Summary Information for the NSF Senior Review and its Relation to NRAO Facilities

This document provides links and background information concerning the NSF AST Senior Review and summarizes key points in the NRAO Response to the Senior Review. This information may be of use in composing correspondence to the Senior Review Committee.

1. Background

The NSF seeks to redistribute $30M / yr in Astronomy Division funds by FY2011 to allow progress on the recommendations of the Decadal Survey and more recent studies such as "Connecting Quarks to the Cosmos," in areas such as ALMA operations and new initiatives such as GSMT, LSST, SKA, etc.

Further information and links to other NSF documents may be found at the NSF AST Senior Review web site
http://www.nsf.gov/mps/ast/ast_senior_review.jsp .

The NRAO response to the Senior Review (31 July 2005 document) is posted on the web at http://www.nrao.edu/pr/NewsColumn/SeniorReview/NRAOSeniorReviewWeb.pdf .

The email address for comments on the Senior Review to the NSF and the Senior Review Committee is
astsenior-review@nsf.gov .

NRAO would appreciate comments and suggestions regarding the Senior Review and copies of correspondence sent to the NSF concerning the review. NRAO will not forward any emails it receives. NRAO's email address for correspondence concerning the Senior Review is senreview@nrao.edu . Private comments by email or telephone to the NRAO Director, Fred Lo, or Deputy Director, Phil Jewell, are also welcome.

2. Facility Stature and the NRAO Mission

- Each of NRAO's existing facilities, the GBT, VLA, and VLBA (and the future ALMA) <u>is the best facility of its type in the world</u>, with regard to every significant observing metric including sensitivity, angular resolution, frequency coverage, and flexibility.

- NRAO's primary mission is to "design, build, and operate large radio telescope facilities for use by the scientific community." Without exception, each NRAO telescope is a major, world-class facility that fills an essential portion of astronomical parameter space. NRAO facilities are complementary to each other and to major facilities at other wavelengths. NRAO's infrastructure and technical expertise make the construction and operation of these and future large facilities possible.

- In recent years, NRAO has already voluntarily closed or transferred to external organizations all its older, smaller facilities, specifically including the 140 Foot, the 12 Meter, and the Green Bank Interferometer.

3. Summaries of Facility Performance and Observing Capabilities

(Excerpted from the NRAO Senior Review Response of 31 July 2005)

Summaries of facility performance or specifications for the GBT, VLA/EVLA, VLBA, and ALMA follow.

GBT:

- Largest fully steerable single-dish telescope in the world.
- The only large telescope having an unblocked aperture.
- Low elevation limit makes 85% of the entire celestial sphere accessible and allows long observations for monitoring transient events, pulsar timing, and VLBI.
- Low-RFI environment thanks to terrain shielding and the unique National Radio Quiet Zone, allowing unique HI and pulsar observations. This offers access to frequencies which might not otherwise be observable, gives greater sensitivity for continuum and pulsar observations, and greater opportunity to observe spectral lines both at rest and redshifted throughout the spectrum.
- Highest pulsar sensitivity of any fully steerable telescope.
- Continuous frequency coverage from 290 MHz–52 GHz (λ = 6 mm to 1 m) currently, to 115 GHz (λ = 2.6 mm) in the future.
- Large effective collecting area (~2,000 m^2) and focal plane capable of accepting feed arrays having thousands of pixels at λ = 3 mm.
- Possibly the best imaging capability of any single-dish radio facility owing to the offset optics; high-fidelity wide-field HI imaging capability.
- The large diameter (in wavelengths) of the filled aperture results in a unique combination of high sensitivity and resolution for point sources plus high surface-brightness sensitivity for faint extended sources.
- Active programs for university instrument development collaborations and for student support.

VLA/EVLA:

- 27, 25-m Telescopes.
- Frequency coverage to 50 GHz.
- Spatial resolution to 40 milliarcseconds at 40 GHz.

VLA enhancements since original construction:

- The λ = 3.6 cm (8.4 GHz) receiving system funded by NASA in the late 1980s.
- The recently completed λ = 7 mm (43 GHz) receiving system jointly funded by Mexico, Germany, and the NSF.
- Beam-forming capability for observing as an element of a VLBI array.
- A fiber-optic link to the Pie Town VLBA antenna, providing an improvement by a factor of two in resolution.

