Arecibo International Astronomy and Ionosphere Observatory

Prologue
We, the Arecibo Science Advocacy Partnership (ASAP, http://www.arecibоscience.org) community, are responding to the "Dear Colleague Letter" (DCL; NSF 16-005)—not as possible proposers but as a substantial and diverse community of involved and concerned scientists, most of whom are active users of the Arecibo Observatory (AO). It is its scientific diversity and flexibility that makes AO a unique institution that encourages the interdisciplinary research which has resulted in the hundreds of M.S. and Ph.D. degrees awarded over its more than half century of ever-evolving uses—AO is a notable institution of graduate and post-graduate education. Research and innovation at AO have resulted in thousands of journal articles spanning an immense scientific range and the Nobel Prize for discovery of the Hulse-Taylor binary pulsar. It is additionally an influential STEM facility for the many thousands of Puerto Rican students, parents and teachers who visit AO each year. It is this diversity of use, and thus diverse possibilities for future use which have made AO both scientifically flexible and challenging to manage within the available institutional and funding paradigms.

Here we suggest some characteristics of a future management structure that will facilitate the continued growth and flexibility of AO well into the 21st century. In particular, we find that this structure must be as flexible and as global as possible. It should incorporate the possibility of multi-national public and private funding, cultivate the development of an even more diverse user base, allow for substantial growth and evolution of the instrumentation, and set the stage for Arecibo becoming part of a larger global educational and research resource that nonetheless remains "hands-on".

The future of AO-unique science is bright. If we factor in substantial but realistic investment in upgrades, the future of AO science is very bright indeed. The multi-institutional, multi-national user community is large. However, current and past management structures have proven a challenging fit to the funding and day-to-day operational realities of AO that necessarily also include the need to respond to a diverse user community as well as the numerous reporting requirements. The management structure we suggest recognizes that AO is an international observatory facility in three major science and science education arenas. We suggest a path forward that allows for global partners.

AO Highlights—

- AO operates the most sensitive radio telescope, planetary radar and incoherent scatter radar (ISR) on the planet.
- AO serves a highly international scientific community and so should be recognized as an international facility.
- A broad array of leading AO science activities is discussed in the ASAP Whitepapers[*].
- One of AO's principal strengths is its flexibility to adapt quickly to new science and techniques, a capability rapidly being lost on other more complex and/or array instruments configured towards certain fixed science goals.
- The new high frequency (HF) ionospheric modification facility combined with AO's radars and optical instruments opens a new era in active plasma physics experimentation.
- The most sensitive ISR (Incoherent Scatter Radar) in the world combined with metals lidar (K, Na, Ca, Ca+, and Fe from resonant scattering), other optical instruments, and the VHF radar make AO the premiere facility for studying the role of meteoroid flux metals in the upper atmosphere and ionosphere.
- AO is uniquely powerful for planetary and Near-Earth-Object (NEO) radar. AO and the Green Bank Telescope (GBT) could, as in the past, be paired for unique new observations particularly of Near-Earth Objects (NEOs).
- AO's great sensitivity is required for gravitational wave detection and study. Single dishes provide important advantages over arrays for certain types of astronomy. For example, AO pulsar timing activities cannot be superseded by the Very Large Array (VLA); see the Appendix study. The capabilities of AO and the GBT are highly complementary—and the loss of either one would cripple leading areas of US astronomical research.
- AO will not be superseded importantly by FAST (Five hundred meter Aperture Spherical Telescope in China), which will not do radar and will not observe above 2 GHz.
- AO is one of the prime research facilities in Latin America and the Caribbean.

AO is now managed by the National Astronomy and Ionosphere Center (NAIC), led by SRI International in cooperation with the Universities Space Research Association (USRA) and the Universidad Metropolitana (UMET) under a cooperative agreement with the National Science Foundation (NSF). The current five-year cooperative agreement controls NAIC operations at least through 2016, by which time the NSF is expected to issue a further request for proposals to manage the Observatory. The NSF currently owns the property on which the Observatory is located, and is under obligation to the Government of Puerto Rico to return this property to a pristine state should it cease to operate the Observatory.

I. Arecibo Scientific and Educational Operations and Activities

The three main scientific research areas at Arecibo Observatory—radio astronomy, planetary radar, and upper atmospheric studies—should be pursued, cultivated and expanded. Similarly, the educational and outreach activities are highly beneficial and should be fostered. The growth of interdisciplinary research due to the close proximity of these core activities underscores the success of the AO "model".

[*] http://areciboscience.org/ScienceMemos.html

Arecibo's three main scientific research areas are interdependent and mutually supportive. ASAP strongly asserts the synergy of the three science areas at AO. There is no area that could be curtailed or abandoned to strengthen others or reduce operating costs.

Space and Atmospheric Sciences: Arecibo was one of the very first instruments with the capability to study the upper atmosphere using incoherent scattering. It remains by far the most sensitive incoherent scatter radar (ISR) world wide and a major component of the ISR chain. This facility has been progressively augmented with state of the art optical and lidar instruments. Thus its potential both for leading science in league with other instruments at higher and lower latitudes and for valuable "space weather" information remains very high. Of special interest is joint work with colleagues at the magnetic conjugate point in Argentina. Further, its newly implemented and upgraded ionospheric heating facility provides one of the most important laboratories for plasma physics anywhere.

Planetary Radar: The Arecibo S-band radar has never had a peer on the planet. AO planetary radar provides spatial resolution comparable to or better than a spacecraft flyby at a tiny fraction of mission costs. Recently, it has focused in support of Congressional mandates to track and characterize near-Earth objects (NEOs) greater than 140m in diameter. Ground-based planetary radar provides the ability to refine orbital predictions for NEOs by many orders of magnitude, preventing the loss of potentially hazardous objects. Planetary radar constrains spins and shapes, discovers satellites, and thus helps estimate masses and densities. Twenty times more sensitive than any other planetary radar, AO provides range resolution as fine as 7.5m for objects down to 3 times the lunar distance. For closer objects, echoes return too quickly to change from transmit to receive modes, but can be received elsewhere, in bistatic operation. Bistatic operations are also critical to maximize the scientific return, because X-band planetary radars at Goldstone have <4m resolution capabilities: transmission at Goldstone and reception at AO maximizes the spatial resolution on the asteroid as well as the detection sensitivity. Other studies for the moon, more distant planets and satellites use Arecibo alone or in combination (bistatically) with the GBT, VLA, Goldstone, and Haystack.

AO radar can be used in bistatic operations with spacecraft radar. The miniRF experiment on the Lunar Reconnaissance Orbiter allowed comparison between transmit-receive pairs at the same angle (for the spacecraft) or different angles (spacecraft-to-ground). These comparisons are important for distinguishing ice content and other differences in subsurface lunar materials. AO enabled mission science to continue after miniRF's transmitter failed, by having the spacecraft receive AO transmissions. Combining different epochs of observation between AO and/or spacecraft radars enable detection of surface and subsurface changes on geologically or volcanically active bodies. We have a clear responsibility to maintain instruments that can assess both the characteristics and potential hazards of other bodies in the Solar System.

