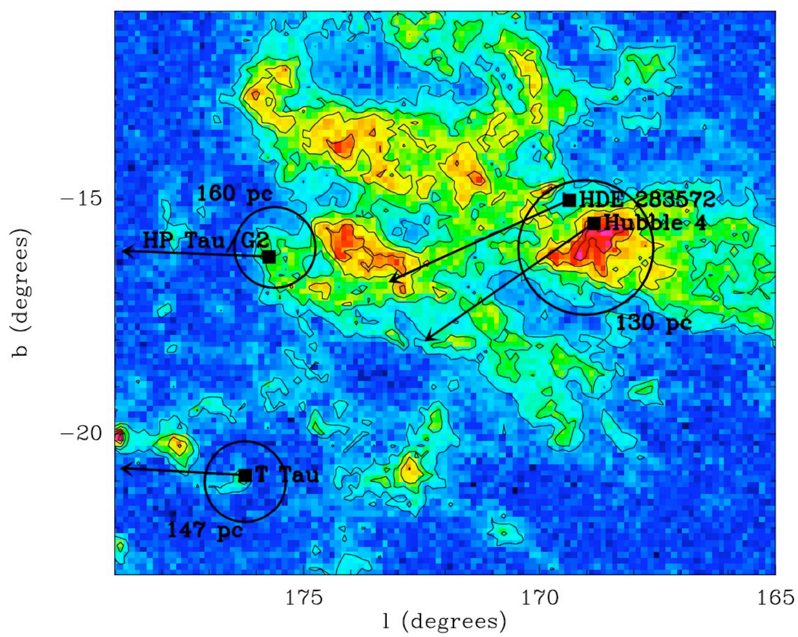
Measuring the Milky Way and the Universe with the VLBA



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1. Summary

The NRAO has established a clear strategic plan (Lo et al., 2009, Astro 2010 position paper, "The Impact of the National Radio Astronomy Observatory") for scientific discovery and technical development in the next decade which leads naturally to a long range vision for radio astronomy. This is one of 5 papers outlining these activities for the Program Prioritization Panel.

The VLBA is the best available astrometric instrument. Recent results have had enormous impact by very accurately measuring the distances to star forming regions and by showing that the mass of the Galaxy has long been underestimated significantly. The program presented here builds on that strength through three technical enhancements designed to improve the astrometric capabilities of the VLBA significantly. They are:

- Replace the original 4.5–5.2 GHz receiver with an EVLA 4–8 GHz system. This receiver will encompass the important 6.7 GHz maser transition of methanol while its 4 GHz bandwidth matches the capabilities provided by the second component:
- Expand the VLBA's signal path to a bandwidth of 4 GHz per polarization, a factor of 8 beyond what will be provided by the upgrade currently under way and a factor of 128 greater than the nominal bandwidth with the current system. This will increase the continuum sensitivity by more than an order of magnitude.
- Add Water Vapor Radiometers (WVRs) to the 22 GHz VLBA receivers. These will used to the increase sensitivity at at high frequency by extending on-source time and to help remove atmospheric gradients when phase referencing.

These upgrades combine synergistically for astrometric parallax and proper motion measurements that are crucial to an understanding of the structure of the Galaxy and of the physics of star forming regions and for improved phase referencing to aid the measurement of H_o to constrain models of dark energy. The 6.7 GHz methanol maser line is a far better marker of massive star formation than anything presently observable with the VLBA. It will allow distances and proper motions to be measured to every high-mass star forming region visible to the VLBA, thereby determining the 3-D structure and dynamics of the Galaxy. The wide bandwidths will allow calibrators about 6 times closer to the target to be used, thereby greatly reducing systematic astrometric errors. They will also allow the observation of ten times weaker sources, expanding significantly the number of stars in regions of low-mass star formation whose distances can be determined precisely. The WVRs will make the use of phase referencing a pracitical technique in the efforts to measure H_0 accurately using water megamasers in AGN. This will remove the flux limits imposed by self-calibration that otherwise preclude study of weak sources, such as those at large distances.

2. Science Case

The activity recommended in this document builds on one of the great strengths of Very Long Baseline Interferometry (VLBI) and, in particular, of the VLBA — the ability to use very precise astrometry to measure distances and transverse motions of objects over large portions of the Galaxy, including in obscured regions not accessible to optical astrometry missions. The requested 4–8 GHz receiver allows observations of what is arguably the best marker to use for such measurements throughout the Galaxy, the 6.7 GHz methanol maser line found in high-mass star forming regions. It also provides adequate bandwidth to take advantage of the large sensitivity increase to be provided by the requested electronics upgrades. The bandwidth upgrade benefits all observations by making weaker target sources and calibrators accessible. The WVRs aid in taking out atmospheric gradients between targets and calibrators that are the major contributor to systematic errors. They also extend the coherence time to increased on-source time while phase referencing at high frequencies. In this section, the astrometric science that drives the details of the upgrade is presented.

