VLBA Sensitivity Upgrade Memo # 4

Mapping the Future of VLBI Science in the U.S.

Committee Members

Sheperd S. Doeleman	(MIT Haystack Observatory)
David H. Hough	(Trinity University)
Shri R. Kulkarni	(California Institute of Technology)
Colin J. Lonsdale	(MIT Haystack Observatory) – *co-chair*
Alan P. Marscher	(Boston University)
Christopher P. O'Dea	(Space Telescope Science Institute)
Greg B. Taylor	(National Radio Astronomy Observatory) – *co-chair*
David J. Wilner	(Harvard-Smithsonian Center for Astrophysics)
Joan M. Wrobel	(National Radio Astronomy Observatory)

August 16, 2004

Executive Summary

VLBI has a long and illustrious history of technical accomplishment and scientific discovery. It is clear to the Committee that the scientific future of VLBI in the US is bright, encompasses a rapidly broadening range of topics, and is largely driven by forthcoming dramatic improvements in sensitivity. Opportunities abound, and in an emerging era of astronomy driven by topic instead of technique and wavelength, VLBI can be expected to play an increasingly pivotal role thanks to its high angular resolution and freedom from astrophysical obscuration. Indeed, the VLBI technique provides astronomers with unique capabilities that significantly expand the breadth of astrophysically targeted investigations, with clear relevance to themes emphasized in the NRC Decadal report "Astronomy and Astrophysics in the New Millennium", as well as the NRC report "Connecting Quarks with the Cosmos" and the associated recent interagency report "The Physics of the Universe".

The science areas to which VLBI will contribute range from protostellar evolution to galactic collision and evolution, and from imaging black hole environments to constraining values of fundamental constants. These benefits lie within easy technological reach, and the scientific rewards are major.

In the US, a history exists of pioneering and global leadership that a decade ago culminated in the only dedicated instrument for VLBI, the Very Long Baseline Array (VLBA). Today, some of that leadership has eroded. Engagement in VLBI research at US universities is at low, unhealthy levels, and the next generation of instrument builders and technologists is not clearly identified. In this report, we examine the reasons for these problems, and identify straightforward measures that should be taken to ensure that the US community resumes a leading role in the promising future of VLBI.

The VLBA has been operational for 10 years, but the resources expended on hardware and software support, upgrades, and investigator support via grants, have not been commensurate with the capital investment or scientific yield and potential of the array. Investments in these resources have significantly lagged the recommendations of the National Academy of Sciences decadal survey of Astronomy and Astrophysics, which suggests grants at a rate of 3% of capital costs per year, and comparable funds for instrumentation renewal. The time is long overdue for significant expansion of VLBA capabilities, and we are fortunate indeed that such expansion can now be implemented at very modest cost. While obvious, these actions must be undertaken in a way that is in line with scientific priorities, and complementary to projected developments in global VLBI capabilities. It is also clear that investment is needed in the university community, and in non-VLBA facilities. Together, these actions will expand and broaden the user base.

The Committee therefore unanimously recommends the following actions, to begin as soon as possible:

- Hardware investments
  - Implement Mark 5 disk based recording on the VLBA, with priority.
  - Equip Arecibo and the Green Bank Telescope with state of the art VLBI equipment, and increase participation of these facilities with the VLBA and global VLBI.

  - Perform inexpensive upgrades to exploit the full 22-86 GHz performance potential of the VLBA antennas.
  - Investigate connections with the Expanded VLA (EVLA) and future facilities to enhance VLBI capabilities.
  - Support the development of sensitive VLBI at millimeter wavelengths using new and planned telescopes such as SMA, CARMA, LMT, and ALMA.

- Software investments
  - Dedicate new resources at the 3 to 5 person level, for the purpose of overhauling user software support for the VLBA, and for global VLBI.
  - Coordinate these activities with foreign partners, and the US university community.

- Astronomical community investments
  - Provide a funding mechanism for improved support of graduate students at US universities to work on VLBI related research. Multiple possible avenues are identified and should be explored.
  - Investigate the provision of funds for financial support attached to time granted to US observers on VLBI networks.

Contents

1 Introduction **6**

2 Scientific Highlights of VLBI and the VLBA **9**

2.1 Massive Black Holes 9
2.2 The Cosmic Distance Scale 11
2.3 The Galactic Center 12
2.4 Rotation in M33 12
2.5 Young Stellar Objects in Formation 14
2.6 Other scientific contributions 16

3 Future Science Prospects **19**

3.1 Imaging a massive black hole - Is General Relativity the true theory of strong field gravity? 20
3.2 Gravitational Lenses - where is the dark matter? 21
3.3 Supernova factories and nascent AGNs - what happens when galaxies collide? 23
3.4 Launching AGN jets - How are relativistic, collimated flows generated? . . . 24
3.5 What are the kinematics of the Galaxy and the Local Group? 26
3.6 What is the role and effect of magnetism in stars? 27
3.7 Super Massive Binary Black Holes - How common are they? 28
3.8 Other science opportunities 30

4 Technical Roadmap **32**

4.1 Sensitivity 32
4.2 High Frequency VLBI 34
4.3 Global VLBI Issues 37
4.4 Software 38
4.5 Roadmap for the Future 39

5 Human Resources **44**

A The Charge **50**

B Survey Results **51**

C Acknowledgements **53**

D Recent VLBA Scientific Productivity **56**

E Telescope Sensitivities **59**

Chapter 1

Introduction

From an assortment of telescopes built for other purposes, Very Long Baseline Interferometry (VLBI) emerged in the 1960s as an innovative technique to obtain angular resolutions orders of magnitude finer than ever achieved before. This opening up of discovery space to milliarcsecond resolution led to the discovery of superluminal motions and relativistic jets in active galactic nuclei (AGN). Today VLBI has a broad impact both through the wide variety of science topics that are addressed, and by defining the fundamental reference frame used by all astronomers.

In the 1980s the idea of a dedicated array for VLBI emerged as the top recommendation for a new ground-based astronomical instrument by the Astronomy Survey "Field Committee" (Field 1982). The Very Long Baseline Array (VLBA) was commissioned in 1993 and has been serving the astronomical community as an independent instrument and in coordination with the European VLBI Network (EVN) during 3 global sessions each year, each lasting about 1 month. Scientific highlights of the VLBA are detailed in Chapter 2.

The scientific potential for VLBI is even greater today. VLBI is poised to take advantage of commercial developments in computing and data storage in order to take a leap forward in sensitivity. At the same time, advances in receiver design and frequency standards offer the potential to push to higher frequencies and thus ever greater resolution. In the next few years significant advances in capability, based largely on sharply increased bandwidths, can be gained with a modest capital investment. On longer time scales of 5-10 years more significant advances in capability are possible, including converting VLBI to real time operations over fiber optic connections and combining the VLBA with the EVLA to form a single powerful and flexible instrument.

This is also an exciting time for astronomical research in general, as has been emphasized in three key reports, namely the NRC reports "Astronomy and Astrophysics in the New Millenium" written by the decadal Astronomy and Astrophysics Survey Committee (AASC) chaired by McKee & Taylor (2001), and "Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century" (Q2C) written by a committee chaired by Turner (2003), as well as the recent NSTC interagency report "The Physics of the Universe" which describes a strategic research plan for the nation. Three of NASA's great observatories (HST, Chandra, and Spitzer) are now in operation, and several large facilities are on the

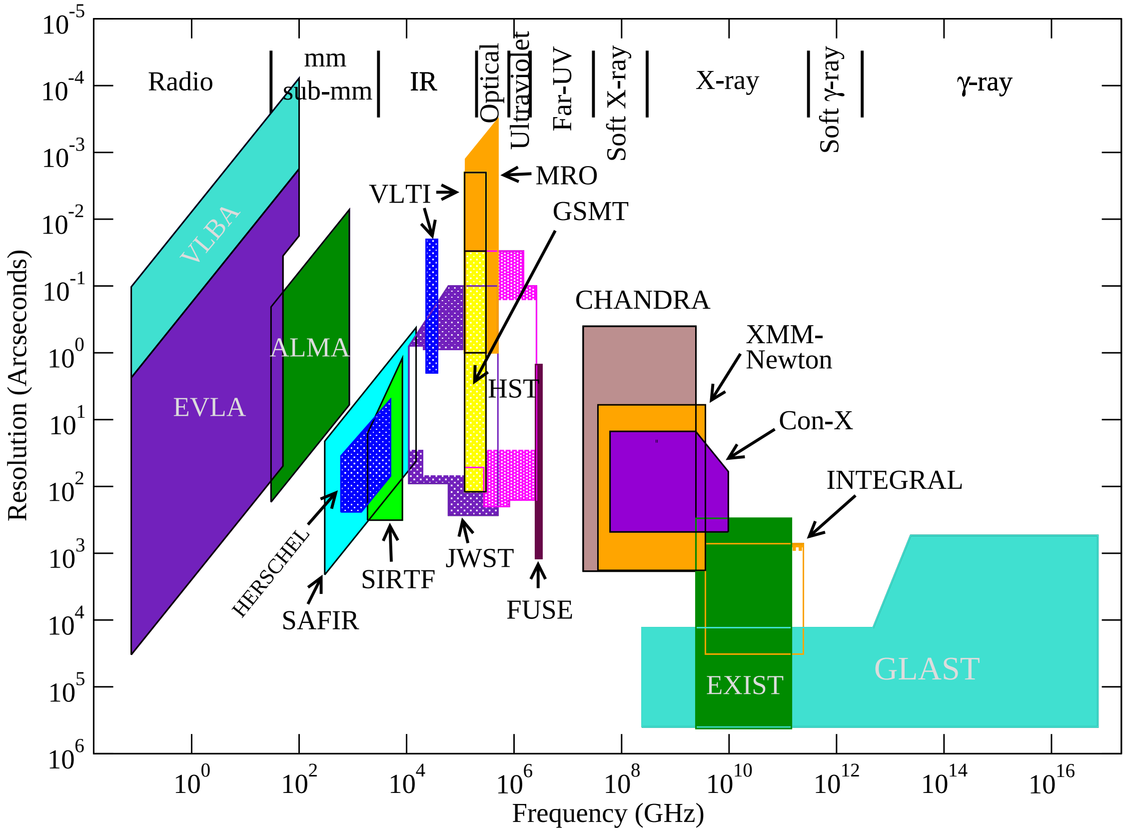

Figure 1.1: A plot of discovery space in resolution versus frequency provided by R. Perley.

horizon including the EVLA, ALMA, and GLAST (see Fig. 1.1). At the high-energy end of the spectrum, the gamma-ray sky is dominated by blazars, microquasars, gamma-ray bursts (GRBs), and pulsars. VLBI will be an ideal partner for studies of these objects with GLAST, AGILE, VERITAS, and other gamma-ray telescopes, imaging the gamma-ray emitting regions in blazars and the after-effects of energetic events in TeV blazars, microquasars and GRBs. In the radio, the VLBA will integrate tightly with the EVLA, and provide matching resolutions over a wide frequency range. As is evident from Fig. 1.1, VLBI provides the highest angular resolution of all astronomical instruments, and future VLBI work recommended in this report will achieve even finer resolution.

At this juncture we also face challenges within the astronomical community. A history of limited funding for VLBI research from NSF and NASA has stifled the development of groups at US universities. At the same time, a substantial number of VLBI researchers at a few universities and centers such as NRAO, USNO, NRL, NASA (JPL and GSFC), CfA, and Haystack continue to make good use of the VLBA and global VLBI. Recently, several recent PhDs who do primarily VLBI research have obtained faculty positions. Further support, especially for graduate students engaged in VLBI research, would stimulate the growth of the university-based VLBI community.

In order to have a coherent plan for VLBI research in the US, the directors of NRAO and MIT Haystack Observatory convened this committee in June of 2003 (see Appendix A for the full text of the charge to the Committee). The aim of the Committee is to identify high priority scientific goals, to devise a technical road map to achieve such goals, and to recommend a course of action that will strengthen and broaden the community of VLBI users in the US.

The Committee was selected to facilitate communications with a broad-based astronomical community. Members were selected from large and small institutions, from across the US, with a broad range of astronomical interests, and with a broad range in VLBI expertise. The Committee held its first meeting at the VLBA 10th Anniversary Meeting in Socorro on June 10 and addressed the participants of that conference on June 12. Input to the Committee was gathered via a web page (`http://www.nrao.edu/VLBIfuture/`), via e-mail, and in a series of open meetings held in Pasadena, Boston, Socorro and Baltimore during the summer of 2003. A survey was also sent out to selected members of the astronomical community and the results can be found in Appendix B. In Appendix C we acknowledge individuals and institutions for the wide range of input provided to the Committee.

In the interests of a timely report, this Committee has had to restrict itself to a core set of topics. As a consequence, we have not been able to cover the likely future of space VLBI research, which will provide a necessary complement to some of the research described, but probably on a timescale beyond the reach of this report. We have also focused on astronomical science, and made only passing references to the exciting science in geodesy made possible by VLBI.

Chapter 2

Scientific Highlights of VLBI and the VLBA

Over the past nearly 4 decades, VLBI has made fundamental contributions to our understanding of the universe. The early pioneers of VLBI received the Rumford Prize from the American Academy of Arts and Sciences for work done in 1967 on quasars and masers. Use of closure phases and fringe amplitudes dramatically improved the quality of the imaging obtainable with VLBI in late 1970s (Readhead & Wilkinson 1978). New telescopes and technical innovations in receivers and recorders (reviewed by Kellermann & Moran 2001) steadily increased the sensitivity, frequency coverage, and resolution leading to the scientific discoveries described below. In June 2003, a meeting was held in Socorro to celebrate 10 years of discovery with the VLBA. This meeting, "Future Directions in High Resolution Astronomy: A Celebration of the 10th Anniversary of the VLBA," had 170 attendees with 63% of them from US-based institutions; about 25% of the participants were students. The 163 papers presented filled four solid days of sessions. Although most (85%) of the papers presented scientific results, the remainder of the papers made a strong case for active development of high-resolution astronomy across the electromagnetic spectrum. Presentations from this meeting can be found on the web at `http://www.aoc.nrao.edu/events/VLBA10th/`. Recent highlights from the VLBA can also be found on the VLBA Image of the Month web site at `http://www.aoc.nrao.edu/vlba/html/VLBA.html`. Here we summarize VLBI's contributions to some critical questions in Astrophysics.

2.1 Massive Black Holes

Understanding the formation and development of massive black holes in the centers of galaxies is a major topic in current astrophysics, and plays a central role in defining the formation processes of galaxies and their energetic histories. Since the 1960s, black holes were widely thought to exist, on theoretical grounds, as the energy sources of quasars and radio jets (e.g. Salpeter 1964; Lynden-Bell 1969); however, little compelling direct evidence for their existence was available until the mid 1990s. The VLBA's 1995 imaging of the elegantly simple accretion disk in NGC4258 (see Fig. 2.1) and the incontrovertible evidence that the

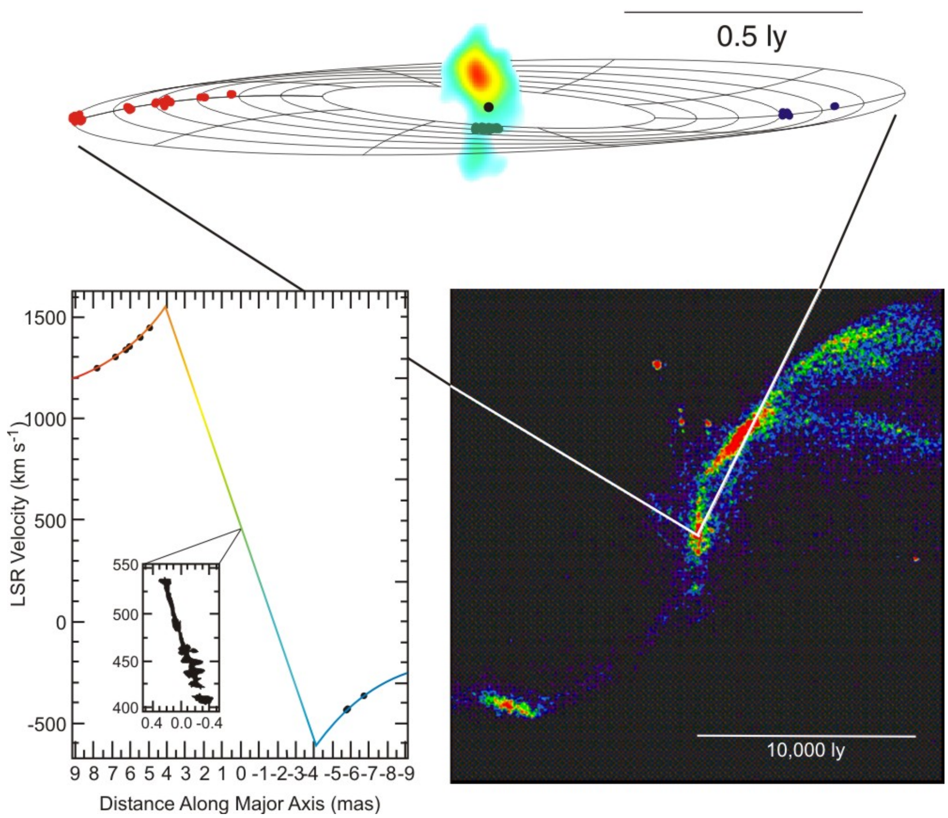

Figure 2.1: (top) VLBA image of the synchrotron continuum emission (in color) superimposed on, and precisely registered with, the VLBA image of the water maser spots. The wire mesh shows the shape of the thin and slightly warped disk derived from the maser positions and velocities (Herrnstein et al. 1996). (bottom left) Velocity-position diagram along the major axis of the accretion disk, which shows the nearly perfect Keplerian motions among the extreme red and blue shifted maser spots (Miyoshi et al. 1995). (bottom right) 1.4 GHz continuum image from the VLA observation of the extended structure of the jet, also known as the "anomalous arms" (Cecil et al. 2000) (provided by L. Greenhill).

disk was bound by a black hole of mass 3.7 x 10^7 solar masses, had a powerful impact on the astronomical community and fueled a major change in thinking about black holes. In the span of a few years in the mid 1990s, black holes went from controversial objects with tentative acceptance to nearly universally acknowledged inhabitants of almost every galaxy. This development has been a principal motivation for the construction of major next generation astronomical facilities such as LISA, Constellation X, and MAXIM.

