## 1. Project Description

# Technology Development for the Square Kilometer Array. II.

A Proposal for the US SKA Consortium

PI Institution: Cornell University




**Results from Prior NSF Support:** PI Cordes has received funds under Grant AST 9819931, *Neutron Stars: Searches, Planets, Kinematics and Calibrators of Interstellar Seeing* (Amount: $180,000. Period: 07/15/99 - 06/30/02.) The work has yielded discovery of new pulsars, a new model for the electron density of the Galaxy, detailed statistical inference of the neutron star velocity distribution, and empirical and theoretical description of interstellar scattering. Co-PI Goldsmith is PI of the Cooperative Agreement under which Cornell University manages the National Astronomy and Ionosphere Center for the NSF, AST 9809484 (Amount: $55,778,000; Period: 10/01/99 - 09/30/04). NAIC operates the Arecibo Observatory, which has yielded many results on atmospheric, solar system, Galactic and extragalactic science.


**Some Acronyms Used:** ATA = Allen Telescope Array; EMT = (International) Engineering Management Team, Chair = Peter Hall (ATNF); ISAC = International Science Advisory Committee, Chair = Chris Carilli (NRAO); ISSC = International SKA Steering Committee, Chair = Jill Tarter (SETI Institute); LOFAR = Low Frequency Array project; RFI = radio frequency interference;

### 1.1. Introduction

The SKA is the next-generation telescope for centimeter-wavelength radio astronomy. It will provide *at least* 20 times the sensitivity of the Arecibo radio telescope and 100 times the sensitivity of existing *radio imaging* instruments such as the GMRT and the VLA.

In August 2001 the US SKA Consortium[1] submitted a proposal to the NSF/ATI program for development of the 'US Concept' that involved an end-to-end, three year program of development that would lead to a 2005 selection milestone for the International SKA effort. The 2001 proposal was funded at \$1.5M over a three year period commencing 1 July 2002, less than 1/3 our total request of \$5.3M. Accordingly, we cut substantial portions of the work effort from the original plan, concentrating on those items most critical to evolving the SKA concept and on potential 'show stoppers' such as cost per square meter of collecting area and considerations of radio frequency interference (RFI). We also earmarked $\sim 10\%$ of the funds to support 1/3 FTE in the International Project Office, specifically a Project Director's position. This position is about to be filled as of the writing of this proposal.

In this proposal, we request funds to cover part of the work effort we originally requested and which we think is now especially important given progress that has been made in the last year. This Project Description is intended to be self contained, but some of the sections have been shortened significantly compared to the 2001 proposal. That proposal covered an end-to-end plan for detailed technology development and an SKA design. The current proposal is patchier in that it de-emphasizes what has been funded under the current grant and it eliminates several areas that were not funded in the first grant nor appear feasible to fund under this request. For reference, our original proposal may be found at `http://www.astro.cornell.edu/~cordes/SKA/` using the links PROJECT SUMMARY and PROJECT DESCRIPTION. Also, a detailed description of the work plan under the downsized budget may be found at the same URL under the link BUDGET IMPACT STATEMENT FOR REVISED BUDGET.

Much of what follows was contained in our proposal of 2001 August. However, we have updated the discussion of the scientific issues, particularly those pertaining to the Epoch of Reionization and to the overall science drivers for the SKA. Science drivers were discussed at length at the recent (13-15 August 2002) Science Workshop for the SKA held in Groningen. The International Scientific Advisory Committee (ISAC) also met in Groningen to discuss these issues. We also describe the recent milestone for the international SKA effort that involved submission by the various international concept groups of "strawman" concepts. These were submitted in June-July 2002 and were discussed at the most recent meeting of the International SKA Steering Committee (ISSC) in Dwingeloo (2002 August 16-17). The US Strawman Concept may be found at the above-mentioned URL with link PDF FILE OF US SKA CONSORTIUM STRAWMAN PROPOSAL VERSION 1.0. It, along with the six-other strawman concepts, may also be found on the URL given below Table 1.

The PI of this proposal is a member of the US SKA Consortium and the ISAC and is an active participant in ISSC meetings. Co-PI Terzian is Chair of the US SKA Consortium, a US representative to the ISSC, and Chair of the International Site Selection Committee. Co-PI Goldsmith is a member at large of the US SKA Consortium. Subcontract co-Is Dickey (UMn), Ellingson (OSU),

[1]The Consortium currently consists of the California Institute of Technology (including JPL), Cornell University (including NAIC = National Astronomy & Ionosphere Center), the Harvard-Smithsonian Center for Astrophysics (including SAO = Smithsonian Astrophysical Observatory), MIT (including Haystack Observatory), the National Radio Astronomy Observatory (NRAO), Naval Research Laboratory (NRL), Ohio State University (OSU), the SETI Institute, the University of California, Berkeley and the University of Minnesota

and Greenfield (SAO) are all members of the US SKA Consortium. Dickey is also on the ISAC and is chair of Working Group 1: the Milky Way Galaxy and Nearby Galaxies (Working Groups of the ISAC are discussed further below).

## 1.2. What is the SKA?

*The SKA will provide enormous increases in capability along* **multiple** *parameter axes with fewer tradeoffs than ever before.* These include sensitivity, sky and frequency coverage and imaging fidelity, while maintaining high resolution in time, frequency and direction.

**The US Effort in the International Context:** The SKA has been an international concept from the start (1994) and it will continue to be so through the development, construction and operational phases. Seven concept designs were recently submitted (July 2002) to the ISSC by the different participating countries:

Table 1: SKA Design Concepts as of 2002 July

| | |
|---|---|
| A large-N array of small parabolic antennas | U.S. |
| Planar phased-arrays | Netherlands |
| Spherical radio (Luneburg) lenses | Australia |
| Cylindrical paraboloids | Australia |
| Nearly flat reflectors with balloon suspended receivers | Canada |
| Very large Arecibo-like dishes | China |
| Large, low-cost parabolic antennas | India |

The concept designs are described in white papers that can be found at `http://www.ras.ucalgary.ca/SKA/ska_memos.shtml` (Memos 17-23). These concepts were reviewed by both the Engineering Management Team (EMT) and the ISAC and evaluated prior to and during the August 2002 Groningen meeting.

Various technologies important to all of these designs are being investigated around the world including imaging simulations, signal processing, interference reduction, and operations. Work proposed here will be coordinated with, and complementary to, efforts conducted in other countries.

**Science:** The extraordinary range of astronomical targets and topics envisioned for the SKA is discussed in *Science with The Square Kilometer Array: A Next Generation World Radio Observatory.*[2] (The science case is being re-worked to take into account evolution of the research forefront in astronomy and astrophysics and changes in technological capability. A new science document will be produced by mid-2004.) The SKA will allow exploration of unique aspects of the radio universe on solar-system to cosmological scales. The SKA will also allow radio science to be conducted on par with innovations expected across the entire electromagnetic spectrum in the next two decades. With its specified sensitivity, angular resolution, and frequency coverage, the SKA concept will provide centimeter wavelength complementarity to telescopes such as ALMA at mm wavelengths, the NGST in the optical and infrared, the VLT (and VLTI), the GSMT, and

[2] A. R. Taylor and R. Braun, editors 1999, (`http://www.skatelescope.org/ska_science.shtml`)

CELT operating in the optical/IR, the LSST (Large-aperture Synoptic Survey Telescope), Con-X in X-rays, and follow-ups to GLAST in the gamma-ray range.

Last, but perhaps foremost, the greatest value of the SKA will be in the new, unanticipated discoveries made with it, which will unfold new questions. This process has happened repeatedly in the past[3] when new regions of observational phase space are explored[4].

Table 2: PROVISIONAL INTERNATIONAL SKA DESIGN GOALS

| PARAMETER | DESIGN GOAL | COMMENTS |
|---|---|---|
| Sensitivity | $A_{\rm eff}/T_{\rm sys} = 2 \times 10^4$ m$^2$/K | 20× Arecibo<br>75× VLA |
| Surface brightness sensitivity | 1K at 0.1 arcsec (continuum) | |
| Frequency range† | 0.15-22 GHz | |
| Redshift coverage | $z < 8.5$ HI, $z > 4.2$ CO(1→ 0) | |
| Detectability of Milky Way in HI (CO) | $z_{\rm max} \sim 2$ (20) | |
| Imaging field of view | 1-10 deg$^2$ at 1.4 GHz | $\frac{1}{2}$ deg (VLA) |
| Multibeam capability | $N_{\rm beams} > 100$ | |
| Angular resolution | $< 0.04$ arcsec at 1.4 GHz | SKA enables VLBI phase referencing to all fields of view |
| Number of spatial pixels | $> 10^8$ | |
| Instantaneous bandwidth | $\sim 20\%$ at high frequency | |
| Number of spectral channels | $> 10^4$ | |
| Image dynamic range | $10^6$ at 1.4 GHz | |

† The US SKA Consortium will consider extending the frequency range to $\gtrsim 32$ GHz.

**The SKA as Radio Science Infrastructure.** The SKA, when included in VLBI arrays, greatly enhances the ability to use weak but plentiful sources for phase calibration, the radio-astronomy equivalent of adaptive optics. When the need arises the SKA can also be used for spacecraft telemetry reception (as the VLA was used for Voyager's Nepture encounter), providing over 100 times the sensitivity of NASA's 70m tracking antennas. It can also be used as the receiving element for bistatic radar measurements of solar system objects, significantly extending the range or size of objects detected and providing images of planets, satellites, asteroids and comets.

**Why is the SKA Challenging Technologically?** A set of provisional design goals has emerged over the last 5 years from a series of international meetings and workshops. These are presented in broad terms in Table 1. It must be kept in mind that parameter values in the Table are desired total ranges for each dimension of the observational phase space. Feasibility and cost issues enforce significant tradeoffs that must be studied carefully in our proposed effort.

