A Five-Year Proposal (2005-2009) for Technology Development at NRAO

Recommendations of the NRAO Observatory Technical Council (OTC).

Version 1.3, 2004-11-05

Over the last few months, the OTC has been discussing priorities for the future Research and Development activities of the observatory. Attached, as a narrative and detailed spreadsheets, are the OTC's recommendations to the Director. Since budgets are always uncertain, we have divided the activities into 3 categories:

1. Priority 1. These activities should be supported even in a very poor observatory funding scenario.
2. Priority 2. These activities are highly desirable and should be supported if possible.
3. Priority 3. These are worthwhile projects, but in recognition of non-ideal funding profiles, the Council understands that funding of this priority is uncertain.

In its discussions, the OTC has already been selective and has rejected a number of projects that the observatory could profitably have supported, but for which sufficient resources are unlikely to be found.

In the course of its deliberations, the OTC noted that the NRAO R&D program has been reduced virtually to zero. ALMA development had become the prime new technical development for the observatory, but the development phase of ALMA is now over. It is particularly important, for the continuing health of the observatory and in order to maintain a modest degree of technical leadership, that at least the Priority 1 items in this R&D plan be funded; without at least a minimal level of R&D activity the observatory is not fulfilling its mission. We are already seeing talented senior engineers leaving the observatory – its pool of high-level talent is the observatory's biggest resource.

The concept of alternative funding sources for R&D received attention in the OTC's discussion. The OTC is unanimous in **not** supporting this concept beyond projects that are natural collaborative efforts in the course of individual staff research initiatives. It would likely cause NRAO to become involved in various activities unrelated to Radio Astronomy, which the OTC feels is going outside the mission of the observatory. It may end up putting us in competition with the universities for funding, which would be damaging to the strong support from the university community on which we are dependent. Not being able to provide adequate R&D funding from our own resources will further discourage bright young engineers from joining NRAO, rather than staying at universities. Although of course we have to face reality in the current funding climate, nevertheless the OTC feels that more is to be lost than gained by relying on external support for R&D activities.

Finally, on behalf of the OTC I would like to ask you to distribute this report to the NRAO Visiting Committee and to any other advisory committee that you deem to be appropriate. This may help to publicize the fact that the observatory has indeed serious plans and hopes of continuing to push the state of the art in Radio Astronomy technology, but that funding for these activities is at a critical level.

Darrel Emerson,

Chair, Observatory Technical Council. October 29 2004.

Five-Year Proposal for Technology Development at NRAO

25 October 2004

Project priorities: *[1]* = highest priority (essential), *[2]* = baseline (necessary), *[3]* = other (non-essential).

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1 Antenna Research and Development

The NRAO seeks to make substantial advances in the throughput and accuracy of its existing and planned antennas. These advances will come in the form of wider instantaneous bandwidth, greater use of the information in the focal plane, and increased pointing and reflector surface accuracy. We will be participating in the development of very large collecting areas as a member of the U.S. Square Kilometer Array Consortium, but the main thrust of our development efforts in the 2005-2010 time period will be in the direction of very low noise, high efficiency antennas and receiving systems at centimeter and millimeter wavelengths; the details of receiver systems developments are presented in the section below.

Barring a dramatic breakthrough in the material sciences, we expect the major advances in antenna efficiency and accuracy to come in the areas of signal processing and metrology. Both of these areas take advantage of the continued exponential increase in computational power driven by commercial interest.

1.1 Focal Plane Arrays *[1]*

The successes of the Parkes, 13-beam receiver and the SCUBA49 bolometer array have demonstrated the new science that can be done by making better use of the information in the focal plane of a conventional reflector. Focal plane arrays open up many new possibilities in spectral line and continuum imaging, wide-field polarization studies, and searches for new pulsars. Factors of 10 to 1000 or more increased focal plane efficiencies remain to be achieved through greater sampling density and greater fields of view. Array receivers also need to be implemented at many more wavelength bands.

The NRAO focal plane array efforts include coherent beam-forming arrays at centimeter wavelengths, heterodyne arrays for millimeter and submillimeter wavelength imaging, and bolometer arrays for millimeter and submillimeter wavelength continuum imaging. The bolometer arrays will be developed in collaboration with experts in bolometer technology. These arrays will be very sensitive continuum mapping instruments with bandwidths covering a large fraction of each of the millimeter-wave atmospheric windows. Eventually, one or more of the ALMA antennas could be outfitted with wide-area-mapping bolometers at wavelengths up to one terahertz and beyond.
Coherent beam-forming arrays are aimed at overcoming the limitations of poor sampling density and off-axis efficiency loss of the current generation of conventional horn arrays. The beam spacing of the Parkes 13-beam array, without beam-forming, is two half-power beamwidths, but full sampling of the focal plane requires 1/4 of this spacing, or a factor of 16 greater sampling density. This can be achieved only through the use of small antenna elements whose signals must be combined in a beam-forming network to synthesize beams with overlapping sky coverage. Since the beam-forming network is completely flexible in its phase and amplitude weighting of the individual element signals, off-axis beams may be formed with full efficiency, the only limit being the physical size of the array. The immediate goal is to produce a 37-element array for the 1.3-1.7 GHz range with 100 MHz processing bandwidth for pulsar searches and HI mapping. We see no fundamental reason why this technique cannot be extended to 30 GHz and above, and to hundreds of beams, limited only by the affordable signal processing power.

