Memo 5: LFT3 Science Operations — Spectral Line Observations

Chenoa D. Tremblay, [2,3,4,5], Will Armentrout, [6], and David R.DeBoer, [1,2]

[1] Sub-department of Astrophysics, University of Oxford, Oxford, UK
[2] Radio Astronomy Laboratory, University of California, Berkeley, CA, 94720 USA
[3] SETI Institute, 339 Bernardo Ave, Suite 200, Mountain View, CA 94043, USA
[4] Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM 87131, USA
[5] National Radio Astronomy Observatory, 1003 Lopezville Rd., Socorro, NM 87801, USA
[5] National Radio Astronomy Observatory, Green Bank Observatory, Green Bank, WV 24944, USA

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1 Introduction

The chemical evolution of the interstellar medium (ISM) underlies the formation of stars, planets, and potentially habitable environments. Much of this evolution is traced by faint molecular emission across the centimeter– and meter–wave regimes, including transitions from carbon-chain molecules, complex organic species, and ions central to cold-cloud and diffuse-cloud chemistry [e.g., 18, 28]. However, many of these transitions are exceptionally difficult to access from Earth due to the combined effects of terrestrial radio frequency interference (RFI), ionospheric absorption, and atmospheric variability [14, 43]. As a result, several key spectral windows—particularly across wide meter-wave bands—remain either inaccessible or severely compromised for high-precision astrochemical studies [30, 37].

The lunar farside provides a uniquely radio-quiet platform from which to overcome these limitations. Shielded from both terrestrial transmissions and, during the lunar night, direct solar radio emission, the farside is the most electromagnetically pristine location in the inner Solar System [8, 23, 5]. Measurements from the Radio Astronomy Explorer missions and more recent electromagnetic environment assessments as well as more recent measurements from the Longjiang-2 satellite confirm that RFI levels on the farside are orders of magnitude lower than at any site on Earth [1, 5, 47]. This environment enables unprecedented access to weak, low-frequency molecular transitions; low-lying rotational states of complex organic molecules; and high-sensitivity studies of the cold, diffuse ISM [41]. A lunar-based observatory could also detect atomic and molecular absorption from high-redshift systems, providing constraints on chemical enrichment and ISM physical conditions across cosmic time [e.g., 10, 16].

Recent developments in lunar surface infrastructure through NASA's Artemis program, commercial lander initiatives, and international partnerships now make it feasible to consider deploying low-frequency interferometers or broadband spectrometers on the lunar surface [9]. Such a facility would enable major advances in astrochemistry by allowing the study of ion–neutral chemistry in primordial clouds, the formation of molecules on dust grain surfaces, the evolution of carbon-chain species in diffuse environments, and the earliest chemical pathways in star-forming regions. **Moreover, the low and exceptionally stable noise environment of the lunar farside would permit long integrations with sensitivities unattainable on Earth or in Earth orbit.**

We aim to take advantage of the current window of opportunity—marked by increasing access to space, the emergence of commercial lunar landers, and a lunar surface that has not yet accumulated significant technological infrastructure—to develop the Lunar Farside Technosignature and Transient Telescope (LFT3). This facility is designed to enable radio astronomy across 1 MHz–2.7 GHz, with the capability to observe at both high spectral and high temporal resolution. Although astrochemistry is not the primary mission objective, the flexibility of the instrument architecture allows astrochemical science to be incorporated naturally into the spectrometer design and observing strategy.

In this work, we explore the scientific potential of conducting astrochemical observations from the lunar farside. We outline key molecular transitions uniquely enabled by the lunar radio-quiet environment, evaluate instrumental and environmental requirements for a lunar-based observatory, and compare achievable sensitivities with those of next-generation terrestrial facilities (e.g., SKA-Low). **The lunar far-side represents a transformative frontier for molecular astrophysics, and the studies presented here illustrate the profound scientific return enabled by a dedicated astrochemistry observatory on the Moon (Figure 1).**

