3 MHz Space Observatory

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ABSTRACT

Little is known about the radio astronomical universe at frequencies below 10 MHz because such radiation does not penetrate the ionosphere. A Cubesat-based observatory for the 1–10 MHz band could be rapidly and economically deployed in low Earth orbit. When shielded by the Earth from Solar emission, it could observe weak extra-Solar System sources. We suggest possible transient and steady sources, and application to study of the ionosphere itself.

Key words: instrumentation: miscellaneous

1 INTRODUCTION

The low frequency (≲30 MHz) radio band has been comparatively little studied because it is difficult to observe from the ground. Science motivations for its study include very high redshift cosmology, low frequency sky surveys, solar/space weather, transient emissions from several classes of astronomical sources, including fast radio bursts (FRB), soft gamma repeaters (SGR), gamma-ray bursts (GRB) and pulsars (PSR), and perhaps serendipitous discoveries.

The ionosphere reflects radiation at frequencies below a varying cutoff of 3–10 MHz, and scintillation may be prohibitively strong even at somewhat higher frequencies. These values depend on the Solar cycle and activity, season and time of day, but impede ground-based astronomy below 10 MHz. The lowest frequency successful ground-based observations appear to have been those of Bridle & Purton (1968) at 10.03 MHz and of Cane (1979) at 5.2 MHz, although some results at lower frequencies have been reported (Reber & Ellis 1956; Ellis 1957, 1965; Getmantsev et al. 1969).

The ionosphere is not an obstacle to space-based observation. In fact, it facilitates observation because it shields space-based instruments from low frequency terrestrial electromagnetic interference, while reflecting the sky. Two low frequency astronomical satellite observatories have been flown, Radio Astronomy Explorer-1 (RAE-1) in a 5850 km orbit (Alexander et al. 1969; Weber, Alexander & Stone 1971) and Radio Astronomy Explorer-2 (RAE-2) in Lunar orbit (Alexander et al. 1975). The prospects of space based low frequency radio astronomy were reviewed in a conference (Kassim & Weiler 1990).

Several space instruments have observed Solar emissions at these low frequencies, including WAVES on the deep space Wind and STEREO spacecraft (Kaiser 2005; WAVES 2020; STEREO 2022). The Sun Radio Interferometer Space Experiment (SunRISE) (Kasper et al. 2019, 2022) is planned for geosynchronous orbit. Because of the high intensity of Solar emissions, observations of extra-Solar System sources are likely to be possible only when the observatory is shielded from the Sun by the Earth, which occurs for satellites in low Earth orbits (LEO) but never, or rarely, in deep space or geosynchronous orbits (GEO).

After a long period of somnolence, technical and scientific progress argue for reviving space-based low frequency radio astronomy. The technical progress consists of the development of “Cubesats”, satellites consisting of one or more 10 cm cubes. These are simple enough that they may be built as student projects. Launch into low Earth orbit (LEO) may be free, piggybacking on other launches. The scientific progress consists of the discovery (Lorimer et al. 2007) of FRB with durations O(1 ms) that have been observed at frequencies as low as 110 MHz; this is now a rapidly developing branch of radio astronomy. The behavior of steady extra-Solar System radio sources at frequencies ≲10 MHz is also unknown; strong steady sources might be located by an observatory in LEO by occultation by the Earth’s limb (or by the Moon, for favorably located sources).

Observations at frequencies ≲10 MHz would constrain FRB radiation mechanisms and environments (because dense plasma prevents the escape of low frequency radiation). Transients and rapidly varying sources are advantageously observed from above the ionosphere at frequencies below the ionospheric cutoff because in LEO the delay between direct and ionospherically-reflected signals would constrain their direction. The peak of the autocorrelation of the baseband signal at this delay would determine the source’s zenith angle even without angular resolution.

Uncharacterized but spatially smooth deviations of the ionosphere from spherical symmetry would limit the accuracy of source localization by this method, but would not greatly affect the strength of the reflected glint and of the peak of the autocorrelation. This peak would still distinguish the transient or rapidly varying source from the background of steady sources as well as from terrestrial interference (which may be
significant even for low frequency exo-ionospheric observation of steady sources (Alexander et al. 1975)). Measurement from an orbiting spacecraft of the zenith angles of two separate transients from the same source would determine its location on the sky.