Coherent beam-forming arrays require technical research and development in close-spaced antenna arrays; low-noise, wideband integrated amplifier-antenna elements; compact IF modules, large-scale cryogenics; and complex, FPGA signal processing component firmware.

1.2 Reflector Accuracy/Metrology *[2]*

This decade will see a vigorous and healthy competition between small (3- to 10-meter) and moderate sized (15- to 30-meter) reflectors for various radio astronomy applications in the continuing quest for more collecting area. No longer can the antennas, receivers, and signal processing sections of a radio telescope be designed in isolation. Effective economics of very large and sensitive collecting areas and high angular resolution will require full system optimization, and one solution is unlikely to fit all wavelengths and scientific purposes. The NRAO will continue to advance the state of the art of moderate to large reflector system accuracy as a complement to the small-reflector efforts going on at the SETI (ATA), JPL (DSNAA), and other institutions. Current hot topics are hydroformed reflectors, and the use of laser metrology to improve surface accuracy and pointing precision. The ranges of diameter and frequency amenable to these techniques need to be explored.

Large reflectors will always have to contend with gravitational distortions of their surfaces and non-repeatable pointing errors from thermal effects and wind. These distortions must be corrected to extend the high frequency capabilities of large antennas. Two complementary approaches to these correction problems will be pursued in the 2005-2010 time period. One is measurement and mechanical correction of the surface, and the other is signal processing of the distorted and offset fields in the focal plane. We understand the fundamentals of both approaches so the major questions to be answered are technical and economic ones. The relative advantages of the two approaches are likely to be different for different reflector sizes and wavelengths, and a hybrid system may make sense in some cases, so a parallel development effort is in order.

A natural match to antenna metrology is the signal processing capability of a coherent focal-plane array. Measured pointing errors and large-scale reflector surface distortions that are too rapid or too expensive for mechanical compensation can be fed to an array's beam-forming algorithm. In a complementary fashion, an iterative solution for large-scale reflector can be made in a way analogous to "self-cal" in aperture synthesis. Economic balances between the accuracy and speed of metrological and signal processing measurement and correction techniques remain to be determined.

1.2.1 Dense Metrology Sensor Infrastructure for Radio Telescope Applications: [2] Dense arrays of sensors (e.g., temperature, anemometer) are prohibitively expensive because environment protection, RFI mitigation, power, and communications can triple the cost of the basic sensor. For example, the per unit cost of our structural temperature sensors is about $450, while the thermistor and readout electronics cost only about $150. Tangible and intangible (e.g., telescope down time, manpower) cost of installing copper for power and communication are also high. These high costs prohibit very useful approaches, e.g., our notional approach for using OTF beam mapping in concert with temp sensors to generate refined gravity and thermal model of GBT primary distortions, or at least provide strong motivation to invest in alternative approaches that scale well.

Technologies driven by consumer communications industries can provide important scales of economy: Micropower implementations mitigate RFI and permit battery operation (it may be possible to use Silicon photocells in indirect sunlight to recharge batteries), the high degree of ASIC integration in transmit and receive circuitry provides for much lowed cost and smaller footprints, and PCB design technologies for RFI suppression may obviate the need for Faraday shields.

Possible communications approaches include low bit rate (10-100 bits per second) LF modulation (100 kHz) riding on existing active surface cabling and obtaining parasitic power from the actuator motors themselves, LF inductively coupled (100 kHz) low bit rate Code Division Multiple Access (CDMA) one-way communications using micropower electronics, batteries, and solar cell charging for a completely copperless solution, and free-space optical (near-IR) low bit rate broadband CDMA with optical repeaters, micropower implementations, and battery/solar cell charging. At least one completely integrated solution (ATMEL ATA5277 and ATA5282) exists for ASK modulation at LF. CDMA support is available as well.

An example implementation for a dense array of structural temperature sensors for the GBT, needed to capture short time and length scale thermal effects (i.e., precision daytime operation), would have these requirements: Target cost of $100 per node and no copper cabling and data rates of about 16 data bits per minute per node. Thus there is potential for 100's of sensors at acceptable cost.