The discovery and characterization of the black hole in NGC4258 required both the very high angular resolution (200 microarcseconds) and high spectroscopic resolution (0.1 km/s) of the VLBA. With these capabilities, the accretion disk, as traced by bright water masers, was found to be in nearly perfect Keplerian motion to an accuracy of a few percent. This led to a mass estimate of similar precision. To date, about 50 so called "Massive Dark Objects" have been identified; but only the central regions of our Galactic Center (because of its proximity) and NGC4258 have well defined rotation curves, and mass estimates of corresponding high precision (a few percent). These two objects are the anchors on the well known black-hole-mass-vs-bulge-velocity-dispersion relation, which may play a fundamental role in the understanding of black hole/galaxy formation (Ferrarese & Merritt 2000; and Gebhardt et al. 2000).

The precise imaging of the masers in NGC4258 had two important secondary impacts. It demonstrated that measurements of gas dynamics could provide a reliable black hole tracer, which increased the credibility of lower resolution measurements based on non-stellar dynamics. Also, this first detailed image of an accretion disk, which showed it to be a remarkably thin structure (aspect ratio of less than 0.2 percent) with a significant warp, provided evidence that may necessitate modifications to the standard AGN paradigm of thick dusty tori surrounding BHs (e.g., Antonucci & Miller 1985).

More than 50 water masers have been identified in galaxies to a distance of 230 Mpc. VLBA studies have shown that several of them have the structure of rotating accretion disks (e.g., Moran, Greenhill & Herrnstein 1999). Increased sensitivity and perfection of phase referencing techniques in VLBI will allow many of these objects to be studied in detail.

2.2 The Cosmic Distance Scale

VLBI, because of is unparalleled resolution and astrometric accuracy, provides a number of techniques for direct trigonometric distances estimates to astronomical objects. Such applications are based on: modeling of maser motions in well defined dynamical systems (Herrnstein et al. 1999); maser observations of galactic rotation (Brunthaler et al. 2004) annual parallax of pulsars (Chatterjee et al. 2004); expansion parallax of supernova (Bartel et al. 2003); and parallax of the Galactic Center (Reid 2004).

For the case of the masers in NGC4258, both the proper motions and accelerations of the maser spots have been measured with the VLBA and fit to a model of a rotating disk with circular Keplerian orbits. The distance estimate obtained is $7.3 \pm 0.3 \pm 0.4$ Mpc (Herrnstein et al. 1999). The two errors are statistical and systematic, respectively, with the latter due primarily to the relatively weak constraint on the eccentricities of the maser orbits. The distance estimate does not provide an accurate direct estimate of the Hubble constant because the galaxy is not sufficiently far away that its peculiar velocity is negligible with respect to the Hubble flow. However, it provides an important check on the supporting calibrations of other techniques that rely on the intermediate distance calibrations of so called standard candles (i.e., the rungs on the distance ladder). For example, the maser distance agrees reasonably well with the distance obtained from the observations of Cepheid variables in NGC4258 by the HST Key project team (Freedman et al. 2001) ($7.8 \pm 0.3 \pm 0.5$ Mpc), after the adoption of Period-Luminosity relations derived from data from the Optical Gravitational Lensing Experiment (OGLE) (Newman et al. 2001; Freedman et al. 2001). The main sources of systematic error are the distance to the LMC and the assumptions about the metallicity of the Cepheid variables. Although the agreement between the two distance estimates is good with respect to the error bars, Caputo et al. (2002) suggest that an even closer agreement is possible with a reasonable adjustment to the Cepheid metallicity model.

2.3 The Galactic Center

The compact radio source in the Galactic Center, Sgr A*, is a low-luminosity version of the engine that powers active galactic nuclei (AGN). VLBI, and in particularly VLBA, observations of Sgr A* have provided crucial data that greatly strengthen the case that super-massive black holes (SMBHs) exist, that they power AGNs, and that Sgr A* is indeed a SMBH.

Astrometric observations with the VLBA over nearly a decade are shown in Fig. 2.2. The apparent proper motion of Sgr A*, relative to extragalactic sources, is exceptionally well determined. The apparent motion is almost entirely in the Plane of the Galaxy. This apparent motion can be accounted for by the effects of the orbit of the Sun around the Galactic Center, including the small but noticeable deviation from the Galactic Plane caused by the 7 km s^{-1} component of the Sun's motion out of the Plane. After accounting for the Sun's motion, the residual or peculiar motion of Sgr A*, perpendicular to the Galactic Plane, is < 1.6 km s^{-1} (Reid & Brunthaler 2004). This exceedingly slow motion indicates that the compact radiative source, Sgr A*, contains $> 10^6$ $M_\odot$.

Imaging of Sgr A* at 7 mm wavelength with the VLBA has shown conclusively that the radio source is smaller than 1 AU in diameter (Bower et al. 2004). Coupling the lower limit to the mass of Sgr A* (from its proper motion) with the upper limit to its size yields a lower limit to the mass density of 2×10^{22} $M_\odot$ pc^{-3}. This astoundingly high density is within a factor of only 1000 of a 4×10^6 $M_\odot$ black hole within its Schwarzschild radius, providing overwhelming evidence for Sgr A* being a SMBH.

The VLBA has also been used to measure the positions and proper motions of red giant (*e.g.*, Miras) stars within 1 pc of Sgr A*. These positions were measured relative to Sgr A* by mapping SiO masers commonly found in the extended photospheres of red giant stars. Since these stars are very bright at infrared wavelengths, the precise radio positions can be used to scale and rotate infrared images of the Galactic Center and then to align them with the radio position of Sgr A* to determine its location on the infrared images to within 10 mas (80 AU for a distance of 8 kpc). This has also aided the calibration of high-resolution infrared imaging used to measure orbits of stars in the Galactic Center (Schoedel et al. 2002, Ghez et al. 2003). Combining the infrared with the radio observations indicates that the gravitational source binding the stellar orbits is coincident with the radiative source (Sgr A*) seen in radio waves. This is the first *direct* linkage of a massive object with the radiative source in an AGN.

2.4 Rotation in M33

Over 80 years ago, van Maanen (1923) claimed to detect the angular rotation of the "spiral nebula" M33 and that this implied such nebulae were nearby and within the Milky Way. The source of van Maanen's error has never been determined. Recently, the VLBA has been used to do van Maanen's experiment correctly and thus determine the distance to M33.

Fig. 2.3 shows an image of the spiral galaxy M33 with the locations of two regions of massive

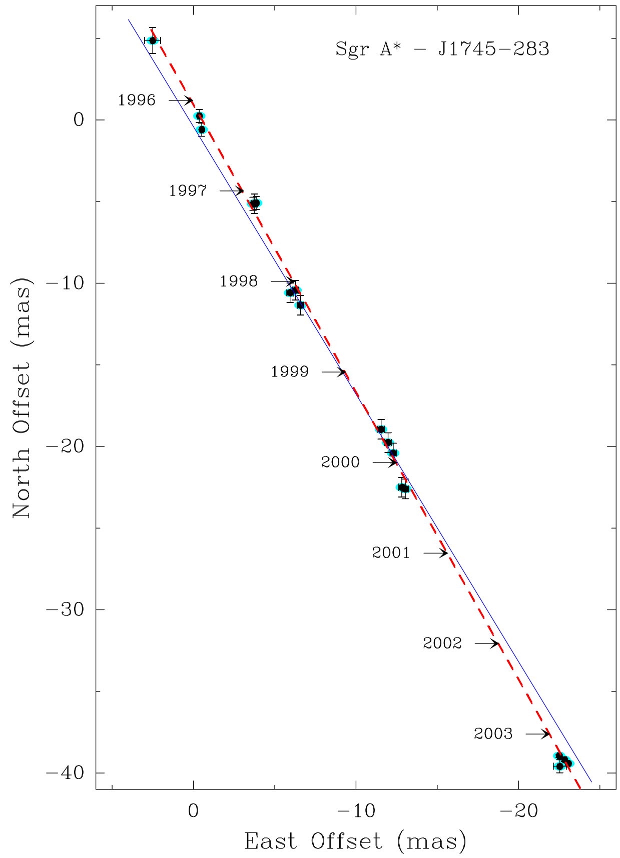

Figure 2.2: Position residuals of Sgr A*, relative to an extragalactic source (J1745–283), on the plane of the sky. The dashed line is the variance-weighted best-fit proper motion, and the solid line gives the orientation of the Galactic Plane. The deviation of the dashed from the solid line is caused by the 7 km s^{-1} component of the Sun's motion out of the Galactic Plane. Sgr A*'s peculiar motion is exceedingly small, < 1.6 km s^{-1}, indicating that it is very massive ($> 10^6$ $M_\odot$).

star formation (IC133 and M33/19). Also indicated are the expected motions on the sky owing to the rotation of the galaxy. These star forming regions exhibit intense H_2O maser emission, similar to the strongest masers seen in the Milky Way. Using the VLBA, Brunthaler et al. (in prep.) have measured the relative motion of these two masing regions with an accuracy of better than 10 μas y^{-1}, based on 4 observations spanning less than 3 years. This is the first time an external galaxy has been seen to rotate!

Combining the angular rotation rate of M33 with its known rotation speed and inclination, determined from HI observations, yields a distance of 695 $\pm$ 105 kpc. This distance is slightly less than the HST Key Project distance of 840 kpc, but the two distance estimates agree within their joint uncertainty. However, since the uncertainty in a proper motion measurement decreases with time spanned as $t^{-3/2}$, in only 3 more years one expects to achieve a distance uncertainty a factor of 3 better than currently achieved. With a geometric distance accuracy of better than 5%, M33 can be used as a primary distance indicator to greatly improve the extragalactic distance scale and estimates of $H_\circ$. A determination of the Hubble constant to better than a few percent would provide a most important complement to the CMB for measuring the dark energy equation of state at $z \approx 0.5$.

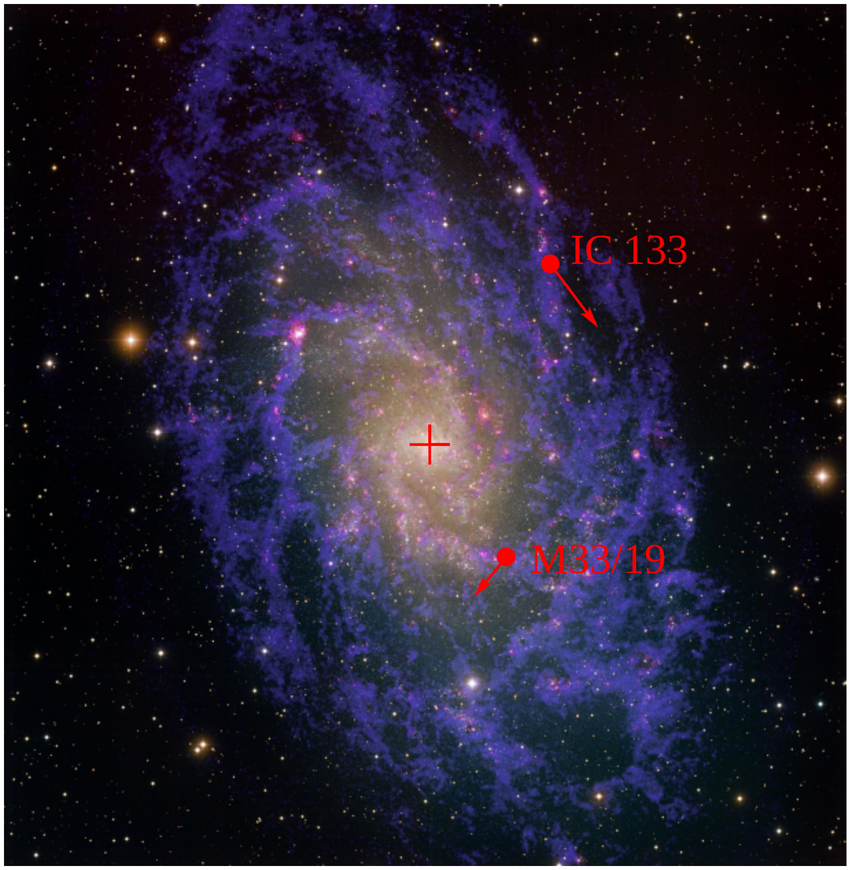

Figure 2.3: Combined radio and optical images of M33 (Triangulum galaxy) by T. Rector (NRAO) and M. Hanna (NOAO). The locations and expected motions of two sites of H_2O masers from massive star forming regions are indicated. VLBA observations over a period of 3 years have yielded the relative motions of these masers, thus one can "see" the galaxy rotate. Combining this measurement with the rotation speed and inclination (from HI data) of the galaxy gives a direct measurement of its distance.

2.5 Young Stellar Objects in Formation

High-mass stars are among the most important components of galaxies because they so strongly influence the energy balance and evolution of interstellar media. Nonetheless, there is no general theory of how high-mass stars form. Chief among obstacles to developing a theory are small sample size, large distances, clustering, confusion, and visual extinctions on the order of 10^2 to 10^3.

A case study conducted with the VLBA (Greenhill et al. 2004, Greenhill 2004) has established by far the most detailed picture of an accreting massive young stellar object (YSO). The object in question lies in the Orion KL region, which is the closest to be forming high-mass stars (~ 450 pc). A long known compact centimeter and millimeter-wave continuum source, commonly designated "source-*I*," marks the location of a deeply embedded YSO (Menten & Reid 1995; Plambeck et al. 1995). Molecular gas surrounding source-*I* is hot enough and dense enough to support maser emission from silicon monoxide, which requires temperatures of 1000-2000 K and densities, n_{H_2}, of $\sim 10^{10\pm1}$ cm^{-3}. Because this emission is highly anisotropic, it is nearly point-like on the sky and high in contrast, making it a good

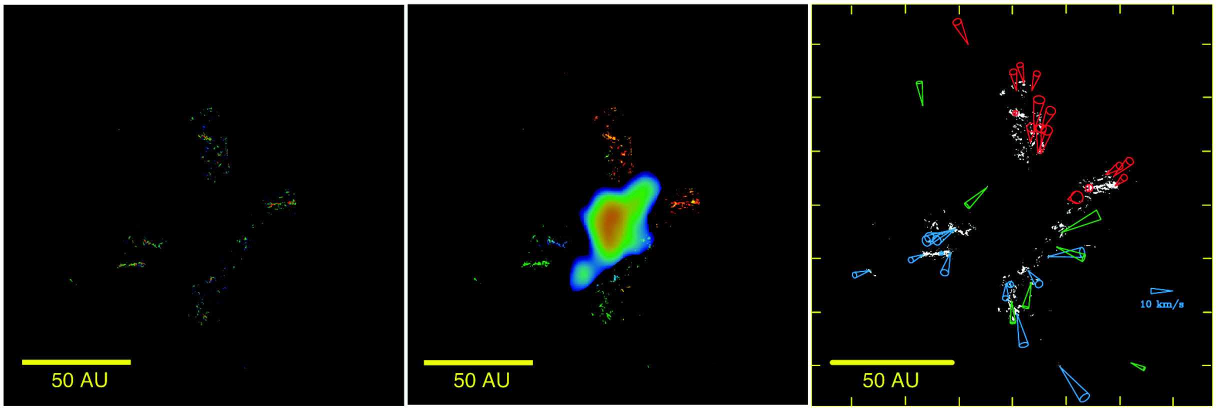

Figure 2.4: Distribution and proper motion of SiO maser emission associated with source-*I* observed with the VLBA. (left) Integrated intensity with the brightest emission coded red. (middle) A plot of the flux weighted mean velocity with colors indicating the Doppler shift. Continuum emission at λ7 mm, mapped with the VLA by Menten & Reid (1995), is shown as color contours. (right) A subsample of proper motions observed over 4 months. The cone lengths reflect the 3D velocity. The aspect indicates inclination with respect to the line-of-sight. Green cones indicate Doppler velocities within 5 km s^{-1} of the systemic velocity.

tracer of bulk mass motions. In time series monitoring of source-*I* over 4 months, intended to track the masers, the VLBA has achieved resolutions in position and 3-D space velocity that are better than 0.1 AU and 1 km s^{-1}.

