Technologies for Low Frequency Radio Observations of the Cosmic Dawn

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Abstract—**The Jet Propulsion Laboratory (JPL) is developing concepts and technologies for low frequency radio astronomy space missions aimed at observing highly redshifted neutral Hydrogen from the Dark Ages. This is the period of cosmic history between the recombination epoch when the microwave background radiation was produced and the re-ionization of the intergalactic medium by the first generation of stars (Cosmic Dawn). This period, at redshifts greater than about 20, is a critical epoch for the formation and evolution of large-scale structure in the universe. The 21-cm spectral line of Hydrogen provides the most promising method for directly studying the Dark Ages, but the corresponding frequencies at such large redshifts are only tens of MHz and thus require space-based observations to avoid terrestrial RFI and ionospheric absorption and refraction. This paper reports on the status of several low frequency technology development activities at JPL, including deployable bi-conical dipoles for a planned lunar-orbiting mission, and both rover-deployed and inflation-deployed long dipole antennas for use on the lunar surface. In addition, recent results from laboratory testing of low frequency receiver designs are presented. Finally, several concepts for space-based imaging interferometers utilizing deployable low frequency antennas are described. Some of these concepts involve large numbers of antennas and consequently a large digital cross-correlator will be needed. JPL has studied correlator architectures that greatly reduce the DC power required for this step, which can dominate the power consumption of real-time signal processing. Strengths and weaknesses of each mission concept are discussed in the context of the additional technology development required.**

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1. INTRODUCTION

Hydrogen, by far the most abundant element in the Universe, has a spectral line at 21-cm wavelength (1.4 GHz) created by the hyperfine transition of the ground state in which the proton and electron spins are aligned parallel or anti-parallel. This transition has been used for decades by radio astronomers to map the distribution and dynamics of neutral Hydrogen in our galaxy and the nearby universe. During the past decade there has been much excitement about the possibility of detected the highly redshifted 21-cm signal from the Epoch of Reionization (EoR), the period during which radiation from the first generation of stars and galaxies re-ionized nearly all of the intergalactic medium from the neutral state it had cooled to as a result of comic expansion [1, 2]. The IGM remains almost totally ionized today, and consequently is transparent to 21-cm radiation.

Multiple ground-based experiments are underway or planned to detect neutral Hydrogen absorption or emission during the EoR. These include the Low Frequency Array (LOFAR) in Europe [3], the Murchison Widefield Array in Australia [4], the Precision Array for Probing the Epoch of Reionization (PAPER) in South Africa [5], and the Long Wavelength Array (LWA) in New Mexico [6]. In addition, observation of the EoR is a primary science goal of the planned Square Kilometre Array (SKA) [7], whose low frequency component will be constructed in Australia. These experiments, while difficult, are likely to eventually succeed at observing frequencies above ~100 MHz (corresponding to redshifts less than about 13, or cosmic ages greater than about 0.3 billion years). However, at lower frequencies corresponding to higher redshifts the Earths' ionosphere and radio interference make observations from the ground increasingly impractical.

There are strong scientific motivations for detecting and eventually imaging the distribution of neutral Hydrogen at even earlier epochs. During the cosmic Dark Ages prior to the EoR the large-scale distribution of neutral Hydrogen traces the infall of baryonic matter into local dark matter density peaks, forming the huge filamentary cosmic web and the distribution of galaxies and clusters of galaxies that we see today. With sufficiently sensitive and accurate Hydrogen imaging at frequencies of tens of MHz we could produce movies of the evolution of this large-scale structure. Such data would be uniquely valuable for cosmological studies of the early universe. In addition, detailed changes in the Hydrogen signal with time can provide constraints on some exotic physics models such as decaying dark matter.

For the reasons mentioned earlier, these data can only be obtained from space. The long wavelengths involved make single radio telescopes unreasonably large (km-scale), so we have concentrated on arrays of small deployable dipoles.

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2. TECHNOLOGY DEVELOPMENT AREAS

JPL has been working on several specific technologies that are relevant for observations of the Dark Ages and Cosmic Dawn. These development areas are described below.

