Current Status and Future Development of Extremely Low Frequency Radio Astronomy Observations: Postprint

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Abstract

Extremely Low Frequency (ELF) represents a critically important frequency band for modern astronomical observations, enabling research on solar eruptions, star formation, galaxy evolution, the early state of the universe, and other significant topics. However, for signals below 10-20 MHz, detection and study are impossible from Earth due to reflection or severe distortion by the ionosphere and the presence of low-frequency radio interference sources. The far side of the Moon offers a unique platform for low-frequency radio observations, representing a uniquely ideal environment compared to Earth. This work surveys representative ELF radio telescopes and presents a retrospective summary of the scientific significance, current development status, and related technologies of ELF astronomical observations. In the foreseeable future, the ELF radio spectrometer onboard China' s Chang' e-4 will be one of the world' s most important low-frequency observation instruments, and this paper provides a preliminary introduction to this device.

Full Text

Preamble

The History and Development of Low-Frequency Radio Observation

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Abstract

The very low frequency (VLF) band represents a critically important region of the radio spectrum for modern astronomical observations. VLF detection enables crucial research on solar eruptions, star formation, galaxy evolution, and the early state of the universe. However, for signals below 10-20 MHz, Earth' s ionosphere causes reflection or severe distortion, while terrestrial radio interference sources prevent effective detection in this frequency range. The far side of the Moon offers a unique platform for low-frequency radio observations, providing an ideal environment compared to Earth. This paper surveys representative VLF radio telescopes and provides a retrospective summary of the scientific significance, current status, and related technologies of VLF astronomical observations. In the foreseeable future, the VLF radio spectrometer aboard China' s Chang' e-4 mission will become one of the world' s most important low-frequency observation facilities. This paper also presents a preliminary introduction to this instrument.

Keywords: radio astronomy; very low frequency; current status; Chang' e-4

Introduction

In 1930, American radio engineer Karl Jansky discovered radio emission from the Milky Way, opening the radio window as a vital new observational band beyond traditional optical and infrared astronomy. Thanks to the transparency of Earth' s atmosphere at radio wavelengths, radio astronomy developed rapidly, achieving remarkable discoveries such as pulsars and measurements of cosmic microwave background radiation. This advancement has been termed the second major revolution in astronomy.

The two most important parameters in radio astronomical observations are sensitivity and resolution. Sensitivity determines the minimum flux density a telescope can detect; higher sensitivity enables detection of fainter sources. Resolution, essentially angular resolution, determines the ability to distinguish between closely spaced radio sources. For low-frequency observations, the development and application of interferometric techniques are gradually enabling high-resolution observations of radio sources. While sensitivity can be improved through larger antenna sizes, longer observation times, and reduced system noise, VLF observations struggle to achieve designed sensitivity due to unavoidable factors: ionospheric absorption, refraction, reflection, and scintillation effects that weaken and severely distort low-frequency signals, as well as terrestrial radio interference. Consequently, radio astronomy has primarily focused on the 30 MHz to 100 GHz range, with relatively limited exploration below 30 MHz. Nevertheless, VLF observations provide new data for understanding physical phenomena related to the universe, galaxies, and stars, and offer the possibility of discovering entirely new astronomical phenomena.

This paper reviews the scientific objectives of VLF radio detection, lists radio telescopes operating below 40 MHz since the 1960s with their basic information and performance parameters, discusses the primary techniques and challenges in VLF radio observations, and introduces the instruments for VLF detection aboard Chang' e-4 (CE-4), China' s pioneering VLF observation mission scheduled for launch in 2018. Finally, we review the history of VLF radio observations and 展望 (look forward to) their future development.