Radio Astronomy: AO's unexcelled sensitivity and versatility—new capabilities can be rapidly deployed—make it the instrument of choice for many research programs studying objects within its field of view. The radio astronomy program is allocated according to a competitive proposal system, and scheduled projects are highly rated in a thorough peer review. High profile science areas such as NANOGrav, relativistic binary pulsars, fast radio transients, and extragalactic HI (neutral hydrogen) studies depend strongly on the Observatory and would be seriously compromised were AO not available.

Interdisciplinary Studies: AO is a major focus for research in the area of radio science that includes scattering theory as applied to, for example, radar meteors. The unique co-axial 46.8/430 MHz radars provide invaluable data for meteor studies including orbits. The ionospheric modification capability provides, along with all of the AO visiting and permanent instrumentation, a laboratory-without-walls to study non-linear plasma physics in space. Various signal processing paradigms have been developed as driven by AO science.

Educational Programs: As an educational facility, Arecibo is magnificent and underused. Its grandeur and sensitivity inspired generations of radio astronomers, space and planetary scientists, and engineers in earlier decades, and young people who visit today find it just as inspiring. More than any other modern facility, AO remains a "hands on" instrument, where novel new ideas can be tested and radiometer, radar, and science and engineering principles revealed and experienced. AO is highly significant to high school students searching for pulsars, ordinary folks doing SETI@HOME, graduate students attending the Single Dish Schools, Puerto Rican high school students participating in the Saturday Academies, and the hundreds of thousands who have visited the Observatory. The REU program has been notably successful over the years with many students returning as graduate students and then users.

Outreach Programs: The AO Visitor Center, with bilingual displays and hands-on activities, is situated not only to host the multitudes of AO visitors, but is also one of the most important scientific facilities well known to the people of Latin America and the Caribbean. Outreach programs to high schools teachers and other such groups have been conducted with good success, but much more important work remains.

II. Conceptual business, financial, and managerial outline

A. Past and Current Management Models

Arecibo Observatory was built by Cornell University in the early 1960s and then operated by Cornell for more than 50 years. No lesser organization could have provided the institutional commitment, breadth of technical inspiration and administrative reach required at that time, and the Observatory is still positively marked in many ways by this history. That commitment carried the Observatory through two major upgrades, both of which reassembled an essentially new instrument within the existing site.

Cornell's management was bifurcated, with a site director concerned with the Observatory operations and a principal investigator in Ithaca handling relations with government organizations, mainly NSF, regarding funding levels and negotiations. This mode of administration remains appropriate and necessary, given the rarity of scientific/technical management organizations on the island.

The current management is split between three organizations, SRI, USRA, and UMET. UMET is a Puerto Rican partner. The three managing partners have only one common policy (the anti-harassment policy) and there are major differences in employee benefits. This three-part administration proved difficult and awkward at first, and many of these early problems have now been worked out, so that the Observatory can, at least, function, but it is still less than optimal. Below we briefly summarize our impressions of their strengths and problems as we assess what forms of management might be optimal and workable for AO:

Space and Atmospheric Sciences. This, the largest of AO's scientific groups, is managed by SRI and was directly managed by the former AO Director until his departure. As SRI assumed overall AO management, it was expected that this group would thrive, that it would receive some inputs and perhaps leadership from SRI's own groups in this area, and that aeronomy would likely claim a larger presence in the overall functioning of the Observatory. None of this has happened. Surely this group has had some successes under SRI management, in particular bringing the heating facility into full operation. However, the group has suffered from a persistent lack of cohesion and leadership.

Radar Astronomy, under USRA management, has generally thrived over the last few years. Separately funded by NASA, this area of AO scientific work has had a more adequate level of staffing and the very significant personnel changes over the last few months have demonstrated a resilience in this group. However, the historical instabilities in funding for this effort, and the division of funding between infrastructure, operations, and scientific investigations leaves significant continued uncertainty.

Radio Astronomy. The Radio Astronomy group, together with the Electronics and Computer sections have also been managed by USRA, with a resident USRA Deputy Director in overall control of these activities. Once most of the turnover issues were resolved, USRA managed their sections capably from a scientific standpoint. A serious flaw showed itself when there were serious personnel problems, and USRA management in Maryland was slow to understand and address the issues. Overall these sections have suffered very seriously from understaffing, and have depended on the loyalty, bordering on exploitation, of a number of key staff, many of them quite senior. All these sections are vulnerable to the ever present risk of losing experienced and very key personnel, and little effort or energy seems to have been put into institutional memory or preparation for new people to assume key positions.

UMET Staffing and Budgetary Control. UMET employs by far the largest section of AO staff and is in charge of most of the budget. They are responsible for purchasing and other budgetary functions, and UMET also operates the Visitor Center. UMET had no experience in managing a scientific institution, and AO encountered multiple initial problems as UMET took control. The situation has greatly improved, but the disciplined management required for operating a sophisticated technical facility is not quite complete.

B. Required Technical Expertise

The complex infrastructure that forms the Arecibo Observatory demands a parallel technical support structure that, in practice, is already widely dispersed. This structure could be formalized under a new management plan. Table 1 lists some of these functions and potential partners.

Table 1 — Necessary AO Technical Functions and Possible Partners

Feed and Receiver Development	NRAO, ATNF, Cal Tech, some in-house
High Power Transmitter Support	Haystack and CPI, SRI
Software Maintenance and Development	In-house
Network Maintenance & Support	In-house
Platform and Dish Structural Support	Amman and Whitney
Optical Instrumentation	Scientific Solutions and various universities

C. A Management Model Emphasizing Service to AO's Stakeholders

The three-part administration structure does not work well and needs to be replaced by a single organization. Examples might be SRI, USRA, NRAO or Haystack. Best would be a Puerto Rican organization, but we are aware of no such group possessing the technical experience to manage the Observatory, an organization on the frontiers of science. The single entity must commit to serving all of AO's stakeholders, which are surprisingly many and diverse. The need is reflected by the larger national and international structure outlined in the Figure 1 proposed organizational chart. This chart includes an independent board of trustees representing the various stakeholders.

The management structure should be organized so that all stakeholders have real, deterministic and significant input into prioritizing new developments as well as continued operations. Along with this topical input must come resource contributions in the form of people, hardware, and funds, not only so that the Observatory can respond to these particular and focused inputs, but also—importantly—to sustain the Observatory's infrastructure, operational, and stakeholder base.

The stakeholders form the equivalent of a management advisory committee. Indeed, this committee should be formally defined and have specific responsibilities. The entity that they advise would be the management organization discussed above, which becomes the functional equivalent of Cornell in the past and SRI/USRA/UMET currently. But, as we have explicitly emphasized above, the current three-part organization needs to be replaced by a single organization.