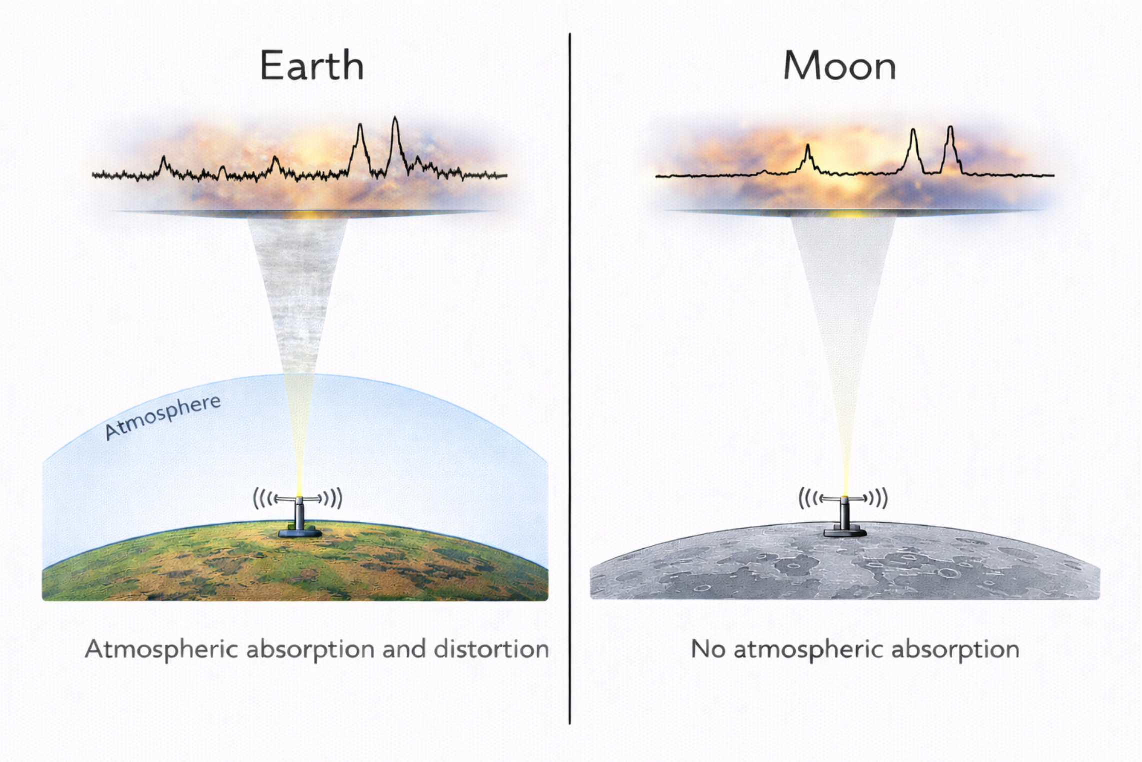

Figure 1: Schematic comparison of radio spectral line observations from the Earth's surface (left) and from an airless body (right). Terrestrial observations are affected by atmospheric absorption, emission, and phase distortion, resulting in increased noise and line broadening. In contrast, observations made above an atmosphere preserve sharper spectral features and improved signal fidelity.

2 Spectral Line Experiments & Design

Conducting astrochemical studies from the lunar farside offers capabilities that are fundamentally inaccessible from Earth or Earth orbit. The farside is the most radio-quiet environment in the inner Solar System, naturally shielded from terrestrial radio frequency interference and from ionospheric distortion that limits low-frequency observations. This unique environment enables continuous access to the MHz regime—frequencies entirely blocked by Earth's ionosphere—and provides an exceptionally stable platform for high-sensitivity spectroscopy across broader bands. Such conditions would allow detection of neutral hydrogen, weak molecular transitions, recombination lines, and chemical tracers that are otherwise obscured or undetectable from Earth-based facilities. As a result, the lunar farside represents a genuinely new frontier for astrochemistry, opening observational parameter space that has never before been explored.

2.1 Extragalactic HI

Hydrogen is the most abundant element in the Universe, and the neutral hydrogen (HI) spin-flip transition at 21 cm (1.420 GHz) serves as a fundamental diagnostic for studies of galaxy formation and evolution. From tracing the distribution of atomic gas in and around galaxies to probing the build-up of baryons across cosmic time, HI plays a central role in understanding the growth of structure in the low- and intermediate-redshift Universe [e.g., 19, 32]. Modern surveys such as DINGO, WALLABY, LADUMA, and CHILES have been designed to measure the cosmic HI density, quantify gas accretion, and study the connection between HI reservoirs, galaxy environment, and star-formation activity [e.g., 33, 15, 3, 12].

Although the 1.42 GHz band is nominally allocated for radio astronomy, terrestrial RFI remains a significant obstacle for deep extragalactic HI surveys. At cosmological distances, however, the observed HI line is redshifted to lower frequencies, shifting outside the protected allocation and into bands that are often heavily contaminated by anthropogenic transmissions. RFI, coupled with instrumental systematics and ionospheric fluctuations, introduces limitations in sensitivity, spectral smoothness, and long-integration stability [e.g., 6, 33]. These effects become increasingly problematic when attempting to detect low-column-density gas, faint satellite galaxies, or the integrated emission of galaxies at $z > 0.3$, all of which require long integrations and excellent spectral baselines, as noted by such surveys as DINGO on the Australian SKA Pathfinder [33].

The observed frequency of the HI line scales as $\nu_{\rm obs} = 1.420\,{\rm GHz}/(1+z)$, shifting into frequency ranges that are not protected and are often heavily contaminated by anthropogenic signals. As the redshift increases, individual galaxies become fainter, and multiple galaxies may fall within a single telescope beam. This motivates both direct detection surveys and statistical techniques such as HI intensity mapping, which measure the aggregate emission of many galaxies as a function of redshift. While ground-based demonstrations of intensity mapping have been achieved [e.g., 31], the method is constrained by bright foregrounds, gain-instability systematics, and RFI that can mask or mimic the cosmological signal.

The lunar farside offers a unique opportunity to overcome several of these limitations. Shielded from terrestrial transmissions and free from ionospheric disturbances, the farside constitutes the most radio-quiet environment accessible within the inner Solar System [e.g., 7]. For extragalactic HI studies, this environment could enable exceptionally stable, long-duration integrations across the full 1–2.7 GHz and sub-GHz bands needed to probe the HI content of galaxies out to intermediate redshifts ($z \sim 0.5$–1). Such observations would facilitate precision measurements of the evolving HI mass function, the cosmic neutral-gas density Ω_{HI}, the connection between gas fractions and galaxy environment, and the role of HI in regulating the baryon cycle during galaxy assembly.

