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National Radio Astronomy Observatory Response to the 2012 NSF Portfolio Review Committee Report

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INTRODUCTION

The National Radio Astronomy Observatory (NRAO) is a national scientific resource for astronomy. The Observatory's radio telescope suite includes the Atacama Large Millimeter/submillimeter Array (ALMA), Karl G. Jansky Very Large Array (VLA), Robert C. Byrd Green Bank Telescope (GBT), and the Very Long Baseline Array (VLBA). These research facilities are a synergistic, operationally-coordinated group of unique instruments that embody US global leadership in radio astronomy and complement current and planned major astronomical research tools, both space-borne and ground-based.

NRAO facilities enable fundamental astronomical research across a vast wavelength range: 0.3 mm to 1m. While individually unique, these facilities are also complementary. The recently completed Jansky VLA will be the most powerful and versatile cm-interferometer for at least the next decade. The GBT provides sensitive single-dish wide-field imaging and spectroscopy up to 3mm, and is the premier pulsar-timing instrument. The VLBA performs imaging and astrometry with the highest available spatial resolution and precision, and provides earth orientation and rotation information to support civil and defense applications. The soon-to-be completed ALMA represents a quantum leap in millimeter astronomy that is already opening exciting discovery space on the thermal cosmos.

Together, recent and continuing developments at the VLBA and GBT, and the new VLA and ALMA facilities, are delivering to the community more than an order of magnitude improvement in observational capabilities, including sensitivity, sky coverage, spatial resolution, and spectral coverage and resolution. Used individually or in combination, NRAO telescopes are well-suited to address many of the science themes of the National Academy of Science's Decadal Survey of the US astronomical community, *New Worlds, New Horizons* (*NWNH*), including placing constraints on the nature of Dark Energy, gravitational radiation, imaging the first galaxies in the Universe during the epoch of reionization, and directly observing the formation of planets in proto-planetary disks.

Since the August release of the National Science Foundation (NSF) Portfolio Review Committee (PRC) report, *Advancing Astronomy in the Coming Decade: Opportunities and Challenges (AACD)*[1], NRAO has received many expressions of deep concern from the US and international astronomy community regarding the report's recommendations and conclusions. Our internal review of *AACD* revealed several areas where additional information, not readily available to the PRC analysis, would improve the clarity of the discussion.

This response to the PRC report is intended to summarize for the community and the NSF the impacts of the loss of these facilities and programs, the subsequent reduction of opportunities for original research by US scientists, and the overall negative impact on the scientific enterprise in this country. It examines the PRC assumptions, constraints, and conclusions, and in some areas offers different conclusions and opinions; we do not exhaustively list all the science and instrumental development occurring on these instruments that may have been overlooked by the committee. Our goal is to assist the community and NSF-AST in making the critical decisions that will determine the future course of US and global astronomy.

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[1] http://www.nsf.gov/mps/ast/portfolioreview/reports/ast_portfolio_review_report.pdf

The primary PRC recommendations that impact NRAO are the proposed divesture of the Green Bank Telescope and Very Long Baseline Array, and, indirectly, the elimination of University Radio Observatory program support by 2017.

If implemented by the NSF, these recommendations would leave the US astronomy research community in a substantially weakened position. In our opinion US leadership in radio astronomy would diminish, critical scientific capabilities that cannot be replaced with other existing open-access facilities in the US or elsewhere would be surrendered, and there would be a reduction of the university community's ability to train outstanding young scientists and engineers. A wide range of research programs that address high priority science themes from *NWNH* and the Planetary Science Decadal Survey, *Visions & Voyages (V&V)*, would be prematurely terminated. Radio wavelength access for university faculty and students across the US would be severely reduced as over-subscription rates at the remaining facilities increased. Innovative instrument development programs underway or planned on the GBT and VLBA would be left unfinished, including development that sustains university instrumentation labs, fosters the next generation of radio wavelength instrumentation builders, and improves the science impact of existing NRAO telescopes.

The NRAO mission mandates the operation and development of forefront facilities. When NRAO facilities are no longer world leading, they are decommissioned. Thus, over the past two decades NRAO has retired several major observing facilities from the NSF funding portfolio, including the Green Bank Interferometer, the 140 Foot Telescope, and the 12 Meter Telescope. In addition, NRAO has recently secured partnership operations funding for the VLBA that now amounts to nearly one-third of the total operations costs, and we are actively seeking similar partnerships for the GBT.

We reiterate our support for the Portfolio Review principles. The PRC deliberated under a narrow charge and a set of highly constrained budget scenarios provided by NSF-AST; addressing these scenarios necessitated extremely difficult choices. We emphasize our support for the key objectives of *NWNH* and *V&V*, which included not only securing resources for major new initiatives but also pursuing major research projects requiring, in some cases, the very facilities now proposed for divestiture.

