

MEASURING THE METRE-WAVE SKY SPECTRUM WITH MILLI-KELVIN ACCURACY: ENGINEERING CHALLENGES AND AUSTRALIAN OPPORTUNITIES

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ABSTRACT

We describe a radio experiment that will test theories of structure formation in the early universe. The 1.42 GHz spectral line of neutral hydrogen, redshifted down to the 45-200 MHz band, traces the ionisation state of the intergalactic medium through the first billion years of the now 14 billion year old universe. Measuring the metre-wave sky spectrum with milli-Kelvin accuracy may thus detect the epoch when the first sources of ionising radiation formed, termed “the epoch of reionisation”. We discuss the engineering challenges presented by this experiment and the opportunities provided by radio-quiet sites in Australia.

INTRODUCTION

Detecting the epoch of reionisation poses several engineering challenges. We describe a pathfinder experiment over 100-200 MHz which requires a receiving system with an 80 dB dynamic range, 8,192 spectral channels, and a 0.1 dB noise figure. The antenna attached to this receiver must have a pattern which is invariant over the 100-200 MHz band and a very good VSWR. Greater than the challenge of assembling this equipment is the challenge of calibrating it. The bandpass, or relative channel to channel gain, must be calibrated to within 0.00003 dB (1 part in 150,000). These challenges may seem formidable, but they are not as formidable as the contribution to science made by a successful detection.

SCIENCE BACKGROUND

The best model for structure formation in the universe is the gravitational growth of density perturbations within a hot big bang cosmology. Several independent observations validate this theory, particularly observations of anisotropies in the cosmic microwave background (CMB) and the power spectrum of the spatial distribution of galaxies. We wish to shed further observational light on the dark path leading from the tiny density fluctuations observed in the primordial universe to the large galaxies and galaxy clusters observed in the today’s universe.

A challenge for the current structure formation model is to explain the thermal evolution of the underlying intergalactic gas, the intergalactic medium (IGM), as it is bombarded by ionising radiation from the first stars and galaxies. It is difficult to understand the feedback mechanisms that govern the thermal evolution of the IGM because current observations do not provide adequate constraints on the variety of models proposed. Observations of the recent temperature of the IGM, together with measurements of the CMB and the absorption spectra of Quasars, suggest that reionisation must have been a complex, multi-step process [1] [2]. Conversely, simulations based on the current model of early structure formation suggest a simple, single-step process [3]. We aim to constrain structure formation models by providing a measurement of the evolution of the IGM over the first billion years of structure formation.

The IGM consists mostly of hydrogen and helium, but we focus specifically on hydrogen due to the prominence of its 1.42 GHz spectral line. We wish to measure this spectral line, averaged over the sky, as it varies with look-back time (redshift) and hence frequency. From this average spectrum we may deduce the ionisation history of the hydrogen in the IGM.

IONISATION HISTORY OF HYDROGEN IN THE EARLY UNIVERSE – WHAT WE KNOW

Fourteen billion¹ years ago, near the very beginning, all matter in the universe was ionised due to the extremely high temperatures associated with the big bang. About 500,000 years later ($z \sim 1088$), this plasma cooled sufficiently to recombine and to form neutral hydrogen and helium. This neutral state persisted for at least a hundred million years (to $z \sim 30$) as implied by WMAP's measurement of the post-reionisation optical depth to electron scattering [2].

Thirteen billion years ago ($z \sim 6$), ionising (Lyman continuum) photons began travelling toward Earth's telescopes from the most distant quasars observed. The spectra of these quasars indicate that the hydrogen in the IGM was predominantly ionised by that time and has remained so until now [4] [6].

The intervening billion years ($30 < z < 6$), between these two observational points, interests us most. During this period there must be at least one change, of order unity, in the ionised fraction of hydrogen. This implies that there should be a step, of order 10 mK, in the integrated, all-sky spectrum of neutral hydrogen [5] in the range 45 – 200 MHz. A detection of one or more such steps will indicate more precisely when in the first billion years of the universe's existence the first sources of ionising radiation formed and what they may have been.