With greater continuum sensitivity, it will be possible to use calibrators about 6 times closer to a target, significantly reducing systematic errors that scale with separation. The VLBA can reach 10 microarcsecond (μas) accuracy in relative astrometry now. The proposed enhancement opens the prospect of reaching about 2 μas. The parallax of a source at 10 kpc, which is beyond the Galactic center, is 100 μas. Therefore it will be possible to measure distances throughout the Galaxy with accuracies well under 10%. The increase in sensitivity also increases by a factor of about 30 the number of continuum sources of any particular class that can be detected. Research that currently measures distances to a few nearby sources with great accuracy will be able to reach far into the Galaxy and obtain similar results. The measurement of distance, without which the basic parameters of energy output and size are not known, is absolutely fundamental to all of astronomy. The improved astrometric capability will also allow accurate measurements of the 3-D motions of galaxies in the local group and beyond (1 μas yr^{-1} is 5 km s^{-1} at 1 Mpc), work that has begun but will be greatly enhanced by the upgrades (see Reid et al. 2009a, Astro2010 white paper, "Motions of Galaxies in the Local Group and Beyond").

The program described here is modest in cost compared to large initiatives for the next decade. Still, it can make important contributions in several key Science Frontiers areas. In the study of the Galactic Neighborhood (GAN), the astrometric studies of methanol masers enable a dramatic improvement in our knowledge of the plane of the Galaxy, particularly in the Galactic plane where optical astrometric telescopes encounter problems due to significant dust obscuration. In the study of Planetary Systems and Star Formation (PSF), the precise VLBA astrometry will enable measurements of 1% accuracy to star formation regions within a kiloparsec, as well as detecting reflex motion of M dwarfs hosting planets as small as 0.1

Jupiter masses at distances of 1 AU from the central star. In the study of Cosmology and Fundamental Physics (CFP), VLBA mapping of water megamasers enables measurement of accurate geometric distances to galaxies. For a large enough sample, this enables the estimation of the Hubble constant while meeting the goal of 1% uncertainty, matching the capability of other state-of-the-art techniques in precision observational cosmology. The subsections below contain details of these and other key investigations, with the appropriate Science Frontier areas of Astro2010 marked."

2.1 Structure of the Milky Way and Local Group (GAN)

Laying out the detailed structure of the Milky Way is critical for understanding a host of astrophysical problems. Finding the distances to star-formation regions is required to determine their luminosities, masses, and sizes, and the ages of the young stars. Measuring the 3-D velocities and distances of regions throughout the Milky Way is required to determine the rotation curve to measure the dark matter mass of the Galaxy, to delineate the spiral structure (even the number of arms is still in debate), and provide specific observational constraints on the spiral density-wave theory that is applied throughout the universe. VLBI is beginning to outline the general plan of the Milky Way (see Reid et al. 2009b, Astro2010 white paper, "Structure and Dynamics of the Milky Way"), using observations of masers in high-mass star forming regions, as shown in Fig. 1. These observations promise distance determinations of 10% or better even on the far side of the Milky Way. Initial VLBA results have revealed that the Milky Way rotation speed is about 15% faster than usually assumed, implying an increase by 50% in the estimated (dark matter) mass of the Galaxy, making it comparable to Andromeda, and indicating that the LMC is bound to the Milky Way, con-

