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APS Whitepaper on

The Status and Future of the Very Long Baseline Array

The Owens Valley 25m VLBA antenna, one of ten identical antennas comprising the VLBA. NRAO/AUI

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The Status and Future of the Very Long Baseline Array

Executive Summary

Since its inception 26 years ago, the Very Long Baseline Array (VLBA) has remained the most productive Very Long Baseline Interferometry (VLBI) array in the world. Its key capabilities are imaging, spectroscopy and polarimetry at milliarcsecond angular resolution and performing astrometry at a precision approaching a microarcsecond. In the coming decade VLBA staff will pursue opportunities to increase the sensitivity of the array and further adapt it to meet the needs of an evolving astrophysical landscape through advances in digital electronics, high-speed fiber-optic networking and adoption of technologies such as wide-band receivers and modern data reduction software used by other radio astronomy facilities. The VLBA will play several important roles in the development of the next generation VLA (ngVLA).

Overview

Introduction

The National Radio Astronomy's (NRAO) VLBA is a VLBI instrument, operated under cooperative agreement with the United States National Science Foundation (NSF) by Associated Universities, Incorporated (AUI). The instrument consists of ten identical 25-meter diameter antennas, which are separated by a range of distances from intrastate (NM) 200 km to transcontinental 8600 km (with the longest baselines between an antenna station on Mauna Kea, Hawaii and one on the St. Croix Virgin Islands). The VLBA is controlled remotely from the Domenici Science Operations Center (DSOC) in Socorro, NM and allows for year-round, dynamically scheduled, in absentia operation. Each VLBA station consists of the 25-m antenna with its associated high-sensitivity receivers, analog and digital electronics, and an adjacent control building that houses a hydrogen maser (providing a stable frequency reference), recording equipment, and the computer control systems. During observing runs the received radio-astronomical signals at each VLBA station are independently amplified, digitized, and recorded on fast, high capacity recorders, using Commercial Off-The-Shelf (COTS) disk drives and media. A peak data recording rate of 4096 million bits per second (Mbps) translates to a bandwidth of 512 MHz in dual polarizations. The physical disk packs are shipped to the central correlation facility in Socorro where the data disks are read and each pair of station data is cross-correlated.

The VLBA is able to observe across the centimeter-to-millimeter radio spectrum in eight discrete receiver bands spanning 1.2 to 96 GHz and two narrow sub-gigahertz bands covering 312 to 626 MHz. All receiver bands produce dual circular polarizations. All observing frequencies are available at all times with rapid, automated selection of receivers and of frequencies within a given receiver. The VLBA can thus be used to observe and image a variety of compact radio sources having brightness temperatures higher than ~10^5 K. The VLBA can be combined with other radio antennas to dramatically improve its sensitivity and image fidelity. The central digital processor which combines the signals from the VLBA antennas consists of a flexible software correlator that supports spectral line, continuum, polarization, and time domain observations (e.g., pulsar gating), as well as multiple phase center correlation. The range of capabilities, the uniformity of the array, and its continuous operation, make the VLBA a unique, versatile instrument.

Key Astrophysics Results

In the last decade the VLBA has made key astrophysical discoveries in a wide variety of areas from measuring the characteristics of asteroids, determining the structure of the spiral arms in our Galaxy, to resolving the jets in a quasar at a redshift of ~6. The VLBA has been used in several different ways to determine the properties of asteroids: occultation

(Harju et al., 2018, *AJ* 156, 155H) was used to constrain the shape of an asteroid and significantly improve the precision of the orbit with a single short measurement; and speckle interferometry where the VLBA received the radar bounced off near earth asteroids to determine their spin and structure (Busch et al., 2011, *Icarus* 212, 649B), illustrating the VLBA's capability as receiving elements of a multi-static radar system. It is well known that the VLBA is an astrometry machine, but it is only in the last decade that this ability has become fully recognized by making many important measurements. The Bar and Spiral Structure Legacy Survey (BeSSeL) completed making discoveries such as the Local Arm being a major branch of the Perseus Arm instead of a spur and the Milky Way having much more mass than previously inferred (Reid 2018, in *IAUS 336* 148; Xu et al. 2016, *Science Advances* 2, 9, e1600878, and references therein). The High Sensitivity Array (HSA; a VLBI array using the VLBA and some or all of the VLA, Green Bank Telescope, Arecibo, and Effelsberg), has also made a significant contribution to gravitational wave physics by showing that the binary neutron star merger GW170817 launched a relativistic jet (Mooley et al., 2018, *ApJ* 868L, 11M). The HSA was able to finally end the Pleiades distance controversy (Melis et al., 2014, *Science* 345, 1029). The VLBA has also been used to shine a light on the Universe close to the epoch of reionization by imaging a relativistic jet at a redshift of ~6 (Momjian et al., 2018, *ApJ* 861, 86).

