The VLBA Upgrade Study

Jonathan D. Romney
NRAO, Socorro

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This memorandum re-issues slides originally presented at an NRAO Long-Range Planning Retreat at Green Bank on 1999 April 23. This presentation concentrates on the science drivers for a VLBA Upgrade developed during an in-house VLBA Upgrade Study. It is re-issued in the Sensitivity Upgrade Memo Series as background material, to demonstrate both the continuity of the current effort, and the contrast in some important details.

The VLBA Upgrade Study

Jonathan D. Romney

National Radio Astronomy Observatory
Socorro, New Mexico

NRAO Long-Range Planning Retreat

1999 April 23

Motivation

The VLBA Has Been Operating Full-Time for Five Years

It has revolutionized VLBI observing techniques and achievable science.

But it has also shown us science that can't be done with the existing system, and areas where improvements are urgently needed.

It's Time Now to Begin Planning a VLBA Upgrade

We believe we can form a good picture now of what we want the VLBA to be able to do in 5 years; 10 years.

Possibilities for symbiosis with VLA Expansion can only be exploited with relatively well-developed VLBA Upgrade plan.

We Recently Launched a VLBA Upgrade Study in Socorro

This is a report on very early considerations, and a request for Observatory-wide input.

Outline

Background: VLBA Achievements

Fundamental Scientific Requirements

Derived Technical Requirements

Development Plan

Background: VLBA Achievements

The VLBA Has Been Operating Full-Time Since 1994

It Has Revolutionized VLBI Techniques and Achievable Science

Phase-Referenced Imaging

Previous observations limited by coherence time of maser frequency standards, and of atmosphere.

VLBA's phase referencing capabilities allow unlimited integration.

Large fraction of current observations use phase referencing technique.

Enables imaging of much fainter sources,

Enables precision relative astrometry, proper motion studies, etc.

Full Polarization Interferometry

Previously only possible at a few frequencies, on a few telescopes; difficult to organize, correlate, calibrate and analyze.

VLBA routinely observes and correlates.

Polarization observations now being done by non-specialists.

Enables study of magnetic environment of both VLBI-scale jets and compact cores.

Targets of Opportunity

Previously impossible.

VLBA has been able to observe within days of gamma-ray bursts, flares in Galactic superluminals, etc.

Enables study of unique, rapidly-evolving phenomena.

Frequent Monitoring Observations

Previously could not obtain more than 4 images in a year (or three images in one month).

VLBA has produced a movie of 46 images covering nearly 2 years.

Enables detailed study of evolving structures with hundreds of features.

Background: VLBA Achievements

(Continued)

Fully Agile Frequency Switching

Previously could not get more than 2–3 frequencies in a year.

VLBA has observed in 6 bands within a few weeks, could do more frequently if necessary.

VLBA often interleaves 2 or 3 bands in one observation.

Enables study of simultaneous radio spectra over two decades.

Enables reliable study of spectral indices, turnovers, cutoffs, etc.

High Throughput of High Quality Observations

Previously obtained occasional, low-sensitivity, uncalibratable result, six months after observation.

VLBA routinely produces excellent results, at significantly higher sensitivity, with excellent calibration, within a few weeks of observation — and as frequently as required by scientific goals.

VLBA has vastly simplified process of proposing, scheduling, and analyzing VLBI observations.

Has provided enormous quantitative enhancement across the entire range of scientific areas accessible to VLBI.

But In the Process, These VLBA Achievements Have Revealed Science the Existing VLBA System Can't Do

VLBA Upgrade Study
Science Requirements

Studies of AGN "Jet Launching Regions"

Jet motions beyond collimation region now well studied in many sources.

But motions closer to core show accelerations, velocity vectors unaligned with collimated jet, brightening waves.

Polarized-intensity structure shows even more chaotic motions.

VLBA has only been able to study this region in a handful of sources. Faint "underlying channel", observed in one (3C84), would not be detectable in most sources, leaving only peaks.

More and better observations require higher continuum sensitivity, especially on short baselines to detect low surface-brightness structure, and on all baselines to image polarized intensity.

Blazars with Gamma-Ray Flares

Flares thought to be associated with production of new superluminal components in inner radio jets.

GLAST expected to detect several thousand such flares.