Some broad statements may be made on the basis of previous studies. The collecting area (1 km$^2$), frequency range (0.15 to 22 GHz), and imaging dynamic range ($10^6$:1) of the SKA are required for faint-source science, particularly sources at high redshift. The higher frequencies are

[3] *Serendipitous Discoveries in Radio Astronomy*, NRAO Proceedings, Eds. K. Kellerman & B. Sheets., 1983
[4] M. O. Harwit, *Cosmic Discovery*, Basic Books, 1981.

also demanded by solar system science (surveys of Kuiper-belt objects), the detection of thermal radiation from nearby stars, and to obtain the greatest resolution.

Extrapolating from designs of existing radio telescopes (e.g. Arecibo, the GBT and the VLA), a square kilometer of collecting area would cost ∼$5B. Entirely new approaches are mandatory for reducing the cost per unit collecting area, for building low system-noise receivers, and for combatting radio frequency interference (RFI). These most likely require different solutions at low and high frequencies. The US SKA Consortium's efforts address all these issues.

**The Telescope is a Network:** The SKA will be an instrument of the digital age. Its design will necessarily exploit exponential increases in digital capability that follow "Moore's Law" to obtain the massive increases in collecting area, imaging capability, and coverage of observational phase space. Moore's Law, the empirical description of growth in digital capability, should continue to apply for at least the next 15 years[5] (i.e. beyond the SKA's nominal completion date). Our work will incorporate such anticipated increases in capability when assessing technical feasibility and costs.

**Definitions for the US Large-N Concept:** The US SKA Consortium is considering "large-N" designs that exploit the economies-of-scale for replicated antennas and digital electronics. "Large N" means a large number of *stations.* In the US plan, we define a station (analogous to a single dish in the VLA, say) to be an array of $N_A$ antennas. A station could consist of a single antenna or $N_A \gg 1$ small antennas or something in between. The signals from these antennas will be combined to form $N_b$ separate *beams.* Stations will be combined into the array that comprises the SKA. Stations will be spread over a sizable area, perhaps over an entire continent or more. The number $N$ of stations will be determined by the cost equation, science requirements, and logistics. In our recent strawman design (July 2002), we included a central core array comprising $\gtrsim$50% of the overall collecting area that would allow near-optimal baseline coverage in imaging applications while also providing sensitivity to low-surface brightness emission and allowing phasing of all antennas into multiple beams for time-domain science and spectroscopy.

The performance of critical elements — antennas, receivers, digital samplers, fiber optic interconnects, beamformers and correlators, and postprocessing — all 'push the envelope' in their requirements.

**Key Development Activities:** Our development activities target the technological challenges outlined in the Roadmap, the aim being a specific design for the SKA to be proposed to the International SKA Steering Committee (ISSC), which has 1/3 membership (currently 6 members) from the US SKA Consortium. Designs will be submitted several times in order that there be appropriate feedback from the international groups overseeing the SKA project (the ISSC, with aid from the ISAC and the EMT). Over the next 3 to 5 years, the number of viable concepts will be narrowed while planning for possible hybrid and prototype arrays will also take place. The goal for the remainder of this decade is to develop the technology into design(s) so that a well-defined project can be presented to the next US decadal survey for astronomy and astrophysics.

[5] *International Technology Roadmap for Semiconductors, 2000 Update*, Semiconductor Industry Association, 2000; `http://public.itrs.net`

Table 3: Comparisons & Synergies In m - cm wavelength Arrays

| Attribute | LOFAR | ATA | EVLA I | EVLA II | SKA |
|---|---|---|---|---|---|
| $A_{\rm eff}$ ($m^2$) | $10^6$@15 MHz | $10^4\eta_A^{\#}$ | $10^{3.9}$ | $10^4$ | $10^6\eta_A$ |
| Frequency range (GHz) | 0.01-0.24 | 0.5-11.2 | 0.3-50 | 0.3-50 | 0.15-22<br>0.15-34? |
| Stations or Dishes | 100 | 350 | 27 | 37 | $\gtrsim 20^*$ |
| Angular Resolution (arc sec) (@1.4 GHz) | 10 @ 50 MHz | 75 | 1.5 | 0.25 | $< 0.04$ |
| Imaging field of view ($deg^2$ @ 1.4 GHz) | TBD | 4 | 0.25 | 0.25 | 1-10 |
| Largest Baseline (km) | 500 | 1 | 30 | 300 | $10^3$-$10^4$ |
| Start Construction | 2004 | 2003 | 2003 | 2006? | 2010 |
| First Operation | 2006 | 2004** | 2007 | 2010 | 2015 |
| Funding† | Neth/NRL/NSF | private | NSF | NSF/NRC | Inter/NSF/? |

\# Aperture efficiency $\approx 0.7$

* The number is 20 only if large Arecibo-type reflectors are used.

** First light with partial array.

† Neth = Netherlands NRC = Canadian National Research Council Inter = International
NRL = Naval Research Laboratory

Additional overarching activities are integral to SKA development: interaction with agencies involved with RFI management worldwide; working with the ISSC on the SKA project as a whole; and outreach activities.

**Parallel & Synergistic Efforts on the ATA, ALMA, EVLA & LOFAR:** The design, construction and/or commissioning of forthcoming arrays will provide important contributions to SKA development: (1) for RFI monitoring and site selection; (2) as testbeds for RFI management, imaging and beam forming, and transient source detection; (3) in providing prototypes or final designs for specific subsystems of the SKA (e.g. antenna, feed and mount designs; digital interconnects and beam formers; imager [correlator], software, operations). Table 2 compares several of the relevant arrays. Our intention is to work synergistically with those organizations involved with the ATA, the EVLA and LOFAR, including Haystack/MIT, NRAO, NRL, SI and UCB. Work proposed here indeed includes collaborations with individuals working on these projects, some of whom are representatives to the US SKA Consortium. Another important aspect of our SKA development work is that a feasibility and cost plan will emerge for the possible use of arrays as station elements for the EVLA.

**Deliverables from the Development Work:** The proposed work will yield interim scientific results, reports, publications, algorithms, inventions, and designs relevant specifically to the SKA. Such intellectual property will contribute to the overall astronomical community in general in addition to leading to the design and construction of the SKA.

**Management Approach for the Development Effort:** The US SKA Consortium has asked Cornell University, through the Department of Astronomy and with the close cooperation of the National Astronomy and Ionosphere Center (NAIC), to lead an NSF-funded effort for SKA development. The present proposal is a second installment on an implementation of this plan. The role of Cornell is twofold: as the umbrella managing institution and as a participant in the development work itself. *All* Consortium member institutions have contributed to the work contained in the prior and present proposals and will participate in this effort. As detailed in the Management Section, interactions between working groups funded under this proposal will be conducted through periodic Consortium meetings, reports, and site visits by the Cornell co-PIs.

### 1.3. SKA Science

Science drivers for the SKA have been discussed since the early 1990s when the prime science goals concerned detection of hydrogen at 21 cm up to high redshifts (and other low-frequency science such as massive pulsar surveys). Since then, the goals have widened considerably owing to the prospects of a great leap in sensitivity, particulary if extended to higher frequencies than originally conceived. The primary reference for SKA science is currently Taylor & Braun (1999), which presents a rich array of solar system to cosmological applications. More recently, the US SKA Consortium discussed SKA science in a Roadmap for US development work[6] that focuses on science areas of particular interest to the Consortium in the context of the large-N concept. Because these documents are readily available, we will summarize the science case only briefly in this proposal. In the last year, SKA science has been revisited in detail at two international meetings (Berkeley 2001; Groningen 2002), where it has become clear that there is great interest in extending the current baseline specifications for the SKA to higher frequencies so that molecular lines (e.g. $H_2O$ and high-z CO) and high-resolution VLBI are enabled. For orthogonal scientific reasons, there is interest in widening the instantaneous field of view at the lower frequencies (e.g. $\lesssim 2$ GHz) to enable deep surveys for radio transient sources and blind surveys for a wide range of Galactic and extragalactic sources. One of the touchstone issues concerns the low frequency capability, e.g. $\nu \lesssim 0.3$ GHz, and whether the Epoch of Reionization can be probed in bands that include background Galactic noise and dense RFI. There is optimism that RFI can be contended with through concerted effort on RFI mitigation and development of receivers that can maintain linearity over a high dynamic range. However, it is important to translate this optimism into reality through demonstrations using existing facilities augmented by new receivers, digital backends, and use of appropriate algorithms. That is part of our proposed work.

In Groningen (August 2002), the "Level 1" scientific areas, defined as those that can be advanced uniquely with the SKA, were identified and compared with the specifications of seven strawman concepts proposed by different groups. The Level 1 science areas are currently:

1. The epoch of reionization (WG3).
2. HI surveys of galaxies and large-scale structure of the universe, continuum surveys and surveys for carbon monoxide (WG4).
3. High-redshift AGNs and inner-disks of AGNs (WG5).
4. Intergalactic medium (thermal and nonthermal) (WG8).
5. Radio transients, pulsars and SETI (WG2).

[6] *A Roadmap for the United States' Development Efforts on the Square Kilometer Array,* `http://www.astro.cornell.edu/~cordes`

6. Galactic HI and Galactic nonthermal emission and magnetic field (WG1).
7. Protoplanetary systems (WG6).
8. Coronal mass ejections and other solar system bodies (trans-Neptunian objects) (WG7).
9. Spacecraft tracking and Geodesy (WG9).