Current Trending Topics

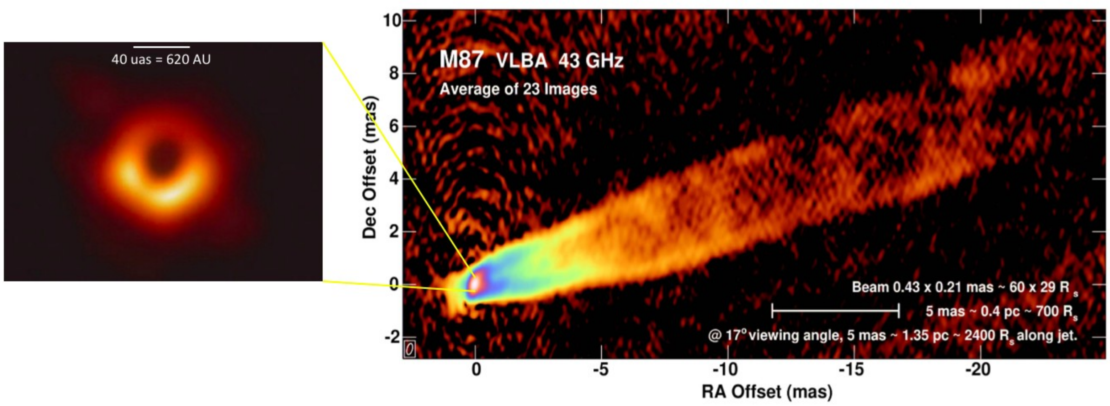
In optical astrometry the European Space Agency's (ESA) Gaia mission has been playing a significant role and will continue to do so into the coming decade. The combination of Gaia results with VLBA astrometric observations have shown the potential to reliably determine the direction of relativistic outflows at parsec-scales (Petrov et al., 2019, *MNRAS* 482, 3023P, and Plavin et al., 2019, *ApJ* 871, 143P). This synergy enables measurements of details that neither Gaia nor VLBA are able to make alone. Another area of great discovery potential, which has already been alluded to by GW170817, is the unique ability by the VLBA to quickly follow-up on potential electromagnetic counterparts of gravitational wave events and monitoring of such across a wide radio frequency range. In addition, by observing a handful of such neutron star mergers with the HSA, it may be possible to provide a new, and completely independent, method of measuring the Hubble constant H_0 (see Hotokezaka et al. 2019, *Nature Astronomy; online Juy 8, 2019*). It is also expected that the VLBA will be able to play a significant role to follow-up on transients discovered by the Large Synoptic Survey Telescope (LSST). With improved localization of fast radio burst (FRB) events expected over the coming years (e.g., Law et al., 2018, *ApJS* 236, 8L), the VLBA enables the study of FRB host galaxies at milliarcsecond (mas)-scale resolution. The VLBA has supported a commensal FRB search and localization program, V-FASTR (Wayth et al., 2011, *ApJ* 735, 97W) for the past eight years which probes FRB parameter space, including a wide range of observing frequencies not covered by other similar programs. Furthermore, with current and improved capabilities of the VLBA at 3 mm wavelength in combination with global mm-VLBI experiments, the VLBA enables supporting observations for the Event Horizon Telescope (EHT) and allows probing relativistic jets at all scales from the shadow of the event horizon out to tens of parsecs. Finally, the Cherenkov Telescope Array (CTA) will become fully operational over the coming decade, further opening the high-energy sky with wider energy coverage and higher angular resolutions than ever before. The known gamma-ray sky is dominated by radio sources (e.g., De Angelis & Mallamaci, 2018 EPJP, 233, 324) with a significant fraction of sources, ~25%, having unknown multi-wavelength counterparts. To maximize the scientific return of the CTA and other high-energy observatories, radio observations at mas-scales are essential both to study known gamma-ray emitting objects as well as to explore the population of unknown objects.