EVLA specifications and observing enhancements:

- Continuum sensitivity improvements from up to a factor of 5 for λ > 3 cm (< 10 GHz) to more than 20 between λ = 3 and 0.6 cm (10 and 50 GHz).

- Operation at any wavelength from λ = 0.6 to 30 cm (1.0 to 50 GHz) yielding two pairs of signals, each pair with opposite polarizations and up to 4 GHz bandwidth, independently tunable to any frequency within any given band.
- A flexible new correlator which will provide over 16,384 frequency channels, process the full EVLA bandwidths, and give frequency resolution better than 1 Hz if necessary.

VLBA:

- Ten identical antennas, with a distribution of antenna locations specifically chosen to optimize aperture-plane coverage and to take advantage of the large additional collecting area of the VLA.
- Routine operation of the array on an unattended basis, with minimal staff (two site technicians) required to perform routine maintenance at each antenna location.
- A dedicated data processor (correlator) matched to the characteristics of the antennas and their recording systems.
- An overall maintenance/operations plan that exploits economies of scale using VLA staff located in Socorro, New Mexico.
- Only full-time telescope imaging objects on sub-milliarcsecond scales.
- Only VLBI instrument that can repeat identical observations on time scales from days to years.
- Only VLBI instrument with identical, commonly calibrated antenna and telescope systems, permitting relatively easy image production.
- Time sampling and common calibration permitting both global and local astrometry with accuracies as good as 10 microarcseconds.
- Only VLBI instrument with excellent sensitivity and imaging characteristics at short wavelengths (1.3 and 0.7 cm, or 22 and 43 GHz), with some imaging capabilities at $\lambda \approx 3$ mm (86 GHz).
- Only VLBI instrument with full-time dynamic scheduling, enabling access to high radio frequencies under the best conditions plus rapid response to time-critical targets such as outbursts of galactic microquasars.
- Sky coverage ranging from the North Pole (90 degrees declination) to about -45 degrees declination for most telescopes, 85% of the sky.

Enhancements (existing or in progress):

- The High Sensitivity Array, consisting of the VLBA, GBT, Arecibo, and Effelsberg.
- Conversion to Mark 5 disk-based recording technology which increases recording time and bandwidth.

ALMA Specifications:

- 10-100 times more sensitivity and 10-100 times better angular resolution than current mm/submm telescopes.
- Located in the Atacama desert in northern Chile at 5000 m elevation, the best accessible site in the world for submillimeter astronomy.
- Up to 64 12 m antennas plus a compact array of 12, 7 m antennas.
- Frequency coverage from 31 to 950 GHz (1 cm to 0.3 mm).
- Spatial resolution of 40 milliarcseconds at 100 GHz, 5 millarcseconds at 950 GHz.
- Point source sensitivity of 1.6 mJy in 1 second, or 8 μJy in 8 hours.

- Will be completed in 2012.
- User support provided through the North American ALMA Science Center.

4. Science Highlights and Potential

GBT Science Highlights:

- Discovery of 27 new millisecond pulsars in the globular cluster Terzan 5, several of which are exotic objects that constrain general relativity and the physics of superdense quark-gluon plasmas.
- Discovery of molecular line emission from high-redshift galaxies, including HCN emission at z = 2.3, CO emission from z > 4 objects, and water-maser emission from a Type 2 quasar at z = 0.66.
- Discovery of discrete neutral hydrogen (HI) clouds in the Galactic halo and the remnants of building blocks for M31 that refine theories of Galactic structure and the origin of high-velocity clouds.
- Discovery of new pre-biotic interstellar molecules and a cold repository of the simplest member of the sugar family, shedding light on the origin of the chemistry of life.
- Determining the nature of the core of Mercury, through bistatic radar observations with Goldstone.