Target-of-opportunity observations at 86 GHz should allow imaging of new components within inner milliarcsecond of core.

Continuum sensitivity of 100 mJy, at 86 GHz, would make several hundred sources available.

Location and Velocity of Gamma-Ray Burst Blast Waves

VLBA observations of gamma-ray bursters pinpoints their birthplace within the host galaxy.

Only two (G970508 and G980703) have been detected by VLBA so far.

More continuum sensitivity (factor of 2) should increase number detectable.

Sufficiently long monitoring should allow measurement of the relativistic blast wave velocity.

Current VLBA can monitor for only about 100 days.

More significant increase in continuum sensitivity (factor of 5) should allow monitoring for 6–7 years.

VLBA Upgrade Science Requirements

(Continued)

Mapping Ionized Gas in AGN Cores — I

A few AGNs (3C84, Mrk 231, Mrk 348) are known to show free-free absorption up to $\sim$10 GHz, against one side of dual jet structures.

Gas distribution believed to be toroidal or disk-like.

Such absorption could not be observed currently in most Seyfert galaxies because cores are too weak at high frequencies.

Might need continuum sensitivity of 50 μJy at 1–5 GHz.

Accurate measurement of free-free absorption requires nearly continuous frequency coverage over 1–5 GHz.

Mapping Ionized Gas in AGN Cores — II

To search for more cases, need to detect sub-parsec jets in nearby Seyferts at 43 GHz, obscured by gas at lower frequencies.

Reasonable search times require unreasonable sensitivities!

Would like to reach at least 100 μJy per beam at 43 GHz.

Mapping Ionized Gas in AGN Cores — III

Some AGNs have extremely high Faraday rotation measures, up to 40,000 rad m^{-2}, often unresolved and coincident with core.

Current sensitivity limits resolution achievable.

Factor of 2 increase in continuum sensitivity would enable measurement of RM at 22 GHz.

Factor of 5 increase would reach 43 GHz, and RM up to 5 Mrad m^{-2}.

VLBA Upgrade Science Requirements

(Continued)

Studies of Galactic "Microquasars"

Galactic superluminals have accretion disks, hot coronae, and relativistic synchrotron jets optically thick from radio to IR.

Opportunity to study many aspects of QSO phenomenon close up.

Thought to contain black holes of $\sim 10 M_{\odot}$; evolve on timescales $\sim 10^4$ faster than AGNs powered by massive black holes.

Observed structure changes on timescale of hours.

Best observed at highest frequencies to minimize Galactic scattering.

Improved observations require more continuum sensitivity, higher spatial resolution, and denser (u, v) coverage.

Line Absorption Against Compact Continuum Sources

Probes fine-scale transverse structure of absorbing gas, along entire line of sight.

Technique can sample gas to high redshift.

HI absorption lines typically very narrow; molecular (CO, formaldehyde) absorption expected also to be narrow.

Recombination lines may be broad.

"Continuous" frequency coverage required; 300–1200 MHz for redshifted HI; 20–50 GHz for molecular lines.

More spectroscopic sensitivity required to sample many lines of sight.

VLBA Upgrade Science Requirements

(Continued)

Cosmological Distance Scale — I

Transverse motions of two-sided jets set constraints on H_0.

Compact Symmetric Objects (CSOs) are best candidates for assumed simultaneous ejections.

Has only been possible to monitor one case (1946+708) so far.

More continuum sensitivity would (factors of 2–5) would allow monitoring of larger samples (10–50 sources).

With a large enough sample, could derive measure H_0 and q_0.

Cosmological Distance Scale — II

Observations of both transverse and radial motions, or transverse motion and radial acceleration, of masers in accretion disk allow direct measurement of H_0.

Has only been possible for one source (NGC 4258) so far.

More spectroscopic sensitivity would allow more cases to be measured, and show (lack of) dispersion in method.

Cosmological Distance Scale — III

Time delays of variations among gravitational lens components allow measurement of distance to lens and thus H_0.

VLBA ideal because: spatial resolution well matched; configuration fixed; frequent monitoring (∼3-day timescale) possible.

Multiple compact components provide additional measurements through relative positions.

Has only been possible to monitor a small number (one?) of relatively bright lenses.

Most lenses discovered in CLASS survey have fluxes of ∼mJy.