Additionally, a stable, RFI-free platform on the lunar farside could provide improved sensitivity to diffuse or low-column-density gas that is otherwise inaccessible due to ground-based systematics. This includes extended HI streams, circumgalactic gas reservoirs, and tidal features that trace gravitational interactions and the impact of dark matter halos on gas dynamics [e.g., 32]. By enabling cleaner measurements of line profiles and velocity fields, lunar-based observations could also contribute to improved constraints on galaxy rotation curves, baryonic-to-dark-matter ratios, and tests of alternative gravity frameworks.

Although challenges remain—including surface operations, thermal stability, dust contamination, and the need for relay communications—the gain stability and spectral cleanliness available on the lunar farside offer transformative potential for extragalactic HI studies. The combination of uninterrupted observing time and an exceptionally low-RFI environment positions the lunar farside as a powerful complement to ongoing facilities such as ASKAP, MeerKAT, FAST, and the forthcoming SKA, enabling deeper insight into galaxy evolution, environmental processes, and dark matter in the low-redshift Universe.

2.2 Galactic Spectral Lines

Low-frequency molecular spectroscopy has emerged as an exploratory frontier in astrochemistry, driven in part by pioneering studies conducted with the Murchison Widefield Array (MWA). [43] have demonstrated both the scientific potential and the technical challenges associated with detecting molecular transitions below ~ 200 MHz. A first blind molecular-line survey between 103 and 133 MHz revealed no new transitions but established stringent upper limits and identified key instrumental limitations, including calibration systematics, RFI, and beam-model uncertainties [43]. Subsequent targeted studies toward regions such as the Orion molecular cloud extended the searchable frequency range, combining observational campaigns with molecular modelling of species such as nitric oxide and its isotopologues [40, 38]. Tremblay's doctoral work [41] further outlined the major systematic barriers—ionospheric distortion, RFI contamination, and instrumental instability—that collectively set a sensitivity floor for ground-based low-frequency molecular searches.

The lunar farside presents an unprecedented opportunity to overcome these limitations. Shielded from terrestrial transmissions and free from ionospheric refraction and absorption, the lunar farside is the most radio-quiet environment in the inner Solar System. This environment enables ultra-stable, long-duration integrations that are not possible from Earth, opening a new regime for molecular-line sensitivity and spectral dynamic range. Observations conducted from the lunar surface could reduce the systematic noise floor by orders of magnitude compared to ground-based facilities, enabling the detection of faint, low-energy transitions that have remained inaccessible.

Several classes of low-frequency astrochemical phenomena stand to benefit uniquely from a lunar-farside telescope. First, many molecules possess rotational, hyperfine, or fine-structure transitions at tens to hundreds of megahertz, often corresponding to high-angular-momentum states, unusual inversion symmetries, or low-lying energy-level splitting. These transitions typically produce extremely weak emission, particularly in cold or diffuse gas, rendering them undetectable with current Earth-based techniques. A stable, RFI-free lunar observatory would enable deep blind surveys for such transitions, increasing the likelihood of detecting rare molecules, isotopologues, and species predicted but not yet observed in the low-frequency regime.

Second, the ability to perform uninterrupted integrations supports wide-field, high-spectral-dynamic-range surveys across star-forming regions, diffuse clouds, and external galaxies. These surveys would provide new constraints on the chemistry of low-density environments, tracing extended molecular envelopes, photodissociation regions, and the outermost regions of molecular clouds where chemical pathways are sensitive to cosmic-ray fields, turbulence, and dust shielding. Detecting low-frequency transitions in these regimes would complement millimetre and infrared astrochemistry by probing cooler and more diffuse phases of the interstellar medium.

Third, lunar-based observations could yield high–dynamic range maps of faint molecular emission, enabling studies of molecular structure in extreme environments. Without ionospheric phase noise or terrestrial RFI, observations from the lunar surface could achieve the stability required to image low-frequency transitions associated with extended HI-molecular interfaces, circumgalactic molecular reservoirs, tidal streams, and molecular gas influenced by galactic outflows or ram-pressure stripping. These observations would offer unique tracers of molecule formation and destruction across a wide range of densities and temperatures.

Beyond total-intensity spectroscopy, a lunar-farside low-frequency observatory would benefit substantially from full-Stokes capability, enabling detailed investigations of the polarization properties of molecular and atomic environments. Low-frequency transitions can exhibit measurable circular polarization through the Zeeman effect, providing a direct probe of line-of-sight magnetic fields in cold and diffuse gas. On Earth, such measurements are limited by ionospheric Faraday rotation, time-variable phase corruption, and RFI-induced polarization leakage, which complicate the extraction of weak Stokes V signatures, particularly at frequencies below a few hundred megahertz [e.g., 34]. A lunar-based array would eliminate ionospheric propagation effects entirely and greatly reduce instrumental polarization systematics, supporting the ultra-stable calibration required for Zeeman experiments. Recent studies highlight the importance of polarization fidelity in low-frequency spectroscopy [e.g., 39], demonstrating that high-quality, full-Stokes datasets are essential for interpreting magnetically sensitive transitions, including potential hyperfine and molecular lines in the tens to hundreds of megahertz regime. Access to stable, broadband, full-Stokes measurements from the lunar farside would therefore enable precise constraints on magnetic field strengths, morphologies, and their role in regulating chemistry, turbulence, and structure formation in diffuse and molecular gas—a parameter space largely inaccessible to current ground-based facilities.