The distribution of SiO maser emission has provided the first maps of gas dynamics at radii of 20-80 AU around a high-mass YSO (Fig. 2.4), where outflow is launched and collimated. Mapping of this region is a unique capability of the VLBA; it cannot be done with current optical and infrared instruments, but understanding what occurs in the case of source-*I* enables substantially improved modeling of more readily available lower resolution data on massive star formation. The motions are a mix of rotation and outflow in two well defined, oppositely directed funnels seen nearly edge on. This geometry has provided the first direct evidence that high-mass YSOs form through disk mediated accretion, as do Sun-like stars, for which our understanding is much better established. Two models may explain the velocity structure of the outflow: (1) the masers trace the interface between the inward directed, rotating accretion flow and a radially directed stellar wind, where material is shocked and entrained into a massive outflow, or (2) the masers trace a wind driven from the accretion disk surface, which follows a helical trajectory along magnetic field lines. In both cases the YSO dynamical mass is on the order of 10 $M_\odot$. Long term mapping of the distribution of 3-D accelerations and velocities will discriminate uniquely well between these models, allowing unambiguous testing of the common assumption that magnetic fields are less important to high-mass star formation than radiation, largely because high-mass YSOs are expected to be radiative rather than convective.

2.6 Other scientific contributions

Here, we list several other scientific contributions to illustrate the breadth of VLBI studies.

- **Acceleration of Jets** One of the earliest results from VLBI was the detection of apparent faster than light (superluminal) motions in quasars (Whitney et al 1971, Cohen et al 1971). We now understand that these are produced by ejection of the emitting material at velocities close to the cosmic speed limit - the speed of light. This was the first demonstration that powerful processes exist in the vicinity of black holes which can accelerate matter to relativistic velocities. VLBI observations reported by Junor et al. (1999) show that the collimation and ejection of the relativistic outflow in M87 must occur on a scale of 0.5 mas or 140 Schwarzschild radii.

- **Properties of Accretion Disks**

  The accretion disks which power the luminous active galaxies lie on scales of micro to milli arcsecs, beyond the resolution of all techniques except VLBI. VLBI observations indicate free-free absorption from the accretion disk in NGC1275 (Walker et al. 2000) and free-free emission from the accretion disk in NGC1068 (Gallimore et al. 1997). These observations indicate the presence of disks extended on the parsec scale containing dense ionized gas.

- **Micro-quasars**

  Micro-quasars appear to be neutron stars or stellar mass black holes in our Galaxy which accrete matter from a companion star. They produce radio jets as do the more powerful quasars. But since they are in our Galaxy we have a spatial resolution about one million times higher than in the quasars, and since they are much less massive than the quasars they vary about a million times faster. VLA and VLBA observations have shown that the micro-quasars produce relativistic outflows, suggesting that this is common in black hole systems regardless of mass (e.g., Ribo 2004) and may be a fundamental part of the accretion process.

- **Supernova Evolution and chemical enrichment**

  Stars are responsible for generating essentially all the heavy elements in the universe including the ones that make up planets and allow life to exist. These elements are re-distributed back into the Galaxy via stellar winds and by supernova explosions. Images of Supernova 1993J in the galaxy M81 over a period of 7 years are shown in Fig. 2.5. The proximity and brightness of SN1993J have allowed detailed imaging over the past decade, which together with optical and X-ray studies at lower resolution allow insights into the physics of the expansion as the blast wave propagates through the previously ejected circumstellar shell. The initial expansion rate was nearly 17,000 km/s, but has since slowed to less than 10,000 km/s. The symmetry in the radio shell suggests that (1) the amount of clumping in the circumstellar shell is fairly modest, and (2) the magnetic field in the circumstellar shell is fairly ordered (Bietenholz, Bartel & Rupen 2003). This project also illustrates the dramatic movie-making capabilities of the VLBA.

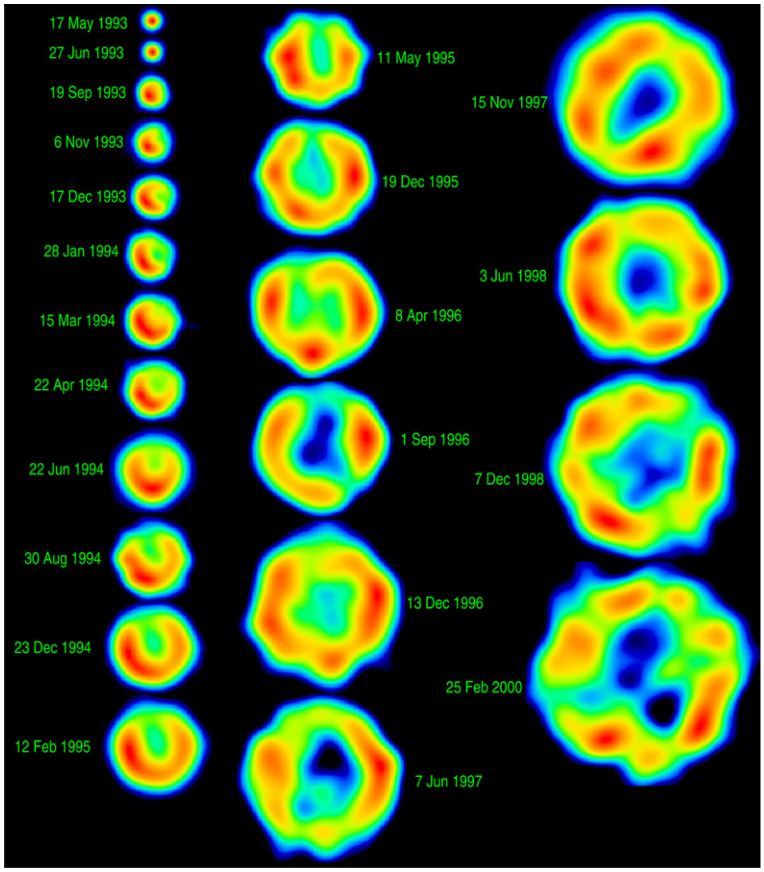

Figure 2.5: The evolution of SN1993J (Bietenholz, Bartel & Rupen 2001).

- **The star formation history of the Universe**

  The process through which galaxies form and evolve is still a mystery. VLBI radio observations are unaffected by dust and can detect radio supernovae in distant galaxies and so measure the star formation rates. Observations of the Ultraluminous Infrared Galaxy Arp 220 using a state-of-the-art global array have detected about 30 supernovae giving a rate of about 2 SN per year (e.g., Diamond et al. 2004). These results show that there is ongoing star formation in both nuclei of this merging system.

- **Testing Models of Gamma-Ray Bursts**

  The most energetic known phenomena in the universe are the gamma ray bursts (GRBs). At this point it is not clear what processes are responsible for releasing the tremendous amounts of energy which are radiated by the GRBs and there are several models. Recent VLBA observations of GRB 030329 have resolved the burst and shown that it is expanding superluminally - consistent with relativistic outflow in the GRB (Taylor et al. 2004). The constraints on the proper motion of the GRB rule out a class of models dubbed "cannon ball models" and support a relativistic jet interpretation.

- **Was Einstein right?**

  A critical underlying prediction of Einstein's Theory of General Relativity is that light will be deflected by massive bodies producing a time delay. Precise VLBI measurements of the deflection of light by the Sun (e.g., Lebach et al. 1995) and Jupiter (Fomalont & Kopeikin 2003) have confirmed GR in the weak field limit and ruled out some alternative models.

Intervening galaxies also act as gravitational lenses - distorting and magnifying background radio sources. The high resolution provided by VLBI allows us to determine the shape of the mass profile in the lensing galaxy and probe its interstellar medium (e.g., Biggs 2004). VLBA observations have shown evidence for substructure in galaxy halos as predicted by Cold Dark Matter models (e.g., Rusin 2002; Metcalf 2002).

Chapter 3

Future Science Prospects

The scientific future for VLBI is rich. Using VLBI, astronomers are able to explore regions of parameter space, non-thermal emission processes, and physical conditions that are unique, in ways that are powerfully complementary to other techniques. Decades after milliarcsecond resolutions were first achieved by VLBI, radio interferometry still offers the best prospect for the highest angular resolution study of a wide variety of astronomical objects and environments.

Impressive though the contributions of VLBI over the past three decades have been, VLBI is poised to make a steadily broader and deeper impact upon the astronomical endeavor. This expansion of the role of VLBI is driven by two key trends.

First, high resolution and high sensitivity astronomy in many wavebands, from submillimeter to X-rays, is rapidly maturing. No longer is it true that objects and phenomena are typically available for study only in a single waveband, and instead a transition to panchromatic astronomy is in progress. It is no coincidence that one of the most important contributions of early VLBI involved objects (radio galaxies and quasars) that were bright enough for detailed study in many wavebands and with complementary techniques, yielding a completeness of observational data that drove important insights. Today, technique-based subfields of astronomy are being blended into a new and more far-reaching enterprise by the rising tide of instrumental capabilities. Typical VLBI targets are becoming accessible to new instruments in other wavebands. Traditionally one of the more isolated fields, VLBI is now merging with the broader flow of modern astronomy, a trend that will inexorably continue and accelerate in coming years.

Second, as will be discussed in detail in Chapter 4, the VLBI technique is poised for rapid growth in sensitivity, usable resolution, and scientific versatility. Provided certain highly cost-effective steps are taken, the scientific reach of the VLBI technique will lengthen dramatically within 10 years. In practical terms, this means that a steadily wider range of targets, from stars to masers to star-forming galaxies and gamma ray burst afterglows, will become accessible to this powerful technique.

In this chapter, we identify some of the most exciting and far-reaching opportunities for VLBI, within the context of broader astronomical priorities. In each case, we identify the enabling technical developments that are required for the science. The path to those developments, and the science-driven priority of each, is discussed in Chapter 4.

3.1 Imaging a massive black hole - Is General Relativity the true theory of strong field gravity?

Radio astronomy has contributed almost all the tests of Einstein's relativity in the weak field regime (for a tiny fraction of the cost of GP-B, LIGO and LISA). It is now poised to lead the way to exploring the strong field regime – around black holes. The best laboratory we have is Sgr A. To date, we are starting to resolve structure on the scale of 1 AU. To see closer to the horizon requires observing at higher frequency. There is only one adjustable parameter, the spin. We can then compare the size and shape of the shadow with simulations (Falcke, Melia & Agol (2000). We will also learn how gas flows and magnetic fields behave that will help us understand more powerful galactic nuclei like M87 and in quasars.*

It is now generally accepted that the central energy source in AGN involves accretion onto a massive black hole (MBH) since energy output and size limits preclude most other phenomena. Study of X-ray emission variability (e.g., Boller et al. 2001) and dynamical studies of masers in Keplerian orbits (e.g., Miyoshi et al. 1995) have greatly strengthened arguments for the existence of MBHs. Yet, for such a widely accepted theory, the detailed processes and physical conditions near the black hole event horizon remain unknown. Exploring black holes is identified as a priority in both the AASC Decadal Survey, and in the Quarks to Cosmos (Q2C) report. This has driven planning for major initiatives such as MAXIM, Constellation-X, and iARISE.

The best prospect for studying an AGN with linear resolutions of a few Schwarzschild radii, (R_{sch}), is SgrA*, the compact radio source at the center of our Galaxy (Balick & Brown 1974). The case for linking SgrA* with emission from a $\sim 4 \times 10^6$ solar mass black hole is now compelling. At a distance of only $\sim$ 8 kpc, R_{sch} of $\sim$ 0.08 AU corresponds to $\sim$ 10 μas, and millimeter wavelength VLBI thus offers the hope of directly imaging the immediate vicinity of the MBH. Present-day observations, which are limited by relatively poor sensitivity as well as λ^2 scatter broadening from the ionized ISM, nevertheless yield size limits that are starting to constrain source models (Bower & Becker 1998, Krichbaum et al. 1998, Doeleman et al. 2001). These recent experiments suggest that VLBI at 86 GHz using the VLBA and planned GBT/LMT sites will be an important step towards probing SgrA* for the presence and properties of intrinsic structure. Its status as the nearest AGN makes SgrA* a source of great interest to a broad astronomical community, and VLBI has a unique and critical role to play in understanding the details of the central black hole: its very existence, whether it is rotating, and the accretion flow properties.

Definitive experiments to explore such unique environments can now be envisaged and planned for, by building upon recent successful VLBI tests at 230 GHz (Doeleman et al. 2003), and pushing to even higher frequencies with fringe spacings as small as $\sim$ 15 μas. Coupled with wide bandwidths and high sensitivities, future high frequency VLBI arrays will be able to make high quality images of SgrA* with linear resolutions of 2-3 R_{sch}, permitting study of large field GR effects that can confirm the existence of a true singularity. GR ray tracing applied to SgrA* shows that as the emission becomes optically thin, a "shadow"

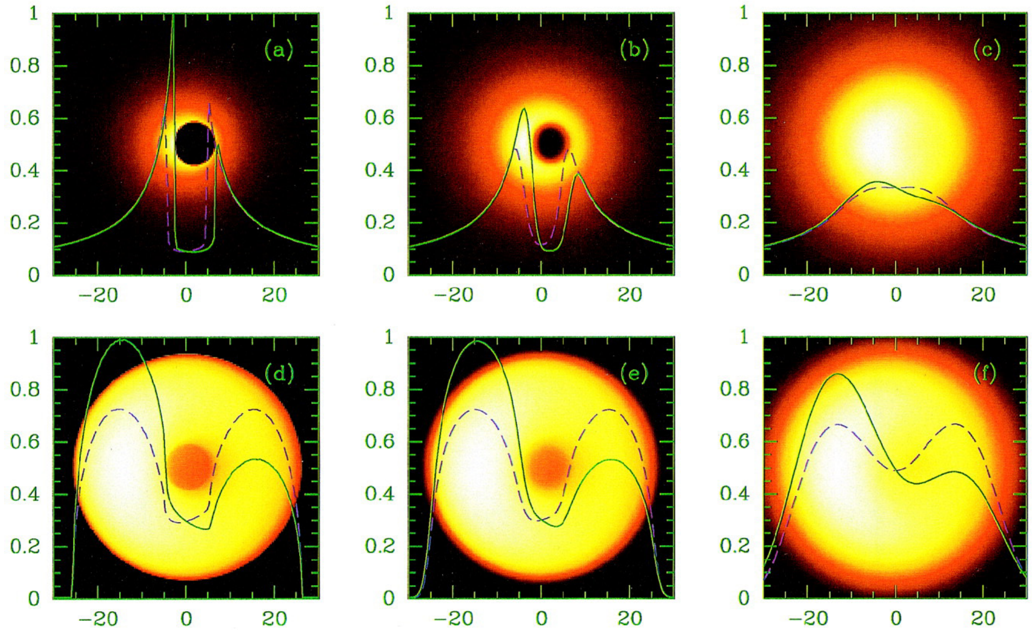

Figure 3.1: Images of optically thin emission surrounding a rotating black hole with the mass of SgrA* with radiating gas in free fall (top row) and a non-rotating black hole with gas in Keplerian orbits (bottom row). Left panels show results of GR ray tracing calculations, middle panels show what a 440 GHz array would see with both scattering and beam size incorporated, and right panels show the emission as seen by a 230 GHz VLBI array with scattering and beam size effects. Dotted and solid lines show horizontal and vertical intensity cuts through the images with the y-axis in relative intensity units. The x-axis is in units of the gravitational radius of the black hole ($0.5\times R_{sch}$). From Falcke, Melia & Agol (2000).

should appear at the center of the SgrA* image, a result of extreme light path bending by the black hole (Fig. 3.1). High sensitivity sub-mm VLBI will extend prospects for similar studies to other objects. For example, the linear resolutions possible for M87, an AGN in a much higher luminosity class than SgrA* with an inferred black hole mass of 3×10^9 solar masses, would be 3-4 R_{sch} with future sub-mm VLBI arrays. Development of mm/sub-mm VLBI will provide a powerful complementary capability for future missions in other wavebands such as Constellation-X.

Enabling capabilities: *very wide bandwidths; high frequency improvements; equipping of new mm and sub-mm apertures for VLBI.*

3.2 Gravitational Lenses - where is the dark matter?

A long standing problem in astronomy concerns the amount and distribution of dark matter that is present in our universe. Gravitational lensing provides a robust method of constraining mass structures, including both luminous and dark matter. Both the unsurpassed angular resolution and planned sensitivity increases of VLBI place the technique squarely at the forefront of ongoing efforts to investigate and characterize the role of dark matter in the cosmos by studying gravitationally lensed systems.

Cold Dark Matter (CDM) models of galaxy formation predict the formation of satellite galaxies or halos, which should account for mass fractions of $\sim 5-10\%$. Optical observations, however, reveal only a small fraction of this mass in our Galaxy, thus highlighting a potential serious flaw in CDM models (Dalal & Kochanek 2002). The resolution to this conflict is now coming into focus through recent high resolution radio imaging of gravitational lens systems. The positions of separate images of a lensed quasar can constrain a smooth isothermal ellipsoidal mass model for the lens, but in some cases (e.g., Marlow et al. 1999), the relative fluxes of the images are inconsistent with the mass model. These so called 'anomalous flux ratios' can be attributed to substructure in the galactic halo that alters the flux of an image but leaves the image position largely unchanged. Dalal & Kochanek (2002) have analyzed a sample of radio lenses, showing the mass fraction concentrated in the substructure to be $\sim 1-7\%$, in broad agreement with CDM theory. An outstanding and important problem is the size scale of the dark matter clumps in these halos. VLBI can directly attack this problem by searching for an expected astrometric equivalent to the anomalous flux ratio effect (Wambsganss & Paczynski 1992, Metcalf 2002). Precise astrometry and structure of lensed images can be used to search for gravitational signatures of satellites that have no luminous counterpart. In the lens MG2016+112 (Koopmans et al. 2002), such a satellite was inferred and then detected in deep optical images. With increased resolution at higher frequencies and higher dynamic range from high bandwidths, VLBI will soon be able to detect the effects of much smaller satellites. If no optical counterpart can be seen this may lead to the first secure detection of a dark matter clump in a galactic halo, and a measurement of its mass.