Imaging

The VLBA remains at the forefront of milliarcsecond imaging capability. While the EHT can image at higher resolution, this is only possible for the few targets that have sufficiently high brightness temperatures at the very high frequencies (> 230 GHz) used by the EHT. Indeed the successful imaging of the M87 black hole provides excellent opportunities for the VLBA to continue to contribute highly valuable insights by imaging Active Galactic Nuclei (AGN) jets. In the case of M87 and Sgr

A* highly interesting questiona are how the accretion disk interacts with the jets, how the jets form and how they evolve further "downstream". Particularly in the case of Sgr A*, where the inner region shows variability on timescales of hours, the image sampling afforded by the VLBA and thus its ability to produce a high fidelity image from relatively short duration data, is highly valuable.

FRBs remain one of the more enigmatic phenomena in the sky. As so little is currently known about these sources, localization is one of the best approaches for understanding the mechanisms behind these transient events. Some early data suggest an association between FRBs and low-luminosity AGN, and that the source of the FRB may not lie in the center of these galaxies. Again, the milliarcsecond imaging capability of the VLBA will prove crucial in localizing the source of the emission. Improving the ability of the VLBA to quickly trigger observing (perhaps from a VLA detection) and produce rapid turnaround imaging of the region will greatly help.



Left: EHT 230 GHz image of the event horizon of the black hole in M87 at an unprecedented resolution of 20 microarcseconds. The image shows the general relativistic shadow caused by the severe bending of space-time around the Schwarzschild radius, R_s, seen as a bright ring with a dark center, indicating the radius of the orbits of the last photons able to escape the extreme gravitational field of the 6 x 10^9 M_o black hole (EHT Collaboration, 2019, ApJ, 875, L1). Right: the VLBA image of the relativistic jet in M87 at 43 GHz with a resolution of about 400 microarcseconds (Walker et al., 2018, ApJ 855, 128). Multiple epochs of observations indicate apparent speeds of jet knots accelerating up to twice the speed of light. The critical science goal in the coming decade is to connect the structures seen on scales of a few R_s, to those in the jet seen on scales of tens of R_s. The VLBA, possibly in conjunction with other observatories, offers the best chance of doing so.

It is worth noting that VLBI and optical interferometry are the two astronomical techniques capable of creating images at milliarcsecond resolution, but historically the two techniques have been restricted to observing mutually exclusive source catalogs. The Very Large Telescope Interferometer (VLTI) in Chile has begun observing a limited number of AGN, including 3C273 (GRAVITY collaboration, 2018, *Nature* 563, 657). Other optical interferometers, such as the Center for High Angular Resolution Astronomy (CHARA), the Naval Prototype Optical Interferometer (NPOI), and the under-construction Magdalena Ridge Observatory Interferometer (MROI) all endeavor to gain significant sensitivity and baseline length in the next decade (see Astro2020 APC whitepapers by Brumelaar et al., and van Belle et al.). With increased sensitivity on both optical and radio fronts, true multi-wavelength astrometry at milliarcsecond scales will be possible for a wide range of stars, AGN, and microquasars.

Astrometry

The VLBA has the best astrometric capability in the world, and has been essential in maintaining and improving the ICRF. Repeatable measurments with precision of 10 microarcseconds have been made in at several different frequencies using different techniques.

For absolute astrometry and reference frames, the simultaneous dual-frequency (2.4/8.4 GHz) observing mode is most often used. The dual band observations are critical to calibrate the delays introduced by the Earth's ionosphere. Due to man-made radio interference, the 2.2 to 2.4 GHz frequency range has deteriorated quite substantially, and so the possibility of both 8/32 GHz and 6/24 GHz dual-frequency observing is being explored, including new receivers that would allow observations at frequencies in the 26.5 to 40 GHz range or updated receivers that would increase sensitivity and tuning range.

VLBA astrometry also remains vitally important for measuring kinematics of objects that are obscured for Gaia, or where higher cadence observations are required. This includes star forming regions, the Galactic center, microquasar orbits, and others. Using single frequency bands the VLBA can perform astrometry relative to a nearby calibrator source, allowing high precision parallax distance and proper motion measurements across the Galaxy.