Little is known about the astrochemical environment below 1 GHz. Some theoretical work has been done around CH [42] and NO [38] but with only tentative detections, it is challenging to predict the necessary conditions for detections. A blind survey across the frequency ranges has benefit of finding the unknown connections that may be necessary to understanding star formation and the ISM in general.

By combining the pioneering groundwork laid by MWA and ASKAP studies with the unparalleled radio-quiet conditions of the lunar farside, LFT3 could open a fundamentally new observational window into molecular astrophysics, enabling discoveries of chemical species, environments, and processes inaccessible to terrestrial observatories.

2.3 Radio Recombination Lines

The diffuse cold neutral medium (CNM; $T_s < 100\,\mathrm{K}$) is a fundamental component of the ISM. Traditionally, the CNM has been studied through HI 21 cm absorption measurements [13], which trace the cold atomic gas along lines of sight toward bright background continuum sources. A powerful and complementary diagnostic of the physical conditions in the neutral ISM is provided by carbon radio recombination lines (CRRLs), which arise when free electrons recombine with ions and cascade through high-n Rydberg states. Because carbon has a relatively low ionization potential (11.26 eV), far-ultraviolet photons readily ionize C atoms in the surface layers of cold, neutral clouds [22]. The subsequent recombination of electrons with C^+ ions produces carbon radio recombination lines, which dominate the observed CRRL spectrum in the Galaxy.

CRRLs at low radio frequencies ($\nu < 1.5\,\mathrm{GHz}$) have been detected throughout the Galactic plane in both emission and absorption using a variety of facilities [e.g., 24, 36, 26]. In addition to probing the thermodynamic conditions of the neutral ISM, Galactic RRLs can also influence the interpretation of global 21 cm "cosmic dawn" measurements, since recombination lines can introduce spectral structure that mimics or contaminates cosmological signals [46].

At very high principal quantum numbers ($n > 300$), corresponding to frequencies below $\sim$ 100,MHz, the populations of Rydberg levels are primarily controlled by collisional processes [44]. These collisions drive the level populations toward thermal equilibrium with their local environment, resulting in CRRLs appearing in *absorption* against bright Galactic continuum emission. At lower n (frequencies $>$ 200,MHz), the level populations become inverted due to the increasing importance of radiative processes, producing *stimulated emission* and CRRLs observed in *emission* [17]. Between 100 and 200,MHz, the transition between absorption and emission occurs at a frequency that depends on the gas density and temperature, and shifts to higher frequencies in higher-pressure environments. This sensitivity makes CRRLs a powerful probe of the pressure, ionization fraction, and thermal state of the diffuse neutral ISM [36]. Furthermore, because RRL transitions occur at regular and predictable frequency intervals corresponding to successive quantum levels, multiple lines can be aligned in velocity space and stacked to significantly improve the signal-to-noise ratio, enabling the detection of extremely weak lines that would otherwise fall below the noise level.

At the lowest frequencies, observations are significantly impacted by the Earth's ionosphere, whose frequency-dependent refraction, absorption, and temporal variability introduce distortions that scale approximately as wavelength squared [41]. As a result, ionospheric effects are especially detrimental for studies of low-frequency ($\nu < 500\,\mathrm{MHz}$) CRRLs, where accurate line shapes, widths, and optical depths are needed to infer gas temperatures and densities [35]. Conducting low-frequency astrochemical observations from above the ionosphere—as provided by LFT3 on the lunar farside—would eliminate these terrestrial propagation effects entirely. Such a platform would enable unprecedented access to faint, narrow CRRLs, free of ionospheric absorption and spectral broadening, thereby providing a uniquely clean view of the physical conditions within cold ionized layers of the Galactic ISM.

2.4 Axion Dark Matter

Astrophysical observations—including galaxy rotation curves, galaxy cluster dynamics, gravitational lensing, and precision measurements of cosmic microwave background anisotropies—provide compelling evidence for the existence of dark matter (DM) in the Universe. Among the most theoretically well-motivated DM candidates are Quantum Chromodynamics (QCD) axions, ultralight pseudoscalar particles originally proposed to resolve the strong CP problem in the Standard Model. Very light axions would have been produced abundantly in the early Universe and remain a leading candidate for cold dark matter.

Direct laboratory searches for axions are actively underway. The most sensitive experiments to date employ the resonant conversion of axions to photons within a microwave cavity immersed in a strong magnetic field [4, 2]. These cavity searches are necessarily narrowband, probing a small region of frequency space at a time because the axion mass sets the resonant condition,

$$h\nu \simeq m_a c^2, \tag{1}$$

where $1\,\mathrm{GHz} \approx 4.136\ \mu\mathrm{eV}$. The observed linewidth is broadened only slightly by the virial motion of Galactic dark matter, with fractional width $\Delta\nu/\nu \sim 10^{-6}$. Consequently, these experiments must tune slowly and systematically, limiting survey speed across the allowed axion parameter space.

