A Vision for cm/m Radio Astronomy in the US

A Whitepaper by the Ad-Hoc Radio Planning Group (ARPG):

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Executive Summary

Our Ad-Hoc Radio Planning Group has assembled to recommend a vision for development, construction, and operation of cm/m telescopes to advance the frontiers of knowledge in physics, cosmology, and astrobiology. Our aim has been to formulate goals and recommendations that can be put forward for discussion in the general astronomical community. Our primary recommendations are as follows:

1. Investigation of the Epoch of Reionization, the properties of Dark Energy and Dark Matter, fundamental tests of gravity, interstellar organic chemistry, and the formation of structures such as galaxies and solar systems, requires development of new cm/m radio telescopes that take full advantage of ongoing, dramatic technology developments.

2. Development and construction of the Square Kilometer Array should remain the primary goal of US cm/m radio astronomy this decade and next, with the US as a major partner in the international SKA project. Other cm/m radio telescopes developed and built over the next decade, as well as the development and exploitation of new technologies under the US SKA Consortium’s Technology Development Project, are essential as technical and scientific pathfinders to the SKA. The exact path to the SKA will depend on the pace of technology development, and we recommend that a subcommittee of the CAA be formed to determine how, within budgetary constraints, pathfinder telescopes built with US participation can best serve the development of the SKA. The committee recommends that construction of the SKA is best done by splitting the SKA into low and high frequency bands, roughly 20 MHz to 1.5 GHz (“SKA-low”) and 1 GHz to 30 GHz (and ideally up to 50 GHz) (“SKA-high”), a plan that needs to be worked out with the international SKA community.

3. Fund the usage of Arecibo and the GBT, the two largest single-aperture telescopes, that allow their enormous scientific potentials to be realized for near term science results and for their utility in testing technologies needed for the SKA.

4. It is essential that centimeter-wave interferometers currently under construction or in operation, namely the EVLA, ATA, and VLBA, be funded adequately by NSF for completion and operation. This will ensure that these instruments can be operated successfully as scientific and technological pathfinders for the high-frequency component of the SKA, as well as forming the backbone for its eventual construction (subject to agreement by the international SKA community).

5. The LWA and MWA should continue to be developed over the next 3 to 4 years, following which we recommend a community-wide assessment, in preparation for the next decadal review, of the best way to implement the capabilities needed in the 20-300 MHz frequency range. Close cooperation among the US low-frequency groups is essential to maximize the efficiency of US efforts relevant to the low-frequency component of the SKA.

6. Collaborations among centers of excellence must be strengthened to best utilize the technical capabilities existing in the US radio astronomy community. To achieve this goal, we recommend formation in 2005 of a cooperative, trilateral organization that includes the two national radio observatories, NAIC and NRAO, and a consortium of universities and laboratories. This organization should include a small (~ 6-member), high-level, standing committee empowered to define and implement an appropriate plan for long-term collaboration.

7. The US must maintain its primacy in the production of instrumentalists and observers at universities. In this regard it is important for the NSF to provide sufficient support to maintain university groups that produce our future scientists and instrument builders. It is vital that university personnel be integrated as much as possible in development and construction projects led by the national observatories, and that, reciprocally, the national observatories be responsive to projects initiated by university and laboratory groups.

8. Nurturing a viable research community in centimeter and meter-wavelength astronomy requires a sensible linkage of telescope time and funding for data analysis. In addition, to ensure broad-based community participation in the SKA and its pathfinder telescopes, an achievable plan is needed for the placement of their data and scientific results into Virtual Observatory archives.

Please see the sections Development Plan and Managing the Vision for details on the time line and organization of radio astronomy efforts.