ENGINEERING REQUIREMENTS

Sensitivity

Sharp changes in the ionisation state of the hydrogen gas imply sharp features in the background spectrum at the level of a few mK. The level of this signal alone does not challenge us. We assume that the Galactic synchrotron emission dominates the system temperature and follows a simple model of 150 K at 150 MHz with a spectral index of -2.6 . This is consistent with cooler parts of the sky at higher Galactic latitudes. Fig. 1 shows that the required 1 mK sensitivity is reached in just 1.4 hrs at the upper end of the band of interest with a 1 MHz channel.

If the Galaxy dominates the system temperature, we need not over-optimize the noise figure of the system. We can allow a receiver with an equivalent noise temperature anywhere up to 10% of the Galactic brightness temperature. Fig. 2 plots the resulting noise figure requirement. A receiver with a noise figure of 0.1 dB will be suitable.

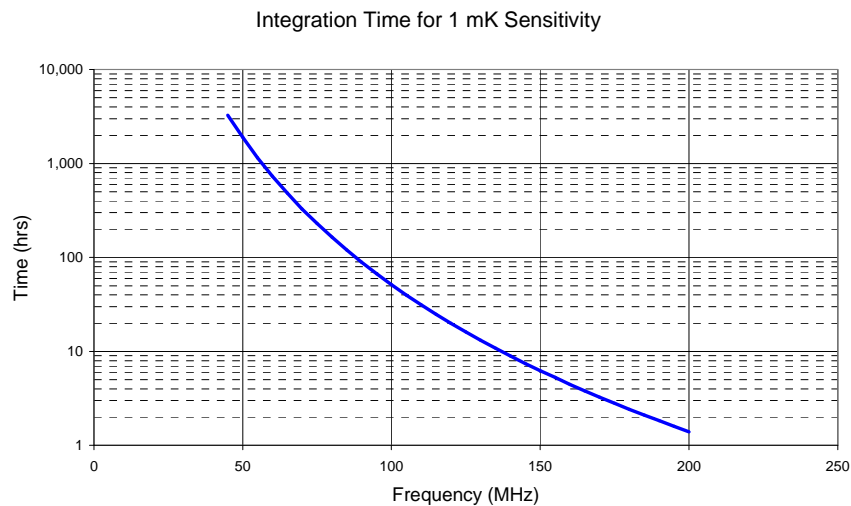


Fig. 1. Integration time to reach 1 mK r.m.s. sensitivity in a 1 MHz channel.

¹ 1 billion = 10^9

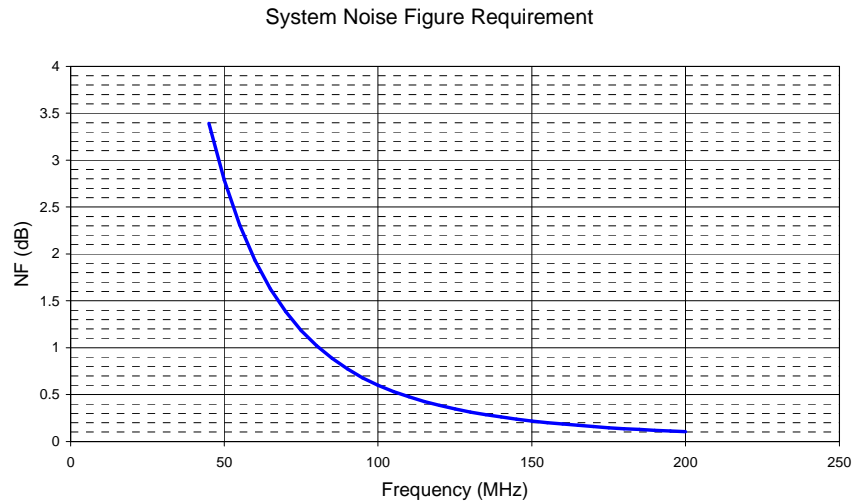


Fig. 2. Receiver system noise figure requirement for the equivalent system noise temperature not to exceed 10% of the sky temperature.