We acknowledge the PRC's strong endorsement of the VLA and ALMA as cornerstones of the US astronomy portfolio moving into the next decade. These are revolutionary facilities that will maintain US leadership in interferometry for the foreseeable future. We also acknowledge the *AACD* report's endorsement for the National Observatory concept as best representing the US interests in large international projects.

Sections 1 and 2 describe GBT and VLBA science programs and technical capabilities that address *NWNH* and *V&V* science themes but were incompletely considered by the PRC. Section 3 examines several PRC recommendations relevant to the health of the profession. This document is primarily aimed at the scientific and technical communities potentially impacted by NSF implementation of the PRC recommendations, but may also be of interest to the general public and other interested parties.

1. THE GREEN BANK TELESCOPE

The NRAO Green Bank Telescope's (GBT) 100-meter diameter collecting area, unblocked aperture, and excellent surface accuracy provide unprecedented sensitivity across the telescope's full 0.1-116 GHz operating range. The GBT is fully steerable, and 85% of the celestial sphere is accessible. GBT's scientific strengths include its flexibility and ease of use, allowing for rapid response to new scientific ideas. The telescope is dynamically scheduled, matching project needs to the available weather. GBT's high sensitivity mapping capability complements high angular resolution interferometers, such as ALMA, VLA, and VLBA. The GBT is also readily reconfigured with new or experimental hardware, and is used by university groups for instrument development. *The NRAO Green Bank Telescope (GBT) is one of the world's most capable single-dish radio telescopes.*

1.1 GBT Science Themes

This section highlights GBT science programs that address *NWNH* and *V&V* science themes and may not have been fully considered by the PRC.

Pulsars

NWNH identified gravitational wave astronomy as a key science frontier discovery area. Pulsar timing arrays probe fundamental physics in a very cost-effective manner, and will likely enable a direct detection of gravitational waves (GWs) by the North American NanoHertz Observatory for Gravitational Waves (NANOGrav) in a part of the GW spectrum complementary to Advanced LIGO and on a similar timescale. About half of NANOGrav's GW strain sensitivity derives from the GBT's combination of sensitivity and sky coverage; the other half derives from Arecibo's point-source sensitivity. Large sky-area pulsar surveys are uncovering new millisecond pulsars (MSPs) that are important to NANOGrav and other science programs. GBT has discovered 100 of the 300+ known MSPs, and has been a leading contributor to a diverse range of other pulsar science. Owing to the relatively small number of known bright, stable MSPs, GBT's full sky coverage is crucial to NANOGrav success, and the telescope's excellent 350 and 820 MHz receiver systems and low-interference environment have enabled its MSP discoveries.

GBT is critical to NANOGrav and a vital component to US Pulsar research.

Dark Energy and Inflation

NWNH identified dark energy and inflation as frontiers of knowledge that can be advanced by astronomical observations in the coming decade. Baryon Acoustic Oscillations (BAOs) serve as an indicator for the effect of dark energy on the expansion of the Universe. The 21cm Intensity Mapping technique, developed at the GBT, is an independent technique for measuring BAOs that may have lower systematic biases compared to other techniques. Intensity Mapping is expected to yield a 3D view of the large-scale neutral hydrogen (HI) fluctuations and a precision measurement of the Universe's expansion history when dark energy started to dominate its energy content. Proof-of-concept GBT observations have demonstrated the feasibility of this technique, and a multi-beam receiver for large-scale observations is under development. Situated in the National Radio Quiet Zone and equipped with this multi-beam receiver, GBT will make essential, independent contributions to the measurement of BAO and dark energy parameters in a rapid and cost-effective manner.

GBT capabilities make it a forefront instrument for large-scale 21cm BAO surveys at redshifts ~1.

Galaxy Cluster Physics and Cosmology

NWNH highlighted the importance of galaxy clusters as probes of gravity and dark energy, and of understanding the exchange of gas between galaxies and the surrounding intergalactic medium. The Sunyaev-Zel'dovich Effect (SZE), measured at radio wavelengths, is a valuable probe of galaxy clusters, the intra-cluster medium, and cosmological parameters. The 3mm MUSTANG bolometer camera on the GBT is a university-NRAO collaboration that has redefined the state-of-the-art in studies of galaxy clusters using the SZE, enabling routine imaging of the SZE with sufficient sensitivity and angular resolution to identify and characterize individual structures in the intra-cluster medium at 10 arcsec angular resolution. Other SZE instruments typically have resolutions exceeding 1 arcmin. A new version of MUSTANG is currently under construction to continue this important work.

GBT plays a leading role in innovative SZE science with galaxy clusters and cosmology.