AGN jet feedback mechanisms (important for galaxy evolution), Galactic kinematics (obtained from astrometric observations of molecular masers), young stellar objects, supernovae, tidal disruption events, pulsar wind nebulae, and others remain research targets that are only possible with, or strongly aided by the VLBA's imaging and astrometric capability.

Reference Frames and Earth Orientation

In addition to astrophysical results, the VLBA has been vital in establishing and maintaining the International Celestial Reference Frame (ICRF), with the third realization of the ICRF adopted by the International Astronomical Union in 2018. The VLBA is also an essential tool to determine Earth orientation parameters (EOP), such as UT1, coordinates of the pole, and celestial pole offsets. The VLBA will be integral to future improvements of both reference frames and EOP determination (see also Johnson et al., 2019, "The Next Generation Celestial Reference Frame", *Astro2020 science whitepaper*). Further improvements to reference frames are particularly relevant for calibrators in the ecliptic, where higher accuracies are needed for future spacecraft navigation needs, particularly for planetary science missions. In addition, pulsars are being explored for deep space on-board navigation, thus accurate astrometry of millisecond-period pulsars is of particular importance.

ESA's Gaia mission, designed to map the three dimensional structure of our Galaxy, has created a new reference frame: the Gaia Celestial Reference Frame (GCRF) which must be tied into the ICRF. Initial studies have shown that Gaia's positional accuracies are comparable to those of the VLBA. Intriguingly for sources observed both with Gaia and the VLBA, positional offsets between the two suggest that Gaia is probing a physically different region of the source (early science suggests different regions of a jet are being detected). This is perhaps not that surprising given the different wavelengths being used but these differences provide an opportunity for new science on the exact nature of these offsets, as well as being vitally important in order to fully understand and utilize the GCRF. To tie the optical and radio reference frames together, discrepancies between optical Gaia and radio VLBA positions have to be understood and corrected to achieve nanoradian (~200 microarcsecond) or less offsets to match the intrinsic accuracies of the ICRF and the GCRF; see e.g., Malkin et al., 2016, *FrASS* 3, 28M. On long timescales, reference frames determined through decades of ground-based radio frequency observations will continue to improve, securing VLBI as the primary technique by which celestial reference frames and EOPs are determined.

Current Status

Partnership with the United States Naval Observatory

In 2017, a new operations agreement with the United States Naval Observatory (USNO) began. The USNO uses time on the VLBA for daily observations to measure UT1-UTC and observations for the determination of Earth Orientation Parameters. In addition, USNO uses VLBA time in support of defining and refining the ICRF and International Terrestrial Reference Frame (ITRF). USNO provides opportunities to other members of the geodetic and reference frame communities to propose for time to use the VLBA. In return, USNO provides operations funding to NRAO for support of the VLBA. This arrangement has stabilized the VLBA's financial situation.

Improved Data Rate Performance

The cost of transporting information from widely separated and remote locations has been a key limitation of VLBI since its inception. In the early days of the VLBA great resources were spent creating or adapting tape recorders for continuous operation at bandwidths above that supported by industry. At commencement of operations in 1993, the VLBA antennas could record 128 Mbps, corresponding to 16 MHz of dual polarization bandwidth at the typical 2-bit per sample quantization. Over the next decade this tape technology grew to support four times this rate and hard disk storage technology caught up.

Around the time that hard drives started replacing tapes, another technical revolution was occurring: digital electronics in the form of Field Programmable Gate Arrays (FPGAs) and high speed samplers superseded capabilities of analog filters and downconverters. In the past decade the capabilities of these FPGAs has continued to grow. Digital electronics has proven it can provide increased stability and repeatability in signal processing. A first-generation "digital back-end" (DBE) was deployed on the VLBA in 2010 alongside the VLBA's second-generation disk-based recorders yielding a sustainable data rate of 2048 Mbps.

Today, through a third-generation disk-based recorder, the VLBA operates at 32 times its initial data rate, corresponding to a factor of 5.6 increase in sensitivity for continuum observing, which would be equivalent to increasing the antenna diameters by a factor of 2.4. For the first time, the recordable bandwidth is comparable to receiver tuning ranges at low frequencies, but with plenty of room for further data rate growth at the higher frequency receivers.