Gravitational lens systems can also be powerful probes of small scale structure near the core of galaxies, regions typically opaque to astronomers in wavebands between the radio and X-rays. Lensing theory predicts (Burke 1981) that most lensing galaxies and background sources should produce an odd number of images with one of the images very near the lensing galaxy core. This a-priori expectation stands in stark contrast to the population of lenses found in the JVAS (Jodrell-VLA Astrometric Survey) and CLASS (Cosmic Lens All-Sky Survey) surveys, which have almost exclusively found 2 and 4 image systems (Rusin & Ma 2001). This contradiction between theory and observation has been interpreted by many authors as due to a large de-magnification of central images by the lens galaxies (Narasimha, Subramanian, & Chitre 1986, Rusin & Ma 2001, Keeton 2003). More centrally concentrated mass distributions produce fainter central images; the central image flux depends sensitively on the density structure of the lens galaxy on ~ 10 pc scales and, if detected, these images could become a powerful probe with which to study galaxy structure and the influence of central black holes (Mao, Witt, & Koopmans 2001). The first such system has recently been found using sensitive VLBI observations (Winn, Rusin & Kochanek 2004).

Detection of central odd images in even a small number of lens systems would provide important new limits on galactic density profiles at very small scales. The radio band is preferred for this work since the optical emission of typical lensing galaxies overwhelms the faint central image. The current sensitivities of deep follow up observations to the JVAS and CLASS surveys place odd image flux density 5σ limits at $\sim 225\mu$Jy and correspond to ratios of (r = central image flux / brightest image flux) ~ 0.001 (Rusin & Ma 2001). With projected sensitivities of future VLBI arrays using large apertures and high bandwidths (1-2 μJy/beam in 2 hours at 1.4 GHz and 5 GHz), new limits on central lensed images can be set that are factors of 25-40 lower than the best recent efforts. It should be noted that for gravitational lenses, with typical image separations of ~ 2 arcseconds, VLBI arrays will be able to self-calibrate on the bright images and coherently integrate as long as needed to search for the central image. Evans & Hunter (2002) predict that a 50-fold increase in current sensitivity levels will enable detection of central images in 50% of the total lenses detected. Mao, Witt, & Koopmans (2001) further predict that in a small number of cases, it should even be possible to find two central images; the extra central image would be due to a central massive black hole and the image properties would allow the black hole mass to be measured. Wideband VLBI observations thus have the potential to dramatically affect our understanding of galactic structure and the existence of massive black holes in the nuclei of normal galaxies.

Anticipated future enhancements of VLBI arrays will also enable gravitational lens systems to be used as "cosmic magnifying glasses" in the study of relativistic jets accelerated in active galactic nuclei. In lens MG2016+112 (Koopmans et al 2002), for example, the lensed AGN has a jet whose extended emission crosses a point of extreme magnification ($\times 300$). This chance alignment could in principle allow 'hyperluminal' motions of microarcsecond jet structures to be observed. While this particular lensed quasar does not appear to exhibit relativistic motions, discovery of a suitably lensed relativistic jet would allow study with unprecedented detail of the process by which jet material is accelerated and collimated.

Enabling capabilities: *very wide bandwidths; large apertures; improved correlator.*

3.3 Supernova factories and nascent AGNs - what happens when galaxies collide?

Galaxy collisions are implicated as one of the key phenomena determining the evolutionary history and current state of the universe. The star formation history of the universe is intimately tied to such events, as is the process of supermassive black hole formation and AGN activity.

Ultraluminous infrared galaxies are laboratories for the processes triggered by galactic collisions. Large quantities of dust and gas fall into the nucleus of the merging system, creating ideal conditions for intense star formation, growth of supermassive black holes, and fueling of AGN activity. These conditions are accompanied by extreme column densities and obscuration between us and the center of activity in such systems, with optical extinctions sometimes estimated to be more than 1000 magnitudes. Recent hard X-ray studies (Komossa et al. 2003, Ballo et al. 2004) demonstrate the existence of buried AGNs which are completely obscured in the optical and infrared. The ability of high resolution radio studies to penetrate the obscuring medium is illustrated by Gallimore & Beswick (2004). These authors, consistent with the findings of others, conclude that significant free-free absorption exists toward the nuclei, even at GHz frequencies.

There are now two merging galaxy systems with clearly identified clusters of young radio supernovae, tracing regions of intense star formation. In Arp 220 (Smith et al. 1998), sensitive global VLBI observations revealed $\sim$12 unresolved sub-mJy sources. Subsequent monitoring recorded the appearance of 4 new sources, and the fading from view of others. More recently, very sensitive observations including Arecibo and the GBT have raised the number of detected sources in Arp 220 to about 30. The second system is Arp 299 (Neff, Ulvestad & Teng 2004), which shows five VLBI-scale sources, exhibiting spectra consistent with a supernova interpretation, and evidence for variability. There are indications that the supernova activity is associated with so-called "super star clusters".

This research will blossom with the provision of higher VLBI bandwidths and improved sensitivity. The nuclei of luminous IR galaxies, and the star-forming regions they harbor, are unobscured only in the radio, submillimeter and X-ray regions of the spectrum. In addition, the regions of interest are physically small, typically smaller than 1 arcsecond in extent in the nearest systems. Until ALMA is operational, VLBI represents the only effective way to probe the innermost active regions of such galaxies. The radio supernovae themselves can be used as probes of the environment, via molecular line absorption, free-free absorption, and maser amplification. The star forming regions can be delineated by the supernova locations, and the activity level can be diagnosed by monitoring. All these studies become more potent as the number of detected supernovae becomes large, placing a high scientific premium on raw continuum sensitivity, with wide bandwidths and large apertures.

The search for buried AGNs demands improved sensitivity at higher frequencies than current studies, in order to reduce the effects of free-free absorption to the nuclei. Studies of such AGNs in conjunction with radio supernova distributions can test ideas about relationships between AGN genesis and nuclear starbursts.

The process of galaxy merging, followed by intense nuclear star formation and AGN genesis, is of fundamental importance in the history of the universe, and features prominently in cosmological modeling. As a powerful diagnostic of otherwise unobservable processes in obscured nuclei, these VLBI studies can yield unique information on a critical phase in the evolution of galaxy merger events.

Enabling capabilities: *very wide recording bandwidths. Arecibo, GBT, EVLA, EVN at 1.6 to 8 GHz.*

3.4 Launching AGN jets - How are relativistic, collimated flows generated?

Cosmic accelerators are responsible for truly remarkable phenomena, from 10^{21} eV cosmic ray particles to powerful relativistic flows that propagate for hundreds of kiloparsecs; the fundamental importance of accelerators is recognized in the Q2C study. High-frequency VLBI polarimetry offers a realistic opportunity to constrain the mechanisms involved in the largest and most powerful known accelerators, those responsible for the creation of large-scale AGN jets.

Relativistic jets in active galactic nuclei (AGN) are the most energetic cosmic accelerators known, yet we are only beginning to understand how such jets form. The high resolution offered by VLBI yields images of jets on sub-parsec scales that can test modern theories and

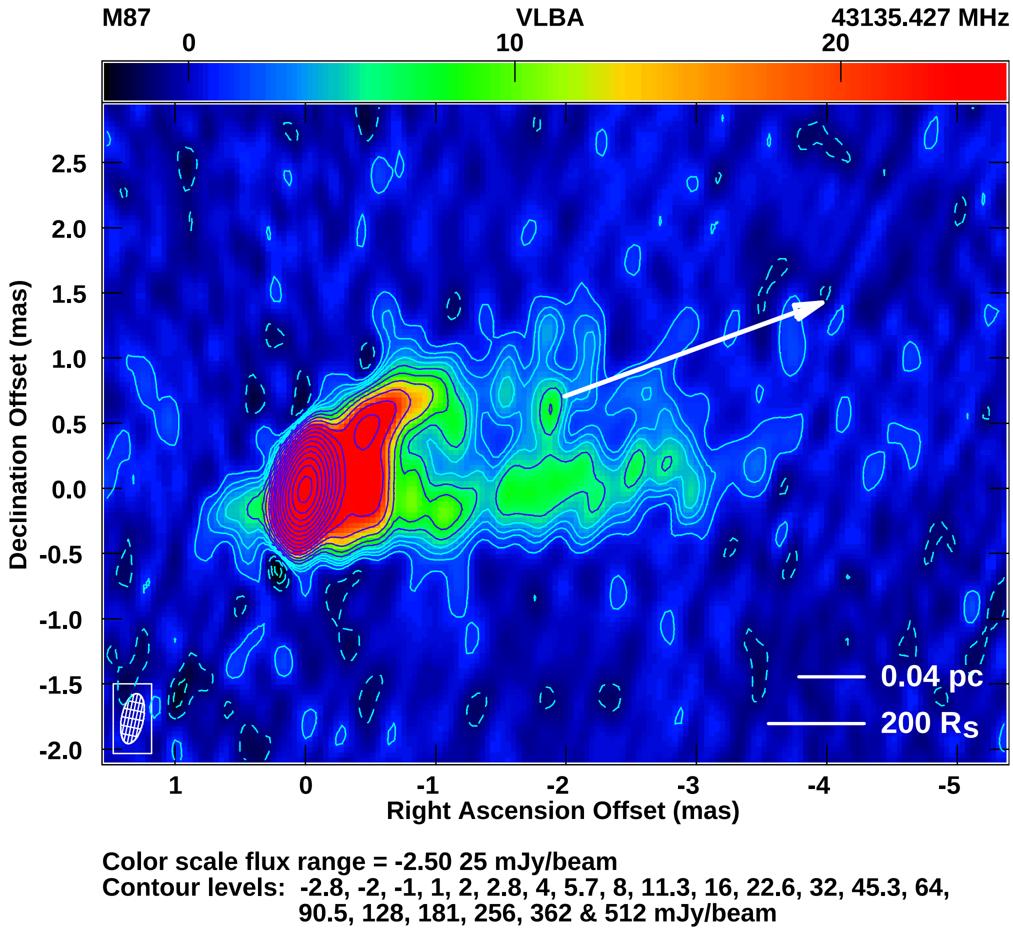

Figure 3.2: VLBA image of Stokes I emission from M87 at 43 GHz from Ly et al. (2004), confirming the large jet opening angle reported by Junor et al. (1999) over the inner 0.5 mas or 140 Schwarzschild radii. Jet emission is clearly detected out to 3 mas or 820 Schwarzschild radii along the direction of the large-scale jet indicated by the arrow. The apparent counterjet is still questionable since it may be an imaging artifact. The hatched ellipse shows the Gaussian restoring beam diameter of 0.39 × 0.17 mas at FWHM.

simulations of jet formation, collimation, and acceleration to highly relativistic flow velocities. Recent magnetohydrodynamic simulations show that a rotating, coiled magnetic field can launch a jet by accelerating and guiding plasma outward along the poles of an accretion disk around a super massive black hole. One basic question, stimulated by numerical magnetohydrodynamical simulations (e.g., Meier et al. 2001) is whether the focusing and acceleration occur close to the black hole or parsecs downstream (Vlahakis & Königl 2004). The VLBA weighs in heavily on this issue, following the imaging of a broad region of the jet of the nearby elliptical galaxy M87 on sub-mas scales (0.02 pc, about 100 Schwarzschild radii; Junor et al. 1999; Ly et al. 2004 - see Figure 3.2). For M87, this inference of magnetic-field collimation could be directly tested through VLBI polarimetry at 43 GHz, but this test requires significant sensitivity enhancements. Such enhancements will also enable VLBI studies of the jet-launching regions in other nearby galaxies. Moreover, future VLBI observations from the ground and in space (iARISE) in the sub-mm and mm regimes will resolve and image the regions within 3 to 10 Schwarzschild radii, revealing the physically rich interplay among accretion disks, magnetic fields, and black holes.

Enabling capabilities: *very wide bandwidths, large apertures above 20 GHz (e.g., GBT, EVN dishes); equipping of new mm and sub-mm apertures for VLBI.*

3.5 What are the kinematics of the Galaxy and the Local Group?

The mass content and distribution of the Local Group, including the dark matter halo, remain poorly constrained due to the lack of proper motion vectors for the galaxies. Precision VLBI astrometry can provide these vectors in the near future. Similarly, astrometric measurements of pulsars, masers and binary stars can provide a detailed structural and kinematic map of our galaxy.

The proper motion vectors of nearby galaxies are key, but still largely missing, parameters for measuring the mass content and distribution in the Local Group of galaxies. Measuring such motions is a prime goal of the Space Interferometry Mission (Shaya et al. 2002). However, astrometric monitoring of interstellar masers in M33 and IC10 with the VLBA is underway and in a few years will detect the expected proper motions of 50-100 μas per year (Brunthaler et al. 2002). Discriminating among possible orbit families for the Local Group requires expanding such VLBI programs to include the faint masers and continuum sources in other galaxies (e.g., IC342), but such progress will require significant sensitivity enhancements. Proper motion measurements also offer an opportunity to obtain geometric distance measurements to M33 and possibly other nearby galaxies with an accuracy of better than 5% (Brunthaler et al. 2002). This would substantially improve the extragalactic distance scale, now anchored to only NGC4258 and to the Large Magellanic Cloud, for which current distance estimates span a range of about 30%.

For the Milky Way, the locations of spiral arms and the rotation speed (and hence mass) are poorly constrained. The near microarcsecond astrometric accuracy of VLBI allows measurement of parallax and proper motion to bright objects throughout the Galaxy, resulting in a structural and kinematic map. For example, most pulsar distances are estimated from their dispersion measures using a model for the Galactic electron density that includes spiral structure. But astrometric monitoring of pulsars at 1.4 and 5 GHz with the VLBA is beginning to yield model-independent distances out to 2 kpc that provide essential calibration points for the electron density model (Chatterjee et al. 2001, 2004; Brisken et al. 2002). Figure 3.3 shows a 5-GHz example from Chatterjee et al. (2004). With the routine addition of telescopes with large collecting areas, parallax signatures could be detectable to 3-5 kpc. Extending these measurements to 10 kpc would vastly improve our understanding of electron densities throughout the Milky Way, but will require the improved calibration techniques (e.g., the use of multiple in-beam phase calibrators) that will naturally follow from significant enhancements in array sensitivity through wider bandwidths.

Enabling capabilities: *software development, wide bandwidths, large apertures.*

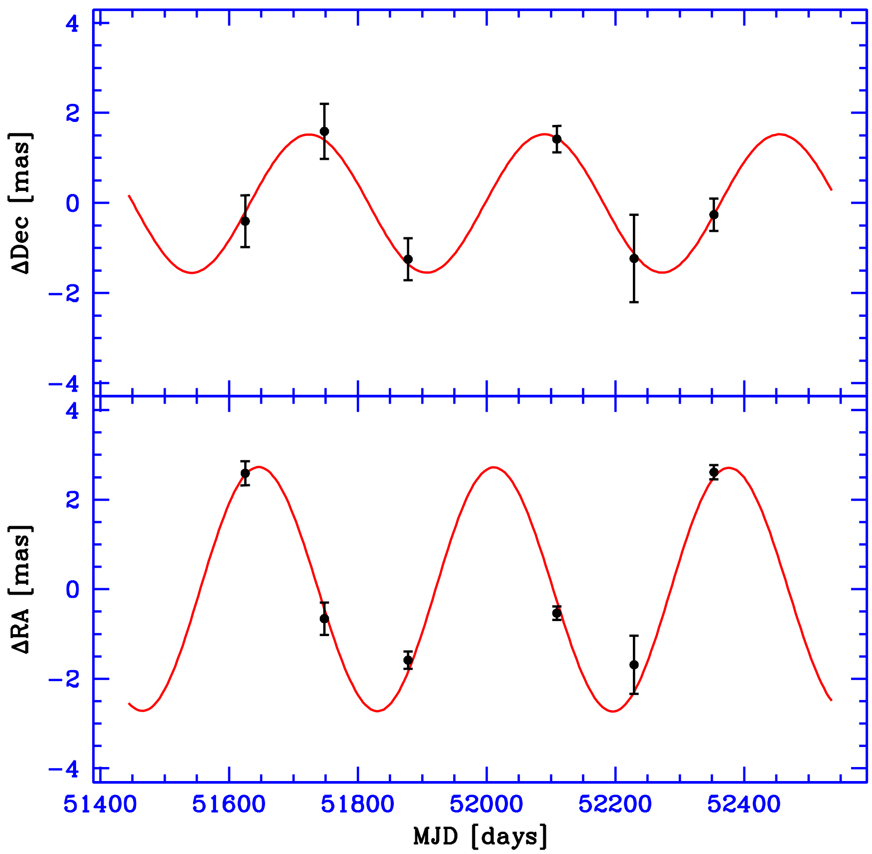

Figure 3.3: The parallax signature of PSR B1929+10 in right ascension and declination, after subtracting the best-fit proper motion from the astrometric positions measured at 5 GHz, a challenging observing frequency for these steep-spectrum sources (Chatterjee et al. 2004). Sinusoids corresponding to the best-fit parallax $\pi = 2.77 \pm 0.07$ mas are overplotted. The implied distance for the pulsar is 360^{+10}_{-8} pc.