Astrophysical environments offer a complementary pathway. Axions can convert into quasi-monochromatic photons in the strong magnetic fields surrounding neutron stars (NS), potentially generating detectable radio emission [21]. Existing radio searches already show promise, approaching sensitivities comparable to leading laboratory experiments while benefiting from inherently broadband frequency coverage. Such high-risk, high-reward observations are well suited to commensal radio systems that record channelized voltages and allow reprocessing for evolving scientific objectives.

More recently, Noordhuis et al. [29] demonstrated that neutron stars may accumulate extremely dense axion atmospheres (exceeding 10^{22} GeV cm^{-3}), which resonantly convert into photons with substantially broader fractional widths, $\Delta\nu/\nu \sim 10^{-2}$–$10^{-3}$. Their simulations predict that such emission may reach intensities of 10^{1}–10^{4} Jy for sources at $\sim 1\,\mathrm{kpc}$ and for axion masses near $10^{-6}\ \mu\mathrm{eV}$. These results significantly broaden the parameter space accessible to radio searches for ultralight dark matter.

Through the Breakthrough Listen program, a team at UC Berkley have conducted a model-independent search for radiative decay or annihilation of ultralight dark matter using archival radio data [25] using the Green Bank Telescope. This method requires only the assumption that virialized dark matter can produce a quasi-monochromatic line whose frequency and intensity are consistent with general Milky Way halo properties. A key strength of their approach is its sensitivity to weak, broad features—signals that would evade many traditional radio-telescope dark matter searches. As a result, the method can probe a wide class of DM models, including those not accessible to current laboratory experiments.

The proposed LFT3 telescope operates at 1 MHz–2.7 GHz, covering much of the frequencies of interest to the axion community. With the beamforming capabilities on LFT3, targets of neutron stars or dwarf galaxies around the Milky Way (also an important target to the community). For sources at a distance of 1 kpc we would need a sensitivity limit of μJ which is achievable by stacking observations over time of regions of the sky of particular scientific interest.

3 Operational Parameters

There are a series of operational parameters to be considered in order obtain scientifically accurate results. We summarize some of the key parameters in Table 1 and provide details in each section below.

3.1 Calibration

Accurate calibration is a critical requirement for spectral-line radio astronomy, particularly when targeting weak emission or absorption features in the presence of bright continuum sources. Errors in bandpass calibration directly limit sensitivity near strong continuum emission by introducing spectral ripples or frequency-dependent gain variations that can masquerade as, or obscure, genuine spectral lines. This effect is especially severe for wide-band instruments operating over large frequency ranges, where instrumental responses vary significantly across the band. Incomplete or inaccurate bandpass solutions can therefore suppress detectability of faint lines adjacent to bright sources and bias measurements of line depth, width, and integrated flux. Extensive experience with low-frequency, widefield arrays such as the MWA has demonstrated that high-fidelity bandpass calibration is essential for reliable spectral-line studies in complex sky regions, including the Galactic plane and bright extragalactic fields [e.g., 27, 41].

Phase calibration errors introduce a different but equally important class of systematics. Residual phase offsets across frequency channels can lead to apparent position shifts of spectral-line emission as a function of frequency, which in turn can mimic astrophysical proper motions or velocity-dependent spatial structure. For spectral-line experiments that rely on precise spatial alignment across channels—such as studies of gas kinematics, absorption against compact background sources, or stacked analyses across multiple epochs—these effects can generate spurious signals or bias inferred velocity fields. In widefield instruments with large primary beams and significant sidelobe responses, phase errors associated with off-axis sources further complicate calibration by introducing frequency-dependent distortions that vary across the field of view. These challenges have been well documented in widefield calibration studies and underscore the need for direction-dependent phase solutions when pursuing high-dynamic-range spectral-line science [48].

Amplitude calibration errors pose a particularly insidious risk for spectral-line experiments, as small multiplicative gain errors can imprint artificial spectral features that are difficult to distinguish from real astrophysical signals. Time- or frequency-dependent amplitude variations may create narrowband excesses or deficits that resemble emission or absorption lines, especially when integrating data over long timescales. In fields containing multiple bright sources within the primary beam and sidelobes—as is typical for widefield, low-frequency observations—these effects can propagate through calibration solutions and contaminate large portions of the spectrum. As demonstrated by MWA all-sky and Galactic-plane surveys, pre-loading an accurate sky model containing the brightest sources is an effective strategy for mitigating these effects and stabilizing calibration solutions across both time and frequency [27, 41]. Such an approach is particularly well suited to instruments operating in stable, radio-quiet environments, where systematic errors rather than thermal noise dominate the limiting sensitivity.

Although calibration from a single source is standard practice for obtaining accurate bandpass and flux solutions in radio astronomy, more robust approaches are often required for widefield instruments. For example, [27] employs sky-based calibration in which all sources within the field are modelled. This approach ensures that additional bright sources do not introduce phase instabilities into the calibration solutions and accurately captures the sky brightness distribution across the full primary beam.

In addition to mitigating the influence of multiple bright sources, sky-model–based calibration enables the correction of direction-dependent effects that become increasingly important for widefield, low-frequency instruments. Variations in the primary beam response, ionospheric phase delays, and polarization leakage can introduce spatially and spectrally dependent errors that are not captured by a single, direction-independent calibration solution. By incorporating an accurate sky model and solving for gains across multiple directions, these effects can be reduced, improving spectral stability. Such approaches have been shown to be essential for achieving high dynamic range and reliable spectral performance in widefield surveys, particularly in regions of complex emission such as the Galactic plane or deep extragalactic fields [e.g., 27, 41].