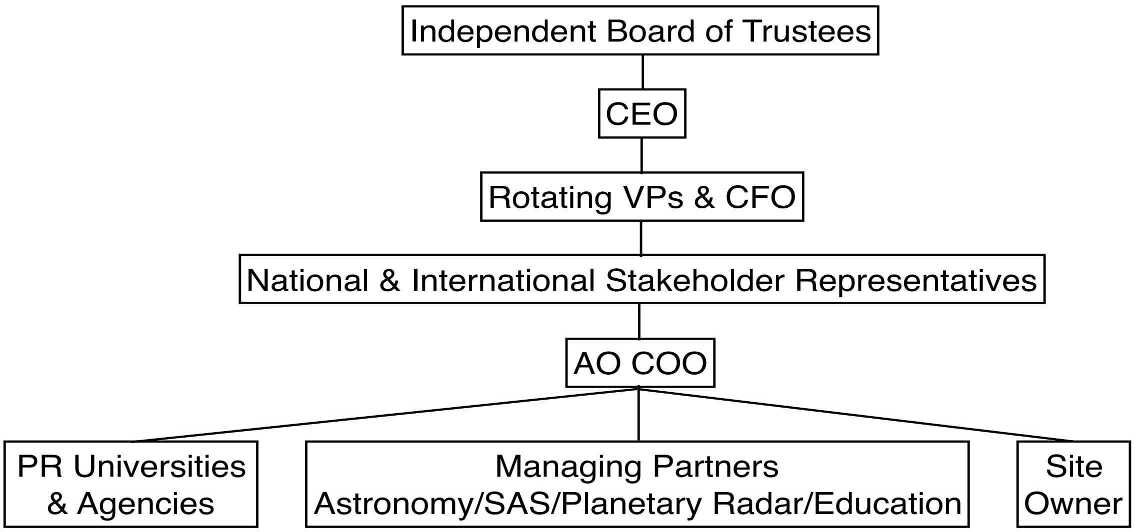

Figure 1. Proposed AO organization chart.

C.1. Scientific Stakeholders

The current AO science operations have suffered because of insufficient resources to keep technology current in its three disciplines. For example, the newly installed 12-m VLBI dish would enhance VLBI calibration and observations, but it has not been instrumented and commissioned for lack of funding.

Arecibo's science stakeholders are international because Arecibo's three science areas are international.[†] Therefore, our title of this document and potential new name for AO is the Arecibo International Astronomy and Ionosphere Center.

Aeronomy

In aeronomy, the science is by nature international because, for example, the conjugate points of the Earth's magnetic field lines fall in different countries—indeed, in different continents. In practical terms, the ISR "World Days" (world-wide use of common radar modes for scheduled synoptic or event-based observations) are highly coordinated and cooperative international endeavors. The AO, Millstone Hill (Massachusetts), Sondrestrom (Greenland), and Jicamarca (Peru) incoherent scatter radars form a unique longitudinal chain of incoherent scatter radars that follow both space weather (e.g., solar coronal mass ejection strikes) and atmospheric phenomena (e.g., stratospheric warming event effects in the ionosphere).

[†] Arecibo has long attracted a diverse international user community; however, this usership became more international in the new millennium because fewer radio astronomers and other specialists were trained at the Observatory during the decade of the 1990s when AO was under renovation and the GBT in construction.

Planetary Radar
In planetary radar, Arecibo Observatory and GBT can do bistatic radar on the Moon (because it is so close) and distant planets (because they are so far). Reception at Arecibo of weak radar echoes from Goldstone provides the optimal combination of spectral resolution and sensitivity. Bistatic operations at AO with international spacecraft instruments enhance the scientific return of space missions. In addition, determining accurate orbits and characteristics of potential Earth-colliding asteroids benefit *all* humankind.

Radio Astronomy
In radio astronomy, Arecibo Observatory participates in European VLBI, U.S. geodetic VLBI, and the space-based RadioAstron VLBI. In addition, the observations enabling eventual detection of gravitational waves by pulsar timing are carried out in several countries at three primary observatories and, in the end, will become tightly coupled internationally because the science needs sources distributed over all portions of the sky. Similar statements can be made about the GBT, and the interdependence of the two instruments for pulsar studies in particular should be recognized and facilitated.

C.2 Education/Public Outreach Stakeholders
We now consider the public education/outreach type of stakeholder. Currently these include Puerto Rican educational organizations, in particular UMET and its associated organizations that have developed the Arecibo Observatory and its Visitor Center into a prominent and highly successful public resource on the island that is widely recognized as excellent.

The current educational activities should be expanded to include the use of telescope time for educationally-based projects. This would greatly increase the attraction for educationally-based organizations in other countries. With AO's location in the Caribbean and its Hispanic heritage, a natural group of countries that could benefit from participating in these activities would be those in Latin American together with Spain and maybe Portugal. After appropriate peer review any non-US group would receive Observatory time or service and would be expected to contribute funds for Observatory support. A proposal for a Puerto Rican Institute for Advanced Studies (PRIAS), that draws on Observatory expertise and facilities, has been developed in outline (see Appendix).

D. Financial Support and Business Model Reflecting AO's Science and Communities

We suggest a financial/business model with a basic Arecibo Observatory budget of some $15M of which roughly 2/3 is supported through US government agency sources and the remaining third from a combination of scientific and international partner sources and revenue-generating activities. This would be apart from educational and outreach activities that are far more difficult to estimate.

Aeronomy
The aeronomy activities at Arecibo are of several different kinds with different needs and lines of support. The AO 430-MHz ISR radar is the long-term workhorse of the aeronomy research area and is used to carry out investigations of many different kinds. In outline these are ISR studies, optical investigations and ionospheric heating experiments. We discuss each of these below.

Ionospheric Modification is again a leading scientific activity of the AO aeronomy group and, given the ancillary instruments, is unique in the world (see Appendix for a summary of the recent campaign). It draws on the ISR and a number of optical and radiofrequency instruments for assessments and measurements. Presumably this is just the sort of excellent and forward looking science that is cultivated by the NSF and should qualify for funding not only from the AGS Division but potentially from Physics or other government agencies. A number of universities and institutes maintain a strong interest in the ionospheric modification research, and they can contribute staffing to this activity.

International Aeronomy Research. As a mid-latitude instrument, AO is dependent on other ISR facilities at higher latitudes both in the North and South to characterize the ionosphere fully. Of particular interest is research at the Observatory's conjugate point in Argentina. The CEDAR (Coupling, Energetics, & Dynamics of Atmospheric Regions) collaboration already reflects the research agendas and needs of this type of ISR science. The Arecibo Observatory is the potential "jewel in the crown" of this collaboration, and the AO role should be cultivated and exploited in terms of reliable long-term funding.

Space Weather Characterization. The Arecibo Observatory excels in this type of investigation. It draws on both the ISR and optical instrumentation, and it can readily be developed into a multifaceted funding stream with some investment for support of Observatory operations.