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Goals of this Document

Centimeter-wave and meter-wave radio astronomy helped define the forefront of astrophysics with discoveries such as the Cosmic Microwave Background radiation, pulsars, gravitational radiation and the invention of aperture synthesis imaging, garnering six Nobel prizes in the process. Given recent developments in areas such as Dark Energy, Dark Matter, the Epoch of Reionization (EOR) of the Universe, and the role of central black holes in galaxy formation and evolution, centimeter and meter-wave astronomy are again poised to play a central role in tackling questions of fundamental astrophysics. New radio telescopes currently being built or developed to attack these and other science goals include the Expanded VLA (EVLA), Allen Telescope Array (ATA), Long Wavelength Array (LWA), Mileura Widefield Array (MWA), and the Square Kilometer Array (SKA). This new generation of telescopes is made possible by new technologies in areas such as signal processing; low cost fiber optics; cheap, compact and reliable cryogenics; wideband receivers; and very low cost antenna design. Despite all of these advances, in the current funding climate it may not be possible to fund all of these projects for development and operation on a timescale that is optimal for their primary science drivers. We have therefore assembled to recommend a plan for development, construction, and operation of centimeter and meter-wave radio telescopes that would enable our primary science goals to be achieved over the next 10–20 years. Our group, the “Ad-Hoc Radio Planning Group” (ARPG), contains members from a number of institutions and projects, and our aim has been to formulate goals and recommendations that can be put forward for discussion in the general astronomical community. This whitepaper is a presentation of those ideas, which the ARPG members have endorsed unanimously.

Transformational Science from Radio Astronomy

Radio astronomy is entering a period of rapid technological advance, unparalleled since the development of the subject after the second world war. The new technologies are based on focal plane arrays, MMIC amplifiers, wide bandwidth feeds, and order-of-magnitude advances in the ability to transport and process massive amounts of data; these have recently produced the first radio cameras. The renaissance in radio astronomy places the discipline in a powerful position for tackling fundamental problems in physics, astrophysics and cosmology. This follows from a set of clearly identifiable science goals that all can agree are fundamental, whose successful completion will be transformational, and that can be attacked with new radio astronomy instrumentation.

Either directly or through multidisciplinary studies, radio astronomy will alter our view of the universe in dramatic new ways by making progress in the following areas:

- Advancing precision cosmology through observations of the CMB, particularly B-mode polarization measurements
- Understanding primordial fluctuations that grow into the cosmic web
- Resolving cosmic structure before and during the formation of galaxies
- Determining the equation of state of Dark Energy and its cosmological evolution
- Understanding the evolution of Dark Matter potentials on scales from galaxies to clusters
- Measuring the reionization history of the universe
- Identifying the first black holes in the universe
- Measuring the first molecules in the universe
- Mapping the intergalactic medium
- Testing gravity in the strong field regime (was Einstein right?)
- Understanding the acceleration of the most energetic particles
- Understanding the chemistry of organic molecules in space
- Synoptic mapping of planet formation in disks around stars
- Exploring star/disk/planet interactions
- Discovering entirely new phenomena, such as those associated with the transient radio universe

Discovery and understanding of these areas requires sensitive, state-of-the art facilities that employ new enabling technologies for conducting massive, high throughput surveys and follow-up analyses.

The Road Ahead: Building the Square Kilometer Array (SKA)

To realize the continuing promise of radio astronomy, new technology is needed that combines the known techniques and capabilities of radio astronomy with key innovations:

- Developing radio-frequency continuum and spectral line cameras of ~ 1000 focal-plane elements, which will transform radio frequency surveys, and be deployed on a wide range of radio telescopes over frequencies from 20 MHz to 180 GHz. Massive surveys using such cameras will pave the way to the SKA.
- A leap in sensitivity by two orders of magnitude achieved by increases in collecting area combined with broadband frontends and backend digital processing systems.
- Development of wide field of view (FOV) telescopes that are essential for conducting surveys of up to $10^9$ objects.
• Improvements in angular resolution at higher sensitivity, enabling imaging (and not just detection) of new (and known) classes of objects and objects at high redshift.
• Developing digital technology to provide flexible use of the collecting area and FOV for surveys and studies of sources in the spatial, time, and frequency domains.

Overall, the unifying path for centimeter and meter-wavelength radio astronomy is to achieve the rich science goals of the SKA. To build the SKA requires an ambitious development program over the next ten years that creates innovations in many software and hardware areas. It is also mandatory that existing telescopes, outfitted appropriately — along with new, pathfinder telescope arrays — be used to achieve intermediate science goals and to test new technologies.