The ordering is roughly from cosmological to local and the WG numbers refer to the current Scientific Working Groups for the international project. These groups consider loosely related topics in some cases. Short working group reports may be found as memoranda on the SKA web site `http://www.ras.ucalgary.ca/SKA/ska_memos.shtml` (memos 5 - 13).

Of the Level 1 science areas, we identify four broad areas in which the SKA can be forseen to make revolutionary advances: **I. The high-redshift Universe**; **II. The transient radio sky**; **III. A Milky Way Census**; **IV. Solar System Objects**. These areas were discussed at length in our 2001 ATI proposal so we do not include that discussion here in order to shorten the current proposal. (The 2001 proposal is readily available from the URL given earlier.) However, we point out that the SKA will allow massive surveys of galaxies, at the level of about $10^{5.5}$ galaxies per $\deg^2$; rotation curves on a significant fraction of these can be obtained. Gamma-ray burst afterglows will be detectable at levels 100 times fainter than at present. The transient sky over a broad frequency range can be characterized for the first time in an unbiased way. Pulsar and other Galactic surveys will yield massive samples that allow tomographic mapping of the ISM and magnetic field and which will provide rare objects suitable for probing General Relativity and the nuclear equation of state. The SKA makes feasible the follow-up timing observations by the fact that it is highly multiplexible into independent beams that can be pointed at multiple objects within the instantaneous field of view. Detection of thermal emission from stars and Kuiper-belt objects will be a new capability at centimeter wavelengths. Use of the SKA as a receiver in a radar system will provide important capability for precision orbit determinations of asteroids, including hazardous near-Earth asteroids.

### 1.4. The US Development Plan

To complement work covered in our downscaled 3-yr ATI program for SKA development, we propose complementary work for an additional 3-year program that is largely a subset of our original 2001 proposal, but with some change in emphasis given developments over the last year.

The combined effort of this and the previous proposal is aimed toward submission of an SKA design concept to the International SKA Steering Committee (ISSC), currently scheduled for 2005, when the ISSC will select a subset of proposed designs for further consideration. Given funding realities, at the recent ISSC meeting in Dwingeloo it was suggested that any final decision on an SKA design be deferred to 2007; however, the nearer 2005 milestone will still exist in order that further refinement or development of hybrid designs (combining two or more concepts) may be made in time for the 2007 selection.

To meet the milestone deadlines, we must further define the scientific domain of the SKA while tackling key technological issues.

Our development plan is based within the context of a large-N concept and develops it into a design. The main work areas are described here. We point out that much of the development work, though directed toward the design goal, is also intended to yield scientific results and technology that will benefit a wider community of astronomers.

In our original 2001 ATI proposal, we outlined a work plan that covered all aspects of a science-to-systems development plan. To accomodate the budget specified by the NSF, we selected the most crucial components of our original plan and drastically cut several activities or removed them completely. The original plan included nine main areas. In the Budget Impact Statement filed with the downsized budget recommendation under which funding commenced 2002 July 1, the modified work plan for these nine areas are as follows:

Original Work Plan and Funding Status Under 2001 ATI Grant

| Work Area | Funding | Comments |
|---|---|---|
| Science Development | NOT FUNDED | No US Science Working Group |
| Radar Capability of the SKA | FUNDED | Modest feasibility study |
| Radio Frequency Interference: Management & Mitigation | PARTIAL FUNDING | Use of large antennas kept; Eliminate purchase/use of ATA antennas. |
| Station Building Blocks: Antennas, Feeds & Receivers | PARTIAL FUNDING | Descope antenna fabrication. Feed & partial Receiver design kept |
| Array Optics: Configuration & Operating Modes | PARTIAL FUNDING | Downsized simulations; Minimal fiber study; No VLBI fiber tests. |
| Post Processing, Data Mining & Archiving | NOT FUNDED | Long term effort needed. |
| Site Survey & Selection | NOT FUNDED | Crucial for site proposal. |
| Systems Analysis of the SKA & Strawman Designs | PARTIAL FUNDING | Downsized effort less than needed for ISSC documentation |
| Education & Public Outreach | NOT FUNDED | Ambitious plan and significant funding needed. |

**Main Work Areas of this proposal:**

The **first** component of this proposal is to develop a system for making pilot observations of the EoR signal. To do so, we propose construction of a multiple beam system to be installed at the Arecibo observatory, which will operate in a frequency band $\sim 100 - 250$ MHz. A backend spectrometer on each of the beams will be used for RFI excision and a search for the EoR signature. This project is closely related to the second in that RFI must necessarily be dealt with in order to hope to detect or place meaningful limits on the EoR signature.

The **second** significant work area concerns RFI, which will limit the performance and science output of the SKA unless new methods are introduced to handle it. Even with the quietest site, RFI must be dealt with at the signal level: suppressed, recognized, and mitigated. Though bands protected for radio astronomy exist, they are too narrow for sensitive, broadband continuum measurements. Morever, redshifted spectral lines make the entire radio band a target for science. We therefore must develop aggressive methods for tackling RFI. We propose to:

(a) Characterize RFI at US sites over a broad range of frequencies; this work will be in

conjunction with NRAO and NRL and their EVLA and LOFAR projects; it will also parallel efforts made elsewhere in the world by our international colleagues, particularly in Australia.
(b) Make preliminary prototype observations using existing telescopes and our own new hardware to invent and demonstrate entirely new methods for mitigating RFI.
(c) Define performance specifications for antenna sidelobes, receiver passbands and dynamic range, and tolerable RFI levels at sites. Science-oriented observations that are especially prone to contamination will be coupled with RFI mitigation studies and undertaken during the proposed 3-yr grant period as demonstrator projects for the US plan. We expect that new science results and new algorithms for RFI mitigation will emerge from this effort.

The **third** component of our project is to acquire a broadband feed and receiver system now being developed for the Allen Telescope Array (ATA) and use it at Arecibo within its Gregorian-optical path. The system bandwidth (0.5 to 11 GHz) is well matched to the capabilities in frequency of Arecibo's primary reflector. With this system we will evaluate the performance of the broadband system in an RFI-rich environment and with high telescope gain. Specific observations will include the tracking of individual pulses from pulsars over the wide band. Of particular interest are the 'giant' pulses from the Crab pulsar that have been detected (so far) at 8 GHz and below using Arecibo. With broadband measurements, intrinsic frequency structure and structure imposed on the signals from interstellar scattering can be decoupled. Giant pulses are also an important prototype for transient signals that may be detected routinely with the SKA from galaxies out to distances $\sim 5$ Mpc.

The **fourth** subproject involves analysis and demonstration of the use of optical fiber, both dedicated and through packet-switched commercial networks, for transmission of broadband data. Grouped with this subproject is an analysis of polarization requirements and capabilities of the large-N design.

The **fifth** activity concerns the appraisal of sites in the southwestern US from an RFI point of view.

By promoting the SKA project and incorporating development work in part at US universities, we expect to re-energize activity both in astronomy/physics departments and in engineering. One of our participating institutions, Ohio State University, is a particular example of engineering involvement in the SKA.

Threading the main work areas are the following questions, answers to which constitute some of the deliverables of the proposed work: §1.10:

- What should the low frequency cutoff of the SKA be?
- How well *can* we mitigate RFI? How close to the radiometer limit can we get?

## 1.5. Demonstrator Project that Targets the Epoch of Reionization, Low-Freqency Recombination Lines & RFI Mitigation

This project aims to test strategies of RFI suppression in an extremely hostile environment while striving for detection of the EoR signal in highly-redshifted hydrogen. We consider an attempt at detecting the EoR signature using existing telescopes to be an important precursor to final specifications for the SKA and the relationship of low-frequency capability of the SKA to LOFAR. Techniques for mitigating RFI that work to enable the spectroscopic study described here will be directly applicable for SKA spectroscopy. The testbed is the Arecibo Observatory, with multiple feeds mounted on the catwalk at its intersection with the paraxial surface of the spherical reflector. The frequency range covers 100 to 250 MHz. The ultimate scientific objective is to obtain very low noise spectra of a narrow strip of sky, to search for the signature of the epoch of reionization in the HI 21-cm line in the redshift range 13>z>4.7. A secondary — and much more tractable — objective is to study the intensities and linewidths of the high-n recombination lines from the Galactic interstellar medium, to derive the density and temperature in diffuse ionized and diffuse atomic clouds at low and high latitudes. A third objective is to search for transient signals on a wide variety of time scales by exploiting the simultaneous measurements taken with a multibeam system and also the daily repetition of measurements taken over a year or two.

**Background:** The Epoch of Reionization (EoR) is one of the most mysterious periods in cosmology. When the universe recombined at z∼1000 it left both the cosmic background radiation (CMB) and the neutral atomic gas (mostly H and He) nearly homogeneous and energetically decoupled. At z∼6, galaxies had begun forming, the radiation field had been supplemented by ultraviolet from young stars and active galaxy nuclei, and most of the remaining inter-galactic gas was ionized. The EoR must have preceeded this, coming somewhere between z of 6 and 10. Recent Keck spectroscopy of absorption toward high redshift QSO's suggests that reionization was still not complete at z=6 (Fan et al. 2002). The earliest stage, when the very first sources of ionizing radiation began illuminating the neutral medium, is still far beyond the reach of optical or IR spectroscopy. Figure 1 shows a recent estimate of the neutral hydrogen fraction, $\langle f_{HI} \rangle$, vs. redshift, z.