Molecular Gas and Neutral Hydrogen

NWNH reinforced the fundamental importance of advancing our understanding of the origin and evolution of galaxies. Radio-wavelength observations of molecular gas and dust are critical probes of the interstellar medium in galaxies in the early Universe, and are key to understanding their formation and evolution, probing the cool atomic and molecular gas that is inaccessible to other wavelengths and techniques. The CO (J=1-0) transition at 115 GHz is the most sensitive, robust tracer of the total molecular gas mass over a wide range of conditions in molecular clouds, while neutral hydrogen emission traces gas flows within and between galaxies. The large collecting area and accurate surface of the GBT combined with its wide frequency coverage make it the only telescope able to perform "blind" CO (J=1-0) searches to determine redshifts and gas content at all redshifts accessible from the ground. The GBT is also the most sensitive telescope for detecting 21cm emission from faint diffuse HI. With its filled, unblocked aperture and location in the National Radio Quiet Zone, the GBT can routinely measure 21cm HI emission lines at the level of a few x 10^{17} /cm^2 with excellent spectral baselines.

Telescope design, siting and instrumentation make the GBT an order of magnitude more sensitive to neutral hydrogen emission than any other observatory.

The Galactic Plane is permeated with a web of dense filamentary clouds of gas and dust where future generations of stars form. Individual cores in these clouds are typically cold (10-15 K), so the spectral lines are brightest at mm and longer wavelengths. The critical angular scales range from an arcsecond to several arcminutes, requiring data from both a single dish telescope and an interferometer. One of the most fundamental tracers for studying dense molecular cores is ammonia (NH_3). This molecule is abundant, and can be used to create maps of the gas temperature and kinematics in regions of both low and high mass star formation. The state-of-the-art for NH_3 imaging combines the GBT for wide-field imaging with the VLA to focus on selected smaller areas.

The GBT is by far the world's best single dish telescope for mapping NH_3, allowing research that would take *prohibitively long on other instruments.*

Astrochemistry and Astrobiology

NWNH identified astrochemistry as a frontier of knowledge that can be advanced by astronomical observations in the coming decade, and identified the detection of biogenic molecules as a priority pursuit of the *NWNH* science implementation plan. Complex biogenic molecules are found on Earth, in comets, and in interstellar space. Their fundamental ground state rotational transitions occur at centimeter wavelengths, and provide the only way to uniquely identify the molecular composition of cold astronomical environments. Over the past eight years, GBT has searched for new molecules over very large spectroscopic bandwidths with almost continuous frequency coverage from 1-50 GHz (recently expanded to 93 GHz), and at very high signal-to-noise and spectral resolution. Since 2004, 18 of the 47 molecules discovered by rotational spectroscopy at cm- and mm-wavelengths were discovered at the GBT, including 4 "biogenic precursor" species. GBT is also acquiring a 300 MHz–50 GHz spectral line database toward Sgr B2(N), an important star-forming region near the Galactic Center.

GBT is an essential instrument for astrochemistry and astrobiology.

Comets

V&V identified comets as critical for understanding a host of scientific issues related to the formation of our Solar System. As remnants of the interstellar material that collapsed to form our Solar System, comets connect our understanding of interstellar medium chemistry to that of our Solar System and are key to the search for biogenic material in stellar systems. A major observational challenge in cometary science is to quantify the extent to which chemical compounds can be linked to an interstellar or protosolar nebular heritage. Radio-wavelength techniques are especially valuable for analyzing the material in cometary comas. The GBT, equipped with a 3mm spectroscopic camera under construction by a university partner lab, is well matched for studying comet physics. Cometary comas are typically spread over scales of ~10^5 km, or several arcminutes at one astronomical unit. Since comet structure can change within hours over multiple spatial scales, studies of comets require rapid measurements over a wide field-of-view with high sensitivity, broad bandwidth and high spectral resolution and with good spatial resolution.

The GBT, equipped with the mm-wave focal plane array camera now under construction by a university-NRAO collaboration, will soon be unsurpassed in its capability for rapidly imaging cometary emission.

1.2 GBT Technical Capabilities

This section provides additional clarification into GBT technical capabilities, and comments on PRC recommendations for transferring GBT science programs to other existing radio telescopes, such as the Arecibo 300m telescope, the Effelsberg 100m telescope, or the phased VLA.

PRC recommendation: Transfer GBT pulsar science to Arecibo or Effelsberg

Pulsar timing techniques regularly monitor a neutron star's rotation by tracking the arrival times of the radio pulses, precisely accounting for every rotation of a neutron star over years to decades. The factor of 3-4 sensitivity improvement of Arecibo compared to the GBT means that if Arecibo can see a pulsar it can "time" it better than the GBT. Arecibo, however, can only observe ~32% of the full sky compared to ~85% with the GBT, and for much of that area, the Arecibo tracking limits and/or zenith-angle sensitivity penalties are quite large. For projects like gravitational wave (GW) detection, which requires many pulsars distributed over the full sky, using only Arecibo would cause a dramatic (at least a factor of 2) reduction in GW strain sensitivity. The observing time penalty for GW detection that would result from the loss of the GBT depends on the amplitude of the gravitational background; if it were in the mid-range of current models, the loss of GBT would add 5-10 years to the expected detection date.