Planetary Radar
NASA currently supports this part of Observatory science, and it is difficult to imagine that this work could be properly supported by any other means. Fuel and transmitter maintenance costs make this work relatively expensive per hour of antenna time, but as discussed above this work has extraordinary importance for life on Earth, and its conduct represents a U.S. responsibility. Currently, NASA research at AO is conducted on a contracted cost basis. NASA would be asked to partner in AO operation and support its share of AO infrastructure, bringing its part of the annual Observatory basic budget to about $5M per year to support operations and maintenance as well as expert on-site staff. We note that the AO S-band radar klystron tubes have historically had a lifetime of about five years and cost nearly $1 million to replace.

Radio Astronomy
AO would largely retain its "open skies" policy, with some exceptions. A substantial fraction of the observing time for US-based investigators would be regarded as covered by NSF AST support. Large projects, once up and established, may be requested to provide independent funding, and international users would be allotted time as funded by their relevant national agencies. NANOGrav, for instance, has sought funding for the GBT, and would be encouraged to help to fund their AO observations. European scientists are major users of the AO, including

use of the instrument for European VLBI activities, and funds to support this work would be requested from the European Union. Similar approaches could be employed with users from other western hemisphere countries.

Given the uniqueness of the AO for SETI observations, and the apparent willingness of private organizations to support this work, we suggest that separate arrangements be made that would fully cover the antenna time and infrastructure costs associated with this activity. Partnering with an appropriate foundation is an obvious possibility.

Education and Outreach
Visitor Center programs and operations contribute significantly to Observatory outreach and generate significant income. These programs should be promoted, redesigned at regular intervals and expanded in reach. Current minimal AO staffing levels in all areas leave little available effort for contributing to this area. Investment in scientific staff will benefit the education and outreach functions of the Observatory greatly.

III. Planning for Transfer of Ownership of the Observatory and its Facilities

The National Science Foundation (NSF) is the owner of the property on which the Observatory is located, and as such has responsibility for all aspects of its use and existence. We note that:

- The current ongoing cost for continued science operations at the AO is some $12M/year.
- If NSF mothballs the Observatory and site, this would require isolation of the site from the surroundings, including constant and expanded security for the site to guard against liability. This would incur a one-time cost for setup and a continued cost for patrols. Moreover, the mothballing activity may be interpreted locally as abandonment of the site by NSF.
- To fulfill its obligation to restore the site to its original environmental state the estimated cost is $88 million[‡]

NSF would appear to welcome transferring title to another independent entity which would assume the obligations and risks. The natural entity is one, discussed above, that takes on site management. With the transfer of title to this entity, the NSF transfers its obligation and risk. The receiving entity would very reasonably be reluctant to assume NSF's liabilities without very significant compensation. NSF should compensate the new owner accordingly. This compensation could take two forms:

- A one-time payment amounting perhaps to a significant part of the demolition costs;
- A commitment of continued funding at a significant level over some agreed period.

[‡] Christine M. Matthews, *The Arecibo Ionospheric Observatory,* Congressional Research Service, Feb 23, 2012, in which she cites: National Science Foundation, Division of Astronomical Sciences, *Report of the Committee of Visitors*, February 7-9, 2011, Arlington, VA, p. 20. The major part of the cost is for dismantling the telescope; little would be saved by preserving the Visitor Center, Visiting Scientist Quarters, maintenance and office buildings.

The new owner would operate the Observatory for science/education purposes and would be responsible for organizing the group of international partners.

Clearly the least costly way forward for the NSF is to follow the approach we outlined above —i.e., to operate the AO in such a way that its full capabilities are available to users and some of the ongoing operating costs come from entities other than NSF. Moreover, this optimizes the scientific, educational, and public value.

This value would be enhanced even further by future additional investment in new technical and scientific capabilities, some possibilities of which are listed below. Such investment greatly increases the possibility of a positive and suitable transfer as well as attracting some forms of revenue-generating activities. All of these investments and considerations increase the AO's capacity to serve as a technical education facility and model within Puerto Rico that will connect it with larger Caribbean and international educational, outreach, and science activities.

We suggest that a solicitation be mounted for needed investment areas or enhancements in AO's capabilities and that these be assembled and evaluated by a suitable panel of experts and/or users. Arecibo's capabilities have been extended and upgraded on several previous occasions, and the adaptability of the facility is one of its great strengths. In the current context it seems imprudent to assess how AO could or should be managed in the nearer future without clearly assessing what deferred maintenance or enhancement might be appropriate to serve it well in coming years both scientifically and economically. We suggest a few items for consideration:

- Repair/refurbishing the 430-MHz ISR to improve its reliability and operability.
- Refurbishing/replacing the S-band klystrons and diesel generator(s) for planetary radar, including possible upgrades to transmitter frequency resolution.
- Fully integrating the 12-m telescope into AO VLBI operations and making it available for observations, including some income-generating activities.
- Construction and installation of a more capacious multi-beam feed perhaps along the lines of the AO-40 instrument under design at Cornell. The primary science applications would be detection of fast radio transients, NANOGrav pulsars as well as HI .
- Design and acquisition of a feed and receiver with 6x the current bandwidth, which has recently become technically feasible. This would greatly enhance accuracy of pulsar timing. The resultant reduction in the number of receivers to be maintained also decreases the weight on the suspended platform.
- Further redesign and upgrading of Visitor Center displays and facilities.
- Investment in temporary or long-term AO housing to enable visits by sabbatical faculty and others.

Longer Term Planning: All scientific facilities have a limited lifespan and planning must be put in place for their eventual closure and decommissioning. The AO is no exception; however, we suggest that the current dire alternatives are premature and in part due to insufficient prior planning.

- The original AO construction is more than half a century old; but the Observatory has

been upgraded twice and now has an expected operational lifetime of more than another decade if well maintained and if its operations are not curtailed by some natural disaster such as a hurricane or earthquake.
- Such a timeline gives good opportunity to plan adequately for AO's closure and decommissioning. Funding can be accrued over this period to defray the costs.

While the NSF understandably desires to transfer the AO to another entity, any other such entity would very reasonably be reluctant to assume NSF's liabilities without very significant support. In consideration of this longer term planning and operational life, the relevant support could be of several different forms:

- Funding to escrow toward eventual closure and decommissioning on this timescale.
- A suitable form of insurance against the possibility that the Observatory's life is curtailed by natural disaster.
- A secure funding foundation over the AO's expected remaining lifetime to anchor other funding and defray the costs of domestic user programs.
- Funding to resolve deferred maintenance issues and achieve enhanced performance so that the AO can retain leading capabilities relative to other national and international facilities and generate as large a portion as possible of its operating costs.

Conclusion: The Arecibo Observatory has already enjoyed a long and very successful life. It is the hope of the Arecibo Science Advocacy Partnership that the Observatory's successes can be continued for many more years with new management and funding structures. The telescope performs better than ever before, and has potential for greater scientific and educational achievements.

