THE MILEURA WIDEFIELD ARRAY

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ABSTRACT

The Mileura Widefield Array (MWA) will be built at an extraordinarily radio-quiet site in Western Australia. This paper describes the initial, 80-300 MHz portion of the array, known as the Low Frequency Demonstrator (LFD).

LFD science targets include the cosmological Epoch of Reionization (EOR), transient radio sources, and space weather phenomena. The array comprises 500 antenna "tiles", each with 16 crossed dipoles, distributed over a region 1.5km across. The design trades complexity in hardware and software subsystems for massive computational power. The LFD will be described in detail, and the status of design and prototyping activities will be summarized.

OVERVIEW

The Mileura Widefield Array (MWA) is designed to implement extremely wide imaging fields of view, measured in hundreds of square degrees, at low radio frequencies, using advanced array design and data processing techniques. The array will be located at the Mileura station in outback Western Australia, which is sparsely populated, and is characterized by extraordinarily low levels of RFI. This favorable environment for low frequency radio astronomy will be protected for the long term by the implementation of a federally regulated radio quiet zone. The site also has low infrastructure costs, is readily accessible from Perth, and provides excellent sky coverage including the inner galaxy. Mileura station has been selected as the Australian candidate site for SKA.

Over the next 3-4 years, the MWA will consist of two demonstrator arrays, one operating in the 800-1600 MHz range led by ATNF, and the other in the 80-300 MHz range led by MIT. These instruments are referred to, respectively, as the New Technology Demonstrator (NTD), and the Low Frequency Demonstrator (LFD) of the MWA. In this contribution, the design, science goals, plans and timeline for the low frequency demonstrator are presented. The LFD is a collaboration between MIT, the Harvard-Smithsonian Center for Astrophysics, a consortium of Australian universities, and the CSIRO Australia Telescope National Facility, with support from the Office of Science and Innovation of the government of Western Australia.

The LFD has three primary science drivers, namely measuring and characterizing emission and absorption in the redshifted 21cm line of neutral hydrogen during the cosmological epochs of reheating and reionization, performing a search for transient radio emission that is 6 orders of magnitude more sensitive than existing surveys in this wavelength range, and conducting remote sensing studies of the heliospheric plasma via interplanetary scintillation and Faraday rotation measurements of background radio sources. In addition, the LFD will support several secondary science goals, including pulsar studies, radio recombination line work, solar burst imaging, and others.

The LFD is implemented as an array of 500 antenna "tiles" distributed over a region roughly 1.5km across. Each tile consists of 16 crossed broadband active dipoles, which are phased together to form a beam on the sky which is 15-50 degrees across, depending on the frequency. A design philosophy has been employed which trades complexity in hardware and software subsystems for massive computational power. This is perhaps best seen in the correlator, which will form all 125,000 simultaneous baselines, with full polarization and 4096 spectral channels, yielding 2 billion visibility measurements every 0.5 seconds. This massively parallel computing approach, which is now affordable thanks to modern FPGA and fiber optic technologies, allows traditionally complex radio astronomy systems to be greatly simplified. Nowhere is this more true than in the software, which is the dominant expense in next-generation arrays of this type.

SCIENCE GOALS

As noted above, the LFD has three primary science goals, involving the Epoch of Reionization, the transient sky, and the heliosphere.

Epoch of Reionization: As the Universe cooled from its ultra high-energy origins, it underwent a Recombination phase in which most protons and electrons combined to form atomic Hydrogen, and the resulting high optical depth rendered the Universe opaque. This 'dark age' persisted until the first structures formed via collapse of primordial density fluctuations, and the resulting luminous sources heated and re-ionized most of the Universe. Understanding the evolution of this process holds the key to some of the most important outstanding questions of astrophysical cosmology: *how did the first structures form and how did the Inter Galactic Medium become reionized?*

The LFD will address these questions using at least two different approaches, observing the highly redshifted 21cm line of atomic hydrogen. First, by utilizing the extremely wide field of view of the LFD, a high precision measurement of the power spectrum of fluctuations in the 21cm line can be made. The LFD has been designed to enable high precision calibration that will allow accurate removal of strong foreground signals, and the extraction of power spectrum measurements. Second, quasars that form at redshifts beyond ~6.5 will be surrounded by a substantially neutral intergalactic medium. Such quasars will produce an ionized "hole" in this medium, similar to Strömgren spheres, that will be observable by the LFD as a characteristic spatial and spectral signature. LFD observations of these EOR signatures will pave the way for larger and more capable arrays in the future.