The VLA will soon be able to be phased over 1-2 GHz bandwidths to provide a high-precision pulsar timing capability. Unfortunately, VLA antenna optics design precludes the 0.1-1 GHz receivers required for dispersion measure monitoring for high-precision timing projects. At the GBT, 300 and 800 MHz receiver systems provides this crucial capability.

The VLA timing precision from 1-2 GHz will also be substantially worse than from the GBT, given the array's 50% lower sensitivity at these frequencies. The sensitivity loss could be compensated for by substantially increasing integration times with the VLA, however the observing time pressure on the VLA, which acquires _no pulsar data_ now, renders this impractical. To replace just the high-precision pulsar timing observations on the GBT with the phased VLA would require about 1500 hours of VLA time per year, or ~30% of the annual VLA science operations. Using one of the community's most capable imaging instruments as "single-dish collecting area" for four months each year would be a misdirection of the instrument's scientific mission.

We also note that wide area pulsar _searches_ at any frequency are impractical with the VLA. The GBT is, and will continue to be, the only North American radio telescope able to conduct pulsar surveys over the majority of the sky. A multi-pixel system on the GBT, of which the first will be tested in January 2013, will increase its capabilities even further.

We acknowledge that the Effelsberg 100m telescope could be used to replace some GBT timing observations. However, it suffers from similar limitations as the VLA for these purposes: it is not equipped with sensitive 0.5-1 GHz receivers, and its 1-2 GHz sensitivity is ~40% less than the GBT. The Effelsberg interference environment is also less favorable compared to the GBT, making timing and search observations more challenging. Finally, only ~40% of the Effelsberg telescope time is open access, and this is heavily used by European scientists as the telescope has excellent instrumentation in other areas, and an extremely strong science program.

The GBT best-in-class point source sensitivity, 85% sky coverage, excellent receivers below 1 GHz, and low-interference environment make transferring GBT pulsar science to Effelsberg or the phased VLA effectively impossible.

PRC Recommendation: Transfer GBT science to the phased VLA

The phased VLA is not a viable observing option for GBT science other than observations of isolated point sources or a small fraction of planetary radar experiments. Sensitive high-fidelity continuum and spectral line total power data (zero spacing data) depend on the collecting area and also the antenna beam response function (point spread function). For an unresolved source, the effective collecting area (taking into account the antenna efficiencies) dominates. Between ~4 and 50 GHz, GBT and VLA sensitivities are comparable, within about 20%. Unlike the GBT, the VLA does not observe above 50 GHz. Below about 1.5 GHz, VLA sensitivities are about half that of the GBT, but VLA is still sensitive to point sources. This is why phased VLA observations of pulsars with known positions are feasible.

However, if the source is resolved (extended), the beam response becomes a significant factor and limitation. The quality of the beam response of a single antenna is determined by the surface accuracy and the overall illumination design, and GBT's unblocked aperture is vastly superior in this regard compared to all other existing large telescopes, with a main beam to sidelobe level of 1000:1. In contrast, the quality of the beam response function of a phased array depends on the number and configuration of antennas in the interferometer. A relatively sparse array like the VLA cannot be used to map extended structure with any fidelity in the phased mode. Indeed, efficient phased array observing strategies (including software beam forming) are a key area of Square Kilometre Array (SKA) development and design driven by its planned large number of antennas.

As noted in *AACD*, the VLA in the cm wave regime, and ALMA in the mm/submm regime, will provide transformational spectroscopic and continuum capabilities at resolutions from a few milliarcseconds to a few arcseconds. However, since interferometers act as spatial filters, they yield no information for spatial scales corresponding to their shortest baselines. Using phased interferometers for wide-field mapping is fundamentally difficult and inefficient. Therefore, moderate angular resolution (few arcsecond to arcminute scale) cm to mm observations, such as those provided by the GBT, are essential. Some astronomical objects are inherently extended with little small-scale structure and can only be studied on moderate spatial scales. Many objects and science questions can only be addressed by assessing the full spatial range of material from the diffuse to compact such that combination of interferometric and single dish data is essential. We note that to deal with exactly this issue, ALMA has implemented the Atacama Compact Array and Total Power Arrays to support the main interferometer. For the Jansky VLA, the GBT is the primary resource for "zero/short spacing" data. In effect, this key point means that moderate resolution capabilities are required for the success of the high resolution capabilities deemed essential by *AACD*.

ALMA and VLA observing time are extremely competitive. The highest-ranked proposals are often those for which concrete examples or predictions for the proposed scientific gain can be unambiguously demonstrated based on previous lower resolution or sensitivity (or both) observations. In the coming decades, access to cm to mm single dish telescopes for US observers will plummet if the PRC recommendations are implemented. CCAT will provide some open access time for the US community, but it is unlikely to satisfy the broad demand that ALMA science will generate. Any shortage of preparatory observations will place US ALMA astronomers at significant disadvantages compared to our international colleagues.