Appendices

Appendix 1. Update on the AO Ionospheric Modification Facility

The first campaign involving Arecibo Observatory's new HF facility took place during the period 9 November through 15 November 2015. For these experiments a narrow transmission band centered on 5.1 MHz was employed. The inaugural experiments were highly successful and the HF facility performed at its designed peak power (100 MW effective radiated power, ERP). However, there were several adverse interactions between the radar antenna structure and the high-power HF wave that resulted in preferred radar beam pointing directions in both azimuth and zenith angle. These problems were incrementally addressed during the actual experiments and by the end of the campaign about half of all problems were resolved. Additional HF facility maintenance time will allow the remaining interactions to be diagnosed and eliminated. Although the ERP of HF transmissions with the new facility were comparable to those of the previous upgraded Islote HF facility, a great deal of new physics was revealed particularly in the area of electron acceleration in a plasma. The reason for this is that since the closure of Islote facility operations in 1998 many advanced radar acquisition and processing techniques have been developed that are extremely useful for HF heating experiments. Consequently, several discovery level journal publications will emanate from the November campaign.

Appendix 2: Proposal for the **Puerto Rican Institute for Advanced Study (PRIAS)**

Need: University graduate/post-graduate education (GPGE) is suffering due to a variety of issues including lack of a critical mass of faculty in many areas such as the space sciences. Universities have not developed sustainable methods of sharing faculty and using available technologies such as "telepresence" for student guidance and science/engineering interactions in general. Additionally, GPGE has become very inefficient due to below critical mass faculties and that the research "action" is interdisciplinary while departments and courses are often based on classical topic areas such as electrical and mechanical engineering. Even at interdisciplinary boundaries GPGE is often highly specialized, as this is the only way to obtain research grants—the generalist is needed. Further, university GPGE needs to be exported to the 2nd and 3rd world—traditional universities cannot easily do this. Unless the paradigm shift in GPGE occurs soon, many graduate programs will disappear and those that remain will specialize rather than generalize. The number of top-notch advanced degree graduates would decline. The declining GPGE would weaken US universities, industry, and the rate of scientific and engineering advances.

Much of the world has no access to premiere research instruments and post-graduate education. Latin/South America does not have a Research 1 GPGE institution. Further, traditional universities cannot respond rapidly to the evolving idea landscape and science entrepreneurship and mentoring need to be vastly improved. Also, formal subjects such as "science management" are not taught as part of PhD preparation as it is often assumed that the best students will become professors.

Approach: The Arecibo Observatory (AO) has always presented a remarkable mix of education and research without placing artificial boundaries between the various disciplines represented in its day-to-day functioning—this unique mix needs to be extended well into the future. In order to address the issues surrounding AO and GPGE, we propose to streamline and globalize GPGE and research while offering unique access to AO along with a new science and GPGE future for AO. We propose establishing the Puerto Rican Institute for Advanced Studies (PRIAS) with $100M-$300M initial donor funding. This level of developed funding allows for the creation of the physical and human structure of PRIAS. PRIAS in turn enables a huge talent pool for scientific and engineering solutions especially in offering a new interdisciplinary path for GPGE. PRIAS would also enable much new science at or related to its core facility AO. PRIAS would offer PhDs (likely jointly with collaborating universities) in core areas creating a new path to innovation. PRIAS should also institute PhD+ whereby talented candidates with PhDs in other areas who wish to pursue research in PRIAS core areas earn a second PhD—the PhD+—thus widening the talent pool. PRIAS provides AO and collaborating institutions a new talent/solution paradigm with a new path to innovation and globalized entrepreneurship. PRIAS strives to become the premier Latin/South American (and then global) research institute initially in the AO core areas but eventually including new areas as they arise—e.g., tropical climate energy issues.

PRIAS charter: Find great talent and important problems and bring them together in a unique environment centered at AO. The PRIAS path for AO would assure a constant flux of world-class scientists, engineers, grad students, and faculty through AO. Such a flux has occurred in the past and is totally necessary for AO's future health.
Appoint a global (not local), high-level board to independently provide guidance towards PRIAS goals.

Benefits: PRIAS is unique with AO as its core facility. PRIAS uniquely bring together faculty, students, and research staff from around the world as enabled by telepresence and joint appointments. Joint appointments and grad students would be funded or co-funded by PRIAS Fellow appointment at the appropriate level. Subjects include space and planetary science, radio astronomy, science management, and associated engineering areas such as signal processing and imaging.

AO and AO science is given a 20-30 year renewal with steady access to the best faculty, scientists, students, and post docs from around the world—a whole new level of diversity—all the while providing a new funding source for AO. Separation of undergrad education and GPGE fosters interdisciplinary research and education while forming a "critical mass" of faculty, students, and post-docs in core areas of AO activity. Undergraduate STEM education would be handled through local universities and would benefit greatly from enhanced access to AO and its staff.
PRIAS would create and foster a new PGE management paradigm whereby colleges and universities do not need to cover all areas but can sustainably maintain world class individual or small group expertise that is shared and leveraged by PRIAS. This requires forging agreements whereby faculty and students are shared via joint paid appointments (fellowships); e.g., talented professors at small colleges have access to grad students and a major research facility. This approach creates new graduates in the US and the rest of world. Talented scientists in the second and third worlds have access to PRIAS—PhDs without borders. PRIAS would bolster PhDs who wish to switch to new areas with the PhD+ program.

PRIAS provides an opportunity to firmly propel AO into the future. This is accomplished through creation of a global "support system" for GPGE and for AO while necessarily also creating the structure to sustain the process via wide community support and commitment to AO and necessary infrastructure improvements.

Appendix 3: Letter Regarding VLA Pulsar Observations to NRAO Director Tony Beasley

To: Anthony Beasley, NRAO Director

From: Scott Ransom (NRAO) and the rest of NANOGrav

Subject: Consequences of replacing the GBT and/or Arecibo with the Jansky VLA for NANOGrav

---

1 Conclusions

While the Jansky VLA (JVLA) is optimally designed to address a wide variety of critical topics in astrophysics, it is highly inefficient and drastically over-designed for radio pulsar timing observations compared to the two world-class NSF-operated single-dish radio telescopes. The JVLA's reduced sensitivity compared to the GBT, and especially compared to Arecibo, would require *thousands of hours* of precious JVLA time per year to match the world-leading timing results currently being generated by the GBT and Arecibo. That time would be almost impossible to acquire since the JVLA is better suited to doing imaging radio science. The lack of sensitive sub-GHz receiving systems would *require* that NANOGrav apply for and use non-US telescopes such as the GMRT and CHIME in order to correct for ISM effects. Finally, pulsar surveys to provide additional MSPs, which along with increased sensitivity will drive future pulsar-based GW science, will be impossible with the JVLA for computational reasons for many years to come. A loss of access to both the GBT and Arecibo would dramatically decrease the discovery space for North American GW science and would signal an effective abdication of US leadership in pulsar science.