**Parameterizing Discovery and Analysis in Radio Astronomy**

The traditional performance measures for radio telescopes have been sensitivity, angular resolution, and frequency coverage. For imaging arrays, criteria such as imaging fidelity and spatial frequency coverage are also important. Today, however, we stand on the verge of a revolution in radio array capability that demands a more comprehensive view of performance, including such factors as simultaneous multibeaming and multifrequency capability, flexibility and agility of various kinds (e.g., electronic pointing, fast switching), a wide and continuous tuning range, high spectral resolution, and other metrics, such as survey speed, and transient source sensitivity. Many of these performance parameters depend to a large extent on digital signal processing architecture and capacity, and on new designs for antenna systems that maximize the information content of the data, upon which the digital systems can operate.

In 2003–2004, the science case for the SKA was developed by initially considering seventeen proposals for science drivers that emerged from the scientific wisdom of a global community of workers that included radio astronomers, multiwavelength observers, and theorists. More than half of the proposals require very wide fields of view to enable high survey speeds. Roughly half the proposals rely on wavelengths of 21 cm and longer, and half of the proposals (not the same half) rely on spectral line measurements. Some require VLBI resolution, some require extreme surface brightness sensitivity, and some require flexibility, quick response, or high time resolution. The lesson to draw from this exercise is that the scientific potential of an array depends on many performance parameters, not just the traditional ones of point source sensitivity, resolution, and frequency coverage. The discussion of future telescopes in the next section draws on the broad multi-dimensional expansion of discovery space enabled by the radio telescopes of the future.

The ARPG recognizes and endorses the need to look beyond traditional performance measures for radio telescopes, and recognizes that the global SKA effort is the appropriate vehicle for developing and implementing next-generation capabilities, in which astronomers of all types and in all countries have a stake.

**Elements of the Vision**

To fulfill the science vision for the SKA, the radio astronomy community needs to take appropriate, intermediate steps in science exploration and technology development that use existing and near-future instruments in a variety of roles. One such role is the all-sky mapping of astronomical foregrounds that must be done at centimeter wavelengths (and mm wavelengths) for the success of measuring polarized CMB emission (especially B-mode polarization) and similarly at meter wavelengths for measuring the EOR signal in redshifted HI observations. Other roles include testing broadband, multiple pixel feed systems, developing algorithms for massive surveys, interference excision, and transient detection, etc. Here we describe the importance of particular telescopes for these roles. The discussion starts with existing instruments, then goes to those under development and finishes with the plan’s backbone, the SKA.

**Arecibo and the GBT:** The largest two apertures in the world are key for conducting deep radio surveys, especially with broadband feed and receiver systems and focal plane arrays developed under the SKA theme. Until the SKA is developed, the ALFA multibeam system on the Arecibo telescope will allow the most comprehensive surveys for pulsars, the deepest probe of the HI mass function, and a comprehensive survey for transients at 1.4 GHz. Multibeam systems at frequencies as high as 11 GHz will provide deep surveys for new molecules. The GBT is the second largest aperture on the planet and its wider declination range and usability at higher frequencies will provide wide sky coverage for surveys of molecules and pulsars. Together, Arecibo and the GBT are now two important nodes for the high sensitivity array (HSA) for VLBI (also including the phased VLA, Effelsberg telescope, and VLBA). The HSA is the initial step needed toward using VLBI on thermal as well as nonthermal sources. The final step will be construction of the SKA.

**EVLA:** The EVLA, whose first phase (EVLA-I) is currently under construction, was one of the leading recommendations of the most recent astronomy decadal committee, as detailed in their report “Astronomy and Astrophysics in the New Millennium.” The primary technical goals of EVLA-I are to increase the bandwidth, spectral coverage, and spectral capabilities by at least an order of magnitude. The EVLA-II concept would expand the EVLA by a factor of ten in linear dimension to focus on a primary science area of “Resolving Cosmic Evolution.” EVLA-II will include construction of eight new antenna stations at distances up to several hundred kilometers from the VLA site and connection of two VLBA antennas to the VLA by fiber optics, in preparation for connecting the EVLA and VLBA completely. This would complement the EVLA-I expansions in sensitivity and spectral capability.