Current Technical Status

Following Hurricanes Irma and Maria in 2017, the St Croix VLBA station was severely impacted. The recovery from these natural disasters will be completed in July 2019, funded through Congressional action to restore the station to pre-hurricane conditions. This work primarily focused on structural repairs and repainting of the antenna structure. With the completion of this work all 10 VLBA stations will be fully operational. In addition, the NSF funded an effort to establish upgraded communication infrastructure at all VLBA stations in support of high data rate transfer through fiber-optic cables to enable reliable communication with each station and to allow for future real-time data transport to a central processor bypassing local recording.

As part of its continuous improvement program, the VLBA has refitted the station control computers and software, replacing original hardware from the 1990's, and upgraded its recording infrastructure. At any given time this allows recording of only a small part of the radio spectrum between 312 MHz and 90 GHz. Of this tuning range, approximately 25 GHz (28%) is accessible through the available receivers. The VLBA is most sensitive from 1.35 – 8.8 GHz, with image sensitivities of about 7 uJy/beam in an 8 hour integration. The typical angular resolutions that can be achieved are 22 – 0.12 milliarcseconds over the available frequency range.

Each station houses a hydrogen maser, providing a stable frequency reference, and a front end synthesizer to convert the receiver output from radio frequency to an intermediate frequency for digitization. The Roach Digital Backend (RDBE) takes the IF, digitizes and processes the signal through an FPGA-based central signal processor and sends the digitized signal to the data recorder. The cross-correlation backend consists of a flexible software correlator (DiFX; Deller et al., 2011, *PASP* 123, 275D) that supports spectral line observations with spectral resolution as low as 2 Hz. It also supports continuum and time-domain observations (e.g., pulsar gating). VLBI traditionally precludes wide field-of-view observations because of the enormous output data rates that would be implied. DiFX evades this limitation by allowing up to several hundred small fields of view (identified by other instruments such as the VLA) to be correlated within the antenna field of view (typically 1 to 30 arcminutes in diameter). The COTS hardware comprising the cross-correlation backend will be updated in 2019 to support higher data rates and more demanding cross-correlation setups. The correlator is equipped with hard-drive "playback" machines that can support up to 32 stations simultaneously.

Ongoing Development Activities

Flexible frequency synthesizer

A new frequency synthesizer has been developed which allows precise tuning of the VLBA with fine granularity. Currently the coarse tuning of the VLBA analog system restricts tuning to alternate 200 and 300 MHz step sizes. This complicates avoidance of Radio Frequency Interference (RFI) and reduces compatibility with other VLBI antennas. This new synthesizer is currently installed at three VLBA antennas and will be deployed at the remaining antennas as funds allow.

High-speed fiber-optic network

A key difference between the VLBA and the VLA is that the VLBA does not correlate the signals between stations in real time. Instead the recorded voltage data is sent via parcel service from each station to the correlator in Socorro, NM. The recording media is recycled, after correlation, to the stations for continuous reuse, with a cycle time of approximately 4 weeks. Operating in real time would be simpler from an operational perspective but has proven overly expensive in the past. However, this is changing. An NSF-funded project is underway to establish fiber-optic links between each site and the correlator (electronic transfer of the digitized baseband data). The capacity of this deployed infrastructure will exceed the current data rate, but the initial operating data rate will remain much lower, at approximately 200 Mbps. While this data rate won't allow the disk-based recording to be discontinued, it will allow development of real-time, low-bandwidth observing modes and will provide new opportunities for increased diagnostic functionality and perhaps some e-transfer (not real-time, but still faster than shipping) capability for observations requiring low latency. This would include migrating some calibration and maintenance observing, such as pointing and focus determination, to a more precise interferometric observation that can be executed in real-time. This real-time development is a critical demonstrator for the long baselines of the ngVLA which will require real-time links at even higher data rates.

New digital architecture

While the recorded bandwidth has episodically increased over the quarter-century of VLBA operations, another factor of 32 remains to capture all of the bandwidth of the higher frequency receivers. Achieving this final factor of increased recorded bandwidth will require updates to the digital electronics. A new digital architecture for the VLBA is being developed which will make full use of COTS electronic components and will be extensible in the future when newer technologies become available. With continuum sensitivity being proportional to the square root of the bandwidth, this represents a very cost effective means to improve the capabilities of the instrument, in lieu of, for example, adding collecting area (in the form of more, or more efficient antennas) which is much more expensive. In addition to advancing the state of VLBI, this new digital archecture will enable new capabilities. Special purpose, commensal back-ends can be developed to search for and localize transient events or perform spectroscopy. It can serve as a low barrier for hosting entry for university-led projects or providing support to third-party equipment in support of space missions or remote sensing.