2 Observational Requirements of NANOGrav

NANOGrav currently observes about 45 pulsars, approximately half each with Arecibo and the GBT. Timing observations require wide-band (capable of covering 600–800 MHz at 1–2 GHz frequencies) coherent dedispersion instrumentation—such instrumentation is now available at the JVLA as well as at GBT and Arecibo.

Observations of duration $\sim$20–40 minutes (required to partially overcome timing limitations due to pulse jitter) are made at two different observing frequencies every 3–4 weeks for each pulsar. The observing cadence is set to over-sample timing variations due to astrometric, orbital, and spin-down effects as well as our expected nHz GW signals. Time-of-arrival (TOA) precision is inversely proportional to signal-to-noise, and therefore telescope sensitivity.

The paired high- (1–2 GHz) and low-frequency (typically 430 MHz at Arecibo and 820 MHz at the GBT) observations are required to remove the time variable dispersive effects of the ISM, which can be orders-of-magnitude larger than our expected GW signals. Currently these observations are taken within 1–2 days of each other, although future simultaneous ultra-wideband observations from $\sim$0.5–3 GHz would be preferred.

NANOGrav's GW sensitivity improves in direct proportion to the number of millisecond pulsars (MSPs) being timed (Siemens et al., 2013). We currently add additional MSPs primarily from ongoing sensitive wide-area GBT and Arecibo pulsar surveys (e.g. PALFA and GBNCC). Our predicted GW sensitivity assumes the continued addition of $\sim$4 MSPs per year to our timing array.

NANOGrav timing observations currently require over 400 hours per year at both Arecibo and the GBT, while the search observations use $\sim$500 hours per year at both telescopes. An additional $10-20$ hours of telescope time per year will be required at both telescopes as we continue to find high-precision MSPs. See Demorest et al. (2013) for detailed information on our last-generation timing efforts and McLaughlin (2013) for a summary of NANOGrav's current work. For additional background information on high-precision pulsar timing see Lommen & Demorest (2013).

3 Using the JVLA for Pulsar Observations

Currently the JVLA performs *no* regular pulsar timing or search observations in its regular observational program, whereas those observations use $\sim$25–30% of the GBT's available time. However, within the last year, the JVLA's Cluster Back End (CBE) has been configured to allow high-precision pulsar timing observations if the array is operated in "phased-array" mode (i.e. with the signals from each antenna coherently summed towards a particular position on the sky).

3.1 Sensitivity

Since pulsars are steep-spectrum radio sources, any high-precision timing at the JVLA would predominately use the L-band receivers (1–2 GHz). Unfortunately, the inefficient illumination of the JVLA dishes at L-band, poorer system temperatures by 5K or more compared to the GBT, and similar available total bandwidths, mean that the GBT is 30-40% more sensitive than the JVLA. If we wanted to compensate for this sensitivity loss with observing time, our observation durations would need to increase by almost a factor of two compared to the GBT. Given the JVLA's current oversubscription rates and the fact that it does no pulsar work means that we would likely get *less* observing time than at the GBT and our TOAs would have 40–50% larger errors. Recent simultaneous exploratory GBT and JVLA observations of two NANOGrav pulsars are shown in Figure 3.

3.2 Sub-GHz Observations for ISM Corrections

The lack of a sensitive sub-GHz observing system at the JVLA is a substantial weakness which would have to be addressed. Without sensitive low-frequency timing observations, the time-varying dispersive effects of the ISM would dominate our error budget. Figure 1 shows that if we simply replace the GBT with the JVLA, within a few years it will take an *additional* couple of years to detect GWs. A larger loss of sensitivity is apparent towards continuous GW signals as shown in Figure 2. If we can secure substantial time on non-US telescopes with a 0.4–1 GHz capability, such as the GMRT in India and CHIME in Canada, we could make the ISM corrections necessary to recover most of the lost GBT capability. *However, securing that non-US telescope time, especially year after year for 5–10 years in the future, adds substantial risk to the project and detracts from US leadership in this enterprise.*

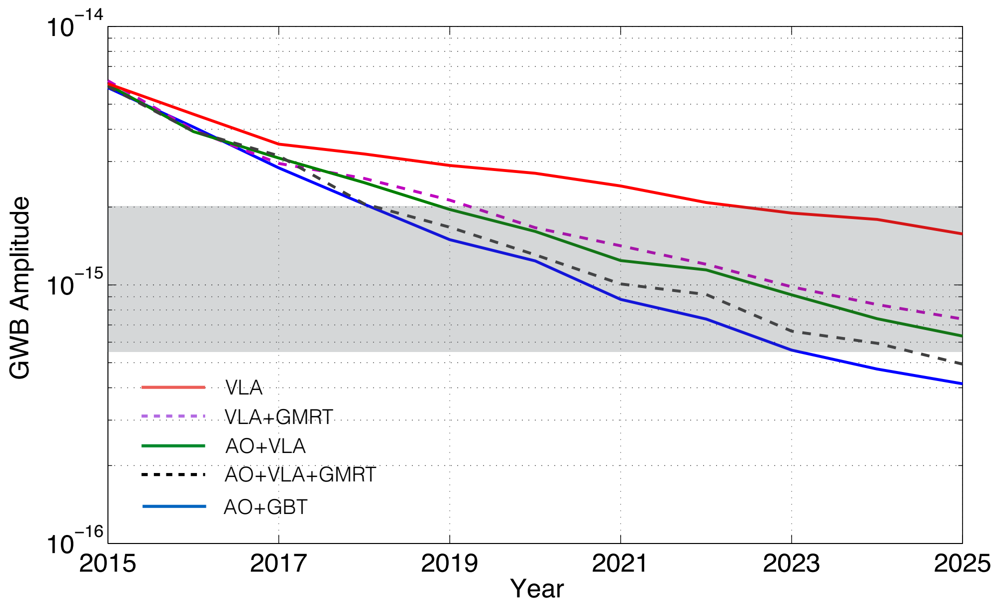

Figure 1: Predictions for NANOGrav's sensitivity to a stochastic GW background assuming a switch from the GBT, and possibly also Arecibo, to the JVLA starting in 2015. The curves represent a 3-σ detection in 90% of the simulations, while the gray band shows the expected range of the true stochastic GW background. The solid lines show timing observations only using US facilities, while the dashed lines show the results of supplementing the US observations with hundreds of hours of lower-frequency time on international telescopes like the GMRT or CHIME. The delays in detection, or equivalently GW sensitivity losses, come from a combination of reduced telescope sensitivity, poorer dispersive corrections (especially when other telescopes like CHIME or the GMRT are not available), fewer MSP additions to the array due to the cessation of GBT and Arecibo pulsar surveys, and less observing time. The effects would be much worse without our nine year baseline of GBT timing data. These simulations assume that we will acquire $\sim$200–250 hours per year of JVLA time with a loss of the GBT, or 450–500 hours per year of JVLA time with the loss of both the GBT and Arecibo.