GBT and VLA are complementary facilities: only a small fraction of GBT science is feasible with the phased VLA. Loss of GBT would severely disadvantage the US community for carrying out leading-edge cm and mm science.

PRC Recommendation: Use the Effelsberg telescope as a GBT surrogate at short λ

AACD suggests that, with divesture of the GBT, the Effelsberg telescope "is a route to the shortest wavelengths, albeit at lower sensitivity" and that "many of the GBT's capabilities are duplicated by other single dishes" with specific reference to Effelsberg, which has "40% open access." In fact, there are many crucial differences between the GBT and the Effelsberg 100m telescope (EB), particularly at high frequencies, that would make it extremely difficult for the US community to carry out their GBT science programs on the EB.

The GBT aperture efficiency at 3.3mm is 35%, compared to Effelsberg's 4%. In terms of collecting area, and assuming equal instrumentation, this factor alone implies that *Effelsberg is 8.75x less sensitive than the GBT at this wavelength, and projects on Effelsberg would require 76x more integration time to achieve the same sensitivity*. The GBT's remotely actuated reflector also corrects gravitational deformations, resulting in no measurable variation in gain above 20 degrees elevation, while Effelsberg incurs changes in gain at all elevations for λ < 2cm. Attempting to execute the GBT's short-wavelength science on EB would be extremely difficult, analogous to attempting 8-meter optical science with a 2.7-meter telescope.

The GBT unblocked aperture and off-axis feed arm design reduces systematics for observations at a wide range of frequencies by providing a clean beam, low sidelobes, higher aperture efficiency, reduced sensitivity to RFI at the horizon, and cleaner spectral baselines. Such systematic errors are fundamental limiting factors that make some classes of experiments impossible without the clean and simple data the GBT design yields. The GBT also sees significant clear, cold weather in the winter, with precipitable water vapor column densities below 10mm for ~2000 hours per year. This is considerably more favorable than the northern European climate.

To quantify the feasibility of moving GBT science to Effelsberg, the GBT science program executed in 2011 (6,658 observation hours) with each receiver was separately analyzed and the expected Effelsberg observing time was calculated, assuming full access to the 40% open access time fraction, and no weather constraints. This analysis indicated that 11 observing years would be required at the Effelsberg telescope to execute one year of GBT science. The 270 hours of GBT MUSTANG and 4mm science observations in 2011 would require more than 5 years to execute on the Effelsberg telescope. Since observations at 3mm are scheduled only in the best ~10% of GBT weather, these would require 55 observing years at Effelsberg, assuming similar weather. This is clearly not tenable: the vast majority of this science is only possible on the GBT.

We note that the 13,000 square-mile National Radio Quiet Zone and the GBT's remote location provide the lowest-RFI environment of any existing, major radio telescope. The nearest major populations centers are 200 miles distant (Washington DC, Pittsburgh). The Effelsberg telescope is much closer to several large population centers, including Bonn (15 miles), Cologne (30 miles), and Frankfurt (80 miles).

The Effelsberg 100m telescope is not a plausible surrogate for the GBT, particularly at short wavelengths.

2 THE VERY LONG BASELINE ARRAY

The NRAO Very Long Baseline Array (VLBA) is an interferometric array of 10 dedicated telescopes on continental-scale baselines of up to 8,600 km. The VLBA provides unique scientific capabilities for the community, delivering imaging resolutions of 0.1 mas and astrometric accuracies reaching 10 µas. The VLBA is carrying out a wide range of scientific programs that address *NWNH* science themes, together with essential national service functions. The US community pioneered very long baseline interferometry (VLBI), and the VLBA is vital to maintaining US leadership in key emerging discovery areas, such as high-precision astrometry and time-domain astronomy. Following NSF direction, over the past several years NRAO has engaged multiple foreign partners who now help fund VLBA operations. This funding is recognition of the array's scientific importance and value, and closing VLBA would cause a loss of US credibility in international partnerships. With modest continued investment by the NSF and our international partners, VLBA will continue to play a critical role in addressing the *NWNH* science themes through this decade and beyond. *The NRAO Very Long Baseline Array (VLBA) is the world's preeminent dedicated VLBI array, and has dominated the field over the past two decades.*

2.1 VLBA Science Themes

Due to technical upgrades and the ongoing interest of the US science community, the VLBA science program has evolved significantly in the 3 years since the *NWNH* science cases were developed. New VLBA results are impacting all of the *NWNH* broad science objectives – Cosmic Dawn, New Worlds, and The Physics of the Universe – providing answers and opening new lines of inquiry for the key questions and discovery areas highlighted by *NWNH*.

NRAO began a Large/Key science program to ensure that the most important science was being conducted, even if significant observing time were needed. These Large/Key Science Projects now comprise ~70% of VLBA observing hours. At the same time, the VLBA Sensitivity Upgrade also enhanced the array's ability to swiftly and flexibly observe smaller time-sensitive programs.

