CONCLUSIONS AND OUTLOOK

The radio sky at low frequencies (\(\nu \lesssim 200\) MHz) contains the faint 21-cm signal of neutral hydrogen from the epochs of cosmic dawn and reionization. Studying these unexplored epochs via the redshifted 21-cm line is expected to revolutionise our understanding of structure formation in the first one billion years of the Universe, and shed light on the nature of the first stars, galaxies, and accreting black-holes, as well as the interstellar and intergalactic medium around these objects (Gnedin & Ostriker 1997; Madau et al. 1997; Furlanetto et al. 2006a; Pritchard & Loeb 2012). Opening this low frequency window to the high redshift Universe is a daunting task due to the faintness of the expected 21-cm signal as compared to astrophysical foreground emission, and challenges associated with calibrating the data against instrumental corruptions and ionospheric propagation effects.

In this thesis, I have studied a number of outstanding problems in high redshift 21-cm observations, while also developing novel observational techniques to circumvent some of the calibration challenges inherent to traditional observational techniques. In what follows, I summarise the main results from my thesis, with the text in italic font further abbreviating the results. Finally, I distil the important conclusions of the thesis, and provide an outlook for continued research.

7.1 Main results

The main results from my thesis may be drawn from two broad lines of investigation: (i) understanding plasma propagation effects (primarily ionospheric) at low radio frequencies, and their impact on high redshift 21-cm observations, and (ii) development of a novel observational technique that employs lunar occultations to interferometrically measure the spectrum of the diffuse (including the global component) radio sky.

7.1.1 Ionospheric effects on high redshift 21-cm observations

The ionosphere is a dispersive medium because its index of refraction is frequency dependent. The refractive index scales with frequency \(\nu\) approximately as \(\nu^{-2}\). Since
the redshifted 21-cm emission is separable from continuum foreground emission primarily in the spectral domain, chromatic (frequency dependent) effects such as ionospheric dispersion and absorption are important sources of signal contamination.

**A homogeneous ionosphere**

In this thesis, I have carried out the first study of the effects of ionospheric propagation (refraction and absorption) on global (or total power) 21-cm observations. Using a 2-layer model (D- and F-layer) that accounts for ionospheric absorption and refraction respectively, I have arrived at the following results (chapter 2).

1. Ionospheric dispersion in conjunction with the Earth’s curvature makes even a homogeneous ionosphere act as a chromatic (frequency dependent) lens that refractively bends electromagnetic rays towards zenith. The bending angle is frequency and zenith-angle dependent, but values for typical night-time ionospheric conditions \( (n_e = 5 \times 10^{11} \text{ m}^{-3}) \) at 45 MHz vary between about 0.4 arcmin to 50 arcmin for zenith angles of \( \theta = 20 \) and \( \theta = 90 \) deg respectively. This refractive lensing brings sky regions that are below the geometric horizon into view of a radio antenna. This leads to an additional antenna temperature that is about 20 K at 45 MHz and has a power law like variation with frequency with spectral index of \(-\alpha - 2\) where \(\alpha\) is the spectral index with which the radio sky temperature varies with frequency. The additional antenna temperature due to ionospheric refraction is about two orders of magnitude larger than the expected 21-cm global signal from the cosmic dawn, and is hence an important effect that foreground subtraction algorithms need to consider.

2. Rays incident on the ionospheric F-layer towards the horizon may undergo total internal reflection and not reach the telescope at all. This leads to a sharp drop in radio power measured at lower frequencies and manifests as a ‘knee’ in the measured brightness temperature versus frequency. The knee occurs at a frequency of about \( \nu \approx 4\nu_p \) where \(\nu_p\) is the F-layer plasma frequency. In periods of large F-layer electron densities in excess of \(2 \times 10^{12} \text{ m}^{-3}\), the knee may occur within the frequency range pertinent to cosmic dawn observations (\(\nu \gtrsim 50 \) MHz). Because astrophysical signal are essentially separated from the global 21-cm signal based on their spectral smoothness, total internal reflections events will lead to sharp modulations in the antenna temperature spectrum and make the foreground subtraction unfeasible. Data acquired under such circumstances must be rejected.

3. In addition to refraction, the ionosphere also causes wave propagation loss due to collisions between the electrons and air molecules. This absorption may be modelled as an additive component with a spectrum of the form \( \nu^\alpha/(\nu^2 + \nu_p^2) \). For typical D-layer night-time electron densities of \(n_e = 5 \times 10^8 \text{ m}^{-3}\) and collisional frequency of 10 MHz, the additive contribution to the measured sky temperature from absorption is about \(-130 \text{ K} \) at 40 MHz, which is also well above the expected global 21-cm signal.