3.3 Pulsar Surveys

NANOGrav depends on continued pulsar surveys to discover additional MSPs to improve our GW sensitivity. Most of the MSPs added over the previous five years have been from GBT surveys, several of which are ongoing and continuing to discover bright, high-precision MSPs. If we lost access to the GBT, these critical surveys would end. Pulsar surveys with radio arrays are incredibly difficult due to the massive data rates generated — tens of thousands of spectra per second for each resolved pixel in the field-of-view. For the JVLA, the data rate would be 10–20 GB/s, and that would have to be stored and then shipped elsewhere for processing. To make the processing even remotely feasible, we would need E-array, which would decrease the processing costs with respect to a D-array survey by a factor of $\sim$100. Simply put, *a JVLA-based MSP survey is practically impossible in the next decade*. Similarly, MeerKAT will not conduct wide-area pulsar surveys within the next decade for these same reasons. SKA pulsar search processing remains one of the most technically challenging parts of that project.

3.4 Imaging vs non-Imaging

Finally, the capabilities that make the JVLA the premier imaging radio telescope in the world, such as excellent image fidelity and dynamic range at four configurable spatial resolutions, are completely unused by pulsar timing observations. Pulsar timing requires only a phased-array data stream from a single point on the sky. However, just generating and using that stream has its own risks:

- Phasing requires telescope time that is not needed at a single-dish telescope, resulting in loss of observing efficiency.
- Phasing of the array is more difficult in the extended configurations of the JVLA.
- RFI can cause loss of phasing efficiency (see Figure 3).
- The stability of polarization properties, an important aspect of high-precision pulsar timing, has not been investigated with phased-array data.
- Absolute time and time transfer at the JVLA has not been investigated as it has not been required at the nanosecond level before.

In general, an array like the JVLA is heavily over-designed for pulsar observations, resulting in costs per hour approximately a factor of three higher than for the GBT. In fact, the GBT is itself even heavily over-designed for pulsar observations (we do not need frequencies >10 GHz, in general). The main requirements for pulsar observations are excellent sensitivity in the 0.3–3 GHz band and full sky coverage. The reason that the next generation "pulsar" telescopes are being built as arrays (e.g. MeerKAT and SKA) is purely because large numbers of small dishes is a cost-effective way to provide that sensitivity and sky coverage.

4 A loss of both the GBT and Arecibo

For the MSPs that are visible from Arecibo, no other telescope can approach the achievable timing precisions due to its unparalleled sensitivity. *NANOGrav would require several thousands of hours of JVLA time to only partly replicate the $\sim$400 hours of Arecibo time we currently use per year*. If we assume that we could get 200–250 hours per year of JVLA time to compensate for the loss of Arecibo 1–2 GHz observations, our arrival time precision would decrease by a factor of $\sim$12, making almost half of the currently observed NANOGrav pulsars at Arecibo useless for GW work.

Without the GBT and Arecibo, the three most sensitive ongoing large-area pulsar surveys for MSPs in the world would cease. Without these and related surveys, such as targeted searches of *Fermi* gamma-ray unassociated sources, the most effective way to improve future pulsar timing array sensitivity (i.e. adding more high-precision MSPs) would be hugely impaired.

The loss of these telescopes would also heavily impact related educational and outreach programs. A key aspect of the Arecibo Remote Command Center (ARCC) is conducting pulsar observations with Arecibo and the GBT. The queue-based operational mode of the JVLA would not allow such activities. The Pulsar Search Collaboratory (PSC) has involved nearly 2,000 middle- and high-school students in analysis of pulsar search taken taken with the GBT. The ARCC students also analyze the search output from GBT and Arecibo pulsar surveys for both scientific and educational purposes. These valuable activities, which are building a diverse STEM pipeline in the US, would cease when the corresponding pulsar searches end.

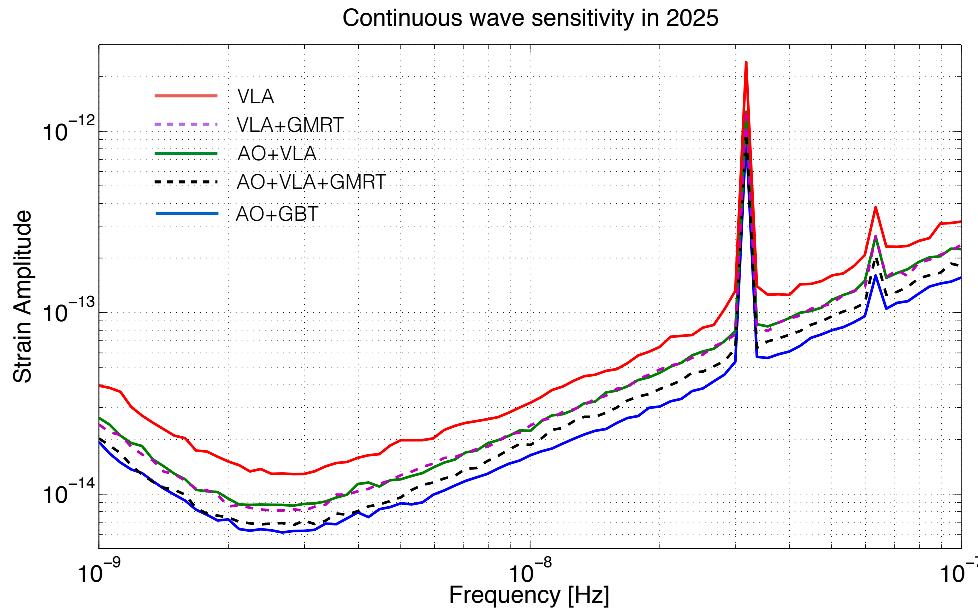

Figure 2: Predictions for NANOGrav's sensitivity to continuous wave GWs in 2025, showing the long-term effects of switching away from the GBT and possibly Arecibo. The line colors and types are the same as in Figure 1. The ∼50% loss of sensitivity when using Arecibo + JVLA (compared to Arecibo + GBT) is due to reduced TOA precision from the Southern pulsar J1909−3744 and from additional systematics caused by inadequate ISM corrections. The latter can be mostly mitigated by using non-US low-frequency telescopes such as the GMRT and CHIME, but with substantial additional risk. If the JVLA alone is used, the sensitivity is a full factor of two less than would be achieved with Arecibo + GBT, corresponding to a detection volumne an order-of-magnitude smaller, thereby making a detection much less likely. As in Figure 1, these simulations assume that we will acquire ∼200–250 hours per year of JVLA time with a loss of the GBT, or 450–500 hours per year of JVLA time with the loss of both the GBT and Arecibo.

Finally, without a large and scientifically-viable single-dish radio telescope, development of new hardware capabilities for pulsar science would be significantly more difficult. For example, we cannot easily test or conduct early science operations of cutting-edge observing systems like the ultra-wideband system (∼0.5–3 GHz) proposed for the GBT using the JVLA. The already devastated university radio groups need such small-scale yet high-impact developmental access.

