NATIONAL RADIO ASTRONOMY OBSERVATORY

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To: Sander Weinreb

From: John Webber

Subject: Proposed SKA work at NRAO

Introduction

The NRAO is interested in participating in preliminary design and prototyping work for parts of the proposed SKA. This document lists specific tasks of interest to the NRAO in the Antenna and Receiver Sub-Project of the USSKA Technology Development Plan.

Statement of Work

The NRAO will perform the following development and prototyping tasks:

1. 11-34 GHz Receiver

   Design and prototype MIC/MMIC front end receiver modules, including low-noise amplifier and first stage of downconversion to selected IF band. Optimize for cost/performance benefit in collaboration with designers of other parts of the system. Package for compatibility with feeds and cryogenics.

2. IF and LO system

   Choose overall back end block diagram including IF band and local oscillator scheme. Design for maximum capability and for compatibility with all bands (where appropriate) so that common components may be used for cost savings. Optimize design for cost/performance benefit.

Estimated total budget by year

The proposed work will require the equivalent of 1 full-time employee over a period of 5 years, and will be a varying mix of 2 to 3 employees working part-time on the SKA, both engineers and technicians. The estimated fully burdened cost in 2003 dollars is $103K per year for each of the 5 years.

There will also be some material costs, which are difficult to estimate without a detailed design. The largest of these expenditures are likely to be foundry charges, which will probably be shared with other SKA receiver development; these are not budgeted here. For budgetary purposes, $40K per year in materials and services is estimated (in 2003 dollars).

The total is therefore estimated as $143K per year for 5 years, in 2003 dollars.

Deliverables

1. 11-34 GHz Receiver

Deliverables: Documentation of designs
LNAs for test on existing antennas
LNAs for test on prototype SKA antennas
Cost study and tradeoffs for full production

2. IF and LO system

Deliverables: Documentation of architecture and designs
Prototype IF and LO modules for all bands
Cost study and tradeoffs for full production

Quarterly reports will be provided to the project. The first prototype hardware will be provided at the end of the second year of development and prototyping. Final, pre-production hardware and full documentation will be provided at the end of the final year.

Intellectual Property

There are no significant intellectual property issues. NRAO will retain the right to use the designs developed in this project for its own purposes. NRAO will retain title to all equipment and other materials purchased for this project which are not in the deliverables list.

Contact Information—street address will change in December 2003

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Square-Kilometer Array (SKA): Background, Strawman Specfications, and Discussion of Problems that can Benefit from Expertise in other URSI Commissions

We invite our colleagues in other Commissions of URSI/USNC to an *Open Forum on the Square-Kilometer Array* at our annual meeting in Boulder on Monday January 4 at 5 PM (place to be announced, but likely the Commission J meeting room). The Square-Kilometer Array is a cm/m wavelength radio telescope with a nominal collecting area of a square kilometer configured to maximize the scientific goals. Specifically we seek input on the scientific goals that may generate further design constraints. The astronomical goals are discussed in documents at various web sites identified below. For example, the Arecibo Observatory is a joint astronomy-ionosphere center, and it is possible that there there will be interest from the atmospheric community in URSI. Further, there are a host of technical problems in achieving an agile, high gain (!) telescope at a fraction of the cost per square meter of conventional telescopes (including Arecibo) that are challenging to members of Commissions A-D.

We look forward to responses of interest *prior* to this Forum.

- Would you like to attend?
- What would you like to hear in an initial presentation?
- Would you like to offer a perspective on scientific applications or technical developments?
- Who else should we contact?

Please let one of know and forward this email to any colleagues that might be interested.

Links to a number of sites involved in SKA development and USNC Mtg information can be found at: *http://astro.berkeley.edu/~dbacker/ska.summary.html http://cires.colorado.edu/ursi/*
This document is also posted there.