Rajan et al. (2016) proposed a deep-space antenna array for low frequency radio astronomy and Bentum et al. (2020) proposed the OLFAR (Orbiting Low Frequency Antennas for Radio Astronomy) system involving hundreds or thousands of satellites, linked to synthesize a large number of apertures. Li et al. (2021) have placed a lander, including a low frequency radio spectrometer, on the far side of the Moon and the necessary data relay satellite in orbit. These or similar projects offer the prospect of great scientific return some time in the future, but at high cost.

We propose a modest instrument that might, at less cost and sooner, perform a preliminary survey of < 10 MHz radio astronomy. It would be based on a Cubesat in LEO with two center-fed orthogonal half-wave dipole antennae; at a nominal frequency of 3 MHz (λ = 100 m) these would be extended to lengths L = λ/4 = 25 m by centrifugal force in each of four coplanar orthogonal directions. This nominal frequency is suggested because it is below the frequencies used by shortwave radio (Wikipedia 2022a) and likely also by over-the-horizon radar (Wikipedia 2022b); cf. the signals observed by RAE-2 in Lunar orbit (Alexander et al. 1975).

The orbital altitude is chosen above the peak of ionospheric electron density, where this density is low enough that it does not preclude transmission of extra-terrestrial radiation at the frequency of observation. A plasma frequency of 3 MHz (electron density ne = 1.15 × 10^5 cm^-3) typically occurs at altitudes of 600–800 km (International Reference Ionosphere 2022), depending on latitude, longitude, season, phase in the Solar cycle and Solar activity. It is desirable to be above this critical altitude most of the time, so a nominal altitude h = 1000 km is assumed. Refraction by the turbulent ionospheric plasma is significant at that altitude, but does not degrade the signal received by an observatory with little or no angular resolution, such as the dipole antennae considered.

At low frequencies the Sun is an intense source of background radiation. We shield our observatory from this background whenever the observatory is in shadow. At equinoxes it is shielded by the solid Earth a fraction

\[ f_{\text{shield}} = \frac{1}{\pi} \sin^{-1} \left( \frac{R_{\oplus}}{R_{\oplus} + h} \right) \approx 0.33 \]

of the time, where we have taken h = 1000 km.

The ionosphere increases \( f_{\text{shield}} \) because it increases the effective (opaque) \( R_{\oplus} \). In addition, ionospheric refraction when the Sun is near the observatory’s horizon may further increase \( f_{\text{shield}} \):

\[ f_{\text{shield}} = \frac{1}{2} + \frac{\phi - \psi}{\pi}, \]

where

\[ \phi = \cos^{-1} \sqrt{1 - \frac{\nu_{p,\text{orb}}^2}{\nu^2}} \]

is the maximum angle of ionospheric plasma refraction, \( \nu_{p,\text{orb}} \) is the plasma frequency at the observatory’s altitude and \( \nu \) is the observation frequency. The depression angle of the critical density horizon

\[ \psi = \cos^{-1} \left( \frac{R_{\oplus} + h_{\text{crit}}}{R_{\oplus} + h} \right), \]

where \( h_{\text{crit}} \) is the altitude at which \( \nu_p = \nu \); for observation to be possible \( h_{\text{crit}} < h \).

Both \( \phi \) and \( \psi \) are small angles for a satellite in LEO. Averaging over the year, \( f_{\text{shield}} \) is multiplied by a factor \( \approx 1 - \epsilon^2/4 \approx 0.96 \), where \( \epsilon \approx 0.41 \text{rad} \) is the obliquity of the Earth’s equator.

In contrast, deep space or GEO observatories like FIRST, SURO-LC, DARIS, Wind, STEREO, SunRISE and OLFAR are illuminated by the Sun; they observe it and its corona, but this background is a severe obstacle to observations of weak extra-Solar System sources. Refraction by interplanetary plasma that broadens the arrival directions of low frequency radiation by \( \Delta \theta \sim 10^\circ \sim 3 \text{ mrad} \) spreads its arrival time by \( \sim 1 \text{ AU}(\Delta \theta)^2/2c \sim 2.5 \text{ ms} \), limiting the possible resolution of interferometry, even with long baselines.

2 THE TELESCOPE

A minimal telescope is shown in Fig. 1. Two orthogonal center-fed half-wave (at the nominal frequency of 3 MHz) dipole antennae are extended from a Cubesat that contains amplifiers, data handling and storage electronics and a higher frequency antenna for transmitting data to a ground station. Power is provided by Solar cells on the Cubesat. Larger telescopes with multiple half-wave antennae (separated by distances \( \sim \lambda/4 \) to minimize capacitive coupling) could provide some angular resolution.