1 Scientific Significance of Very Low Frequency Radio Observations

The cosmic Dark Ages contain initial state characteristics of early matter distribution, while the Epoch of Reionization reflects the evolution from neutral to ionized hydrogen in the early universe. Detecting these epochs is essential for understanding cosmic evolution and testing cosmological models. During the Dark Ages, no stars had yet formed, and the intergalactic gas was too cool to produce optical radiation, making optical observations impossible. After the first generation of stars and galaxies formed, their radiation ionized surrounding neutral hydrogen, creating ionized bubbles that expanded and merged throughout the universe. This transformation of intergalactic neutral hydrogen to ionized hydrogen constitutes the Epoch of Reionization, which contains information about the first stars and galaxies. Current detection of these epochs relies on observations of the familiar neutral hydrogen 21-cm line, produced by electron spin-flip transitions between energy levels of $\pm 1/2$ in neutral hydrogen atoms. This transition requires very low energy and has an extremely low probability of being absorbed during propagation. The 21-cm line from the Dark Ages and Reionization can be observed today, but cosmic expansion redshifts the wavelength, lowering the frequency. For the high-redshift universe ($z = 11.4$ to $z = 20$ or higher), corresponding frequencies fall in the VLF range of 115 MHz to 70 MHz or lower. Thus, VLF radio observations play an irreplaceable role in cosmological research.

Relativistic electrons moving in magnetic fields produce synchrotron radiation, the primary mechanism for generating low-frequency radio emission. Theoretical models relate interstellar magnetic fields, relativistic electron energies, and observed spectra. Low-frequency radio emission mainly originates from high-energy electrons in the Milky Way. By observing low-frequency radio emission, we obtain information about relativistic electrons and magnetic field distributions, understanding cosmic ray production and propagation mechanisms as well as galactic structure. Electron density and kinetic temperature in ionized hydrogen regions are key observational targets; at low frequencies, these regions appear in absorption, making observations of low-frequency absorption lines important for studying their characteristics.

Solar radio burst observations constitute a major part of solar radio research. Based on spectral characteristics, solar radio bursts are classified into five types: Type I bursts have short durations; Type II bursts have narrow bandwidths with rapidly decreasing frequency; Type III bursts have even narrower bandwidths and higher drift rates; Type IV bursts accompany Type III bursts with similar drift rates but broader spectra; and Type V bursts correspond to continuous spectra with very wide bandwidths. Types II, III, IV, and V all have meter-wave radio emission components. Current theory suggests that meter-wave (VLF) radio emission originates from the most critical region of energy release and conversion during solar eruptions (heliocentric distances of 1.2–2.5 solar radii, corresponding to frequencies of tens to hundreds of megahertz), which is also an important region for solar energetic particle production. Therefore, VLF radio data carries rich information about solar eruption processes and particle acceleration and radiation mechanisms, making the VLF radio window extremely useful for solar and space physics research. WIND/WAVES and STEREO/WAVES have focused on detecting VLF radio sources from the Sun and space. VLF solar observations can also address: physical mechanisms and evolution of coronal magnetic fields; flare physics; space weather; quiet Sun physical properties; and prominence detection. VLF radio observations will deepen our understanding of the physical mechanisms underlying daily solar activity.

In 1955, Bernard Burke and Kenneth Franklin accidentally discovered Jupiter' s radio burst phenomenon. Since then, low-frequency radio detection has become a common tool for planetary research. Jupiter' s radio bursts concentrate in the meter to hectometer wave range (tens of megahertz), so VLF observations help understand Jupiter' s intermittent radio emission mechanisms and magnetospheric characteristics. In exoplanet research, theoretical models such as magnetic energy, kinetic energy, and coronal mass ejection (CME) models predict exoplanet candidates with VLF radio emission. Observing these candidates will test these theoretical models.

Beyond these examples, many known celestial objects produce low-frequency radio emission, including supernova remnants, quasars, intergalactic medium, and galaxies. Thus, low-frequency radio observations can address major astronomical questions and expand our understanding of the universe.

2.1 Ground-Based Very Low Frequency Radio Telescopes

VLF radio observations began remarkably early—Jansky' s initial radio observations used a frequency of 18 MHz. After World War II, scientists converted military radar systems for radio astronomy, making the UK, France, and Australia early centers for low-frequency radio observations. This period marked a flourishing development of ground-based VLF radio telescopes. While ground-based construction is most economical, Earth' s ionosphere acts as a natural high-pass filter, severely distorting meter-wave signals (10–40 MHz) that reach the surface. The ionospheric cutoff frequency (typically 10 MHz) depends on ionospheric properties; lower ionization allows easier propagation. Therefore, site selection becomes the most critical factor for effective ground-based VLF observations. Ionization reaches its minimum at mid-latitudes away from magnetic poles, in regions known as ionospheric troughs—these are ideal VLF observation locations. Figure 1 [Figure 1: see original paper] shows the distribution of mid-latitude ionospheric troughs.

