HISTORY OF NSF'S EARLY SUPPORT FOR VERY LONG BASELINE INTERFEROMETRY (VLBI) AND BLACK HOLE OBSERVATIONS, 1966-1985

1966: CONSTRUCTION BEGINS FOR VLBI EXPERIMENT.

The experiment is planned to be carried out between NRAO's 140-foot telescope in Green Bank and Arecibo in Puerto Rico.

Construction and experiment projections: *The equipment for a very long baseline interferometer experiment is under construction for use at a 610 megacycles per second (a wave length of 49 centimeters) and operable between any two radio telescopes capable of working at that frequency. Initial operation is expected between the Arecibo 1,000-foot telescope in Puerto Rico and the NRAO 140-foot telescope early in 1967. The effective baseline between these two sites (about 1,500 miles) will be 5.2 million of these wavelengths, making it possible to discriminate between radio sources separated by a few hundredths of a second of arc (a few millionths of a degree).*

1967: NRAO INITIATES VLBI EXPERIMENTS.

In May 1967, the first successful run was made between Green Bank's 140-foot telescope and the Naval Research Lab's antenna at the Maryland Point Observatory—a baseline of 250 miles. In June, the experiment was expanded to include the 120-foot antenna at Haystack (then a facility of MIT-Lincoln Laboratory)—a baseline of 500 miles. Experiments were also initiated between Green Bank's 140-foot telescope, the Mark II antenna at Jodrell Bank in England and between Green Bank and the Hat Creek antenna at the University of California Berkley.

Description of VLBI process: *NRAO successfully initiated a series of very long baseline interferometer experiments in which any given radio source can be observed simultaneously at a given frequency by two telescopes separated at large distances without the need for a physical connecting link between them. The resolution obtainable is directly governed by the distance of separation (baseline) and we can now achieve baselines equivalent to the diameter of the earth—though with limited coverage. Data at each telescope are recorded on magnetic tape while accurate timing pulses are placed on tapes by mutually synchronized "atomic" clocks. The tapes are later analyzed by computer where fringes are seen unless the source is fully resolved.*

Technical specs: *The independent local oscillator interferometer receiver was constructed in conjunction with astronomers at Cornell University-Arecibo Ionospheric Observatory and the University of California La Jolla. The first successful run was made between the 140-foot telescope and the NRL antenna at the Maryland Point Observatory at a frequency of 610 Megahertz over a baseline of 250 miles or 4.62X10(to the 5^{th}) wavelengths. The same group in June 1967 operated a VLB experiment between the 140-foot antenna and the 120-foot antenna Haystack facility of MIT-Lincoln Laboratory at 18cm. wavelength over a baseline of 500 miles…A group from MIT-Lincoln Laboratory shared facilities at the latter baseline at the frequency of the OH line and showed the linear size of the OH emission region in the source of W3, which is 6,000 light years away, to be less than a diameter of Jupiter's orbit. This corresponds to a resolution of .006 seconds of arc. Experiments in these two series are continuing between the NRAO 140-foot telescope and the Mark II antenna at Jodrell Bank in England, and between the NRAO 140-foot and the Hat Creek-antenna of the University of California, Berkley.*

1968: VLBI EXPERIMENTS EXPANDED TO INCLUDE SWEDEN AND QUASAR OBSERVATIONS.

VLBI experiments are conducted by synchronizing radio telescopes, recording data on magnetic tapes, collecting the tapes and processing them with computers. In 1968, VLBI experiments expand to include Hat Creek in California, Haystack in Massachusetts, Onsala, Sweden, and Green Bank in West Virginia. Measurements were taken of radio source 3C 273.

