CHAPTER 8

VLBI and the Very Long Baseline Array

Beginning in the 1950s radio interferometers and arrays of antennas were connected by cable, waveguide, or radio links separated by up to a hundred kilometers or more. Starting in 1967, radio astronomers in the US and Canada began to experiment with independent local oscillators and broad band tape recorders to record data collected by widely separated antennas, a technique which came to be known as Very Long Baseline Interferometry or VLBI. Using radio telescopes spread throughout the United States, Australia, and Europe, VLBI baselines were increased to thousands of kilometers, and ultimately to space, with baselines ranging out to hundreds of thousands of kilometers.

Within the United States, the informal US VLBI Network initially managed the complex logistics of organizing simultaneous observations by many radio telescopes, each with their own management and their own scientific programs. European radio astronomers later organized the European VLBI Network (EVN). The non-optimum location of the antennas being used for VLBI and the difficulty of scheduling observations flexibly led NRAO to construct the Very Long Baseline Array (VLBA), consisting of ten 25 meter diameter antennas spread throughout the United States from St. Croix in the US Virgin Islands to Hawaii. With an angular resolution as good as 0.0001 arcsec, the VLBA was the highest angular resolution telescope in the world. Observations with the VLBA have revealed the nature of jets ejected from the supermassive black holes found in quasars, shown the structure of cosmic masers associated with the birth and death of stars, determined the expansion rate of the Universe independent of the traditional cosmic ladder, measured the rotation of the Milky Way, and determined with great precision the relativistic bending of radio waves.

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8.1 Independent-Oscillator-Tape-Recording Interferometry[1]

With its overall dimensions of 35 km, the Very Large Array (VLA) at the time represented about the longest practical interferometer baseline with direct electrical connections. As early as the 1950s and 1960s radio astronomers at Jodrell Bank, led by Henry Palmer, began to experiment with radio links to provide a common frequency reference and to return the data from a remote antenna to Jodrell Bank, where they were correlated with data from the Jodrell Bank 250 foot antenna. In a series of elegant observations, they gradually extended their interferometer out to baselines of 115 km to show that some radio sources were smaller than an arcsec (Allen et al. 1962). Later the Jodrell Bank radio astronomers teamed up with a group at the Malvern Royal Radar Establishment to link two antennas separated by 127 km. Observing at wavelengths as short as 6 cm, Palmer et al. (1967) were able to demonstrate that some radio sources were as small as 0.05 arcsec. The Jodrell Bank to Malvern radio link involved two repeater stations. Extension to longer baselines was impractical or at best would exceed radio observatory budgets.

However, motivated by the Jodrell Bank results, the rapid variability of radio quasars,[2] the observation of low frequency cutoffs in the quasar radio spectra,[3] and observations of interplanetary scintillations,[4] several radio astronomy groups around the world had begun to think about further extending interferometer baselines using atomic frequency standards as independent oscillators and high speed (broad bandwidth) tape recorders to record the data at each end of the interferometer for later playback and correlation.

Early VLBI Development The first serious discussions of independent-oscillator-tape-recorder-interferometry apparently took place in Moscow in early 1962 (Matveyenko et al. 1965). Realizing the potential applications of this powerful technique, the Russian scientists wanted to publish and patent their ideas, but were thwarted by Soviet bureaucracy and secrecy (Matveyenko 2013). The following year, during Jodrell Bank Director Bernard Lovell's visit to the USSR, Leonid Matveyenko discussed the possibility of doing interferometry between Jodrell Bank and the USSR. However, neither Jodrell Bank nor the Russians were able to develop or obtain the needed instrumentation, and nothing resulted from these discussions. Matveyenko, Nikolai Kardashev, and Gennady Sholomitsky (1965) were finally able to publish their paper, but they wrongly concluded that the sensitivity depended inversely on the interferometer baseline length because they incorrectly assumed that integration times were limited by the natural fringe rate.

VLBI became a practicality as a result of three key technical advances: precision atomic clocks to provide precise time and frequency,[5] high speed tape recorders capable of recording the broad bandwidths needed to obtain adequate interferometer sensitivity,[6] and fast digital computers to correlate the data, all of which became commercially available in the mid-1960s. Starting in

1965, unaware of the Soviet work, two groups, one in Canada and one in the United States, began to develop a VLBI capability. The Canadian group used analog-type tape recorders, which had just become popular in the TV industry, to record a 1 MHz IF bandwidth. The observing frequency was 448 MHz (67 cm), and time synchronization was facilitated by simultaneously recording timing data on the audio track. In order to compensate for any timing uncertainties, the speed of one of the playback systems was adjusted until the appearance of interference fringes signaled proper time alignment.[7]

The NRAO program was initiated by NRAO scientists Barry Clark and Ken Kellermann, who were joined by Professor Marshall Cohen from Cornell and David (Dave) Jauncey, a Cornell postdoc who had just arrived at Cornell from Australia as part of the new Cornell-Sydney University Astronomy Center. After informal discussions between Cohen and Kellermann in August 1965, the following month Kellermann approached NRAO Director David Heeschen about possible funding to develop a tape-recording independent-oscillator interferometer. When asked about the cost, Kellermann was caught off guard as he and Cohen had not really thought about cost, so he threw out a guesstimate of $100,000. After a brief pause to check the status of the NRAO budget, Heeschen responded with, “Will $50,000 be enough until the end of the year?” That was it! No proposal. No review committee. No debates within NRAO or discussions with the radio astronomy community. Work could begin immediately. A few days later, however, perhaps perceiving that this might become a big enterprise, or perhaps just wanting to cover himself in case it was a failure, Heeschen asked for a short written proposal which was quickly produced.[8] An equally brief proposal was submitted to Cornell which shared in the development costs.[9] Heeschen’s formal request to the NSF to include $100,000 in the budget for “an independent local oscillator interferometer” came six months later.[10]

The NRAO group chose to use digital rather than analog recordings. The sensitivity of a digital interferometer depends on the number of bits recorded and correlated. This, in turn, is proportional to the product of the observing time and the bandwidth (bit rate). The length of the integration time is limited by the coherence of the independent local oscillators or the atmosphere and ionosphere. Since each bit is recorded at a precise time determined by an atomic clock, the digital recording is self-clocking which reduces the need for precise stability of the record-playback system. The data are then precisely aligned in time in the playback computer. By storing and shifting the data bits, it was easy to examine a range of time alignments to compensate for any uncertain timing or antenna location. In order to minimize development costs and to be able to do the correlation in a general purpose computer, NRAO used standard computer reel-to-reel tape drives to record one-bit digital data at 720 kilobits per second (kbps) appropriate to sampling a 360 kHz bandwidth at the Nyquist sampling rate.[11] Each 12-inch reel of tape lasted about three minutes, and it took about an hour to correlate each pair of tapes in the NRAO IBM 360/50 computer.

Fig. 8.1 Hewlett-Packard Model 5065A Rubidium frequency standard and power supply used to maintain time and to determine the local oscillator frequency for the early NRAO VLBI experiments. Credit: NRAO/AUI/NSF

To optimize the sensitivity and to compensate for the necessarily narrow bandwidth which was limited by the recording system, the NRAO-Cornell team planned to use the 1000 foot Arecibo radio telescope at one end of the interferometer baseline and the newly completed Green Bank 140 Foot Telescope at the other. Claude Bare from the NRAO Electronics Division joined the team to provide engineering support. The commercially available Hewlett Packard HP 5065A Rubidium standard (Fig. 8.1) was used as the time and frequency reference.[12] Considering the advertised frequency stability of one part in 10^{11}, NRAO felt that this would be adequate for operation at 611 MHz (50 cm) for integration times up to a few hundred seconds. At the time, this was also the highest frequency where the Arecibo telescope was operating.

Two approaches were considered to synchronize the separate clocks at each end of the interferometer. The most straightforward method was to first bring a running clock to Washington by car, where it was synchronized with the US master clock at the US Naval Observatory (USNO), and then driven to Green Bank where it would be synchronized with a second clock, which would then be carried by car or by commercial airline to the other end of the interferometer baseline. Since transporting clocks more than a few hundred miles was impractical, the NRAO group also used the 100 kHz LORAN C stations located along the east coast of the United States and at several offshore European sites. Each LORAN C station broadcast a characteristic time code that was synchronized with the USNO master clock.[13] At nighttime when ionospheric disturbances were low, the timing signals could be measured with an accuracy of a few microseconds.

Serious development work at NRAO began in late 1965 with the design of the recording hardware by Claude Bare and the correlator software by Barry Clark. A friendly rivalry developed between the NRAO and Canadian groups, with frequent telephone exchanges reporting successes and problems. As described by Norman Broten (1988),

> During all of this time Kellermann and I had stayed in touch. It was a remarkably friendly competition between the two teams striving to be the first to use successfully tape-linked interferometry. Scarcely a week would go by without the phone ringing, either in Ottawa or at Green Bank, to keep both teams abreast of each other's progress. … Later in the experiment the response to a telephone call would be "Got any fringes yet?"

All of the US participants were, at the same time, involved in other projects. Bare was responsible for supporting other Green Bank digital systems; Clark, Cohen, Jauncey, and Kellermann all were pursuing various observational programs, and Clark was busy with the VLA design (Chap. 7). Probably the project did not proceed as fast as might have been possible, but following successful bench tests in October 1966, NRAO sent one of the recording terminals to Arecibo for the first observations. Jack Cochran, then an NRAO technician, traveled to Puerto Rico to install and operate the equipment. Somehow Pan American Airlines lost track of the shipment, which was finally inexplicably traced to a warehouse in Baltimore. Tired of waiting, Cochran had returned to Green Bank to spend the Thanksgiving holidays with his family.

Following Cochran's return to Puerto Rico, the first observations between Green Bank and Arecibo were finally made in January 1967, but were unsuccessful. There were no interference fringes observed. A second experiment in February was equally unproductive, and it was never clear what was wrong with either set of those first observations with Arecibo. All of the equipment was returned to Green Bank to be carefully checked. On the night of 5–6 March 1967, the NRAO group ran a successful test on a 650 meter baseline between the 140 Foot Telescope and one of the 85 foot antennas of the Green Bank Interferometer. Interference fringes were readily found the next day after correlation on the Charlottesville IBM 360/50 computer.

The first successful observation using well-separated antennas was on 8 May 1967, again using one of the Green Bank 85 foot antennas and the Naval Research Laboratory 85 foot antenna at Maryland Point (Fig. 8.2), a distance of 220 km or 460,000 wavelengths at 610 MHz (Bare et al. 1967). Three sources, 3C 273, 3C 286, and 3C 287, were unresolved and demonstrated that the system worked as expected. However, considering the relatively long wavelength, the resolution was no better than had been previously obtained by the Jodrell Bank-Malvern radio linked interferometer at 6 cm (Palmer et al. 1967).

Fig. 8.2 NRL 85 foot radio telescope at Maryland Point, used together with the Howard Tatel 85 Foot telescope in Green Bank for the first successful NRAO VLBI observation. Credit: NRL

Probably the first successful VLBI observations of real astrophysical interest was by the Canadian group using a 3074 km transcontinental baseline at 448 MHz (67 cm) between the Algonquin Park 150 foot radio telescope and a 25 meter antenna located at Penticton, British Columbia. These observations were made on 13 April 1967, nearly a month before the Green Bank-Maryland Point observations, but they were not able to successfully correlate the data until 21 May, a few weeks after the US data were correlated. The Canadian observations directly demonstrated that several quasars were less than a few hundredths of an arcsec in diameter. Both groups reported their results at the August 1967 URSI Radio Science Meeting held in Montreal.

Meanwhile, an MIT/Haystack group was using a radio-linked interferometer on a 13.4 km baseline between the Millstone Hill 84 foot antenna and the Agassiz 60 foot radio telescopes to show that OH maser sources appeared unresolved with angular dimensions less than a few arcsecs (Moran et al. 1967a). These maser sources were highly variable and so were expected to be very small. In June 1967, the MIT/Haystack group joined forces with the NRAO/Cornell group to observe both quasars and OH masers on a 845 km baseline between the Haystack 120 foot radio telescope and the Green Bank

140 Foot Telescope. These observations showed that both quasars (Clark et al. 1968a) and 1.7 GHz OH masers (Moran et al. 1967b) had angular structures less than a few hundredths of an arcsec.

In August 1967, both the MIT/Haystack and NRAO/Cornell groups used the 85 foot radio telescope at the University of California Hat Creek Observatory together with the Green Bank 140 Foot Telescope to extend the interferometer baseline to 3500 km to demonstrate structures on scales less than 0.01 arcsec (Clark et al. 1968b; Moran et al. 1968). Also in August, the Green Bank-Arecibo baseline finally gave results at 611 MHz (Jauncey et al. 1970). The next step was to go to shorter wavelengths, but negotiations with the University of California to install a 6 cm receiver on the Hat Creek Telescope fell through. Coincidently, at about the same time, Olaf Rydbeck, head of the radio astronomy program at the Swedish Onsala Space Observatory, was asking his former student, Hein Hvatum, how they could get into VLBI. An observational program was quickly formulated, and recorders and clocks were shipped to Sweden for a January 1968 experiment at both 6 and 18 cm. The Green Bank-Sweden baseline was 6319 km long, and showed that some quasars and active galactic nuclei (AGN) were smaller than one thousandth of an arcsec. This was the highest angular resolution ever obtained for any astronomical observation; indeed, probably for any measurement. One thousandth of an arcsec is equivalent to reading ordinary newsprint at a distance of 100 miles.

These were exciting times for the NRAO VLBI group, who shipped or carried tape recorders, receivers, atomic clocks, and many pounds of magnetic tape to radio observatories around the world. Within a year, interferometer baselines had increased to intercontinental distances and the angular resolution to better than one thousandth of an arcsec. Although the principles were straight forward, there were enormous technical and logistical challenges to obtaining agreements to use antennas at observatories that may have been scheduled for other programs, shipping materials and supplies, synchronizing clocks, and dealing with failed atomic clock batteries, as well as building and installing new, often untested equipment at unfamiliar observatories. Anything that could go wrong, often did go wrong. Unlocked oscillators, time synchronization errors as large as one second, crossed polarization, incorrect wiring, and wrong frequency settings were not uncommon, and any one such error would lead to no fringes, which generally wasn't discovered until after the experiment was over.

The MK I[14] VLBI System was used extensively from 1967 to 1971. Observing was very labor intensive. An experienced person could record, rewind, dismount, and mount a new tape in 12 minutes, but two or three observers were needed at each telescope to support a multi-day observing session. On occasion, more tape would accidently end up on the floor than on the rewind reel. More than 100 tapes were recorded at each station in a single 24 hour observing session. A three station experiment meant three baselines had to be correlated, one at a time; a four station experiment, six baselines. So a single 24 hour experiment could mean 300–600 hours of playback at the NRAO IBM 360/50 in Charlottesville.

In 1966, Marshall Cohen left Cornell for the University of California San Diego, and two years later moved to Caltech, where he started a major VLBI program. Many of the later VLBI leaders were trained at Caltech as students or as postdoctoral fellows. Caltech operated a 360/75 machine that was able to correlate MK I VLBI tapes about five times faster than the NRAO 360/50, but the normal charges to use this facility to process VLBI tapes were prohibitive. Instead, Cohen was able to arrange to use time late at night at no charge, but only if he provided the personnel to run the machine and change tapes. Following the completion of the Caltech OVRO 130 foot radio telescope in 1968, when it was no longer part of the proposed Owens Valley Array (Sect. 7.2), the 130 foot became a workhorse for VLBI.

Meanwhile, the Canadian group continued their observations at 408 and 448 MHz with a total of ten successful single baseline observations extending across Canada and to Jodrell Bank (Broten et al. 1969; Clarke et al. 1969). Many of the experiences and logistical problems encountered by the NRAO group were experienced as well by the Canadian VLBI observers (Broten 1988). In particular, the Canadian group had replaced their studio TV recorders with the less reliable but more portable Ampex VR600 recorders (Sect. 8.4).

8.2 Penetrating the Iron Curtain

Following the 6 cm VLBI observations with baselines to Sweden (Kellermann et al. 1968), VLBI had quickly reached a resolution of about 0.001 arcsec (1 milli-arcsec). Many sources, particularly quasars, still had unresolved features. The longest baselines were already a significant fraction of the Earth's diameter, so it was clear that the only way to further improve the angular resolution would be to go to shorter wavelengths or to space, but the only radio telescopes outside the United States that could work at short centimeter wavelengths were located in the Soviet Union. Although this was during the depths of the Cold War, in February 1968, Marshall Cohen and one of the authors (KIK) boldly wrote to Viktor Vitkevich, a well-known leader of Soviet radio astronomy, suggesting a VLBI experiment between the NRAO 140 Foot Telescope and the Lebedev Physical Institute's precision 22 meter antenna located at the Puschino Observatory near Moscow. Although both Cohen and Kellermann had previously met Vitkevich, they did not realistically expect that a US-USSR VLBI experiment involving the exchange of highly sensitive atomic clocks and high speed tape recorders would be feasible, so were not surprised when they initially received no response to their letter.

But to their pleasant surprise, after five months Vitkevich responded by telegram, followed by a letter from his colleague Leonid Matveyenko, reporting that the proposed experiment had been approved by the Soviet Academy of Sciences. However, Matveyenko suggested that instead of using the 22 meter dish at Puschino, the program use the more precise 22 meter dish in Crimea.

Much later, NRAO learned that during the five month period before sending his response, Vitkevich, with the aid of the Soviet astrophysicist Iosef Shklovsky, had sought and gained approval not only from the USSR Academy of Sciences but also from the Soviet political and military authorities (Matveyenko 2013).

In spite of the Cold War tensions there were no objections from NRAO or the NSF to the proposed experiment, but NRAO first had to obtain an export license from the US Department of Commerce for all of the specialized equipment that would be temporarily sent to the USSR, including a commercial atomic clock and a high speed computer tape recorder.[15] There was an additional, potentially more serious military concern. VLBI observations are used by radio astronomers to investigate the size and structure of cosmic radio sources, but there are also a variety of terrestrial applications, including the precise determination of the Earth's axis of rotation as well as the distance between the two antennas that form the interferometer. It was just these two quantities that are needed for the precise delivery of ICBMs. While the Soviet government had similar concerns, there was a curious asymmetry. Since accurate US maps were publicly available, any American adversary could derive the distance from the Crimean radio telescope to any potential US target, such as the Pentagon, the White House, or a US based missile site. However, since maps of the USSR were not accessible to Americans, or to anyone outside of those who needed to know, there was no reciprocity. Indeed, it was widely recognized that even tourist maps of Moscow were deliberately distorted.

Clark and Kellermann were not surprised to receive a visit one day in Green Bank from two men who identified themselves as representing the US Defense Intelligence Agency. They wanted to know all the details of the proposed observations. It was clear from the questions asked that they were remarkably familiar with VLBI and what it could and could not do. They correctly noted that it would be easily possible for NRAO to corrupt the baseline and Earth rotation information without compromising the intended astronomical goals of the proposed experiment, but NRAO refused to take part in any such charade. In the end, it was agreed that since accurate global mapping was becoming widely available from satellite imaging, there were really no security concerns as long as either Clark or Kellermann were present with the equipment at all times. Rather, it appeared that the intelligence agencies on both sides recognized that there were no secrets in this business, but their goals were to not make it easy for the other side, and to not give away information.

Following a visit from two Russian scientists to Green Bank,[16] the first observations were scheduled for October 1969 at both 2.8 and 6 cm. The ensuing program turned out to be a logistical challenge. All of the NRAO instrumentation and 25 cartons of magnetic tape were sent by air to Moscow, where it was supposed to be sent on to Crimea. However, the Russians claimed that the tape recorder was too big to fit into the cargo hold of a Russian jet, so arrangements had to be made to send it by train. But the recorder was also over the train weight limit, and required an appeal for a waiver from the Soviet Academy of Sciences. Telephone or telex communications between the USSR and the US were at best unreliable. Calls had to be booked in advance, perhaps to give the intelligence agencies on both sides the opportunity to listen. Often one side or the other would be barely audible, and after a few minutes of yelling, the connection would be broken.

The biggest problem concerned the synchronization of the atomic clock in Crimea with the one in Green Bank.[17] Normally, VLBI observations made use of the extensive network of LORAN C stations established to facilitate navigation. Each LORAN C station broadcast accurate timing signals that were synchronized by periodic visits from USNO personnel carrying an atomic clock that had been synchronized to the master clock at the US Naval Observatory in Washington. However, the LORAN C station in Turkey, just across the Black Sea from the Crimean radio telescope, had not yet been synchronized with Washington. The backup plan was to synchronize the clock in Leningrad using a LORAN C station in the Baltic Sea and to carry the running clock by plane to Crimea. But the American LORAN C transmissions were blocked by a powerful Soviet imitation. The Russian radio astronomers denied any knowledge of any such Soviet transmission, but it later turned out that it was well known to the Swedish timekeeping service. Plan C involved shipping a running atomic clock from Sweden, recharging the batteries at the Leningrad Pulkova Observatory, and then flying it to Crimea. Since the batteries had died during the first flight from Leningrad to Crimea, the clock was returned to be resynchronized. The running clock was then placed on the floor of the commercial flight along with a backup car battery. The American and Russian radio astronomers, equipped with their voltmeter, ran back and forth from their seats to check on the health of the battery during the flight. With hindsight it is hard to believe that the Soviet authorities allowed such activities, which might be compared with having Russian scientists playing with a lot of sensitive equipment on an American flight from New York to Miami.

The scheduled observations were split into two parts, with a gap of several weeks to allow time for the tapes to be correlated in Charlottesville. A few of the first tapes recorded in Crimea were hand carried to Moscow, but when it turned out to be difficult to arrange for them to be shipped by air freight to New York, they were just given to a PanAm pilot at the airport with instructions that they would be picked up by a colleague at New York's Kennedy Airport. During the gap between the two observing sessions, the NRAO scientists were taken on an escorted trip to Armenia and Uzbekistan. Many years later, it was learned that as soon as the Americans left Crimea on their trip, KGB engineers arrived to take careful notes and photographs of the sensitive US instrumentation.

After a few false starts, characteristic of the early VLBI experiments, the observations were successfully completed over the 8035 km long baseline and resulted in the then record angular resolution of 0.0004 arcsec, or only a few light-years at the distance of the quasar 3C 273 (Broderick et al. 1970). Following the close of the marathon observing session, the Russian scientists insisted on celebrating the occasion with toasts to VLBI and to continued

Fig. 8.3 From left to right, Ivan Moiseev, John Payne, and Viktor Effanov celebrate the conclusion of the first US-USSR VLBI observations in October 1969. Seated is an unnamed member of the Crimean radio telescope staff. Credit: KIK/NRAO/AUI/NSF

Russian-American friendship. While the Americans were able to deal with the Russian beer and vodka, it was a challenge to keep up with the Russian hosts who downed shots of (nearly) pure (190 proof) alcohol washed down with beer (Fig. 8.3).

Two years later, a second experiment, this time at wavelengths as short as 1.3 cm, using NRAO's new MK II VLBI recording system gave another factor of two improvement in resolution (Burke et al. 1972). In subsequent years the Russian radio astronomers, led by Leonid Matveyenko, built their own MK II compatible recording and playback systems. Russia became a regular participant in global VLBI observations using a variety of radio telescopes located throughout the USSR, and in 2011 launched the very successful space VLBI mission, RadioAstron (Sect. 8.9), extending VLBI baselines to more than 250,000 km in length.

It was only through the cooperation and support of the Soviet Academy of Sciences, Aeroflot, and governments on both sides that it was possible to rise above the pervading culture to carry out one of the few scientific collaborations of that Cold War period that involved the exchange of sensitive instrumentation. Although there had been a long-time exchange program between the US and the Soviet Academies of Science, it was typically shrouded on both sides in suspicion of the visiting scientists. The support of the Soviet Academy and the US government to grant the needed export license was crucial, as the USSR VLBI experiments were perhaps unique in that they were initiated and organized from the ground up by the participating scientists, with a minimum of government or even institutional involvement.

The good will established by the 1969 joint experiment nearly evaporated when the return shipment of the atomic clock, tape recorder, state-of-the-art digital instrumentation, as well as 25 cartons of recorded computer tape, apparently disappeared. As part of the agreement with the Commerce Department, NRAO had agreed that the Russians would return all of the American instrumentation immediately after the experiment was concluded. When the purported shipment apparently did not arrive in the US, NRAO followed with two weeks of frantic queries to PanAm and Aeroflot, along with a series of telegrams to the USSR with increasing concern and threats about the impact to future exchanges. To the embarrassment of NRAO, everything turned up in an Air France warehouse in New York where it had been sitting for two weeks. To avoid a repetition of this awkward situation after the 1971 experiment, the NRAO team was taken to the Moscow airport to witness the loading of the return shipment on an Aeroflot plane bound for New York. Sitting in the truck on the tarmac, as the plane left the ground, Matveyenko proudly informed the NRAO group, "Now it is your problem."

8.3 Faster than Light

In October 1970, an MIT/Haystack group observed the strong quasars 3C 273 and 3C 279 at 7840 MHz (3.8 cm) on a 3900 km baseline between the Haystack 120 foot antenna near Tyngsboro, MA and the NASA Deep Space Network Goldstone 210 foot dish near Barstow, CA (Knight et al. 1971). Both antennas used low noise maser amplifiers to give improved sensitivity over earlier observations, as well as hydrogen maser frequency standards for improved phase stability. These observations, colloquially referred to as "Goldstack," were not intended to study the structure of compact radio sources, but to measure the apparent change in the relative position of 3C 279 due to relativistic bending as it passed close to the Sun.[18] Nevertheless, for the first time, the observed fringe amplitudes were of sufficient quality to show unambiguously that both sources contained at least two distinct components. The separation of the two components was accurately determined as only 0.005 arcsec.

Four months later, in February 1971, both Whitney et al. (1971) and Cohen et al. (1971) repeated the October observations using the same equipment. Cohen et al. observed 31 sources including 3C 273 and 3C 279. Irwin Shapiro had made the October 1970 results available to the NRAO-Caltech group, who wanted to see if there had been any changes in their structure since the Knight et al. observations made four months earlier.

By this time, Cohen had moved to Caltech, and he assigned third-year graduate student David Shaffer[19] the task of analyzing the data which had been correlated on the Caltech IBM 360/75.[20] When Shaffer plotted the data, he was surprised to note that 3C 279 had changed in a manner reflecting an increase in the separation of the two components. Knowing the distance of 3C

279, Shaffer calculated the speed of separation to be three to four times the speed of light and burst into Cohen's office to pronounce his discovery. The results for 3C 273 were less clear, but also indicated component motion greater than the speed of light, a phenomenon which came to be referred to as "superluminal motion."

Although they were initially alarmed at this apparent violation of special relativity, Cohen et al. (1971) soon realized that superluminal motion had, in fact, been previously predicted by Martin Rees (1967). A long-standing problem of astrophysics was that the rapid variability of the powerful radio emission from quasars seemingly implied such small dimensions that they would rapidly self-destruct.[21] However, Rees pointed out that if the radio source was expanding or moving toward the observer at close to the velocity of light, the radiation would be focused along the direction of motion and so appear to be more luminous than it was if the radiation were assumed to be isotropic. Moreover, since the source of radiation was nearly catching up to its own radiation, any changes in luminosity seen by a distant observer located nearly along the direction of motion would appear to happen in a shorter time span than the intrinsic change. Thus, the apparent velocity could be arbitrarily large.

Whitney et al. (1971) also noticed the apparent superluminal motion when comparing their data taken four months apart. Both groups presented their results at the 13–14 April 1971 Rumford Symposium (Rogers and Morrison 1972) (Fig. 8.4). They considered alternate interpretations, including properly phased time variability in a set of stationary sources such as one observes on a

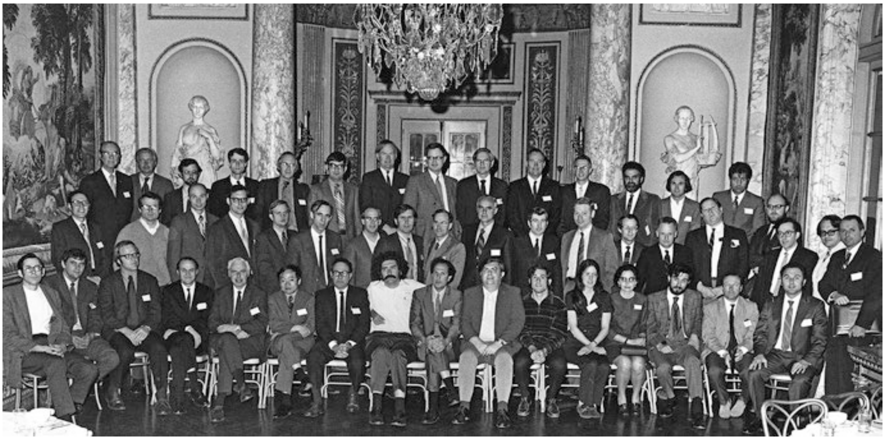

Fig. 8.4 Members of the NRAO-Cornell, MIT-Haystack, and Canadian VLBI teams gathered in Boston in April 1971 to receive the Rumford Medal of the American Academy of Arts and Sciences. From the NRAO-Cornell team, Dave Jauncey is seated in the front row 2nd from the left, Marshall Cohen, 7th from left, and Ken Kellermann, 9th from left. Barry Clark is standing in the rear center

movie marquee, or a searchlight effect where stationary material is excited by a shock front moving at an oblique angle. Also, because the Goldstack observations covered only a limited part of the Fourier Transform plane, it would be possible to reproduce the limited data with a time variable, more complex, but stationary morphology. Interestingly, the near equal double structure of 3C 279 observed in 1970/1971 has never been repeated. The actual structure of 3C 279 is indeed much more complex than a simple double, and the early interpretation of superluminal motion based on the limited data then available was probably premature, but nevertheless has been confirmed by later more detailed imaging of radio sources and their kinematics (e.g., Lister et al. 2016). However, perhaps the biggest challenge to superluminal motion came from the small but persistent group of scientists who argued that quasars are closer than indicated by their large redshifts, and so the observed angular motion would correspond to a much slower linear velocity (e.g., Burbidge 1978). These arguments continued for decades and only died when their proponents died.

8.4 Advanced VLBI Systems

The NRAO MK II VLBI System Although the NRAO digital VLBI system proved to be more reliable and easier to use than the Canadian analog system, there were several serious limitations. Tapes were expensive and only ran for three minutes, the tape drives were large and heavy and thus expensive to ship, and the narrow 360 kHz bandwidth limited the sensitivity. Processing time on general purpose computers was lengthy, which in some cases meant expensive. Nevertheless, compatible recording units were built at Haystack and used by CfA and NASA Goddard Space Flight Center (GSFC) for a series of geodetic studies. Soon after the first successful experiments, under the leadership of Barry Clark, NRAO began the design of an advanced recording system referred to as the MK II VLBI system. The NRAO MK II system used the same portable Ampex VR660C helical scan TV recorder then in use by the Canadian VLBI group, but recorded digital instead of analog data. Each reel of two-inch wide tape lasted for three hours instead of the three minute MK I tapes, weighed only about 10 pounds, and recorded a 2 MHz bandwidth with one-bit samples at 4 Mbps (Clark 1973). Initially seven record units were built by NRAO in cooperation with the Leach Corporation. Requiring only IF, 5 MHz, and a 1 pulse per second timing signals, the MK II units could be easily transported for temporary use at other observatories. By the end of 1976, 19 MK II units were in operation throughout the world either built by NRAO or built elsewhere following detailed designs made available by NRAO.

Allen Yen, one of the architects of the Canadian VLBI system, had advised NRAO against using the VR 660 recorder which the Canadians had found to be unreliable. Although the NRAO team anticipated that digital recordings would be more robust to timing irregularities or to imperfections in the tape itself, variations in the mechanical alignment among the different units used for

Fig. 8.5 Mark II VLBI correlator at NRAO offices in Charlottesville. Two reels of 2 inch wide tape are shown mounted on the VR660 video tape recorders. Credit: NRAO/AUI/NSF

recording and playback led to difficulties in playback, with losses in synchronization and unacceptably high error rates. An elaborate set of interactive mechanical adjustments in the playback units required considerable experience and skill to successfully play back MK II tapes (Fig. 8.5). Moreover, the recording problems were exacerbated by the use of government surplus tape, which turned out not be suitable for the VR 660 recorder. After years of frustration and unreliable observations, thousands of pounds of tape were buried in Green Bank. In 1976, at the suggestion of Yen, the record/playback units were replaced by the more reliable IVC 825 recorder that used one-inch wide tape. The IVC machines, manufactured by the International Video Corporation, proved to be more reliable than the VR 660s and required fewer adjustments on playback. But each reel of tape only lasted one hour, and playback errors were still a problem.

A major breakthrough occurred in the late 1970s with the introduction of the home Video Cassette Recorder (VCR). During the course of extended visits to NRAO, Caltech, and the Max-Planck-Institut für Radioastronomie (MPIfR) in Bonn, Germany, Yen developed remarkably inexpensive modifications which could be applied to consumer VCRs to record MK II compatible data. Each tape cost only a few dollars instead of a few hundred dollars, and could be inexpensively shipped by regular (customs-free) first class mail instead of the complex and costly air freight shipments required for the Ampex and

IVC tapes. With their simplicity, low cost, and wide-spread availability, dozens of MK II units were built and operated at radio observatories throughout the world, including Europe, Russia, China, South Africa, Brazil, and Australia. Global VLBI became a practicality, with some experiments using ten or more separate telescopes to obtain milli-arcsec images of unprecedented resolution and image quality.

Initially the MK II tapes were correlated one baseline at a time on a two-station correlator operated in Green Bank. Later the correlator was expanded to simultaneously play back tapes recorded at three telescopes and the spectroscopic capability was increased from 32 to 288 and finally 512 frequency channels. With the growing use of VLBI, the MK II correlator evolved from an experimental operation to an NRAO facility, and was moved from Green Bank to Charlottesville to enable easier access to visiting users. At first, VLBI investigators came to Charlottesville to operate the processor themselves, but with the growing demand for time and the complexity of the playback operation, trained operators provided support in the same manner as the NRAO telescope operators. As in the case for telescope users, NRAO helped to defray the cost of travel to Charlottesville, provided access to the NRAO computing facilities, and support for publication page charges. Other MK II correlators based on the NRAO processor were later built and put into operation in Germany, the USSR, and China for limited use by investigators in these countries.

Frustrated with the long delays at the NRAO correlator, Marshall Cohen and Arthur Niell of JPL built a two-station MK II processor at Caltech which was expanded to five stations in 1978. Later, in collaboration with JPL, Caltech built a large playback facility that allowed up to 16 MK II tapes to be simultaneously played back and correlated. The Caltech/JPL processor had no spectroscopic capability, but starting in 1986 it became the correlator of choice for multi-station MK II continuum observations (Cohen 2007).

The MIT/Haystack MK III VLBI System Not long after the first successful VLBI observations in 1967, NASA initiated an ambitious geodetic VLBI program initially using a MK I compatible recording system. In order to obtain increased sensitivity, a new broadband record system, known as MK III, was developed at the Haystack Observatory with NASA funding (Rogers et al. 1983). Like the NRAO MK I and MK II VLBI systems, the MK III system recorded 1-bit Nyquist sampled data but used a Honeywell Model 96 multi-track instrumentation recorder to simultaneously record up to 28 tracks each at up to 4 Mbps (2 MHz bandwidth) sustained rate, giving better than a five times improvement in sensitivity over the NRAO MK II system. Initially the tapes were all correlated in a special processor built at the Haystack Observatory, but other processors were later put into operation at the MPIfR and at Caltech/JPL. However, with a tape speed of 135 inches per second, each 9200-foot-long tape only held about 13 minutes worth of data. Since each reel of the one-inch wide tape cost about $250, the astronomy community continued primarily to use the less sensitive and less expensive MK II system. Although as early as

1975 there were fully developed plans within NRAO to build a large MK III correlator in Charlottesville, there were never sufficient funds to begin any construction. All MK III astronomy observations were correlated at Haystack, Caltech/JPL, or at the NASA Goddard Space Flight Center, and later at Bonn.

Real Time VLBI Although the advances in magnetic tape recordings allowed improvements in VLBI data rates and sensitivity, the recordings were often defective, resulting in large playback errors. Moreover, shipping the large quantities of magnetic tape was both expensive and logistically demanding. International experiments had additional complications requiring customs clearance, sometimes accompanied by demands for tariffs. On one occasion, when clearing tapes being returned to the US after being recorded in Australia, the Los Angeles Airport customs officer wanted to collect import taxes, even though the tapes were owned by the NSF and had only been sent to Australia a few weeks earlier. Apparently, as he explained, now that the tapes contained data they were more valuable, and so were subject to import taxes. As he tried to explain, Hollywood movies that were filmed abroad were taxed, but it was the movie content, not the film that was taxed. Fortunately, in that particular instance, whether it was because he was told that the tapes only contained noise and no information, or whether he just tired of arguing with astronomers who clearly had no money, he gave up and cleared the shipment.

Even more important than the cost, inconvenience, and reliability of magnetic tape recordings, as previously discussed, any one of a number of errors in timing, polarization, or other technical malfunctions could ruin observations, and it might be weeks or months before the tapes were correlated and the failure recognized. Several approaches to suitable long-distance, broad-bandwidth, real time data links were considered, including a series of microwave radio links, late nighttime use of the national television network, and communications satellites, but all appeared prohibitively expensive. In 1976 and 1977, a team of US and Canadian radio astronomers were able to obtain time on the Canadian Communications Technology Satellite (CTS) (later named Hermes) for a series of real time VLBI Observations, first between the Green Bank 140 Foot Telescope and the Algonquin Radio Observatory (ARO) 150 foot antenna, and later between OVRO and ARO (Yen et al. 1977). The CTS was a joint project of the Canadian Department of Communications and NASA, and was available at no cost for approved investigations.

The successful real-time CTS-based VLBI observations were made at 10.7 GHz (2.8 cm) using a 10 MHz wide IF bandwidth (20 Mbps data rate, five times that of the MK II tape recording system). The one-bit IF data streams were time stamped based on timing signals from independent hydrogen maser clocks at each end and sent from Green Bank, via the geostationary CTS transponder, to ARO where they were correlated in real time. Because there was an approximately 0.25 second delay in the signal from Green Bank arriving at ARO, Benno Rayher at NRAO built a 0.27 second 5.5 million-bit delay line for the 20 Mbps ARO data stream. Small fluctuations in the data path length were accommodated by the 64 channel (3.2 μsec) correlator built by Yen at the University of Toronto.

As with tape recording VLBI, the hydrogen masers also provided independent coherent local oscillator reference signals. A later series of observations used the ANIK-B synchronous satellite to synchronize the local oscillators at two radio telescopes located in British Columbia, and the NRL radio telescope at Maryland Point, Maryland (Knowles et al. 1981). These phase coherent observations were used to demonstrate the feasibility of geodetic, time synchronization, and Earth rotation VLBI observations.

Between 1977 and 1980, European radio astronomers studied a real time link using the European Large Satellite (L-SAT) to distribute both data and local oscillator signals to European radio telescopes. However, their ESA sponsored investigation never progressed beyond the Phase A Study.[22] Starting in 2006, the EVN began to accept proposals for real time VLBI whereby the data are sent by fiber from the observing stations to JIVE for correlation, with data transmission costs supported by the European Commission. A similar capability was demonstrated the following year in Australia. This so-called eVLBI has become increasingly popular for time-critical observations such as flaring AGN.