While sky-model–based calibration provides substantial advantages for widefield instruments, it introduces its own limitations. The fidelity of the calibration solutions depends directly on the completeness and accuracy of the sky model; missing or poorly characterized sources can bias gain solutions and imprint artificial spectral structure. Moreover, real astrophysical signals not included in the model—particularly weak, narrowband features—may be partially absorbed into calibration solutions, leading to signal suppression. Transient instrumental effects, including cosmic-ray–induced electronic glitches or short-duration gain instabilities, can further contaminate solutions if not carefully flagged. Finally, inaccuracies in primary beam models or polarization leakage terms may introduce frequency-dependent errors that mimic or obscure true spectral-line signatures. Robust validation strategies and independent consistency checks are therefore essential components of precision spectral-line calibration.

In the context of LFT3, the long-term instrumental stability and radio-quiet environment of the lunar farside provide a uniquely favorable framework for achieving the bandpass, phase, and amplitude fidelity required for sensitive spectral-line measurements. However, even in this environment, sky-model–driven calibration remains dependent on the completeness of the source model and the accuracy of the primary beam characterization, necessitating careful validation to avoid suppressing real spectral features or introducing artificial structure.

3.2 Time Resolution

In all science cases discussed here, achieving the sensitivity required to detect the targeted spectral features will necessitate temporal stacking. The most efficient approach would involve on-board processing of beamformed data—either directed toward specific targets of interest or through an incoherent beam spanning the full field of view. To ensure that stacking coherently reinforces weak spectral lines, all spectra must be transformed into a common reference frame (e.g., the barycentric frame) prior to accumulation. Data could also be buffered on LFT3 and subsequently stacked over longer timescales when the target becomes observable again.

An initial temporal resolution of approximately 8–10 s is adequate for most observing modes, with the flexibility to average over longer intervals to enhance sensitivity provided the target remains inside the instrument's instantaneous field of view. Ground-based arrays employing fixed dipoles typically achieve this either through fringe stopping or by recording data in short segments, applying geometric corrections for the source location, and subsequently averaging the corrected data. If individual dipoles are treated as separate elements, cross-correlating their signals yields low–angular resolution visibilities, enabling coarse imaging of the region in which spectral features are detected.

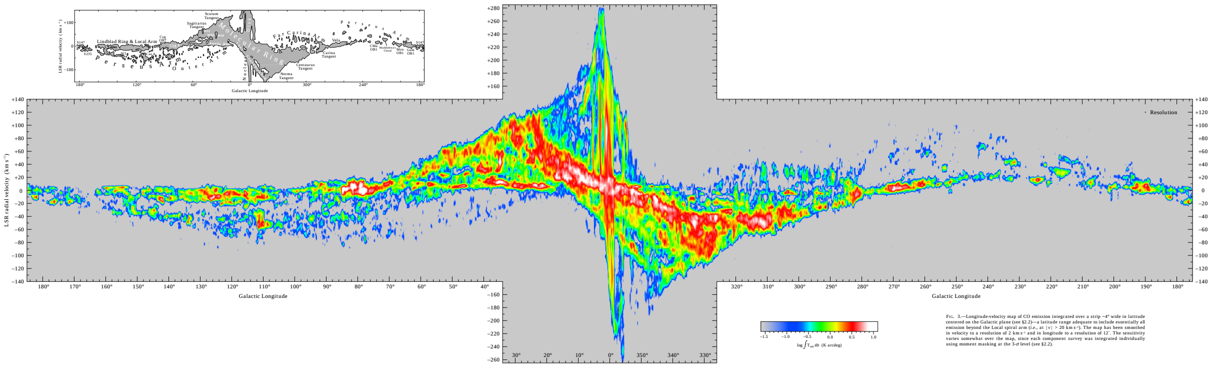

Figure 2: Plot showing the velocity structures of the Milky Way Galaxy through a map of CO by Dame et al. [11].

3.3 Spectral Resolution

To minimize storage requirements, observations may be restricted to selected spectral windows tailored to the key science objectives. For maximal flexibility, the capability to define multiple narrow-band windows would enable coverage of several atomic or molecular transitions without recording data in frequency regions where no lines are expected. Using the CO map of the Galaxy [11] as a guide, the required velocity span for molecular transitions within the Galactic disk is approximately ±280 km s^{-1} (Figure 2), while for extragalactic HI the velocity span may extend to ±600 km s^{-1}.

Radio recombination lines (RRLs), however, introduce additional considerations. At high principal quantum numbers corresponding to low observing frequencies, collisional and radiation broadening can significantly increase the intrinsic linewidth, particularly in dense or high-pressure environments. As a result, RRL windows may require broader velocity coverage than purely molecular lines, and flexible spectral window definitions are necessary to ensure complete capture of both absorption and emission profiles. Accounting for this frequency-dependent broadening is essential for accurately measuring line widths, optical depths, and thermodynamic properties of the cold neutral medium.