In the *AACD* report, the VLBA was seen to provide the critical capability "subarcsecond cm continuum follow-up to sources detected at other wavelengths." It also fulfilled several other "supporting" capabilities. In light of recent and near-future results enabled by the sensitivity upgrade, particularly in astrometry related programs, we can readily demonstrate that a number of these capabilities are more than just "supporting" and offer unique and compelling opportunities for *NWNH* science.

This section highlights several VLBA science programs that address *NWNH* and *V&V* science themes and were incompletely considered by the PRC.

Astrometry

NWNH identified astrometry as a key science frontier discovery area, and the VLBA's micro-arcsecond astrometric capability is producing an explosion of new scientific results. The Bar and Spiral Structure Legacy Survey (Reid et al), for example, is a 5-year project that is using new VLBA instrument and processing capabilities to accurately map the structure of the Milky Way via measurements of water and methanol masers in Galactic star forming regions.

A key to extracting astrometric science from the VLBA is the availability of medium to long-term sample monitoring. Over the next several years, a project to directly determine the distance to the Pleiades will resolve the "Hipparcos controversy" and make key contributions to the field of stellar evolution. Further, in less than 3 years the VLBA, working in conjunction with the VLA and the GBT, has the ability to measure the proper motion and geometric distance of the Andromeda Galaxy, and improve our understanding of Local Group dynamics. Another ongoing project is measuring distances and the three-dimensional structure of young, low mass star clusters in Gould's Belt. The VLBA has also already measured parallax distances and proper motions for 30 pulsars in our Galaxy, and has obtained the first accurate parallax distance to a black hole.

The VLBA has unsurpassed micro-arcsecond astrometric capability, providing critical independent data to calibrate a variety of distance-estimation methods.

Extra-Galactic Distance Scale and Dark Energy

NWNH identified an improved understanding of the origin and evolution of the universe, and the origin and physics of black holes as fundamental to future progress in astronomy. The Megamaser Cosmology Project (MCP), using observations of H_2O megamasers at 22 GHz with the GBT and VLBA, is a natural extension of the 1998 VLBA distance measurement to NGC 4258 that anchored the Hubble H_0 Key Science Project. The MCP has to date measured H_0 to 7%, will improve this measurement to the few-percent level in the coming years, and will use this result to help constrain the nature of dark energy.

This technique is probing galaxies distant enough to be within the Hubble Flow, and is the only technique that can bypass the standard distance ladder and directly (geometrically) measure H_0 at <3% uncertainty. The MCP is also determining accurate masses of the supermassive black holes (SMBH) at the cores of these galaxies. The SMBH masses obtained to date anchor the M-σ relation at lower masses, in particular for dust-shrouded systems where optical spectroscopy is not effective, and hint at a deviation for the relation for higher-mass systems. (We note the GBT is also a critical component of the MCP program, both for the discovery of new megamaser systems and as part of the High Sensitivity Array for VLBI follow-up).

The VLBA is directly (i.e. geometrically) measuring the Hubble Constant to < 3% uncertainty, constraining dark energy models, and is accurately measuring black hole masses.

Super-Massive Black Holes, Relativistic Jets, and Extreme Energetic Phenomena

NWNH identified understanding how black holes, grow, radiate and influence their surroundings as a key science frontier question. Observations of the relativistic jets seen in the cores of radio-loud Active Galactic Nuclei (AGN) were identified as important capabilities by *NWNH*. The VLBA is leading a revolution in our understanding of the physics around SMBH, and of extremely energetic events such as Gamma-Ray Bursts (GRBs) and Supernovae (SNe). The *Fermi* satellite has opened new windows on high-energy AGN, and ongoing VLBA programs – such as the Monitoring Of Jets in Active galactic nuclei with VLBA Experiments (MOJAVE) program and a variety of other sub-milliarcsecond imaging monitoring projects – are providing unique probes of the structure and polarization of the inner jet regions.

The recent discovery of a new class of Gamma Ray transients has been attributed to the long sought after "tidal disruption event" (TDE) caused by a star falling into a SMBH. VLBA observations have placed limits on the size of the expanding blast, constraining the Lorentz factor. Future VLBA observations will likely resolve the expanding radio source on timescales of ~2 years, which would confirm relativistic expansion. Late-time VLBA observations in the next few years will be critical to provide critical evidence for or against the TDE origin hypothesis. If confirmed, these events provide constraints on aspects of the growth and feeding of SMBH.

In the past, VLBI observations of radio supernovae (SNe) were limited by sensitivity, but the VLBI Sensitivity Upgrade has provided greatly improved capabilities for SNe studies.

VLBA is critical for understanding high-energy physics and for the direct determination of sizes, expansion velocities, and shapes of radio emitting regions.

2.2 VLBA Technical Capabilities

The VLBA has been re-invented in ways that maximize its scientific productivity and improve its flexibility and responsiveness, especially for science that takes advantage of the array's astrometric precision. Sensitivity and field-of-view limitations have historically impacted VLBI more than connected-element interferometry. Since the *NWNH* publication in 2009, the VLBA has significantly improved both of these metrics, creating an essentially new instrument. This section provides clarification and additional insight into VLBA technical capabilities.