3.6 What is the role and effect of magnetism in stars?

Magnetic fields play a central role in the formation of stars, including the accretion flow and planetary system formation processes. Magnetic activity is also closely related to the evolution of many types of stars. Bright, polarized radio emission from magnetized plasmas can be studied in revealing detail using the high resolution and sensitivity of VLBI.

At multiple stages of evolution, stars can be radio bright with gyrosynchrotron emission at times exceeding the radio output levels from the Sun by three orders of magnitude. This bright and compact emission indicates dynamically important magnetic fields that govern multiple fundamental processes in star formation, binary interactions, and brown dwarf flares. While current VLBI experiments can target only the brightest, atypical systems, improved VLBI sensitivities in coming years will offer exciting opportunities to study the role of magnetic fields in a wide variety of stellar systems.

Magnetic fields are central to protostellar evolution. Seed fields are compressed during cloud collapse and influence protostellar rotation rates, thereby affecting future magnetic field generation due to dynamo action. Once the central object has condensed, its magnetic field determines the inner accretion disk radius and serves to control accretion flows as well as collimated bipolar outflows via coupling to ionized material. Radio and X-ray bursts are associated with reconnection events of kilogauss fields in physically small circumstellar regions. Useful coordinated radio and X-ray studies of these bursts will require high VLBI resolution (0.1 to 0.3 mas) and sensitivity (less than 0.1 mJy). Such VLBI capabilities are possible within a decade, for example at 43 GHz using wide bandwidths, ALMA, the GBT and the VLBA. The gyrosynchrotron emission from these sources will be maximum at several 10's of GHz and ALMA will be targeting these sources with angular resolution at the 10-15 mas level. Using the phased ALMA array, 43 GHz VLBI should be able to follow-up on many of the compact, non-thermal sources.

Brown Dwarfs (BD) have also been observed to flare in the radio, but do so with $L_{\text{radio}}/L_{\text{X-ray}}$ ratios that far exceed those observed in other non-thermal stellar flares (Berger et al. 2001, Berger 2002). A deviation from empirical $L_{\text{radio}}/L_{\text{X-ray}}$ relations (Guedel 2002) is not unexpected given that the photospheres of BDs are not ionized and links between X-ray and radio activity may not operate as in normal stars. High sensitivity VLBI will thus be a necessary complement to X-ray studies of this BD activity. BD flares observed so far also exhibit high degrees of circular polarization indicating a coherent process. VLBI observations will be indispensable in constraining the size scale and brightness temperature of the poorly understood emission mechanism.

Close tidally interacting binary systems also emit via gyrosynchrotron processes. This emission may be due to large coronal loops from one object, or instead to an interacting magnetosphere between the two orbiting objects. In the case of the RS CVn system UX Ari (Beasley & Guedel 2000), no thermal or non-thermal model adequately reconciles the X-ray and VLBI observations. Detailed polarization-sensitive VLBI images with improved sensitivity and resolution will be needed to constrain field geometries.

Enabling capabilities: *wide bandwidths; large apertures; high frequency improvements; equipping of new mm and sub-mm apertures for VLBI.*

3.7 Super Massive Binary Black Holes - How common are they?

If super massive black holes form when the Universe is young, then mergers should frequently produce binary black holes in galactic nuclei. As these systems coalesce they could provide copious gravitational radiation and their orbits provide tests of strong gravity. VLBI offers a way to find and study these systems. Identifying such systems is also one of the scientific goals for the Space Interferometry Mission (SIM).

Binary black hole systems have been predicted for some time (Begelman, Blandford & Rees 1980) and invoked to explain such phenomena as precessing jets (Gower et al. 1982, Merritt & Ekers 2002), but have never been observed directly on scales smaller than a kiloparsec. Super massive black hole binaries are potential sources of strong gravitational radiation, and thus of critical importance for LIGO, LISA and ASTROD (De Paolis et al. 2003). If the black hole is actively accreting matter then it is likely to be readily identifiable in the radio as an AGN. For a small separation (1 pc) pair the orbital velocity is about 0.01c and could

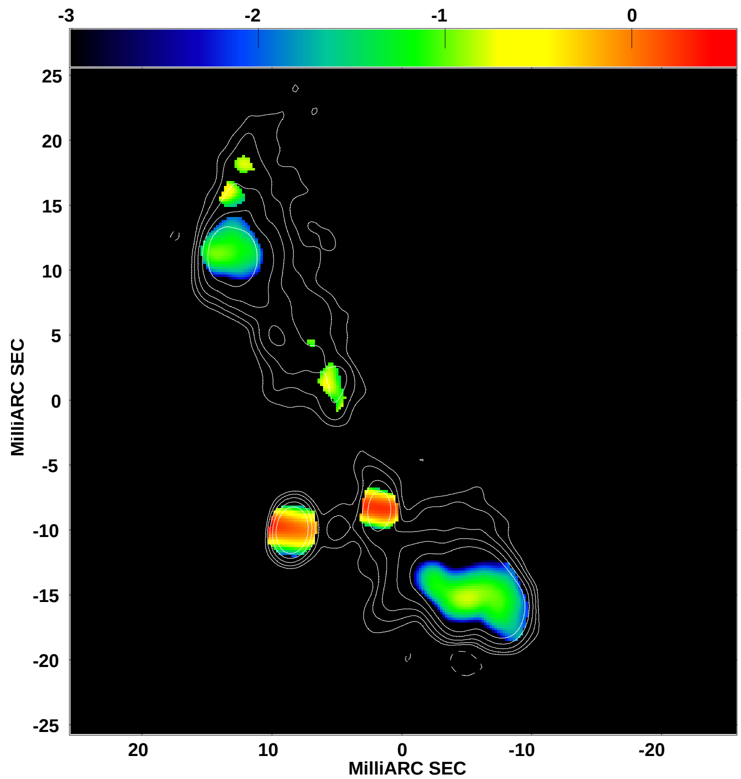

Figure 3.4: Spectral index distribution of 0402+379 between 5 and 15 GHz from VLBA observations in 2003. The contours are taken from the 5 GHz observations and are set at 3 sigma, increasing by factors of 4 thereafter. Note that while both the north and south hotspots have a steep spectrum, both core candidates (the compact central components) have an inverted spectrum. From Maness et al. (2004).

be measured over 5-10 years for systems at distances less than 100 Mpc. VLBI observations at high resolution open up the possibility of determining the orbital properties of the system, and should a close separation system be found, providing a view of the system in its final stages.

Recent VLBA observations discovered what may be the first binary black hole system with a separation of less than 10 parsecs (Maness et al. 2004) to be directly imaged. Two strong, compact, flat-spectrum core candidates are found in the nucleus of the compact symmetric object 0402+379 (see Fig. 3.4). If this candidate binary black hole system is confirmed then it should be possible to probe the dynamics of the system. Colliding galaxies have been the subject of intensive study; however, the separation of the parent galaxies' nuclei in these cases has always been large (at least 100 times the projected separation seen in 0402+379). In understanding the dynamics of galaxy mergers, it would be useful for us to have examples of colliding galaxies that are close to the end of the process. VLBI surveys at high frequencies are needed to identify more systems, find closer pairs, and to characterize what a merger event looks like at late times. We already know of several unusual aspects about the 0402+379 system, including the presence of neutral hydrogen within the nucleus redshifted by 1000 km/s with respect to the systemic velocity.

Enabling capabilities: *very wide bandwidths.*

3.8 Other science opportunities

Here, we list several other promising avenues of research, to illustrate the breadth offered by high-sensitivity future VLBI facilities.

- **How do massive black holes evolve in time?** Deep fields observed across the electromagnetic spectrum, from space and from the ground, can be filtered with VLBI for candidate AGN at cosmological distances. This filtering helps constrain models for the growth of massive black holes over cosmic time. This is only one example of the way in which sensitive VLBI surveys over wide fields of view will be scientifically valuable. **Enabling capabilities:** *Wide bandwidths, new correlation facilities.*

- **What do GRB and SN explosions look like?** Prompt emission from supernovae and gamma ray bursts is readily detectable, and late-time observations are possible given improved bandwidths and sensitivities. The angular resolution of VLBI in such cases would provide precise localizations and can resolve the afterglow, providing unique information about the energetics of the explosions and the nature of the circumburst environment. These observations also place strong constraints on the theoretical models. By implementing much higher sensitivities at higher frequencies and thereby higher resolutions, more distant and more numerous targets can be fruitfully attacked. **Enabling capabilities:** *Very wide bandwidths, VLBA 43 and 86 GHz performance optimization, inclusion of large 43 and 86 GHz apertures (GBT etc.).*

- **How do jets decelerate?** Higher continuum sensitivities will allow more sophisticated radio-loud AGN studies, in more numerous and fainter sources, leveraging improved synergy with observations at other wavelengths. Examples include gamma-ray emitting regions of sources detected by GLAST and VERITAS, sources exhibiting optical and IR polarization variability, and sources with Chandra jets whose properties suggest jet deceleration. In addition, higher bandwidths and sensitivities will allow observations at higher frequencies and usable resolutions. The improvements will allow meaningful study of subluminal motions in low luminosity sources. **Enabling capabilities:** *Wide recording bandwidths, usage of large apertures (GBT, Arecibo, EVLA, ATA, EVN).*

- **How do Evolving Stars Return Mass to the Galaxy?** Stars in the late stages of evolution return matter to the interstellar medium through prodigious stellar winds (red giants) and titanic explosions (supernovae). Matter returned from stars is enriched in heavy elements which makes life possible. Molecular masers provide powerful probes of complex region between the stellar photosphere and the dust formation zone. As VLBI encompasses higher frequencies with good sensitivity, many more masing transitions will become accessible. Generally, physical constraints on the environment are most effective when multiple transitions of a molecule are simultaneously observed. The scientific value of VLBI in this area can thus be expected to grow rapidly as the transition-rich millimeter and submillimeter regimes are opened up. **Enabling capabilities:** *Equipping of new mm and sub-mm apertures for VLBI.*

- **What are the environments of quasars like?** The compact continuum radio sources produced by quasars can illuminate the obscuring clouds of dust and gas. Given sufficient collecting area and sensitivity, molecular line absorption VLBI experiments can provide powerful probes of this obscuring medium. Faraday rotation measures can reveal information about the magnetic field strengths and topologies. **Enabling capabilities:** *Usage of large apertures (GBT, Arecibo, EVLA, ATA, EVN).*

- **Does the fine structure constant change with time?** It is possible to constrain cosmological evolution of the fine structure constant, through high redshift VLBI observations of OH absorption associated with HI absorbers. **Enabling capabilities:** *Usage of large apertures (GBT, Arecibo, EVLA, ATA, EVN).*

Chapter 4

Technical Roadmap

Early VLBI instrumentation involved state-of-the-art engineering and costly, specialized equipment. This was amply justified by the scientific capability created, and by the effective leveraging of investment represented by large telescopes around the world. Nevertheless, the ad-hoc VLBI networks presented difficult and persistent organizational, operational and performance challenges, facts which led to the commissioning of the VLBA ten years ago. The VLBA, however, was designed and built at a time when custom-built recording and correlation systems were still the only practical path to useful bandwidths.

The opportunity now presents itself to leverage new data handling technologies, not only for the VLBA but also for new high-frequency telescopes, to dramatically enhance the sensitivity of VLBI, and to extend the range of scientifically useful sensitivities to higher frequencies and higher angular resolutions. In this chapter, we present these opportunities, and offer recommendations for both hardware and software investments over the coming decade. The Committee believes that the cost-effectiveness of these measures is sufficiently high, and the anticipated scientific return sufficiently broad and profound, that a compelling case exists for their timely implementation.

4.1 Sensitivity

Traditionally, VLBI sensitivity was limited by short coherence times, low bandwidths, and the need to detect fringes on the target source in a few minutes. To a large extent, this limitation has been overcome via the technique of phase-referencing. This technique, which can be applied even at frequencies as high as 43 GHz, has become routine only because of the efforts of the geodetic community in maintaining a correlator model and building a dense grid of phase calibrators on the sky. The Committee enthusiastically applauds our geodetic colleagues for these efforts.

Imaging of faint sources is thus now routine, and until recently the only practical way to further enhance the sensitivity of a VLBI experiment was to add collecting area, such as adding Arecibo to VLBA observations and incorporating the GBT. However, fueled by dramatic advances in the storage capacity and speed of commercial hard disks, VLBI recording technology is poised to evolve rapidly over the next 3-5 years enabling sustainable recording rates at the 10 Gb/s level. This will represent a 20-fold increase over maximum tape drive recording rates. To put this in perspective, note that in 1983 the maximum recording rate for the then new MarkIII VLBI system was 224 Mb/s. The current maximum recording rate at the VLBA, possible only through special arrangement, is 512 Mb/s, an increase by only a factor of two in twenty years.

At the heart of this evolution are new magnetic disk based recording systems that use arrays of off-the-shelf hard disks. The current Mark5a VLBI recording system has a maximum recording rate of 1 Gb/s, and multiple units in parallel can be combined with MarkIV data acquisition hardware to yield recording rates up to ∼2 Gb/s. The primary advantage of disk based systems over tape systems is the order of magnitude difference in price: a Mark5a system can be purchased for $16K. Media costs for disks are currently below $1/Gb and are dropping quickly while tape costs are $2/Gb and show no sign of decreasing. Correlator efficiency also increases with disk systems, which cut overhead associated with tape synchronization and tape positioning.

The EVN has already committed to upgrading all their telescopes to Mark5 systems and will be completely disk based by the end of 2004. At the VLBA, a move to the current Mark5a system would allow continuous 512 Mb/s recording for up to 21 hours with no need to change disk media (assuming 300 GB hard disks are used in two packs of 8 drives each). A new Mark5b system is under development and will interface directly to the VLBA base band converters enabling 1 Gb/s recording with current VLBA acquisition hardware within the next year. At 1 Gb/s rates, hard disk capacities will have to increase to 600 GB or two Mark5b units used in series to maintain continuous recording for 21 hours.

In parallel with disk systems, development of quasi real time VLBI through internet and optical fiber data transfer (dubbed e-VLBI) is gaining momentum. Feasibility tests on long baselines at rates of 100s of Mb/s have been achieved and high bandwidth infrastructure will expand to keep pace with commercial and industry requirements. Exploration of this "media-free" technique will involve developing transfer protocols that make optimal use of available internet bandwidth; the challenge of establishing broadband connections to remote VLBI sites must also be addressed. Over a 10 year horizon, multi-Gb/s transfer rates for e-VLBI can be expected.

No changes in either the VLBA receiver front ends or at the VLBA correlator would be required for 1 Gb/s recording rates. As recording rates increase through the use of parallel Mark5b units or enhancements to the system, modifications to existing local oscillators and IF systems, VLBI backends, as well as correlators themselves will be required. A growth path exists to bit rates as high as 64 Gb/s for the VLBA over the next 10 years if technical developments planned for EVLA systems are used to enhance VLBA stations. This path is outlined in Section 4.5 along with costs for each stage as estimated by the Committee.

In addition to these developments in bandwidth, efficiency improvements in existing telescopes, combined with new large apertures coming on line, will significantly increase the sensitivity of future VLBI arrays. Table 4.1 shows how the capability of the VLBA will evolve as bandwidth increases and as receiver improvements at 22, 43 and 86 GHz wavebands are implemented (see next section). If the GBT is added to the VLBA, these sensitivities typically improve by factors of 2-3. If the largest available apertures are used at cm wavelengths, exceptionally good continuum sensitivities result (Table 4.2). Figure 4.1 shows the baseline sensitivities possible using all VLBI capable antennas today and how sensitivity can improve as bandwidth increases. Spectral line VLBI will gain some benefit from bandwidth increases due to the increased number of phase referencing calibrators made possible with increased continuum sensitivity.

Table 4.1: Thermal map rms noise for the VLBA at various wavelengths and at recording rates that should be possible within 10 years. Wavebands for which the recording rate is not possible are marked with an 'x'. Entries for 22, 43 and 86 GHz beyond the present time have dual values in the table with the second reflecting anticipated receiver and dish upgrades in these wavebands. Overall improvements should be factors of 1.4, 1.4 and 1.5 respectively. Assumed integration time is 8 hours and rms is in units of microJy/beam.

Frequency	(GHz)	0.3/0.6	1.4	2	5	8	15	22	43	86
Present:	256 Mb/s	192	26	28	27	27	47	77	124	446
1-2 yrs:	1 Gb/s	x	13	14	13	13	24	38,27	62,44	225,150
3-5 yrs:	4 Gb/s	x	6.5	7	6.5	6.5	12	19,14	31,22	113,75
5-10 yrs:	16 Gb/s	x	x	x	3.25	3.25	6	9.5,7	15.5,11	57,38

Table 4.2: Thermal map rms noise at cm wavelengths for an Ultra Sensitive VLBI array comprising the largest apertures: GBT (100m), Arecibo (300m), Jodrell Bank (72m), Effelsberg (100m), phased Westerbork (100m). Assumed integration time is 2 hours (Arecibo transit) and the rms in microJy/beam. These sites can use new Mark5 recording systems at present. An 'x' is shown where fractional bandwidths become too high for the receiver.