8.5 VLBI NETWORKS

In order to determine radio source structure in any detail, simultaneous or near simultaneous observations over a range of baseline spacings and orientations are necessary. Under the leadership of Marshall Cohen, what had now become the NRAO-Caltech VLBI group arranged to use the 85 foot radio telescope at the Harvard Radio Astronomy Station near Fort Davis, TX to supplement the telescopes in Green Bank and at OVRO, as well as the telescopes in Sweden and later Effelsberg, Germany. In support of the Fort Davis VLBI observations, NRAO provided a MK II record system, frequency standard, and receivers for 2.8 and 6 centimeters.

The US VLBI Network As described in Sect. 8.1, the early VLBI observations were all organized by the scientific investigators. Each series of observations necessitated writing separate proposals to each observatory, innumerable phone calls to arrange for the common observing time at multiple telescopes, shipping equipment and magnetic tapes, and arranging for people to travel to the telescopes to change tapes, to run the experiment, and then travel to Charlottesville to oversee the correlation of tapes. After the discovery of superluminal motion, the pressure for repeated observations to monitor radio source kinematics strained the available resources and personnel. The three-station VLBI correlator in Charlottesville required multiple playback passes to deal with the increasing number of four and five or more station observations, and was hopelessly backed up. Moreover, the record-playback system proved to be unreliable. At best, the multiple interactive adjustments needed to play back tapes recorded on different recorders required skill and patience; often playback error rates were so bad that the data had to be discarded. At other times, it was not clear if a low measured amplitude was real or the result of record/playback errors. Other issues included the lack of an antenna in the Midwest to complement the cluster of radio telescopes in the Northeast and in California, and the lack of antennas that worked well at short centimeter wavelengths.

In April 1974 NRAO held a meeting in Charlottesville to confront the mounting VLBI problems and to plan for the future. The 25 participants agreed that in principle a new dedicated array of properly located modern antennas, complete with standard instrumentation including hydrogen maser frequency standards, and a large central processing facility were needed to meet the increasing requirements of the growing VLBI community. Such an ambitious program was clearly in the future, and a short term solution, even if not ideal, was needed to exploit the growing opportunities for VLBI research.

The group envisioned a three-phase program:

1. Given the limited funds available, and recognizing the independent management of existing US radio observatories, the existing radio telescopes should be organized to the extent possible.
2. A new antenna located in the Midwest should be built to fill in the "Midwest Gap" in baseline coverage.
3. NRAO should pursue the design of a new array of antennas dedicated for VLBI.

Over the next few years, a series of reports called "VLBI Network Studies" were written to address the three phases discussed in Green Bank.

I. A VLBI Network Using Existing Telescopes (Cohen 1977)
II. Interim Report on a New Antenna for the VLBI Network (Swenson et al. 1977)
III. An Intercontinental Very Long Baseline Array (Kellermann 1977)
IV. On the Geometry of the VLBI Network (Swenson 1977)

Interested scientists continued to meet to discuss the formation of a US VLBI Network in order to provide reliable, versatile, and convenient facilities for VLBI observations and to provide an organization to discuss VLBI problems of national interest (Cohen 1977). Cohen (2000) later recalled that he adopted the term "network" rather than "array" as the NSF objected to "array," since NRAO was already building the VLA and the NSF was concerned that Congress might wonder why radio astronomers needed two arrays. Five organizations, NRAO/Green Bank, MIT/Haystack, Harvard/Fort Davis, Caltech/OVRO, and the University of California/Hat Creek, each committed one week of coordinated observing time to VLBI every two months. The University of Illinois and the USNO agreed to make their telescopes available at the Vermillion River and Maryland Point Observatories respectively. A Network Users Group (NUG) was organized to provide a single source for receiving and refereeing proposals, to organize the distribution of magnetic tapes, and to coordinate the observations and correlation. The NUG, which included some 40 VLBI scientists, met regularly, usually in connection with the annual URSI meeting in Boulder, CO, and addressed many of the proposal and scheduling issues. The NUG also organized a Technical Committee to establish standards, but logistical and technical problems continued as the NUG had no power or funds to implement changes at the participating observatories, which each had their own priorities.

Volume IV (Swenson 1977) of the "VLBI Network Studies" series addressed the question of the so-called "Midwest Gap" in the array of existing antennas. Both the University of Illinois[23] and the University of Iowa proposed to construct a new Midwest antenna to plug the existing gap and to ultimately become the first antenna of a multi-element dedicated array. The proposals were supported by the NUG and were seriously considered by the NSF, but before funding became available the motivation for the Midwest telescope was overtaken by the VLBA.

In 1981, six groups, Caltech, Harvard-Smithsonian, MIT, University of California at Berkeley, University of Illinois, and University of Iowa, signed an MOU to form a VLBI Consortium with the goal of increasing the effectiveness of the Network by making observations more convenient and more reliable. For legal reasons connected with NRAO's status as a national facility, NRAO did not initially join the Consortium, although at least one NRAO scientist participated in each Consortium meeting as an at-large member, and NRAO participated in all Network organized activities. In 1986 this arrangement was formalized when NRAO became an Associate Member of the VLBI Network Consortium. Each member contributed $2000 a year to the Consortium, which could then purchase recording media and arrange for their distribution among the observatories and the correlators at Caltech or NRAO, set technical standards, and handle proposal reviewing and scheduling. Each observatory appointed a VLBI friend to help support in-absentia observing. No longer was it necessary for the observers to provide personnel at each telescope. With a single proposal, a small group, or even one person with a good scientific project, could now get simultaneous observing time at all the radio telescopes operated by Consortium members.

The European VLBI Network (EVN) Starting with the 1968 and 1969 VLBI observations with Sweden and the Soviet Union, European radio observatories became increasingly involved in VLBI observations, generally using NRAO MK II recorders but on occasion borrowed MK III systems. The data were mostly correlated in Charlottesville at the NRAO MK II processor. In 1977 the MPIfR began an ambitious VLBI program with the construction of first a MK II and later a MK III playback system and, in August 1978, the MPIfR hosted a major international VLBI Symposium in Heidelberg, Germany, attended by about 100 scientists.

Inspired by the US VLBI Network, and following a series of informal meetings, in March 1980 the directors of five European radio observatories[24] met in Bonn and agreed to create the European VLBI Network (EVN), and then in 1984 created the more formal Consortium of European Radio Astronomy Institutes for Very Long Baseline Interferometry. The EVN formed a Program Committee to review proposals three times a year and to schedule VLBI observations every two months. A Technical Working Group (later Technical and Operations Group) specified standard observing frequencies, polarization standards, and data formats. As in the US, the EVN accepted proposals from any qualified scientists, including those with no European affiliation, and provided local support at the individual telescopes. Italy built two new radio telescopes dedicated to VLBI, one near Bologna and one in Sicily, and other radio telescopes in UK were added to the EVN.

As the number of antennas involved in EVN observations increased, the three-station MPIfR MK II processor became oversubscribed due to the multiple passes required for each observation. Some of the larger MK II experiments were processed at NRAO or Caltech, or, in the case of MK III observations, at Haystack. MPIfR built a three station MK III processor which was later expanded to five stations, but even this was inadequate to handle the growing number of multiple antenna observations, and priority was given to experiments involving MPIfR staff.

Following several unsuccessful attempts to fund a large European VLBI processor, in 1993 the Dutch government established the Joint Institute for VLBI in Europe (JIVE) in Dwingeloo to build and operate a 16 station MK III processor to support European VLBI observations. Richard Schilizzi was appointed the Director of JIVE. With the support of the EVN observatories, EVN observations have, since 1999, been processed at JIVE, which has developed into the center of VLBI research in Europe. In addition to its role in processing EVN observations, JIVE archives the correlated EVN data.

The EVN ultimately grew to more than 20 telescopes at 15 institutes in 12 countries, including some in Africa, Asia, and North America. A unique feature of the EVN has been the series of well attended EVN Symposia and the EVN User Committee meetings, which started in 1993 and have been held every two years since 1994. These symposia, which are usually held in conjunction with one of the regular EVN Director's meetings, have served to coalesce the European VLBI community and specifically to introduce new young scientists to VLBI opportunities. More detailed discussions of the EVN are given by Porcas (2010), Booth (2013, 2015), and Schilizzi (2015).

Global VLBI To accommodate transatlantic observations, the EVN and NUG combined to schedule "Global" VLBI observations, which often also included radio telescopes elsewhere in the world. As many as 18 different antennas (e.g., Reid et al. 1989) were included in some of these global observations. In Japan, scientists began a VLBI program, partly motivated by geodetic interests relevant to potential earthquake prediction. Other VLBI networks were initiated in Australia, Korea, and China. In South Africa, a former NASA tracking antenna at Hartebeesthoek was given to the South African hosts and instrumented for VLBI. Initially, most global VLBI observatories used the simple and economical MK II record system, which was gradually replaced by MK III and later VLBA-compatible recording systems, although for a while Canada, Jodrell Bank, Australia, and Japan each continued to use their own incompatible recording systems.

8.6 Planning the VLBA

The first discussions about building a dedicated Very Long Baseline Array (VLBA) began at NRAO in the summer of 1973.[25] Shortly after the 1974 meeting in Charlottesville, Dave Heeschen set up a "VLBA Design Group to continue the development of the concept of a dedicated Intercontinental Array and to help upgrade the present activities in VLB Interferometry."[26] Following the Charlottesville meeting, Swenson and Kellermann (1975) discussed the status of VLBI and some early ideas about a dedicated VLBA. A more complete description of a ten element dedicated Intercontinental Very Long Baseline Array based on tape-recording interferometry was prepared at NRAO as a collaborative effort of NRAO and external scientists and engineers, especially those from Caltech and Haystack Observatory (Kellermann 1977). The NRAO report noted that in addition to addressing a wide range of astrophysical problems, the proposed array could be used for precise tests of General Relativity and for interplanetary spacecraft navigation, and would have applications to a variety of terrestrial phenomena including the measurement of Earth tides and continental drift, accurate global clock synchronization, and the possibility of earthquake prediction. Like other NRAO facilities, the VLBA would operate as a single instrument available to all scientists based on competitive proposals. The proposed VLBA consisted of ten 25 meter diameter antennas, at least eight of which were in the continental United States. Placing the other two antennas in Hawaii and Spain or the Azores would increase the angular resolution to be about the largest possible on the surface of the Earth. Locations in Alaska, Iceland, Mexico, and Easter Island were also discussed to improve the north-south resolution. Unlike the VLBI Network antennas, which were originally built for other purposes, the proposed Intercontinental Very Long Baseline Array antenna elements would be more optimally placed, but with consideration of road access and the availability of power. Each antenna would be supported by a small staff to maintain the instrumentation and the antenna, change tapes, and arrange for their transportation to and from the central processor. However, overseeing the observations, pointing the antennas, changing frequency, etc. would be under the control of a remote central operator.

The proposed VLBA was based on demonstrated technology: VLA type antennas and receivers and MK II or MK III recording and playback systems. The biggest challenge was to provide sufficient staff to change tapes as often as four times an hour, devising a robot tape changer, or developing a cost effective real-time satellite data link. Another challenge was the lack at the time of a commercial source of the hydrogen masers needed to provide the necessary frequency stability for operation at wavelengths as short as 1 cm. NRAO estimated the VLBA construction cost to be about $26 million, and the operation plan called for a staff of 53 including two people at each antenna site to oversee the observations, change tapes, and provide basic technical support.

At this time NRAO was in the midst of the VLA construction (Chap. 7) and was also being pressured to build the 25 meter millimeter radio telescope (Chap. 9) which had received considerable support from the Greenstein Decade Review Committee (Sect. 7.4). Support for the VLBA was divided, even among practicing VLBI scientists. More meetings were held, but NRAO had inadequate resources to pursue serious engineering work on the VLBA, and little progress was made.

In 1979, a conceptually similar idea, called the Canadian Long Baseline Array (CLBA), was proposed by Canadian radio astronomers "to serve the needs and interests of Canadian astronomers." The proposed CLBA contained eight antennas located in Canada and one in France for both scientific and political reasons.[27] The Canadians proposed using larger antennas for better sensitivity, but the VLBA operated at a shorter wavelength so would have better angular resolution.[28] The US and Canadian groups discussed a possible collaboration, but the Canadian group thought that their government would be more receptive to a purely Canadian project. Perhaps reflecting their true fears, the Canadian radio astronomers also expressed concern that any joint effort with the US would be dominated by the Americans, and felt that the CLBA was a chance for Canada to take the lead. At a meeting of the Canadian Astronomical Society, Ernie Seaquist, Chair of the CLBA Planning Committee, claimed that "the CLBA is currently funded," and that the funding prospects were poorer in the US, so that the CLBA would be built before any US instrument.[29] Instead of reacting to the challenge of competition from Canada, William E. (Bill) Howard III, then the NSF Director of Astronomical Sciences and a former NRAO Assistant Director, saw the CLBA as his solution to the growing competition between the VLBA and the NRAO millimeter telescope and asked, "Why not let the Canadians do it?" By 1983, the positions on both sides had softened, but only slightly. Both the Canadians and Americans wanted to go ahead with both the CLBA and VLBA proposals. At an April 1983 meeting in Charlottesville, the two groups discussed ways to collaborate in the unlikely possibility that both arrays were built.[30] There were many compatibility issues, particularly regarding the recording systems used. All of the VLBA technical, scientific, and management memos were available to the Canadian group and some Canadians participated in the VLBA Working Groups, but little information flowed in reverse. The CLBA was chosen by the National Research Council of Canada over several other big science projects. However, with increasing CLBA cost estimates and the deteriorating economic situation in Canada, funding never materialized; the CLBA initiative eventually died, and Canadian radio astronomers turned their attention to other directions.

Although there was as yet no formal proposal requesting NSF funds for the VLBA, informal exchanges between NRAO and the NSF led to the inclusion of the VLBA in the Astronomy Division's planning for new starts, but after the NRAO 25 meter millimeter wave telescope, and in competition with the planned KPNO NTT 15 meter optical telescope, along with one or two 10 meter submillimeter telescopes, as well as a wide range of upgrades, instrumentation, and support for existing telescopes at all wavelengths.

Uncertain about the commitment of NRAO and concerned about input to the upcoming Decade Review of astronomy, Marshall Cohen, a member of the Decade Review radio panel, began a semi-independent design effort at Caltech in collaboration with JPL, although many of the same people, including NRAO scientists and engineers, participated in both the NRAO and Caltech design programs. The broad goals which would motivate the design of both the NRAO and Caltech arrays were discussed in a meeting held in January 1980 at Caltech, which was attended by about 30 scientists and engineers. The participants agreed that ten antennas would be a reasonable compromise between cost and imaging quality. Caltech issued the results of their design study in September (Cohen et al. 1980), in time for consideration by the Decade Review Committee. The existence of two institutions pushing for a VLBA added credibility to the project, and the item by item comparison of the independent cost estimates ultimately led to a better understanding of the VLBA construction costs.

Encouraged by a specific request from the NSF for a "Conceptual Proposal" and by the apparent increase in community support, NRAO responded by resuming its VLBA design program. In May 1980, NRAO Director Morton Roberts appointed a formal VLBA Design Group to re-examine the scientific motivation and technical feasibility of the VLBA.[31] Working Groups on antennas, configuration, correlators, data transfer, electronics, feeds, front ends, local oscillator, recording systems, monitor and control, operations, post processing, science, sites, and management focused on preparing a new report, and continued throughout the VLBA construction period to oversee the design and provide engineering support. NRAO staff were joined by Working Group members from the US and Canadian VLBI communities, particularly members from Haystack and Caltech, who led the recorder and correlator groups respectively. From 16–18 September 1980, a group of some 70 astronomers, geodesists, and engineers from Canada, Germany, the Netherlands, and Italy, as well as from the US, met in Green Bank to iron out the differences between the NRAO and Caltech studies. The first day was devoted to scientific presentations highlighting recent VLBI research, followed by a VLBI NUG meeting. The second day began with overviews of the Caltech-JPL, NRAO, and Canadian design concepts, followed by discussions of the array configuration, the antennas, front end, record, local oscillator, and playback designs. The Green Bank meeting consolidated the main concepts behind the VLBA and served to unite its supporters to urge action from NRAO.[32]

Following the Green Bank meeting, the 1977 NRAO report was updated to reflect the scientific and technical progress over the preceding three years. The February 1981 "Very Long Baseline Array Design Study" included only antennas located in the United States, but also considered the use of real time satellite links to replace the expensive and commercially unavailable hydrogen masers, and also an upgraded MK III system that could allow an order of magnitude increase in capacity of each tape, allowing a single tape to last for up to six hours instead of 13 minutes (Kellermann 1981). The proposed construction and annual operating cost of the VLBA were given as $39.1 million and $3.8 million respectively. In order to help prepare a formal proposal to the NSF and to consolidate the community, in November 1981 Roberts appointed a VLBA Planning Group of external scientists to advise on the preparation of an actual proposal to the NSF for VLBA construction.[33] Although the Planning Group was initially expected to function for only a few months, it remained in existence until June 1985 when it was dissolved by Paul Vanden Bout.

8.7 Funding the VLBA

In December 1978, the National Academy of Sciences began its next Decade Review of Astronomy and Astrophysics. Patrick Thaddeus from Columbia chaired the Radio Astronomy Panel. VLBI interests were represented by Marshall Cohen from Caltech and Bernard (Bernie) Burke from MIT.[34] Both the NRAO and Caltech reports had demonstrated the potential scientific impact of a dedicated VLBI system, that such an array was technically feasible, and that the cost could be reliably estimated. However, the VLBA was competing with a proposed high altitude 10 meter submillimeter telescope and the long overdue 100 meter class fully steerable short centimeter wavelength dish, as well as the need for maintaining and upgrading the VLA and Arecibo. Although early in their deliberations Thaddeus and the Radio Panel placed the VLBA as the highest priority new start for radio astronomy in the coming decade, there were still important undecided issues. Who would build it? What was the right tradeoff between the number of antennas and cost? What was the best recording system?

To address these and other questions, Thaddeus took the unusual step of bringing the key VLBA protagonists to his country cabin in rural New York to thrash out the issues. Although he expressed enthusiasm for the VLBA project, Thaddeus was concerned that in order to sell it to the parent Survey Committee, and later to the NSF and Congress, it would be necessary to keep the cost below $30 million. But $30 million was insufficient to build a ten element array. This generated vigorous discussion about the minimum number of antennas needed, whether some existing antennas could be used instead of building all new ones, the broad issue of international participation, and the optimum funding schedule. Unlike the strict confidentiality of later Decade Reviews, both the NSF and NRAO personnel had the opportunity to comment on and contribute to successive drafts of the reports of both the panels and the main committee.

As expected, the final report of the Radio Panel listed the VLBA as its clear first priority for new ground-based construction (Thaddeus 1983).[35] Based on the NRAO and Caltech design studies, the Committee suggested a total construction cost of $35 million. The Radio Panel report also listed space VLBI as the first priority for space radio astronomy and gave strong endorsements to the construction of a 100 meter class centimeter wavelength telescope, primarily for the support of space VLBI. At the same time, the Ultraviolet, Optical, and Infrared (UVOIR) Panel was divided among those who argued for a state-of-the-art large ground-based OIR telescope and those who wanted more intermediate class instruments. Unable to reach a consensus on priority, the UVOIR Panel recommended as their first priority both a "national New Technology Telescope (NTT) of the 15-m class for optical and infrared observation," and "the construction at good sites of several smaller national telescopes with apertures between 2.5 and 5 m" (Wampler 1983, pp. 98–99).

The parent survey steering committee, chaired by Harvard's George Field, endorsed the construction of the VLBA as the first priority for all of ground-based astronomy in the 1980s with a price tag of $50 million that included ten years of operation funding (Field 1982).[36] The Committee also noted, "The 25-Meter Millimeter-Wave-Radio Telescope, which was recommended in an earlier form in the Greenstein report, has not yet been implemented" but left unanswered any recommended priority between the VLBA and the 25 meter telescope, both proposed NRAO projects. Moreover, the Panel made no recommendation about who would build or who would manage the VLBA once built. As with the proposed VLA and the OVRO Array a decade earlier, Caltech and NRAO were again competing for NSF support.