VLBA Sensitivity Project

The VLBA Sensitivity Upgrade Project (https://science.nrao.edu/facilities/vlba/sensitivity) increased the sustainable VLBA bandwidth by a factor of 8, from 32 MHz to 256 MHz per polarization, which yields a substantial factor of 2.8 increase in sensitivity.

First science at this increased bandwidth began in February 2012; and the final new operations modes will be implemented by January 2013. The DiFX correlator now allows hundreds of phase centers within the primary beam to be simultaneously correlated with only a modest decrease in throughput, enabling survey science at milli-arcsecond resolution for the first time. The VLBA was recently used to simultaneously image 96 separate sources in the Chandra Deep Field South; and a survey of FIRST sources surrounding known VLBI calibrators has already probed more than 10,000 sources at milli-Jansky flux density levels in less than 200 hours of observing. The deployment of new 4-8 GHz receivers to the VLBA over the past 2 years has enabled observations of the bright 6.7 GHz transition of methanol, a capability that is supporting a revolution in our understanding of the structure and kinematics of our Galaxy, and much more.

In addition to standalone VLBA science operation, the array's 10 antennas also operate in conjunction with the GBT and VLA as part of the "High Sensitivity Array." The sensitivity provided by inclusion of these additional largest collecting-area elements, in combination with the imaging performance and geographic distribution of VLBA antennas, is supporting many innovative science programs requiring sensitivity unmatched by other VLBI arrays.

The VLBA science program encourages innovative small projects as well as Large/Key Projects. The VLBA operational model and DiFX software correlator have demonstrated significant flexibility on short timescales. A unique transient detection experiment, for example, has been running commensally at the VLBA correlator for over a year. The 10 geographically-distributed VLBA telescopes offer local interference discrimination and provide the option to determine the location of a transient burst to sub-arcsecond precision. Finally, the VLBA has begun to develop an ultra-rapid response capability. A 10-minute response time has been demonstrated in a case where an IR observation of an outburst in the Galactic Center triggered VLBA observations.

VLBA's improved sensitivity and new capabilities are opening new research areas, including several NWNH science topics.

International Celestial Reference Frame (ICRF)

From the outset the VLBA was designed to be a critical component of the International VLBI Service that maintains the terrestrial and celestial reference frames. VLBA contributions to the 2009 International Celestial Reference Frame-2 (ICRF2) were critical: the VLBA provided 28% of the measurements that resulted in an average reduction in position errors of 58%. The VLBA is also credited with significant densification of the reference source grid. It is this reference frame that defines the J2000 coordinate frame used by all modern astronomy and planetary ephemerides.

Reference frames require maintenance on multiple timescales. On the day-to-week timescale, the Earth's rotation phase (UT1–UTC) is unpredictable and must be determined through short VLBI observations of quasars. These measurements are vital for maintaining GPS system precision. The VLBA is now performing daily (UT1–UTC) observations via a US Naval Observatory contract. On timescales of months, the Earth's rotation axis precesses and nutates; and on timescales of years to decades, the sources defining the reference frame evolve in structure and brightness, and the continents drift. The VLBA is well suited to the improvement and maintenance of the vital ICRF on all these timescales. These activities are critical to US national interests across many federal agencies and activities; several civilian and defense activities (including maintenance of the GPS constellation) depend on these data.

VLBA plays an important role in infrastructure development and maintenance for astronomical and national purposes; other US agencies are paying their way on the instrument alongside the astronomical utilization.

Spacecraft Tracking

We note that interplanetary spacecraft navigation is a significant, largely untapped VLBA capability. NRAO has demonstrated 10 μarcsec tracking accuracy for spacecraft moving within the gravitational potential of the Solar System, a precision equivalent to 10m at 1 AU distance. In some cases, NRAO has demonstrated initial results within hours of observation. The VLBA offers baseline redundancy over NASA Deep Space Network capabilities, providing more robust measurements that do not require special transmitter packages on the spacecraft. In addition to service observing to support interplanetary navigation, the VLBA spacecraft tracking capability has supported scientific endeavors. An ongoing program has been conducting precise astrometry on the Cassini spacecraft orbiting Saturn, for example. An improved mass for Saturn's moon Iapetus was an early result of this work, and a recently scientific publication used VLBA data to improve the ephemerides of the outer Solar System.

3 HEALTH OF THE PROFESSION

NRAO plays a crucial role in supporting the health of the astronomical and engineering professions.