Most of the techniques and instrumentation being developed for the EVLA will be important for the design and development of the SKA, including the following:
A proposal for EVLA-II presently is before the NSF. All the above techniques will be needed for EVLA-II, and the completed EVLA can form a nucleus for expansion to the SKA, with additional SKA collecting area added at the central and outlying EVLA sites. The exact nature of the solutions to the above technical problems will depend on the relative funding profiles for EVLA-II and for SKA technology development. If EVLA-II is not funded in the near-term, we support a path to the SKA that accomplishes much of the EVLA-II science using revolutionary technologies developed for the SKA between now and early next decade. Of particular interest for both EVLA-II and SKA is the cost curve for collecting area as a function of antenna diameter, which is expected to evolve rapidly given adequate funding for technology development. The costs of receivers, data transmission, and data processing should decrease with time but at a different rate than the antenna costs, which depend on new manufacturing techniques. Hence an EVLA-II with first construction funding in 2011 or 2012 would look quite different from an EVLA-II whose funding begins in 2007.

VLBA: The VLBA occupies a unique niche in the panoply of US astronomical capabilities, in terms its astrometric accuracy and imaging capability on sub-milliarcisecond scales. Furthermore, the VLBA stands poised at the threshold of a revolutionary increase in sensitivity, propelled by the application of new and inexpensive digital technology to rapidly expand bandwidths by up to two orders of magnitude.

In August 2004, the report of the Lonsdale/Taylor (LT) committee entitled “Mapping the Future of VLBI Science in the US” was submitted to the Directors of NRAO and Haystack Observatory, and was copied to the NSF. It can be found at web.haystack.mit.edu/vlbi/pdf/future.pdf. The report discusses the fact that “the resources expended on hardware and software support, upgrades, and investigator support via grants, have not been commensurate with the capital investment or scientific yield and potential of the array”. A vision for reinvigorating US VLBI is presented, which will enable a range of high-impact future science investigations. These science investigations are critical as part of the path to the SKA, which has science goals requiring imaging of faint sources at milliarcsecond resolution.

Technically, the pace of progress in fiber-optic communications is such that, perhaps sooner than anybody was projecting even 18 months ago, all major radio astronomy apertures will be linked to multi-gigabit pipelines, and the distinction between VLBI and connected-element arrays will evaporate. A fiber-connected EVLA and VLBA infrastructure is ideally suited to development and testing of SKA technology, and staged deployment of expanded high-frequency collecting area.

High resolution science is least impacted by wide-field imaging challenges associated with stations composed of arrays of small aperture antennas. For these reasons, enhancing the VLBA with new technology is an essential part of a financially and technically responsible plan that builds the SKA out from the EVLA, to the VLBA, in order to achieve its ultimate science goals. To summarize:

- The unique scientific role of the VLBA should be exploited by following the recommendations of the LT report.
- The VLBA is a crucial platform for developing, testing and implementing technologies for the longest SKA baselines.
- The future of high resolution radio astronomy is in the direction of vastly greater collecting area that will provide sub-milliarcsecond resolution on thermal as well as nonthermal sources, and this can be accomplished by building on the investment in a combined EVLA and VLBA.