Strategic Plan

Improving the User Experience

The VLBA has a multi-faceted strategy to maintain and build the user community. First, the bandwidth (and hence sensitivity) will be increased through use of the new digital system. Increasing the sensitivity will both enable more types of objects to be observed and make observations in general easier by allowing for closer weaker calibration sources. This will enable higher precision astrometry also as it will increase the SNR and allow for closer weaker calibrators with less relative calibration error. Second, we currently and will continue to support user community outreach via community day events, where between one and three VLBA scientific staff visit institutions upon request and give presentations and tutorials about the VLBA and its use. We also plan to follow the very successful example of the VLA and Atacama Large Millimeter Array (ALMA) by hosting VLBA Data Reduction Workshops where PIs can reduce their own data at NRAO, with experts available for immediate consultation and assistance. Third, we are implementing a data reduction service. Initially this service can be requested by novice VLBA users when they propose for observing time. This service aims to improve the user experience by encouraging non-expert users to propose observations on the VLBA and will eventually lead to NRAO providing Science Ready Data Products (SRDP) for most observations.

Technical and User-Focused Developments in the Next Decade

The following development concepts will provide the VLBA with (1) its best sensitivity available using new or upgraded wide-band receiver systems (in lieu of adding collecting area), (2) exquisite imaging by improving the sampling of a wide range of baselines, employing new or advanced joint observing opportunities with other radio observatories, and (3) landing VLBI observations (including the VLBA) into the most modern data reduction software available, leading to science-ready data products.

New 26 — 40 GHz receiver

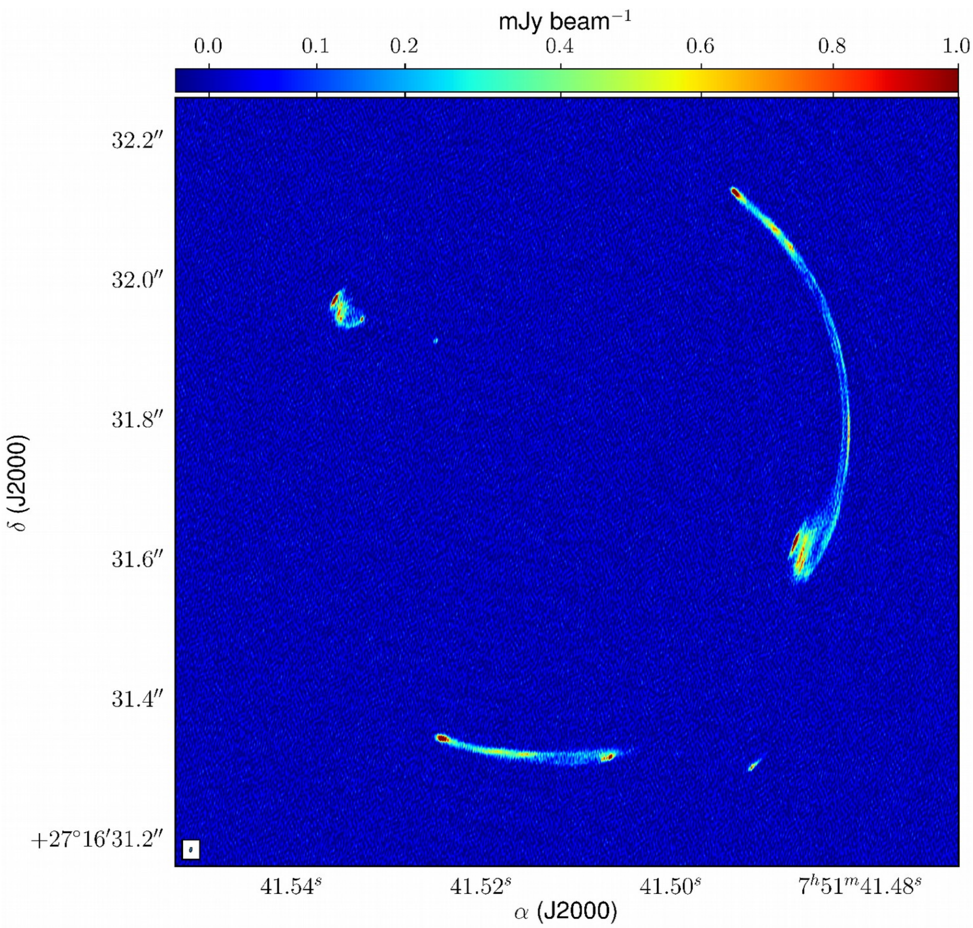
The 26.5-40 GHz (Ka-band) system has a high priority due to the potential for precision astrometry using that comparatively short wavelength, with minimal noise contributions and phase fluctuations caused by atmospheric water vapor. This receiver would facilitate a transition from the interference-plagued 2-GHz band currently used in a 2.4/8-GHz combination, to an 8/32-GHz pair, with a substantial reduction in radio interference of the type that is occurring increasingly in the 2.4-GHz band. A strong case has been made for this upgrade by VLBA partners involved in maintaining and upgrading the ICRF.