Note that such a solution would not only benefit the GBT but would enable scaleable retrofits of existing radio telescopes, that, when coupled with the GBT thermal/gravity pointing model, could substantially improve the pointing and focus performance of many radio telescopes.

1.2.2 Position and Displacement Sensors for the GBT: [2] Despite successes in using combined thermal and gravity models to improve GBT pointing and focus, we believe that some form of position or displacement sensing will be required for achieving the goal W-band pointing and focus performance. The current rangefinder design would require engineering improvements, e.g., beam pointing accuracy and stability, and modifications to the existing rangefinder constellation geometry would be required as well.

There is a strong possibility that a fixed baseline network of distance measuring devices could provide the majority of needed position and pose information on the alidade and tipping structure, including low-order Zernike corrections to the primary (holography experiments strongly suggest that the dominant wavefront errors are not due to small scale random primary figure errors, but rather due to large scale distortions).

We anticipate that system and error budget studies will be completed in 2005, and propose that in parallel the technology and performance of low-cost displacement sensors be studied. Possible approaches include leveraging scales-of-economy in the telecommunications semiconductor industry to redesign the existing rangefinder approach for low cost and fixed baseline measurements (this has been partially accomplished by Payne and Parker for JPL, the LMU (Laser Measurement Unit)). Possible alternatives and enhancements could use fiber-optic signal processing for interferometry, photonics for beam steering, etc.

Design objectives include accuracy on the order of 20 microns on a 50 meter baseline, approximately 10 Hertz measurement rates, small form factors (approximately one cubic foot), robust operation over temperature, minimal maintained and high availability so that complete system MTBF (Mean Time Between Failure) is harmonious with observing schedules, mitigation of condensation on optics, simple interface (mechanical, communications, and software), design for manufacture, design for RFI mitigation, and a target per-unit cost of $2000. Rough design studies indicate that it is likely that these objectives could be met.

1.3 Ultra-Wideband Feeds *[3]*

The current NRAO telescopes use feeds with typical bandwidths of about 30% of their center frequency. There is a growing number of scientific problems that require instantaneous frequency coverage over several octaves or more. Also, the desire for continuous frequency coverage from a few hundred MHz to close to 100 GHz at the VLA and the GBT makes the use of individual, 30% bandwidth receiving systems nearly unmanageable. There is an immediate need for the development of multi-octave feeds of moderate efficiency for particular observing requirements, an important application being that of the EVLA-II prime focus receivers. There is also a long-term requirement for wideband receivers with the same system temperature and aperture efficiency as our best narrowband systems. The first can be satisfied by following the lead of the ATA on zig-zag or similar wideband antenna structures connected to low-noise amplifiers. To achieve high-efficiency, broadband receiving systems a considerable amount of further development work is required in both antenna pattern control and amplifier noise match over wide bandwidths. Work along these lines is proceeding as part of the FASR preliminaries and funded by an MRI.

1.4 Physical Optics *[1]*

The design and analysis of feed systems with multiple optical components and analysis of overall telescope optics requires accurate simulation programs. These programs are based on techniques such as physical optics, uniform geometrics theory of diffraction and Gaussian beam analysis. Grasp 8 and SatCom Workbench are examples of such commercial programs. SatCom, developed at Ohio State University for the USA Satellite Industry Code Consortium, is better suited to our needs. S. Srikanth has been negotiating with the Ohio State University and it appears that we will be able to purchase a license to a modified version of SatCom Workbench containing most of its capabilities for ~$15k per year. This program will be used by engineers at all NRAO sites.

2 Receiver Technology

2.1 Amplifiers *[2]*

2.1.1 Introduction: Microwave amplifiers are crucial to all coherent radio astronomy receivers. Below ~100 GHz, cooled amplifiers are connected directly to the antenna feed, while at higher frequencies an IF amplifier is used following a mixer; in each case, the amplifier is at the point of lowest signal strength and its properties largely determine the overall instrument sensitivity. Since 1985, the NRAO CDL has set the world standards for amplifiers and receivers using HFETs in the frequency range from 1 to 118 GHz. NRAO designs are used in all radio astronomy observatories worldwide, in the majority of CMBR anisotropy mapping experiments including MAP, DASI, CBI, and VSA, and also in the NASA and ESA Deep Space Networks. Recent developments involving monolithic microwave integrated circuits (MMICs) have not yet found their way into widespread use in radio astronomy, but the NRAO will expand its ongoing program to make appropriate use of this new technology.