The required spectral resolution depends on both observing frequency and the intrinsic linewidth of the targeted transition. For narrow Galactic molecular lines, maintaining adequate velocity resolution at low frequencies ($\sim 1\,$GHz) requires fine channel spacing, typically on the order of $\sim$300 Hz, to resolve line structure and enable accurate stacking. At higher frequencies, channel widths of $\sim$500,Hz are generally sufficient for comparable velocity precision.

To account for the collisional and radiation broadening that can occur when observing RRLs we need to account for a substantial increase the linewidth, reducing the need for extremely fine channel spacing while increasing the required total bandwidth per window. In contrast, extragalactic HI observations typically target velocity widths of several hundred km,s^{-1} and therefore can tolerate coarser spectral resolution (e.g., $\sim$10 kHz). Spectral resolution should therefore be selectable to match the astrophysical linewidth of interest rather than being fixed solely by observing frequency.

3.4 Observation Styles

Beamforming can be implemented in two complementary modes. Coherent beamforming combines voltages in phase toward a specified direction and therefore provides the highest sensitivity when the source position is known. In contrast, incoherent beamforming sums power from all elements, trading some sensitivity for a significantly larger field of view and greater robustness when searching for strong or spatially extended spectral lines. A sky resolution (for the incoherent beam) on the order of one degree would be sufficient to localize detections for subsequent, higher-angular-resolution follow-up with ground-based facilities.

3.5 Data Products

For science analysis, the most useful data products are either a time-averaged power spectrum or a calibrated flux-density spectrum expressed in Janskys. In both cases, accurate flux calibration is required to establish the absolute amplitude of any detected spectral features.

The output from LFT3, should include a time averaged power spectrum toward each source. After reference frame correction the signals should not show a Doppler drift, and therefore a dynamic spectrum is not required. This should limit the data rates required.

Table 1: Representative observing modes and data products for key LFT3 science cases.

Experiment	Spectral Resolution (Hz)	Time Resolution (s)	Data Type
Extragalactic HI	500–1000	8–10	Beamformed spectra
Galactic Spectral Lines	100–500	1–10	Beamformed or incoherent spectra
Radio Recombination Lines	100–300	1–5	Full-Stokes spectra
Axion Dark Matter	1–10	<1	Voltage time series / power spectra

4 Comparison to Ground-Based Facilities

Across all bands considered for LFT3, ground-based observations continue to suffer from substantial RFI contamination, frequency-dependent ionospheric distortion, and limited spectral access. The experience with instruments such as the MWA [45], LOFAR [35, 36], and other low-frequency facilities demonstrates that even modest levels of RFI can remove large fractions of the available bandwidth. In some cases [e.g., 43], more than half of the theoretically observable transitions must be discarded, significantly reducing sensitivity and preventing robust detections. These limitations inevitably bias studies of the ISM, obstructing the ability to build statistically meaningful catalogues of low-frequency spectral lines.

The LFT3 spectral range directly addresses these limitations. By operating above the ionosphere and free from Earth-generated RFI, LFT3 can continuously access frequency bands that are partially or completely unavailable from the ground. The lack of RFI excision requirements alone represents a substantial gain in both sensitivity and usable observing time. In Figure 3 we have highlighted several molecular and atomic transitions—including NO, CH, SH, and both hydrogen and carbon RRLs—that fall within the LFT3 coverage. These lines remain largely unexplored, not because of scientific irrelevance, but because the practical constraints of ground-based radio astronomy have prevented systematic study. However, they have theoretical and laboratory studies that provide us with information about at what frequencies and energies we would expect to detect them [38, 35, 42].

The ability to observe these transitions has important implications for our understanding of the cold, diffuse, and partially ionized phases of the ISM. For example, CRRLs trace gas at the interface between molecular and atomic regions, providing a unique probe of environments where star formation is regulated by a combination of turbulence, cosmic rays, and magnetic fields. Our results reinforce earlier conclusions that CRRLs are particularly susceptible to RFI contamination at low frequencies. Removing this constraint would allow more complete sampling of the CNM and would enable direct comparisons between CRRLs, H I, and dust-based tracers across a much wider range of Galactic environments.

Similarly, the low-frequency molecular transitions accessible to LFT3 offer opportunities to investigate physical conditions in regions that are optically thick at higher radio frequencies. High-mass star formation is an especially relevant case: massive young stellar objects reside within dense, ionized environments where free–free absorption restricts ground-based observations above $\sim$ 200,MHz [20]. Low-frequency molecular tracers may therefore provide one of the few avenues available for probing the ionized–molecular interface within these regions [43]. While the angular resolution achievable at meter wavelengths may limit detailed imaging of sub-parsec structure that can expand out to around 30 arcseconds, integrated spectral measurements across compact and classical HII regions can still constrain magnetic fields, ionization conditions, and chemical stratification through linewidths, optical depths, and polarization signatures.

Finally, because LFT3 will not be constrained by the frequency-specific scheduling limitations inherent to ground-based facilities due to planetary and solar weather (i.e. wind, snow, solar flares, etc.), it can support wide-area, discovery-driven spectral surveys. Such surveys would allow for the identification of rare or previously undetected transitions and would help quantify the prevalence of low-frequency lines across different Galactic environments. The discussion here suggests that many of these transitions may simply remain unknown due to observational barriers rather than astrophysical rarity.