See you in Boulder in January,

Don Backer, UC Berkeley, Chairman of Commission J

Rick Fisher, NRAO Green Bank, Former Chairman of Commission J

John Dreher, SETI Institute, Mountain View

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SUMMARY:
I. Background
II. Technical Problems
III. Strawman Specifications
IV. Glossary

I. Background

The international astronomical community is planning the next generation radio telescope for frequencies between about 15 MHz and 20 GHz. The main goal of this effort is to construct an effective collecting area of about one square kilometer while maintaining a system noise temperature under about 50 K above about 500 MHz. Collecting area may be traded for better system temperature as long as the quotient is about 2×10^4 m^2/K. We recognize that covering three decades of frequency in one instrument may require too many compromises, so two or three antenna systems that share infrastructure and maybe signal processing electronics are being considered within the constraints of a fixed total budget. At low frequencies, arrays of small elements, on the order of half wavelength in size, appear feasible. At high frequencies it seems certain that reflectors of some kind will be required to reduce the total number of first amplifying elements. The configuration of the SKA – filling factor and maximum baseline between elements – is open to discussion as both frequency range, scientific goals and technical limits interact strongly. A maximum baseline around 500 km is likely.

A large scientific project of this sort might cost on the order of $US 500 million. The strawman specifications for the Square-Kilometer Array as of mid-1998 along with a glossary of terms is attached at the end of this document.

II. Technical Problems Needing Work

The following is a rough list of the technical problems associated with designing and building the Square-Kilometer Array that we have identified so far. Many of the problems are interrelated so they cannot be taken in isolation. Also, some of the problems are rather unique to radio astronomy.

1. *Electrically short array elements.* At frequencies below about 200 MHz the system noise temperature will be dominated by sky noise that depends on wavelength to the power 2.6. Hence, the antenna element does not need to be power matched to the amplifying element at low frequencies as long as the power transfer does not fall off faster than the noise increases with increasing wavelength. Densely packed elements with a resonant frequency around 200 MHz and a quarter-wave spacing over a ground plane at this frequency satisfy this requirement, in principle. Can the reactive components of short elements be controlled well enough to realize the required power transfer? How are mutual coupling and signal combining handled? Are there other ways of designing an array to cover the 15 to 200 MHz frequency range which produce frequency-independent collecting area and sky-dominated system noise?

2. *Multi-octave, power-matched array elements.* Can an array of small elements, on the order of half wavelength in size, be designed for the 200 to 2000 MHz range? Assuming that something like 10^8 elements can be manufactured cheaply enough, is there an array design that will cover a decade of frequency with constant collecting area and a system temperature under 50 K? The collecting area of intrinsically broadband elements (log spirals, log-periodic dipoles, or sinuous antennas) falls as frequency squared unless they are packed as close as half a wavelength at the high frequency limit. Could the low frequency mutual coupling be dealt with? Is there a fractal antenna design which interleaves elements of more limited bandwidth that will cover a decade of frequency contiguously? The engineers at the Netherlands Foundation for Research in Astronomy (NFRA) are actively pursuing this problem and problem 1; see web sites referenced above.

3. *Decade-bandwidth feed for a parabolic reflector.* Can we realize a parabolic reflector feed for the 2 to 20 GHz range that maintains good phase, illumination, and spillover efficiency without the need for mechanical complexity? This feed must allow room for an amplifying element refrigerator that cools to at least 80 K. The Radio Astronomy Laboratory in Berkeley is working with the SETI Institute on a log-periodic antenna design that looks promising, but there may be other approaches.

4. *Adaptive RFI rejection.* Radio astronomy can obviously benefit from the adaptive filtering and adaptive null-steering techniques of the radar, sonar, and other engineering communities. The typical radio astronomy signal-to-noise ratios of -30 to -50 dB raise a number of new questions. Can we achieve RFI suppression to this level without raising the system noise or distorting the frequency response characteristics of our radiometers? Can we steer phased array nulls without distorting the response of the array in the direction of measured cosmic signals. We are asking for an array dynamic range of 50 dB or so in the sense that strong radio sources in the field of view or in sidelobes must not mask sources 10^5 times weaker. This potentially puts a stiff requirement on the array's frequency and spatial response stability which must not be upset by adaptive techniques. One of the toughest RFI rejection problems will be the suppression of signals from low earth orbit satellites. Work on adaptive techniques has been started at the NFRA and National Radio Astronomy Observatory (NRAO) as well as a few other institutions.