Major uncertainty is model of gravitational potential of lensing object; can be improved by constraints based on milliarcsec-scale structure.

More continuum sensitivity required to observe enough lenses for good H_0 measurement, and to improve models of gravitational potential.

VLBA Upgrade Science Requirements

(Continued)

Astrometry, Parallax and Proper Motion of Galactic Objects

Tie radio and optical reference frames.

In addition to distances, pulsar parallaxes and proper motions yield constraints on origins of high-speed pulsars, calibration of Galactic electron density models.

Proper motions of masers in SNR shocks yield expansion speeds and distances.

Currently able to do pulsars to about 1 kpc.

More continuum and spectroscopic sensitivity required, especially at higher frequencies, to enlarge sample.

Much more sensitivity required for frame tie!

Wideband frequency coverage, 800 MHz–2.3 GHz (possibly including L/S band dual-frequency capability) required for ionospheric calibration.

Extragalactic Astrometry

Measure parallactic distance to M31.

Measure proper motion ("sloshing") of central black hole in the potential well.

MicroJansky sensitivity required!

Same ionospheric calibration requirements as for Galactic case.

ARISE Space VLBI Mission

Science requirements will be presented in a separate talk.

May provide some non-NSF funding for VLBA Upgrade.

VLBA Upgrade Study
Technical Requirements

. . . As Abstracted from Science Requirements

Greater Continuum Sensitivity

Can be achieved through more collecting area, say 6–10 additional antennas. Distribution of antennas discussed below.

Can be increased further through greater bandwidth — but likely to be limited by recording system.

— Plan for 128 MHz RF BW per polarization, already under development, would provide up to 2-fold increase in sensitivity. Might be achievable in 5 years.

— Goal of 1 GHz RF BW per polarization matches ARISE target, provides 3–6-fold increase in sensitivity. Might be achievable in 10 years.

— Goal of 8 GHz RF BW per polarization matches VLA Expansion target, provides 8–16-fold increase in sensitivity. Would probably require dedicated fiber network.

Greater Spectroscopic Sensitivity

Can be achieved only through more additional antennas.

Greater Low-Brightness Sensitivity

Requires at least some new antennas located close to VLA: thus identical to VLA "A+" antennas.

Greater Spatial Resolution

Requires at least some new antennas located beyond US territory.

Some "new" antennas might include dedicated VLBI antennas already operating in European countries, if we want to establish an "International VLBA".

Other new antennas required in Canada or South America; possibly at ALMA site.

Continuous Frequency Coverage

Particular ranges of interest: 300–1200 MHz; 800 MHz–2.3 GHz; 1–5 GHz; 20–50 GHz.

Additional dual-frequency pairs may also be necessary.

VLBA Upgrade Technical Requirements
(Continued)

New Signal Processing Systems

. . . required to support higher bandwidth, additional antennas.

New recording system — including automated tape changing.

New correlator.

Still Under Discussion

Additional antenna(s) at each VLBA site?
- Small phase-reference antenna.
- ALMA (-type) antenna.
- Low-frequency antenna.

New dual-frequency dichroic systems?

Fiber links to replace entire recording system!?

Greater spectral resolution?

Symbiosis with VLA Expansion

VLBA Upgrade likely to have many technical requirements in common with VLA Expansion.

One element, the "A+ SubArray", is will be available to both at no significant extra cost. VLA Expansion's requirements for number and siting are more exacting, should take precedence.

IF/baseband signal electronics could have substantial commonality.

New correlator (if separate from VLA Expansion correlator) could be built as *third* in parallel with ALMA and VLA Expansion.

Dual functionality should be kept in mind in design of equipment for either upgrade.

VLBA Upgrade Study
Development Plan

Initial Exploration

Currently still gathering science requirements from NRAO staff.

Community Input

Plan to continue initial exploration through June.

Then start soliciting input from VLBA user community *and* more general astronomical community.

Assemble "Pre-Proposal"

Probably maintain as hypertext document on NRAO web site.

Preliminary version must be available in time for inclusion in AUI re-bid proposal to NSF.

International Meeting

Tentatively planned in January 2000.

To develop scientific and technical requirements further.

Goal is to have a solid proposal available by mid-2000.

Your Input Welcome *Now!*