The Transient Universe: The LFD has a powerful combination of collecting area, instantaneous field of view, bandwidth, collecting area, and effective observing time. Together, these constitute a capability to detect transient radio sources in the 80-300 MHz range that is at least 10^6 times better than previous observations. Potential targets include pulsar giant pulses, prompt emission from gamma ray bursts, extrasolar planets that may exhibit scaled-up version of Jovian decametric bursts, and many others, including phenomena that are as yet unsuspected.

The Heliosphere: Study of the heliosphere is of major practical significance, because heliospheric disturbances such as coronal mass ejections (CMEs) are responsible for space weather phenomena and geomagnetic storms, which can adversely affect space assets and communication systems. Low frequency radio astronomy can provide a powerful remote sensing capability due to the effects of propagation of radiation from distant sources through the heliospheric plasma. Such effects generally scale as wavelength squared, and so are large at LFD frequencies. The LFD can be sufficiently well calibrated that accurate measurements of these propagation effects becomes practical. The most important effect is Faraday rotation, which provides a much-needed diagnostic of the heliospheric magnetic field. When combined with measures of electron density and density fluctuations (including IPS measurements from the LFD itself), a much more comprehensive view of the heliosphere will be in reach, leading to improved space weather prediction capabilities.

ARRAY DESIGN

A key characteristic of the LFD design is that the array contains no moving parts since the antenna elements are fixed dipoles, and that it will be pointed by electronic steering. System architecture will be heavily dependent on modern digital processing techniques and software control. Table 1 summarizes the specifications of the LFD.

Table 1. Core array specifications

Frequency Range	80-300 MHz
Number of receptors	8000 dual polarization dipoles
Number of tiles (4x4 dipoles)	500
Effective collecting area§	~8000 m^2
Field of view	15°-50°
Configuration	Centrally-condensed pseudo-random array ~1.5 km diameter
Angular resolution§	3.4 arcmin
Instantaneous bandwidth	220 MHz (sampled); 32 MHz (processed)
Point source sensitivity¶	20 mJy in 1sec; 0.33 mJy in 1 hr
Number of baselines	124,750
Multi-beam capability	Up to 16, per polarization
Width of spectral channel	8 kHz
Number of spectral channels	4000
Time resolution	0.5 sec (imaging), 125 μsec (beamformer)
Polarization	Full Stokes

§ At 200 MHz ¶ 32 MHz bandwidth at 200 MHz

The MWA will be an imaging interferometer array consisting of 500 antenna ‘tiles’, each a 4×4 array of crossed vertical bowtie dipoles, for a total of 8000 dipoles. The tiles will be installed in a region of ~1.5 km diameter, totaling ~8000 m^2 of collecting area at 150 MHz, and produce an electronically-steerable beam with a field-of-view ranging from 15° (at 300 MHz) to 50° (at 80 MHz). Figure 1 shows the planned layout. A notable feature of the array is extremely low sidelobe levels in the synthesized beam, which enables robust calibration and high precision imaging spectroscopy in support of the key science goals.

The entire 80-300 MHz RF from each tile is digitized at the corresponding node, decimated to a selected 32 MHz subset of the full range of the array, spectrally filtered to 4K channels of 8 kHz resolution, and transported to a central processing facility. There, 125,000 baselines are correlated, producing ~4 billion visibilities every half second. The input to the correlator is also shared with a digital beamformer for tracking of a limited number of sources with high temporal resolution.

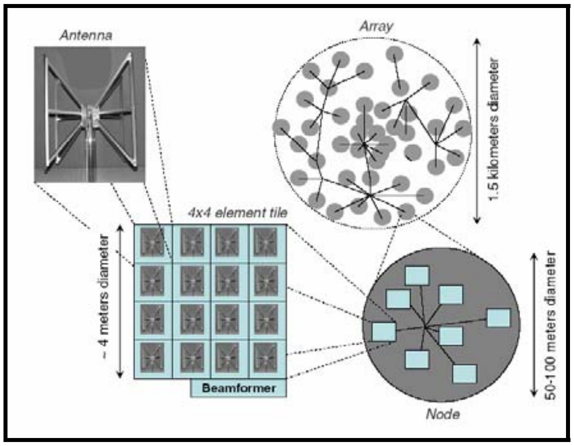

Figure 1. Schematic of the physical layout of the array.

Each of the main components of the LFD is described briefly below.