VLBI provides greater resolution: *Advanced techniques in the use of multiple radio telescopes can produce a degree of resolution equivalent to the ability to measure the size of a postage stamp in Sweden, as seen from Green Bank, or to measure the size of an automobile on the moon. At the same time, they point he way toward the answers to questions of both theoretical and practical interest.*

Technical description of VLBI process: *Radio interferometry with intercontinental antenna separations has been carried out on the radio continuum at the OH line frequency through the use of independent radio telescopes that are precisely synchronized by atomic clocks located at each telescope. Data are recorded simultaneously at each telescope on magnetic tapes and are later brought together and processed in a computer. Radio telescopes at Hat Creek, CA; MIT-Lincoln Lab, MA; Onsala, Sweden; and Green Bank have been used in a coordinated set of these VLB experiments. Preliminary results on the radio source 3C 273 indicate that a part of the radiation comes from the known position of a star-like optical object, the quasar. The quasar itself is a double object and measurements were made of its component parts.*

1969: NRAO ACTS AS THE CLEARING HOUSE FOR VLBI EXPERIMENTS.

Very long baseline interferometry continued during the year with NRAO acting as a clearing house for various groups throughout the nation who want to use the new 3- and 6-cm. portable VLB receivers that became operational during the year. New terminals and a fast computer-processor are under construction and will markedly increase the rates at which data can be taken and analyzed.

1972: VLBI EXPERIMENTS FIND EVIDENCE OF EXPANSION IN THE UNIVERSE.

Transcontinental observations made over the previous two years found evidence that radio sources were expanding, or separating, as viewed from the earth. Theories of the expansion were being further tested with new VLBI systems at NRAO and at Haystack, with NSF support.

Evolving VLBI process: *Digital Very Long Baseline (VLB) interferometry is an observing technique used at the NRAO and certain other observatories. Recordings of a celestial radio source are made simultaneously at two or more widely separated sites, using atomic clocks for synchronization. Later, inter-comparison of the recorded data from all sites involved permits construction of a model of the spatial structure of the radio source with extremely high angular resolving power.*

Scientific discoveries: *One of the most exciting finds to come from the new technique is the discovery of 'super relativistic' expansion in radio sources. During a series of transcontinental observations made from 1970 to the present, the visibility patterns of several sources were found to change with time, indicating that the parts of the sources were separating as seen from the earth.*

1974: TECHNOLOGICAL DEVELOPMENTS IMPROVE SIGNAL CORRELATION AND PROCESSING.

Key upgrades occurred in 1974 to improve the processing and correlation of signals and recorded data from the telescopes simultaneously observing as part of the VLBI network.

Equipment upgrades: *Very Long Baseline Interferometer (VLBI) experiments are conducted using stations located throughout the world. The NRAO Mark III VLBI tape processor is being upgraded to include more correlation channels and to allow simultaneous processing of tapes from three telescopes. A new hydrogen-maser frequency standard is being installed at Green Bank to improve the phase stability for VLBI experiments.*

1975: NEW COMPUTERS AID DATA ANALYSIS.

A minicomputer was installed at Green Bank's 140-foot telescope to facilitate on-line data analysis.

Minicomputer installation: *During the year, a minicomputer was installed at the 140-foot telescope for on-line data analysis. Programs are available for spectral-line processing, and continuum programs are being developed. With these programs the observer can quickly make a first analysis of his data, and thus can better judge, for example, which observations need further integration time. About 25 percent of the observing time on the 140-foot telescope was used for very long baseline (VLB) interferometry, in both line and continuum studies.*

1976: VLBI NETWORK GROWS TO 8 LOCATIONS.

During the past year a total of 270 visiting observers (including 75 students) representing 83 institutions used the NRAO telescopes. A new feature of the 1976 program was use of the 140-foot telescope at Green Bank in a network of telescopes performing simultaneous observations over transcontinental baselines. This multi-station, very long baseline interferometer, which provided a resolution at least 100 times that of existing optical instruments, was used to study the fine structure in radio sources. The most complex of these experiments involved telescopes at eight locations.

1977: VLBI EXPERIMENTS PROBE GALACTIC CENTERS.

Radio astronomers are also probing the galactic core and last year employed a Very Long Baseline Interferometer (VLBI) to identify a large but relatively compact bright object at that location. The object was 200 astronomical units (an astronomical unit is the mean distance between the Earth and the Sun) in diameter. The VLBI network consisted of three radio telescopes located in Massachusetts, West Virginia, and California.

1978: EQUIPMENT UPGRADES IMPROVE VLBI OBSERVATIONS.

The Mark III Very Long Baseline recording system developed jointly with NASA has been successfully tested on an experiment using the NRAO 42-meter telescope and the Haystack antenna. A second system is now being built for use at other sites.