		1.4 GHz	5 GHz
Present:	1 Gb/s	2.6	3.4
1-3 yrs:	4 Gb/s	1.3	1.7
3-5 yrs:	16 Gb/s	x	0.85

4.2 High Frequency VLBI

High frequency VLBI holds the promise of delivering high resolution in new and important spectral regimes. Compelling advantages of mm/sub-mm VLBI include:

- High resolution: 8000 km baselines at 230 GHz give fringe spacings of ~ 34 μas.
- AGN cores become optically thin.
- Scattering in ionized ISM decreases as λ^2.
- Faraday depolarization decreases as λ^2.

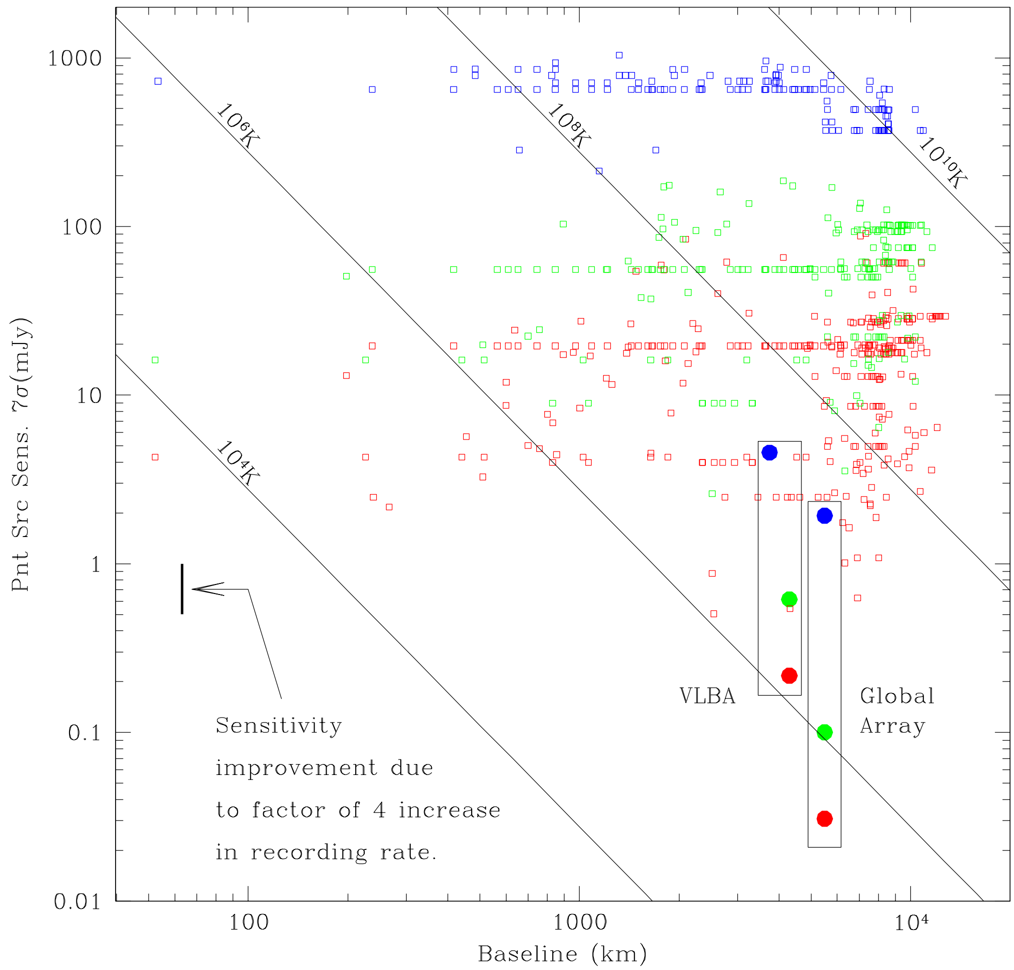

Figure 4.1: Sensitivities of VLBI baselines and of two arrays. Open squares are detection thresholds for individual VLBI baselines: Blue (86 GHz), Green (22 GHz) and Red (5 GHz). These baseline detection limits are for 2 minute VLBI scans using a recording rate of 256 Mb/s. Filled circles show feature detection limits on maps made with the VLBA and with a Global VLBI array. These array limits are for long integrations using Earth rotation aperture synthesis. Sloping lines represent brightness temperatures. The improvement in sensitivity resulting from a factor of 4 increase in recording rate is shown as the bold vertical line in the lower left. Increases in recording rates to 1 Gb/s, 4 Gb/s and 16 Gb/s are foreseen over the next 10 years - a net sensitivity increase of $\times 8$.

- Higher frequency windows allow study of new astronomical maser transitions.

The first ad-hoc 3mm wavelength VLBI observations were carried out in the early 1980's (Readhead et al. 1984), with the CMVA (Coordinated mm-VLBI Array) forming in 1996 to facilitate worldwide observations in the 3mm band. The VLBA then expanded its operations to include 3mm band observations in 2000 using a subset of its 10 antennas, and has continued to add more antennas: 8 currently have 3mm receivers. At higher frequencies, recent experiments at 129, 147 and 230 GHz have obtained VLBI fringes on long (8000km) baselines yielding fringe spacings of $\sim 34\mu$as (Krichbaum et al. 2002, Doeleman et al. 2003).

Until recently, high detection thresholds on existing global arrays restricted 86 GHz VLBI observations to the brightest AGNs. New high bandwidth VLBI recording systems coupled with planned large mm/sub-mm apertures will address this historic difficulty and significantly expand the role of mm/sub-mm VLBI in a number of important scientific investigations over the next decade. A baseline between the LMT and GBT, for example, will have sufficient collecting area to lower the current best 86 GHz detection thresholds by over a factor of 4. With a recording rate of 10 Gb/s, an LMT-ALMA baseline will have a detection threshold of 8 mJy in 10 seconds at 230 GHz, a factor of 50 below the current best 230 GHz limits.

The extension of VLBI to frequencies above 43 GHz presents difficult technical challenges. Atmospheric turbulence often sets the coherent averaging time to intervals below 20 seconds with correspondingly high detection thresholds. High frequency observations are also more sensitive to phase noise in station electronics and to the frequency stability of hydrogen maser references. At an observing frequency of 450 GHz, for example, typical H-masers will cause a VLBI signal loss of $\sim 50\%$ in a 10 second average. In addition, most mm and sub-mm single dish facilities do not have VLBI quality station electronics, and they require low noise, high stability frequency references to be temporarily patched in for VLBI observations. On the other hand, mm arrays have stable electronics, but when used as VLBI elements the antenna signals must be coherently summed prior to VLBI recording.

Bandwidth and collecting area increases will lower detection thresholds set by atmospheric coherence times at high frequencies. And use of Water Vapor Radiometers (WVRs) at all mm/sub-mm VLBI sites can provide a means of partially correcting VLBI data for atmospheric induced phase fluctuations, thereby increasing effective coherence times (Tahmoush & Rogers 2000). An important point to note is that sensitive baselines involving large apertures can effectively 'phase up' a VLBI array that includes smaller dishes. All baselines to the large aperture provide station-based fringe corrections that allow baselines connecting smaller dishes to integrate well beyond the coherence time that would normally be imposed by the atmosphere. At the very highest VLBI frequencies (450 GHz and above), new frequency standards will be required with greater stability than current Hydrogen masers.

At 86 GHz, VLBA performance is currently limited by a combination of pointing errors, antenna efficiency, polarization purity, atmospheric coherence, and bandwidth limitation.

- RMS pointing errors are $\sim$ 7 arcsec under optimal conditions resulting in gain errors at the 20% level. An enhanced continuum total power capability for the VLBA dishes would allow pointing offsets to be measured more quickly and on fainter sources. Current total power measurements use a 16 MHz BW, but 500 MHz is available.

- The average VLBA dish efficiency is near $\sim 13\%$ due to dish panel mis-alignment and sub-reflector deformation. On most VLBA dishes these problems can be addressed with sub-reflector resurfacing and panel adjustments guided by holography measurements and brought to the 20-25% level.

- To reduce the relatively large polarization leakage (only $\sim$ 10 dB isolation between R and L channels now), remanufacturing of the 86 GHz septum polarizers would be required.

- Exploration into outfitting VLBA sites with WVR units could lead to increased coherence times. Another possibility is to enable dual frequency 22 GHz/86 GHz recording to phase correct high frequency data with higher signal to noise data at the lower frequency.

In addition to the above 86 GHz improvements, planned VLBA receiver enhancements at both 22 and 43 GHz will boost sensitivity in these bands by a factor of ~ 1.4. Estimated costs for some of these improvements are given in Section 4.5. Table 4.3 shows how the sensitivity of high frequency VLBI arrays will evolve as bandwidths increase and planned mm/sub-mm apertures become available. High bandwidth VLBI backends for these new facilities will have to be procured.

Table 4.3: Potential map rms noise for mm wavelength VLBI arrays using future large apertures at 16 Gb/s recording rates for a 6 hour integration. The rms is given in units of microJy/beam.

Band GHz	Array	map rms microJy/beam	resolution microarcsec
43	VLBA + GBT + ALMA	4.5	150
86	VLBA + GBT + LMT + ALMA + CARMA	7	80
230	SMA + LMT + CARMA + ALMA + SMT	15	30

4.3 Global VLBI Issues

The national effort in VLBI science and techniques is dominated by NRAO and the VLBA. VLBI is, however, a global endeavor, and the VLBA is scientifically and technically complementary to other VLBI facilities, both inside and outside the US. There are vital benefits to the US astronomical community in making sure that interoperability of VLBA and outside systems is maintained, and that significant resources continue to be allocated toward VLBA participation in the global VLBI effort.

Current technical strengths of the VLBA relative to non-VLBA assets here and abroad include superior image fidelity and usability with more streamlined data analysis, access to a wider variety of observing modes (e.g., monitoring, or rapid frequency switching), and overall flexibility. Observing time on the dedicated VLBA is also several times more abundant than on the ad-hoc global arrays.

EVN facilities currently enjoy the benefit of large physical collecting areas, and more modern recording systems capable of wider bandwidth, which combined translate to higher sensitivity. The list of radio astronomy facilities in the US, or in which the US has significant ownership, is both substantial and growing. At centimeter wavelengths, the VLA, GBT and Arecibo are currently operational. During the coming decade, the Allen Telescope Array (ATA) will come on line with collecting area to rival the VLA, while the VLA itself will be upgraded to the EVLA. Combined, these facilities represent many times the collecting area of the VLBA (but do not, by themselves, constitute a high fidelity imaging VLBI array).

It is essential to recognize that the scientific breadth and potential of both classes of facility (VLBA and non-VLBA) together significantly outweigh that of either on its own. In particular, participation of the VLBA in global experiments typically improves the imaging properties of the array dramatically, despite the modest contribution of the VLBA antennas to overall sensitivity. Often, this improvement is due to information provided by the numerous and well-placed VLBA baselines which permit more reliable and unambiguous mapping of relatively bright, yet complex structure, thereby boosting dynamic range and effective sensitivity of the full array. For this and other reasons, VLBI science is clearly best served by a balanced approach.

The US effort in VLBI should continue to be inclusive, with support for global experiments, and specifically, comprehensive support for VLBI using large non-VLBA US telescopes. This support needs to cover the full life cycle of VLBI investigations, not just telescope and correlator time. In particular, convenient user-friendly software that facilitates inclusion of non-VLBA telescopes in experiments should be a high priority, and its development should be coordinated with foreign colleagues.

The emerging field of mm-VLBI should be supported, and as the European community moves forward, the U.S. community should invest the resources required to bring 86 GHz VLBA operations up to their potential. This will become increasingly important in conjunction with the bandwidth upgrades simultaneously recommended by the Committee. Commissioning of 86 GHz operations on the GBT is also a key step in the progression toward a major new scientific capability.

Finally, VLBI at frequencies higher than 86 GHz is anticipated to become a priority during the coming decade. It is vital to coordinate the activities of the US VLBI community, including NRAO and VLBA resources, with the steps necessary to enable short wavelength VLBI. These activities involve preparing the LMT, CARMA, SMA, and ALMA for VLBI operations, with wideband recording equipment, appropriate LO systems, and mechanisms for time allocation and coordination in VLBI observing sessions.

4.4 Software

As with many modern techniques and instruments, software is absolutely vital to obtaining scientific results with VLBI and the VLBA. Calibration of most VLBI data is carried out within AIPS. A large number of tasks are executed in sequence to perform correlator corrections, *a-priori* amplitude calibration, parallactic angle corrections, ionospheric corrections, clock corrections, and polarization calibration. These tasks and a step-by-step guide to their use are documented in the AIPS Cookbook. The AIPS group at NRAO consists of 3 scientific programmers (∼2 FTE), a scientist who develops the pipeline and VLBA archive (0.5 FTE), a fraction of a scientist/manager (0.1 FTE) and a systems support person (0.2 FTE). Much of this effort is VLBI-related. The total effort is at the level of ∼3 FTE. However, in addition to supporting the VLBA, the small AIPS group supports the reduction of VLA data, as well as an average of 10 new installations worldwide each week. Direct, VLBI-related code development and maintenance is at a low level in terms of staffing.

NRAO has invested much effort in aips++, with the current intent that this modern software package be used for future NRAO instruments such as ALMA and the EVLA. Unfortunately, aips++ has not delivered significant functionality for VLBI, and none is planned in the near term. It remains unclear whether aips++ will become useful for VLBI in the longer term.

Since all interactions of the astronomer with their data proceed through the software tools available, development and maintenance of software and accompanying documentation is of critical importance. Thanks to heroic efforts in the AIPS group, the majority of VLBA observations can be reliably processed using a few scripts, or a calibration pipeline. However, the Committee received consistent input from a significant number of community members, as well as from individuals serving on the Committee itself, that the current state of VLBI-related software leaves much to be desired. For experiments which include non-VLBA telescopes, experiments which attempt non-standard observing or correlation modes, or experiments which are affected by data errors of various kinds, the full complexity of VLBI is made visible to the investigator. The overwhelming majority of respondents to our community survey regard collaboration with an expert as the best way to utilize VLBI. The Committee regards the current state of VLBI-related software and documentation as a continuing impediment to access by a broader, non-specialist community.

The resulting priority and Committee recommendation is clear. To prepare VLBI in the US for the coming increases in capabilities, and to make it suitable for integrating the technique into the mainstream of modern astronomy, a major increase in software development effort is urgently needed. Without such effort, much of the potential scientific return from VLBI will be endangered or lost, and the overall health of both US and global VLBI will be impaired. The required investment in software resources represents a tiny fraction of the VLBA capital investment, and a small fraction of the current VLBA operational budget.

Specifically, the Committee recommends that NSF and the NRAO devise a means to allocate additional resources at an appropriate level (estimated by the Committee at 3 to 5 full-time people), to create an improved end-to-end user-friendly VLBI software system over the next 5 years. This system, which may or may not be based on existing packages, should seamlessly accommodate experiments using non-VLBA telescopes, as such experiments are an integral part of the present and future US VLBI effort. The software efforts should be carried out in cooperation with VLBI software development efforts in Europe to avoid redundancy and maximize the benefit for all users.

To this end, we suggest that a study group be formed to determine priorities for VLBI software functionality, and to define the scope and detailed mission of a new software effort dedicated to user support of VLBI. This study group should comprise both expert observers and analysts with broad experience in VLBI techniques.

4.5 Roadmap for the Future

The previous subsections highlight the prospects for availability of technical improvements to VLBI capabilities during the coming decade. Few if any of these improvements can be accomplished without expenditure of resources. In this chapter we propose a phased approach to the implementation of key improvements, in a manner and at a cost that is commensurate with the scientific value to be gained, and with the appropriate and effective use of the research infrastructure already in place. We consider the software effort recommended in the previous subsection as a separate, ongoing investment in the technique, and in this subsection we concentrate on hardware capabilities.

The costs and timescales below were assembled from presentations to the committee by external experts, and while necessarily approximate, are considered to be generally reliable. More detailed studies of the actual material expenses and manpower costs will be needed as well as an implementation plan developed in concert with the appropriate funding agencies. The quoted timescales are based on projections of technical readiness, and the Committee's views on appropriate scientific return on investment, but are of course subject to decisions by funding agencies.

We recommend three phases of development, lasting 2, 3, and 4 years, respectively. Assuming the proposed activities begin in FY2005, and end in FY2013, then Phase I corresponds to FY2005-2006, Phase II to FY2007-FY2009, and Phase III to FY2010-FY2013.

Phase I

The priority during this period should be to migrate the VLBA from tape-based recording to Mark 5 disk-based recording, as fast as possible. There are sound reasons for the urgency in this effort.