Other new or upgraded receivers

The Expanded VLA (EVLA) project, in the first decade of this century, developed a series of wide-band high performance receivers that fully span the 1 to 50 GHz range. The VLBA has adopted one of these receiver systems — the C-band receiver that operates from 4 to 8 GHz. Due to its sensitivity and flexibility this receiver has become one of the most requested on the VLBA. The VLBA X-band (8-9 GHz), Ku-band (12-15.4 GHz), and Q-band (41-45 GHz) receivers all stand to see significant sensitivity upgrades through use of more modern low-noise amplifiers. Additionally, through use of EVLA-developed feeds and polarizers, these systems can be extended to cover a wider range of frequencies.

New joint observing arrangements

VLBI is naturally a cooperative venture. In its early days, ad hoc arrays of antennas were painstakingly coordinated to enable VLBI. The VLBA's operations model, which includes ten identical antennas operated centrally by a single organization, revolutionized VLBI. While the VLBA is excellent at many types of observing (as noted above), its capabilities can be greatly improved when joining forces with other individual antennas or other VLBI networks. Primary drivers for these extended arrays include increased sensitivity through vastly greater collecting area, improved imaging characteristics through increased baseline sampling, and high resolution through observing with distant antennas, including those in Earth orbit. In addition to frequently participating in HSA observations, the VLBA has arrangements with the European VLBI Network (EVN) for "Global" observations. VLBA is also a key component of the Global Millimeter VLBI Array (GMVA), which observes at 3mm wavelength in two campaigns each year for five-six days in each session. Several European antennas, the GBT, and sometimes ALMA cooperate in this venture. Opportunities remain to expand upon these extended array efforts. Options include greater cooperation with the East Asian VLBI Network and improved flexibility and availability of the existing arrangements.



VLBA+EVN image of gravitational lens system MG J0751+2716 at 1.65 GHz. The striking image fidelity is a result of the large number of baselines in this combined array and the wide range of spatial scales being sampled. Spingola et al., 2018, MNRAS 478, 4816S.

CASA support and SRDP

The official data reduction package for ALMA and the VLA is the Common Astronomy Software Applications (CASA), which provides a Python-based interface for interactive and scripting input. This package was developed as a successor to the Astronomical Image Processing System (AIPS) which is still used by the VLBA. Currently CASA lacks some of the VLBI-specific calibration procedures included in AIPS, but recent developments by a group at the Joint Institute for VLBI, European Research Infrastructure Consortium (JIVE) have been closing the gap. NRAO sees it as essential that CASA ultimately becomes the official data reduction package for the VLBA for two primary reasons. First, a large and growing fraction of radio astronomers are more familiar with CASA than AIPS; providing the community a common package will reduce the time to learn how to calibrate and image data from the major radio and millimeter observatories. Second, NRAO has begun developing infrastructure that would deliver SRDP to users. In this operational model, users would receive calibrated data and reference images that are produced by a CASA-based pipeline. This stands to reduce the burden on astronomers and make these instruments more accessible to non-experts. The ngVLA is being designed with SRDP output as a primary driver. Development of data reduction pipelines for the VLBA will develop heuristics that are critical to the early success of long baseline ngVLA SRDP.