4. For a realistic sky model and with the inclusion of ionospheric refraction and absorption effects, using the spectral smoothness of astrophysical foreground alone for foreground subtraction will lead to a loss of about 50 percent of the variance in the 21-cm signal signal. In chapter 2, I demonstrate a simple principle component
analysis based technique that exploits the spatial structure in foregrounds (as opposed to the featureless global 21-cm signal) in additional to spectral smoothness, and show that it outperforms parametric foreground fitting techniques (exploiting spectral-smoothness only) proposed before (Pritchard & Loeb 2010b).

The turbulent ionosphere

The above results were obtained for the case of homogeneous ionospheric layers. In addition, the ionosphere also has a turbulent component. Density, and hence refractive index turbulence in the ionosphere, spatially distorts the emergent electromagnetic wavefront. This manifests as amplitude and phase scintillation, called ‘visibility scintillation’, on the observer plane.

In this thesis, I have studied the effects of wave propagation through a turbulent plasma as a problem of Fresnel diffraction from a phase modulating screen. A single spatial wave-mode in plasma density perturbations scatters an incoming plane wave from a point source so as to create two coherent and symmetric copies, or ‘speckles’, of the source on the diffraction plane. The primary propagation effect from this wave mode may be understood as the interference on the observer’s plane of the source with its coherent speckles. I have developed an analytical framework to compute the aggregate effect of various plasma wave-modes on a distribution of sources in the sky. In doing so, I have for the first time, derived expressions for the visibility variance and the associated spatial temporal and spectral coherence of scintillation noise for an arbitrary sky-intensity distribution and an arbitrary power spectrum of ionospheric plasma density fluctuations. In developing this framework and its application to the case of 21-cm observations, I have arrived at the following results (chapters 3 & 4).

1. For baselines far exceeding the Fresnel length ($r_F \approx 300$ m at 150 MHz), visibility scintillation is largely explained by an antenna (and source direction) dependent ionospheric phase— the so called ‘pierce-point’ approximation. However, for baseline comparable to or shorter than the Fresnel scale $r_F$, refractive scintillation of the sky is the dominant effect and cannot be cast as an antenna dependent ionospheric phase: the widely used pierce point approximation breaks down.

2. Scintillation noise variance from an ensemble of point sources randomly distributed on the sky is the same as that from a single source with a flux-density given by the rms flux-density of the ensemble.

3. With the above result used in conjunction with realistic values for the ionospheric phase power spectrum, and statistics of radio source flux-density distribution, I have shown that for the range of baseline lengths and frequencies relevant for high redshift 21-cm observations, visibility scintillation noise, if left unmitigated, is comparable to the nominal values for thermal noise. Hence in certain regimes (described below) current and future high redshift 21-cm experiments must consider this additional scintillation noise in their uncertainty estimation.

4. The angular (between 2 sources), spatial (between redundant baselines) and temporal coherence function of scintillation noise can all be abstracted into a common covariance-function of the corresponding displacement on the phase screen $\Delta s$: 

...
• For coherence on an angular separation of $\Delta \ell$, the said displacement is given by $\Delta s = h\Delta \ell$ where $h$ is the distance to the phase screen.

• For temporal coherence on a timescale of $\Delta \tau$, resulting from a lateral motion of ‘frozen’ turbulence with velocity $v$, the displacement is given by $\Delta s = \Delta \tau v$.

• For spatial coherence between redundant baselines separated by a vector $\Delta b$, the displacement if $\Delta s = \Delta b$.

5. The angular, temporal, and spatial coherence function of scintillation for a displacement of $\Delta s$ has disparate behaviour in two limiting baseline-length regimes:

<table>
<thead>
<tr>
<th>Regime</th>
<th>Half-power width of scintillation coherence function</th>
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6. During gridding, visibilities are typically averaged into a given $uv$-cell over a temporal interval of $\Delta \tau_{cell} = d_{prim}v/(2b)$, where $d_{prim}$ is the primary aperture diameter. Choosing a self-calibration solution cadence of $t_{sol} = \Delta \tau_{cell}$ will mitigate about half of the scintillation noise variance. Reducing $t_{sol}$ further logarithmically improves the efficiency of self-calibration.

7. For baselines comparable to or shorter than the Fresnel length, the angular coherence scale for visibility scintillation is given by $2r_F/h$ where $h$ is the distance to the phase modulating screen (ionosphere). The typical fields of view of 21-cm experiments far exceed this value. Hence phase referencing with a single bright in-field source is impossible for ionospheric calibration of 21-cm observations.