- Disk-based recording offers substantial savings in VLBA operational costs when operated at current bandwidths. These savings come from elimination of high maintenance costs for VLBA tape drive units in both personnel and materials.
- Disk-based recording will increase the sustainable bandwidth on the VLBA, with attendant sensitivity gains. These gains will provide a valuable immediate boost to VLBA science. The goal during this period should be sustainable 1 Gb/s operation.
- Starting in 2004, the VLBA will be the only VLBI facility in the world still using tape. As the premier VLBI instrument in the world, this is a regrettable situation that will reduce global capabilities as the various correlators decommission their tape drives. The duration of such a situation should be aggressively minimized.

The total hardware and media investment to switch the VLBA to modern disk-based recording systems at 1 Gb/s is on the order of $3M, and will not involve any modifications to the existing receiver and downconversion electronics. We believe it is unwise to wait for uncertain NASA funding related to spacecraft tracking in order to implement this needed upgrade to the VLBA.

During Phase I, it is also recommended that both Arecibo and the GBT be equipped with state-of-the-art disk-based recording systems. These large apertures are the most sensitive dishes in the world, and as such are uniquely valuable US-based VLBI resources. Leveraging these resources to the maximum extent, and at nominal cost, is clearly indicated. These facilities should be encouraged to continue and expand their participation in scientifically valuable, high sensitivity experiments.

The steps to increase high frequency capabilities at the VLBA as detailed in Section 4.2 should also be implemented in this phase:

- Subreflector modifications to increase dish efficiency, modifications to the 86 GHz septum polarizers, and 22 and 43 GHz receiver enhancements to increase sensitivity: $800K.
- Investigation of WVR and dual-frequency observations: $(to be determined).

Phase II

During this phase, the Committee recommends investment in the expansion of VLBI capabilities on two fronts.

- Disk-based recording bandwidths should be increased to the 4-16 Gb/s range by cost-effective exploitation of progress in commercial technologies. The WIDAR correlator at the EVLA should replace the VLBA correlator, and operations of the VLA and VLBA should be merged. The second phase of the EVLA, the New Mexico Array (NMA), with an addition of 8 new antennas, will blur the distinction between the VLA and the VLBA and eventually lead to a single instrument that can be optimally apportioned to maximize the scientific return.

  The cost estimates for broadbanding the VLBA to 16 Gb/s would include: $4M for LO/IF modifications to station electronics, $2M for upgrading the S, C and X band VLBA receivers to new EVLA receivers with higher bandwidths, and $3M for the next generation disk based recording system capable of 4-16 Gb/s rates (includes media). No funds would be required for correlation as the planned EVLA correlator will have sufficient extra capacity to correlate all VLBA baselines. Total cost: $9M.

- Simultaneously, VLBI at millimeter wavelengths should be aggressively implemented, via installation of recording systems and frequency standards, at emerging new telescopes such as LMT, CARMA, SMA, and the first ALMA dishes. The emerging, powerful new mm-VLBI array should be managed as a single entity with the cooperation of participating observatories, and with convenient community access.

  To bring a new VLBI station on line in this phase will require: a hydrogen maser ($175K), a new disk-based recording system capable of 4-16 Gb/s ($20K), digital base band converters for 1-4 GHz bandwidths ($50K - $200K), for a total of $245K - $395K. Some of the sites expected to participate in high frequency VLBI already have H-masers and could upgrade to high bandwidth systems for much less.

These capabilities will require significant financial resources, but in return yield major new instrumental capabilities that can be expected to produce important and valuable scientific returns, as previously discussed.

During this phase, both US and global technology development efforts related to the Square Kilometer Array (SKA) may be expected to start bearing fruit, for example in the form of advanced data transport techniques over commercial networks. It is also likely that prototypes of SKA antenna systems, of substantial scope and of interest for inclusion in VLBI arrays, will be appearing. The US VLBI community should maintain close links with the SKA community, and exploit opportunities of mutual benefit.

Phase III

The emphasis in this phase, based on current projections, should be on a transition from recording systems to direct fiber links, accompanied by continued emphasis on bandwidth expansion (perhaps to as high as 64 Gb/s systems). Also during this phase, plans for the SKA will be solidifying. Sometime during the next decade, we anticipate that the distinction between VLBI and connected-element instruments will vanish, first due to integration of the VLBA and EVLA, and later due to the advent of the SKA. Tight integration with SKA technologies and facilities should be pursued. In the long term, the goal should be to maximize the scientific utility of existing telescopes and VLBI infrastructure within a global instrument based on SKA technology, or derived from SKA development efforts.

Table 4.4 provides a summary of the roadmap and the science that will be enabled by each phase. Table 4.5 provides a list of the scientific topics discussed in Chapter 3, numbered according to section, 1-7, and shows what the critical enhancements are to enable each line of investigation.

Table 4.4: Summary of Recommendations

Goal	Implementation	Rough Cost*	Phase	Science
Larger Bandwidth	Mark5 Recording at VLBA	$3M	I	1-8c, 8e-f
	broadband VLBA receivers	$9M	II	1-8c, 8e-f
	expand correlator + fiber		III	All
Larger Aperture	equip Arecibo & GBT	$200k	I	3,4,5,6,8
High Frequency/Resolution	VLBA 22-86 GHz upgrade	$800k	I	1,4,8d
	new mm VLBI systems	$245-395k ea	II	1,4,8d
Improve Software	3-5 FTE for 5 years	$300-500k/yr	I,II	All
Improve Community (Chap.5)	Graduate Student Funding	$200k/yr	All	All

* These costs are estimates based on expert external input to the Committee. An actual implementation will require a thorough plan and complete accounting.

Table 4.5: Impact on Science. In cases where the benefit is modest we mark these with a '+', and where it is critical to the science we mark it with an 'X'.

Science	Larger Bandwidth	Larger Aperture	High Frequency	Better Correlator
1. Imaging a massive black hole	X	+	X	+
2. Gravitational lenses	X	X	+	+
3. Supernova factories	X	X		+
4. Launching AGN jets	X	X	X	+
5. Proper motions in the galaxy & group	X	X	+	+
6. Magnetism in stars	X	X	X	+
7. Identifying sources of gravitational rad.	X	+	+	+
8a. Deep fields	X	+	+	X
8b. Prompt emission from SNe and GRBs	X	+	+	+
8c. Low power AGN	X	X	+	+
8d. Molecular masers	+	+	X	+
8e. AGN environments	X	X	+	+
8f. Fine structure constant	+	X	+	+

Chapter 5

Human Resources

In order to remain scientifically vibrant, any field needs both leadership from active senior researchers as well as a steady infusion of young talent. There is a general feeling within the astronomical community that VLBI in the US is thin in both areas. In particular, there is not enough VLBI research based at universities.

Historically, this situation can be traced to planning problems and inaccurate projections during the latter stages of VLBA construction, and subsequent resource restrictions. The National Science Foundation support of the university observatories and VLBI network correlator was withdrawn more than two years before the VLBA became fully operational. In addition, the universities were only weakly involved in instrumentation for the VLBA, and opportunities—as well as financial support–for students to work on VLBI-related PhD theses were limited, despite the tremendous growth in scientific opportunity made possible by the VLBA. The completion of the VLBA at the beginning of 1995 was not accompanied by sufficient financial support for individual research grants by the NSF. In that year, only three VLBA-related grants were awarded. A major emphasis on funding VLBA research would have been appropriate in an effort to stimulate inventive projects using NRAO's new instrument. Yet, in 1996 and 1997, the situation worsened, with NSF awarding only one grant that concentrated on VLBA studies and another two with minor VLBI components. Two senior members of the community have commented that their proposals were rejected despite excellent reviews; hence, the quality of the VLBA-based funding proposals seems not to have been the underlying problem. The situation did improve slightly in subsequent years, but an analysis of publicly available (but not necessarily complete) information from the NSF website indicates that only a few percent of NSF astronomy research grants supported VLBI research between 1995 and 2003.

The majority of VLBI scientists are employed at research centers such as NRAO, USNO, NRL, NASA (JPL and GSFC), CfA, and Haystack. This has been partly responsible for the dearth of VLBI researchers at US universities: a number of the scientific staff at the research institutes have the outstanding records and teaching abilities that would have made them highly competitive were they to have sought faculty positions. On the other hand, several junior astronomers engaged in VLBI research have recently obtained faculty positions. This demonstrates the attractiveness of VLBI science in the intellectual marketplace, and suggests that funds targeted toward support of graduate students doing VLBI research would stimulate growth of the university-based VLBI community. The funding could be in the form of one or more of the following:

- Support of graduate-student stipends, travel, page charges, and limited tuition costs when VLBA time is awarded for research that will form a major part of the student's PhD thesis.
- NSF or NRAO graduate fellowships for VLBI research.
- Partial funding of NSF proposals for VLBI research that are ranked just below the full-funding level, such that they are adequate to support a graduate student.

There is a notable contrast between the NASA and NSF style of supporting observational research. At NASA, awards of observing time are accompanied by funds to carry out the research. The same model could be used for ground-based programs. However, this model would need adequate funding beyond the current level of support for individual NSF research grants, since the latter provide more comprehensive and longer-term support for research groups.

The majority of US astronomers that consider themselves members of the VLBI community perform the bulk of their work in the radio domain. An increasing portion of astronomical research, on the other hand, is tending toward panchromatic observations. The VLBI research centers, most notably NRAO, should encourage these multiwaveband astronomers to become involved in the ongoing development of VLBI. This includes participation in the review of observing proposals and membership on the NRAO Users Committee, Visitors Committee, and VLA/VLBA Scheduling Committee. The Committee acknowledges that this has occurred to some extent in the past, but believes that more emphasis on the involvement of panchromatic astronomers is necessary. In addition, NRAO needs to make the VLBA as easy to use as an optical or X-ray telescope. This requires modern software for scheduling the observations, reducing the data, and making images—not just for total intensity imaging of bright sources at centimeter wavelengths, but also for faint sources, polarized intensity imaging, spectral-line projects, and millimeter wavelengths.

Bibliography

Antonucci, R. R. J., & Miller, J. S. 1985, ApJ 297, 621.

Balick, B. & Brown, R. L. 1974, ApJ, 194, 265

Ballo, L., Braito, V., Della Ceca, R., Maraschi, L., Tavecchio, F., & Dadina, M. 2004, ApJ, 600, 634

Beasley, A. J. & Güdel, M. 2000, ApJ, 529, 961

Begelman, M. C., Blandford, R. D., & Rees, M. J. 1980, Nature, 287, 307

Berger, E. et al. 2001, Nature, 410, 338

Berger, E. 2002, ApJ, 572, 503

Biggs, A. 2004, in Future Directions in High Resolution Astronomy eds. Romney & Reid.

Bietenholz, M. F., Bartel, N., & Rupen, M. P. 2001, ApJ, 557, 770

Bietenholz, M. F., Bartel, N., & Rupen, M. P. 2003, ApJ, 597, 374

Boller, T., Keil, R., Trümper, J., O'Brien, P. T., Reeves, J., & Page, M. 2001, A&A, 365, L146

Bower, G. C. & Backer, D. C. 1998, ApJ, 496, L97

Bower, G. C., Falcke, H., Herrnstein, R. M., Zhao, J., Goss, W. M., & Backer, D. C. 2004, Science, 304, 704

Brisken, W. et al. 2002, ApJ, 571, 906

Brunthaler, A., Reid, M., Falcke, H., Greenhill, L.J., & Henkel, C. 2002, Proceedings of the 6th EVN Symposium, eds. Ros et al.

Brunthaler, A., et al. 2004, in preparation

Burke, W. L. 1981, ApJ, 244, L1

Caputo, F., Marconi, M., & Musella, I. 2002, ApJ, 566, 833

Cecil, G., et al. 2000, Ap.J., 536, 675

Chatterjee, S., Cordes, J. M., Lazio, T. J. W., Goss, W. M., Fomalont, E. B., & Benson, J. M. 2001, ApJ, 550, 287

Chatterjee, S., et al. 2004, ApJ, 604, 339

Cohen, M. H., Cannon, W., Purcell, G. H., Shaffer, D. B., Broderick, J. J., Kellermann, K. I., & Jauncey, D. L. 1971, ApJ, 170, 207

Dalal, N. & Kochanek, C. S. 2002, ApJ, 572, 25

De Paolis, F., Ingrosso, G., Nucita, A. A., & Zakharov, A. F. 2003, A&A, 410, 741

Diamond, P., Lonsdale, C.J., Smith, H.E., & Lonsdale, C.J. 2004, in Future Directions in High Resolution Astronomy eds. Romney & Reid.

Doeleman, S. S. et al. 2001, AJ, 121, 2610

Doeleman, S. S. et al. 2003, in Future Directions in High Resolution Astronomy eds. Romney & Reid.

Evans, N. W. & Hunter, C. 2002, ApJ, 575, 68

Falcke, H., Melia, F., & Agol, E. 2000, American Institute of Physics Conference Series, 522, 317

Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9

Field, G.B. (Ed), "Astronomy and Astrophysics for the 1980s", Vol 1: Report of the Astronomy Survey Committee, National Research Council, Washington, National Academy Press, 1982.

Fomalont, E. B., & Kopeikin, S. M. 2003, ApJ, 598, 704

Freedman, W. L., et al. 2001, ApJ, 553, 47

Gallimore, J. F., Baum, S. A., & O'Dea, C. P. 1997, Nature, 388, 852

Gallimore, J. F. & Beswick, R. 2004, AJ, 127, 239

Gebhardt, K., et al. 2000, ApJ, 539, L13

Ghez, A. M., et al. 2003, ApJ, 586, L127

Gower, A. C., Gregory, P. C., Unruh, W. G., & Hutchings, J. B. 1982, ApJ, 262, 478

Greenhill, L. J., Chandler, C. J., Reid, M. J., Diamond, P. J., & Moran, J. M. 2004, Proc. IAU Symp. 221

Greenhill, L. 2004, in Future Directions in High Resolution Astronomy eds. Romney & Reid.

Guedel, M. 2002, ARA&A, 40, 217

Herrnstein, J. R., Greenhill, L. J., & Moran, J. M. 1996, ApJ, 468, L17

Herrnstein, J. R., et al. 1999, Nature, 400, 539

Junor, W., Biretta, J. A., & Livio, M. 1999, Nature, 401, 891

Keeton, C. R. 2003, ApJ, 582, 17

Kellermann, K. I., & Moran, J. M. 2001, ARAA, 39, 457

Komossa, S., Burwitz, V., Hasinger, G., Predehl, P., Kaastra, J. S., & Ikebe, Y. 2003, ApJ, 582, L15

Koopmans, L. V. E., Garrett, M. A., Blandford, R. D., Lawrence, C. R., Patnaik, A. R., & Porcas, R. W. 2002, MNRAS, 334, 39

Krichbaum, T. K. et al. 1998, A&A, 335, L106

Krichbaum, T.K. et al., 2002, 6th European VLBI Network Symposium on New Developments in VLBI Science and Technology, held in Bonn, June 25th-28th 2002, eds. E. Ros, R. W. Porcas, A. P. Lobanov, & J. A. Zensus, Max-Planck-Institut fuer Radioastronomie (Bonn), p. 125

Lebach, D. E., Corey, B. E., Shapiro, I. I., Ratner, M. I., Webber, J. C., Rogers, A. E. E., Davis, J. L., & Herring, T. A. 1995, Physical Review Letters, 75, 1439

Ly, C., Walker, R. C., & Wrobel, J. M. 2004, AJ, 127, 119

Lynden-Bell, D. 1969, Nature, 223, 690

Maness, H. L., Taylor, G. B., Zavala, R. T., Peck, A. B., & Pollack, L. K. 2004, ApJ, 602, 123

Mao, S., Witt, H. J., & Koopmans, L. V. E. 2001, MNRAS, 323, 301

Marlow, D. R., et al. 1999, AJ, 118, 654

McKee, C. F., Taylor, J. H., et al. 2001, *Astronomy and Astrophysics in the New Millennium*, National Research Council, National Academies Press, Washington, DC

Meier, D. L., Koide, S., & Uchida, Y. 2001, Science, 291, 84

Menten, K. M. & Reid, M. J. 1995, ApJ, 445, L157

Merritt, D., & Ekers, R. D. 2002, Science, 297, 1310

Metcalf, R. B. 2002, ApJ, 580, 696

Miyoshi, M. et al. 1995, Nature, 373, 127

Moran, J. M., Greenhill, L. J., & Herrnstein, J. R. 1999, ApA, 20, 165

Narasimha, D., Subramanian, K., & Chitre, S. M. 1986, Nature, 321, 45

Neff, Ulvestad, & Teng 2004, submitted

Newman, J. A., et al. 2001, ApJ 553, 562

Plambeck, R. L., Wright, M. C. H., Mundy, L. G., & Looney, L. W. 1995, ApJ, 455, L189

Readhead, A.C.S., & Wilkinson, P.N. 1978, ApJ, 223, 25

Readhead, A.C.S. et al. 1984, Nature, 303, 504

Reid, M. J. 2004, in preparation

Reid, M. J. & Brunthaler, A. 2004, ApJ, submitted

Ribo, M. 2004, in Future Directions in High Resolution Astronomy eds. Romney & Reid.