2.1.2 MMIC Technology: *[2]* The use of MMICs in radio astronomy has been pioneered outside the NRAO, but these integrated circuits are now in some circumstances competitive in performance with discrete-component low-noise HFET amplifiers, at least at longer mm wavelengths. For such possible applications as a spectroscopic array receiver at 86 GHz for the GBT, MMICs are a possible altermative to MIC designs. Some MMICs are already being used at NRAO as power amplifiers within the local oscillator (LO) chain for ALMA and this is being developed for room-temperature use for intermediate frequency (IF) signal amplification for ALMA and the EVLA. The NRAO has already acquired the necessary design tools and has designed several MMIC circuits in both GaAs and InP technology for use in the ALMA LO chain. Before MMIC devices can be employed routinely as low-noise amplifiers in radio astronomy receivers, further investigation of noise limitations is needed, as well as careful consideration of the life-cycle economics of development and implementation. The NRAO will continue to explore further applications of MMICs, including their use both as low-noise RF amplifiers, LO power amplifiers, and IF amplifiers in radio astronomy receivers.

2.1.3 HFET noise theory, modeling, and repeatability at cryogenic temperatures: *[2]* The introduction of the Pospieszalski noise model of the HFET had a great impact on low noise amplifier design. Although this noise model predicts extremely well the noise behavior of FETs and HFETs for different frequencies and physical temperatures, the relation of one of its parameters, the equivalent drain noise temperature, to the fundamental noise mechanisms in the FET is not well understood. Understanding this connection could pave the way for future improvements and establish the limits of current low noise HFET technologies. In the next five years, the NRAO will conduct research to further this understanding, including studying the physical origin of the drain noise in HFETs.

2.1.4 1/f noise in HFETs and its influence on radiometer properties: *[2]* The subject of 1/f-like gain fluctuations in HFET amplifiers is of great importance in radiometric instruments, especially those which attempt to measure continuum radiation. In order to increase sensitivity, these instruments take advantage of the extremely broad bandwidth of HFET amplifiers to the point where the sensitivity is no longer limited by noise and bandwidth but by random gain fluctuations. Although some work has been done to quantify this behavior, the physical sources of this effect need further study and experimentation. This will complement the proposed research into radiometer architecture (see below) and associated observing strategies for minimizing the effect of random receiver variability, especially as applied to the continuum observing capability of the GBT and ALMA.

2.1.5 Heterostructure Bipolar Transistors noise theory and limitations: *[3]* Recently, the InP Heterostructure Bipolar Transistor (HBT) has started to compete with the InP HFET for the title of the fastest three-terminal semiconductor device. A cutoff frequency f_T and maximum frequency of oscillation f_{MAX} approaching 300 GHz, have been demonstrated. Due to the nature of the fundamental noise sources in HBTs, they are not expected to compete with the InP HFET in ultra low noise amplifiers, especially at cryogenic temperatures. Nevertheless, due to their expected much lower 1/f noise, they are expected to provide very broadband amplification with minimal 1/f random gain variations. At present, not much is known about the noise performance of InP HBTs either at room or at cryogenic temperatures. Development of a good understating of these devices will determine whether they can be effectively used in radio astronomy receivers, especially in broadband continuum radiometers. The proposed research will investigate the use of the HBT in wideband amplifiers with low 1/f noise.

2.1.6 InP HBT small and medium scale ICs in radio astronomy instrumentation: *[2]* InP HBT technology is very amenable to the production of small and medium scale integrated circuits. From the point of view of radio astronomy instrumentation, there are three different possible unexplored applications which we plan to investigate:

- Very broadband single-ended and/or differential amplifiers for use in amplifier chains. As described above, these should have much lower 1/f gain fluctuations than corresponding HFET amplifiers. Amplifiers with bandwidths from dc to 40 GHz have been demonstrated.
- Static frequency dividers with demonstrated clock frequencies of 90 GHz could revolutionize the design and construction of phase-locked loops in radio astronomy instrumentation.
- Very broadband (up to 50 GHz) Gilbert cells can be used as very fast analog multipliers, which could revolutionize the construction of radio astronomy correlation receivers.

2.2 SIS Mixers

2.2.1 Introduction: For the foreseeable future, SIS mixers are expected to be the preferred front-end for coherent receivers at millimeter and the longer submillimeter wavelengths. The nearly quantum-limited sensitivity of niobium SIS receivers extends to about 600 GHz, corresponding to the superconducting energy gap of Nb. The planned research and development is aimed at extending the useful frequency range of SIS mixers as high as 2.6 THz and would ultimately allow SIS receivers to operate at ~12 K (cf. 4 K for current SIS receivers). If successful, the work on new superconductors will be a major breakthrough in millimeter and submillimeter receiver technology.