1979: COSMIC JETS AS POTENTIAL EVIDENCE OF BLACK HOLES.

VLBI experiments investigate theories that connect cosmic jets to the existence of black holes and provide a "radio picture."

Growing interest in galactic cores: *There has been intense interest in recent years in the study of the central cores of galaxies. There are a number of reasons, including the possibility that certain galactic nuclei generate the prodigious amounts of energy needed to power giant radio wave sources, that others may be responsible for the enigmatic quasar phenomenon, and that still others may be the sites of massive black holes. However, there is also evidence, from very long baseline radio interferometry (VLBI) and studies of variability timescales, that the physical dimensions important in these types of nuclear activity are several orders of magnitude smaller than can be resolved by any single existing or planned telescope system. Astronomers are, as a consequence, limited to investigation of the various large-scale effects seen to be associated with active nuclei.*

Cosmic jets observations: *One of the more intriguing of such phenomena has been the recently discovered narrow radio jets, which may extend hundreds of thousands of light years from the center of a galaxy into neighboring space. Astronomers at CalTech discovered one such jet emanating fom the core of galaxy NGC 6251…The violent events that cause such an outpouring of energy are the subject of much study and theoretical speculation. It is possible that NGC 6251 contains a large black hole that is swallowing stars in its vicinity. The energy released by the stars as they fall into the black hole could well account for the prodigious energy output from NGC 6251.*

VLBI provides image of cosmic jet: *The detailed radio "picture" of the jet was obtained using the technique of very long baseline interferometry. Radio astronomy antennas located at the Haystack Observatory in Massachusetts, the National Radio Astronomy Observatory in Green Bank, West Virginia, and the Owens Valley Radio Observatory in California scheduled simultaneous observations of the galaxy. Analysis of the combined radio signals produced the fine detail required to probe the interiors of the distant galaxy.*

1980: RECEIVER UPGRADES AT GREEN BANK.

In the past year the fully steerable 43-meter telescope at the Green Bank observing site in West Virginia has been equipped with a new low-noise 5- to 25-GHz maser receiver. This wide band system improves the efficiency of the telescope, allowing new searches for molecular species and observation of extragalactic sources by the techniques of very long baseline interferometry.

1981: CONTINUED TECHNOLOGICAL IMPROVEMENTS ASSIST VLBI EXPERIMENTS.

The rapid pace of recent astronomical discoveries has been largely due to the accelerated rate of technological advance. New techniques such as very long baseline radio interferometry and computer picture processing have improved the resolution or clarity of observations by several orders of magnitude.

Upgrades at NRAO's Greenbank: *The two single-dish (91-meter and 43-meter) telescopes at Green Bank, West Virginia, are heavily booked by observers. Their interest is spurred by a new 5-to25-gigahertz upconverter-maser receiver, especially effective for molecular studies and the 300-to 1,000-megahertz, cryogenically cooled maser receiver designed for pulsar observation programs. Pressure has increased for use of the 43-meter telescope for very long baseline interferometry (VLBI) programs. Broadband Mark III recording systems with high information density are operational, and there has been increasing interaction with the European VLBI network.*

Description of VLBI process: *The technique of very long baseline interferometry (VLBI) is a fairly recent development. It has enabled radio astronomers to see the detailed structure of emitting objects with a clarity that rivals or exceeds that previously attained only at optical wavelengths. The method involves the comparison of simultaneous observations by two or more widely separated radio telescopes. A wavefront from a radio source generally arrives at two such instruments at different times; combining simultaneous observations results in wave interference that yields precise angular information essential to the accurate determination of position and structure. A resolution of better than one-thousandth of a second of arc has been achieved, corresponding to a separation of light-years in even the most distant galaxies.*

Scientific discoveries, tracking Quasar 3C 273: *The application of VLBI has resulted in the discovery of rapid expansion in certain extragalactic objects. In four extreme cases (three quasars and one galaxy), this expansion apparently exceeds the speed of light, assuming that the objects are at the great distances implied by their velocity of recession and the expansion of the universe. Actual faster-than-light, or superluminal, motions are contrary to the theory of relativity, so the phenomenon has been interpreted as a relativistic deflection of light emitted from material in rapid motion almost directly toward the observer. Timothy Pearson and his colleagues at the Owens Valley Radio Observatory of the California Institute of Technology have monitored the quasar 3C273 for three years. They used four or five antennas in California, Texas, West Virginia, Massachusetts, and West Germany.*

1982: LOOKING INTO THE CENTER OF THE MILKY WAY GALAXY.