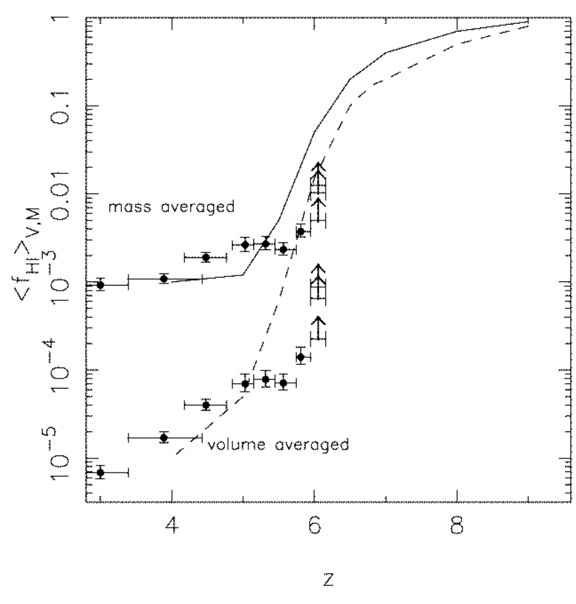


Fig. 1.— A plot of the atomic hydrogen fraction plotted against redshift, showing the transition between a predominantly neutral and a predominantly ionized inter-galactic medium, as modeled by Fan et al. (2001).

The 21-cm line is a natural tracer to study the EoR, since it comes directly from the neutral atomic hydrogen. If we detect the 21-cm emission from the primordial hydrogen before or during the EoR, we could follow the progress of the ionization as a function of redshift, and measure the inhomogeneities of the density leading up to galaxy formation. However, to detect the 21-cm line requires that its excitation temperature differ from that of the CMB; in equilibrium, emission balances absorption, leaving no detectable line above or below the background continuum. Before any star or galaxy formation generates UV that can excite the Lyman $\alpha$ transition, the 21-cm line excitation is locked to the CMB. The density is too low for collisions to significantly lower the excitation temperature toward the gas kinetic temperature, which is cooler than the CMB, except in the highest density clumps, $\delta n/n > 50$ (Tossi et al. 2001). Once there is a significant UV radiation field, absorption and reemission of Ly $\alpha$ photons bring the excitation temperature into equilibrium with the kinetic temperature of the gas through the Wouthuysen-Field effect (Loeb and Barkana, 2001 and references therein). Meanwhile, the gas temperature is rapidly increasing as the radiation field heats and eventually ionizes it. Thus the excitation temperature of the 21-cm line vs. redshift follows the curve shown schematically in figure 2.

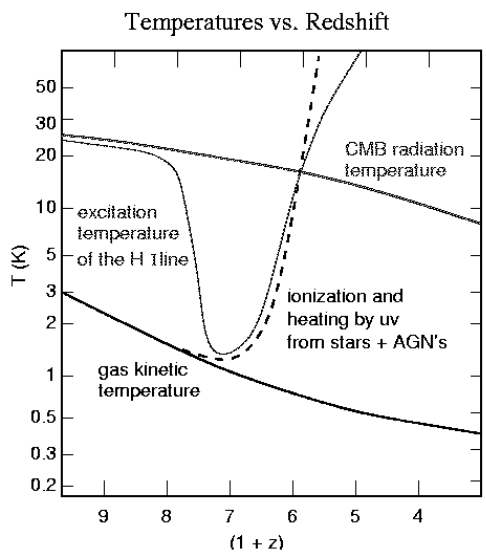


Fig. 2.— A schematic diagram of the variation of the 21-cm line excitation temperature with redshift. See the discussion by Madau, Meiksin, and Rees (1997)

A theoretical estimate of the brightness temperature of the redshifted 21-cm line from the EoR is 28mK (Loeb and Barkana, 2001) at $\sim$ 150 MHz (z=8.5). This is a weak signal, but it would be detectable at the 6 $\sigma$ level in 100 kHz channels [$\delta$(cz)=200 km s$^{-1}$] with a system temperature of some 500K (background limited by the Galactic synchrotron emission) after integration time of $\sim$30 hours. Thus the raw sensitivity needed is not difficult to achieve, and mapping the brightness distribution would be feasible for an array like the SKA or LOFAR which have a high multiplex advantage (large primary beam relative to the synthesized beam width). For a single dish telescope mapping this effect is more challenging, but possible for a dedicated instrument.

Once the redshifted 21-cm line is detected from the EoR, the critical problem is to measure the spatial power spectrum of irregularities, similar to the CMB power spectrum whose features are measures of cosmological parameters. For the EoR line, the power on different scales will indicate first (at high redshift where the line is seen in absorption) how strong the density irregularities are on various scales, and later (at lower redshift where the line is in emission) how the radiation field from the first generation of stars and AGN's is distributed. Theoretical models predict angular sizes of one to a few arc minutes for the strongest fluctuations. Thus a resolution $\sim 30''$ (baseline $\sim$15 km) is optimal and the LOFAR and the SKA are currently specified to achieve this resolution. For a single dish the angular scales that can be studied are larger, two degrees and up. Measuring the fluctuations on these largest scales as a function of redshift is the first step toward the full angular power spectrum that will come in five to ten years when these large arrays are available.

**Using Arecibo:** The spherical reflector of the Arecibo 305m telescope offers the possibility of multiple feeds observing simultaneously at different declinations and hour angles. This is particularly useful at meter wavelengths, where the phase errors due to the difference between a sphere and a parabloid are insignificant over a large area of the primary, even without correction by line feeds or secondary reflectors. In a pioneering experiment, Weintroub et al. (1999, also Weintroub 1998) installed a single, fixed feed on the catwalk (the bridge connecting the ground with the telescope superstructure) to enable a long duration study of a single declination on the sky (figure 3). The catwalk intersects the paraxial surface at a point corresponding to declination $\sim -7°$; the beam of a feed placed at this position is roughly equivalent in sensitivity and resolution to that of a 100m diameter paraboloid. It is not steerable, it drifts around the sky at the sidereal rate, always covering the same circle at constant declination. To offset the declination of the feed from -7 deg to -5.4 deg (to cross the Orion nebula) requires that the feed be suspended about 10 feet below the catwalk, nearer to the triangle.

Weintroub et al.'s objective was to detect HI in protoclusters at z$\simeq$5 (240 MHz), but they were blocked from achieving any astrophysically significant results by massive radio frequency interference (RFI). This project is a return to the long-duration drift-scan concept, applying modern techniques of RFI suppression to enable a much deeper search for high z HI emission and ab-

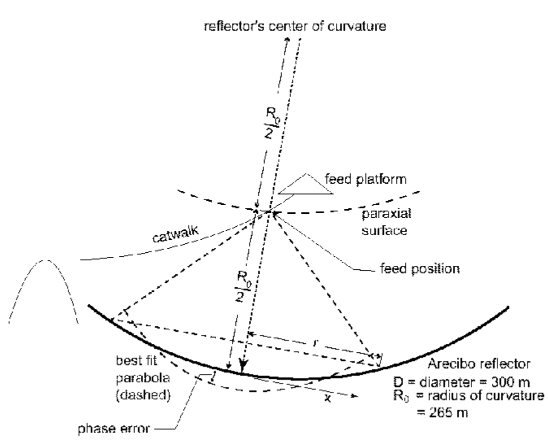


Fig. 3.— A section view showing the relationship between the Arecibo dish and catwalk (from Weintroub, 1998). The radius of the optimum illuminated area on the primary reflector is about 50m.

sorption. In particular, we will use a set of multiple feeds, which will allow significant excision of RFI.

**Single Dish vs. Interferometric Study of the EoR:** Detection and mapping of the 21-cm line from the EoR is of such fundamental importance for understanding the early universe that many observatories will strive to contribute to its detection and analysis. Ultimately it will be necessary for both interferometers and single dish instruments to measure the spatial fluctuations vs. frequency over a broad range of angular scales. The situation is very similar to the CMB (Cosmic Microwave Background) irregularity spectrum, which has been mapped by a variety of instruments, each sensitive to a limited range of angular sizes. Interferometers such as LOFAR and possibly the GMRT (Giant Metre-wave Radio Telescope, will be sensitive to angular scales $\lesssim 1$ arcmin to $\sim 30$ arcmin (baselines $\sim 0.25$ to $> 10$ km at 150 MHz). The SKA will extend the analysis to even smaller scales, with better precision over the entire range. But it is also necessary to determine the fluctuation amplitude on very large scales (several degrees); only a single dish telescope like Arecibo can achieve this, because the zero UV spacing is needed, which interferometers cannot measure.

**RFI Mitigation:** The RFI environment between 100 and 250 MHz is as bad as anywhere in the electromagnetic spectrum, and Puerto Rico is one of the noisier places in the world at these frequencies. The SKA will likely be sited in a more protected place, but its higher sensitivity will require RFI suppression techniques that are on the same level or better than those that will be needed for this experiment. Thus this project represents a test of these techniques that is as challenging as the SKA requirement. Weintroub et al. find typical RFI levels some five times their system temperature, whereas the Galactic recombination line work described below requires rms noise about $10^{-3}$ times the system temperature. RFI suppression therefore needs to be better than 40 dB. This is very challenging, but possible. The question is, over what fraction of the band will it be possible to achieve this noise level for many hours per day?

**Galactic Recombination Lines:** Ionized gas in the process of recombining causes emission and absorption at very high quantum levels which correspond to frequencies in the 100-250 MHz band. There are 107 sets of recombinatino lines (H, He, C, etc.) between 100 and 250 MHz, from H403$\alpha$ at 100.1 MHz to H297$\alpha$ at 249.75 MHz, with corresponding carbon lines displaced higher in frequency by about 70 KHz.