The second priority for ground-based astronomy was the 15 meter New Technology [optical] Telescope (NTT) which was deemed to be of equal scientific merit to the VLBA, but not yet technically ready for construction. So the report recommended only that the NTT "*design studies … are of the highest priority and should be undertaken immediately*" (Field 1982, p. 16). The National Optical Astronomy Observatory undertook design studies for a 15 meter OIR telescope, but as of 2019 the largest optical-infrared telescopes operating in the United States are only in the 8–11 meter class. A 24 meter equivalent Giant Magellan Telescope (GMT) is under construction in Chile, and a Thirty Meter Telescope (TMT) is planned pending the identification of a suitable site.[37] Meanwhile a 39 meter equivalent diameter telescope, known as the Extremely Large Telescope (ELT) is under construction in Chile by ESO.

During the Field Committee deliberations, the NSF National Science Board discussed "Big Science Policies and Procedures." The NSB recognized "Big Science" projects not only cost a lot to build, but would have a continuing operating cost that with level or even declining budgets could adversely impact a broad range of other programs in the field. The Board wisely set a high bar for supporting big projects at the NSF and defined a demanding procedure for funding "big science."[38]

The VLBA Versus the 25 Meter Millimeter Wave Telescope After years of planning and development, in 1977 NRAO had sent a proposal to the NSF to build a 25 meter millimeter wave telescope on a high altitude site chosen for low water vapor (Sect. 10.3). In January 1980, President Jimmy Carter's FY1981 budget proposal included $1.7 million for the engineering design of the 25 meter millimeter telescope, but a few months later the proposal was withdrawn by the NSF following a $70 million cut in the NSF budget. Carter's budget proposal for FY1982 again included a start for the 25 meter telescope, now on a proposed three instead of four year construction schedule. But with the nation dealing with high unemployment and inflation resulting from the unprecedented gasoline prices brought about by the Iran Oil Crisis, incoming President Ronald Reagan's economic recovery plan froze all FY1982 new starts, specifically mentioning the 25 meter telescope,[39] and the 25 meter telescope did not appear in the FY1983 budget request. However, the Decade Review Radio Panel had made an early decision, probably in 1980, not to re-evaluate "ongoing programs approved by previous advisory committees." Specifically, their report noted that "the most important such project in radio astronomy is the 25-m millimeter-wave telescope proposed by the NRAO." Assuming that better times lay ahead following the end of the Iran Hostage Crisis, the Radio Panel Report stated that, "<u>The present report of the Panel on Radio Astronomy is predicated on the assumption that the 25-m telescope will be constructed during the early or middle years of the 1980's</u>" (Thaddeus 1983, p. 212) [original underlining]. Similarly, the parent Survey Committee emphasized "the importance of approved, continuing, and previously recommended programs," and specifically noted that "The 25-Meter Millimeter-Wave-Radio-Telescope … has not yet been implemented" and would permit "the United States to maintain its leadership in this exciting and highly productive field" (Field 1982, pp. 13–14, 120). Both the Radio Panel and the parent Survey Committee stopped short of making the difficult decision of how to proceed if the 25 meter was not funded.

Meanwhile work on both projects continued at a low level at NRAO. With the new strong Field Committee recommendation for the VLBA, as well as a letter writing campaign from the VLBI community, and the long outstanding but still unfunded 25 meter project, Roberts was faced with a dilemma. NRAO was just bringing the VLA into operation with inadequate staff and an insufficient operating budget, and was dealing with conflicting pressures from the VLBI and millimeter communities for another new start. These were two fields, millimeter astronomy and VLBI, that had been started at NRAO, but where US leadership was being threatened. The NRAO scientific staff itself was split over the two projects (Gordon 2005, pp. 140–145), and there was growing concern from both communities that nothing was happening.

To help decide on the best approach, Roberts convened an ad-hoc committee to adjudicate between the two projects.[40] The committee met in the Washington offices of AUI on 25 January 1982. Their views ranged from

"25 meter with enthusiasm; the VLBA not yet ready; stay with mm telescope;" to "VLBA new, more attractive and more saleable; VLBA to maintain credibility of Field Report; 25 meter no longer attractive."[41] As Roberts later reported to the NSF, the committee felt that the scientific case for both projects was "equally strong" and that "a majority favored seeking funds in the FY1984 budget for the 25 meter telescope."[42] Following a discussions within NRAO, and realizing the long term impact "to the astronomy community in general and on NRAO in particular," Roberts wrote to Francis Johnson, NSF Assistant Director for Astronomy, Atmospheres, Earth and Oceans, to "urge the NSF to include the 25-meter telescope in its plans for FY1984." He also told Johnson, "We will complete, as rapidly as possible, the preparation of a VLBA proposal for submission to the NSF."[43]

This ambiguous NRAO position, along with the lack of any clear recommendation from the Field Committee, left the NSF in a quandary. They could not fund both NRAO radio astronomy projects in the coming decade and sought the advice of their own Astronomy Advisory Committee (AAC)[44] which met on 5–6 April 1982 at the NSF in Washington. Mort Roberts made the good suggestion to the NRAO and Caltech VLBA advocates that "it would be completely inappropriate to use that occasion to push for one's own proposal. Not only inappropriate but ineffectual, for the details of approving one proposal versus another will not be left to the AAC, but will be based on peer reviews and internal gyrations within the NSF."[45]

The presentations for the millimeter telescope went first, but ran overtime, leaving little time for the VLBA and for probing questions about the CLBA, the differences between the Caltech and NRAO plans, the use of existing radio telescopes instead of building new ones, and other delicate concerns. During the discussion following the presentations, the committee noted that the 25 meter proposal was clearly getting old; Japan had just completed the 45 meter Nobeyama millimeter wave telescope, and the 30 meter IRAM millimeter telescope on Pico Veleta, in the Spanish Sierra Nevada, was already under construction. On the other hand, the 25 meter concept was mature, while there was no real proposal or engineering design for the VLBA. The 25 meter was "shovel ready;" the VLBA was not.

Nevertheless, soft spoken committee member Richard McCray unexpectedly suggested that the time had passed for the millimeter telescope and that the VLBA represented a new opportunity to extend US leadership in this important area which had broad applications beyond astrophysics. McCray was a respected theoretical astrophysicist and had been a member of the Field Committee, so his comments were taken seriously, and the committee subsequently recommended unanimously that the NSF pursue funding for the VLBA, and at the same time voted seven to three to not go ahead with the 25 meter proposal.[46] Two weeks later, Roberts wrote to the NSF Director, John Slaughter, to "request that the NSF set aside our request for funds to construct [the 25-meter millimeter wave telescope]"[47] This was the effective end of the NRAO 25 meter project. Although Roberts' controversial action left a bitter taste among the millimeter astronomers, including those at NRAO, it would eventually lead to a major new US initiative in millimeter astronomy (Sects. 10.6 and 10.7) as well as to the funding and construction of the VLBA.

At its 19 October 1982 meeting, the AAC revisited the VLBA and unanimously passed the following resolution:[48]

> The Very Long Baseline Array radio telescope was recommended by the Astronomy Survey Committee as the highest priority new facility for ground-based astronomy. The Astronomy Advisory Committee recommends that the NSF seek the necessary funds to construct this facility as soon as possible.

Interestingly, another major previously approved but still unfunded project was the Space Infrared Telescope Facility (SIRTF). But unlike the NRAO 25 meter telescope, the infrared community and NASA did not abandon SIRTF, which was finally realized with the launch of the Spitzer Space Telescope in 2003, and its subsequent very successful mission.[49]

Multidisciplinary Use of the Very Long Baseline Array The response of any radio interferometer depends not only on the structure of the radio source, but also on the interferometer baseline length and its orientation, the coordinates of the radio source, and the local oscillator frequencies. In practice, the data are correlated using a range of probable fringe rates and time delays which are then examined in a computer to find the fringe rate and delay that gives the maximum interference fringe amplitude. Working backward, the observed fringe rate and delay can then be used to determine with great accuracy the geometry of the interferometer baseline and the relative time offset between the two antennas. It was, therefore, immediately clear from the first 1967 VLBI observations that in addition to astronomy and astrophysics, VLBI techniques also had a variety of important terrestrial applications, including the measurement of Earth rotation (UT1), polar motion, Earth tides, continental drift, and possibly earthquake prediction (e.g., Gold 1967; Cohen et al. 1968). Since radio source coordinates can be determined with great precision, VLBI is also used for precise tests of General Relativistic gravitational bending, for spacecraft navigation, and to locate lunar and planetary exploration vehicles.

Although NRAO and the VLBI community had promoted the VLBA to the NSF and the Field Committee based partly on the geodetic and other non-astronomical applications, the design discussions had not really responded to the needs of these other applications. It was clear that support of the geodetic community as well as the astronomy community was needed before the NSF would fund the construction of the VLBA. At Bernie Burke's initiative, the National Research Council held a two-day workshop at the National Academy of Sciences in Washington on 6–7 April 1983.

During the course of the Workshop on Multidisciplinary Use of the Very Long Baseline Array (NAS 1983), it became increasingly clear that although the geodetic community needed and wanted the VLBA, their support was predicated on NRAO being more sensitive to the needs of geodesy in designing the array, calibration procedures, providing auxiliary instrumentation, and in dealing with proposals and scheduling. To better accommodate the wide range of non-astronomical observations discussed at the workshop, NRAO agreed to increase the elevation range of the antennas, to increase their slew speed, to provide for simultaneous observations in the 4 and 13 cm bands commonly used for geodetic studies, and to increase the number of IF channels. All of these modifications added to the construction cost. From the viewpoint of the astronomy user, perhaps the most serious compromise was the choice of the IF system and some frequency bands to be compatible with existing geodetic VLBI systems rather than the VLA. Interestingly, the NAS meeting was not only funded by the NSF, NASA, and the NOAA National Geodetic Survey, but also by the Defense Advanced Research Projects Agency (DARPA) and the Defense Mapping Agency.

The NSF and Congress As with the VLA (Chap. 7) and the GBT (Chap. 9), obtaining VLBA construction funding was complex, but in each case for different reasons. Following the NSF Astronomy Advisory Committee decision in April 1982 and the President's Office of Science and Technology Policy (OSTP) briefing, things moved very fast, at least at first. The following month, Roberts sent the formal proposal for a Very Long Baseline Array (Kellermann 1982) to the NSF Director, John Slaughter, requesting "funds for such construction and operation."[50] In accordance with the agreement with Caltech, the front page of the proposal noted that it had been "prepared in collaboration with the California Institute of Technology." The NSF was still remembering the 25 meter situation and was unsure of NRAO's intentions. Roberts wrote to NSF Assistant Director Francis Johnson in July, saying, "*We* [NRAO] *conclude that we must now ask that the VLBA proposal be accorded the highest priority on the Foundation's agenda,* … [and] we look forward to vigorous support of the VLBA project by the NSF and the NSB and hope that significant planning, design, and development funding will be available in FY 84." [italics in original].[51]

By this time Bill Howard had left the NSF over the disruption resulting from the reversal of support for the nearly funded 25 meter telescope in favor of the VLBA,[52] and had been replaced by Laura (Pat) Bautz as the NSF Astronomy Division Director. Larry Randall, the NSF Program Officer for NRAO and later Head of the Astronomy Centers Section, generously interacted with the NRAO Project Manager, (KIK), over the preparation of the VLBA proposal and the development of a budget plan for its construction, as did Kurt Weiler, who had specific responsibility for the VLBA at the NSF. During the final preparation of the proposal, some concern was raised that "VLBA" was not a very inspiring name, and that it might be easily confused with the VLA. Other names considered included "Trans American Radio Array (TARA)", "Trans American Radio Telescope (TART)", and "Trans American Telescope (TAT)". NRAO decided to adopt the appealing Caltech name, *Transcontinental Radio Telescope*, or *TRT*, much to the dismay of the NRAO secretary who had to retype the proposal. But noting that they were already discussing the VLBA with the Office of Management and Budget (OMB) and Congress, Larry Randall rejected the name change, and the proposal had to be retyped yet again using "VLBA."

The 1982 proposal submitted to the NSF specified a construction budget of $50.729 million and an annual operating budget of $4.15 million. Characteristically, the NSF and the community focused their attention on the capital cost with little consideration paid to the operating cost. Indeed, NRAO never received the full incremental operating funds needed for the VLBA, and in particular, the annual $500,000 requested to upgrade the instrumentation never materialized. NRAO proposed an optimum five year construction plan to start in FY1984 that included a first year of engineering design along with the construction and corresponding site acquisition for the first antenna prototype. The plan initially called for $2.5 million for engineering design and to procure the first antenna, with the rest of the construction spread out over the next three years.

By this time, the price of oil and the rate of inflation had stabilized and Jay Keyworth, President Reagan's Science Advisor, announced that he was looking for "high leverage" areas where modest investments would have a "high impact" with regard to the 1984 budget. In response to Keyworth's request, the NAS appointed seven Briefing Panels to identify "those research areas within the field which are most likely to return the highest scientific dividends as a result of additional federal investment."[53] One of the authors (KIK) was a member of the "Briefing Panel on Astronomy and Astrophysics," which was chaired by George Field. Unlike most NAS studies and reports, this one was remarkably fast. It was just over a month between the appointment of the panel and the final report and presentation to OSTP, and "the Briefing panel quickly and unanimously identified the VLBA as the number one priority to bring to the attention of OSTP for a 1984 new start."[54] Field and NAS President Frank Press presented the report of the Briefing Panel on Astronomy and Astrophysics to Keyworth and other OSTP staff on 15 October 1982. Apparently Keyworth had already read the report, and told Field that "the briefing had revealed nothing new to them," and the one-hour presentation was dominated by the broader issues of the space station and NASA's emphasis on technology over science. In response to Field's "concern that the NSB looks unfavorably on large projects such as the VLBA," Keyworth reassured him that "OSTP, not the NSB, decides such issues," and that "several of the items were already being taken care of."[55]

The National Science Board, nervous about continuing operational requirements of big projects and their impact on grant support, only approved $0.5 million funding for the VLBA in FY1984. However, OSTP and OMB restored the full $2.5 million in President Reagan's budget proposal, which was included in the Congressional FY1984 NSF Appropriation as part of a large increase in the administration's support for science.

Although the VLBA had not yet gone through the NSF review process, Reagan's FY1985 budget request included $15 million for the first year of a four year VLBA construction project planned at approximately $15 million per year. Nevertheless, the NSF apparently still wanted to review the proposal and obtain endorsement from the National Science Board. In preparation for a presentation to the NSB, the NSF sent the NRAO proposal out for peer review, and convened a "blue-ribbon panel" led by Joseph Taylor from Princeton to make recommendations on the overall soundness of the project, management, technical specifications, staffing, timing, and costing.[56] In preparation for the September NSB meeting, the Review Panel met at the NSF on 30–31 May 1984. Their report concluded that the VLBA was scientifically important, the specifications were appropriate and attainable, the staffing and management plans were adequate, construction and operating costs credible, and the time scale realistic. But the panel suggested that the contingency be increased to 15 percent.[57]

However, in spite of the support from OMB and OSTP, the VLBA ran into an unforeseen snag in Congress. Massachusetts Representative Edward Boland was the powerful Chair of the House Appropriations Sub-Committee on Housing, Urban Development (HUD), and Independent Agencies that had jurisdiction over the NSF appropriations. Boland had little regard for astronomy or astronomers, apparently because of an earlier battle with supporters of the Hubble Space Telescope, and he pushed to include more funds to support supercomputing and for science education at the NSF. Five years earlier, at the dedication of the Five College Radio Astronomy Observatory 14 meter millimeter-wave radio telescope, Boland told the gathered astronomers that hard times were coming and not to expect money for more new radio telescopes, and he decided to hold the VLBA hostage to achieve his goal of increasing support for science education.

Boland's Chief of Staff, Richard Mallow, was also a formidable adversary. He had just authored a report supporting increased funding for supercomputing and cautioning against funding the VLBA and other Field Committee recommendations in view of the projected increasing costs of the Space Telescope and other ground-based optical telescopes in Arizona, Hawaii, and Chile. According to another Congressional staff member, "Dick Mallow tries to run the committee, but the other staff members do not always let him have his way."[58] Armed with Mallow's report, Boland argued that "it is more important that the NSF put more money into science education than into VLBA." To complicate the situation, Boland and Mallow's interest and support for computing was not entirely unwelcome at NRAO, since the Observatory was also interested in obtaining a super computer to deal with the growing volume of data from the VLA.

George Field and others wrote Boland a strong letter of support for the VLBA, explaining that the federal government spent a lot more on science education than was found in the NSF budget, and that the VLBA correlator was itself at the frontiers of computing technology.[59] In response, Boland remarked,[60] "This nation's future does not and will not depend on building the VLBA. It does depend, however, on how adequately we educate our children—particularly in science and mathematics." Field, Kellermann, and others tried to defend the VLBA with visits to key Congressional Offices,[61] but were unable to see either Boland or Mallow.

The "old boy network" then went to work to save the VLBA. MIT Professor Bernie Burke, a long-time supporter of VLBI and the VLBA, brought the VLBA problem to the attention of the MIT Dean of Science John Deutch and past MIT President Jerry Wiesner. Wiesner was a friend of Speaker of the House Tip O'Neill, who represented the old 8th Congressional District which included Cambridge. O'Neill previously shared living accommodations in Washington with Boland and reportedly persuaded Boland not to kill the VLBA in the House appropriations bill.

Following the community pressure, Boland allowed the VLBA to remain in the FY1985 House appropriations bill at the requested $15 million, but the bill stipulated that this money could not be spent until the NSF FY1986 budget request included at least 8.5 percent for science education.[62] The Senate appropriations bill also included the requested $15 million and, with the help of New Mexico Senator Pete Domenici and Jake Garn, Chairman of the Senate Appropriations Committee, eliminated the House education rider.

With $15 million for the VLBA included in both the House and Senate appropriations bills, the prospects looked encouraging. But to everyone's apparent surprise, when the House-Senate Conference Committee met on 26 June 1984, they "compromised" and appropriated only $9 million for FY1985 and retained the proviso that no money could be obligated until 1 April 1985, six months into the fiscal year,[63] and then only if Boland's education requirement were met in the NSF's proposed FY1986 budget. Boland had suggested a 4th quarter (July 1985) start for the VLBA, apparently a widely used tactic to avoid implementing an approved program, and the Senate had countered with a February start. April 1 was a compromise, but the final bill also specified that NRAO could not issue a Request for Proposals (RFP) for the antennas until after this date. When Mallow found out that an RFP had already been issued on 9 March, he reportedly went "non-linear."[64] Further, when Boland's committee agreed to include $15 million in the House Bill for the VLBA, they reduced the overall appropriation for the NSF AAEO Division by $12 million in order to minimize the impact to the federal deficit. But when the VLBA funding was reduced to $9 million by the Conference Committee, the AAEO cut remained, resulting a net loss of $3 million. The NSF was not happy about this, and suggested that community pressure was not necessarily useful and might even be counterproductive.[65]

When Kellermann met with Senator Domenici staffer George Ramonas in the Senator's office on 16 August 1984, he was assured that "As long as Pete Domenici is in the Senate, the VLBA will be protected, particularly if he remains as part of the majority party," but Ramonas acknowledged that Boland would probably try to remove the VLBA from the 1985 budget at the time of the FY1986 Appropriation Committee hearings in the spring of 1985.[66] Although the House and Senate HUD Appropriations sub-committees had to deal with 13 separate agencies and a total of $59 billion of appropriations, the VLBA had become a pawn in the OMB-House-Senate-NSF relationship. Reportedly most of the discussion at the House-Senate Conference for the FY1985 appropriation was devoted to the VLBA. Ramonas was a valuable contact in following the NSF-Congressional debates until he left Domenici's office in early 1985. When George Field later spoke with Ramonas's replacement, Joseph Trujillo, Trujillo indicated that he had never heard of the VLBA.[67]

The FY1985 VLBA construction funding was finally released to NRAO on 15 May 1985. By this time, reflecting the increased level of contingency suggested by the Taylor Committee and the projected inflation over a proposed project stretch-out, the expected cost of the VLBA had risen to $68.2 million.