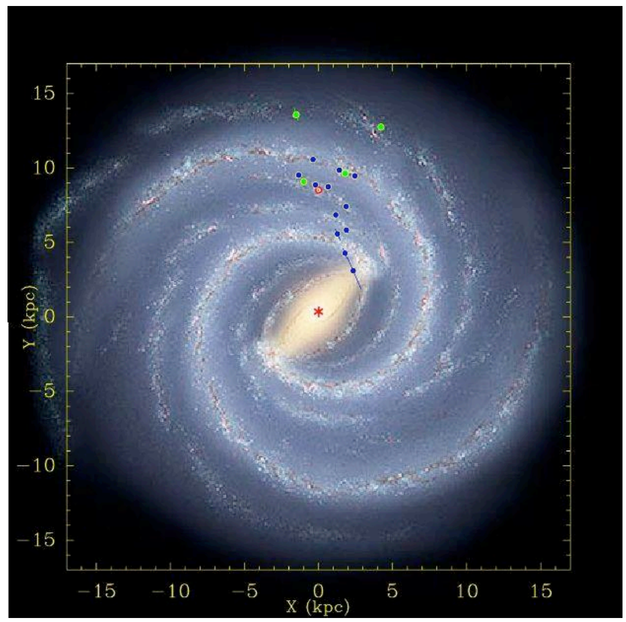

Fig. 1.— Locations of high-mass star forming regions for which trigonometric parallaxes have been measured with VLBI. Blue dots are 12 GHz methanol masers and green dots are water masers. Distance error bars are indicated, but most are smaller than the dots. The red symbols mark the Galactic center and the Sun, 8.5 kpc from the center. The background is an artist's conception of Milky Way (R. Hurt: NASA/JPL-Caltech/SSC), viewed from the North Galactic pole, which has been scaled to place the star forming regions in the spiral arms.

trary to previous results. Astrometry using the VLBA has achieved accuracies as good as 10 μas. However, sensitivity limitations and systematic errors currently restrict the number of regions and targets that can be studied.

The 4–8 GHz receiver that is a major component of this activity will markedly enhance the accuracy and scientific benefits of the technique. The VLBA will be able to observe the 6.7 GHz line of methanol for the first time. Maser emission in this line is typically 1–2 orders of magnitude stronger than that from the 12.2 GHz methanol line on which most previous VLBA results are based, so far more sources, and more distant sources, can be seen. Additionally, the methanol sources tend to be less intrinsically variable than other strong masers such as water, an important factor for proper motion and parallax observations that require a minimum of one year to complete. These factors make the 6.7 GHz methanol line by far the best to use for measurements of the structure and dynamics of the Milky Way. Indeed, it will allow the VLBA to make accurate direct distance measurements to most high-mass star forming regions in the Galaxy (that can be seen from northern latitudes), and for the first time reveal its spiral structure and 3-D velocity field. The increased bandwidth of the receiver and new electronics will enable the use of weaker continuum calibrator sources, which thus can be found much closer to the targets in the sky. This offers the promise of reducing the astrometric accuracy limit to $\sim 2\mu$as, similar to the mission goals for SIM, and better than Gaia. Further, the radio observations by the VLBA can reach into obscured regions of the Galactic plane and interiors of molecular clouds not observable to these optical space missions because of dust obscuration.

If such a goal can be reached, it will be a key driver for the addition of more collecting area after 2020, enabling fainter masers to be targeted. This will contribute to accurate measurements of nearby galaxy motions, characterizing the distribution of mass (including dark matter) in the Local Group.

2.2 Star Formation in the Milky Way (PSF)

In recent years, distances to both low- and high-mass star-formation regions (SFRs) in the Milky Way have been measured using VLBA astrometry, providing distances of 0.5–5% accuracy to active stars in nearby SFRs such as Taurus, Ophiuchus, and Orion (see Loinard et al. 2009, Astro2010 white paper, “The Space Distribution of Nearby Star-forming Regions”). The figure on the cover of this activity white paper shows an example — the position, distance and tangential velocity vectors of the four young stars in Taurus, superimposed onto the CO(1-0) image of Taurus from Dame et al. (2001, ApJ, 547, 792). VLBI astrometry is the only way to get good distances to SFRs since the stars are very obscured. Typical errors using other methods (including Hipparcos) are 20–40%. A key limitation has been the small number of stars that can be measured in each region, because the stellar activity yields weak radio emission. The study of Ophiuchus shows the great power of this method and the need to expand sample sizes. VLBA parallax studies of Ophiuchus suggest that what was always thought of as one SFR may be two or more superimposed, but an expanded sample size is needed for definitive conclusions. The proposed VLBA bandwidth increase will permit measurements to be made of not just a few stars in the nearest SFR, but of 50–100 stars in Taurus and Ophiuchus alone, and a dozen or more in Orion. This will reveal the full *dynamic 3-D structure* of the nearby SFRs. The sensitivity upgrade will not only expand the number of stars in nearby SFRs but also extends the distance to which stars can be detected. Currently, almost all nearby SFRs have been or are in the process of being measured. With the sensitivity upgrade this can be expanded from a handful of nearby regions to an area of 20 kpc^2 the Galactic plane of around the sun (with $< 5\%$ errors).

In the coming golden age of molecular astronomy that will be enabled by ALMA, it will be especially important to understand exactly how far away the objects under study are. VLBA parallaxes promise to provide that crucial information.