Rusin, D. & Ma, C. 2001, ApJ, 549, L33

Rusin, D. 2002, ApJ, 572, 705

Salpeter, E.E. 1964, ApJ, 140, 796

Schödel, R., et al. 2002, Nature, 419, 694

Shaya, E. J., Borne, K. D., Nusser, A., Peebles, P. J. E., Tonry, J., Tully, B. R., Vogel, S., & Zaritsky, D. 2002, Science with the Space Interferometry Mission, 27

Smith, H. E., Lonsdale, C. J., Lonsdale, C. J., & Diamond, P. J. 1998, ApJL, 493, L17

Tahmoush, D.A. & Rogers, A.E.E., 2000, Radio Science, 35, 1241

Taylor, G. B., Frail, D. A., Berger, E., & Kulkarni., S. R. 2004, ApJL, in press

Turner, M.S. et al. 2003, *Connecting Quarks with the Cosmos*, National Research Council, National Academies Press, Washington, DC

van Maanen, A. 1923, ApJ, 57, 264

Vlahakis, N., & Königl, A. 2004, ApJ, 605, 656

Walker, R. C., Dhawan, V., Romney, J. D., Kellermann, K. I., & Vermeulen, R. C. 2000, ApJ, 530, 233

Wambsganss, J. & Paczynski, B. 1992, ApJ, 397, L1

Whitney, A.R. et al. 1971, Science, 173, 225

Winn, J. N., Rusin, D., & Kochanek, C. S. 2004, Nature, 427, 613

Appendix A

The Charge

May 30, 2003

The Directors of the NRAO and the MIT Haystack Observatory have decided to convene a committee made up of members of their staffs and representatives of the US astronomical community to consider the scientific future of VLBI in the US. With emphasis on ground-based VLBI, the Committee will map a science and technology plan for the next decade.

In particular, the following three main objectives are to be addressed:

(1) Develop the future science vision and identify in what areas VLBI investigations can continue to make significant contributions to key problems in astronomy and astrophysics. Linkages to other scientific areas such as astrometry, geodesy, navigation etc. are to be considered.

(2) Investigate what technical developments in VLBI systems need to be pursued, particularly those that exploit emerging technologies, in order to accomplish the scientific goals. Examples may include enhanced sensitivity through larger telescopes and wider bandwidth, increased resolution, exploration of the frontier at short millimeter wavelengths, and improved efficiency of operations through the application of modern information technology.

(3) Review the issues of US VLBI demographics and US scientific leadership within the international community partnerships. In particular, identify what aspects of the discipline are in need of special attention in the US. Examples may include training of students, involvement of university-based groups, and expanded user base.

The Committee will be co-chaired by Colin Lonsdale (Haystack Observatory) and Greg Taylor (NRAO). The Committee should complete its study in roughly three months, starting in mid-June 2003, and produce a brief report on its findings and recommendations. It is anticipated that, following review, the report will be released to the NSF and to the community at large.

Joseph Salah, Director, Haystack Observatory
Fred Lo, Director, NRAO
Jim Ulvestad, Assistant Director, VLA/VLBA Operations

Appendix B

Survey Results

The Committee sent questionnaires to 47 individuals, selected to represent a broad range of astronomical science. Information was requested regarding the expertise of the individual, and regarding their opinions on the current state of VLBI in the US. In addition, respondents were encouraged to provide any additional information, opinions and insights they may have. Useful responses were obtained from 20 people. Below is a matrix which gives a count of the number of respondents who considered themselves active in each combination of technique and scientific field.

It can readily be seen from this matrix that our 20 respondents sample a fairly broad cross-section of the astronomical community. We therefore took their collective input to be representative of the broad community in our analysis, conclusions and recommendations.

	Solar System	Stars and evol.	SNe & pulsars	ISM	Normal galaxies	Active galaxies	Large Scale Struct.	CMB	Cosmo-logy	Other
VLBI	2	6	2	2	1	8			2	4
Single dish radio	1	3	2	1		3				
VLA/MERLIN/ATCA	1	6	1	3	3	8			1	2
Infrared		1		1	1	4			1	1
Optical		4		1	2	7	1		1	
UV		1				3				
X-ray		3	1	1	2	8	1		1	1
Gamma-ray		2	1			4				2
Computer modeling		2	1		1	6	1		1	2
Theory	1	1	3	3	1	8	3	1	2	4

Respondents were asked the following four questions.

1. Do you consider yourself to be familiar with the VLBI technique, its capabilities and scientific contributions? All but one of the respondents answered in the affirmative.

2. Do you now use, or have you in the past used, the VLBI results of others to enhance or motivate your work? Responses were unanimously positive.

3. If there were ready availability of graduate student support or other financial support for VLBI research, would it make a difference to the likelihood of you doing such research? Two thirds of respondents indicated that it would make some difference. The remainder were evenly split between no difference and a big difference.

4. If you wanted to do VLBI observing and did not know how, how would you go about it?

Among the choices of learning how, using VLBA and NRAO support, or getting an expert collaborator, almost all respondents indicated that an expert collaborator was preferred.

The many detailed remarks and responses generated by the survey, as well as many unsolicited comments and suggestions from individuals not targeted by the survey, were collected together and considered as an ensemble by the Committee in its deliberations.

Appendix C

Acknowledgements

The Committee expresses it appreciation to the following individuals who provided information and/or attended the open meetings:

Eric Agol, California Institute of Technology, CA
Hugh Aller, University of Michigan, MI
James Anderson, New Mexico Tech, NM
Ski Antonucci, University of California, Santa Barbara, CA
Michell Begelman, University of Colorado, CO
Edo Berger, California Institute of Technology, CA
David Boboltz, United States Naval Observatory, DC
Alan Bridle, National Radio Astronomy Observatory, VA
Walter Brisken, National Radio Astronomy Observatory, NM
Shami Chatterjee, National Radio Astronomy Observatory, NM
Mark Claussen, National Radio Astronomy Observatory, NM
Judy Cohen, California Institute of Technology, CA
Ruth Daly, Pennsylvania State University, PA
Jeremy Darling, Carnegie Observatories, CA
Vivek Dhawan, National Radio Astronomy Observatory, NM
Steve Durand, National Radio Astronomy Observatory, NM
Jean Eilek, New Mexico Tech, NM
Martin Elvis, Harvard-Smithsonian Center for Astrophysics, MA
Eric Feigelson, Pennsylvania State University, PA
Alan Fey, United States Naval Observatory, DC
Dave Finley, National Radio Astronomy Observatory, NM
William Forrest, University of Rochester, NY
Robert Fritzius, MS
Jack Gallimore, Bucknell University, PA
Ralph Gaume, United States Naval Observatory, DC
Miller Goss, National Radio Astronomy Observatory, NM
Paul Green, Harvard-Smithsonian Center for Astrophysics, MA
Lincoln Greenhill, Harvard-Smithsonian Center for Astrophysics, MA
Manuel Guedel, Paul Scherrer Institut, Switzerland
Philip Hardee, University of Alabama, AL

Graham Harper, University of Colorado, CO
Ed Himwich, Goddard Space Flight Center, DC
Luis Ho, Carnegie Observatories, CA
Ian Hoffman, University of New Mexico, NM
Peter Hofner, New Mexico Tech, NM
Liz Humphreys, Harvard-Smithsonian Center for Astrophysics, MA
Ken Johnston, United States Naval Observatory, DC
Dayton Jones, Jet Propulsion Laboratory, CA
Tom Jones, University of Minnesota, MN
Svetlana Jorstad, Boston University, MA
Jeff Kern, New Mexico Tech, NM
Kerry Kingham, United States Naval Observatory, DC
Chris Kochanek, Harvard-Smithsonian Center for Astrophysics, MA
Leonia Kogan, National Radio Astronomy Observatory, NM
Sergei Kopeikin, University of Missouri, MO
Julian Krolik, Johns Hopkins University, MD
Phil Kronberg, Los Alamos National Laboratory, NM
Joe Lazio, Naval Research Laboratory, DC
Jean-Francois Lestrade, Observatoire de Paris, France
Charles Lillie, TRW, CA
Chun Ly, University of Arizona, AZ
Chopo Ma, Goddard Space Flight Center, DC
Kevin Marvel, American Astronomical Society, DC
Julie McEnery, University of Wisconsin, WI
Mark Mckinnon, National Radio Astronomy Observatory, NM
Fulvio Melia, University of Arizona, AZ
Neal Miller, Goddard Space Flight Center, DC
Amy Mioduszewski, National Radio Astronomy Observatory, NM
Felix Mirabel, Commissairat a l'Energie Atomique, France
Maryam Modjaz, Harvard University, MA
George Moellenbrock, National Radio Astronomy Observatory, NM
Warren Moos, Johns Hopkins University, MD
Jim Moran, Harvard-Smithsonian Center for Astrophysics, MA
Steve Myers, National Radio Astronomy Observatory, NM
Peter Napier, National Radio Astronomy Observatory, NM
Frazer Owen, National Radio Astronomy Observatory, NM
Pat Palmer, University of Chicago, IL
Tim Pearson, California Institute of Technology, CA
Peggy Perley, National Radio Astronomy Observatory, NM
Rick Perley, National Radio Astronomy Observatory, NM
Bob Phillips, MIT Haystack Observatory, MA
Sterl Phinney, California Institute of Technology, CA
Ylva Pihlstroem, National Radio Astronomy Observatory, NM
Glenn Piner, Whittier College, CA
Bob Preston, Jet Propulsion Laboratory, CA
Michael Ratner, Harvard-Smithsonian Center for Astrophysics, MA

Tony Readhead, California Institute of Technology, CA
Mark Reid, Harvard-Smithsonian Center for Astrophysics, MA
Kathy Robertson, National Radio Astronomy Observatory, VA
Terry Romero, National Radio Astronomy Observatory, NM
Jon Romney, National Radio Astronomy Observatory, NM
Kris Sellgren, Ohio State University, OH
Lorant Sjouwerman, National Radio Astronomy Observatory, NM
Dick Thompson, National Radio Astronomy Observatory, VA
Jim Ulvestad, National Radio Astronomy Observatory, NM
Steve Unwin, Jet Propulsion Laboratory, CA
Craig Walker, National Radio Astronomy Observatory, NM
John Wardle, Brandies University, MA
Ann Wehrle, Jet Propulsion Laboratory, CA
Alan Whitney, MIT Haystack Observatory, MA
Paul Wiita, Georgia State University, GA
Pam Wolken, Jet Propulsion Laboratory, CA
Bob Woodruff, Boeing-SVS, Inc, CO
Bob Zavala, New Mexico State University, NM
Jun-Hui Zhao, Harvard-Smithsonian Center for Astrophysics, MA

The Committee would like to express a special thanks to Tony Beasley, Roger Blandford, Lincoln Greenhill, Jim Moran, Tim Pearson, Tony Readhead, Mark Reid, Irwin Shapiro and Ed Wollack for providing insightful comments on early drafts of this report. The reviewers were not asked to endorse the conclusions or recommendations of the Committee. The final content of the report is entirely the responsibility of the Committee.

Appendix D

Recent VLBA Scientific Productivity

The Committee considered several metrics in an attempt to measure the scientific productivity of the VLBA. For all years up to and including 2002 there have been a total of 416 refereed publications with the VLBA. Since 1998 the rate has been steady at about 60 publications/year. This is about a factor 3 less than that of the VLA which has produced an average of 173 publications/year over the same period. This difference can be attributed to the longer integration times needed for the VLBA, and the fact that many VLBA projects involve multiple epochs to see how sources change with time. Another metric worth considering is the 34 PhD theses carried out worldwide to date that have been donated to the NRAO library in which VLBI played a leading role. We also computed the cost/publication ratio for the VLBA over the past three years to be $100k/publication. This value is about three times that for the VLA, but is similar to that for other ground based radio observatories and is a factor ∼6 less than that for HST.

The VLBA publications cover a wide range of topics, and we below list counts of journal keywords for 180 publications in 2000-2002. Journal keywords were unavailable for an additional 15 refereed publications. Compiled by A.K. Robertson, Observatory Librarian, NRAO.

Num.	Journal Keyword
1	Absorption
5	Accretion
5	Accretion Disks
1	Active Galactic Nuclei
1	Addenda
1	Atmospheric Effects
10	Astrometry
1	Astrometry, Galaxies: Active
1	Astrometry, Pulsars: Individual
1	Astrophysical Jets
1	Binaries: Close
1	Black Hole Physics

Num.	Journal Keyword
5	Galaxies: BL Lac Objects: Individual
1	Galaxies: Clusters: General
1	Galaxies: Compact
1	Galaxies: Distances and Redshifts
2	Galaxies: Elliptical and Lenticular
1	Galaxies: Evolution
1	Galaxies: General
47	Galaxies: Individual
12	Galaxies: ISM
55	Galaxies: Jets
5	Galaxies: Kinematics and Dynamics
4	Galaxies: Magnetic Fields

Num.	Journal Keyword
5	BL Lacertae Objects: General
11	BL Lacertae Objects: Individual
1	cD
1	cD Galaxies: Nuclei
3	Circumstellar Matter
1	Cosmology: Dark Matter
4	Cosmology: Distance Scale
15	Cosmology: Gravitational Lensing
1	Cosmology: Observations
1	Errata
1	Extinction
78	Galaxies: Active
5	Galaxies: BL Lacertae Objects: General
2	Gamma Rays: Bursts
3	Gamma Rays: Observations
1	Gamma Rays: Theory
3	Gravitational Lensing
1	Hydrodynamics
1	Infrared: General
1	Instrumentation: Interferometers
1	Instruments
2	ISM: Clouds
1	ISM: Dust
4	ISM: General
1	ISM: H I
4	ISM: H II Regions
9	ISM: Individual
9	ISM: Jets and Outflows
2	ISM: Kinematics and Dynamics
1	ISM: Magnetic Fields
4	ISM: Molecules
2	ISM: Structure
2	ISM: Supernova Remnants
1	Line: Profiles
1	Low-Frequency Variability
1	Magnetic Fields
28	Masers
1	Methods: Data Analysis
1	Methods: Observational
1	Methods: Statistical
1	Plasmas

Num.	Journal Keyword
28	Galaxies: Nuclei
2	Galaxies: Quasars: Absorption Lines
1	Galaxies: Quasars: Emission Lines
19	Galaxies: Quasars: General
23	Galaxies: Quasars: Individual
3	Galaxies: Radio
1	Galaxies: Radio Source: Individual
1	Galaxies: Spiral
3	Galaxies: Starburst
8	Galaxies: Seyfert
5	Galaxies: Structure
1	Galaxy: Center
1	Galaxy: Center, Scattering
1	Radio Sources
2	Radio Sources: General
1	Radio Sources: Variable
1	Relativity
5	Scattering
4	Shock Waves
1	Spacecraft
1	Stars: Activity
5	Stars: AGB and Post-AGB
6	Stars: Binaries: Close
1	Stars: Binaries: General
8	Stars: Circumstellar Matter
2	Stars: Coronae
1	Stars: Evolution
8	Stars: Formation
18	Stars: Individual
1	Stars: Imaging
2	Stars: Magnetic Fields
1	Stars: Mass-Loss
2	Stars: Neutron
2	Stars: Pre-Main-Sequence
3	Stars: Pulsars: General
2	Stars: Pulsars: Individual
1	Stars: Rotation
1	Stars: Supergiants
1	Stars: Supernovae: General
2	Stars: Supernovae: Individual
1	Stars: Variables: General

Num.	Journal Keyword
22	Polarization
1	Positional Data
1	Pulsars: Individual
10	Quasars & Quasars: General
15	Quasars: Individual
9	Radiation Mechanisms: Nonthermal
1	Radiation Mechanisms: Thermal
14	Radio Continuum: General
60	Radio Continuum: Galaxies
4	Radio Continuum: ISM
13	Radio Continuum: Stars
1	Radio Emission Lines
3	Radio Lines: Galaxies
5	Radio Lines: ISM
1	Radio Lines: Stars

Num.	Journal Keyword
2	Stars: Variables: Other
1	Supergiants
1	Supernova Remnants
1	Supernovae: Individual
6	Surveys
4	Techniques: High Angular Resolution
1	Techniques: Image Processing
55	Techniques: Interferometric
1	Techniques: Polarimetric
3	Turbulence
1	VLBI
3	X-Rays: Galaxies
1	X-Rays: Individual
3	X-Rays: Stars

Appendix E

Telescope Sensitivities

Table E.1: System Equivalent Flux Density (SEFD) values for selected telescopes worldwide. These values are used to calculate VLBI array image noise levels, and are a good indicator of telescope sensitivity with the lower the number the better. All values are expressed in Jy.

Antenna	0.3/0.6	1.4	2	5	8	15	22	43	86	230 GHz
VLBA	2220	300	322	312	307	550	888	1436	5170	–
Phased VLA	120	17	–	17	15	55	47	61	–	–
GBT	30	10	12	13	13	10	23	200	500	–
Effelsberg	70	20	160	20	20	–	140	600	3000	–
Jodrell MKI	132/83	40	–	–	–	–	–	–	–	–
Jodrell MK2	–	335	–	320	–	–	910	–	–	–
Westerbork	150/90	30	60	60	120	–	–	–	–	–
Arecibo	18	5	6.6	8.3	21	–	–	–	–	–
SMT	–	–	–	–	–	–	–	–	–	15000
CARMA	–	–	–	–	–	–	–	–	1700	2500
LMT	–	–	–	–	–	–	–	–	350	500
SMA	–	–	–	–	–	–	–	–	–	2500
ALMA	–	–	–	–	–	–	–	40	60	100