2.2.2 Technology Development for 350-μm (780-950 GHz) Heterodyne Receivers: *[1]* At present, no receivers for this band can achieve performance comparable with that of good SIS receivers below 600 GHz. It is therefore appropriate for the NRAO to carry out technology development for this band. The goal is to develop reliable, inexpensive, quantum-limited receivers based on NbTiN SIS mixer technology which has given promising, though not yet consistent, results in other laboratories. This will put us in a strong position to bid on the ALMA Band 10 receiver production. This work will be done in collaboration with the Semiconductor Device Laboratory at the University of Virginia with whom the NRAO has an established record of successful development of Nb SIS receivers for the 12-m telescope and, more recently, for ALMA. In the last year, UVA has purchased major equipment which puts them in a position to start work immediately on NbTiN circuits.

2.2.3 New materials for SIS mixers: *[3]* Two superconducting materials unexplored for SIS mixer applications are magnesium diboride (MgB_2, T_C=39 K) and BKBO ($Ba_{1-x}K_xBiO_3$, T_C = 26 K). SIS mixers based on BKBO should be useful to 1.7 THz, while MgB_2 mixers should operable to ~2.6 THz (cf. Nb, with T_C=9 K, which is useful to ~600 GHz). MgB_2 tunnel junctions have not yet been demonstrated, and this material appears to have a double energy gap, which might reduce its usefulness as an SIS mixer. However, simple BKBO tunnel junctions have been demonstrated with good I(V) characteristics of the type required for a low-noise mixer. Tunneling characteristics have also been demonstrated in BKBO/Nb junctions. Mixers based on BKBO would be ideal for observation of the N^+ line at 1.4 THz. We plan to design mixers and test circuits using these materials and evaluate the performance of devices produced at foundries external to the NRAO.

2.3 Specific Receiver Systems

2.3.1 Continuum Radiometer Development: *[3]* Single-dish continuum radiometry at frequencies from 30 GHz to 900 GHz is needed for recovering all the flux from extended continuum sources; this information may be combined with interferometer data to yield accurate high-resolution images. Gain fluctuations prevent typical receivers from achieving Gaussian-noise-limited performance. Conventional correlation receivers split the sky signal into two paths which are amplified independently and then cross-multiplied to cancel uncorrelated amplifier noise while retaining the desired signal. The pseudo-correlation receivers developed for the Microwave Anisotropy Probe satellite accomplish rapid beam switching by splitting sky signals from two feeds into two paths which are amplified independently, with a phase switch accomplishing subsequent separation of the signals from the two feeds and canceling amplifier gain fluctuations. We will investigate the use of load-switched and sky-switched radiometers with state-of-the-art implementations of pseudo-correlation and conventional correlation noise reduction schemes to approach the ultimate performance. For ALMA, it is essential that the single-dish maps of a source use exactly the same frequency band as the interferometric observations, which rules out using bolometers for the continuum observations. We will determine the optimum receiver configuration as a function of science goals and frequency and sky conditions, analyze results of the planned pseudo-correlation receivers for the GBT at 30 and 86 GHz, and design and build continuum receivers for frequencies up to 900 GHz.

2.3.2 Development of a 1.4 THz Receiver: *[3]* The 1.4 THz atmospheric window is usable at the ALMA site. A receiver for this band is needed for observations of N^+. We propose to develop either an SIS receiver using one of the new medium-T_C superconductors (see above), or a hot electron bolometer mixer receiver and test it, probably with one of the ALMA antennas dedicated to single-dish observing.

2.4 Local Oscillator and Signal Sources

2.4.1 Highly Integrated Multiplier Chains: *[2]* Compact LO systems are a prerequisite for large beam-forming array receivers and coherent focal plane arrays, for which LO distribution is a major difficulty at present. Current millimeter and submillimeter local oscillators use a cascade of frequency multipliers with a lower frequency driver.

The component multipliers are generally in separate waveguide blocks which are cascaded to achieve an output in the desired LO band. The inherently poor input and output match of diode multipliers, combined with the long (in wavelengths) waveguide paths between multipliers, usually results in limited LO bandwidth, or suckouts—bands within which there is little or no power. It is planned, as a follow-on to ALMA LO work, to develop highly integrated LO multiplier chains consisting of a cascade of Schottky diode multipliers on a single chip or on multiple chips in the same waveguide block with the driver amplifier. This approach would capitalize on advances in composite Si/GaAs and GaAs/InP material systems which would allow the use of the most appropriate materials for the different sections of the circuit. Another approach to submillimeter power generation which we will investigate is based on solid state vacuum devices recently proposed at JPL. NRAO is well positioned to pursue both these lines of research, with access to fabrication facilities at University of Virginia and the University of Michigan. In addition to applications in radio astronomy, this work would be useful to military and commercial phased array and focal plane array receivers for space or ground applications.