These lines are typically 20 km/s (10 KHz) wide (Anantharamaiah et al. 1994). For hydrogen, the line strength depends directly on the emission measure, whereas for carbon the line goes from emission to absorption over the range $\simeq$50 to 300 MHz, depending on the density and temperature of the medium (Kantharia et al. 1998). The carbon line is of particular interest, since carbon is partially ionized over a broad range of ISM conditions, including the warm ionized medium, warm neutral medium, cool neutral medium, and even the outer layers of molecular clouds (all these qualify in some sense as photodissociation regions, a category best defined by the presence of singly ionized carbon). The fact that this carbon is cold enough to be seen in absorption not only against bright continuum sources but even against the diffuse galactic non-thermal background is a puzzle, as kinetic temperatures of 30K or less are indicated (Roshi et al. 2000). The line widths also present a puzzle; they seem to go more quickly into collisional broadening than expected, which indicates surprisingly high densities (Payne et al. 1994).

In this experiment we will achieve radiometer noise levels of $5 \times 10^{-4}$ times the system temperature in **a single drift** over each beam area, with resolution 10 KHz (20 km $s^{-1}$). This alone should be adequate to marginally detect the recombination lines from the inner galaxy, where the diffuse Galactic synchrotron emission will completely dominate our system temperature ($\simeq$500K). At high and intermediate latitudes the Galactic synchrotron will give brightness temperature of about 200 K. It is a very fortunate coincidence that we can position the feed so as to drift across the Orion Nebula in the outer galaxy. This giant HII region has such a high emission measure that the Hn$\alpha$ lines will create a comb of roughly 3 K antenna temperature lines, separated by 1.2 MHz.

**Objectives:** The first step of this project is to detect the comb of recombination lines from Orion over a significant fraction of the 100 - 250 MHz band. This first step may be possible without any RFI suppression at all for some narrow segments of the band. Recent monitoring (Ghosh and Velez, 2001) suggests perhaps 10 percent of the total 100 MHz will need only visual inspection to remove the RFI, while perhaps 60 percent more will have noise near the radiometer limit if we can achieve 25 dB of RFI suppression. As we go deeper, coadding spectra from day after day, we should begin to see the comb of recombination lines from the diffuse ISM at low latitudes. These will be 10 to 100 times fainter than from Orion, so they will require much more effective RFI mitigation (40 to 45 dB). This represents the second goal of the project, i.e. to map the carbon recombination lines over roughly $\pm 10^\circ$ of latitude on either side of the galactic equator.

**The Reionization Signature:** This goal of this stage of the project is to detect or to put a significant upper limit on the redshifted 21-cm line emission or absorption from the epoch of reionization. The profile of this signal with frequency depends on the 21-cm excitation vs. redshift (figure 2). Probably it will show a transition between absorption and emission at some frequency. The variation in $T_B$ averaged over the $1^\circ$ (FWHM) Arecibo beam will be relatively smooth in frequency, unlike the recombination lines or possible redshifted HI emission from proto-clusters. Thus the signature of a detection of this effect will be increased rms fluctuations across the sky which vary with frequency across the band. It will only be possible to trust a detection of these variations if they remain fixed in the sky over many weeks of observations, **and** if we see no corresponding variations in the much narrower Galactic recombination lines. The point is that using the recombination lines we will be able to tell whether we have achieved a sufficiently high level of gain and baseline stability and RFI suppression to trust a detection of the broader band variations of the EoR signal.

**Transient Detection:** We expect the radio sky to contain transient sources. Expected classes include highly modulated pulsars (giant pulses, eclipsing pulsars) and flare stars. Other classes may include entirely new kinds of coherently emitting sources or known sources showing scintillation modulations. With the combination of a multibeam system and many repetitions of the same region of sky, we can attempt (modulo RFI) to detect transient sources on a wide range of time scales (millseconds to months). Realistically, we expect RFI to limit the success of such attempts at these low frequencies but we also acknowledge that a concerted effort using this approach is unprecedented and will produce many lessons learned.

**Description of Work Effort:** The single-feed system used by Weintroub was extremely vulnerable to RFI. The four-feed system we propose will allow strong discrimination of RFI, which will appear in all four feeds, from celestial signals appearing in only one feed. In addition, we propose to install an additional feed on Carriage House 1 (CH1, which carries the 430 MHz line feed and a 1.4 GHz line feed used to acquire data for the `SETI@HOME` project.) The CH1 feed will provide a signal from a direction very different from those sampled by the fixed 4-feed array, thus providing an important RFI-sampling signal that will be unaffected by crosstalk with the feed array. The fixed feed system will be used to acquire data for several hundred days over the same declination range. This project will be a collaboration between the University of Minnesota, Ohio State University, Cornell and NAIC. Details of this project from an RFI standpoint are given in §1.6.

Table 4: Distribution of Work Effort for the Catwalk EoR Project

| | |
|---|---|
| University of Minnesota | Observing strategy |
| (Dickey) | RFI mitigation |
| | Data analysis |
| Ohio State University | Digital spectrometer back ends |
| (Ellingson) | RFI mitigation |
| NAIC & Cornell University | Antennas, receiver front ends & optical fiber |
| (Goldsmith, Cordes) | RFI mitigation |
| | Data analysis |

The antennas used in the four-feed array present a nontrivial design challenge. As shown in Figure 3, the area that can efficiently be illuminated with a pointlike feed subtends a full angle $\simeq 21^\circ$, which corresponds to a feed gain $\sim$ 21dB. This is somewhat large for typical antenna designs, but can be achieved with helical and yagi antennas with some effort. In addition to the gain constraint, we must balance the beamwidth and spacing of the feed antennas with their cross coupling.

We will investigate both yagis and helices in the first half year of the project (effort at Cornell with consulation with OSU and perhaps other institutions). The uncooled receivers will include sharp bandpass filters and notch filters where necessary. The RF signals will be brought down to the operations building at Arecibo where they will be mixed to baseband, digitized and channelized in a digital filterbank comprising FPGA based polyphase filters. Filter outputs will be shipped to PC computers for modest real-time processing and storage. RFI will be removed through a joint analysis of the 4+1 array data. The final processing will be done on a small PC cluster running Linux (funds not requested here for that system; that will exist through acquisitions by NAIC for general purpose computing.)

### 1.6. The Radio Frequency Interference Problem: Management & Mitigation

Demands on the radio spectrum are a natural consequence of the rapid pace of telecommunications and wireless technology. Radio astronomy must take a stance of coexistence with active use of the spectrum and many strategies must be taken to achieve the science-demanded sensitivity of the SKA. Our goal is to provide deliverables in the form of constrained RFI environments, algorithms and software for mitigation, and science results that are enabled by the algorithms.

Proposed work will consist of the following general activities:

(1) Survey sites for RFI levels (and other factors). We are optimistic that science can be done in large portions of the frequency range specified in Table 1. However, our ability to do so depends on RFI signal levels being low enough that receiver linearity is maintained. Because sites outside North America are being investigated by our international colleagues, we will focus on sites in the southwestern US and possibly Mexico, with strong participation from NRAO, NRL and Cornell.

(2) Characterize RFI at existing radio facilities and develop methods for suppressing it from measured signals using a variety of methods.

(3) Deploy the 4+1 (cat-walk + carriage house) feed and receiver system that targets HI in the redshift range $4.7 \lesssim z \lesssim 13$ (100-250 MHz) (cf. §1.5).

*Deliverables:* The catwalk system can be used to test several RFI suppression technique. We will be able to measure directly the level of suppression achieved over a given bandwidth at various times of day. We will also consider a number of mitigation techniques. By suppressing RFI by 30 to 35 dB, we should obtain an excellent map of the diffuse ionized medium of the Milky Way through its recombination line emission, particularly H and C. If we are able to suppress RFI by 45 to 50 dB, we may be able to detect the epoch of reionization through enhanced fluctuations in the CMB emission due to absorption or emission by the HI line in the redshift range 5 to 10. Dickey (UMN), Ellingson (OSU), Cordes(Cornell) and NAIC will conduct this research.

(4) Installation of a wideband (0.5-11 GHz) ATA feed at the Gregorian focus at Arecibo will allow broadband studies of pulsar signals amid intense RFI (c.f. §1.7).

### 1.7. Using an ATA Log-periodic Feed at the Gregorian Focus at Arecibo

The feed currently being developed for the Allen Telescope Array is a a dual polarization, log-periodic feed that operates over a 20:1 band (0.5 - 11 GHz). The US SKA Consortium is currently investigating extension of this design to a higher frequency band that extends to at least 22 GHz (work by S. Weinreb at Caltech/JPL).

Usage of the feed in the ATA involves analog propagation of the entire RF bandpass after an initial stage of amplification to a central processing facility. Broadband MMIC amplifiers are now being investigated for this purpose by the ATA and at JPL.

We propose to acquire an ATA feed and front-end receiver and install it at the Gregorian focus of the Arecibo telescope. The overall band is nearly perfectly matched to the frequency response of the Gregorian reflector system. The RF band would be brought to the operations building where it would be processed by an analog IF/LO system to allow baseband sampling of subbands.

With such a system, several studies of importance for SKA development and spinoff science become viable. First, using a telescope with high gain, we can assess the operation of the broadband system in an RFI rich environment. We expect this to be challenging because there will be issues of

Fig. 4.— Views of the log-periodic feed being designed for the Allen Telescope Array for (from the US SKA Large-N Small-D Concept Design White Paper).

nonlinearity of the receiver. Science-oriented observations include the tracking of individual pulses from pulsars over a long frequency track. The differential dispersion delay across the band ranges from milliseconds to hundreds of milliseconds, depending on the pulsar. Of particular interest is the Crab pulsar, whose 'giant' pulses may be detected individually despite the large contribution to the system noise from the Crab Nebula. Recent observations have detected giant pulses at up to 8 GHz at Arecibo with time durations as short as 2 nanosec (T. Hankins, private communication). On a practical basis, two or more fast-sampling backends (with GHz bandwidths) can be used to sample the pulse at widely spaced frequencies. The advantage of having instantaneous access to the entire band is that spectra of single pulses can be acquired and the effects of multipath scattering in the interstellar medium and in the Crab Nebula's dense filaments investigated. It is not yet clear whether some of the temporal structure seen by Hankins et al. is intrinsic to the pulsar or a combination of intrinsic and scattering effects. Because scattering effects are highly frequency dependent, one can hope to disentangle the situation through broadband measurements. The Crab pulsar observations are of interest in their own right, but serve as an important demonstrator and platform for technique development for anticipated SKA (and LOFAR) studies of transient sources.