ATA: The ATA will add new capability to radio astronomy, making possible a nearly-all-sky extragalactic HI survey to \( z = 0.16 \) at high sensitivity (\( \sim 100 \mu \)Jy/beam) and moderate resolution (1 arcmin). It will also allow widefield surveys for radio transients with timescales from 10 ms upward, simultaneous multiple pulsar monitoring, measurement of magnetic fields via Zeeman splitting over large angular extents, and other kinds of observations enabled by the wide FOV and flexible operating modes. In order to provide this new capability, new technologies have been and will continue to be developed that will serve as proof-of-concept for various SKA developments. The ATA itself is a first-stage prototype for the SKA by showing that the Large-Number/Small-Diameter (LNSD) concept is both workable and can bring down the cost of a high-frequency SKA by a factor of at least 5 over conventional designs. It is the focal point for the development of large-N high bandwidth correlators in collaboration with industry consortia that will serve as a prototype for new correlator designs for the SKA. It will be a test bed for the critical task of RFI mitigation studies and for antenna feeds with up to 5 octaves of bandwidth. Such feeds will keep high-frequency SKA costs low by having a single feed for the entire bandwidth of the telescope. Most importantly, the ATA will serve as a development test bed for new technologies that are expected to develop during the design phase of the SKA, such as low-cost fiber drivers and inexpensive high clock rate digitizers.

LWA: The Long Wavelength Array (LWA) will open the relatively unexplored frequency range below 90 MHz by capitalizing on breakthroughs in ionospheric calibration that finally permit very low frequency arrays larger than \( \sim 5 \) km. The \( \sim 400 \) km LWA will realize improvements in both angular resolution and sensitivity by at least an order of
magnitude and, coupled with wide FOV and multi-beaming capability, will efficiently exploit one of the last unexplored regions of astrophysical discovery space. The LWA frequency range favors studies of nonthermal and coherent emission processes including transients, and is closely linked to shock physics, high-energy phenomena, and the high-redshift Universe. Key scientific themes are cosmic evolution including the first super-massive black holes and diffuse emission in clusters to trace Dark Matter potentials and to define relaxed systems that will constrain Dark Energy. Another key scientific goal is acceleration of cosmic rays, including the highest energy particles of unknown origin. LWA-observed nonthermal phenomena in supernova remnants, radio galaxies, and clusters closely couple to processes traced by future high energy space missions such as GLAST.

The LWA is being developed by the Southwest Consortium, which includes the University of New Mexico, the University of Texas Applied Research Laboratories, the Naval Research Laboratory, and the Los Alamos National Laboratory. A goal of the LWA project is to engage academic researchers, postdocs, and students outside the traditional radio astronomy structure in a hands-on construction, testing, and observing environment as a means of re-invigorating US radio astronomy at the university level. The LWA will be centered near the current VLA and built in stages in order to develop working solutions to technical problems such as pre- and post-correlation RFI mitigation, angle-dependent self-calibration and wide-field imaging; these issues also are challenges for other existing and planned instruments. Early stages will leverage and complement the VLA 74 MHz system by initially adding outlier stations to improve angular resolution and aperture-plane coverage. The LWA will also serve as a pathfinder for a very-low frequency, low cost capability on the SKA.

**MWA:** The ultimate goal of the MWA project is to develop powerful new capabilities for radio astronomy below about 1.6 GHz, optimized for extremely wide fields of view and unprecedented sensitivity for a variety of survey applications. It is intended to pave the way for key capabilities of a low-frequency SKA. The first stage of the MWA has specific scientific goals, and is under way as a joint project led by MIT and the CSIRO Australia Telescope National Facility (ATNF), with strong participation from the Harvard-Smithsonian Center for Astrophysics and a number of Australian universities, as well as the government of Western Australia. The initial goal of the MWA project, in the next 3-4 years, is to create two complementary, co-located but substantially independent scientific demonstration instruments, one led by MIT in the 80-300 MHz frequency range, and the other led by ATNF in the 800-1600 MHz range. They are referred to, respectively, as the Low Frequency Demonstrator (LFD) and New Technology Demonstrator (NTD).

There are three key science goals of the LFD, which though labelled a demonstrator instrument, has the capacity for high-profile science. First, the LFD is designed to detect and characterize redshifted 21cm emission from the EOR, with high precision and painstakingly minimized systematic errors. Such a result would be of profound cosmological significance and broad interest. Second, the LFD will conduct a search for transient radio emission that is 6 orders of magnitude more sensitive than any previous work, yielding a variety of scientific opportunities. Third, the LFD will allow high-resolution remote sensing of the heliosphere via measurement of propagation effects, and it offers the prospect of constraining the magnetic field properties of coronal mass ejections, with associated benefits for space weather prediction. The LFD has several secondary science goals, such as pulsar research, measurement of interstellar medium properties, and the study of radio recombination lines. Following the demonstrator phase, the full MWA facility would cover a broader frequency range, with much higher sensitivity and higher angular resolution, addressing a broad range of additional research areas.