Australia’ s Tasmania Island lies in an ionospheric trough region, and Australia exploited this geographical advantage in the 1970s to conduct astronomical observations with a VLF array. The Llanherne low-frequency array (Llanherne) performed sky surveys of the southern sky at 3.7, 5.6, 8.3, 13.0, and 16.5 MHz. Figures 2 [Figure 2: see original paper] and 3 [Figure 3: see original paper] show radio contour maps of portions of the southern sky, representing the most complete and effective scientific data obtained from ground-based VLF observations to date. Additionally, Australia built a series of VLF arrays based on Shain cross and Mills cross configurations starting in 1958. The Sydney 19.7 MHz “Mills Cross” radio telescope (Sydney) conducted a high-resolution survey in 1961 with a resolution of [2,25], results consistent with Tasmanian measurements.

Early telescopes covering 0–30 MHz included Hornsby Valley Field Station (HVFS) and Fleurs Field Station (FFS). HVFS used passive radar to map lunar surface topography, discovering rugged terrain, while FFS focused on Jupiter, concluding that active plasma in Jupiter’ s atmospheric electrical regions collides to produce low-frequency radio bursts. Table 1 lists basic information and parameters for some early ground-based low-frequency radio telescopes from the 1960s–70s.

Early low-frequency arrays had relatively low resolution, preventing effective observations of individual sources and enabling only partial southern sky surveys. Even for surveys, early equipment and simple data processing yielded rough, low-precision data. Observing conditions were extremely demanding: solar quiet periods, winter nights, and constant attention to interference from other stations. Nevertheless, Australia’ s early VLF observations were crucial, producing the first galactic VLF radio contour maps and laying the foundation for later VLF radio astronomy development.

Later ground-based telescopes such as Ukraine’ s UTR-2, France’ s NenuFAR, Australia’ s Bruny Island Radio Spectrometer (BIRS), Culgoora radio spectrometer, India’ s GEETEE, and the US Clark Lake Teepee-tee achieved high-resolution observations. UTR-2, one of the largest meter-wave telescopes, achieved 30 angular resolution, obtaining 3D structural variation maps of solar radio bursts and detecting celestial low-frequency carbon recombination lines. Combined with other Ukrainian radio telescopes (URAN), it formed an interferometer network with baselines up to 900 km, substantially improving resolution. UTR-2 is currently being upgraded to GURT, with an increased upper frequency limit of 80 MHz, covering targets including Earth’ s magnetosphere, lunar environment, solar radio, galaxies, and pulsars. Together with smaller telescopes similar to UTR-2, it forms the Ukrainian radio astronomy network. BIRS and Culgoora focused on solar observations, with BIRS detecting solar Type II and III burst groups in 1992, and GEETEE producing the first 2D images of discontinuous, slowly varying radio sources in the outer corona and detecting celestial low-frequency carbon recombination lines. Table 2 lists relevant parameters and observations for these ground-based VLF telescopes.

With advancing technology, improved computing power, and expanded data storage, constructing large radio arrays became feasible. For VLF radio astronomy, Europe' s LOFAR and the US LWA represent the world' s most advanced low-frequency facilities. LOFAR operates in two bands, with low-frequency receivers covering 30–80 MHz, matching LWA' s band. Both target cosmic dawn, cosmic rays, pulsars, solar radio, planetary physics, and use dipole antennas in massive arrays. LOFAR at 55°N longitude favors extragalactic observations, while LWA at 34°N can observe the galactic center region. Table 3 compares these ground-based VLF arrays.

Ground-based VLF observations remain extremely difficult. Beyond selecting excellent sites, substantial work is required on hardware, data processing methods, and software to improve interference resistance, resolution, and sensitivity. Early meter-wave observations used swept-frequency analyzers (SFA), acousto-optical spectrometers (AOS), filter banks (FB), and digital correlators (DAC), which couldn' t simultaneously optimize sensitivity, time resolution, dynamic range, and instrument size. Later, scientists from Paris-Meudon Observatory and Australian Space Research developed digital spectrometers for real-time high-quality signal acquisition. Modern arrays like LOFAR now face challenges of massive data storage and rapid, efficient processing. Ground-based VLF telescopes remain indispensable for low-frequency radio astronomy.