As an alternative feed, S. Weinreb (private communication) is investigating a priorietary, broadband antenna design of TRW. Should the TRW feed become available on the relevant time scale, we will consider using it in this project in addition to the ATA feed. In both cases, the beam width is well matched to the illumination requirements of the tertiary in the Gregorian optics at

Arecibo (15 dB illumination taper at $\pm 60^\circ$.

Costs are modest for this project. The feed and receiver, combined with fiber optics for Arecibo are about $20K. IF/LO components and backend electronics are another $20K. Data acquisition systems will include those on hand at Arecibo (e.g. the WAPP systems = Wideband Arecibo Pulsar Processor systems based on the Canaris correlator chip) and T. Hankins' fast sampling oscilloscope (2 GHz sampler).

### 1.8. Use of Fiber Optic Networks and Polarization Capabilities of the SKA

The SKA research group at the Harvard-Smithsonian Center for Astrophysics (L. Greenhill, A. Goodman, and B. Gaensler) is partially funded through NSF (from the 2001 ATI/SKA grant) to perform preliminary study of fiber optic data transmission on commercial networks, as may be used in the Square Kilometer Array (SKA). The work level represents a substantial downscope of the originally proposed activities. Herein, the SKA group at the CfA proposes to expand the existing program to include (1) a demonstration of fiber optic data transmission, and (2) a study of what instrument specifications are necessary to enable the polarization science in the SKA project goals. Both items were part of the proposal before the downscope.

**Fiber Transmission of SKA Data on Commercial Networks:** The large-$N$ SKA concept proposed by U.S. investigators will strike a balance between science and affordability. One challenge of having thousands of receiving elements is how to transport data to the central correlator facility. The broad bandwidth and high data rates of the SKA will demand fiber optic transmission of signals. However, the wide geographic distribution of the antennas will probably preclude exclusive use of dedicated fibers. The alternate (cost-saving) strategy is to use existing commercial switched networks for some fraction of the array.

Use of *dedicated* fiber has been demonstrated for a short baseline (50 km) and narrow bandwidth (200 MHz) by the real-time NRAO link between the Very Large Array (VLA) and the Pietown antenna of the Very Long Baseline Array (VLBA). Gigabit per second tests of dedicated fiber between two antennas hundreds of kilometers apart are planned by MIT/Haystack, and engineering studies of a larger, many-antenna system will be part of the yet-to-be-proposed second phase of the VLA Expansion (ELVA) project. However, none of these efforts addresses the use of commercial *switched* networks, which present new technical challenges, specifically, the reassembly and massive buffering of data.

The proposed project is driven by a concern that if relatively free availability of fiber is assumed in planning a large-$N$ array, and if the assumption proves wrong, then array capability will be diluted and science goals will require greater capital costs or redefinition.

**Description of Work - Fiber:** The proposed supplemental funding will accelerate work that is already planned to begin in mid-2003, permit execution of technical design, and support demonstration of concept. At current funding levels, the activities for Year 1 (see below) are spread over two years, and they are the only work planned.

Year 1 will include analysis of present and planned infrastructure and services in the telecommunications industry, as well as a study of the VLA/VLBA electronics and array control systems.

Study of the VLA/VLBA is necessary for two reasons. First, they are the intended demonstration test-beds. Second, they are working centimeter-wave interferometers from which engineering lessons may be learned and applied.

Year 2 will include design of a signal transmission and processing system, though some of this work may be accomplished in the first year. Year 3 will include implementation and demonstration of real-time data transmission and buffering, probably using the antennas of NRAO instruments (i.e., the VLA and VLBA). Especially in years 2 and 3, the proposed work would evolve into a collaborative effort with NRAO electronics engineering staff. The evaluation, planning, and design can be accomplished with relatively simple consultation, while the demonstration would require more intensive cooperation. NRAO has agreed to cooperate in the demonstration, subject to availability of funding for the second phase of the EVLA.

Design implementation will most likely involve conversion of the Pietown antenna to switched network service, connection of the Kitt Peak or Mauna Kea VLBA antennas to local fiber optic trunk lines, and test correlation. NRAO plans to install three different two and three baseline test correlators (to support ALMA and EVLA development) at the VLA site between 2002 and 2005. This work will conclude with a critical review of plans for data transmission under consideration by SKA consortia in Europe and Australia. The totality of results in this area will contribute significantly to our SKA design and cost estimates.

**Polarization:** Studies of radio polarization are a part of all of the Level 1 science areas identified and agreed upon for the SKA. However, to achieve accurate, high-sensitivity polarimetry free of excessive systematics requires that explicit design choices be made early. This is a lesson learned from experience with existing radio science projects (e.g. ALMA).

The only polarization requirement currently stipulated for the SKA is a purity of –40 dB. This specification is a good first step but it is insufficiently detailed to ensure that the wide variety of complex experiments planned for the SKA will be feasible. The polarization studies proposed here are driven by concern that, without detailed analysis informing the design and development process, some key science may not be possible.

**Description of Work - Polarization:** The proposed supplemental funding will support two projects associated with SKA development, after which detailed polarization specifications for the US SKA concept will be formulated.

First, for each of the "Level One" science goals identified by the SKA International Science Advisory Committee (ISAC), we will carry out modeling and simulations intended to determine design requirements related to future polarimetry programs (e.g., overall polarization purity, off-axis purity, image dynamic range, and time resolution). Groups within the US SKA consortium responsible for antenna and receiver design will use the results of the polarization analysis in their work. Through the ISAC (of which Gaensler is a member), we will also disseminate our results to SKA teams in other countries.

Second, a critical, unresolved issue is the balance between polarization purity intrinsic to the antenna and receiver systems, and what can be achieved through calibration and other off-line processing. Once front-end designs are finalized, we will simulate the polarimetric response of the interferometer, consider appropriate calibration strategies, and confirm the polarization performance of the instrument.

## 1.9. Site Survey & Selection

The US SKA Consortium recognizes that the southwestern US is a potentially viable site for the central portion of the SKA, with possible long baselines to sites in Mexico and Canada. Therefore the Consortium has indicated to the ISSC that it intends to propose a US site for the SKA to be considered by the ISSC in competition with other world-wide sites that include Australia and sites in South America and South Africa. To submit a site, the EMT and ISSC require substantial characterization of site properties, including physical access, weather, power and fiber access, and, of course, RFI. (A more detailed statement about information required from siting proposals is given at the end of this section.)

We therefore wish to undertake surveys of possible sites in North America, particular the Southwestern US and Mexico. Because the number of stations in the US concept is large, it is premature at this time to characterize specific station sites. Rather, our plan is to characterize a relatively small number of representative sites that cover the range of baselines for the core and intermediate subarrays of the SKA. Present discussions center around configurations involving a core array with at least half the collecting area within $\lesssim 50$ km, a few tens of percent within $\lesssim 500$ km, and the remainder on 'VLBI' baselines (out to multiples of 1000 km).

Most of this effort will concern quantitative measurement and analysis of RFI and weather. However, we will also qualitatively examine other issues, including local geology, logistical access, power and fiber access, and security issues.

For our effort there is considerable synergy with site selection and monitoring for the LOFAR and EVLA projects. Over the last year we have had discussions with NRAO (P. Napier, F. Owen and R. Perley) about joint site characterization for our and EVLA purposes. We have had similar discussions with NRL (N. Kassim) about site monitoring for LOFAR. More recently, we have discussed such synergies with the Southwest Consortium (N. Duric), consisting of the University of New Mexico, New Mexico State University, New Mexico Tech, the Applied Research Lab (UT Austin), and the Los Alamos National Laboratory. Our plan is to work closely and collaboratively with NRAO, NRL and the SWC on site testing. The various projects require different frequency ranges, but together require characterization of the entire range from 10 MHz to 50 GHz.

**Site Surveys:** The vicinity of the VLA is being surveyed by NRAO in order to determine the locations of eight new stations that are being considered for phase II of the EVLA. In addition, NRL is seeking a site for a LOFAR prototype station that can work as an outlier with the 74 MHz VLA and is coordinating its efforts with NRAO for this task. The NRL LOFAR site evaluation committee is working with NRAO to conduct an RFI monitoring program at low frequencies. We propose to join this effort and collaborate with NRAO and NRL in an extended site survey that will cover the SKA frequency bands. In this process we plan to build upon the existing NRAO documentation on the VLA and EVLA site surveys to evaluate physical conditions at and near the VLA site out to about 500 km from Socorro. We will assume various SKA configurations and analyze the feasibility of their geographical location within 500 km of the VLA. Our goal is to obtain thorough knowledge of RFI levels in these areas and identify possible SKA cluster sites.

It is apparent from the anticipated size that an area centered on Socorro would overflow (approximately 20%) into Mexico. We anticipate discussions with scientific authorities in Mexico regarding the possibility of locating some of the SKA clusters in the Chihuahua/Sonora region in northern Mexico.