For FY1986, the NSF and OMB requested $11.5 million for continued construction of the VLBA, but again asked for only $51 million for science education, and in defiance of previous instructions from Boland, they had deferred spending $31 million from the prior year's appropriation. At the 1986 budget hearings on 26 March 1985, Representative Boland was incensed at the NSF and the administration and informed Keyworth that, "The Administration doesn't seem to have any trouble finding money for VLBA. But it can't help with science programs for children." Keyworth responded by pointing out that the VLBA was the highest priority in astronomy and had gone through extensive peer review, adding, "I cannot think of a scientist in America who is a recognized authority in astronomy who questions the utility and viability of the VLBA," to which Boland retorted "Outside of astronomy, do you find any enthusiasts?" Under pressure from Boland, NSF Director Erich Bloch agreed to the further VLBA funding delay until May 15. There was more at stake than the FY1986 funding level.[68] Since Boland had cleverly delayed obligating the FY1985 funds, NRAO feared that if the FY1986 VLBA funding was zeroed out by the appropriations committee, Boland would then contrive to reverse the FY1985 VLBA appropriation, possibly leading to the same fate as the 25 meter millimeter dish. Fortunately for NRAO, the discussion at the hearing drifted away from the VLBA to the relative merits of HST and the Keck 10 meter telescope.

Two days later, in the Senate hearings, Domenici chastised Bloch for delaying the NSF science education program and spoke in strong support of the VLBA. Bloch responded that he could not fund the VLBA unless the rest of the NSF budget was preserved, but Domenici reminded Bloch that Congress, not the NSF Director, makes these decisions.[69] Again, George Field, Maarten Schmidt (AAS President) and Peter Boyce (AAS Executive Officer) led a letter writing campaign to Representatives and Senators involved in the appropriations process. As finally passed, the 1986 HUD-Independent Agencies Appropriations (P.L. 99–160) included $9 million for the VLBA, and this amount became the de-facto basis for the more or less level funding in subsequent years. The construction budget went first from three years at $20 million each, to four years at \$15 million, and finally eight years at \$9–\$11 million a year. However, as it developed, it would have been challenging to have completed the VLBA on the original schedule. The design and production of the record and playback systems would prove to be more difficult and time consuming than originally anticipated, and it was fortunate that the NSF not only stretched out the funding, but added funds to account for inflation and increased management costs over the additional years.

8.8 Building the VLBA

The 1982 VLBA proposal noted the considerable technical progress made since the 1977 NRAO Design Study. In particular, Readhead and Wilkinson (1978) and Cotton (1979) had demonstrated how to recover most of the phase information from VLBI observations to produce full synthesis images with milli-arcsec or better resolution. At the same time recording data rates had increased, allowing bandwidths comparable to that of the VLA. The order of magnitude improvement in tape storage density offered a comparable reduction in consumption of tape, with a corresponding decrease in the cost of shipping tape and the ability to operate for many hours without human intervention. Meanwhile, the progress made with low noise cooled FET amplifiers offered both a cost saving and improved reliability over parametric and maser amplifiers.

The Antenna Configuration The far-flung location of the VLBA antennas presented a new paradigm for NRAO. Starting with the construction phase, in addition to Arizona, New Mexico, Virginia, and West Virginia, NRAO had to become licensed to do business and obtain legal counsel in eight additional states. The configuration of the array presented another challenge. The ten antenna sites would ideally be located to give the best imaging capability, but there were practical aspects to consider. The antennas had to be on land and it was important to avoid areas of high tropospheric water vapor such as the southeast or northwest parts of the country. Southern locations were preferred over northern locations to maximize access to the southern sky. Locations near the VLA and Socorro were desired both to exploit the finite size of the VLA when used with the VLBA, and to provide a convenient center for maintenance. Other considerations included availability of water, power, and communications, road access, freedom from RFI, low winds, proximity to transportation services for shipping magnetic tapes, security, and the ease of acquiring the land. Location at or near another radio observatory was considered attractive as a source of logistical support, but this turned out to be naïve, as the staff at most observatories did not have the expertise, training, or special skills needed to support the unique VLBA instrumentation. As pointed out by Napier (2000) each site had its own logistical, legal, and technical challenges—a bankrupt contractor at Ford Davis, a contract award protest at Owens Valley, DOE bureaucracy at Los Alamos, and environmental concerns at Hancock.

NRAO assumed that access to government-owned land would be more straightforward than private or institutionally-owned land. In fact, the opposite was true. The small plot of land needed for a VLBA antenna could be readily purchased or leased from private owners. But it was a bureaucratic nightmare to transfer land from one federal agency to another agency, and long term agreements were subject to changing agency personnel and changing priorities.[70]

Everyone agreed that each antenna should probably be on US soil, although some overtures were made about locating one antenna in Mexico to improve the north-south resolution.[71] There was also discussion about possibly placing one element at the Canadian radio astronomy observatory in Penticton, BC, instead of Washington, but this was discouraged by the NSF. In order to maximize the resolution of the VLBA, two of eight antenna sites were chosen to lie outside of the continental United States, but still on US territory. The antenna site in Hawaii presented a unique challenge. Except for the high altitude locations on Mauna Loa, Mauna Kea, and Haleakala, the water vapor content over the rest of the Island state was judged to be unattractive for radio astronomy. Extensive radio transmissions from an Air Force Laboratory on Haleakala rendered it unacceptable. The National Atmospheric Laboratory on Mauna Loa, which provides the important historical records of carbon dioxide in the atmosphere, did not want radio astronomers running around and possibly contaminating their measurements. Moreover, Mauna Loa is an active volcano and would have required a dyke to protect against possible lava flow. Mauna Kea, of course, was the home of many optical telescopes and offered good supporting infrastructure. The summit of Mauna Kea within the so-called "science reserve" was unattractive due to icing[72] and the prevailing high winds at the summit. So a site was chosen at an 11,800 foot location, but because it was outside of the "science reserve" long negotiations with the local governments and the University of Hawaii were necessary. Normally, the University of Hawaii requires a "guaranteed entitlement of UH scientists to a specified amount of observing time" at astronomy facilities located on Mauna Kea. The University of Hawaii waived this requirement "in view of the vital role of a Hawaiian VLBA antenna," but in return, the University asked for 100% of the single dish observing time on the Mauna Kea antenna. This was unacceptable, but NRAO did agree "to carry out tasks related to maintaining the radio frequency properties of astronomical sites in Hawaii."[73] And finally, NRAO agreed to give the UH astronomers some access to single dish observing, but this capability was never implemented, and the issue has been long forgotten.

The most eastern site was first planned to be in Puerto Rico. A location near the Arecibo Observatory where it could be supported by Arecibo personnel was interesting, but was rejected due to concerns about interference from the powerful ionospheric and planetary radar systems used at the Observatory. NRAO staff found another site at an about to be abandoned CIA communications station on Puerto Rico's southern coast that was shielded by a mountain range from the Arecibo radar. However, that location was threatened by a planned Voice of America powerful transmitting station right next to the intended VLBA site. At Frank Drake's suggestion, NRAO found a site on the island of Saint Croix. Being located near sea-level on a Caribbean island, the Saint Croix site not only suffered from the high precipitable water vapor content, but the salty damp air meant that the antenna had to regularly be repainted with a special corrosion-resistant paint. Moreover, dealing with the local legal system and a developer who objected to having the view of the ocean obscured by the 25 meter dish became a continuing issue. It wasn't until 1998, five years after the completion of the VLBA, that NRAO was finally given the approvals needed to make the erection of the VLBA antenna on Saint Croix legal. Construction of the Saint Croix antenna had just begun and only the concrete foundation existed at the time of Hurricane Hugo in 1989, but damage to the rest of the island delayed the completion of the antenna. Finally, Hurricane Maria in 2017, which caused widespread destruction on the island, did not do major damage to the antenna, but the impact to communication and transportation limited the operation of the antenna for many months.[74]

A different type of controversy arose over the location of the northeastern antenna site. While needed for good imaging quality, sites anywhere in the North East were subject to potential RFI due to the large population density throughout the region and the poor tropospheric conditions resulting from the large cloud cover and water vapor content prevalent throughout the area. Sites at the Five College Radio Observatory in central Massachusetts, near the University of Rochester in New York, and even in Canada were all considered. Craig Walker, who was responsible for optimizing the antenna configuration, argued for a location in northern New England, and Cam Wade located an attractive site in New Hampshire only about 50 miles from the MIT Haystack Observatory. But George Seielstad, the NRAO Assistant Director for Green Bank, argued that it would be more cost effective to place the VLBA antenna in Green Bank, where it could be supported by the existing Green Bank staff at no increased cost and with little impact to the array imaging capability. The arguments between optimizing the Array configuration and supporting Green Bank with a new antenna became very divisive within NRAO, but were finally decided in favor of the New Hampshire location. Figure 8.6 shows the final configuration adopted for the location of the VLBA antennas.

Construction The expected VLBA construction cost at the time of the proposal was $50.7 million, including an inventory of spare parts and 13 percent contingency. The annual operating costs were estimated to be about $4 million. After President Reagan signed the NSF budget in July 1983, which included $2.5 million for the VLBA design, NRAO rented additional office space in Charlottesville, and began the process of developing a staffing plan, completing a detailed work schedule, and establishing annual budgets. Hein Hvatum was appointed VLBA Project Manager and Kellermann became the Project Scientist. When Hvatum retired in 1987, Peter Napier,[75] who had been the Deputy Project Manager, took over as Project Manager.

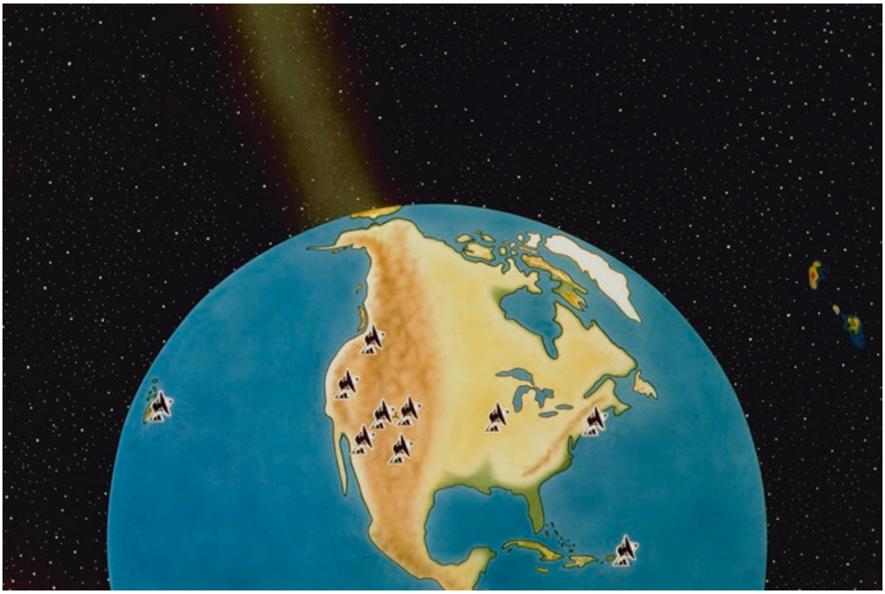

Fig. 8.6 Locations of the VLBA antennas: St. Croix, VI; Hancock, NH; North Liberty, IA; Fort Davis, TX; Los Alamos National Laboratory, NM; Pietown, NM; Kitt Peak, AZ; Owens Valley, CA; Brewster, WA; and Mauna Kea, HI. Credit: NRAO/AUI/NSF

The antenna elements were the most expensive part of the VLBA. In response to their RFP, NRAO received three bids to construct the ten antennas. TIW Systems Inc. and Radiation Systems Inc. (RSI) each proposed a conventional wheel and track antenna, while the Electronic Space Systems Corporation (ESSCO) proposed a pedestal mounted antenna enclosed in a radome. Following an independent analysis of the technical and business aspects of each proposal, NRAO chose RSI as the contractor for the ten antennas. The contract signed with RSI on 19 December 1984 for $19.61 million called for a five-phase approach, with each phase subject to authorization pending the availability of funds. In order to minimize state taxes, the contract was in two parts, one for the design, fabrication, and delivery of each antenna, and the other for the assembly and testing on site. But due to subsequent reductions in the expected NSF rate of funding, the contract with RSI was later renegotiated to deliver only two instead of three antennas a year.

While the Field Committee had recommended the construction of a VLBA, they were properly silent on who should build and operate the array, correctly leaving that as an NSF decision to be based on proposals and peer review. Although there had been acrimonious conflicts over the VLA and Owens Valley arrays (Sect. 7.2), NRAO and Caltech had worked together in developing plans for the VLBA and in advocating support from the community, even though their roles in the construction and operation of the VLBA were not clarified by the Field Committee. While it was becoming clear to Cohen that the construction and operation of a facility of the scope of the VLBA was probably beyond their interests and capability, Caltech still wanted to preserve some significant involvement. Maybe Caltech could build and operate the processor? But NRAO would not accept the responsibility for operating the VLBA without control over the processor, and several options were discussed. Maybe the processor could be located in Pasadena and be operated by NRAO. Maybe there should be two processors, one in Pasadena and one at NRAO.[76] NRAO needed Caltech's continued support if the VLBA was to be built. Perhaps more importantly, Caltech and the Jet Propulsion Lab (JPL) had a lot of experience and expertise on antennas, correlators, and imaging software that was vitally important for building the VLBA.

NRAO and Caltech staff met in Albuquerque, NM on 1 October 1981 to discuss how to best collaborate on the VLBA project.[77] Although Caltech recognized that NRAO would be the lead organization, they wanted to be "co-proposer," sharing decision-making responsibility through a joint "steering committee," but this was not acceptable to NRAO. Discussions and exchanges of seven draft MOUs continued for more than a year. NRAO stressed its need to maintain control, while Caltech stressed the value of its expertise and support.[78]

NRAO and Caltech finally agreed that Caltech would design and build the VLBA playback processor or correlator, but that when completed it would be moved to the NRAO. But there was no agreement about where NRAO should locate the processor or the VLBA Operations Center, and this became a matter of serious contention. The VLBI consortium leaders, especially from Caltech and MIT, continued to argue for a location near a major university to facilitate interaction with the broad astronomical community, while NRAO was more concerned about the logistics of VLBA operations and coordination with VLA operations. Even within NRAO, the VLBA debate triggered discussions about possibly shifting VLA operations to Socorro or Albuquerque from the array site on the Plains of San Agustin and possibly relocating the NRAO Headquarters. Four options were considered for the VLBA Operations Center: (a) Socorro, to facilitate coordination and to share resources with the VLA, (b) Charlottesville, where the NRAO Headquarters was located, (c) Albuquerque, which would provide some of the advantages of locating in Socorro, but perhaps provide more attractive living conditions for the VLBA staff and conceivably even VLA staff, and (d) co-location with VLA Operations on the Plains.

At the request of AUI, in September 1983 Mort Roberts appointed a committee to "review and advise on NRAO's selection of a site for the VLBA Operations Center."[79] Paul Vanden Bout, from the University of Texas and Chair of the NRAO Visiting Committee, was appointed as the committee chair.[80] The Vanden Bout committee was informed by a detailed report of the VLBA Operations Working Group, chaired by Carl Bignell, which examined the advantages and disadvantages of each option along with the potential impact on VLBA operations.[81] Vanden Bout's committee concluded that the control of the array operations and correlation of array data should be done at a common site, and that the Array Operations Center should be located near the VLA, specifically in Socorro or Albuquerque.[82] The committee, however, declined to make a recommendation on the location of the NRAO central offices, commenting only that "this issue depends on the future development of NRAO's activities," and that they found no connection between recommending a site for VLBA operations and the question of moving the NRAO headquarters to a new site.[83]

The discussions about moving the NRAO Headquarters slowly died away, but the decision to co-locate the VLBA and VLA operations had a profound impact on both facilities. The VLBA construction plan included funds for a VLBA Operations Center. Senator Pete Domenici was able to convince the New Mexico State Legislature to issue a $3 million bond that allowed New Mexico Tech to construct an Array Operations Center (AOC) which housed both the VLA and the VLBA operations staff. As a result, the VLA scientific, engineering, and business staff were able to move from the VLA site to Socorro, saving a two-hour daily commute. Locating all VLA personnel at the site had served well during the construction period, but by the 1990s, the operation had become sufficiently mature and most staff were not needed each day at the site, especially when the daily commute had some adverse impact on both the VLA operations and on staff morale. Ground breaking for the new combined Array Operations Center took place on 26 June 1987, and the AOC was opened for business on 8 December 1988. In 2008 the AOC was renamed the Pete V. Domenici Science Operations Center (DSOC) recognizing Domenici's "strong and effective support for science," and his role in securing Congressional support for the VLA as well as the VLBA along with the New Mexico legislature's support for the AOC (Fig. 8.7).

Perhaps the biggest technical challenge facing the VLBA was the choice of the recording system (Rogers 2000). The NRAO MK II VCR based system was reliable, relatively inexpensive, and could record for up to three hours on a single tape costing only a few dollars. But the MK II VCRs only recorded at 4 Mbps, limiting the bandwidth to 2 MHz. NRAO proposed to implement an upgrade based on work by Allen Yen at Toronto that would allow VCRs to record at 12.5 Mbps. The Haystack MK III system had a demonstrated recording rate (bandwidth) of 112 Mbps, or 28 times greater than the MK II system. But the MK III Honeywell Model 96 tape transport was very expensive; a single tape cost about $250 and lasted for only 13 minutes. The NRAO proposal suggested using a bank of eight upgraded MK II VCRs with a robot tape changer that would allow 24 hours of unattended recording at 100 Mbps (Fig. 8.8). Haystack proposed replacing the standard 28 track MK III headstack with a newly designed moveable 36 narrow track headstack that would allow multiple 128 Mbps passes on a single half-inch tape.

Fig. 8.7 The VLA-VLBA Array Operations Center, later named the Pete V. Domenici Science Operations Center (DSOC) in Socorro, New Mexico. Credit: NRAO/AUI/NSF

Neither the upgraded NRAO MK II based system nor the upgraded Haystack MK III based system had been demonstrated, and considerable design work was still needed in each case. While there was some technical preference within NRAO for the MK II based system, MIT wanted to stay involved,[84] and NRAO agreed that MIT/Haystack would develop the VLBA recording system based on the upgraded MK III system. As the Haystack record system pushed the state of the art for magnetic tape recordings, its development suffered from continually increasing costs and corresponding delays. This led to constant tension between NRAO and Haystack/MIT. As a nonprofit university, neither Caltech nor Haystack/MIT could accept fixed priced contracts, and Hein Hvatum liked to complain that the Caltech/MIT definition of a deliverable was a new proposal asking for more money. As with Caltech, the increasing tensions between NRAO and Haystack and what NRAO called the Haystack/MIT/Caltech "grant mentality" resulted in NRAO assuming responsibility for the production of much of the record/playback system. However, responsibility for the design of the challenging tape recorder upgrade remained with Haystack, since they had the unique expertise and experience to engineer the recorder to demanding specifications.