**SKA:** The SKA currently is specified to cover 0.1 to 25 GHz in a configuration that provides both high-angular resolution and sensitivity to low-surface brightness extended emission. The long-term science vision implies that great returns can be expected by extending the frequency coverage to as low as 20 MHz and up to as high as 50 GHz, a natural limit imposed by the Earth’s atmosphere. (Note that 50 GHz is the frequency for CO 1 → 0 at z = 1.3 or CO 2 → 1 at z = 3.6.) The SKA project has become a focal point for forward-looking radio astronomers across the globe as an opportunity to implement a much needed boost in capability in all performance parameters, particularly those that depend on digital processing. But the volume of parameter space encompassed by major expansion of all these parameters at once, in the same instrument, is enormous, and correspondingly unaffordable, in our view.

The committee believes that the wide-ranging scientific goals attributed to the SKA can be best realized through construction of two instruments that implement new technologies in a cost-effective, optimized way. A low-frequency SKA ("SKA-low") can be optimized for physical collecting area and wide fields of view, while a high-frequency SKA ("SKA-high") can instead be optimized for very wide bandwidths and a frequency range that better complements ALMA. Since neither instrument must meet all SKA specifications, total costs are sharply reduced. SKA-low may itself consist of two primary antenna types: dipoles for frequencies below ~300 MHz and low-precision paraboloids from approximately 0.3 to 1.5 GHz. SKA-high would employ higher precision paraboloids. Development work for all three antenna types of the SKA needs to commence as soon as possible.

For the currently specified SKA scientific and technical goals, we support and recommend the plan of building upon EVLA and VLBA infrastructure for a (possibly) reduced-collecting-area SKA above ~1 GHz (e.g., see VLBA subsection above), while simultaneously pursuing a larger collecting area instrument below ~2 GHz at an internationally selected site. Since the total collecting area likely will drive the cost of SKA-high, we recommend a careful assessment of high-frequency SKA science that could be achieved with an instrument having a total collecting area of 0.1–0.3 square kilometers. Crucial for a baseline design for the SKA are the near-term activity of the ATA described above, the pathfinder aspects of the LWA and MWA, EVLA/VLBA technology and science development, and the US SKA Consortium’s Technology Development Project. US-funded efforts for the SKA of course must be coordinated with the international SKA project.
ENABLING TECHNOLOGIES

Innovations in radio technology that must be harnessed for the next generation radio telescopes and which can be used to achieve science goals in the interim include the following:

1. Antenna manufacturing methods that provide robust, low-cost collecting area that exploit economies of scale.
2. Efficient broadband feeds and receivers having at least decade bandwidths.
3. Focal plane arrays using MMIC technology and expected increases in digital processing speeds for beam forming.
4. Correlator and backend processors that can accommodate broadband signals from many thousands of front-end systems.

The requisite development work in these broad areas must begin now in order to reach important milestones for the SKA and also to exploit interim innovations for science using existing and prototype telescopes. This work requires the combined expertise and efforts of a broad coalition of radio astronomers in the US and their colleagues in other countries.

DEVELOPMENT PLAN

Here we sketch a broad development plan that responds to the changing funding landscape in the US.

First, we would like to emphasize that all the projects under consideration in this document had their origins in the pre-2001 world when, among other things, the NSF’s budget was proposed to double during this decade. If that were still the plan, the committee would emphatically endorse funding of all the projects because of their high quality and the richness of their science goals and deliverables.

In the present funding environment that at best is a no-growth situation, we nonetheless strongly endorse funding the EVLA-II project through the NSF/MRE line and support the other projects according to timelines that can be accommodated within the NSF/AST budget. We point out also that construction funding is coming from or may come from non-NSF sources, including private funding for the ATA, DoD and DoE funding for LWA, and partial international funds for the EVLA, MWA, and SKA. However, operating and data processing funds are likely to be requested from the NSF for all the projects.