![Figure 1. Sketch of orbiting exoatmospheric radio telescope for observations at 1–10 MHz (numerical values in text apply for \( \nu = 3 \text{ MHz} \)). Knudsen cell thrusters set the structure rotating, extending the wire antennae. The thrusters are aligned tangentially by ties to insulating aramid fibers, tightened by centrifugal force but that have no electromagnetic effects.](image-url)
2.1 Parameters

A minimum antenna wire radius is set by the requirement that resistive losses in the wire be small compared to its radiation resistance. For a resistance $\Omega$ in an Al wire of length $\lambda/2$ the wire radius

$$r = \sqrt{\frac{\lambda/2}{\pi \sigma_{Al} \Omega}} \approx 0.21 \sqrt{\frac{10 \text{ Ohms}}{\Omega}} \frac{\lambda}{50 \text{ m}},$$

(5)

where the conductivity of aluminum $\sigma_{Al} = 3.6 \times 10^7 \text{ mho/m}$ (1 mho = 1/ohm). This corresponds to 26 AWG (American Wire Gauge). The mass of the two half-wave antennae is modest:

$$M = 2\pi r^2 \rho_{Al} \lambda/2 \approx \frac{\lambda^2 \rho_{Al}}{2\sigma_{Al} \Omega} \approx 40 \left(\frac{3 \text{ MHz}}{\nu}\right)^2 \left(\frac{10 \text{ Ohms}}{\Omega}\right) \text{g.}$$

(6)

2.2 Sensitivity

The detection threshold is a flux density

$$F_{\text{thresh}} = \frac{S}{N} \frac{4\pi k_B T_{\text{rec}}}{N \lambda^2 G_{\text{rec}} \sqrt{B_{\text{int}}}} \approx 0.5 \frac{S/N}{10} \frac{T_{\text{rec}}/30 \text{ K}}{\sqrt{(B_{\text{int}}/10^6)}} \text{ Jy,}$$

(7)

where $S/N$ is the required signal to noise ratio, $\lambda = 100\text{ m}$ the radio wavelength, $T_{\text{rec}}$ the noise temperature of the receiver, $G_{\text{rec}}$ the telescope’s antenna gain (taken as unity for a dipole), $B$ the receiving bandwidth and $t_{\text{int}}$ the integration time.

For a receiver bandwidth of 1 MHz and an integration time of 1 s (a pulsar with a duty factor of 0.01 observed for 100 s; the sensitivity may be further improved by coherent processing at a hypothetically or known pulsar period), $Bt_{\text{int}} = 10^6$. For a 1 ms FRB $Bt_{\text{int}} = 10^3$ and the detection threshold increases to about 15 Jy. This may be compared to L-band FRB fluxes of a few Jy, but the flux densities of most radio sources increase rapidly with decreasing frequency, and might be expected to be much greater at 3 MHz. Pulsars typically have UHF and L-band spectral indices $\sim -1.6$ (Lorimer et al. 1995), extrapolating to flux densities $\sim 10^4$ times higher at 3 MHz than at 1 GHz.

2.3 Data Download

A satellite in equatorial orbit passes over a near-equatorial ground station once per orbit. Data can be stored and downloaded with each passage over the ground station. The satellite would be within 2000 km for about 300 s each orbit, implying a minimum data transmission rate of $\sim 10^3$ samples per second for a receiver bandwidth of 3 MHz.

The required mean power to transmit a dual polarization base-band signal sampled at a rate $2\nu_{\text{obs}}$ to a ground-based telescope of diameter $D$ at a range $R$ is

$$P_{tr} = \frac{64\pi \nu_{\text{obs}} R^2 (S/N) k_B T_{\text{data}}}{D^2 G_{tr}} \approx \frac{60 \text{ mW}}{G_{tr}} \frac{S/N}{10} \frac{T_{\text{data}}}{30 \text{ K}} \left(\frac{R}{2000 \text{ km}}\right)^2 \left(\frac{12 \text{ m}}{D}\right)^2,$$

(8)

where $S/N$ is the receiver signal-to-noise ratio, $T_{\text{data}}$ the data receiver noise temperature and $G_{tr}$ is the transmitter gain.