Though there were delays at Haystack in meeting the specified performance, the resulting VLBA recording system was a remarkable technical achievement. It recorded over 20 million bits of information on a square inch of magnetic

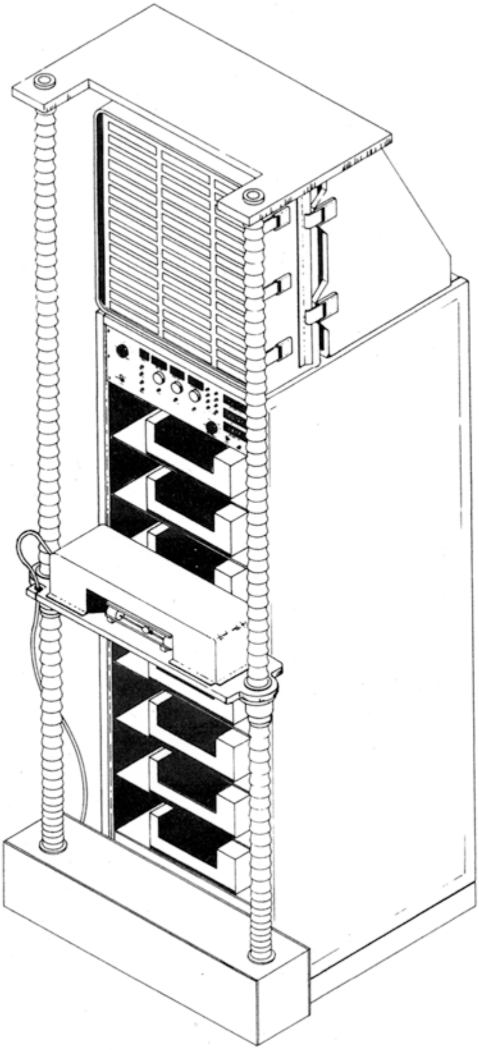

Fig. 8.8 Artist's conception of the proposed bank of eight modified consumer TV Video Cassette Recorders using a robot cassette changer to allow up to 24 hours of unattended VLBA recording at a 100 megabit per second data rate. The VCR concept was abandoned in favor a MK III based recording system. Credit: NRAO/AUI/NSF

tape. Each 3.4 mile-long 38 micron-wide track of data deviated from a straight line by less than 0.001 inch. With 14 passes on each tape, a 14-inch reel of tape lasted for 10.5 hours at the nominal 128 Mbps recording rate, so that by using two recorders the tapes needed to be changed only once every day. For special experiments requiring higher sensitivity, the tapes could be run at twice the nominal speed to record at 256 Mpbs (128 MHz bandwidth) and on occasion the two tape drives were run in parallel, each at twice the nominal speed, to record at 512 Mbps (256 MHz bandwidth). In order to facilitate the use of other radio telescopes with the VLBA, VLBA-compatible record systems were fabricated and delivered at cost to radio observatories around the world.

Although the VLBA record system met the design goals, it pushed the state-of-the-art bit density, and recordings were sensitive to environmental conditions. Prior to recording, tapes needed to be stored in a room with carefully controlled temperature and humidity, and were easily damaged by friction heating as the tape rubbed against the transport tape edge guides at 140 inches per second. Before recording, each tape had to undergo a "pre-pass" to relax strains introduced during shipping. Nevertheless, recordings were not always error free, and the lifetime of the expensive headstacks was limited. A major improvement in the sensitivity, reliability, and operational ease of the VLBA occurred in 2007 when the tapes were replaced by commercial computer disk drives. Later advances in disk recording technology led to recording rates up to 2 Gbps, resulting in a factor of four increase in sensitivity for continuum observations over the original VLBA 128 Mbps tape recording system. By 2010, some 40 years after the first NRAO software correlator that ran on IBM 360, computers had been replaced by more powerful hardware correlators, the original VLBA hardware correlator was replaced by a cluster of commercial computers running a program known as DiFX (Deller et al. 2007).

As happened with the VLA construction, the annual NSF budget allocations were in a constant state of negotiation with OMB and Congress, resulting in continuing adjustments of the VLBA construction funding. By 1985, more than 30 separate budget scenarios had been prepared in response to constantly changing NSF requests. Probably the most serious funding impact was a result of the gap introduced in the FY1985 Congressional appropriations bill and the cut from $15 to $9 million. In order to purchase the long-lead times for all ten antennas, the NSF Astronomy Division considered supplementing the VLBA Congressional appropriation with a few million dollars of Division funds. But the NSF director was reportedly too "terrified of Boland" to reprogram NSF funds for the VLBA,[85] and it became necessary to delay work on the receivers, masers, record system, and processor, as well as renegotiate the antenna contract with RSI. Meanwhile, there was pressure from the user community, represented by the VLBI consortium, to fully instrument each antenna as it was completed and provide a correlator in order to begin observing programs, resulting in continual tension between NRAO and the VLBI community.

For two reasons, NRAO wanted to maintain the antenna construction schedule to the extent possible. First, if the contractual arrangements with RSI were not maintained, the cost of the antennas was likely to increase. Second, there was the residual concern that if the NSF or Congress were to cut off VLBA funding, it was important to at least complete the construction of all ten antennas, assuming that one way or another the instrumentation would somehow get built. However, maintaining adequate funding to complete the antennas on schedule meant that funding for other parts of the project would need to be deferred. In particular, this meant delaying the playback processer work at Caltech.

The VLBA playback processor was in a sense the brain and heart of the VLBA (Romney 2000). This was where the tapes from the ten remote sites were returned to be simultaneously played back and the data correlated. Using time stamps from a hydrogen maser atomic clock encoded at each antenna at record time, the tapes were synchronized at playback time to a small fraction of a microsecond and the signals from each antenna were correlated with the signals from each of the other nine antennas. Caltech did not have the resources to keep the correlator design team during a several year delay in funding, and agreed to terminate the correlator contract, which shifted back to NRAO, a move which was not completely unwelcome at NRAO. Jonathon (Jon) Romney, who had originally been hired at NRAO to work with the Caltech group, assumed responsibility for finishing the VLBA playback system in Charlottesville. Exploiting the delay resulting from the reduced level of funding, Romney and his group decided on a then unconventional approach to the design of the correlator, an idea originally suggested by Marty Ewing at Caltech and based on a concept proposed by the Japanese scientist Yoshihiro Chikada.[86] The VLBA correlator used a custom designed "FX Chip" which itself turned out to be a challenge, and had to undergo several rounds of prototyping before a satisfactory version was fabricated.[87]

When completed in 1992 and moved to Socorro, the VLBA correlator was able to execute nearly a trillion (10^{12}) multiplications a second, and supported up to 20 simultaneous playback systems, allowing the use of up to ten external antennas as well as the ten VLBA elements (Romney 2000). Alternatively the 20 playback drives could be used to support a double data rate (512 Mbps) if two drives were simultaneously used to record at double the sustainable rate (256 Mbps). The VLBA divided the data into 16 IF bands, each 8 MHz wide, and was not fully compatible with the MK III systems being used elsewhere which divided the data into 64 bands, each 2 MHz wide. But with time, VLBI systems at radio observatories around the world were modified to conform with the VLBA standard.

As a result of the constant budgetary concerns and the need to defer aspects of the VLBA construction, along with a confident, but naïve belief that most of the needed post-processing software was already available, NRAO did not devote sufficient resources to post-processing software development. As a result, VLBA users depended on the widely used Caltech Difmap VLBI package and on the Astronomical Image Processing System (AIPS), which had been developed for VLA data analysis. It would be several years after completion of the VLBA hardware before the VLBA could be considered fully operational and could be used by the non-expert observer. But the monitor and control software also lagged the hardware, in part due to a late start, and this impacted testing of the correlator (Walker 2000).

The last antenna at Mauna Kea was completed in April 1993, and was followed by the formal VLBA dedication on 20 August 1993 (Fig. 8.9). Pete Domenici, who played such a vital role in funding both the VLBA and AOC construction, was the keynote speaker. As Paul Vanden Bout later recollected, Domenici's staff and others were amused when, despite having it spelled out in large letters on a strip taped to the top of the podium, Domenici kept referring

Fig. 8.9 VLBA dedication on 20 August 1993. US Representative Joe Skeen (left) and NRAO Director Paul Vanden Bout (right) watch as Senator Pete Domenici scans the bar code below the word "Start" to initiate observations of the galactic hydroxyl (OH) gas cloud known as W3OH. The bar code triggered lights for each station on the displayed map, sequencing from east to west, and put a message on operators' screens prompting them to manually start the actual pointing sequence. Credit: NRAO/AUI/NSF

to the "Very Large Big Array." The final VLBA construction cost was $85 million, considerably more than the proposed $50.7 million. Much of the increase was the result of the stretched out, nearly level NSF funding and the consequential incremental purchases, and the need to maintain the standing army for the seven year construction period. Nevertheless, it would still be some years after the 1993 dedication before the VLBA became fully operational, including the specialized data reduction software needed to transform the data into high quality astronomical images.

The VLBA was arguably unique in having the broad involvement of the potential user community in specifying the design and contributing to its development. The Working Groups met regularly by teleconference and occasionally in person to discuss the many issues as they arose. However, the VLBA had an unexpected unfortunate consequence for VLBI research in the United States. It was understood by everyone that the construction of the VLBA would likely lead to the termination of NSF funding support for the operation of the OVRO, Iowa, Illinois, Fort Davis, Texas, and Haystack antennas that were being used in support of VLBI Network observing. The first casualty of the VLBA was the critically located antenna at Fort Davis following the rejection of Harvard's 1986 proposal to the NSF to operate the antenna through 1989, although the VLBA construction had barely begun. This was followed by the gradual but premature termination of NSF funding for VLBI support at OVRO, Haystack, Iowa, Hat Creek, and Illinois, which limited their participation in Network VLBI activities using the partially completed VLBA.

The closing of these facilities for VLBI itself was not a surprise, nor necessarily a disappointment, to their faculties and students, since it meant the end of their responsibilities to support VLBI observations in which they had no scientific involvement. But unexpectedly, the faculty and staff at these university radio observatories also lost their research funding, which had previously been packaged as part of the observatory operations grants. This had a long-ranging impact, specifically to the VLBA and more broadly to US radio astronomy. Without research support, it was just those university scientists that had developed VLBI techniques, including their active participation in the design of the VLBA and in supporting the proposal to build the VLBA, that were forced to turn their attention elsewhere. At Caltech, former VLBI scientists migrated to millimeter and optical astronomy, went to JPL to work on NASA missions, or left radio astronomy. Readhead and Tim Pearson devoted the next years to building an interferometer in Chile to investigate the small scale structure in the cosmic microwave background. At Haystack, the VLBI group focused their activities on NASA-supported geodetic research. At Berkeley, Don Backer became increasingly involved in pulsar, SETI, and Epoch of Reionization (EoR) research. Perhaps more important in the long term was the loss of students who had to follow the money. As a result, following its completion in 1993, the VLBA was used primarily by scientists from Harvard/Smithsonian, USNO, and NRL, with funding from Smithsonian and DoD respectively, as well as NRAO and foreign-based scientists. Indeed, much to the irritation of the NSF, about half of the available VLBA observing time has been used by non-US-based scientists, largely from Europe, but increasingly from China, Japan, and Korea, and ironically this probably contributed to the later NSF decision to divest from the VLBA (Sect. 8.10).

Transition to Operations[88] VLBA operations began as early as 1987, starting with the first completed VLBA antenna at Pie Town which was used to supplement the existing VLBI Consortium antennas. Additional VLBA antennas were added to the VLBI network antennas as they were completed. Initially, proposal review and scheduling were handled by the existing VLBI Consortium scheduling procedures, but starting in 1992, these activities were assumed by VLBA Operations. To support the Consortium observations, pending completion of the VLBA correlator, MK II terminals were installed at the first seven VLBA antennas, and the data continued to be correlated at the Caltech/JPL processor. Data obtained using the broad band VLBA recorders were initially processed at Haystack, Caltech, Goddard, or Bonn as appropriate. For these observations with the Consortium antennas, the capabilities at the stations included recording on narrow track recorders using either thick or thin tapes, or recording with the older wide track recorders. Maintaining capabilities to process all combinations stressed the operational capabilities of the processors.

During this period of "interim" VLBA operations, the NSF was unsympathetic to requests for interim "pre-operating" funds. Even after the completion of the VLBA, NRAO never received the planned additional $7 million annual operating funds. This impacted other NRAO operations as well as slowing upgrades to the VLBA.

8.9 Orbiting VLBI (OVLBI)

From the time of the first VLBI experiments, radio astronomers appreciated that there were no theoretical limits to the resolution of radio interferometers. Interferometers the size of the Earth were easily and quickly implemented. By going to space, baselines could be extended without limit, and the possibility of Earth-Space VLBI, commonly referred to as "Space VLBI," or "Orbiting VLBI" (OVLBI) was recognized as early as the Field (1982) Report. Its Radio Astronomy Panel Report (Thaddeus 1983) boldly suggested that a space VLBI mission required no new technology, and recommended that the VLBA be supplemented with a 25 meter orbiting radio telescope with compatible instrumentation, including IF data transmission to the Earth via the NASA Tracking and Data Relay Satellite System (TDRSS).

Probably the first serious Orbiting VLBI proposal was made in 1976 by Burke (MIT), Kellermann, and others, who suggested putting a 4 meter antenna on SpaceLab. The proposal was almost successful, but was beaten out by an infrared mission that apparently had broader engineering and surveillance applications. Burke's team proposed again in 1978 to orbit a 30 meter diameter antenna, but NASA later withdrew from the SpaceLab program. In 1979, Burke suggested that the NASA Venus Orbiting Imaging Radar antenna could be used as a variable spacing interferometer during its voyage from Earth to Venus. But after initial approval, NASA concerns about being able to stow the antenna before going into orbit around Venus killed Burke's ambitious VLBI project. Next, Burke and Frank Jordon (JPL) led an unsuccessful effort to fly a VLBI mission on the Space Shuttle.

The first demonstration of the practical feasibility of doing radio interferometry from an orbiting spacecraft came not from a mission designed for the purpose, but from the NASA TDRSS. In 1986 and 1987, a team of scientists from the US, Japan, and Australia, led by Gerry Levy from JPL, used a 4.9 meter antenna onboard the first NASA TDRSS antenna at 2.3 GHz (13 cm) together with 64 meter antennas in Australia and Japan to demonstrate the feasibility of Earth to space VLBI (Levy et al. 1986; Levy 1989). The TDRSS spacecraft are in geostationary orbit, and operational restrictions allowed only a restricted range of observations to give a maximum projected baseline up to 2.15 Earth diameters (27,400 km). These OVLBI observations demonstrated, for the first time, that some radio sources had brightness temperatures as high as a few times 10^{12} K, at or above the traditional Inverse Compton Limit supporting the existence of bulk relativistic motion (Linfield et al. 1989).

Starting in the early 1980s and continuing for the next three decades, US and European radio astronomers, sometimes separately, sometimes collaboratively, proposed a number of Earth to space interferometers including QUASAT,[89] the International VLBI Satellite (IVS),[90] and the Advanced Radio Interferometry between Space and Earth (ARISE) mission.[91] With primary support from ESA, NASA, and the US National Academy of Sciences, numerous reports were written and meetings held in Gross Enzersdorf (Austria), Budapest, Bologna, Noordwijk (Netherlands), Paris, and Tokyo, and in the US at NRAO (Green Bank and Charlottesville), JPL (Pasadena), NASA (Cape Canaveral, Florida), and at the NAS (Washington DC). Burke and Frank Jordon (JPL) led the effort in the US, and Richard Schilizzi in Europe. Kellermann, and later Bob Brown and Larry D'Addario, represented NRAO at these meetings. To coordinate these efforts, COSPAR set up an ad-hoc Committee on Space VLBI under the leadership of Graham-Smith of the UK. Meanwhile, the four space agencies from the US (NASA), Europe (ESA), Japan (ISAS), and the USSR (Intercosmos) set up their own Inter-Agency-Consultative-Group to exchange information on international OVLBI planning. The Global VLBI Working Group (GVWG) was organized at the 1990 URSI General Assembly in Prague at the suggestion of NRAO Director Paul Vanden Bout and URSI Commission V Chair Ron Ekers to coordinate both space and ground-based observing and tape management. Many of the same people from the small OVLBI community served on these multiple committees.

Considerable development work went into the studies, but none of the proposed US or European missions ever reached the launch pad. Launching large radio telescopes into Earth orbit is very expensive, and radio astronomy was doing very well from the ground. Within both Europe and the United States, radio astronomers were only looking to space to enhance their resolution, and they could not compete with the many proposals for infrared and high energy astrophysics missions where the science and the scientists were completely dependent on opportunities to observe from above the Earth's obscuring atmosphere. Moreover, except for spectroscopic observations or a few specialized observations relating to the maximum brightness temperature of synchrotron sources,[92] improved resolution can be obtained more easily and more cheaply by simply observing at shorter wavelengths. As a result, the relatively small radio astronomy community was unable to convince NASA or ESA to support a space VLBI program. However, they were more successful in Russia and Japan.

OVLBI also presents another challenge. Unlike other space astrophysics programs, OVLBI requires a network of ground radio telescopes to form the ground-based ends of Earth-Space interferometers. Moreover, typical space programs share the use of ground stations to send their data back, and OVLBI requires the full time use of at least two ground stations to receive the broadband spacecraft data on a continuous basis. The need for NASA and ESA to team up with the ground community and surrender their control of the mission may explain their reluctance to become involved in OVLBI. In the US, the separation of funding for ground- and space-based astronomy between the NSF and NASA complicated the funding situation.

The 1984 meeting in Gross Enzendorf not only provided a focus for the proposed QUASAT mission, but western scientists heard, for the first time, about the proposed Japanese VSOP and Soviet RadioAstron OVLBI missions from Masaki Morimoto and Roald Sagdeev respectively. Morimoto was well known to US and European radio astronomers, not only for his role in building the Japanese 45 meter radio telescope at Nobeyama, but also for his boisterous, alcohol-enhanced after dinner performances at numerous scientific conferences. Sagdeev, by contrast, was the prominent director of the Soviet Space Research Institute (IKI) who was an advisor and confidant of Mikhail Gorbachev, but at the time, was not known personally to the US or European radio astronomers.[93] Each of the two missions established their own international advisory committees—the RadioAstron International Science Council (RISC) for RadioAstron and the VSOP International Steering Committee (VISC) for VSOP. Both VSOP and RadioAstron were identified in the 1991 Decade Review of Astronomy and Astrophysics (Bahcall 1991) as excellent opportunities for international collaboration in astronomy, and recommended by the Radio Panel (Kellermann 1991) for NASA support for US participation in both missions.

VSOP The Japanese VLBI Space Observatory Programme (VSOP) was approved as an experimental mission by ISAS and was launched on 12 February 1997 aboard the first test flight of the Japanese Space Agency M-V rocket. It was widely assumed by the participants that the acronym VSOP was chosen by Morimoto after his favorite beverage. However, after launch, the spacecraft was renamed Highly Advanced Laboratory for Communications and Astronomy (HALCA). HALCA carried an 8 meter diameter dish into an elliptical orbit with a 21,400 km apogee, and was instrumented with receivers for 22 GHz (1.3 cm), 4.85 GHz (6 cm), and 1.66 GHz (18 cm). Unfortunately, the 1.3 cm system was damaged at launch. Without 1.3 cm, the resolution of VSOP/HALCA at the shortest wavelength (6 cm) was no better than the VLBA at 2 cm, and the opportunity to study H_2O maser emission was lost. VSOP remained in operation for six years, and was used primarily to study quasars at both 6 and 18 cm, and also made observations of pulsars and OH masers (Hirabayashi et al. 2000a). During the six-year lifetime of the mission, the VISC oversaw the proposal and scheduling process. NRAO played several important roles supporting VSOP operations. Starting in 1997, after modifications under Jon Romney's leadership to accommodate Earth to Space baselines, NRAO processed data from VSOP using the VLBA correlator. Larry D'Addario was successful in obtaining funds from NASA to build and operate a ground station in Green Bank using the old 15 meter antenna previously used as the remote station of the GBI. Ed Fomalont spent time at ISAS providing support for planning observations and analyzing data after it was correlated.

A later Japanese initiative, tentatively named VSOP2, proposed to use a 9 meter diameter antenna with cooled receivers at 5, 22, and 43 GHz in an elliptical orbit ranging from 1000 to 25,000 miles. To provide advisory support, the VISC was reconstituted as VISC-2. JPL, in collaboration with NRAO and US radio astronomers, requested NASA support for US supporting activities. The SAMURAI (Science of AGNs and Masers with Unprecedented Resolution in Astronomical Imaging) proposal requested NASA funding for a VSOP-2 tracking station, along with operational support for data analysis, and use of the VLBA and GBT. However, although VSOP 2 was initially approved by ISAS, they subsequently canceled the VSOP2 program due to technical problems and escalating costs.