Deployable Dipole Antennas for Spacecraft

The Dark Ages Radio Explorer is one example of a possible first-generation space mission to detect the sky-integrated neutral Hydrogen signal from redshifts greater then 10-15 [8]. Such missions require antennas that are usable over a wide fractional frequency range and capable of being fit into small launch volumes and deployed reliably once in space. A deployable bi-conical dipole antenna that is able to meet these requirements (Figure 1) has been prototyped and RF tested at JPL, with encouraging results (presented in §3).

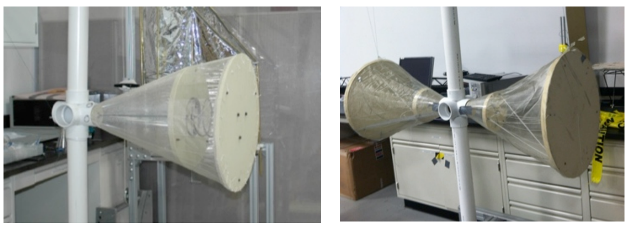

Figure 1. (Left) One half of a deployable conical dipole antenna. (Right) An alternative design for a deployable conical dipole antenna. Antenna is 1.5 m end to end.

Rover-Deployable Antennas for the Lunar Surface

Long dipole antennas based on conductor-coated polyimide film that could be unrolled on the lunar surface have been considered for many years [9, 10]. These could extend for tens of meters to allow reception of frequencies even lower than needed for Dark Ages observations. Frequencies below tens of MHz are relevant for solar radio bursts, lunar ionosphere studies, and searches for magnetospheric radio emission from exoplanets. Because of the mechanical simplicity and very low mass of polyimide antennas, small rovers like the Axel (Figure 2) are adequate for deployment even over rugged terrain. Field tests of a motorized antenna deployment attached to an Axel rover are currently underway in the JPL Mars Yard.

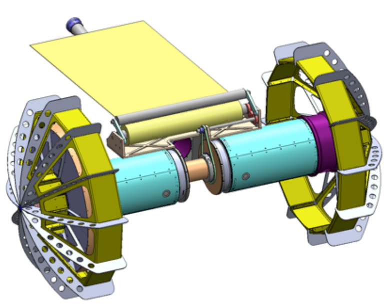

Figure 2. Diagram of polyimide file (yellow) being deployed from a two-wheeled Axel rover [11].

Inflatable Antennas for the Lunar Surface

An alternative technique for deploying polyimide antennas is inflation of a rolled tube (Figure 3). This avoids any need for a rover, and thus is particularly suitable for use with a secondary payload experiment on a lunar lander (Figure 4).

Figure 3. Lab deployment test of an inflatable dipole antenna. The copper foil visible inside the transparent plastic tube is the antenna element. The antenna is symmetric, but only one side is shown in this figure.

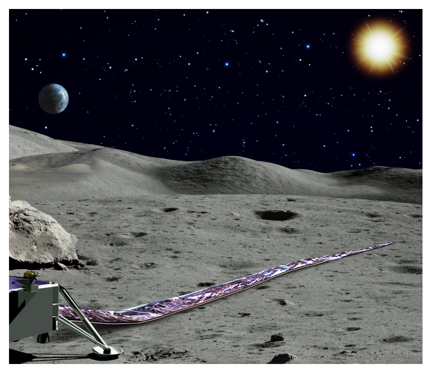

Figure 4. Artist concept of a polyimide film antenna deployed from a lunar lander.

Low Frequency Active Baluns and RF Amplifiers

Bandpass stability and calibration are key requirements for the detection of faint neutral Hydrogen spectral signatures in the presence of much stronger foreground signals (primarily from synchrotron radiation of cosmic rays in our galaxy). To address one aspect of this issue, we measured the gain vs frequency of a prototype low frequency front end (active balun and receiver) over a wide range of temperatures to determine the sensitivity of the bandpass shape on physical temperature. Based on these measurements we can set a limit on the required instrument temperature control.

Low Power Digital Signal Processing

Following detection of neutral Hydrogen signals from the Dark Ages and Cosmic Dawn, the next challenge will be to image the angular distribution of the signal over the sky as a function of frequency. This will require interferometers with baselines up to tens of km and a large number of antennas. The cross-correlation of data from a radio array containing N antennas scales as N^2, so it is clear that for large N the scale of digital processing can become very large. More specifically, the electric power consumption of a large-N cross correlator can become unaffordable. Studies of multiple correlator architectures to minimize power have been carried out, resulting in concepts for ASICs capable of reducing power consumption by more than an order of magnitude compared to prior correlator implementations. This opens the possibility of large-scale real time data correlation in space, leading to a vast reduction in required downlink data rates to Earth.