Taken together, these results indicate that LFT3 occupies an observational niche that has remained underserved. By opening a spectroscopic window that is effectively closed from the ground, the mission would enable a more complete characterization of the ISM and provide new opportunities to test models of star formation, chemical evolution, and the structure of the cold neutral medium.

5 Conclusion

The lunar farside provides an exceptionally radio-quiet and ionosphere-free environment that enables spectral-line studies inaccessible from Earth. Across the frequency range of 1 MHz–2.7

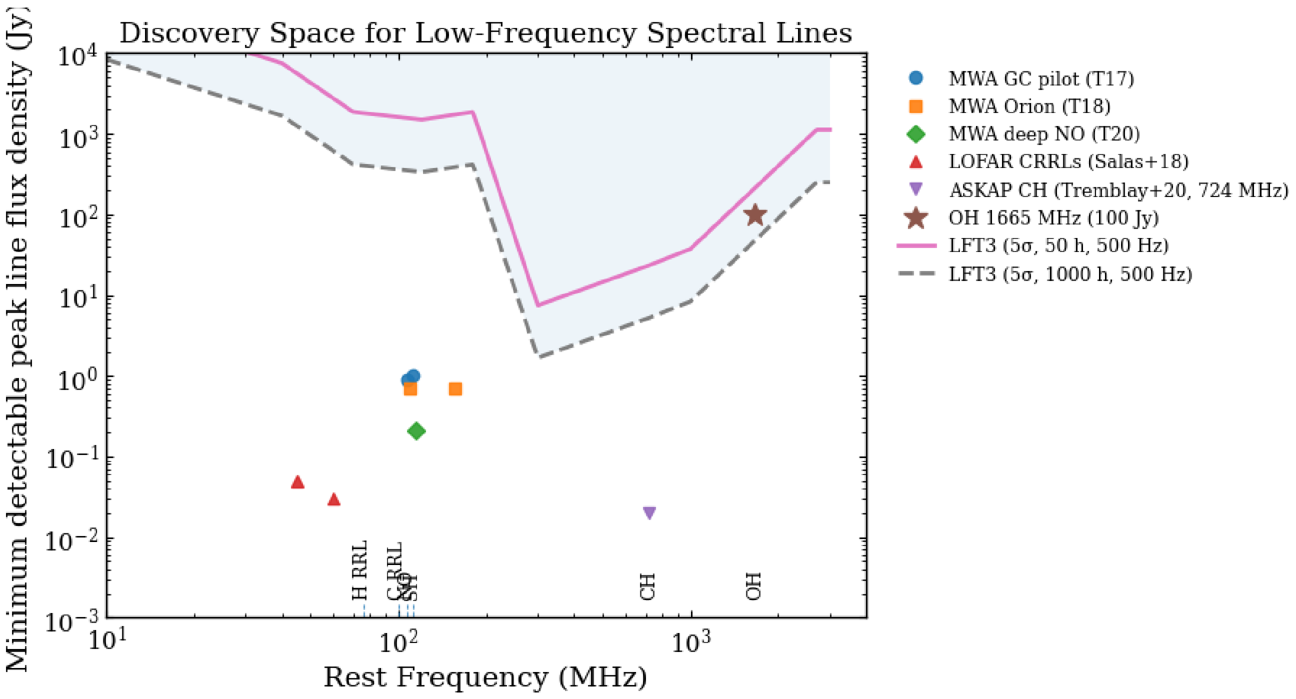

Figure 3: Plot showing the discovery space of LFT3. The points represent upper limits or tentative limits of low-frequency spectral lines with an overlay of the expected sensitivity of LFT3. Although LFT3 is not as sensitive as the ground-based interferometers it does limit the ionosphere refraction and ability to observe across a wider frequency range. Additionally, with so few studies working in this low frequency range, LFT3 offers a new discovery space for astrochemistry.

GHz, a facility such as LFT3 would overcome the dominant limitations that affect ground-based arrays—radio-frequency interference, ionospheric distortion, and long-term gain instability—and would permit continuous, wide-band observations with stable system response.

The science cases examined here demonstrate that LFT3 would substantially advance low-frequency astrochemistry, recombination-line studies, and extragalactic H I intensity mapping. Access to weak molecular transitions (e.g., CH, NO, SH), carbon and hydrogen recombination lines, and redshifted atomic hydrogen across intermediate lookback times would allow measurements of physical and chemical conditions in diffuse gas well below current sensitivity limits. Because stacking, long coherent integrations, and multi-window spectral modes are feasible in the farside environment, LFT3 can probe column densities and optical depths that are orders of magnitude beyond what can be achieved from the ground.

These capabilities complement terrestrial instruments such as LOFAR, ASKAP, and MeerKAT by providing coverage of spectral regions that remain inaccessible or severely RFI-limited on Earth. LFT3 would, therefore, add genuinely new discovery space rather than incremental improvement. The resulting dataset would inform studies of ISM structure, astrochemical pathways, magnetic environments (via full-Stokes measurements and Zeeman diagnostics), and potential narrowband signatures from exotic physics.

In summary, a farside low-frequency telescope such as LFT3 offers transformative potential for spectral-line astrophysics. By enabling stable, interference-free access to broad spectral windows and intrinsically weak transitions, it would open an observational regime that cannot be replicated by existing or planned ground-based facilities.

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