Science Potential of the GBT:

With future large format arrays:

- Making high-resolution images of young star-forming regions and starless cores. These sources often show unique features only at certain wavelengths, such as clumps of N_2H^+ that reveal the presence of cold material not seen in the continuum by interferometers.
- High-resolution imaging of Sunyaev–Zeldovich (SZ) clusters at redshifts z > 1 to help determine their dynamical states, important for mass estimation and subsequent cosmological tests.
- Searching for SZ signatures from large X-ray cavities in cluster cores or in AGN jets.
- Deep surveys for high-redshift star-forming galaxies. Galaxies similar to Arp 220 in the redshift range 5 < z < 8 should have flux densities ≈ 100 μJy at λ = 3 mm. The Penn Array will be able to cover 10 arcmin^2 with 10 μJy beam^{-1} rms noise in 5 hours. A 6,400-pixel array would cover 1 deg^2 in 18 hours, making the GBT among the fastest telescopes for finding z > 7 galaxies.

With large bandwidth spectrometers and pulsar backends:

- Detection of high redshift galaxies using spectrometers covering entire wavebands (such as the UMd/NRAO Zpectrometer which will cover the entire 26-40 GHz receiver band at once).
- Deep astrochemistry observations covering multiple spectral lines in single observations.
- Wide bandwidth pulsar observations at S-Band and higher frequencies that maintain sensitivity, but minimize the effects of Galactic Plane dispersion.

VLA Science Highlights:

- The presence of ice at the north pole of Mercury.
- Images resolving the extended coronae of supergiant stars such as Betelgeuse.
- Discovery of superluminal motion in galactic microquasars.
- The fundamental structures at the center of the Milky Way galaxy on many different scales.
- Physics and images of a wide variety of jets in radio galaxies and quasars.
- Numerous gravitational lenses, including Einstein rings.
- Afterglows, hosts, and energetics of gamma-ray bursts.

EVLA Scientific Potential:

- The only full-time astronomical interferometer combining a complete coverage of centimeter wavelengths down to λ = 0.6 cm, sub-arcsecond resolution, and a large number of antennas. This provides excellent instantaneous two-dimensional aperture-plane coverage for outstanding snapshot imaging in addition to Earth-rotation aperture synthesis.
- Continuous wavelength coverage from λ = 6 mm to 30 cm (1 to 50 GHz).
- Sampling of all angular scales from 50 milliarcseconds through many arcminutes by means of the wide wavelength span and the use of the four principal configurations.
- Beam-forming capability providing the sensitivity of a 130 m single dish for VLBI observations.
- Sky coverage ranging from +90 degrees to -47 degrees declination, 87% of the sky.
- Scientific observing day and night, year-round, with dynamic scheduling.
- Three proposal opportunities per year plus rapid-response capability for the most time-critical astronomical observations.
- Production of calibrated data and reference images for all observations made in straightforward "standard modes".

VLBA Science Highlights:

- Measurement of the geometric distance to the Seyfert galaxy NGC 4258 and a direct measurement of the mass of its central black hole.
- Imaging the superluminal motions of gamma-ray blazars, and relating them to their gamma-ray emission, with full polarization capabilities.
- Detection of the proper motion and measurement of the three-dimensional velocity of the galaxy M33 in the Local Group.

VLBA Scientific Potential:

- Direct imaging of the expansion of several supernovae and one GRB afterglow in external galaxies, as well as imaging the distributions of individual recent supernovae in obscured starburst galaxies such as Arp 220.
- Measurement of the proper motion of Sgr A* and demonstrating its coincidence with the massive black hole at the center of the Milky Way.

- Imaging the collimation of a radio jet within 100 Schwarzschild radii of the massive black hole in an AGN.
- Measurements of parallaxes and proper motions of pulsars and X-ray binaries (microquasars), providing their distances and inferences about their birthplaces and the physics of their formation in supernova explosions.
- Anchoring the orientation of the universal quasar inertial reference frame with 20 microarcsecond accuracy.

ALMA Scientific Potential:

- The ability to detect spectral-line emission from CO or CII in a normal galaxy like the Milky Way at a redshift of $z = 3$, in less than 24 hours of observation.
- The ability to image the redshifted dust continuum emission from evolving galaxies at epochs of formation as early as $z = 10$.
- The ability to image the gas kinematics in protostars and in protoplanetary disks around young Sun-like stars at a distance of 150 pc (roughly the distance of the star-forming clouds in Ophiuchus or Corona Australis), enabling the study of their physical, chemical, and magnetic-field structures and to detect the tidal gaps created by planets undergoing formation in the disks.
- The ability to provide precise images at an angular resolution of 0.1 arcseconds. Here the term "precise image" means being able to represent correctly, within the noise level, the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness.