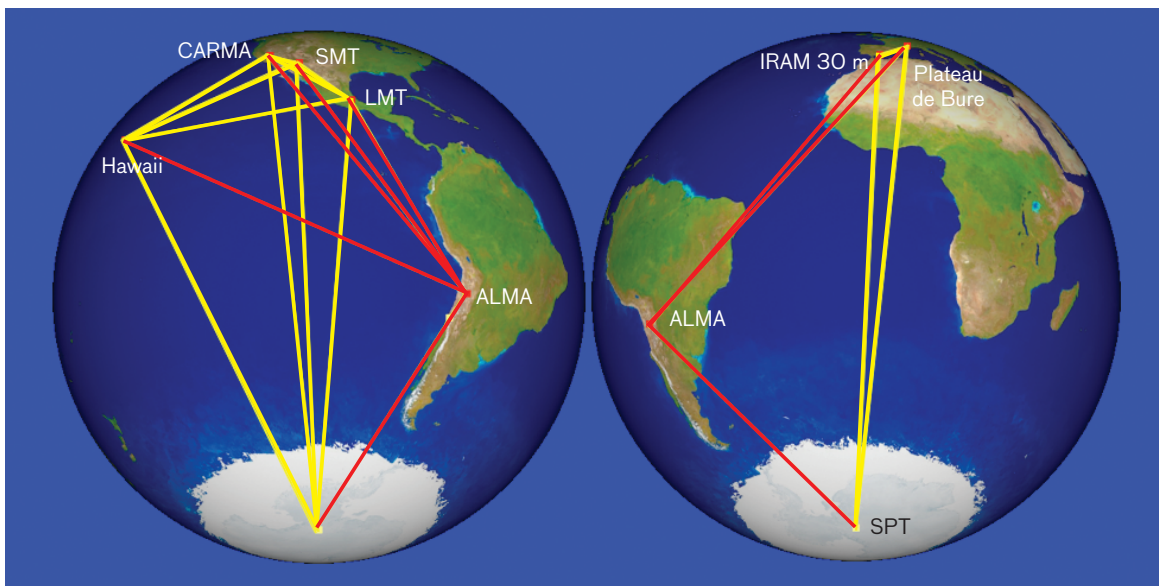

FIGURE 17. The two views of the Event Horizon Telescope (western and eastern sets of antennas/baselines) are shown from the direction of the center of our galaxy. The lines indicate the interferometer baselines of the array, and the red lines highlight the extraordinarily sensitive baselines to the Atacama Large Millimeter/submillimeter Array (ALMA). CARMA is the Combined Array for Research in Millimeter-wave Astronomy; SMT is the Submillimeter Telescope; LMT is the Large Millimeter Telescope; IRAM is the Institut de Radioastronomie Millimétrique; and SPT is the South Pole Telescope.
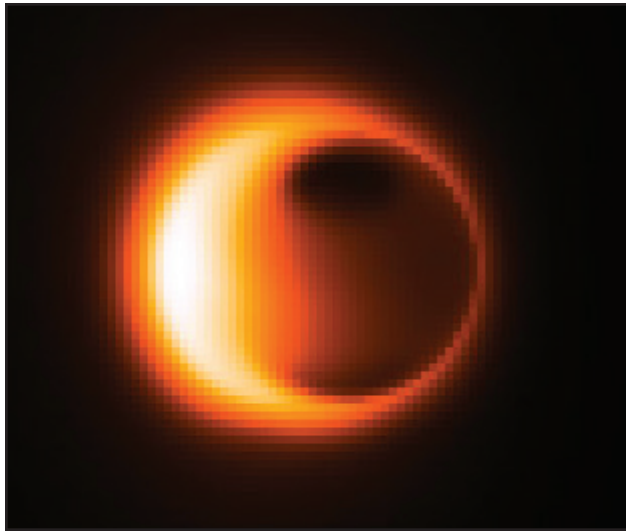
FIGURE 18. This model shows the hot accretion flow around the black hole in the center of the Milky Way galaxy (courtesy of Avery Broderick, Perimeter Institute for Theoretical Physics, Canada). The black-hole spin vector is oriented upward, and the approaching side of the accretion flow (on the left side) is enhanced because of relativistic Doppler boosting. General relativity predicts a dark circular shadow surrounded by a bright ring with a diameter of about 50 microarcseconds.

Upgrades currently under way for the EHT include the installation of extremely wide-bandwidth equipment capable of recording 64 gigabits per second at both new and existing sites. The upgrades will transform the EHT into an extremely sensitive, global array. The baseline coverage of the completed EHT will be sufficient to image the black hole "shadow" predicted by general relativity. The completed EHT will be able to detect small structures in the accretion flow around Sgr A* on timescales much shorter than the innermost stable circular orbital time period of a few minutes, allowing scientists to probe the Kerr space-time metric around the black hole. Full-polarization observations will be able to track rapid changes in the structure of the magnetic field, which are believed to be dynamically important in modulating the accretion flow and launching jets. In sum, by creating an Earth-sized telescope, MIT Haystack Observatory is reimagining what is possible in the study of black holes, and will soon be making observations to image and time-resolve these exotic objects.

Future Directions

Haystack Observatory continues to be a center of excellence specializing in projects at the intersection of science and technology. By developing technology for radio science applications, the observatory advances its mission to study the structure of our galaxy and the larger universe, to advance scientific knowledge of our planet and its space environment, and to contribute to the education of future scientists and engineers.

Rapid advances in digital technologies will enable future innovation, cost reduction, and performance enhancement across a wide range of radio science instrumentation, thereby providing new opportunities to achieve mission goals. The recently upgraded 37-meter telescope, now called the Haystack Ultrawideband Satellite Imaging Radar, will be used for astronomical measurements that will enrich the observatory's ability to make important scientific discoveries. From the Earth's atmosphere through the solar system and our own galaxy, to the distant quasars and the farthest reaches of the early universe, powerful new observing capabilities developed and deployed by Haystack Observatory promise to deliver exciting revelations and pose challenging new questions about our universe. ■

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ABOUT THE AUTHORS

Alan R. Whitney is a retired associate director and principal research scientist at Haystack Observatory, serving as interim director from 2006 to 2008 while the search for a new permanent director was executed following the retirement of long-time (23 years) director Joseph Salah. He joined the observatory in 1974 after spending the better part of several years there as an MIT graduate student under Prof. Irwin Shapiro. Most of his career has been associated with developing and using very-long-baseline interferometry (VLBI) for both astronomy and geodesy. He has also been very active in developing and promoting a number of international standards for VLBI in an effort to make VLBI both easier for everyone and more accessible for newcomers to this global enterprise. He received his bachelor's degree in 1966, master's degree in 1967, and doctoral degree in 1974, all from MIT in electrical engineering.

Colin J. Lonsdale is the director of MIT Haystack Observatory. He joined the observatory in 1986 as a research scientist, pursuing investigations into galactic and extragalactic radio sources of various kinds, using VLBI techniques. He served as scheduler for the U.S. VLBI network and developed software and techniques to support the geodesy applications of VLBI for NASA. He was promoted to principal research scientist in 2001, was appointed assistant director of the observatory in 2006, and assumed the directorship in 2008. More recently, he initiated and led a series of projects at Haystack involving low-frequency imaging arrays, with particular emphasis on systems designed to achieve wide fields of view. He received his bachelor's degree in astronomy and applied mathematics from the University of St. Andrews, Scotland, in 1978, and his doctorate in radio astronomy from the Victoria University of Manchester, Jodrell Bank Observatory, U.K., in 1981.

Vincent L. Fish is a research scientist at Haystack Observatory. He specializes in VLBI of celestial objects at centimeter and millimeter wavelengths. After completing a doctoral thesis and postdoctoral research studying astronomical masers in star-forming regions, he joined Haystack in 2007 and became involved with the Event Horizon Telescope project. He earned bachelor's degrees in physics, mathematics, and Earth, atmospheric, and planetary sciences from MIT in 1997, and a doctorate in astronomy from Harvard University in 2004.