2.4.2 Photonic Local Oscillators, Test and Calibration Sources: [2] With the huge drive towards commercial application of fiber optic components in the 1.5 micron communication band comes an opportunity for applying these newly-developed components in radio astronomy. Of interest in generating THz frequencies are highly stable narrow-linewidth lasers and optical amplifiers, to name just two of the rapidly growing list of available components. Components very familiar to microwave engineers—couplers, isolators, etc.—have been available for several years in the 1.5 micron communications band. The availability of, for example, an oscillator at 200 THz with a free running line width of several KHz opens the door to innovative solutions to long-standing technical problems.

This line of research will benefit ALMA. At present, the ALMA baseline design uses photonic techniques to distribute a high frequency (~100 GHz) reference signal to the 64 antennas. At the antenna, this reference signal is multiplied to yield the final local oscillator frequency, which can approach 1 THz. A simpler solution would be to distribute the actual local oscillator frequency to a high frequency photomixer that would generate the LO directly. The problem here is the availability of high frequency photomixers and the mounting of these devices in a suitable launching structure. However, there has been considerable progress in the past few years; recently, a UTC (uni-traveling carrier) photodiode mounted in WR-10 waveguide has produced 5 mW at 100 GHz and several microwatts at 230 GHz.

Central to the success of any development effort to utilize photonics for radio astronomy is the availability of the necessary components. We propose to exploit this technology in collaboration with both commercial and research organizations.

The development of THz bandwidth photodetectors is of great interest to researchers in the fields of THz imaging and also has possible application in the rapid screening of baggage in the airline industry.

2.5 Cryogenics

2.5.1 New Cryogenic Technology: [2] Fundamental improvements to wideband receiver performance and the use of low noise amplifiers in focal plane arrays need a substantial reduction in the size and weight of our receiver packages. This requires basic changes in Dewar design, thermal isolation techniques, and vacuum windows to permit a closer integration of amplifier and waveguide components. Section 2.5.2 outlines development work on new refrigerator technology. A parallel effort will be conducted to find, test, and adopt new cryogenic construction materials. For example, the ATA receiver Dewar, which is only a few centimeters in length, uses a special crystalline glass that acts as both a vacuum window and a thermal isolator to the cooled transmission line. Preliminary tests of low density foam indicate that they may have the required mechanical, dielectric, sealing, and moisture resistance properties for use in compact, cooled RF component designs.

2.5.2 Cryocoolers [2] For more than 30 years, achieving the highest sensitivity for radio telescopes at centimeter through sub-millimeter wavelengths has required cooling the front end electronics to cryogenic temperatures. Sometimes a temperature near that of liquid nitrogen (77K) is adequate, but more often it is worthwhile operating in the 10-20 K range. For current superconducting front ends, temperatures near 4K are needed, and for some bolometers, <1 K is essential. In all these temperature ranges, the refrigeration technologies employed on practical ground-based telescopes have changed very little in two decades. On the other hand, substantial advances have occurred in recent years outside of radio astronomy. Cryocooling for space-based applications has produced some improvements, and technologies such as pulse tubes have been made practical. New and highly efficient types of gas compressors have also been developed. At the same time, improvements in receiver design, such as increases in bandwidth so that fewer channels are needed to cover a given frequency range, have reduced the number of components and thus the amount of cooling power needed in some applications. One priority application is to design an appropriate cooler for the EVLA-II prime focus receivers. Proposed focal plane array receivers bring their own special cryogenic requirements. We plan to exploit the new technologies by adapting them for use on the next generation of telescope front ends. This requires establishing a cryogenics development team that can make use of existing physical facilities (including shops and test equipment) and expertise. Benefits are expected to include reduced power consumption and greatly increased reliability for traditional centimeter and millimeter wavelength receivers, and support for focal plane arrays containing many elements.

2.6 Other Receiver and Measurement Technology

2.6.1 Wideband Components: *[2]* The current trend in radio astronomy instruments is to provide almost continuous frequency coverage over the range permitted by the telescope optics (e.g., 1 to 50 GHz for the EVLA). Only by developing very broadband components (>2:1 frequency ratio) is it possible to keep the number of bands (and hence the number of receivers) small. It is planned to develop very broadband passive components—feeds (see also Section 1.3 above), polarizers, couplers, diplexers, frequency selective surfaces, etc.—with minimum size for a given bandwidth. Compact feeds, in particular, are essential if focal-plane array receivers are to be realized. In addition, we will explore the adaptation of new technologies (e.g., microwave bandgap structures) to radio astronomy applications.