3. RECENT RESULTS

Deployable Dipole Antennas for Spacecraft

Because of the need for high precision calibration of the instrumental bandpass response, there is concern that the use of a deployable antenna might introduce variations in RF performance with frequency that would be difficult to model accurately. To address this concern, we have constructed prototype deployable and fixed broad-band conical dipole antennas with identical dimensions (Figure 5) and measured their feed point impedance over the full frequency range of interest in an EMC chamber (Figure 6).

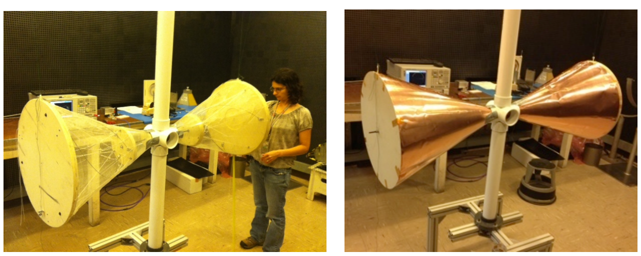

Figure 5. Deployable (left) and fixed (right) bi-conical dipole antennas in an EMC test chamber at JPL.

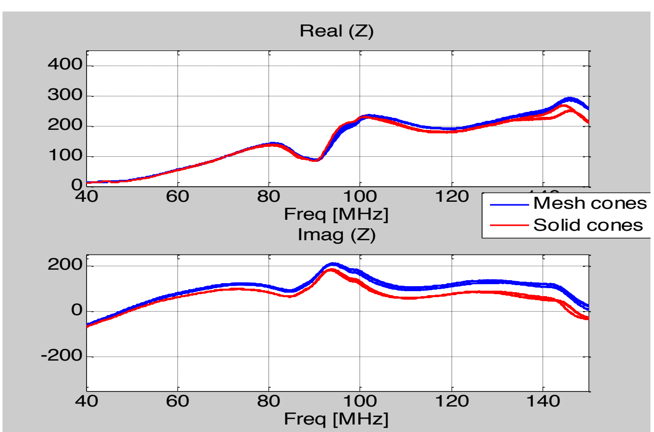

Figure 6. Comparison of feed point impedance between deployable and rigid antennas, measured in an EMC shielded chamber. The excellent agreement between the two antennas indicates that the deployable version does not introduce any unexpected RF performance issues.

Rover-Deployable Antennas for the Lunar Surface

A polyimide file deployment mechanism has been designed and built at JPL. The design compensates for the forward motion of the rover, and thus prevents any motion of the deployed polyimide film across the surface. This design has been successfully tested (Figure 7).

Figure 7. Demonstration of polyimide antenna deployment from an Axel rover.

The rover shown in Figure 7 is intended to operate in rugged terrain, and can carry instruments and sampling tools within the axel and wheels. For smooth terrain a variety of other small rover design are available, including one developed at the Ames Research Center that has been used to deploy polyimide film under telerobotic control by astronauts on the International Space Station (Figure 8). Teleoperation by astronauts at the Earth-Moon L2 point is one possible option for deploying instruments on the lunar far side [12].

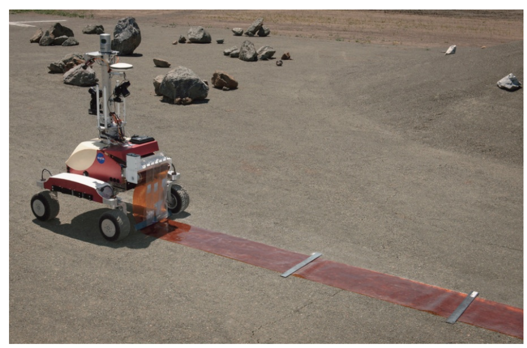

Figure 8. Ames rover deploying a long polyimide antenna during a test of telerobotic operations (figure from the NASA Lunar Science Institute's LUNAR Consortium).