Antenna Tiles: The prototype LFD element is a pair of crossed, active bowtie antennas of open-frame construction that will be installed over a ground screen. Figure 2 below shows a prototype antenna installed at Mileura Station. The production model will feature a wire mesh screen laid directly on a flattened piece of ground, with a modified antenna support structure. The analog beamformer (grey box) contains a control board, switchable delay lines implemented as coplanar waveguides on PC boards, and power combiners. It outputs two RF signals on coaxial cables, one for each polarization.

Figure 2. Prototype LFD antenna tile at Mileura

Digital Receivers: The weak RFI environment at the Mileura site in Western Australia allows the use of an 8-bit direct sampling receiver. Key elements of the receiver system are a fast, 8-bit A/D sampling the entire RF band, and a two-stage FPGA-based polyphase filterbank delivering 4000 spectral channels each 8 kHz wide, for a total instantaneous bandwidth of 32 MHz. This spectral channelization constitutes the “F” part of the “FX” correlation architecture, and is performed in the field, at the location of each node (see figure 1 above). Signals are then aggregated for transport via fiber to the central processor.

Central Processing: The central processor system can be divided into three distinct operations: routing and reordering, cross-correlation, and signal combination. These three functions are to be implemented on two distinct board designs, with specific functionality depending on the programming of Xilinx FPGAs. The top level architecture of the signal processor is illustrated in figure 3.

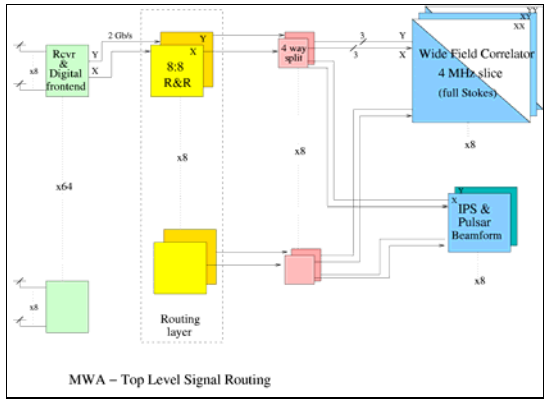

Figure 3. Top-level view of correlation and beamforming systems.

The data coming from the digital receivers will be aggregated into 2 Gb/s serial data streams. Each stream will consist of single-polarization data from 8 antenna tiles, organized as 4K point spectra, and concatenated for each of 8 antennas, repeated at 125 μsec intervals. In order to make efficient use of correlator resources, data streams need to be formed containing more antennas over a smaller band of frequencies. This operation is accomplished within a routing network, the primary component of which is the Routing & Reordering module which is FPGA-based. The routing layer aggregates the data into streams of 64 antennas, and reorders the data (corner turner) to provide suitable input signals for the Wide Field Correlator.

The correlation module will carry out the cross-multiplication and integration of up to 125,000 antenna pairs for each of 4 polarization products. The cross-correlations are formatted and dumped at 0.5 second intervals to maintain a full field-of-view. The array digital beam-former combines signals from all 500 antennas, and provides high time resolution data in a for a single sky location. Sufficient resources exist to implement 16 simultaneous beams.

Calibration System: The calibration system of the LFD is responsible for calibrating both the instrument and the ionosphere in near real time, producing calibrated snapshot images of the full 15-50 degree field-of-view and generating calibration data suitable for use in the analysis of the scientific data. The ionospheric irregularity length scale is typically much larger than the size of the array, but smaller than the antenna field of view at ionospheric heights. Thus, in any given direction, all baselines encounter the same ionospheric phase gradient, and the apparent sky formed by simple inversion of visibilities will be coherent with source positions distorted in rubber-sheet fashion. Comparison of apparent and actual source positions then yields full ionospheric calibration information. The calibration data will be used to remove the visibility contributions of bright point sources, and contaminating sources from outside the primary field-of-view, in order to eliminate sidelobe confusion capable of interfering with scientific uses of the data. The ionospheric, power pattern, and polarization calibrations are then used to create calibrated images as a function of frequency and polarization.

CURRENT STATUS

At the time of writing, the LFD has undergone extensive prototyping with antennas installed at Mileura, and characterization of both equipment performance and site characteristics has been carried out. The results are very encouraging, and summaries can be found at http://web.haystack.mit.edu/arrays/MWA/ under news items. Contingent upon funding, finalization of the design will occur in the spring of 2006, and the first scientific observations will occur toward the end of 2007.

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