2.6.2 Integration of Wideband Feeds with Amplifiers: *[2]* Extremely broadband feeds (>10:1 frequency ratio) with integrated low noise amplifiers would be valuable for radio astronomy applications such as pulsar and solar burst studies requiring simultaneous multiple frequency coverage. The challenge is to obtain good feed performance and low noise temperature over the full bandwidth with high dynamic range. This requires the integration of amplifiers with the feed structure while maintaining control of circuit impedances to ensure a wideband noise match between antenna and amplifier. This work has high priority for GBT receiver upgrades and eventual phased array feed technology. It is directly applicable to the EVLA-II prime focus receiving system and to many future radio astronomy instruments such as the Frequency Agile Solar Radio telescope (FASR), and the Square Kilometer Array (SKA). Outside radio astronomy, this technology would be useful for software radio applications and wide-bandwidth front-ends for digital electronic warfare receivers.

3 Signal Processing and Transmission

3.1 Digital Signal Transmission: *[2]* As the capacity of digital processing increases, the bottleneck to achieving larger instantaneous telescope bandwidth shifts to the signal transmission. This is especially important at short centimeter, millimeter, and submillimeter wavelengths where the usable spectrum still exceeds the maximum bandwidth normally supported by telescope electronics, and provides an opportunity for improved sensitivity in continuum observations. Transmission distances also need to be increased, so that connected-element arrays can be expanded to fill the resolution gap between them and VLBI.

We plan to develop electronics to support state-of-the-art data links on optical fiber in a way that is optimum for transmission of astronomical signals. Note that this is substantially different from communication networks because (a) fixed, point-to-point connections are needed, rather than a flexible network; (b) delay stability is critical; and (c) relatively large bit error rates are tolerable. We can nevertheless exploit the rapid development of photonic technology being financed by the telecommunications industry. In the 2005-2009 period, we expect that it will be cost effective to transmit 40 Gb/s on one optical carrier and more than 1 Tb/s on one fiber.

Besides the supporting electronics, the fiber transmission medium is needed. There are three approaches: install our own cables; lease dark fibers in commercially-owned cables; and lease bandwidth on commercially-owned networks. The choice depends on rapidly evolving pricing structures that in turn depend on marketing considerations which are beyond our control but demand our close attention. It is likely that leasing of dark fiber will be cost effective for the distances of the New Mexico Array, so we intend to pursue that option aggressively. At the continental distances of the VLBA, we will continue to investigate the feasibility of real-time transmission.

3.2 Satellite Based LO Reference Distribution: *[2]* As connected-element synthesis arrays expand, distribution of precise timing information becomes more difficult. In VLBI, independent, but expensive, stable oscillators are used to avoid such distribution. In both cases, it has long been possible, but prohibitively expensive, to accomplish the distribution using commercial satellites, in spite of the fact that very little bandwidth is required. Recent changes in commercial channel leasing practices now make it possible to obtain the necessary bandwidth at reasonably low cost.

We plan to develop the necessary ground electronics to exploit this method, including correction for variation in the path delay due to satellite motion. If successful, the most immediate application would be the New Mexico Array, but it may be even more valuable to the VLBA, to global VLBI, and to the future SKA.

3.3 Wide Bandwidth Digitization: *[1]* The present state-of-the-art in high speed analog to digital conversion includes bandwidth to 6 GHz and sampling rates to 20 GHz at resolutions of 6 to 8 bits. Such devices are produced commercially for use in expensive instruments such as oscilloscopes, but they are not readily available separately. The state-of-the-art in radio astronomy lags far behind, with 4 GHz sampling rate at 3 bits resolution planned for ALMA but not yet available. Commercial developments are aimed at greater resolution than is needed for the noise-like signals of radio astronomy.

We plan to bring the radio astronomy technology up to at least the commercial state-of-the-art, with a goal of achieving 10 GHz Nyquist-sampled bandwidth, by exploiting existing devices from the commercial world where possible but probably by developing new chip-level devices. Such wideband digitization can lead to large simplifications of receivers and signal transmission systems by reducing the number of separate channels. Even when the observing bandwidth is much smaller, wideband digitization allows digital signal processing to start earlier in the receiving chain, opening opportunities for sophisticated filtering and multi-beam tracking when, as expected, the necessary processing power becomes available.

3.4 RFI Mitigation Techniques: *[2]* Man-made interference is already a major problem for radio astronomy, and will certainly get worse as use of the spectrum proliferates. Observations outside the bands allocated to radio astronomy are essential to take advantage of the sensitivity offered by wide bandwidths and to the study of highly red-shifted spectral lines. Development of countermeasures in the form of analog and digital signal processing is imperative. It is proposed to advance the development of several specific techniques that now look promising. Such advanced techniques for interference mitigation will be essential for efficient use of our instruments.