Antenna

The signal that interests us is constant over the whole sky so we may choose an antenna of arbitrary aperture. We are considering low gain antennas with sizes comparable to a wavelength (1-7 m in the band of interest) and smooth, frequency independent radiation patterns. If the antenna pattern varied with frequency it would add unwanted spectral structure to the measured sky spectrum. Fig. 3 depicts one type of antenna, the flat spiral, which may satisfy our requirements.

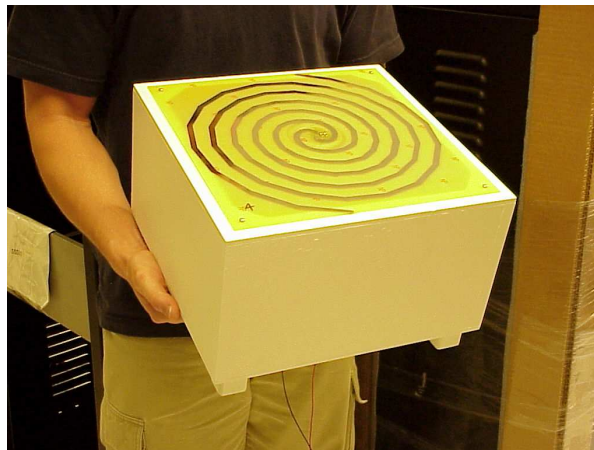


Fig. 3. Example of a cavity backed, planar, RHCP spiral antenna with a frequency independent beam. This particular antenna was designed for the ARGUS antenna array and covers 900-1700 MHz with a VSWR better than 2.5:1 [7].
Image courtesy of Steve Ellingson, Ohio State University.

Spectral Dynamic Range

The Galactic synchrotron emission will dominate the operating levels of the receivers, and hence set a lower limit for their required dynamic range. Using the same model for Galactic brightness temperature as earlier, we calculate the intrinsic dynamic range required of the receiving system as the ratio between the Galactic emission and the desired 1 mK sensitivity. A dynamic range of 56 dB is required to cover the whole band. In practice, a further allowance of 25-70 dB may be necessary to accommodate linear operation in the presence of radio frequency interference (RFI) as shown in Fig. 4.

By dynamic range, we specifically mean spectral dynamic range. That is the range between the true signal power in each channel and the erroneous signal power in each channel due to harmonics and intermodulation products. We limit harmonics and even order intermodulation products by selecting an observing band equal to or less than an octave. Initial modelling of odd order harmonics for a commercial, bipolar LNA suggests that it will be suitable for RFI levels representative of Mileura in Australia [8].

Spectral Resolution

We require a fractional redshift resolution $\Delta z/z$ of 1% to achieve the science goals of the experiment. A 1 MHz channel bandwidth corresponds to $\Delta z/z \sim 0.5-2\%$ depending on the redshift. Finer spectral resolution is necessary to recognize, if not mitigate, interference. A simple investigation of the data collected at Mileura showed that RFI is most efficiently excised with resolutions equal to or better than 12 kHz.

Quantisation Levels

The spectral analysis may be performed by a correlation spectrometer, a polyphase filterbank, or an FFT. All of these may be implemented in hardware or software and most likely all could be engineered to meet the spectral resolution and dynamic range requirements. A remaining question is: how many quantisation levels are required, prior to the spectral analysis, in order to achieve the overall desired spectral dynamic range? We may select from the simple, 1-3 bit systems employed by traditional radioastronomy systems or the more complex, 8+ bit systems being designed for SKA [10] and LOFAR [11].