5. *Optical signal processing.* Aside from cost considerations, we are reasonably certain that the digital techniques of sampling, beam forming, and spectrum analysis are straightforward and understood. Does optical signal processing have a place in the array? What are the linearity and dynamic range properties of optical processing? What types of optical operations have an economic advantage over digital techniques? Would this influence the beam-forming architecture of the array?

6. *Signal transmission.* The Square-Kilometer Array will be distributed in a few tens of sub-arrays over distances of up to 500 km. Optical fiber signal transmission seems like an obvious choice for tying the array to a central processor. What are the dynamic range properties of wideband optical fiber modems? Can we transmit a 20-GHz passband containing considerable RFI as well as noise-limited radio astronomy information simultaneously in one fiber? At what point in the beam-forming hierarchy does the cost of fiber modems become prohibitive?

7. *Low cost amplifier refrigeration.* Above about 300 MHz the system noise of the Square-Kilometer Array will depend considerably on the first amplifier noise figure. Design studies so far indicate that cooling the first amplifier stages to 80 K or lower will be more economical than building more collecting area, at least above 1 or 2 GHz. What refrigerator technology will offer the best reliability, lowest cost, and smallest

power consumption? Cold head physical size may be an issue when integrated with a broadband reflector feed that operates to 20 GHz. The cost of amplifier cooling can affect the optimum reflector size since more expensive refrigerators dictate fewer cooled amplifiers and, hence, fewer, larger reflectors. The failure rate of refrigerators over a 20 or 30 year lifetime must be extremely low.

8. *Mutual coupling in small-element arrays.* The effects of mutual coupling on beam formation, beam steering, amplifier noise crosstalk, and array blind spots must be understood well enough to predict the performance of the array at all beam pointing angles. How does one calibrate and compensate for the effects of mutual coupling for optimum array efficiency?

9. *Arrays as reflector feeds.* At least one proposal for the Square-Kilometer Array requires the use of a phased array as the feed of a large reflector. The basic concept has been demonstrated at the NRAO with a prototype array feed, but work remains to be done on the effects of mutual coupling, cooling of a distributed array for good noise figure, and increasing the array bandwidth by using more densely packed array elements. Array feeds have been used in the radar and satellite communications industries, but none of those applications have yet used full sampling of the focal plane field that is required for radio astronomy systems.

10. *Optimum reflector size.* Above 1 or 2 GHz there is little doubt that the Square-Kilometer array will require reflectors for the initial concentration of cosmic signals. Suggested configurations range from inexpensive 3m dishes to nearly flat or spherical reflectors in the 200m to 500m range. At this point there is no obvious winner since the low cost of small reflectors is offset by the need for more low-noise amplifiers, refrigerators, and beam-forming network components. The optimization matrix is complex and hard to quantify. For example, small reflectors offer a wider instantaneous field of view, but large reflectors allow large and probably more efficient receiver packages. Do off-axis reflectors offer sufficient advantages in efficiency and lower sidelobe response to offset their polarization and more complex feeding disadvantages? Considerable mechanical engineering expertise is needed in this optimization process. Reflector design work is proceeding at Berkeley, the Dominion Radio Astrophysical Observatory in Canada (DRAO), and in China.

11. *Digital beam-forming architecture.* What are the economically optimum signal processing architectures for wide field of view, high spectral resolution, wide instantaneous bandwidth, and RFI tolerance. We cannot afford to cover all of this parameter space simultaneously, at least not in the early life of the array. How does the architecture affect flexibility in reallocating processing power? What dynamic range do we need at each level of the architecture? What part involves general purpose processors and where is special purpose hardware used? Considerable thought has been given to these problems at the SETI Institute.