5 Summary

If the JVLA were to replace the GBT and/or Arecibo for NANOGrav observations, NANOGrav could still, in principle, achieve its goal of directly detecting and characterizing low-frequency gravitational waves (GWs), albeit with *substantial* additional risk. The detection would likely take an additional 2–3 years and would require the use of non-U.S. telescopes for the sub-GHz observations to correct for interstellar medium (ISM) effects, using methods that are not yet demonstrated. The NANOGrav JVLA 1–2 GHz observations would require *at a minimum* 200–250 hours per year to compensate for the GBT and a similar or even larger amount of time to compensate for Arecibo, decreasing the time available for other science projects that better utilize the JVLA's unique high-fidelity imaging and multiple spatial resolution capabilities. If the JVLA were required to replace *both* the GBT and Arecibo, NANOGrav would experience dramatically reduced sensitivity and probability for GW detection, and would provide much less effective basic physics tests. To better but still *only partially* recuperate the lost 1–2 GHz timing precision from both the GBT and Arecibo would require more than 1000 hours per year of JVLA time.

References

Demorest, P. B., et al. 2013, ApJ, 762, 94

Lommen, A. N., & Demorest, P. 2013, Classical and Quantum Gravity, 30, 224001

McLaughlin, M. A. 2013, Classical and Quantum Gravity, 30, 224008

Siemens, X., Ellis, J., Jenet, F., & Romano, J. D. 2013, Classical and Quantum Gravity, 30, 224015

Appendix A: Observational Capabilities

	JVLA	GBT	Arecibo
High-freq Timing System	L-band	L-band	L-wide
Usable Bandwidth (MHz)	800	650	600
SEFD (Jy)	14.4[a]	9.5	3.0
Sensitivity[b]	0.73	1.0	3.0
Low-freq Timing System	P-band	820 MHz	430 MHz
Usable Bandwidth (MHz)	70(?)	190	20
SEFD (Jy)	$\sim$150	14	10
Low-freq Survey System	P-band	350 MHz	327 MHz
Usable Bandwidth (MHz)	70(?)	90	70
SEFD (Jy)	$\sim$150	30	16

[a]From EVLA Memo 152 assuming 26 antennas
[b]$\sqrt{\mathrm{BW}}$/SEFD scaled so GBT$\equiv$1. Higher is better.

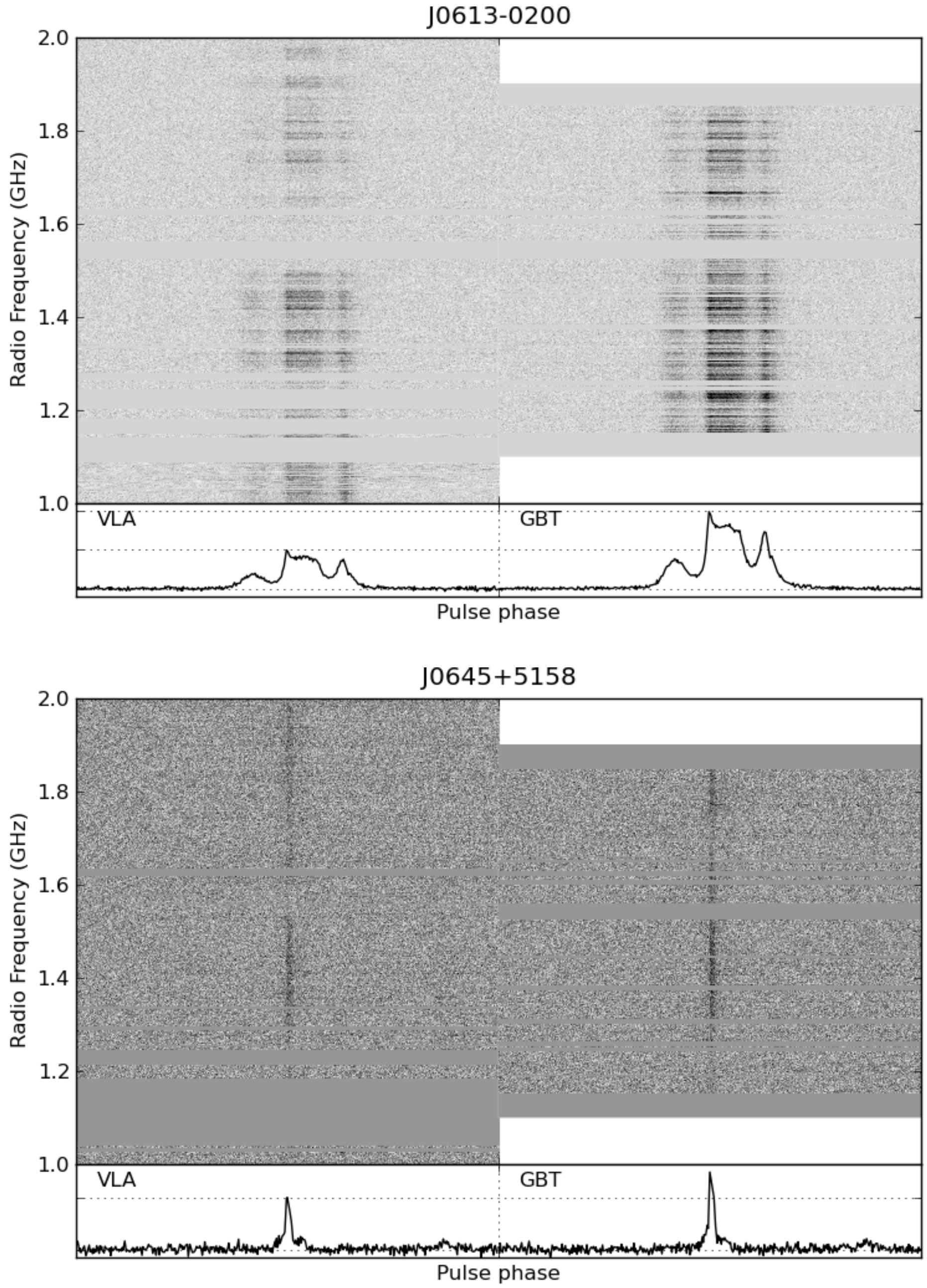

Figure 3: Simultaneous observations of two NANOGrav pulsars taken with the JVLA and the GBT. Each observation was approximately 50 minutes in duration. The data have been normalized such that the off-pulse noise levels are the same for each telescope. The nominal band passes of the L-band receivers are shown in gray, and gray bands without noise indicate where interference (RFI) was excised. For the observation of PSR J0613−0200 (top), the S/N of the GBT detection is a factor of two larger than for the JVLA. This was due to a loss of phasing efficiency caused by strong RFI for the Southern source. The observation of PSR J0645+5158 (bottom), a significantly weaker Northern source, shows a ∼50% improvement in S/N for the GBT, much closer to the ∼30–40% improvement that we expect from simple radiometer calculations.