Transition to the ngVLA

The ngVLA (see e.g., Selina et al., 2018, *SPIE Astronomical Telescopes & Instrumentation* AS18, 10700 and McKinnon et al, 2019, "ngVLA: The Next Generation Very Large Array", *Astro2020 APC whitepaper*) project has adopted a long baseline component (the Long Baseline Array, LBA; not to be confused with the Australian Long Baseline Array), which will greatly improve the capabilities of the VLBA and integrate long baseline observations seamlessly into the ngVLA operations model. In summary, the ngVLA core and medium baselines cover a footprint that includes four VLBA antennas. To ensure the ngVLA long baseline capabilities exceed that of the VLBA, the outer 6 VLBA 25m antennas will be replaced by 30 ngVLA 18m antennas, representing a factor of 2.5 increase in long baseline collecting area, but an increase by factor of 3 to 5 in sensitivity due to the unblocked apertures and improved optical precision.

Should the ngVLA be funded, the LBA will be constructed in the early 2030s. Until this time comes, the VLBA will serve several important roles in the ngVLA context. First, the VLBA will remain the flagship VLBI array and will be essential for maintaining and further developing VLBI expertise in the U.S. Second, the VLBA is a natural platform for development and early testing of some ngVLA technologies, ranging from digital electronics, time synchronization and data transport, to calibration and data processing. Finally, the VLBA antennas provide a long history as precise reference points in the International Terrestrial Reference Frame (ITRF). A transition of several years having stations in common between at least a portion of the VLBA array and a portion of the LBA will be critical for maintaining continuity in the ITRF.

VLBA as a testbed for ngVLA technologies

The ngVLA and VLBA will evolve in parallel, providing significant opportunities for technology transfer in both directions. The VLBA will be able to offer a working VLBI framework to ngVLA antennas as they are brought to life. Early testing using a VLBI correlator and well understood VLBA "reference" antennas can be used to characterize and commission the new antennas over a wide frequency range even in advance of delivery of the ngVLA correlator. The VLBA will be exploring challenges, opportunities and techniques associated with wide-band networks. Since many of the VLBA sites will host ngVLA LBA antennas, VLBA site development (e.g., broadband communication, electrical infrastructure, and environmental monitoring) will directly benefit the ngVLA. Conversely, ngVLA developments stand to be adopted by the VLBA. Long distance time and frequency transfer is being studied as an alternative to hydrogen masers for ngVLA antennas. In addition to the VLBA serving as a test apparatus, it could benefit through shedding the need for these expensive clocks. There exist some common development threads for the two instruments. For example, best practices for calibration of long baseline interferometry using linear polarization feeds (as will be done by ngVLA) or mixing linear and circular polarizations can be explored using existing VLBI data with direct applicability to both instruments. ngVLA is developing a water vapor radiometer which would produce a phase calibration signal based on radiometric observations made simultaneously with an atmospheric water line. The VLBA will benefit greatly from such calibration systems, when available, by extending the coherence time of the instrument allowing fainter objects to be studied and improving astrometric precision.

Schedule

The schedule below shows a plausible sequence of notable events in the upcoming decade. Some of these events are contingent on funding that has not yet been identified and the schedules, especially in the mid-to-late coming decade, are subject to change.

Year	Milestone	Comments
2019	VLBA operational at 4 Gbps	Done! Available to proposers
2020	New flexible synthesizers deployed	Designed; deployment subject to funding
2021	Limited real-time correlation	Diagnostics, pointing, low bandwidth observing
2022	New digital architecture deployed	Development has begun
2022	VLBA demonstrated at 8 Gbps	Using new digital architecture
2023	Ka-band receivers deployed	Subject to external funding
2023	Full CASA support for VLBA	Subject to external developments
2023	Prototype ngVLA antenna to VLBA fringes	Part of ngVLA antenna design verification
2023	VLBA operational at 8 Gbps	
2025	SRDP pipeline for VLBA available	
2028	Full bandwidth (10+ Gbps) fiber to all stations	Subject to affordability
2031	First production LBA ngVLA antenna installed	At or near existing VLBA site
2034	ngVLA LBA complete	VLBA transition to ngVLA

Summary

At 26 years of age, VLBA observations continue to contribute, often in unexpected ways, to current astronomy topics. It is extremely well poised to respond to triggers in time-domain astronomy, including FRBs and gravitational wave events. In the next decade the VLBA will contribute to the understanding of binary neutron star mergers, will add critical independent measurements to aid in resolution of the Hubble Constant tension and will further inform our understanding of the structure of the Milky Way Galaxy. Most excitingly, the VLBA will contribute to understanding of phenomena yet to be discovered.