2.2 Space-Based Very Low Frequency Radio Satellites

As mentioned, Earth' s ionosphere and human-made radio interference make ideal ground-based VLF observations extremely difficult. Space detection effectively reduces these effects. The earliest VLF space detection attempts were made by teams from Harvard University, University of Michigan, Canadian DRTE, and Cambridge University, who demonstrated feasibility and necessity by studying solar and Jupiter radio bursts, cosmic microwave background, and ionospheric electron density distribution. Space observations primarily involve placing detectors in orbit for long-term monitoring, though some missions use rocket-borne receivers for short-term specific-frequency observations, such as France' s 1967 rocket experiment at 1.16 MHz and 2.4 MHz from 1600 km altitude. Table 4 lists basic information for some space VLF radio telescopes since the 1960s.

The RAE series pioneered space VLF radio detection. Despite technical limitations, terrestrial radio interference, and inter-antenna interference that prevented acquisition of effective scientific data, these experimental explorations provided valuable experience for later missions. WIND/WAVES and

STEREO/SWAVES enable both single-point and coordinated multi-point observations. Figure 4 [Figure 4: see original paper] shows a multi-point solar radio burst observation from December 7, 2007, where WIND/WAVES and STEREO/SWAVES (A,B) simultaneously detected Type III bursts.

Future space VLF telescopes will focus on using aperture synthesis for high-resolution imaging, such as the US-proposed Astronomical Low Frequency Array (ALFA) mission, which would deploy 16 dipole-equipped satellites in Earth orbit to form a 100 km effective aperture array operating at 0.03–30 MHz.

2.3 Lunar-Based Very Low Frequency Detection Programs

The Moon' s far side is uniquely suitable for radio astronomy. Always facing away from Earth, it blocks terrestrial noise, acting as a natural filter. The Moon' s ionosphere is much thinner with a lower cutoff frequency. Compared to orbiters, surface-based detectors provide a more stable platform for precise relative positioning and phase coherence. The Moon' s rotation provides sky scanning, and its windless, waterless environment reduces maintenance costs. The concept of lunar-based radio telescopes emerged in the 1960s. In 1964, Gorgolewski proposed a lunar-orbital synthesis array for high-resolution nighttime radio observations and solar observations during lunar day. In 1985, Burns proposed long-baseline Moon-Earth interferometry. The 1990s saw a surge of proposals: Douglas and Smith suggested a 15×15 km array, NASA established a Lunar Far-Side Low Frequency Array project group, and various concepts were developed for implementation between 2002–2018.

The first lunar-based low-frequency array to reach design stage was the Astronomical Lunar Low Frequency Array (ALLFA), proposed by Hughes Aircraft Company in 1992. ALLFA planned an 8-year development with a 2000 launch, landing at Chaplygin crater, operating at 0.1-30 MHz using 40 crossed-dipole antennas (0.3 m long) in an elliptical array. Antennas would be deployed by rovers, with the lander at the array center and a relay satellite at Earth-Moon L2 for communications. Designed sensitivity was 10 Jy with a 12-year lifetime.

The International Lunar Far-side Observatory and Science Station (ILFOSS) proposed landing at Olshevsky crater with operating frequencies of 1, 3, 10, and 30 MHz using 1 m single-dipole antennas. Phase I included 5 stations, expanding to 300 in Phase II in a circular array configuration, with -13 dB sensitivity and 10-year design life.

In 1997, ESA proposed the Very Low Frequency Array on the Lunar Far Side (VLFA), also targeting Olshevsky crater for low-frequency sky surveys, solar physics, and exoplanet source searches. VLFA would comprise 300 crossed-dipole antennas (4 m long) in a Y-shaped array, receiving 0.5–16 MHz signals.

Current projects include ESA' s Lunar Radio eXperiment (LRX), NASA-funded Dark Age Lunar Interferometer (DALI), and Lunar Array for Radio Cosmology (LARC).