2.3 Water Megamasers and Dark Energy (CFP)

A well-known Hubble constant (H_0) can provide a new, substantive, independent constraint on joint analyses of the Cosmic Microwave Background, Baryon Acoustic Oscillations, and Supernova light curve data that are intended to constrain the nature and time variability of dark energy, the curvature of space, and even Neutrino mass. Distance measurements to distant galaxies, which may be obtained via VLBI study of water megamaser sources in the nuclei, contribute to estimation of H_0. Ultimately, an accuracy of 1% is required. The goal for the next decade is high-accuracy, direct distance measurements for at least 10 galaxies with known small peculiar motions (Braatz et al. 2009, Astro2010 white paper, "Cosmology with Water-vapor Megamasers"; Greenhill et al. 2009, Astro2010 white paper, "Estimation of the Hubble Constant and Constraint on Descriptions of Dark Energy").

Ultimately, multiple VLBI techniques will be required to achieve a large set of measurements. The earlier white papers treat combinations a mix of studies that leverage space-ground baselines (Greenhill et al. 2009, Astro2010 PPP on SAMURAI) and the technique of self-calibration, using different configurations of moderate and high-sensitivity ground antennas. A broadband upgrade of the VLBA, which improves availability of calibration sources, and implementation of WVR tools, which increases atmospheric coherence time by a factor of two or more, makes phase referencing a powerful tool for megamaser studies. The net effect is to relax minimum flux-density constraints that restrain study of very weak (presumably distant) sources, making net integration time on the array the primary consideration. As argued in by Greenhill et al., the best megamaser targets may be those at $cz > 6000\,\mathrm{km\,s^{-1}}$, for which fractional peculiar motion will be smallest. Successful application of phase referencing will increase the number of known practical targets in this velocity range from perhaps as few as 1 to as many as 5 — with added benefits for masers to be discovered by ongoing efforts over the next several years. Because the EVLA and GBT are key elements in an effective array for this task, WVR installations there will be required. The addition of the Large Millimeter Telescope would also be strongly beneficial.

2.4 Radio Interferometric PLanet search (RIPL) (PSF)

RIPL is a current VLBA project to search for planets orbiting M dwarf stars via their gravitational reflex. M dwarfs, with typical masses of 0.1 $M_{\odot}$, are the most populous stars in the Galaxy; the propensity for planet formation around such low-mass stars compared to better-studied, more massive stars is an open question that is being addressed with this project. The ongoing study is sensitive to the presence of roughly Jupiter-mass planets orbiting near 1 AU. This research is intrinsically sensitivity limited. The Green Bank Telescope is included to enhance the sensitivity of the current study. The stellar radio emission is broad-band and thus will benefit markedly from the ongoing and proposed bandwidth expansions. Fig. 2 shows the current and future sensitivity of 3 year VLBA searches for planets around M dwarf stars. SIM will allow superior astrometry on a small subset of stars and only after its full mission. RIPL and its higher-sensitivity successors will make significant impacts in the study of low-mass star formation. Moreover, the planets that may be found orbiting these nearby low-luminosity stars are prime candidates for direct imaging/spectroscopic follow-up with existing and planned ground-based optical/IR telescopes. For more information see the NSF ExoPlanet Task Force white paper by Bower et al., available as arXiv:0704.0238.

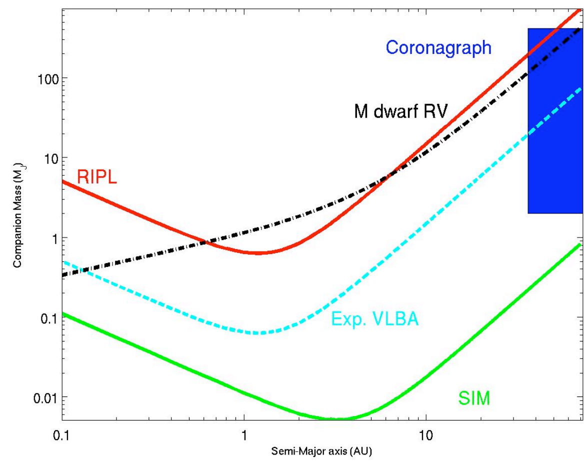

Fig. 2.— The mass detection limit of RIPL as a function of orbit size. Solid red is the sensitivity of the ongoing 3 year experiment. Dashed cyan is the sensitivity of a 3 year experiment performed with the 16 Gbps record rate that will be realized by 2015. The black dot-dashed line illustrates the detection threshold of complementary radial-velocity based planet searches using modern ground-based optical telescopes. Currently coronograph-based techniques are not competitive with other techniques and thus do not help answer the central question of relative planetary abundance for M dwarfs and their more massive stellar counterparts.

3. Technical Overview

To enable the exciting science described in the previous section, a new frequency band must be opened and the sensitivity of the VLBA must be increased dramatically. The new frequency band includes the 6.7 GHz methanol maser line that is expected to provide the best markers with which to measure the Galaxy, but cannot be observed with current receivers. Also, to enable large improvements to observations of weak sources at high frequencies, including water megamasers, measures should be taken to reduce the effects of short time scale fluctuations in the tropospheric water vapor.