This power is modest, even with a dipole transmitting antenna ($G_{tr} \approx 1$); a 1U Cubesat intercepts about 10 W of sunlight, providing $>1$ W of photovoltaic power with a duty factor (q.v., Eq. 1) $\approx 0.67$. The signal transmission rate may be further reduced by on-board processing.

3 ORBITAL LIFETIME

The mass of wire (Eq. 6) is small compared to the typical mass $\sim 1\text{ kg}$ of a 1U Cubesat, but the projected area of the antennae, each of length $\lambda/2$, is $2 \times 2r\lambda/2 \approx 400 \text{ cm}^2$ (Eq. 5), several times the projected area of a 1U Cubesat. Equating the work done by atmospheric drag to the decrease in energy of the satellite (noting that half the work done by gravity goes to increasing its kinetic energy), the orbital altitude $h$ decreases at a rate

$$\frac{dh}{dt} = \frac{4 C_d a L \rho_a}{M_{\text{Cube}} \sqrt{G M_{\text{Earth}} R_{\text{orb}}}} \approx 0.022 \frac{1 \text{ kg}}{M_{\text{Cube}} 10^{-16} \text{ g/cm}^2} \frac{\rho_a}{1 \text{ kg}} \text{ cm/s,}$$

(9)

where $R_{\text{orb}}$ is the orbital radius (from the center of the Earth), $M_{\text{Cube}}$ is the mass of the Cubesat, $\rho_a$ is the atmospheric density, $M_a \approx 6.0 \times 10^{27} \text{ g}$ is the mass of the Earth and the drag coefficient $C_d$ is taken as unity.

The scale height of the atmosphere at altitudes of interest (800–1200 km) is about 20 km because of its elevated temperature. As a result, the characteristic orbital lifetime

$$t_{\text{orb}} \equiv \frac{20 \text{ km}}{\frac{dh}{dt}} \approx 3 \frac{M_{\text{Cube}} 10^{-16} \text{ g/cm}^2}{1 \text{ kg}} \frac{\rho_a}{\text{ y.}}$$

(10)

At these altitudes $\rho_a$ is sensitive to the Solar cycle and activity (Jacchia 1970; Roberts 1971), and also depends on time of day (but not much on season at equatorial latitudes). It is more useful to specify the air density than the geometrical altitude, and it must be recognized that the orbital decay time (Eq. 10) may decrease rapidly and unpredictably with Solar activity.

4 DEPLOYMENT

The antennae must be extended by centrifugal force by setting the telescope rotating. Because of its small size, not much angular momentum can be imparted to the Cubesat by forces applied to its surfaces, but even a small initial angular momentum can begin the process of extension by rotating the Cubesat. As the antennae extend, thrusters at their ends produce increasing torques.

Several problems must be addressed:

(i) The thrusters must be simple, light, and cheap.
(ii) The thrusters must continue to act over an extended time, perhaps hours or days, as the antennae gradually extend, increasing their lever arms.
(iii) The thrusters must be remain tangentially oriented. The tiny torsional stiffness of the thin wire antennae that connect them to the Cubesat is insufficient to align them.

Nor could tubular (or partial tubular) antennae be both stiff enough and have walls thick enough for handling within the mass budget.
The first two problems are solved by using Knudsen cells (Garland, Nibler & Shoemaker 2009) as the thrusters. A low vapor pressure compound, such as naphthalene, would gradually escape through an aperture at one end of each cell, with its recoil providing the thrust.

The third problem is solved by connecting the ends of the antennae with fine electrically insulating fiber, such as aramid, as shown in Fig. 1, and fixing the Knudsen cells to the fibers. Aramid fibers are available as thin as 170 dtex (1 dtex is defined as a mass of 1 g/10 km) corresponding to a radius of about 60 µm = 0.006 cm (this is also expressed as a length per unit mass Nm = 60, where 1 Nm is 1 m/g). These fibers have the negligible total mass of about 2.5 g. Each fiber has a tensile strength of tens of N, orders of magnitude greater than its tensile load at an angular rotation rate of 3.6/s (Eq. 13); it is only necessary that the rotation rate be much greater than the orbital angular frequency \( \omega_{orb} \approx 10^{-2} \text{s}^{-1} \) in low Earth orbit to maintain the geometry.