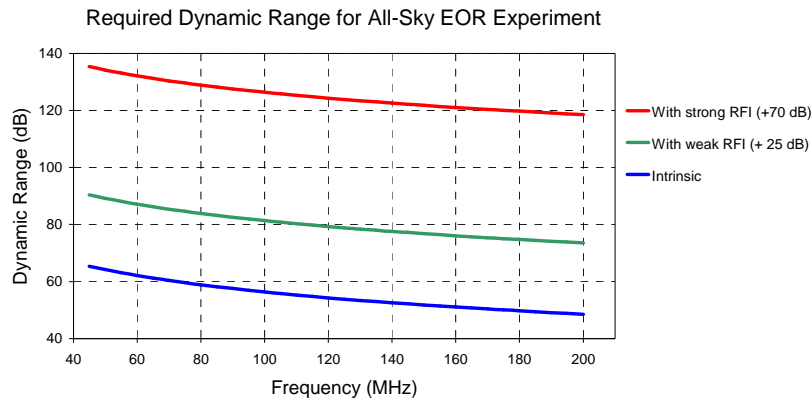


Fig. 4. Required dynamic range (DNR) for all-sky detection of the epoch of reionisation. The *blue* line shows the DNR required when the Galaxy dominates system temperature. The *green* line shows the DNR required to cope with peak interferers 25 dB above the level of the Galactic emission as experienced at a radio-quiet Australian site [8]). The *red* line shows the DNR required to cope with peak interferers 70 dB above the level of Galactic emission as experienced at a European site [9].

OBSERVATION & CALIBRATION

The observed spectrum from any system configuration will display:

1. an additive contribution (receiver noise, ohmic emission from the antenna elements, ground emission, and atmospheric emission);
2. a multiplicative contribution (the band-pass function of the receiving system); and
3. erroneous spectral features due to sky emission from directions off the bore-sight.

We must minimise all of these features, and then model and remove their remaining contributions with 1 mK accuracy.

Minimising and Calibrating the Additive Contribution

Configuring the system as a correlation receiver will minimise the additive contribution. The signal should be split as early as possible in the RF chain. One could even split the signal before the antenna, in free-space, by using a partially reflecting screen. This option requires duplication of the entire RF chain including the antenna.

If there are only passive elements prior to the signal split, we may calibrate the remaining additive contribution by varying their temperature. Any ohmic emission should vary in direct proportion to physical temperature.

Minimising and Calibrating the Multiplicative Contribution

The regularity with which the multiplicative, or bandpass, calibration must be applied is minimised by maximising the gain stability of the receiving system. The bandpass calibration is ideally implemented by measuring the response of the system with and without the desired signal at the input. Normally this would be effected by pointing the telescope toward and away from the source of interest. However, we seek a global signature which is all over the sky and thus there is no “off-source” position for this type of calibration. Possible alternative methods include:

1. frequency switching;
2. differential measurements between the galactic plane and high galactic latitudes;
3. operating the system as an interferometer to remove the global signal by means of a high-pass, spatial filter;
4. blocking the global signal with an opaque foreground source such as the Moon or Cas-A; and
5. blocking the antenna with RF absorber.

Minimising and Cancelling Off-Axis Responses

Off-axis responses are minimised by choosing a simple, low gain antenna with a frequency independent beam pattern as discussed earlier. Any residual off-axis response must be modelled and used in conjunction with a sky model to predict and hence subtract its contribution from the measured spectrum. This may require observations of sources in the target field with other metre-wave radio telescopes.

FOREGROUND SOURCES

A perfectly calibrated sky spectrum, with all instrumental effects removed, will still be contaminated by a number of foreground sources. In the absence of RFI, the total average sky spectrum will include the constant CMB (~ 2%), the desired hydrogen emission/absorption spectrum against the CMB (~ 0.001%), and the following foreground sources [5]:

1. the integrated emission from extragalactic sources (~ 27%);
2. Galactic thermal (free-free) emission (~ 1%); and
3. Galactic synchrotron emission (~ 70% at 150 MHz).

These must all be accurately modelled and removed from the total average sky spectrum to leave the hydrogen emission/absorption spectrum with 1 mK accuracy. This is not a simple task, but will be aided by the fact that all the natural foreground sources have smooth radio spectra [5]. They may thus be removed by fitting a low order polynomial or by some form of trend analysis. More recent modelling of this foreground confusion hints that it may be more difficult and require advanced statistical methods [3].

RADIO FREQUENCY INTERFERENCE – AN AUSTRALIAN ADVANTAGE

Our primary strategy for avoiding interference is to go where it is not. An Australian advantage is the availability of radio-quiet sites such as those proposed for LOFAR and the SKA.