**Requirements:** To examine RFI levels in the southwestern USA, we need to monitor a representative number and variety of sites within at least 500 km of Socorro. This will require collaboration with NRAO, NRL and the SWC, and participation of a technician to assemble necessary equipment and make measurements. The effort will be coordianted by Co-I Y. Terzian (Cornell). These surveys will include substantial travel in the southwestern USA and northern Mexico (3 trips per year, each trip of about two weeks duration). Though NRAO is conducting significant surveys for the EVLA at sites of the order of 200 km from the VLA, we need to extend such surveys out to about 500 km as required by the SKA.

Hardware needed includes a portable broadband spectrum analyzer, with input from test antennas and amplifiers. We will choose a cost-effective transport based on lease or purchase of a van-type vehicle. Because site testing is a long-term proposition, the investment in hardware will be cost-effective. We anticipate that our activities in the US will help set the requirements for international site testing; if need be, our hardware can be used after 2007 on non-US sites as well.

**Hardare Needed:**

| | | |
|---|---|---|
| Spectrum Analyzer | $\lesssim$ 50 GHz | \$50-\$60k (with discount)<br>(e.g. Agilent 8565EC) |
| Antennas & receivers | | \$20k |
| Tower for antennas | | \$5k |
| Amplifiers | | \$2k |
| Computer & recording | | \$5k |
| Infrastructure, transport | Batteries, generator, etc. | \$18k |
| Total | | \$100k |

The current international plan defined by the ISSC is to require submission of preliminary white papers on sites on 1 July 2003 for discussion at the next, yearly International SKA meeting in Geraldton, Australia. Given that funding for this proposal will have just commenced, we will base our preliminary white paper on extant RFI measurements and preliminary characterization of those southwestern sites made by NRAO. The white papers are intended to be "rolling" documents, updated yearly until a site is selected in 2007 (according to the current draft plan discussed at the August ISSC meeting in Dwingeloo and which is likely to be approved at the next meeting in Arecibo, January 2003).

**Year 1:** We will (a) join the EVLA/LOFAR surveys, (b) determine new outer potential SKA station sites, (c) prepare evaluation procedures, and (d) examine environmental and security issues for the potential sites, (d) begin site testing, (e) report comprehensive RFI results on web site; (f) update site evaluation white paper originally submitted to the ISSC on 1 July 2003.

**Year 2:** continue the same work and augment it by monitoring RFI at sites more extended than the EVLA; update white paper.

**Year 3:** continue monitoring work and update white paper.

**Outline of Contents of White Papers Expected from Host Countries:** A draft outline received from the Site Selection Committee is as follows. While many of the items requested can and should be attended to at a future date, it is important that RFI monitoring and characterization begin as soon as possible (c.f. item B.2 with bold emphasis added). Some of the other items, such as availability of fiber-optic trunks, will be identified through joint work with NRAO and the LOFAR project.

A. Maps (based on a GIS database) which show the following for the region:

1. extent of territory to be used for siting (overlaid with geographical coordinates)
2. population density and land use
3. roads and rail links
4. major air traffic routes
5. broadcast transmitters (with frequencies)
6. radars (with frequencies)
7. fixed microwave links (with frequencies)
8. annual rainfall and wind data
9. topography
10. existing fibre optic trunks
11. the location of major metropolitan centers (possible operations centers)
12. the location of radio environment test sites (see later)

B. Analysis of radio quietness, including:

1. notice of intent from the local regulator(s) that they are committed to creating and maintaining radio quiet zones in the region.
2. **results of surveys of the radio environment made in the region** (with some sort of certification of the technique and equipment used). Data products must conform to a pre-determined format and standard.
3. prediction of the evolution of the radio environment over the lifetime of the SKA

C. Report on the nature of the ionosphere over the region.

D. Critical review of political and economic stability in the region.

E. Analysis of labor costs.

F. Analysis cost of land acquisition and/or hire.

G. Critical review of technical and scientific resources in the region.

H. A plan and costing schedule of how the high-bandwidth data links would be implemented (including use of existing/planned telco infrastructure).

## 1.10. Technology & Science Deliverables

The proposed work will lead to specific intellectual property in the form of scientific results, reports, publications, algorithms, software and, most importantly, a plan for constructing the Square Kilometer Array. Below we itemize the complete list of deliverables from our original 2001 budget. This list was shortened substantially in our downsized budget. Here we indicate which of these is covered in the downsized 2001 grant (designated "I"), which are covered in the present grant request ("II") and which are still tabled ("T"):

1. A preliminary design for the SKA that will be presented to the International SKA Steering Committee in 2003 and a final design in 2005 (I).
2. Defined key science projects that require the SKA and the design requirements they impose. (T)
3. Characterization of RFI, including implied limitations to SKA performance and prognosis for effective mitigation (I, II).
4. Collateral science results from pilot observations that target epoch-of-reionization hydrogen (II) and transient source detections (T).
5. Algorithms, software and documented results for RFI mitigation techniques as applied in a range of contexts (single dish antennas with focal plane arrays; arrays with small baselines; and arrays with large baselines) (I, II).
6. Specification, performance and cost of primary antennas of different design (I + implied NASA effort for Deep Space Network considerations [S. Weinreb]).
7. Specification of low-cost antenna fabrication techniques for several antenna concepts (e.g. on-axis paraboloids, off-axis paraboloids, and shaped reflectors). (I + Weinreb DSN considerations).
8. Specifications and performance of wideband feed antennas suitable for the SKA (I [partial]).
9. Specification of low-cost, low-noise, wideband receiver designs (I + Weinreb DSN effort + ATA effort).
10. Simulations and metrics for assessing array performance, including imaging dynamic range and RFI suppression, among others (I [partial], some T).
11. Cost equations for arrays that are maximally digital and for SKA design(s) in particular (I).
12. A site selection report (II).
13. A suite of outreach materials and implementation in existing visitor facilities (T).

Parenthetically, we note for a few of these items that some work relevant to our effort is being conducted by S. Weinreb (CIT/JPL) under the auspices of Deep Space Network (DSN) feasibility studies, for which he is receiving funding from NASA.

# 2. Coordination & Oversight

## 2.1. Summary of Work Effort

Table 5 summarizes the work effort of our SKA development work funded under the 2001 proposal (labelled 'I') and potentially funded under the current proposal ('II'). The work areas indicated in the columns reflect the original breakdown expressed in our large 2001 proposal. As may be seen, with this second proposal many — but not all — of the original work areas are restored with this request. Two main areas that are not include (1) establishment of a science working group working explicitly with the US SKA Consortium and its concept; and (2) outreach. As time goes on, the scientific capabilities and tradeoffs involved with the US design must be considered in detail when we need to submit a detailed design to the ISSC. For the time being, this work will be done by the Consortium and its collaborators as our institutional contributions to the SKA effort. We regret not having explicit funds for Education and Public Outreach (EPO) because the SKA development context is an excellent forum for teaching the science students and the public about the electromagnetic spectrum and astrophysics; also the development effort itself can lead to provision of infrastructure and educational projects in radio astronomy at the secondary and college levels. Our first proposal contained a substantial EPO section the worked at several educational and public levels. At some point in the future, we will consider requesting a supplement to our NSF funded development work for EPO.

Table 5: PROPOSED WORK EFFORT:

| WHO | $ | Man | Sci | RFI | A+F+R | Array | Data | Site | Radar | Sys + Costs | Out |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CIT/JPL | I | | T | | I | T | | | | I | T |
| Cornell | I, II | I | T | I, II | | | T | T,II | I | I | T |
| Haystack - MIT | I | | T | | | I | T | | | T | T |
| NAIC | I,II | | | | I | | | | | | T |
| NRAO | — | | √ | √ | √ | √ | √ | √ | | √ | T |
| NRL | — | | √ | √ | | T | T | √ | | | |
| OSU | I, II | | | I, II | | | T | | | | |
| SAO | I, II | | T | | | I, II | | | | | |
| SI | T | | | T | | | | | | T | T |
| SWC | — | | | | | | | √ | | | |
| UCB | T | | | | T | T | | | | | |
| UMN | I, II | | II | II | | | II | | | | |
| IPO | I | I | | | | | | | | | |

$ = Funding requested, Man = Management, Sci = Science Target Studies
RFI = RFI Management, Mitigation and Editing
A+F+R = Primary/Secondary Antenna Analysis, Feeds, Receivers
Array = Array Optics (configuration, connectivity, beamformer/imager)
Data = Data Mining, Management and Archiving, Site = Site survey studies
Rad = Radar capability, Sys + Costs = Systems Analysis and Costing, Out = Outreach
IPO = International Project Office; 1/3 FTE funded under Grant I.

I $\Longrightarrow$ funding under Grant I (submitted 31 Aug 2002)
II $\Longrightarrow$ funding requested under this proposal
T $\Longrightarrow$ work area is tabled because of lack of funds, in Grant I and/or in current request.
√$\Longrightarrow$ work in area is implied through liaison with to organization.

SWC = Southwest Consortium; for other institution names, see p. 2

### 2.2. Consortium/Cornell Management Plan

The Cornell co-PIs will administer the grant as well as lead Cornell's individual SKA activities. Administration will involve the Astronomy Department's Administrative Director, Dr. Elizabeth Bilson, who works closely with Cornell's Office of Sponsored Programs (OSP).

The US SKA effort must proceed quickly with scientific studies and technical developments. Accordingly, the activities funded by NSF at all involved institutions should be reviewed frequently. The appropriate oversight body for this review process is the US SKA Consortium. Consortium (face to face) meetings take place semiannually for this purpose. In addition the PI will interact closely with all co-Is via telecons, site visits, and the web. We will implement a web-based US SKA Consortium Memo Series for reporting and exchanging results of work conducted under any grant that ensues from this proposal.

Cornell is responsible for submitting progress reports to the NSF; these will be based on reports from individual institutions and outcomes of the semiannual reviews conducted by the US SKA Consortium.