As the antennae extend these fibers will also be made taut by centrifugal force. Thrusters tied to them would be aligned tangentially, so their recoil forces spin up the entire system, keeping it taut and stable. The moment of inertia of the four-armed (two \( \lambda/2 \) dipole antennae) telescope shown in Fig. 1 is

\[
I = \frac{4\pi}{3} L^3 r^2 \rho_{Al} \approx 8 \times 10^7 \text{g-cm}^2, \quad (11)
\]

where Eq. 5 has been taken for the wire radius \( r \).

Free molecular flow from Knudsen cells imparts an angular momentum

\[
\mathcal{L} = L m_p \sqrt{\frac{2 k_B T}{\pi m_g}}, \quad (12)
\]

where \( m_p \) is the mass of propellant gas exhausted, \( m_g \) its molecular weight and \( T \) its temperature. \( T \), and hence the vapor pressure and evaporation time, are determined by the radiative properties of the outsides of the Knudsen cells. For naphthalene at 300 K the rotation rate

\[
\omega = \frac{\mathcal{L}}{I} \approx 3.6 \frac{m_p}{10 \text{ g}} \text{s}^{-1}. \quad (13)
\]

For \( m_p = 10 \text{ g} \) the load on the wire at the Cubesat is \( \pi r^2 \rho_{Al} L^2/2 \approx 1.5 \text{N} \) and the tensile stress \( \omega^2 \rho_{Al} L^2/2 \approx 1.1 \times 10^8 \text{dyne/cm}^2 \), less than a tenth of the tensile strength of aluminum. The peripheral velocity \( \omega L \approx 90 \text{m/s} \).

If the telescope plane is inclined at an angle \( i \) to its orbital plane its spin angular momentum and plane precess (as a result of the Earth’s gravitational torque) around its orbital angular momentum at a rate

\[
\omega_{pre} = - \frac{\omega_{orb}}{\omega} \cos i \approx -3.5 \times 10^{-7} \cos i \text{s}^{-1}, \quad (14)
\]

or about one radian per month for the assumed parameters. Spin precession slews the broad dipole antenna pattern on the sky at an angular rate \( \omega_{pre} \sin i \) with angular amplitude \( i \). Significantly faster or slower precession can be obtained by choice of \( m_p \) and hence of the rotation rate \( \omega \). The rotational plane of a telescope whose orbit is not equatorial will also precess because of Earth’s equatorial bulge, but (if its spin and orbit are aligned) at a much slower rate than given by Eq. 14.

5 SOURCES

There are no known extra-Solar System point sources of radiation in the 1–10 MHz range, but the mean emission of the Crab pulsar was detected at 38 MHz (Hewish & Okoye 1965) before its discovery as a pulsar!. History has shown that observations in new regimes often discover new phenomena. For example, studies of atmospheric ionization discovered cosmic rays, radio astronomy discovered active galactic nuclei (and inferred supermassive black holes), time-resolved radio astronomy discovered pulsars, X-ray astronomy discovered a zoo of neutron stars and stellar-mass black holes, and pulsar astronomy led (in binary pulsars) to the confirmation of the theory of gravitational radiation and to the archival discovery of FRB.

5.1 Transient and Variable Sources

Interstellar and intergalactic dispersion and scattering make the detection of transients difficult at low frequency. However, the autocorrelation of the baseband voltage peaks at a lag corresponding to the delay between the direct and ionospheric-reflected paths and may enable the detection of even heavily broadened and dispersed transients. This is only possible for an observatory in LEO, for which the direct and reflected signals have similar strength. Very close old and slow pulsars with small dispersion and scatter broadening, “dead” at higher frequencies, might be detectable in the 1–10 MHz band, as might novel interstellar plasma processes.

Coherent emission from FRB has been detected at frequencies as low as 110 MHz (Pleunis et al. 2021) and 120 MHz (Pastor-Marazuela et al. 2021), with no evidence of a low frequency turnover or cutoff. Colgate & Noerdlinger (1971) speculated about coherent supernova emission at low frequencies, Usov & Katz (2000) about coherent gamma-ray burst emission, and it is not known if pulsars emit radiation in the 1–10 MHz band.