12. *Array configuration.* What is the best compromise of array configuration for angular resolution, low surface brightness sensitivity, RFI cancellation or insensitivity, high dynamic range, and calibratability? This optimization will require extensive simulations with models of the cosmic source distributions and expected instrumental and environmental errors. Quite a bit of expertise already exists in radio astronomy on the correction of atmospheric and ionospheric phase distortions, but the Square-Kilometer Array pushes the required dynamic range by at least one or two orders of magnitude.

III. SKA Strawman Specifications

Aeff/Tsys: 2×10^4 m^2/K

Sky coverage: $> 2\pi$ steradians incl. central Galaxy

Frequency range 0.03 - 20 GHz

Imaging Field of View: 1 square deg. @ 1.4 GHz

Number of instantaneous pencil beams: 100

Maximum primary beam separation:

low frequency: 100 deg
high frequency: 1 deg @ 1.4 GHz

Number of pixels: 10^8

Angular resolution: 0.1 arcsec @ 1.4 GHz

Surface brightness: 1K @ 0.1 arcsec (continuum)

Instantaneous bandwidth: 0.5 + f/5 GHz

Number of spectral channels: 10^4

Number of widely spaced, simultaneous frequency bands: 2

Clean beam dynamic range: 10^6 @ 1.4 GHz

Calibratable polarisation purity: -40 dB

IV. Glossary

Aeff/Tsys: The effective collecting area divided by the system temperature. This is the proportional to λ^2 * G / T. *Aeff/Tsys* may be a function of frequency.

Sky Coverage: The solid-angle area of the celestial sphere that can be seen by the array with Aeff/Tsys greater than half of its maximum value. This does not say anything about tracking time or about UV coverage when used in VLBI.

Total Frequency Range: The total frequency tuning range of the instrument. This may be divided into sub-ranges with different antenna technologies, and it is not necessarily contiguous

Imaging Field-of-View: The instantaneous, contiguous solid-angle area of the sky that can be imaged, given a sufficiently capable correlator. This area will be a function of frequency.

Number of Instantaneous Pencil Beams: The number of "phased array" pencil beams that can be placed simultaneously within the Imaging Field-of-View for point source observations such as pulsars, stars (including SETI), and VLBI.

Maximum Primary Beam Separation: This spec assumes that the square-kilometer array will have at least two levels of beam forming. Signals from small antennas (dipoles, small dishes, etc.) are combined to form an array element primary beam, and signals from array elements can be combined in a correlator to make a map within the primary beam or combined directly to form one or many pencil beams within the primary beam. More than one primary beam could be formed within the pattern of the small antennas. The Maximum Primary Beam Separation specifies how far apart these primary beams can be formed simultaneously.

Number of Pixels: The number of spatial resolution elements in a map synthesized within the Imaging Field-of-View.

Angular Resolution: The maximum angular resolution of the array as determined by its largest linear extent (longest baseline).

Time Resolution: The time interval between independent intensity outputs from the array. For example, this may be detected samples from a phased array for pulsar work or a time series of maps for solar or planetary observations.

Surface Brightness Sensitivity: The minimum detectable (5-sigma) continuum surface brightness for a specified resolution, e.g., 1K @ 0.1 arcsec. This may be a function of frequency.

Instantaneous Bandwidth: The widest contiguous frequency range that may be observed simultaneously given enough correlator or other processing capability. Typically this means the widest selectable IF filter bandwidth before the digitizer.

Number of Spectral Channels: The number of independent frequency samples from the array after all signal processing.

Number of Simultaneous Frequency Bands: The number of widely spaced frequency ranges that may be observed simultaneously. For example, a stellar flare study might want to observe at 1.4 and 5.0 GHz at the same time, each with instantaneous bandwidths of 0.3 GHz.

Clean Beam Dynamic Range: The best intensity dynamic range that may be obtained in a fully processed synthesized map, as limited by unknown errors in the array or its environment.

Calibratable Polarization Purity: The error in Q, U, and V Stokes parameters as a fraction of I for a strong radio source after all data processing, as limited by unknown errors in the array or its environment.