8. In a compact array wholly within the Fresnel scale, baselines experience coherent visibility scintillation. However the number of incoherently scintillating ‘facets’ in the sky is larger than the number of available visibility constraints. A fully filled compact array provides sufficient constraints to solve-for about 50% of the scintillation noise variance. Evaluating the improvement in ‘calibratability’ from longer baselines needs more work.

9. Though weak scintillation is a broadband phenomena it is observed by sparse arrays such as LOFAR and MWA with a highly chromatic point spread function due to stretching of the baselines in the Fourier plane with frequency. Hence scintillation noise is largely confined to the well understood ‘wedge’ in the cylindrical power spectrum space. It is important to note that even though such arrays may achromatically sample the Fourier plane after Earth rotation synthesis, the relevant point spread function to consider for scintillation noise calculations is the snapshot point spread function within the coherence timescale for scintillation.

10. Though fully filled arrays such as HERA and SKA (core) are scintillation noise dominated at all baselines, they have a mostly achromatic sampling function in the Fourier plane even within a snapshot. This allows one to filter/remove scintillation noise along with smooth spectrum foregrounds.
7.1: Main results

7.1.2 Lunar occultation of the diffuse radio sky

An interferometer is a differencing instrument, and as such is insensitive to an all-sky (global or monopole component) signal. However, by observing the occultation of a global signal by the Moon, interferometers can measure the brightness contrast between the occulting object and a global background. Using LOFAR data between 35 MHz and 80 MHz, I have demonstrated this technique of interferometrically measuring a global signal for the first time. This has not only opened a novel observational route to measure the global 21-cm signal interferometrically, but also brought into focus unique lunar science that a new generation of low frequency radio telescopes such as LOFAR are capable of. Regarding lunar occultation observations, I have arrived at the following results (chapters 5 & 6).

1. The Moon reflects man-made radio frequency signals which may be called ‘Earthshine’. Since the lunar surface is smoothly undulating on the scale of a wavelength at LOFAR-LBA frequencies (35 MHz to 80 MHz), Earthshine manifests as a compact source at the centre of the lunar disc. Based on the known rms slopes on the lunar surface, Earthshine is expected to be ‘scatter-broadened’ to about 4 arcmin in angular extent. Since the lunar disc is much larger (about 30 arcmin), Earthshine can to first order, be independently modelled and isolated from the occultation response.

2. Initial determinations of the magnitude of Earthshine (35 MHz to 80 MHz) reflected from man-made space debris suggest that if the effective scattering cross section of debris exceed about 175 m$^2$ at an 800 km height, or just 15 m$^2$ at 400 km height, then Earth based global 21-cm experiments may be adversely affected.

3. Earthshine between 35 MHz and 80 MHz is at a level of a few Jy, is variable in frequency, and can reach values as high as 15 Jy in isolated frequency channels. Based on this measurement, Moon-based high redshift 21-cm experiments must conservatively design from an isolation (towards the Earth) of about 80 dB between 35 MHz and 80 MHz.

4. Since the Moon moves with respect to the ‘fixed’ stars by about 12 deg per day, differencing visibilities on two consecutive nights is an effective way to subtract confusion from unmodelled sources in the sky. Using such a differencing experiment, I have measured the Moon-background contrast to an accuracy of about 2% within a 1 MHz spectral baseline.

5. With the improved inter-night differencing data, we are currently limited by a non-zero covariance between the lunar flux and reflected Earthshine estimates. Inclusion of longer baselines (≲ 5 km projected) from LOFAR’s remote stations may be instrumental in overcoming this source of confusion in lunar flux measurements.

6. The Moon reflects the radio sky. Taking the reflected Galactic emission with a previously measured lunar albedo of about 8% yields an unrealistically high brightness temperature of the Moon of about 720 Kelvin between 35 MHZ and 75 MHz. However, the Moon is expected to have a sub-soil rock (or substrate) at a depth comparable to the wavelengths relevant for high redshift 21-cm experiments. Reflections from the two interfaces (vacuum-soil and soil-rock) are expected to interference in
an manner akin to thin-film interference seen in soap bubbles. Taking this effect into account increases the disc averaged albedo of the Moon to about 20% and yields a lunar brightness temperature of $420 \pm 100$ Kelvin.

7.2 Conclusions

In this section, I will draw general conclusions based on the main results of my thesis.