3.4.1 *General*: *[2]* Improvements are needed in the dynamic range of low-noise amplifiers and mixers. This needs to be done as part of comprehensive receiver designs which result in lower harmonic distortion and higher saturation thresholds in frequency ranges where RFI signals are strong. We need to stay abreast of industry development of analog-to-digital converters that offer low distortion over a wide dynamic range and wide bandwidth.

3.4.2 *Digital Filtering*: *[2]* Flexible filtering to allow rejection of interference-contaminated regions within the receiver bandwidth is important for systems in which wide bandwidths are used to obtain high sensitivity in continuum observations. Digital filtering is particularly suitable, especially if the response is programmable so that the passband can be shaped and bandstop filters inserted as desired. The frequency response can then be optimized for the requirements of a specific observation.

3.4.3 *Spatial Nulling*: *[2]* In arrays of antennas, both phased arrays and synthesis-imaging arrays, it is possible to find matrix transformations of the array signals or correlations that are orthogonal to interfering signals while retaining sky map information with little distortion. Theoretical studies and simple demonstrations of the technique have been published. The effects on deconvolution procedures such as the CLEAN algorithm need to be investigated with the aim of producing images with high dynamic range. Application to the VLA will require the development of appropriate processing software.

3.4.4 *Blanking and Adaptive Cancellation*: *[2]* Through collaborative research at NRAO, UVa, and BYU several pulse blanking and adaptive cancellation algorithms have be developed to the point that they can be implemented in high-speed signal processing hardware, such as field programmable gate arrays (FPGAs) for use on both single dishes and synthesis arrays. Modern FPGA development tools and in-house programming expertise need to be acquired to take full advantage of this research and signal processing technology. Personnel will be required for associated software development and operational testing. Continued research in this area will pay additional dividends.

3.4.5 *Signal Propagation*: *[2]* Models for signal propagation by diffraction around the Earth's surface and over irregular terrain are required for radio astronomy bands that are shared with active services. These are used for management of the Green Bank quiet zone, and in some cases for definition of coordination zones around radio astronomy stations. Legal challenges to the National Radio Quiet Zone's signal strength restrictions have shown the need for much better field testing of existing propagation models and for the development of more accurate algorithms. These models need to be extended to higher frequencies than have been required in the past. Collaborations with university experts in this field are being sought, and a higher level of measurement capability and effort is required. Basic algorithms for the higher frequency bands will also become available through the Radiocommunication Sector of the ITU, and NRAO will adapt them to specific sites as required.

3.5 Advanced Digital Correlators: *[1]* The large cross-correlators needed for synthesis arrays, and the smaller but still complex auto-correlators used for high-resolution single dish spectroscopy, are amenable to the relentless advance of digital semiconductor technology described by Moore's law. On the other hand, development of the special purpose machines needed for astronomy is a significant and time-consuming effort. On balance, it is worth considering a new generation of correlators every 5 to 10 years, either as replacements at existing telescopes or for new telescopes. In addition, some new architectural ideas have been worked out since the time that the designs of the present generation of correlators (including the EVLA and ALMA correlators now being built) were frozen.

We plan to pursue these new architectures and to exploit the improvements in semiconductor processing to develop new machines for several applications, including: replacement of the GBT spectrometer; a next-generation correlator for ALMA; and a correlator for synthesis arrays with hundreds to thousands of elements, such as the SKA.

3.6 Water Vapor Radiometers: *[3]* By measuring the quantity of precipitable water vapor along the line of sight, it is possible to deduce, and hence to correct for, atmospheric fluctuations that cause errors in the phase measured by an interferometer. The technique has been applied at the OVRO and IRAM interferometers to improve the dynamic range of imaging and it is being installed on the VLA; initial tests at the VLA have demonstrated the expected imaging improvements. ALMA will rely heavily on the technique. The water vapor may be measured by millimeter-wave radiometers measuring either continuum radiation or measuring directly the wings of one of the water vapor spectral lines in our atmosphere; an alternative scheme uses an IR radiometer to measure the atmospheric water vapor. Further research is desirable in instrumentation and practical application of this phase compensation technique.

COST SUMMARY

	All projects		**Priority 1 projects**		**Priority 1+2 projects**	
	M&S $	FTE	M&S $	FTE	M&S $	FTE
2005	$2,468,200	67	$814,000	12	$1,731,000	60
2006	$2,059,750	63	$715,750	11	$1,632,750	59
2007	$2,146,750	63	$691,750	10	$1,608,750	58
2008	$2,081,000	64	$365,000	9	$1,282,000	57
2009	$1,674,000	62	$385,000	9	$1,302,000	57
5 years	$10,429,700	319	$2,971,500	52	$7,556,500	291