NRAO and NRL researchers make observations of the center of the Milky Way galaxy using the Very Large Array in New Mexico. Evidence points to black hole at the center of the galaxy.

Observing the center of the Milky Way: *The center of our Milky Way galaxy, lying in the constellation Sagittarius, is one of the brightest radio sources in the sky. It was the first extraterrestrial radio source detected (in 1932), but for years it remained mysterious. Recently, Robert Brown of NRAO and Kenneth Johnston of NRL have succeeded in observing the galactic center. Using the Very Large Array telescope, they have discovered, at the center of the dust ring, an exceptionally small and luminous radio source whose core has a remarkable, spiral like pattern.*

Evidence correlated with VLBI experiments: *The spiral pattern of opposing gas jets immediately suggests similar forms glimpsed in quasars by a high-resolution radio technique called very long baseline interferometry…This prodigious energy output is best explained as the by-product of an in fall of gas and dust from a rotating disk to a central, supermassive black hole embedded in an otherwise normal galaxy. Excess material may be expelled along the axes of such a disk, and a spinning black hole would cause the disk to wobble, producing the spiral jets we see.*

1983: NRAO BEGINS VERY LONG BASELINE ARRAY (VLBA) DESIGN STUDY.

After submitting a proposal to the Foundation for a Very Long Baseline Array, consisting of 10 antennas (25 meters each) stretching from Hawaii to Puerto Rico. NRAO staff started plans for a one-year design study in 1984. This array would dramatically improve resolution over that of any existing ground-based telescope and would open up whole new areas of research in astronomy.

1984: NSF-SUPPORTED RESEARCH PRODUCES NEW RADIO MAP OF BLACK HOLE.

NSF support for VLBI: *In 1984, ground-based and theoretical astronomy were supported through five grant programs to more than 140 universities, plus funding for three National Astronomy Centers. Far-reaching scientific advances include these: High-resolution radio maps—made by the Very Large Array and other telescopes through the technique of very long baseline interferometry—display unprecedented detail in the cores of the Milky Way and other galaxies. The maps reveal surprising similarities in those cores, such as the probable presence of super massive, gas-accreting black holes.*

VLA radio map of black hole: *Accretion of interstellar matter by a central black hole may be the energy source of the violent phenomena seen in quasars and the nuclei of some galaxies. The VLA observations of our galactic center, made by Kwok-Yung Lo and Mark Claussen at the California Institute of Technology, mark the first time that the infall of gas has been directly seen in any galactic core or about any black hole.*

VLBA preparations: *NRAO has begun technical design of the Very Long Baseline Array, a system of 10 antennas located between Hawaii and Puerto Rico and operated as a single instrument. The Array will dramatically improve resolution and sensitivity over the capabilities of any existing radio telescope, opening new areas of research in astronomy.*

1985: VERY LONG BASELINE ARRAY PROMISES GREATER RESOLUTION AND ANSWERS TO ASTRONOMICAL THEORIES.

VLBA: *The Very Long Baseline Array will have unprecedented resolution, more than any optical telescope present or planned. With a telescope of this resolution, one could stand in New York, pick out a dime in Los Angeles, and read its motto, "In God We Trust."*

Hopes for VLBA research: *Astronomers will use this array to study, among other things, the ancient, violent quasars, star-like sources of radio waves so far away they must have formed soon after the universe began. Quasars may be young galaxies, or a type of galaxy that only formed early on…Astronomers speculate that these objects are not stars at all but black holes into which stars fall, colliding and swirling into a disk around the black hole before they disappear. What the energy source at the center of quasars actually is and how, if galaxies began as quasars, they settled down into stable middle age, are questions astronomers hope to answer with the Very Long Baseline Array.*