7.2.1 Ionospheric effects on the 21-cm global signal

The effects of ionospheric refraction and absorption are about 2 orders of magnitude larger than the expected 21-cm global signal from the cosmic dawn. For moderate ionospheric conditions ($n_e \lesssim 2 \times 10^{12}$ m$^{-3}$), they have a smooth spectral structure akin to the foreground emission, and as such are not a fundamental limitation to global 21-cm experiments. Due to the large dynamic range between foreground plus their ionospheric effects, and the expected cosmic dawn signal, foregrounds may not be fitted away to the desired level as generic parametric functions. A better way forward is to determine optimal basis functions that more accurately describe the spectrum of observed foregrounds (rather than pre-supposed parametric functions) by independent means. One such avenue is provided by the spatial structure of foregrounds—the frequency evolution of the spatially fluctuating foreground component provides effective basis functions that can be used to fit foregrounds in the sky averaged (global) spectrum. This in conjunction with calibration constraints obtained from embedding the dipole measuring the global signal into an interferometric array is a promising way forward for measuring the global 21-cm signal from the cosmic dawn (chapter 2).

7.2.2 Ionospheric effects on the 21-cm fluctuations

Ionospheric effects have been postulated to be a major challenge to current 21-cm power spectrum experiments such as LOFAR and MWA. In this thesis, I have developed the first rigorous treatment of the statistics of visibility scintillation for widefield arrays such as LOFAR and MWA. For reasonable ionospheric conditions (diffractive scale $\gtrsim 10$ km at 150 MHz) ionospheric uncertainties, though larger than thermal noise in certain regimes, are largely confined to the well understood ‘wedge’ in cylindrical power spectrum space, and as such do not pose a limitation to current 21-cm power spectrum experiments.

Since a significant fraction of the 21-cm signal lies within the ‘wedge’, I have also considered the prospects for mitigating ionospheric effects via self-calibration. Most of the sensitivity to the 21-cm signal comes from short baselines that are within the Fresnel scale ($r_F \approx 310$ metre at 150 MHz). Such baselines experience source dependent but baseline independent visibility scintillation. Hence calibration algorithms that solve for a source dependent but antenna independent gains may be more effective in mitigating scintillation noise that traditional antenna based solutions.

Scintillation on short baselines within the Fresnel scale have very small angular coherence and temporal coherence scales with makes mitigation via self-calibration difficult. Compact arrays will not possess sufficient number of constraints to mitigate more than
about half the variance from scintillation noise via self-calibration. More work is needed to assess the utility of using moderately long baselines \( (r_F \lesssim b \lesssim \text{few km}) \) to calibrate for scintillation noise on short baselines where bulk of the cosmic signal lies.

For baselines larger than the Fresnel scale, scintillation noise rapidly increases with baseline length. Yet, contrary to intuition, longer baselines are also more ‘calibratable’. This is because both the coherence area on the sky and the coherence timescale of scintillation increase with baseline length, allowing one to solve in less number of directions over longer solution intervals. Hence ionospheric effects may not pose a major hurdle to studies of isolated sources with very long baselines \( (b \gtrsim 10\text{ s of km}) \).

Future arrays such as HERA and SKA will have a fully filled snapshot \( uv \)-coverage. This will allow one to exploit the broad-band nature of visibility scintillation (weak-scattering regime) to filter out scintillation noise along with smooth spectrum foregrounds. As such, even though these arrays will be scintillation noise dominated on all baselines, ionospheric effects will not pose a limitation to 21-cm observations.

### 7.2.3 Lunar occultation of the diffuse sky

In this thesis I have presented the first low-frequency image of the Moon and demonstrated a novel technique of employing lunar occultations to measure a global signal interferometrically for the first time. This work has yielded an improved understanding of the (i) the merits and limitations of this technique, (ii) the RFI environment on the Moon, and (iii) prospects for unique lunar science with current low-frequency telescopes.

Differencing visibilities on two nights is an effective technique to mitigate sidelobe confusion in the lunar occultation experiment. With improvements in ionospheric calibration to correct for differential refractive shifts in source positions on the two night, and with the advent of arrays (such as the SKA) with filled \( uv \)-coverages, chromatic sidelobe confusion will perhaps not be a limitation to this experiment. Instead, the improved Moon-background contrast measurements (chapter 6) have brought the focus on the reflection properties of the lunar regolith, and their impact on the experiment. Inclusion of data from longer baselines along with improved theoretical modelling of the lunar albedo are required to probe the existence of a diffuse (non-specular) component of reflected Earthshine (due to Rayleigh scattering from boulders for instance) that may impose limitations on a 21-cm experiment with the occultation technique. Similarly, since the Moon has a layered structure (soil-bedrock etc.) interference of reflected emission from various layers may lead to unwanted spectral ‘ripples’ in the apparent lunar temperature. The finding of this thesis prompt a deeper investigation into the limitations of the above factors on the occultation experiment.