In the non-ideal situation where NSF/MRE funds are unavailable for the EVLA-II project in the remainder of this decade and support for new projects from NSF/AST is sparse, the ARPG recognizes that an economical plan is needed that optimizes the science and technology return both in the short term and the long term. Our suggestion for this unhealthy but hopefully short-term situation is as follows.

1. Fund EOR prototyping and demonstrator projects (e.g. MWA) that may make the first detection of the EOR signal and which will provide important input for follow-on arrays. These will tap the rich information content of cosmic EOR structure in much the same way that instruments such as CBI, WMAP, and Planck extract precision cosmological parameters from structure in the CMB. The appropriate follow-on array is the low-frequency part of the SKA.

2. Provide ancillary funding for university work that develops infrastructure for the lowest frequency bands, which are appropriate for the LWA project, and which will lead to an array that opens the very low frequencies to sensitive exploration for the first time.

3. After a few years of development on these low-frequency projects, the committee would like to see a community-wide assessment of how to proceed with the LWA and MWA projects.

4. Fund aspects of the ATA that allow its usage for radio astronomy and particularly for those observations and algorithm development that are important for the SKA. Operational support for the ATA can ramp up as more antennas are put into operation over the next few years.

5. Fund the usage of Arecibo, the GBT, the EVLA and the VLBA at levels that allow their enormous scientific potentials to be realized for near term science results and for their utility in reaching the overarching goal of building the SKA. This funding should include much needed support for observations and data analysis that are required to have a viable radio astronomy community.

6. Fund the Technology Development Project for the SKA, suitably rescoped to address the important technology development required to implement the vision of this paper, and to allow a project baseline design to be costed in advance of the next decadal survey.
The broad suggestion for constructing the SKA is as follows:

1. After the prototyping and demonstration phases, the lowest frequency (20 MHz to 300 MHz, say) collecting area could be built in the latter part of this decade because the antennas are inexpensive and adequate signal processing capability will exist by that stage. Among other science areas listed in the section, *Transformational Science from Radio Astronomy*, high-sensitivity investigations of the EOR would be enabled with this instrument.

2. The intermediate frequency range (300 MHz to ~ 2 GHz) is likely to be prototyped in Western Australia this decade with modest amounts of collecting area. It is advantageous for the US to participate in this process and minimal funds would be needed during this decade. The US SKA Consortium would propose to the decadal survey (~ 2009) that the US participate in construction of this portion of the low-frequency SKA in the first half of the next decade. This mid-range SKA will yield transformational constraints on the Dark Energy equation of state using massive surveys along with results on other science goals discussed previously.

3. The high-frequency SKA (1 to 30 GHz or higher) is proposed by us to be a continuation of the EVLA and the VLBA. Its lead time from a technological point of view is longer than that for the low-frequency SKA. Construction for SKA-high would also be proposed to the next decadal survey. Scientific return from SKA-high will include mapping of Dark Matter through massive weak lensing surveys, detection of CO molecules produced by the first stars, detection of the first black holes, and probing gravity by timing pulsars, especially those with black hole companions, including the massive black hole in the Galactic center.

**MANAGING THE VISION**

Progress in the radio astronomy vision requires that resources in the US — facilities, centers of excellence, and personnel — be marshalled in a concerted, efficient effort that aims at common, agreed-upon goals. This necessarily implies the need for cultural changes in the way that university groups work on a best-effort basis as compared to national observatories that work toward targeted deadlines. To facilitate cooperation and collaboration of national observatories and university groups and to strike a much-needed balance in the distribution of effort and responsibility, we suggest a trilateral organizational structure that includes NAIC, NRAO and a “university” consortium (which would also include laboratories, such as NRL). This trilateral organization would identify and muster resources that exist within NRAO and NAIC, the two organizations that receive the largest amounts of radio-astronomy funding from the federal government, and smaller groups at universities, laboratories and institutes, which can be organized into a consortium, similar to the US SKA Consortium. To identify areas of common technology development and ways in which they can be funded and deployed, a small (~ 6 member) steering committee would be formed that comprises representatives from each of the three primary organizations (NRAO, NAIC and Consortium). This would be a standing committee and could be appropriately named the Radio Astronomy Strategy and Action Committee. We suggest formation of such a committee in mid-2005.