RFI surveys of the prospective LOFAR sites covered the entire band of interest (45-200 MHz). The resulting reports from Australia [8], the USA [12], and the Netherlands [9] represent radio-quiet sites deemed suitable for the world's most sensitive metre-wave radiotelescope.

The three sets of data were taken with similar equipment so we may make a simple judgement of the strength of RFI by comparing the maximum deviations of the median signal from the median noise in the range 45-200 MHz. This yields a maximum excess median RFI power of 25 dB for Mileura in Australia, 40 dB for the South-West United States and 70 dB for Drenthe in the Netherlands. Attempting the experiment in Australia may thus relax the dynamic range requirement by 15-45 dB.

Third order intermodulation products are visible in the US FM band data showing that a low gain antenna and amplifier similar to that required for our experiment, may be pushed into non-linear modes by the stronger interferers. In the Netherlands data, the FM band is so crowded that FM channels cannot be distinguished from their third order intermodulation products. Australia is the best option for experiments over the entire band of interest. The South-West USA might be competitive at the upper frequencies, but is not so good through the FM band.

Major spectrum allocations in the band of interest include broadcast radio (FM); broadcast television; various satellite systems; aviation communication and navigation; and miscellaneous fixed and mobile services. Band usage at Mileura in Australia is reported in [13] together with the discovery of a 23 MHz band of pristine spectrum from 151 to 174 MHz at this site.

A PATHFINDER EXPERIMENT

We plan an initial experiment covering 100-200 MHz corresponding to searching for neutral hydrogen in the epoch of reionisation within the more recent redshift range of $6 < z < 13$. This increases the probability of success in our initial work in several ways.

1. The upper frequency band covers the lower redshifts where there is expected to be a reionisation signature regardless of whether or not reionisation first took place at higher redshifts [1].
2. The antenna size is halved for the upper frequency band, making antennas cheaper and more portable.
3. The observing time to reach the required sensitivity is minimised (Fig. 1).
4. The dynamic range requirement is much more relaxed in the higher frequency band (Fig. 4).
5. Communication requires smaller fractional bandwidths at higher frequencies and so communications channels (FM/TV) occupy smaller fractional bands at higher frequencies, possibly reducing the problem of radio interference.
6. Limiting our bandwidth to an octave greatly reduces the effect of even order nonlinearities in the receiver chain. We may ignore second order intermodulation products if there are no strong signals at the band edges and the skirts of the RF filter are sufficiently steep.

In one year, we hope to build the necessary equipment for making an observation of the all-sky neutral hydrogen signature of the epoch of reionisation, develop a suitable calibration technique, and make a first observation on a remote, radio-quiet Australian site. Thereon we may choose to redesign at the same frequency or to attempt a detection in the lower, 45-100 MHz band corresponding to a redshift range of $30 < z < 13$.

Table 1. Summary of specifications for a 100-200 MHz pathfinder experiment.

Parameter	Nominal Specification
Frequency Range	100-200 MHz
Antenna	low gain frequency independent beam
Integration Time	2 days (8 days for off-the-shelf LNA)
LNA Noise Figure	0.1 dB (1 dB if off-the-shelf)
Receiver Spectral Dynamic Range	≥ 80 dB
Spectral Resolution	≤ 12 kHz
Quantisation Levels	to be determined

LESSONS FOR SKA/LOFAR

This first data set will answer many questions about how best to calibrate the bandpass of not only our equipment, but LOFAR and the low frequency band of the SKA. We may learn important lessons for achieving the vast spectral dynamic range requirements of these hypersensitive instruments. In the long term, a successful detection would allow the optimisation of the SKA for imaging the expected spatial fluctuations in the reionisation signal. These spatial fluctuations are expected to contain an amount of information that is orders of magnitude larger than any other cosmological probe [14]. In the short term, we will learn just how good radio-quiet sites in Australia are by attempting a core piece of SKA science on one of them.

DISCUSSION & CONCLUSION

This is a high risk, high gain experiment that has the potential to test theories of structure formation in the early universe. We must minimise the scientific risk by maximising the technological lessons we learn along the way. It is our hope that the technical challenges presented by this experiment will engage the Australian engineering and radio science community. The broader the technical input, the greater the chance of success.

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