RadioAstron Discussions of space-based interferometer systems in the USSR go back to the 1960s, but the details of the early planning have been lost to Soviet era secrecy. RadioAstron, also known as Spectrum-R, was one of three planned Soviet space astrophysics missions developed at the Cosmic Research Institute (IKI), the others being Spectrum-UV and Spectrum-X-gamma to work in the ultraviolet and high energy parts of the spectrum respectively. Each of the planned Soviet missions was led by an influential and respected Soviet academician—Nikolai Kardashev for RadioAstron, Alexander Boyarchuk for Spectrum-UV, and Rashid Sunyaev for Spectrum-X-γ, who vigorously competed for scarce resources. For years, the claimed priority for the first launch of the Spectrum series of satellites seemed to depend on who you were talking to.

Unlike VSOP, which was only 22,000 km above the Earth, Kardashev planned that RadioAstron would go out to 100,000 km, which he later extended to 350,000 km, close to the distance to the Moon. Like VSOP, RadioAstron required international participation, partly to provide access to large ground radio telescopes, partly to obtain the advanced VLBI recording technology not available in the Soviet Union, along with the need to have a global tracking network. From the beginning, the Western RISC members, as well as prominent scientists in the Soviet Union, argued against the high orbit proposed by Kardashev, first on the grounds that due to inverse Compton scattering, there would be no radio sources so small that they could be detected on such long interferometer baselines. Second, they argued that even if such small sources existed, interstellar scattering, at least for observations at the longer wavelengths, would likely broaden the source size, also rendering it unobservable with the high resolution corresponding to such long interferometer baselines.

It seemed for years that launch of RadioAstron was always scheduled to be five years from the date of inquiry, possibly reflecting the need to keep the project within the rolling Soviet five-year plan. When Kardashev lost his bid to become director of IKI he moved his whole team to the newly formed Astro Space Center (ASC), part of the well-known Lebedev Physical Institute, but due to space limitations at Lebedev, the ASC physically remained in the IKI building. The dissolution of the Soviet Union in 1991 and the ensuing deterioration of the Russian economy further delayed the mission. Kardashev managed to keep the RadioAstron team intact, but for at least a decade there was little progress toward a launch.

In 1989, Soviet Academicians Andrei Sakharov and Vitaly Ginzburg wrote to NASA Administrator Admiral Richard Truly asking for NASA support to provide tracking and data acquisition for RadioAstron and for funding for NRAO to build VLBA terminals for recoding the downlinked data in the USSR. The letter was signed by Sakharov only two weeks before he died.[94] Three months later, Vice President Dan Quayle, who headed the National Space Council, informed the Soviet ambassador to the US and issued a press release announcing that the US would participate in RadioAstron.[95] NASA set up a "Joint Working Group" specifically to deal with US-Soviet collaboration on astrophysics space missions.[96] US scientists, particularly from JPL and NRAO (Brown, D'Addario, Kellermann, and Weinreb), met frequently to develop plans for NRAO participation in RadioAstron. However, with the ensuing delays and uncertain status on the Russian side, as well the widely held skepticism about the choice of the orbit, NASA never got involved in RadioAstron, in spite of the NAS Decade Review which recommended "moderate" support from NASA for both VSOP and RadioAstron (Field 1982). Later, at the request of Kardashev, NRAO did build two low noise 1.3 cm FET amplifiers for RadioAstron which were sold to the ASC at cost after obtaining the necessary export license. The 1.3 wavelength receiver was particularly important for the success of RadioAstron, as it provided the highest resolution for continuum sources and was also needed for observations of the 1.3 cm H_2O maser sources.

RadioAstron was finally launched successfully from the Baikonur Cosmodrome in Kazakhstan on 18 July 2011. The spacecraft contained a 10 meter diameter antenna and receivers for the 1.3, 6, 18, and 92 centimeter bands. At the time of the launch Russia had only one ground station at Puschino, near Moscow, to receive the IF data from the spacecraft. A second ground station was badly needed to support observations when the satellite was not in view of Puschino. Since the high orbit extending out to 350,000 km, a high gain antenna was needed, and the retired NRAO 140 Foot was an obvious choice. But the 140 Foot antenna had been mothballed years earlier, and considerable work was needed before it could be restored to operational status. As NASA funding to support these activities never materialized, and OVLBI was beyond the purview of NRAO's NSF funding, shortly after the launch of RadioAstron NRAO and the Astro Space Center executed an MOU whereby the ASC provided the funds needed to refurbish the 140 foot antenna and to operate it as a downlink for RadioAstron. The Astro Space Center built a copy of the instrumentation used at Puschino and brought a team to Green Bank to install the equipment and to train the NRAO staff in its operation. Under a series of further MOUs, the 140 Foot antenna continued to downlink data from RadioAstron for later correlation in Bonn or in Moscow. After six years of operation, the on-board hydrogen maser that provided the local oscillator reference signal finally died, and starting in July 2017, both Green Bank and Puschino have transmitted to the spacecraft a real time local oscillator link referenced to ground-based masers. Following the loss of communication with the spacecraft, scientific observations with RadioAstron ceased in early 2019.

Starting in 2012 RadioAstron was used with a variety of ground-based radio telescopes to study quasars, OH and H_2O masers, pulsars, and the ISM, as well as doing tests of General Relativity with angular resolution as fine as 10 microarcsec. The RadioAstron scientific program was based on annual open calls for proposals which were reviewed by an international Program Review Committee.[97] For observations requiring the highest sensitivity, the GBT was used as the ground end of the Earth-Space interferometer. Much to the pleasant surprise of Western colleagues, RadioAstron observations showed fringes out to more than 200,000 kilometers, demonstrating brightness temperatures more than 10^{13} K, or several orders of magnitude greater than the Inverse Compton Limit for stationary sources (e.g., Kovalev et al. 2016; Pilipenko et al. 2018). The observation of fringes at 18 and even 92 cm on surprisingly long baselines has led to a new understanding of turbulence in the ISM and the nature of refractive scintillations (e.g., Johnson et al. 2016).

8.10 REFLECTIONS

The extraordinary milli-arcsec angular resolution of images made with the VLBA has enabled a wide range of galactic and extragalactic astronomy observations as well as important geodetic studies of continental drift and Earth rotation. As anticipated in the 1982 VLBA proposal, continuing observations of AGN jets have been a large part of VLBA observing programs, with data on individual sources now extending to as much as 25 years. Although much has been learned about the shapes (e.g., Pushkarev et al. 2017), kinematics (e.g., Cohen et al. 2007; Kellermann et al. 2007; Lister et al. 2016; Jorstad et al. 2017), and polarization (Homan et al. 2018) of AGN jets, there is still much unknown about how the jets are launched, collimated, and accelerated to nearly the speed of light.

Phase referencing, only briefly mentioned in the proposal, has become an important and routine part of the VLBA.[98] Precision VLBA astrometric measurements at unprecedented levels (Reid and Honma 2014) have been a pleasant surprise, more than meeting the proposal promises, and have enabled the determination of parallaxes (distances) to radio source throughout the Galaxy and the better delineation of its spiral arms (Reid et al. 2016) and overall structure, including size and rotational velocity. One of the important successes of the parallax measurements was the resolution of the distance controversy to the Pleiades star cluster (Melis et al. 2014).

Probably the single biggest impact of the VLBA, one of critical importance to cosmology, has come from the direct geometric measurement of the distance to the galaxy NGC 4258 to an accuracy of 3 percent through precise temporal monitoring of the motions of water masers in Keplerian orbits about the galaxy's center (Herrnstein et al. 1999, 2005; Miyoshi et al. 1995). This has provided an accurate anchor for the Cepheid distance scale (Riess 2016). This work has led to the Megamaser Cosmology Project that determined the Hubble Constant, based on maser distances alone, to an accuracy of 5 percent (Reid et al. 2013). These measurements also led to the best evidence for the existence of a supermassive black hole (10^8 solar masses) in another galaxy.

Throughout this period, the VLBA has also contributed to studies of Earth orientation and plate tectonics (e.g. Petrov et al. 2009), tests of general relativity (e.g., Fomalont et al. 2009), and interplanetary spacecraft navigation (e.g., Jones et al. 2011). The ongoing USNO program makes daily VLBA measurements to provide Earth orientation and rotation parameters needed for precision navigation. However, there have been some duds as well. Observations of stimulated radio recombination lines, which was claimed to be of "particular interest" in the 1982 proposal, never materialized.

Many VLBA observing programs have involved other radio telescopes, mostly in Europe, but also in Australia, Japan, China, Korea, and South Africa. More recently, the Large Millimeter Telescope (LMT) in Mexico and ALMA in Chile have been used to supplement millimeter VLBI. The use of these external antennas improves the image quality over that of the VLBA alone, but introduces compatibility and operational complexities of the kind that existed before the VLBA and that the VLBA was intended to eliminate. A particularly attractive mode of operation has been the High Sensitivity Array (HSA) which adds two or more of the large radio telescopes at Green Bank, Bonn, Arecibo, and the VLA[99] to the VLBA.

By the end of the 20th century, the VLBA had to an extent become a victim of its uniqueness. Because telescopes at other wavelengths do not have the resolution comparable to that of the VLBA, the range of VLBA scientific investigations has had little overlap with the interests of the broader American scientific community. Quasars, AGN, cosmic masers, and radio stars are point sources to OIR, X-ray, and γ-ray telescopes. Moreover, the US VLBI community never fully recovered from the loss of funding resulting from the VLBA construction and the termination of university based VLBI grant support. At the same time, VLBI has thrived in the rest of the world. Modest VLBI Networks were created in Australia, Russia (KVASAR Network),[100] China, Korea, and Japan to complement the broader East Asian and Asia-Pacific VLBI Networks. As part of the African SKA program, Africa has begun an ambitious program to repurpose redundant communication dishes for VLBI. Within Europe, VLBI has received strong national support, as well as generous funding from the EU, perhaps as a relatively non-controversial and relatively inexpensive means of promoting European unity. The EVN has expanded to include observatories in Africa, China, and even the US Arecibo Observatory.

Unlike the user community at other NRAO facilities, only about half of the VLBA users have been from US-based institutions, many from NRL, USNO, SAO, and the NRAO staff, rather than from the university community. Faced with limited operating funds and in anticipation of increased demands for operating funds for the planned Large Synoptic Survey Telescope (LSST), DKIST, and ALMA (Sect. 10.7), the VLBA became a likely target for decreased NSF funding. Claiming that future NSF budgets would grow no faster than inflation, in 2005, the NSF charged a "Senior Review Committee" to "examine the impact and the gains that would result by redistributing ~$30 million of annual spending from [Astronomy] Division funds."[101] As a boundary condition of the study, the NSF specified, "we will not use resources from unrestricted grants programs (AAG) to address the challenges of facility operations or the design and development costs for new facilities of the scale of LSST, GSMT, SKA, etc." AUI was asked to make "the case for and priority of each component of NRAO (VLA, VLBA, GBT, ALMA operations, etc.), along with a defensible cost for each." In addition, the NSF asked that AUI provide "as realistic an estimate as possible of the cost and timescale that would be associated with divestiture of each component."[102]

In its report, the Senior Review Committee recommended that

> The Radio-Millimeter-Submillimeter base program should comprise the Atacama Large Millimeter Array, The Green Bank Telescope, and the Expanded Very Large Array [JVLA], operations together with support for University Radio Observatories and technology research and development through the Advanced Technologies and Instrumentation Program.[103]

The Committee went on to recommend that

> The National Astronomy and Ionosphere Center and the National Radio Astronomy Observatory, … should seek partners who will contribute to personnel or financial support to the operation of Arecibo and the Very Long Baseline Array respectively by 2011 or else these facilities should be closed.

Unless additional non-NSF sponsors could be found, the VLBA was clearly in trouble. Over the next few years, NRAO did reduce VLBA operating costs, but at the expense of reduced user support and poorer reliability. An agreement was reached with USNO by which USNO helped to support the VLBA in order to carry out their time measurements. Additional support to keep the VLBA operating was provided by the Universidad Nacional Autonoma de México (UNAM) in Mexico, MPIfR, and the European Radio Net. This external support helped, but was not sufficient to keep the VLBA operating. "In order to assess the most promising scientific areas for the VLBA, as well as review the options for new operational models and explore opportunities for additional support of VLBA operations," NRAO Director Fred Lo invited national and international observatory directors, NSF staff, and VLBI leaders to participate in a "Workshop on the Future of the VLBA."[104]

More than 60 scientists from 12 countries attended the Charlottesville Workshop held on 27–28 January 2011 (Fig. 8.10). Unfortunately, the start of the workshop was delayed by a major snow and ice storm which swept the East Coast on 26 January. Many participants spent the night at various airports or were on the road for up to nine hours to drive the 110 miles from Dulles Airport to Charlottesville. One participant obtained refuge in the back seat of a police vehicle when his rental car became stuck in the road. Following a series of talks on the major VLBA observing programs, the status of the various international VLBI networks, and discussions about recent and planned technical improvements, the participants agreed that the VLBA should emphasize key science and other large projects that involved less support from NRAO staff. The workshop participants also pledged sufficient external support that, combined with further cost saving measures, would enable NRAO to continue to operate the VLBA. In return NRAO would recognize the contributions of subscribers by awarding them a larger fraction of observing time, meaning less time for Open Skies proposals, even from US-based observers.

However, even this tough approach proved to be inadequate. The 2010 Astronomy Decade Review, "New Worlds and New Horizons" (Blandford 2010), provided an ambitious new agenda for the NSF Astronomy Division, which now faced potential additional operating funds for the highly recommended OIR, GSMT,[105] and LSST projects as well as for a variety of moderate programs. The NSF projected astronomy budgets were unable to support

Fig. 8.10 MPIfR Director Anton Zensus (right) confers with USNO Scientific Director Kenneth Johnston at the January 2011 Charlottesville VLBA Workshop. Credit: KIK/NRAO/AUI/NSF

these new initiatives as well as all of the existing facilities. James (Jim) Ulvestad,[106] the NSF Astronomy Division Director, convened a new "Portfolio Review Committee, Advancing Astronomy in the Current Decade: Opportunities and Challenges," that was charged with recommending the "AST portfolio best suited to achieving the decadal survey goals" under several budget scenarios. The Committee, chaired by Daniel Eisenstein[107] from Harvard, considered the whole AST portfolio of new and existing facilities and recommended that "AST divest from [the VLBA and GBT] before FY17," and that

> Within the context of open skies, the NSF should look to leverage its assets to maximize the ability of U.S. astronomers to access non U.S. capabilities or to obtain contributions toward operations and maintenance costs for U.S. facilities with high fractions of foreign users.[108]

In response to the Portfolio Review Committee report, when the AUI Cooperative Agreement to operate NRAO was due to expire in 2015, the NSF issued a competitive program solicitation for proposals to operate only the NRAO Jansky Very Large Array (JVLA), the North American share of ALMA, and the Charlottesville Central Development Lab.[109] It was the first time in the 60 year history of AUI management of NRAO that the NSF did not renew the NRAO five-year contract or Cooperative Agreement based on a non-competitive proposal. This time, a competing proposal was submitted to manage NRAO by the Southeastern Universities Research Association (SURA). Following a lengthy and detailed evaluation and review process, the NSF awarded AUI two new ten-year Cooperative Agreements, one to manage the North American share of ALMA and the other for NRAO operation of the JVLA, the Charlottesville Headquarters, and the Central Development Lab, effective 1 October 2016. Management of the Green Bank Observatory (GBO) and the VLBA under the Long Baseline Observatory (LBO) continued under an extension of the previous Cooperative Agreement, but with reduced funding for operations. Moreover, the LBO and GBO were established as new independent observatories, reporting directly to AUI and not as part of NRAO.[110] However, AUI appointed NRAO Director Tony Beasley as the AUI Vice President for Radio Astronomy, with direct responsibility for the NRAO, GBO, and LBO. Walter Brisken, a long-time member of the Socorro staff, was named as the LBO Director reporting to Beasley.

As planned when the decision was made to locate the VLBA operations in Socorro, the long-time operation of the VLBA jointly with the VLA as part of NRAO's New Mexico Operations was very effective. Many of the scientific, technical, computing, and administrative staff seamlessly supported both instruments. The new split, mandated by the NSF, added an extra layer of administration. The LBO did not have sufficient staff or resources to manage proposal review, human resources, or other administrative responsibilities, and depended on NRAO for these tasks, and it continued to use the nrao.edu email server. As mandated by the NSF, the LBO reimbursed NRAO for the cost of providing these various services. Considerable effort by AUI, NRAO, LBO, and the NSF was devoted to preparing the guidelines by which the LBO would operate as an "independent observatory" which was not really independent, and the NSF provided a one-time $1.5 million budget increment to set up the needed administrative framework.

Under the leadership of Brisken and Beasley, the LBO concluded an arrangement by which the USNO paid for half of the cost of the VLBA operations and development in return for half of the observing time to conduct observations to determine UT1 and other Earth rotation parameters. Smaller agreements with Australia, China, the MPIfR, the New York University in Abu Dhabi (UAE), and DoD provided additional financial support in return for observing time, enough that the NSF was satisfied that NRAO had created a sustainable operations model for VLBA. Following a non-competitive AUI proposal requested by the NSF, the once-threatened VLBA was reintegrated back into NRAO effective 23 October 2018. While providing less Open Skies observing, especially for small individual investigator projects, the long term stability of the VLBA was assured.

NOTES

1. Discussions of high resolution imaging in radio astronomy and the development of the NRAO-Cornell independent-oscillator-tape-recording interferometry system are given in Burke (1969), Kellermann and Cohen (1988), Moran (1998, 2000), and Kellermann and Moran (2001). The development of the Canadian long baseline interferometer system was reviewed by Gush (1988), Broten (1988), and Galt (1988). Section 8.1 is based, in part, on these papers.
2. Assuming that the variability time scale cannot be shorter than the light travel time across the source and knowing the distance to the quasars, the rapid variability suggested that the angular dimensions of variable radio sources was probably ≤0.001 arcsec.
3. For many quasars, the radio spectrum shows a sharp cutoff at low frequencies thought to be due to synchrotron self-absorption which is only important for very small dense radio sources.
4. Very small diameter radio sources scintillate or "twinkle" in the turbulent interplanetary medium in the same way that stars twinkle due to atmospheric turbulence.
5. In directly connected or radio linked interferometers, a common local oscillator (LO) signal is sent to each antenna where it is mixed with the incoming radio frequency (RF) signal to produce an intermediate frequency (IF) baseband signal. In VLBI systems the common LO is replaced by separate oscillators that are stabilized by atomic frequency standards that are sufficiently stable that they maintain coherence for the integration period—typically a few minutes to tens of minutes. The required stability is of the order of the reciprocal of the observing frequency. The atomic frequency standards are also used as atomic clocks, to provide synchronization of the recorded signals. The required

stability is of the order of the reciprocal IF bandwidth. For these early VLBI systems this was of the order of 1 microsec. Modern VLBI systems are generally stabilized by hydrogen maser frequency standards, but due to their greater cost and the lack of commercial sources of hydrogen masers, many of the earlier VLBI systems used the simpler and less stable commercially available Rubidium standards.