Cornell will oversee the integral aspects of the development effort funded by this proposal insofar as they contribute to the bottom-line goal of submitting design(s) from our work to the International SKA Steering Committee.

Cornell, along with the rest of the US SKA Consortium, will assess and evolve the effort in the context of other national and international developments in meter and centimeter wavelength radio infrastructure. One visit/yr by the PI to each institution can be done with coordinated trips to institution groups (e.g. west coast, east coast, OSU + NRAO + NRL), or 3 trips/yr.

Cornell contributions to the US SKA effort, as the lead institution, include: (1) The time of the PI and co-Is in administering the grant and leading technical efforts by Cornell in several areas discussed below; (2) Administrative support from the Astronomy Department's Administrative Director and from the Office of Sponsored Programs; (3) Technical support from faculty, staff and students of the Astronomy Department; (4) Organization of student research programs oriented toward SKA development, including undergraduate and graduate students; (5) Contributions of office and lab space in the Space Sciences Building at Cornell for both management and technical development; The Cornell technical effort may require additional space that can be provided at the Cornell/NAIC lab at Maple Avenue; (6) Public relations through the Cornell News Service and assistance from Media and Technology Services; (7) Contribution to the ongoing refinement of the scientific case for the SKA, by drawing on the many faculty, research associates and graduate students involved in research in relevant and complementary subject areas; (8) Consultation with the Cornell Theory Center (CTC) regarding data archiving.

### 2.3. Management Plans for Individual Institutions:

#### *2.3.1. Cornell Management Plan*

**Summary of Work:** For development work, Cornell will be involved with site surveys, RFI mitigation studies, and pilot observations of highly redshifted HI and transient signals.

**Contributions to the Development Effort:** We will obtain data using existing or soon-to-exist telescopes for the purpose of designing and testing algorithms for RFI mitigation. This RFI effort will be in close collaboration with groups at NRAO, OSU, the SI and the University of Minnesota. Cornell will collaborate closely with NRAO and NRL on site surveying in the Southwestern US and in Mexico. Cornell will study the use of the SKA as a radar system for solar system science.

**Year 1:** Acquire hardware (with OSU and UMinn) for the catwalk feed at Arecibo; Acquire hardware for site testing and begin site testing.

**Year 2:** Continue with activities above. Analyze data obtained from the catwalk system with appropriate software development. Acquire ATA feed and receiver and install at Arecibo (working closely with Arecibo staff). One or more publications by the end of Year 2 on RFI mitigation techniques. Evolve design concepts in conjuction with the Consortium.

**Year 3:** Continue with activities above. Continue refining design concept in conjuction with the US SKA Consortium and with feedback from the ISSC, ISAC and EMT. Update site report based on RFI monitoring.

**Personnel and Work Load:** Professors D. Campbell, J. Cordes, P. Goldsmith and Y. Terzian will be involved in the Cornell development effort as well as managing the entire Consortium effort in this proposal (see Consortium Management Section). In combination with his role as PI, JMC will put 2.5 man months into the project (combining the work proposed here with that funded in the downscoped grant resulting from the 2001 ATI proposal).

We expect that one or more Masters of Engineering students will be involved with technical aspects of our work plan while Astronomy and Physics PhD students will be involved with astrophysical considerations.

**Institutional Contributions:** Cornell will provide computer support and space for the project. We expect to use the Cornell Theory Center for some of the intensive data processing along with workstations in the Space Sciences Building.

### *2.3.2. NAIC Management Plan*

**Summary of Work:** The NAIC effort will focus on (1) construction and installation of the antennas, front-end receivers and optical fiber connections to a 4+1 catwalk feed system for the EoR project; (2) acquiring and installing a wideband ATA feed antenna and associated receiver components and fiber connection into the Gregorian dome system. and (3) integration of RFI monitoring hardware into a usable system and participating in the RFI monitoring characterization of sites in the US Southwest.

Item (1) will be done in the second half of the first year of funding after an antenna design is chosen.

Item (2) will occur in the second year of the project. We will acquire an ATA feed from UC Berkeley early in the second year.

Item (3) will be ongoing during the full three years of the grant period. Purchase of hardware will be done in the first year and assembled into a portable unit.

### *2.3.3. OSU Management Plan*

**Summary of Proposed Work:** OSU's primary contribution to this project will be to develop a 10-input-channel, 150-MHz spectrometer for the proposed Arecibo EoR search system. OSU's spectrometer will accept 10 IF inputs at a common, fixed center frequency (provided by NAIC's front end RF subsystem), and perform digitization, channelization, correlation, integration, data acquisition, and RFI management functions.

**Timeline:** The emphasis in Year 1 will be on design and prototype development. By the end of Year 1, we plan to complete and demonstrate a benchtop-mounted single-channel (i.e., one 150-MHz-bandwidth processing path) proof-of-concept prototype. We also plan to have a completed design for the final system at this point. In Year 2, we will construct the actual 10-channel spectrometer, deliver it to Arecibo, and support the integration and test of the completed system. This activity is likely to continue into Year 3. The balance of Year 3 will be focussed on support for the science activities using the spectrometer, implementation and refinement of RFI mitigation functions, other refinements to the system as necessary, documentation of the completed design, and dissemination of this information to the radio astronomy community.

**Personnel:** The OSU PI will be Dr. Steve Ellingson, Research Scientist, at the level of 2 person-months per year. Dr. Ellingson will serve as systems engineer for the spectrometer development as well as being specifically responsible for the analog, digitization, data acquisition, and RF management aspects of the system. Dr. Grant Hampson, Sr. Research Associate - Engineer, will participate at the level of 6 person-months per year. Dr. Hampson is an expert in the design of high-speed digital signal processing hardware, and will be specifically responsible for the channelization, correlation, and integration aspects of the system. We are also seeking funding to support one graduate student in Electrical Engineering to work with Drs. Ellingson and Hampson, as well as support for 1 technician at 10

**Funding:** OSU seeks salary support as discussed above. To facilitate the development, construction, and installation of the spectrometer, OSU requests \$20K, \$10K, and \$3K in materials and supplies for Years 1, 2, and 3 respectively. Also, we request \$3K/year for travel expenses associated with multi-institutional collaboration and on-site efforts at Arecibo. A nominal budget of \$8.5K, \$8.9K, and \$6.6K per year is requested for support staff of the researcher's laboratory organization (the OSU ElectroScience Laboratory), which are not already supported through indirect costs. These include machine shop personnel, draftsmen, and editorial assistants.

### *2.3.4. SAO Management Plan*

**Management Plan - Fiber:** For an assumed start date of July 2003, analysis of present and planned commercial fiber services will last until October 2003. Study of the VLA/VLBA will require 6 to 9 months. Initial design studies will occupy another 6 months, concluding with initial analyses of SKA design specifications and constraints related to fiber transmission of data (e.g., bandwidth and transmission efficiency). Experience gained in creation of the VLA link to Pietown suggests that design and construction will require 6 months each. Deployment of hardware and the start of the testing will begin in 2005 (when EVLA resources should be available). Testing and refinement of operational techniques and VLA/VLBA-specific components should require 6 to 12 months. The project will be complete by mid 2006.

The CfA group proposes to employ an experienced electronics engineer half-time for three years to conduct the proposed program. Because of the need for consultation and collaboration with NRAO staff, approximately half of the engineer's time on the project would be spent in Socorro, NM each year.

PI Greenhill and Co-I Goodman will devote approximately 5% to 10% of their effort to supervision, coordination, and analysis of test results. From late 2005 to mid 2006, they will concentrate on analyses of SKA design constraints driven by practicality and cost-benefit models imposed by the intensive use of commercial fiber optics.

**Management Plan - Polarization:** Most of this work will be carried by a postdoctoral researcher supervised by Co-I Gaensler. Over three years, the postdoc will spend approximately 15% of his/her time on SKA polarimetry, chiefly on modeling and construction of simulations. Gaensler will be responsible for dissemination of results and coordination with other SKA research and development groups.

### *2.3.5. UMN Management Plan*

**Summary of Proposed Work:** The University of Minnesota, represented by Prof. John Dickey, will have primary responsibility for the "catwalk project," which involves placing feeds and receivers on the Arecibo telescope at the intersection of the catwalk and the paraxial surface. This is a collaboration with Ohio State University and with NAIC. The ultimate goal is to give the "acid test" to all techniques proposed for RFI suppression, by subjecting them to an extremely hostile electromagnetic environment in the 100 to 250 MHz range. Scientific objectives include study of the Galactic interstellar medium through mapping hydrogen and carbon recombination lines, and a search for the signature of the Epoch of Recombination (EOR) through the 21-cm line at redshifts of 6 to 10. The project will constitute the Ph.D. thesis work of a graduate student at the University of Minnesota, who is to be funded in part by this grant.

**Personnel:** The project will be led by Dickey, working with a graduate student at Minnesota. Ellingson (OSU) will help develop the digital hardware, and NAIC engineers will help design and install the antennas and analog section. Cordes & colleagues (Cornell) will facilitate installation of the catwalk feed and will contribute to RFI mitigation algorithms and data processing. Funding is requested for three years of support for the grad student at Minnesota, and modest equipment purchases.

**Timeline:** The catwalk project has three stages, corresponding to the three years of this grant. In the first year we hope to get the feeds and receivers installed, and have sufficient signal processing hardware to allow us to take spectra. In the second year we hope to characterize the RFI, and to perfect the calibration of the system to the point where we can see the comb of recombination lines from the Milky Way ISM. In the third year we will implement at least two forms of RFI mitigation, measure the level of suppression which each provides and the fraction of the total band which is useful for deep integrations, and try to set a limit on the EOR fluctuation spectrum.