Leadership in Radio Astronomy

NWNH (Section 3) notes that NRAO facilities "can lay legitimate claim to international leadership in their capabilities, at least for now," but that this leadership is being challenged by advances abroad. If the NSF implements the Portfolio Review recommendations presented, the US will surely cede this hard-won leadership position immediately and for the foreseeable future. The US community would lose access to two, unique and forefront facilities, whose capabilities are required for the scientific fulfillment of NRAO's other two facilities, ALMA and VLA. In the GBT, the community would lose one of the most significant platforms in the US for instrumentation development by university researchers and students, and with the VLBA, it would lose the carrier of critical observing technologies required for next-generation facilities and its contributions to the astronomy, civil and defense communities. NRAO, a national technology repository, would lose a significant fraction of its staff and observing infrastructure, including the scientific and engineering intellectual capital built up over decades – a nearly irreplaceable resource.

Over the past few decades, the source of this intellectual capital has often been the US university community. NRAO depends on leading-edge scientific and technical contributions from university-based scientists and engineers to help define, design, build and operate our facilities. Loss of the University Radio Observatories (URO) program would terminate a critical feeder system for the next generation of scientists and instrument builders. A significant part of the "core competency" of the GBT and the VLBA, and indeed the entire radio-millimeter-submillimeter system, lies in the US astronomy community: the university astronomers who conduct their science and discovery with these research facilities; the students, and post-doctoral fellows who are trained by the university community and NRAO; and the dedicated staff who design, develop, build, and operate these facilities. A large fraction of NRAO's university partners are intimately involved in instrument and operations development at the GBT. Instruments like ALMA and the VLA do not easily lend themselves to instrument and technology explorations by university groups and other interested community members. NRAO strongly believes that providing that kind of scientific and technical test-bed capability (while attempting great standalone science) is important to ensure the future of the field. The loss of fundamental research infrastructure will necessarily result in a loss of core US competency – human, scientific, and technical – at a time when the nation's edge in international science and technology is under threat.

Advanced Instrumentation Development

Support for the development of the new technologies required to build and commission advanced astronomical instrumentation is important to NRAO and the health of astronomy. Green Bank and Socorro are major instrument development sites, and the NRAO Central Development Laboratory in Charlottesville has pioneered numerous new technologies and instruments that have been proven on radio telescopes around the world.

Sensitive single dish telescopes, such as the GBT, are vital to advanced instrumentation development. Most radio astronomy instrumentation is deployed on single dishes prior to its replication across interferometric arrays, and GBT is an indispensible test bed for novel receiver designs. Additionally, much of the new instrumentation for GBT, VLBA, and VLA is built in collaboration with university and Federal lab research groups, leveraging NRAO staff efforts, supporting university faculty, and providing valuable training for the students who will become future instrument builders.

Redeploying the Green Bank instrument development program to other US facilities is impractical, and while many future digital back ends could conceivably be developed around the phased VLA, new feed, receiver, and digitizer designs generally must first be deployed on single dish telescopes. Other than the GBT, the only single dish telescopes in the PRC recommendations are Arecibo and CCAT. Arecibo is an excellent instrument over its frequency range and sky coverage, but it is not appropriate for developing mm-wavelength technologies, and the telescope design and infrastructure make new technologies testing problematic. CCAT is an exciting project now under development, but its planned maximum operating wavelength is 2.2 mm, i.e. shorter than the GBT's 3 mm limit. CCAT and GBT are scientifically complementary, and cannot replace each other for scientific and technical purposes.

NSF support for the GBT is the core funding for operation of the NRAO Green Bank site, and the recommended divestment of the telescope may lead to closure of the entire site, with significant indirect impacts. Green Bank's location within the West Virginia and national radio quiet zones, and its extensive support infrastructure, are attractive for staging developmental projects. Green Bank currently hosts, for example, the northern Precision Array to Probe the Epoch of Reionization (PAPER) telescope, an instrument managed by a university-NRAO partnership that also operates a 64-element PAPER array in South Africa. The 45-foot telescope at Green Bank, built as part of the interferometer then transformed into a satellite ground station, is in active use as the Solar Radio Burst Spectrometer; and the University of Texas is now installing a Low Frequency All Sky Monitoring Array to study the transient Universe.

Training the Next Generation

It is critical to the health of the profession that our future science and engineering leaders be trained using state-of-the-art research facilities, including the GBT and VLBA. The NRAO telescope system offers open-access to investigators in all career stages. Green Bank and Socorro are active host sites for the NRAO Research Experience for Undergraduates program that has trained 1000+ students over the past half-century; many have gone on to successful careers in science, technology, engineering, computing, and mathematics. A co-operative education program brings undergraduates to Green Bank throughout the year to work with astronomers, electronics and software engineers. Jansky and Reber post-doctoral fellowships hosted at Green Bank and Socorro are integral to the observatory's commitment to train the next generation. Every two years, Green Bank co-hosts a summer school in single-dish radio astronomy with Arecibo that draws 60+ students to learn hands-on the techniques of professional radio astronomy. The Synthesis Imaging School is held in Socorro every two years, attracting 150+ students for unique and valuable training in radio astronomy aperture synthesis and imaging.