Options for increasing the sensitivity are limited. The existing VLBA receivers are already very close to state-of-the-art in performance. Increasing the collecting area will probably have to wait for the construction of SKA-high, perhaps as the North America Array (NAA) for which another activity white paper is being submitted by Myers et al. Expanding the bandwidth is the most cost-effective approach to increasing sensitivity, although it is only effective for continuum sources. Nevertheless, the large factors of increase made possible by the digital electronics revolution justify a concentration on this approach.

An important aspect of that justification is the fact that VLBI astrometry is often performed using a differential technique, known as phase referencing, which effectively measures relative position offsets between the target source and one or more reference sources with known coordinates tied to the International Celestial Reference Frame. Systematic errors, primarily due to the atmosphere, are minimized as the target and reference sources become closer in the sky; closer reference calibrators that become observable at increased sensitivity thus increase the accuracy of the differential astrometric result. Since the calibrators are continuum sources that benefit from the bandwidth increase, the upgrade provides a substantial enhancement of the phase-referencing technique that applies to both maser-line and continuum target sources.

The phase referencing technique involves switching between calibrator and target on time scales during which atmospheric phase fluctuations are below some acceptable level. If those time scales are too short, there is too much overhead in moving the antennas and the time on-source is too small a fraction of the total telescope time. At the higher frequencies of the VLBA, this is a serious concern. Also, if the differences between the phase offset due to water vapor in the directions of the calibrator and target are too different, the results obtained with this technique are degraded. The WVRs are designed to provide a measure of the instantaneous water vapor content of the atmosphere along the line-of-sight. They can be used both to lengthen the phase referencing cycle time, thereby reducing the overhead of the telescope moves, and to reduce the tropospheric phase errors due to the switch in position. The correlation of WVR observables with delays for calibration is not always perfect, but

VLBA observations at $\sim$ 20 GHz are right on the boundary of where phase referencing works well and where the tropospheric fluctuations are too large. Thus an improvement by a modest factor of two, which seems to be a conservative estimate of what the WVRs can provide under many conditions, would be a major benefit.

The bandwidth goal of an overall 128-fold increase will be realized in stages. The current sustained bandwidth is 32 MHz per polarization (256 Mbps data rate). An expansion program already under way will increase this to 512 MHz per polarization (4 Gbps) by 2011. The required data rate in bits per second (bps) of the data transmission is 8 times the bandwidth per polarization (Hz) — a factor of 2 each for dual polarization, Nyquist sampling, and 2 bits per sample[1]. The activity described in this paper is a substantial extension beyond that stage, to a sustained bandwidth of 4 GHz per polarization (32 Gbps). For comparison, the EVLA, which is not throttled by a long-distance data transmission system, has 8 GHz per polarization.

The 128-fold bandwidth expansion corresponds to an increase in sensitivity by a factor of 11. Assuming standard $\log N/\log S$ statistics, this would decrease the average target-reference separation by a factor of 6, so the systematic errors of astrometric observations should be reduced by a similar factor.

The primary roadblocks to wider bandwidth are the small fractional bandwidth of some existing VLBA receivers and feeds, the intermediate-frequency system's 512 MHz bandwidth per polarization, and the limitations of data-recording and correlation systems. The following sections outline the technical upgrades required to move beyond these roadblocks and realize the activity's goals.

The new 4–8 GHz receiver and the enhanced bandwidth involve minimal technical risk. Well-established, recent EVLA designs can be used, with only minor modifications, for the receiver and the wide-band 4 GHz intermediate-frequency system. The digital sampling and filtering techniques already under development for the 512 MHz upgrade can be adapted directly to the wider bands available from the new receiver and several of the exiting, higher-frequency receivers. A further evolution of the wide-band recording system will be required; this is the only technology driver involved in this activity. The VLBA's new software correlator will only require additional processors to handle the expanded load. Power and cooling requirements are expected to remain low.

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[1] It is expected that most wide-band experiments will record data with 2 bits per sample. It will be possible to record data with 1, 2, 4 and possibly other numbers of bit per sample. Here and elsewhere in this document 1 Gbps should be interpreted as 1024 Mbps.

3.1 4–8 GHz Receivers

A new receiver will be required to cover the methanol line near 6.7 GHz and to provide wide bandwidth for continuum (calibrator) observations in that part of the spectrum. This receiver will be identical to the 4–8 GHz receiver deployed currently or in the near future on NRAO's Expanded Very Large Array (EVLA) instrument. Funding has been requested in a 2009 NSF MRI proposal.

3.2 Feeds

The EVLA-design receiver will require a new feed design, modified to accommodate the VLBA's optical characteristics which differ from those of the EVLA. NRAO has the required in-house expertise, and indeed some such modifications have been designed previously.

3.3 Local-Oscillator/Intermediate-Frequency (LO/IF) System

A well-understood path to a wider-bandwidth LO/IF system is just to duplicate the system being implemented on the EVLA, but for half the total bandwidth. In addition, some modifications to filters and maybe mixers in the high frequency receivers will be required to make a full 4 GHz bandwidth usable, but those are not expected to be difficult or expensive.

The SKA, especially SKA-high (or NAA), will need an order-of-magnitude lower-cost LO/IF system. Current SKA technical development projects are working toward such systems. NRAO engineers are also exploring the use of the latest technologies to build systems that might work for SKA or for future EVLA/VLBA projects. Such alternatives will be considered seriously when the VLBA upgrade is designed, but none are yet ready to serve as the basis for a cost estimate.

3.4 "Digital Backend" Sampler/Filter

As part of the current, first-stage upgrade to 512 MHz bandwidth per polarization, NRAO has engaged in a collaboration with the CASPER Laboratory at UC Berkeley, South African SKA Project Office, and Haystack Observatory. The resulting unit combines a fast analog-digital converter with an FPGA-based digital filter to replace all functions of the existing VLBA subsystems from the IFs to the recording system. The same system will be used in the South African SKA pathfinder. Prototypes of the hardware platform for this device have been tested successfully, and the FPGA firmware should be ready for prototyping in the current year.

The same approach remains viable for the proposed further 8-fold bandwidth expansions, using a newer FPGA series and more boards.

3.5 Recording System

The bandwidths of VLBI systems have always been throttled by the capability of the data transmission system. In the past, the only option was to record the data on some sort of recording device, such as tape or disk, and ship it to the correlator. Those devices have limited but growing capacity and data transfer rates. Fiber systems now offer an alternative that will be discussed later, but obtaining access to adequate bit rates at an affordable cost is still a problem.

NRAO is collaborating with Haystack Observatory and Conduant Corporation to develop the Mark 5C VLBI recorder, with a 4 Gbps capability, in a design based on industry-standard data protocols and commodity disk drives. The first three such units were completed in March 2009. We expect a next-generation recorder based on the same approach to achieve 16 Gbps in a single unit by mid-decade. For comparison, consider that the 1 Gbps Mark 5A recorder became available in quantity in 2004 and the step to quadruple the recording bandwidth has taken 5 years; another bandwidth quadrupling is needed.

This development is one of the main technology drivers for the proposed activity, and some relevant considerations are discussed in more detail in Section 4.2.

3.6 Correlator

The VLBA's original, hardware-based correlator will be replaced by a software correlator in 2009. It is expected that this system could be expanded to handle the additional processing load imposed by wide-band observations simply by the inclusion of additional processors of the most cost effective type at the date of purchase. Mixing different generations of CPUs is not a problem. Recently, CPU performance per dollar has doubled roughly every 1.5 years, outstripping the pace of recording media price drops. Presently, the cost of the CPUs required for software correlation is about 15% of the recording media cost. We expect this to fall to 12.5% by 2011, and have conservatively used this ratio for the remainder of project.

3.7 Water Vapor Radiometers

The basic concept of a WVR is to measure the strength of an atmospheric water vapor spectral line and use that to deduce the path delay induced by that water vapor. For the VLBA and EVLA, the line of interest is the one at 22.235 GHz — the same transition measured in the water megamaser project, but in this case in thermal equilibrium (not masing) and pressure broadened to a few GHz in width. Typical WVRs measure the system temperature on the center of the line and at a number of frequencies in the line wings. Applying the prediction for the line shape from an atmospheric model to these measurements can form observables that are highly correlated with atmospheric phase fluctuations.

A significant complication in the use of WVRs is that the magnitude of the line temperature fluctuations depends on the temperature of the emitting gas, which does not significantly effect the path delay. The temperature of that gas is a function of height above ground and that function is not constant and is normally not known. Only the surface temperature is normally known and that can be a poor indicator of the temperature at altitude. These complications have so far made it impossible to have a fixed relation between the measured temperatures and the interferometer phase. It is, however, possible to calibrate the relationship between WVR observable and atmospheric delay via observation of a bright source. It is with such calibration that WVR data has proved useful in the past.

WVRs can be part of the observing system on the telescope or can be separate, standalone devices. The latter allows the use of tipping scans and other measurements around the sky without affecting the main observing. The former is more likely to be looking at exactly the same beam as the interferometer and is also likely to be less expensive, especially if it is an add-on to an existing receiver. The system proposed here is an add-on to the existing 22 GHz receivers. An advanced WVR design for the EVLA will be a perfect match for the VLBA. Some results from a prototype study are available in Chandler et al. 2004, EVLA Memo 73 "Results of Water Vapour Radiometry Tests at the VLA"[2]. A proposal from 2004 giving the basic technical design, which is close to what is suggested here, is given in Chandler et al. 2004, EVLA Memo 74 "A Proposal to Design and Implement a Compact Water Vapour Radiometer for the EVLA"[3]. We would implement the full 5 channel system described in the latter document so that it would be the same as EVLA, although the utility of the outer channels would be compromised by the narrower bandwidth of the VLBA receiver. The tests in the first memo were done with a three channel system equivalent to what would be available on the VLBA.

The activity white paper for the EVLA (Ott et al.) is also requesting WVRs to enhance the high frequency capabilities of that instrument. Essentially the same units, developed and deployed by the same teams, will be used for both instruments.

While it is anticipated that the WVRs will be a significant benefit to phase referencing, they are by no means required to obtain the primary benefits of the 4–8 GHz receiver or the bandwidth upgrade.

[2]Available at `http://www.aoc.nrao.edu/evla/geninfo/memoseries/evlamemo73.pdf`

[3]Available at `http://www.aoc.nrao.edu/evla/geninfo/memoseries/evlamemo74.pdf`

4. Technology Drivers

This activity depends on further development of only one technology, high speed data recording. It would also benefit from research into methods to use WVR data. All other aspects could be done with technologies already deployed on the EVLA, under development for the current, preliminary VLBA bandwidth upgrade, or by simple extension of computer technology to future capabilities.

For data transmission, an alternative being pursued vigorously at the Haystack Observatory, and by groups in Europe, Japan, and Australia, is eVLBI — transmission of the data in real time, or perhaps after buffering on disk, over fiber links. Such a system offers significant operational advantages, as well as potential benefits for some science areas. A large system such as the SKA will likely require such links for a viable operation. However, the data rates required are very high by the standards of other users of the commercial networks, so normal tariffs are prohibitive. For the SKA, the radio astronomy community will need to find a way to gain access to the required links. The VLBA would be a natural testbed for deployment of a prototype system. An alternative path to the use of real time links might be through the partnerships that NRAO is forming to share the costs of operating the VLBA. Some of the potential partners do have specific requirements for real time data transmission and would likely help fund and deploy such a system.

The following technology driver sections address the potentially beneficial research into the optimum use of WVR data and the required development of a wider-band recording system.

4.1 Water Vapor Radiometers

The WVRs were described in Section 3.7 and the referenced VLA memos. We include them as a technology driver not so much because there is doubt about how to make them, but because it could be very useful to have further development of the methods and tools to use their data in an optimal fashion to improve VLBA phases. The previous testing (referenced in Section 3.7) points the way toward gaining significant benefit. The factor of 2 improvement in coherence time that would impact the megamaser project, for example, is a modest requirement and should be achievable under the low-opacity weather conditions ordinarily allocated for megamaser studies. Continued research would likely lead to improved results. Numerical weather models of the 3-D temperature and pressure of the atmosphere, for example, may provide the meta-data required to improve the correlation of the WVR observable with tropospheric phase. For these reasons, we include in the budget one FTE-year in 2016 for a scientist to study the use of the WVRs and of phase calibration methods in general.

4.2 Recording System

The recently completed Mark 5C recording system is probably not suitable for direct extension by the desired 8-fold factor. However, the basic concept appears to remain the best option for an upgraded system: a wide-band interface to a special-purpose, high-speed controller which in turn writes and reads data to and from multiple individual storage units, which are encapsulated in a removable module. The development of broader bandwidth recorders and storage modules in the U.S. will likely continue to be a collaboration among MIT Haystack Observatory, Conduant Corporation, and NRAO.

A practical 32 Gbps system will probably require a somewhat different configuration than the current Mark 5 storage module containing 8 disk drives. For the high bit rate, more storage devices are likely to be required. Flash memories may well be the most suitable basic storage devices several years from now. They are already surpassing disk drives in speed, and have several other obvious advantages such as durability and consistency of I/O speed. Prices currently remain higher than disk drives, but are falling rapidly.

For sustained operation at the expanded, 4-GHz per polarization bandwidth (32 Gbps recorded data rate) that is central to the activity proposed in this paper, a total media pool of 53,914 TB is required. Assumptions in computing this requirement include: full-time availability of the ten VLBA stations, plus the GBT and EVLA for 20% of the observing time of each; a 50% observing efficiency (i.e., the fraction of time actually recording data); and a 30 day observing/processing turnaround.

Planning for procurement of such volumes of data storage media requires a careful balance between expanding the media pool early to expand scientific capabilities, and minimizing cost by waiting for the anticipated significant and continuing cost decreases. A convenient balance is achieved by planning procurements at level dollar costs over a continuous period of several years, so that less capacity is purchased early in the period when prices are high, and the largest fraction is obtained at the lowest prices at the end.

To quantify the cost decreases, we apply a fairly well-determined exponential law, with a cost-halving time of 2.28 years, derived from the VLBA's history of disk-drive purchases for Mark 5 use. As a benchmark for extrapolation using this law, we adopt a point based on NRAO's most recent procurement, in September 2008, at a unit price of $0.340/GB including the essential housing for the shippable data module.

Applying the level-expenditure concept to expansion of the VLBA media pool over the four years 2014–2017 yields a planned annual procurement that would support the following mean observable bandwidths through these years: 0.6, 1.4, 2.5, and finally 4 GHz per polarization in 2017.

5. Organization, Partnerships, Status

The VLBA is a facility of the National Radio Astronomy Observatory with time allocated to astronomers from the United States and around the world based on the scientific quality of proposed research.

As a result of the 2005-2006 Senior Review, the NRAO must find half of the operating cost of the VLBA from non-NSF sources. NRAO is confident that the required partners will be found.

The NRAO Time Allocation Committee will emphasize key scientific projects on the VLBA. The time allocation committee is willing to make significant awards of observing time to meritorious, large projects in order to achieve major scientific results. Examples of such projects will likely include those described in Section 2.

A predecessor to the activity described in this document has already begun, and has included significant partnerships. The amplifiers of the 22 GHz receivers were upgraded to modern standards to significantly reduce the system temperature during 2007. That project was largely funded by the German Max Planck Society.

A partnership of the Berkeley CASPER lab, MIT Haystack Observatory, NRAO, and the South African SKA Project Office is developing the VLBA digital backend (VDBE), the sampling, filtering and formatting system required for the upgrade to 512 MHz per polarization (4 Gbps) now in progress. The Mark 5C recording system is a partnership of NRAO, Haystack Observatory, and the Conduant Corporation.

Funding for the 4–8 GHz receiver required for this activity has already been requested in an MRI proposal to the National Science Foundation. The Max Planck Society will be providing 30% of the funding for that project if it is accepted.

Eight Mark 5C recorders were purchased recently by The National Council on Science and Technology (CONACYT) of Mexico, for use at VLBA stations, in response to requests from Mexican astronomers involved in some of the key projects of the science case for this activity. Further funding may be available from this source. Significant scientific contributions could be made to VLBI science, including megamaser and mm VLBI projects, if the 50m Large Millimeter Telescope on Pico de Orizaba in Mexico is equipped for VLBI. This is also advocated in the Astro2010 activity white paper on the Event Horizon Telescope.

The above international collaborations indicate the global interest in the VLBA and a willingness on the part of some VLBA users to support it financially. It is likely that further partnerships will develop as this activity continues.

6. Activity Schedule

This section gives a list of primary milestones.

- **2010:** Complete the installation of the systems capable of providing 512 MHz per polarization (4 Gbps). This project is in an advanced stage of development. It includes a new digital backend, a new recording system (Mark 5C), and a new software correlator, along with the software necessary to integrate the equipment with the existing VLBA operations.
- **2011:** Finish acquisition of adequate recording media and correlator processors to support sustained 512 MHz per polarization observations.
- **2011:** Complete the installation of the 4–8 GHz EVLA receiver on the VLBA pending funding request to the NSF MRI program that was submitted in January 2009.
- **2011:** Begin design of a 16 Gbps data transmission system, expandable to 32 Gbps (for 4 GHz bandwidth per polarization).
- **2011:** Begin design of a 4 GHz per polarization LO/IF system. This might be simply a choice to deploy the EVLA system, but potentially less expensive options will be investigated.
- **2014:** Complete deployment of hardware for the 4 GHz per polarization LO/IF system.
- **2014:** Complete deployment of hardware for a data transmission system capable of operating at 32 Gbps (4 GHz bandwidth per polarization).
- **2014:** Procure adequate media and correlator resources for operation at mean data rate corresponding to 0.6 GHz bandwidth per polarization.
- **2015:** Procure adequate media and correlator resources for operation at mean data rate corresponding to 1.4 GHz bandwidth per polarization.
- **2016:** Procure adequate media and correlator resources for operation at mean data rate corresponding to 2.5 GHz bandwidth per polarization.
- **2017:** Procure adequate media and correlator resources for operation at sustained data rate corresponding to 4 GHz bandwidth per polarization.