Inflatable Antennas for the Lunar Surface

Multiple deployment tests over areas containing a high density of rocks have demonstrated that inflating tubes can climb over large obstacles and continue to extend along a linear path. This mechanically simple approach is less flexible than rover deployment, but because it does not require a rover it greatly simplifies instrument integration with a lunar lander and deployment operations. Deployment of long symmetric dipoles from ground-level packages and from a platform on a mockup lunar lander have been successfully carried out at JPL (Figures 9-12).

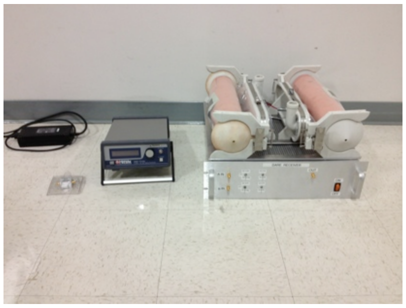

Figure 9. Concept testing mechanism holding two rolls of thin plastic tubing containing conductive strips. A package similar to this could be mounted on a lander and deploy a dipole antenna tens of meters in length. The associated low frequency receiver and spectrometer is contained in the box under the two antenna rolls.

Figure 10. One arm of a dipole antenna after a successful inflation-driven deployment test off of a lunar lander mockup in the JPL Mars Yard.

Figure 11. Both arms of a long dipole antenna after inflating and unrolling from the top of a mockup lander.

Figure 12. Deployment test over large rock field.

Low Frequency Active Baluns and RF Amplifiers

To better understand the temperature control requirements on the RF systems needed for Cosmic Dawn observations, we measured the variations in gain and bandpass shape of a prototype low frequency receiver over a 70 C range of physical temperature.

Figure 13 shows the prototype RF components mounted in a temperature controlled chamber, and Figure 14 shows the resulting bandpass curves.

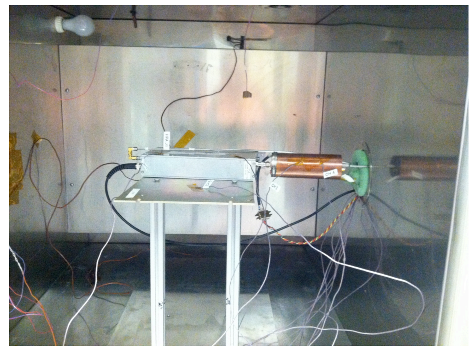

Figure 13. Active balun and low frequency receiver in thermally controlled test chamber.

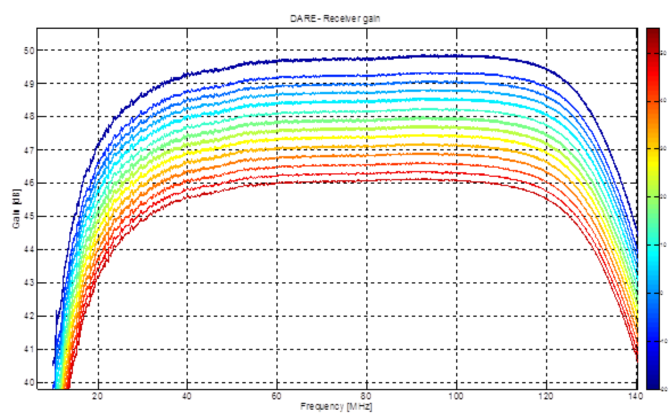

Figure 14. Prototype receiver bandpass (gain vs frequency) from 10 to 140 MHz. The vertical axis is gain from 40 to 50 dB, and the colors represent different physical temperatures from -17 to +52 C.

Based on these curves, we calculate that variations in the bandpass response can be calibrated to a level of 10^{-6} if the temperature is controlled to ±0.5 C. This is not a difficult requirement to meet.

Low Power Digital Signal Processing

Most digital signal processing in radio interferometry is not mathematically complex, but can be challenging because of the tremendous data rates involved. Even simple operations such as cross-correlation of digitized signals from antennas can become unaffordable due to power consumption when scaled up to radio arrays with very wide bandwidths, a large number of antennas, or both.

In the case of future space-based radio arrays to image the distribution of neutral Hydrogen at high redshifts, the low observing frequencies preclude wide observing bandwidths. However, the need for sensitivity and excellent imaging quality will require a very large number of low frequency antennas. And, of course, electric power is a much more valuable resource in space than on the ground.