5.1.1 Localization

The ionosphere is a good reflector at 3 MHz, so the telescope would observe the reflection of a transient by the ionosphere as well as the direct signal. The time lag \( \delta t \) between them determines the source’s zenith angle (in a flat-ionosphere approximation)

\[
\theta \approx \cos^{-1} \frac{2H}{c \delta t}, \quad (15)
\]

where \( H \) is the satellite’s height above the effective reflective layer, localizing the source to a circular arc on the sky. Simultaneous detection by two telescopes would confine the source location to the two intersections of these arcs. Use of Eq. 15 requires knowing the instantaneous height of the reflective layer, which varies with Solar activity, but which can be measured in real time if the telescope emits a pulse and observes its reflection. Rapidly varying or impulsive sources within the Solar System, anthropogenic or natural, may be localized by this method. In fact, the reflective surface of the topside ionosphere is not flat or even accurately spherical because of ionospheric turbulence, but varies and is not precisely known, limiting the accuracy of this method of source localization.
If a source emits a varying signal, even if it is not impulsive, its direction can be localized by this method, using its autocorrelation to determine $\delta t$, or cross-correlation between two or more satellite telescopes. The zenith angle $\theta$ varies as a satellite moves in its orbit; rather than fitting to a constant $\theta$, $\delta t$ would be fitted to a function of time that depends on the orbital parameters and the source’s position on the sky (or in three-dimensional space for nearby sources). This would require accurate knowledge of the satellite’s orbit, not accurately Keplerian because of atmospheric drag and solar radiation pressure, but determinable by observation of a beacon on the satellite.

5.1.2 Dispersion and Broadening

Dispersive time delays are large at low frequencies (where the dispersion measure $\text{DM}$ has been scaled to convenient values for FRB):

$$\Delta t = 2.3 \times 10^5 \left( \frac{\text{DM}}{500 \text{ pc-cm}^{-3}} \right) \left( \frac{3 \text{ MHz}}{\nu} \right)^2 \text{ s,} \quad (16)$$

and

$$\frac{d\Delta t}{d\nu} = -1.54 \times 10^5 \left( \frac{\text{DM}}{500 \text{ pc-cm}^{-3}} \right) \left( \frac{3 \text{ MHz}}{\nu} \right)^3 \frac{\text{ s}}{\text{MHz}}. \quad (17)$$

As a result, a signal that is impulsive at its source is unrecognizably broadened at 3 MHz after propagating through a dispersive medium characteristic of FRB or even of Galactic pulsars.

In addition to dispersion, multipath scattering broadens transients (Krishnakumar et al. 2015). This can be a large effect at low frequency because it scales approximately as the $-4$ power of frequency. However, the scattering measure (its coefficient) varies by several orders of magnitude among sources, and may be very small for nearby objects, such as the closest old “dead” pulsars. Although the number of pulsars detected at higher frequencies is smaller, old neutron stars, dead at higher frequencies, might pulse in the 1–10 MHz band. There are $\sim 10^8$ neutron stars in the Galaxy, so that the nearest is likely at a distance of $\approx 20$ pc.

Dispersion and multipath scattering between the source and the Solar System do not affect the geometrical time delay $\delta t$ between the direct and the ionospherically reflected signals (the ionospheric dispersion measure from the altitude at which 3 MHz radiation is reflected to deep space is only $\sim 10^{-6} - 10^{-7}$ pc-cm$^{-3}$). Hence the autocorrelation of the signal received by an observatory in LEO would show a narrow peak at the geometrical time delay $\delta t$ (Eq. 15).

As the observatory moves in its orbit, a source’s zenith angle $\theta$ and autocorrelation peak $\delta t$ vary. As discussed in Sec. 5.1.1, with knowledge of the orbit dependence on time of an autocorrelation peak may be measured, indicating the presence of a variable (dispersed burst) source as well as its location on the sky; only one orbiting observatory would be required. Additional positional information may be obtained from the times of occultation by the Earth’s limb.

5.2 Steady Galactic Sources

Electron cosmic rays emit incoherent but nonthermal radio synchrotron radiation, and provide a well-understood background. The absorption of this radiation by interstellar ionized gas diagnoses the spatial and temperature distribution of that gas (Ellis & Hamilton 1966; Weber, Alexander & Stone 1971; Alexander et al. 1975; Cane 1979). The proposed system would extend these observations to lower frequencies where the interstellar plasma absorption, varying as the $-2$ power of frequency, is greater. It may also be possible to infer the absorption along paths to very bright discrete sources, such as Cygnus A, a diagnostic of the interstellar medium along its line of sight, by observing the change of its contribution to the sky-integrated signal as it enters or leaves Earth occultation.