By observing man-made RFI reflected by the Moon, I have studied the RFI environment on the Moon— an important consideration for the design of recently proposed Moon based radio astronomy missions. I find that such experiments should conservatively design for about 80 dB of Earth isolation to detect the global 21-cm signal from the cosmic dawn. For Earth based observations of the said signal, I find that RFI reflected off man-made debris (in orbit around the Earth) may be an important source of
contaminant not considered before. Better modelling of the effective scattering cross-section of debris is required to reach hard conclusions on the limitations to global 21-cm experiments posed by such debris.

Detecting the global 21-cm signal via the occultation technique within reasonable integrations times ($\sim 1$ day) will have to await arrays such as SKA that have high filling factors (in their cores). However, the penetration depth (in the lunar regolith) for electromagnetic waves for frequencies relevant to cosmic dawn studies is tens of metres—depths at which little is known about the thermal state and composition of the regolith. Hence studying the reflected emission (Earthshine and Galactic), as well as thermal emission from the Moon at these frequencies can lead to unique lunar science in the near future.

7.3 Outlook and concluding remarks

Observing the highly redshifted 21-cm signal from the epoch of formation of the first luminous sources in the Universe is a very challenging task. The signal has eluded detection by a host of industrious astronomers for well over four decades. However, the last decade has witnessed a profound increase in understanding of the astrophysics of this epoch as well as better constraints on the redshift range that experiments need to target. This has lead to construction of the largest and most complex radio telescopes at low frequencies till date.

While a first detection of the 21-cm signal from these epochs may be forthcoming, the astronomical community is yet grappling with challenges inherent to high dynamic range observations at low radio frequencies. In this thesis, I have made the first concerted effort to study an important and thus far overlooked problem in low frequency observations, namely plasma propagation effects through the Earth’s ionosphere. I have developed a theoretical framework to compute the statistics of ionospheric effects in radio interferometric data. With this framework, we are now in a position to compute the ‘calibratability’ of any generic array. Such an effort will provide invaluable inputs to the design and trade-off studies currently being carried out for ambitious arrays such as the SKA, as well as HERA and future upgrades to existing arrays (LOFAR, MWA, GMRT, low-frequency VLA). It will also be an invaluable mathematical tool to clearly define observational (and calibration) limits set by the ionosphere for a given observational goal.

My work on the statistics of ionospheric effects has also shown that traditional antenna based gain solutions (from self-calibration) may not optimal in mitigating scintillation noise, particularly on short baselines where most of the sensitivity to the 21-cm signal lies. Developing novel calibration algorithms to mitigate ionospheric scintillation noise will form an important aspect of my future efforts.

My work on plasma-propagation effects has also opened interesting avenues for understanding the media themselves. The energy injection mechanism that drives ionospheric turbulence for instance is still unknown. The ionospheric calibration solutions obtained from current arrays may in the near future resolve this outstanding problem. In this thesis, I have studied the statistics of visibility scintillation for an arbitrary sky brightness
distribution—an important extension of previous studies. This formalism essentially frees us from studying (interplanetary and interstellar) plasma by observing the scintillation of isolated point-sources, and may lead to the measurements of turbulent properties on scales that are not accessible by traditional single source observations.

The lunar occultation experiment is an excellent example of one that has opened more questions and avenues for scientific investigation than has provided definitive answers for! While studying the various systematic effects in order to explain what the data show, the focus has shifted to studying the thermal and reflected Galactic emission from the Moon. Since lunar thermal emission at frequencies relevant for 21-cm observations comes predominantly from layers that are tens to hundreds of metres deep, such data provide an excellent opportunity to study the thermal and dielectric properties of the lunar regolith at thus far inaccessible depths. Since low frequencies are also sensitive to plasma propagation effects, data from current arrays such as LOFAR may also be instrumental in studying the circumlunar plasma whose density and even existence has been the matter of much dispute, but whose effects are important in understanding lunar interaction with the Earth’s magnetic field and the interplanetary medium. Understanding the plasma environment on the Moon will also benefit future lunar landing missions.

I sincerely hope that the combined efforts of the current generation of radio astronomers will soon lead to the first confirmed detection of the elusive 21-cm signal from high redshifts. As this thesis and the work of my colleagues has shown, the path towards this goal involves a deep understanding of astrophysical foregrounds, wave-propagation effects, and signal processing algorithms. Deep understanding nearly always leads to new discoveries, and the path towards high redshift science though arduous, is sure to be as scientifically rewarding as the destination itself. I thus foresee a future in which current instruments will lead to discoveries that they were not even designed for—discoveries of equal significance if not more!
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