Consequently it will be essential to minimize the power consumption for this type of instrument. A detailed study of the effect that cross-correlator architectures have on power consumption led to a new approach that minimizes data movement between chips (Figure 15) [13]. Data movement accounts for the majority of total power consumption in most correlator designs.

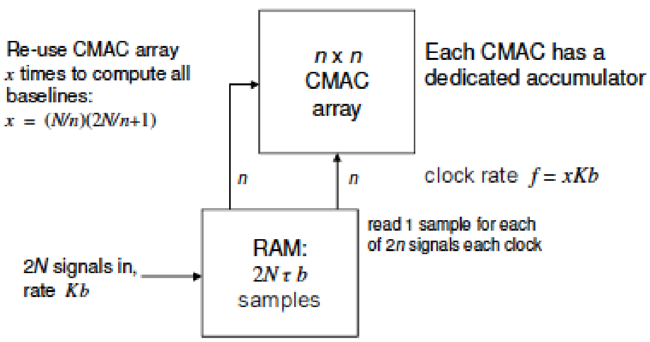

Figure 15. Simplified diagram of a correlator ASIC designed to minimize power consumption [13].

The low power ASIC design reduces data transfers by loading a fixed time interval of data from all antennas into a large on-chip memory and re-using the computational cells multiple times until the correlation products for all baselines have been calculated [13]. There is a tradeoff between the number of antennas and the observing bandwidth that a single ASIC can accommodate. The correlation process is independent from one frequency channel to another, so the total required bandwidth is obtained simply by using an appropriate number of correlator chips in parallel. This approach is far more power efficient than CPU, GPU, or FPGA based correlator concepts. The current JPL ASIC design is highly flexible and can be used for arrays having between 64 and 2048 antennas.

For even larger arrays, multi-chip architectures utilizing separate memory and CMAC ASICs are needed, but even then a practical limit on the number of antennas exists. This is approximately 10^4 with current IC technology. Ways to more effectively correlate data from substantially larger arrays are currently being examined.

One way to accommodate more antennas is to group them into beamformed clusters, and only cross-correlate the beamformed outputs from the clusters instead of data from every individual antenna element. This reduces the size of the correlator at the expense of instantaneous field of view (and perhaps additional calibration issues). A study of power efficient ASIC architectures for array beamforming has also been carried out recently [14]. These studies were originally motivated by concerns about power consumption of digital signal processing for the Square Kilometre Array, but the results are also relevant for the low frequency space-based arrays considered here.

4. Discussion

The current generation of ground-based low frequency radio arrays are expected to detect the neutral Hydrogen signature from the EoR. Future observations of higher redshift neutral Hydrogen from the earlier Dark Ages and Cosmic Dawn epochs will need to be done from space because of the combined constraints of the ionosphere and terrestrial interference. The primary motivation for the technology development described here is to reduce risk for any of several possible future space mission proposals.

There are four main instrumentation issues that will be relevant for any future space-based radio observations at frequencies well below 100 MHz. These issues are:

1. The long wavelengths involved make the physical size of any antenna with significant gain unwieldy for use in space. Thus, interferometer arrays using dipoles or other low-gain antennas are the most likely way to obtain high angular resolution, with the associated need for significant signal transport and real-time digital signal processing.
2. Antennas with very large fractional bandwidths are needed, and are difficult to design especially if the antenna is necessarily electrically short.
3. Although the basic design of low frequency radio receivers is well understood, the extreme dynamic range of the input signal and noise levels call for unusually high receiver response stability and calibration.
4. Digital data processing for large radio arrays can require a massive amount of electric power. This is always a concern because of the impact on the cost of operations, but it is particularly worrisome for an array in space where the availability of power is often extremely limited.

We have made progress in each of these areas during the past couple of years. As a result, we have a better idea of the appropriate conceptual designs for both single antenna and large array instruments.

5. Conclusions

The scientific potential of observing the evolution of neutral Hydrogen during the Dark Ages and Cosmic Dawn is now widely recognized, and has been endorsed by the most recent Decadal survey of astronomy and astrophysics. The required observations will need to be done with space-based instruments. The technology development work reported in this paper is intended to provide risk reduction for future mission proposals in this area.

6. ACKNOWLEDGEMENTS

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BIOGRAPHY

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