6. The sensitivity of radio telescopes depends inversely on the square root of the instantaneous bandwidth.
7. The Canadian group consisted of N.W. Broten, T.H. Legg, J.L. Locke, C.W. McLeish, R.S. Richards from the Canadian National Research Council; R.M. Chisholm from Queens University; H.P. Gush and J.L. (Allen) Yen from the University of Toronto; and J.S. Galt from the Dominion Radio Astrophysical Observatory.
8. B.G. Clark and K.I. Kellermann, 3 November 1965, General Considerations for a Very Long Baseline Interferometer, NAA-KIK, VLBI, Box 1.
9. Cohen et al., 22 November 1965, Some Considerations for a Very Long Baseline Interferometer between the Arecibo Ionospheric Observatory and NRAO, NAA-KIK, VLBA, History and Development.
10. DSH to R.M. Robertson, NSF Associate Director for Research, 15 April 1966, appended to the AUI-BOTXC minutes, 20 May 1966.
11. The NRAO MK I and later MK II VLBI systems used 1-bit samples of the digital data following a scheme developed by Sander Weinreb (1963) as part of his MIT PhD thesis. The data were sampled at twice the reciprocal bandwith, known as the Nyquist sampling rate. Harry Nyquist was a member of the Bell Laboratories staff and a contemporary of Karl Jansky. The correlation of 1-bit data suffers a loss of sensitivity of by a factor of $\pi/2 = 1.57$ compared with analog data, but is technically straightforward and is insensitive to gain fluctuations. The VLBA can use either 1-bit or 2-bit digitizing of the baseband data. With the bit rate limited by the recording technology, 2-bit digitizing at the Nyquist rate can cover only half of the bandwidth, but the sensitivity is about the same as 1-bit digitizing at the Nyquist rate.
12. Rubidium frequency standards made use of the hyperfine transition of rubidium-87 atoms at 6834682610.904 Hz.
13. The LORAN C (LOng RAnge Navigation) was used to locate the position of US naval ships. By comparing the time of arrival of transmissions from different LORAN C stations, ships could accurately determine their position without the need to depend on clear weather for traditional celestial navigation. When used for VLBI, the location of the observatory was known from conventional surveying techniques, and so knowing the distance to each LORAN C station, and thus the propagation time and the time that signals were transmitted, gave the accurate time at the observatory.
14. The nomenclature Mark I or MK I, II, III etc. was adopted by Barry Clark following the tradition of designating generations of naval equipment.
15. The Hewlett Packard HP 5065A Rubidium clock and 556 bits per inch (720 kilobits/sec) computer tape recorders were controlled items with potential military application.
16. One of the visitors, Dr. Leonid Matveyenko from the Lebedev Physical Institute, was a student of Shklvoskii and had been involved in the earlier discussions with Lovell. Matveyenko was accompanied on this initial trip by Dr.

Ivan Mossiev, who was in charge of the radio observatory in Crimea. For the actual observations one of the present authors (KIK), along with NRAO engineer John Payne, traveled to the USSR to supervise the installation and operation of the NRAO instrumentation.

17. In order to carry out a successful VLBI observation, the clocks at the two ends need to be synchronized to about an accuracy of the order of the reciprocal bandwidth. With the MK I system in use at the time, this corresponded to about 1 microsecond.
18. The classical test of relativistic light bending was first made during a solar eclipse in 1919. Sir Arthur Eddington barely measured the bending by an amount close to the predicted 1.75 arcsec at the limb of the Sun, which was widely acclaimed as confirmation of Einstein's theory of General Relativity. In later years Eddington's results were questioned. Radio measurements improved the precision to about ten percent, but the advent of VLBI opened an opportunity to greatly improve the accuracy.
19. Shaffer had begun his radio astronomy career as an NRAO summer student in 1966 through 1969. After receiving his PhD at Caltech in 1974, he spent a year at Yale, returned to NRAO as a member of the scientific staff for four years, and then spent the rest of his career at Radiometrics Inc. providing support for the MIT/NASA geodetic VLBI program.
20. Correlation of a pair of 3 minute tapes on the IBM 360/75 was about ten times faster than on the NRAO 360/50 computer.
21. When the energy density in a synchrotron radiation field exceeds the energy in the magnetic field, the relativistic elections lose energy by the Inverse Compton effect which produces X-rays, further enhancing the Inverse Compton losses.
22. Very Long Baseline Radio Interferometry Using a Geostationary Satellite, ESA Phase A Study, 1980, SCI (80) 1; ESA Study of the Ground Segment, 1981, SCI (81) 5. Although NRAO was not directly involved in this activity, Kellermann was then on leave from NRAO as a Director at the MPIfR, and participated in the study.
23. A New Midwest Antenna for the VLBI Network. A proposal to the NSF by G.W. Swenson, PI, June 1978, NAA-KIK, VLBA, History and Development.
24. Bologna, Jodrell Bank, MPIfR, Onsala, and Westerbork.
25. K. I. Kellermann, 1973, Some Thoughts on the Construction of an Intercontinental Very Long Baseline Array (VLBA), NRAO Internal Memo, NAA-KIK, VLBA, History and Development.
26. DSH to J. Broderick (VPI), B. Burke (MIT), T. Clark (Goddard), M. Cohen (Caltech), T. Clark (Goddard), W. Erickson (Maryland), M. Ewing (Caltech), S. Knowles (NRL), J. Moran (Harvard), A. Rogers (MIT), D. Shaffer (Interferometrics Inc.), G. Swenson (Ill), I. Shapiro (Harvard), 18 July 1974, NAA-KIK, VLBA, History and Development.
27. Report of the 13th meeting of the Canadian Astronomical Society, 3 June 1982, NAA-KIK, VLBA, History and Development.
28. The CLBA initially proposed to use 25 meter antennas, but later increased the size to 32 meter for greater sensitivity. The shortest wavelength of the 32 meter antennas was 1.3 cm compared with the 7 mm limit of the VLBA 25 meter antennas. "A Proposal for a Canadian Very-Long-Baseline Array," NAA-NRAO, NM Operations, VLBA. See also NAA-AHB, Canadian Long Baseline Array for more details of the CLBA.

29. Report of the 13th meeting of the Canadian Astronomical Society, op. cit.
30. Seaquist to KIK, 28 July 1983, NAA-KIK, VLBA, History and Development; A. Bridle and C. Walker, VLBA Memo No. 237. http://library.nrao.edu/vlba/main/VLBA_237.pdf
31. KIK, VLB Array Memo No 1, 22 May 1980, NAA-KIK, VLBA, History and Development. http://library.nrao.edu/vlba/main/VLBA_01.pdf
32. NAA-KIK, VLBA History and Development, Box 2.
33. Membership included D. Backer (UC Berkeley), B. Burke (MIT), M. Ewing (Caltech), K. Johnston (NRL), R. Mutel (Iowa), A. Rogers (Haystack), I. Shapiro (MIT), J. Welch (UC Berkeley).
34. Other Radio Panel Members were F. Drake (Cornell), M. Roberts (NRAO), J. Taylor (Princeton), J. Welch (University of California, Berkeley), and R. Wilson (Bell Labs).
35. Although the reports of the panels were published as Volume 2, and appeared in print only in 1983 after the Volume I report of the main committee, the reports of the panels were made available earlier to the main committee as input to their deliberations.
36. The first overall priority was AXAF, the Advanced X-Ray Astrophysics Facility, which was finally launched in 1999 and given the name “Chandra X-ray Observatory.”
37. A site near the summit of Mauna Kea had been selected, but legal challenges from local groups have resulted in years of uncertainty and delay.
38. Big Science Policies and Procedures, 203rd meeting of the NSB Appendix D, 19 January 1979, NAA-KIK, VLBA, History and Development.
39. *Washington Post*, 11 February 1981.
40. Committee members were B. Burke (MIT), R. Dicke (Princeton), G. Field (Harvard), H. Friedman (NRL), D. Hogg (NRAO), J. Taylor (Princeton), P. Thaddeus (Harvard), and R. Wilson (Bell Labs).
41. KIK notes of 25 January 1982 meeting, NAA-KIK, VLBA, History and Development.
42. MSR to Slaughter, NSF Assistant Director, AAEO, 1 February 1982, NAA-NRAO, Director’s Office, NSF Correspondence.
43. Ibid.
44. AAC membership at the time was J. Beckers (Chair-Arizona), E. Becklin (Hawaii), B. Burke (MIT), R. Giacconi (STScI), F. Gillet (KPNO), D. Hogg (NRAO), R. Humphreys (Minnesota), R. McCray (Colorado), D. Osterbrock (Santa Cruz), P. Pesch (Warner and Swasey), J. Taylor (Princeton), and A. Wolfe (Pittsburgh).
45. MSR to KIK, 18 February 1981, NAA-KIK, VLBA, History and Development.
46. Bautz to MSR, 30 June 1980, NAA-NRAO, Director’s Office, NSF Correspondence.
47. MSR to Slaughter, 19 April 1982, NAA-NRAO, Director’s Office, NSF Correspondence.
48. Kurt Weiler draft notes, 5 January 1983, NAA-KIK, VLBA, History and Development. Weiler was the NSF AST program manager for the VLBA.
49. SIRTF was initially approved by NASA for launch and return to Earth after the completion of the mission by the space shuttle, but concerns about contamination from the shuttle led to a redesign as a free-flyer.

50. MSR to Slaughter, 14 May 1982, NAA-NRAO, Director's Office, NSF Correspondence.
51. MSR to Johnson, 30 July 1982, NAA-NRAO, Director's Office, NSF Correspondence.
52. KIK interview with WEH III, 23 September 2011, NAA-KIK, Oral Interviews. https://science.nrao.edu/about/publications/open-skies#section-8
53. G. Low to KIK, 9 September 1982, NAA-KIK, VLBA, History and Development. Low was the Chair of COSEPUP.
54. KIK to MSR, 17 September 1982, NAA-KIK, VLBA, History and Development.
55. Field to Briefing Panel, 29 October 1982, NAA-KIK, VLBA, History and Development.
56. K. Weiler to Taylor, 30 March 1984, NAA-KIK, VLBA, History and Development. Other members of the Panel were B. Chrisman (Yale), R. Neal (SLAC), I. Shapiro (CfA), J. Welch (Berkeley), and R. Wilson (Cornell).
57. Report of the NSF VLBA Review Panel, 2 July 1984, NAA-KIK, VLBA, History and Development.
58. Nancy McGeown (from Representative Lindsey Boggs staff) to KIK, 16 August 1984, KIK to MSR, Hvatum, Hughes, 22 August 1984, NAA-KIK, VLBA, History and Development.
59. The letter was signed by G. Field (Harvard), J. Bahcall (Princeton), B. Burke (MIT), A. Code (AAS President), B. Oliver (Hewlett-Packard), C. Sagan (Cornell), M. Schmidt (AAS President-elect), and P. Thaddeus (Harvard). Additional letters of support were written by Haystack Director Joe Salah and Ed Ney from the University of Minnesota. NAA-NRAO, NM Operations, VLBA.
60. Boland to Field, 5 June 1984, NAA-KIK, VLBA, History and Development.
61. On 1 May 1984, Kellermann, Field, Thaddeus, and Peter Boyce, American Astronomical Society Executive Officer, met with a number of key Senate and House members and their staffs.
62. VLBA: A Congressman's Victory over NSF Project, *Physics Today*, October 1984, p. 56.
63. NSF to MSR, 28 June 1984, NAA-NRAO, NM Operations, VLBA.
64. Joel Widder (NSF Legislative Affairs) to KIK, KIK to Roberts, Hvatum, Hughes, 2 August 1984, NAA-KIK, VLBA, History and Development.
65. Bloch to NSB, 18 September 1984, NAA-NRAO, NM Operations, VLBA.
66. Ramonas to KIK, 16 August 1984, KIK Memo to Roberts, Hvatum, Hughes, NAA-KIK, VLBA, History and Development.
67. PVB to KIK, 7 March 1985, NAA-KIK, VLBA, History and Development.
68. House Appropriations Sub-committee on HUD minutes for 26 March 1985, NAA-KIK, VLBA, History and Development.
69. Senate Appropriations Committee hearing, 28 March 1985, NAA-NRAO, NM Operations, VLBA.
70. Only 15 years after the erection of the antenna, the Los Alamos National Laboratories (LANL) informed NRAO that for undisclosed security reasons, they wanted to remove the VLBA antenna situated in a remote part of the Laboratory site. Fortunately for NRAO, LANL management, and apparently their priorities, changed, and following some exploratory discussions, they did

not press the case. W. Press to F. Lo, 6 November 2002, NAA-KIK, VLBA, History and Development.

71. MSR to L. Rodriguez, 18 May 1982, NAA-KIK, VLBA, History and Development.
72. In 1993, 17 surface panels on the Mauna Kea antenna were damaged by ice falling from the feed support legs and had to be replaced.
73. R. Hall to PVB, 11 April 1989, NAA-NRAO, NM Operations, VLBA.
74. The Saint Croix VLBA antenna is located only 250 meters from the sea.
75. Napier (2000) has discussed the planning and construction of the VLBA.
76. KIK to Roberts, 2 November 1981, NAA-KIK, VLBA, History and Development.
77. NRAO was represented by Roberts, Clark, Hvatum, and Kellermann; Caltech by Cohen, Moffet, Readhead, and Rochus Vogt (OVRO Director).
78. Correspondence and internal memos among Ken Kellermann and Mort Roberts (NRAO), Marshall Cohen, and R. Vogt (Caltech); and Bernie Burke and John Evans (MIT), 1981–1982, NAA-KIK, VLBA, History and Development.
79. PVB to MSR, 20 December 1983, NAA-NRAO, NM Operations, VLBA, Box 3A.
80. Other members of the committee were: B. Burke (MIT), A. Davidson (Johns Hopkins), R. Dicke (Princeton), A. Hogg (Lowell), D. Hogg (NRAO), G. Preston (MWPO), M. Reid (CfA), and J. Taylor (Princeton).
81. VLBA Array Operations Center Site Selection Report, C. Bignell (Chair), December 1983, NAA-KIK, VLBA, History and Development.
82. Report of the VLBA Advisory Committee, 20 December 1983, NAA-KIK, VLBA, History and Development.
83. Ibid.
84. J. Evans to MSR, 1 December 1981, NAA-KIK, VLBA, History and Development. Evans was the Haystack Director.
85. PVB to KIK, 10 January 1985, NAA-KIK, VLBA, History and Development.
86. In a conventional radio array such the VLA, the data are first correlated with many different delays or lags introduced in each baseline pair, and then Fourier Transformed to obtain a spectrum of the fringe visibility. The VLBA uses a so-called FX correlator by which the data from each antenna, after digitizing, are first Fourier Transformed and then multiplied with the other antennas to give the visibility spectrum on each baseline. As the largest FX type correlator ever built, and the first one built outside Japan, it involved considerable risk and development time, but in the end was less expensive to fabricate. An earlier FX correlator was built for the Nobeyama 5-element millimeter array in Japan.
87. The custom designed VLBA correlator chips were later made available for a VLBI processor built at the Shanghai Astronomical Observatory and for a radio telescope in Mauritius.
88. Walker (2000) discusses early VLBA operations.
89. QUASAT *(Quasar Satellite)—A VLBI Observatory in Space*, 1984, in Proceedings of a Workshop held at Gross Enzersdorf, Austria (Noordwijk: ESA), NAA-KIK, VLBI, Space VLBI, Box 1; QUASAT A Space VLBI Satellite Assessment Study, ESA SCI (85) 5, NAA-KIK, VLBI, Space VLBI, Box 1; QUASAT, a VLBI Observatory in Space, a Proposal to NASA from JPL, NAA-KIK, VLBI, Space VLBI, Box 2. QUASAT received high marks for scientific

merit and technical feasibility, but the projected budget was greater than the ESA ceiling, and it was disqualified only a few days before the competitive review in October 1988 held in Paris.

90. IVS—An International Orbiting Radio Telescope, 1991, ESA SCI (91) 2, NAA-KIK, VLBI, Space VLBI, Box 2. The IVS proposal was based on a 20 meter diameter dish which was to be launched on the ill-fated Soviet Energia space shuttle and included scientists from the USSR, as well as from Europe and the US.
91. IVS and later ARISE proposed a 25 meter class antenna operating down to 3 mm wavelength in an elliptical orbit reaching up to 50,000 km. ARISE was recommended by the 2001 Decade Review, Astronomy and Astrophysics in the New Millennium (Taylor and McKee 2001), but NASA never provided funds to support the proposed US activities.
92. Because the resolution of an interferometer is given by $\theta = (\lambda/D)$ and the brightness temperature T is proportional to $S\lambda^2/\theta^2$, the maximum brightness temperature that can be observed depends only on the flux density and the square of the interferometer baseline, D, and is independent of wavelength.
93. Sagdeev later married Susan Eisenhower, daughter of the former US President Dwight Eisenhower, and immigrated to the United States, where he joined the faculty at the University of Maryland.
94. Ginzburg and Sakharov to Truly, 2 December 1989, NAA-BFB, Space VLBI.
95. Press release from the Office of the Vice President, 8 March 1989.
96. Kellermann and Kardashev (IKI) represented RadioAstron in the Joint Working Group, which was chaired by Charles Pellerin (NASA) and Rashid Sunyaev (IKI); Sunyaev was the project leader for the competing Spectrum-X-γ mission.
97. See http://www.asc.rssi.ru/radioastron/index.html for further details about RadioAstron and a list of relevant publications.
98. Phase referencing is a technique by which the antennas are rapidly switched between a reference calibration source and the target source. Phase referencing was in common use with connected element interferometers to improve the phase distortions due to tropospheric or instrumental instabilities. The adoption of phase referencing for VLBI with independent local oscillators increased the effective integration (averaging) time thus greatly improving the sensitivity.
99. Although the VLA and Westerbork telescopes are themselves arrays, all of the antennas can be electrically connected to operate as a single telescope with collecting areas equivalent to a 135 and 94 meter diameter dish respectively.
100. The Russian KVASAR (QUASAR) network consists of three 32 meter dishes originally built for precision measurements of Earth rotation and geodynamics by the Russian Institute of Applied Astronomy.
101. Report of the NSF AST Senior Review Committee, From the Ground Up: Balancing the NSF Astronomy Program, 22 October 2006, NAA-KIK, VLBA, History and Development. https://www.nsf.gov/mps/ast/ast_senior_review.jsp Committee members were T. Ayres (Colorado), D. Backer (Berkeley), R. Blandford, chair (Stanford), J. Carlstrom (Chicago), K. Gebhardt (Texas), L. Hillenbrand (Caltech), C. Hogan (Washington), J. Huchra (Harvard-Smithsonian), E. Lada (Florida), M. Longair (Cambridge), J.P. Looney (Brookhaven), B. Partridge (Haverford), V. Rubin (DTM).

102. W. Van Citters (NSF Division of Astronomical Sciences Director) to Ethan Schreier (AUI President), 7 April 2005, NAA-KIK, VLBA, History and Development.
103. Ibid.
104. KYL to recipients, 25 October 2010, NAA-KIK, VLBA, History and Development.
105. GSMT (Giant Segmented Mirror Telescope) was the generic name given to the proposed Thirty Meter Telescope (TMT) and the 20 meter Giant Magellan Telescope (GMT).
106. Ulvestad had come to the NSF from NRAO, where he had been the Assistant Director for New Mexico Operations and later head of the NRAO New Initiatives Office. Before coming to NRAO, Ulvestad was at JPL where he played a prominent role in space VLBI programs.
107. Other Portfolio Review Committee members were J. Miller (Lick, Vice-Chair), M. Agueros (Columbia), G. Bernstein (Penn), G. Blake (Caltech), J. Feldmeier (Youngstown), D. Fischer (Yale), C. Impey (Arizona), C. Lang (Iowa), A. Lovell (Agnes Scott), M. McGrath (NASA), M. Norman (UCSD), A. Olinto (Chicago), M. Skrutskie (Virginia), K. Schrijver (Lockheed Martin), J. Toomre (Colorado), R. Walterbos (New Mexico).
108. Advancing Astronomy in the Coming Decade: Opportunities and Challenges. Report of the National Science Foundation Division of Astronomical Sciences Portfolio Review Committee, 14 August 2012, NAA-NRAO, NSF Portfolio Review. https://www.nsf.gov/mps/ast/ast_portfolio_review.jsp
109. NSF Program Solicitation NSF 14-568, 25 November 2014.
110. The GBO management is discussed further in Sect. 11.9.

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