Issues and actions that the committee could address include:

1. Identifying hardware projects that require multi-institutional collaboration, an excellent example being the development of focal-plane arrays and their usage on existing telescopes (such as the GBT and Arecibo).
2. Identifying a plan for allocating resources to develop common user interfaces and data reduction software.
3. Development of a plan for funding national observatory instrumentation or software that is developed at universities. A benefit of this approach is that hardware and software can be deployed on multiple telescopes with common interfaces and specifications.
4. Planning large-scale surveys that are expected to be a growing usage of telescope time and which may require coordination between multiple instruments across the entire electromagnetic spectrum.
5. Making preparations for the next decadal survey that ensures that the radio astronomy community speaks with a unified and forceful voice.
6. Serving as a liaison between the US community and international communities on an as needed basis. For example, the success of the North American Program in Radio Astronomy (NAPRA) can be expanded to other collaborations, such as the SKA project.
7. Developing and evolving a US policy for “open skies” that takes into account strategic collaborations between US institutions and foreign institutions.

**SUMMARY OF RECOMMENDED ACTIONS**

— See Executive Summary —
## Appendix
### Acronyms Used

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<th>Acronym</th>
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<tr>
<td>ALMA</td>
<td>Atacama Large Millimeter Array</td>
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<td>ARPG</td>
<td>Ad-hoc Radio Planning Group (the authors of this white paper)</td>
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<td>ATA</td>
<td>Allen Telescope Array</td>
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<td>ATNF</td>
<td>Australia Telescope National Facility</td>
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<td>CAA</td>
<td>Committee on Astronomy and Astrophysics</td>
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<td>CBI</td>
<td>Cosmic Background Imager</td>
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<td>Cosmic Microwave Background</td>
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<td>GBT</td>
<td>Green Bank Telescope</td>
</tr>
<tr>
<td>GLAST</td>
<td>Gamma-ray Large Area Space Telescope</td>
</tr>
<tr>
<td>HSA</td>
<td>High Sensitivity Array</td>
</tr>
<tr>
<td>LFD</td>
<td>Low Frequency Demonstrator</td>
</tr>
<tr>
<td>LNSD</td>
<td>Large-Number/Small-Diameter array concept</td>
</tr>
<tr>
<td>LWA</td>
<td>Long Wavelength Array (to be proposed)</td>
</tr>
<tr>
<td>MIT</td>
<td>Massachusetts Institute of Technology</td>
</tr>
<tr>
<td>MMIC</td>
<td>Monolithic Microwave Integrated Circuit</td>
</tr>
<tr>
<td>MWA</td>
<td>Mileura Widefield Array (proposed)</td>
</tr>
<tr>
<td>NAIC</td>
<td>National Astronomy and Ionosphere Center</td>
</tr>
<tr>
<td>NAPRA</td>
<td>North American Program in Radio Astronomy</td>
</tr>
<tr>
<td>NRAO</td>
<td>National Radio Astronomy Observatory</td>
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<tr>
<td>NSF/AST</td>
<td>National Science Foundation Astronomy Division</td>
</tr>
<tr>
<td>NSF/MRE</td>
<td>NSF Major Research Equipment</td>
</tr>
<tr>
<td>NTD</td>
<td>New Technology Demonstrator</td>
</tr>
<tr>
<td>RFI</td>
<td>Radio frequency interference</td>
</tr>
<tr>
<td>SKA</td>
<td>Square Kilometer Array</td>
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<tr>
<td>VLBA</td>
<td>Very Long Baseline Array</td>
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<tr>
<td>VLBI</td>
<td>Very long baseline interferometry</td>
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<tr>
<td>WMAP</td>
<td>Wilkinson Microwave Anisotropy Probe</td>
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