The opacity at 3 MHz (Spitzer 1962)

$$\kappa_{3 \text{ MHz}} = \begin{cases} 1.05 \times 10^{-17} n_e^2 \text{ cm}^{-1} & T = 100 \text{ K} \\ 1.8 \times 10^{-21} n_e^2 \text{ cm}^{-1} & T = 10^4 \text{ K}, \end{cases} \quad (18)$$

where the electron density $n_e$ (in cm$^{-3}$) is assumed to come from singly ionized species. In a weakly ionized ($n_e = 0.03$ cm$^{-3}$) cool (100 K) cloud the absorption length is $\sim 30$ pc and varies nearly $\propto T^{3/2}$, while in a warm ($10^4$ K) ionized intercloud medium ($n_e = 0.01$ cm$^{-3}$) in pressure equilibrium with a cool neutral cloud with $n_H = 1$ cm$^{-3}$) the absorption length is $\sim 150$ kpc.

Cool clouds may be opaque, but cosmic ray electrons within them produce an internal source of radio radiation. Condensation into clouds likely increases their cosmic ray density and magnetic field, so they may be net emitters in comparison to the extraGalactic background. The warm ionized intercloud medium is transparent, transmitting the extraGalactic background.

5.3 The Topside Ionosphere

The spatial structure of the topside ionosphere (Banks, Schunk & Raitt 1976; Pignalberi et al. 2020; Prol et al. 2022) may be probed by observing the reflection of 3 MHz radiation from a beacon on this or another exospheric satellite. If the reflective layer is disturbed by ionospheric gravity waves (or otherwise) the location of the reflective glint varies, and can be inferred from the time delay between the reflected and direct signals.

The delay requires correction for propagation through layers in which the electron density is high enough that the signal group velocity is significantly less than $c$, and its path is bent by refraction. Because the electron gyrofrequency is 1–2 MHz, the effect of the geomagnetic field is significant and the ordinary and extraordinary modes must be considered separately within the ionosphere. Observation of this delay would be a unique probe of the varying topside ionosphere.

6 DISCUSSION

Even without angular resolution, it would be possible to probe the Universe in this unexplored frequency band:

- A single dipole antenna (or co-located orthogonal dipoles) would be sensitive to transients. Time intervals between direct and ionospherically reflected signals would provide positional information.
- A dipole antenna would measure a sky average (weighted
by its gain) temperature, yielding information about the interstellar medium not obtainable in any other manner. Models of the interstellar medium predict the antenna temperature of a dipole, and can be tested by its measurement.

- A dipole antenna observing the reflection of an exospheric beacon would measure the variability of the topside ionosphere.

Angular resolution would provide additional information:

- A single dipole telescope (or two orthogonal dipoles) whose rotation axis is not parallel to Earth’s would precess, even in equatorial orbit. This would sweep its dipole beam pattern across the sky, providing some angular resolution of steady emission like that of the interstellar medium.

- Resolution could be obtained by aperture synthesis with a larger telescope comprising multiple dipoles. This could resolve interstellar cloud structure.

- Aperture synthesis using multiple, widely spaced, dipoles in equatorial orbit could narrowly constrain the locations of transients, but would be poorly matched to the broad angular scales of interstellar clouds. More closely spaced dipoles would be a better match to that angular structure. Knowledge of the dipoles’ locations (although not necessarily active station-keeping) to allow for unpredictable differences in atmospheric drag would be required; this could be provided by GPS.

An equatorial orbit would permit data downloads to a single ground station every orbit, minimizing data storage and download rate requirements. The orbit of such a satellite, locked to the Earth’s equatorial bulge, would not precess. If rotating in the Earth’s equatorial plane, its spin would also not precess.

Large, low frequency space-based antennae are plausible candidates for demonstration of in-space manufacturing and assembly. Such structures would need to be quite large (≈ km) in order to provide even degree-scale resolution at these long wavelengths. Before such a costly and technically challenging demonstration it would be prudent to develop a “pathfinder” Cubesat-scale telescope to explore the signal characteristics to be observed by a larger instrument.

An extended antenna wire poses a collision risk for other satellites. Its effective cross-section for a 1 m satellite would be ≈ 50 m². This is much larger than the satellite’s ≈ 1 m² cross-section for a small piece of space debris, but the proposal is only for one observatory while lethal debris are numerous. If the wire is thin enough collision might not be catastrophic to the satellite.

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DATA AVAILABILITY

This theoretical work generated no original data.

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