In January 2015, ESA proposed the FARSIDE mission for lunar far-side landing in 2020, using a relay satellite at L2 for communications. FARSIDE would carry a VLF interferometer for radio astronomy, with spectrometers on both lander and relay satellite for interferometry. The lander spectrometer would operate at 16 kHz-40 MHz using 2-3 dipoles >5 m long, while the relay spectrometer would cover 1-40 MHz with 2-2.5 m antennas.

China will launch Chang' e-4 in 2018, also carrying a VLF spectrometer for scientific detection. Table 5 lists the basic scientific objectives of FARSIDE and Chang' e-4.

3 Basic Methods for Low-Frequency Radio Observations

3.1 Interferometry Techniques

VLF radio astronomy typically uses interferometry to improve resolution and eliminate random errors. As shown in Figure 5 [Figure 5: see original paper], electromagnetic waves from a distant source arrive at two antennas separated by baseline b with a geometric delay. The visibility function from this delay' s correlation yields sky brightness in all directions. For 2D observations, let u, v, w be the three orthogonal components of baseline b, with w pointing toward the source. The visibility function is:

$$\mathcal{V}(u,v) = \iint I(l,m) e^{-2\pi i(ul+vm)}\, dl\, dm$$

where l, m are small angular offsets from the source center, $\mathcal{V}(u,v)$ is the measured visibility function in the u-v plane, and *I(l,m)* is the source brightness. The source image is obtained through inverse Fourier transform of the visibility function.

Space interferometry requires data storage and downlink for ground processing. Interferometers use correlation receivers outputting the average product of two antenna voltages. If noise or interference affects only one antenna, the correlated output becomes zero, suppressing receiver noise and harmful interference affecting only one antenna. Compared to single-dish observations, interferometry provides superior interference resistance.

3.2 Antennas

VLF observations typically use dipole antennas due to their simple structure, ease of design, and flexible array configuration for desired polarization. Dipole antennas offer improved gain patterns over monopoles with satisfactory directional characteristics. For a linear dipole, radiated power is:

$$P = \frac{I_0^2}{2} \left(\frac{L}{\lambda}\right)^2$$

where L is antenna length, is wavelength, and I is antenna current. Since power scales with length squared, higher radiated power requires longer antennas—especially critical for VLF where long wavelengths demand substantial antenna lengths. This explains why early RAE series antennas reached 229 m. However, such long antennas present technical challenges for space missions (deployment, mutual interference) and increase costs. Ground-based long antennas are relatively easy and inexpensive to construct, and arrays can improve directivity. Early Australian arrays used long linear dipole arrays. Modern designs employ shorter, foldable/deployable antennas to reduce weight and mutual interference.

4 Chang' e-4 Very Low Frequency Radio Detection Payload

China' s low-frequency radio astronomy program began relatively late. In the 1990s, the Space Solar Telescope (SST) project proposed carrying a VLF spectrometer, with a prototype developed. After three decades of effort since scientists first proposed space-based VLF spectrometers for solar and planetary measurements, Chang' e-4 will achieve China' s breakthrough in space-based VLF observations.

Chang' e-4 comprises a lander and relay satellite, scheduled for 2018 launch, carrying four VLF observation instruments: a lander VLF spectrometer, a relay satellite VLF spectrometer, and two lunar orbit ultra-long wavelength astronomy microsatellites. Primary scientific objectives include solar low-frequency signal observation and lunar space environment monitoring.

4.1 Lander Low-Frequency Radio Spectrometer

The Chang' e-4 lander VLF spectrometer, developed by the Institute of Electronics, Chinese Academy of Sciences, uses a three-component (tripole) active antenna consisting of three orthogonal 5 m electric dipoles for electromagnetic wave reception. The antennas mount on the lander top—one vertical and two parallel to the surface. The spectrometer has two bands: low band 0.1–2 MHz with 5 kHz spectral resolution, and high band 1–40 MHz with 100 kHz resolution. Dynamic range exceeds 75 dB. Lander electronics (telemetry modulators, power controllers) generate strong low-frequency noise that can interfere with or overwhelm solar burst signals. To mitigate this, 20 cm short antennas were added for interference suppression. These short antennas, being close to the lander, receive primarily lander noise, enabling noise cancellation in the long-antenna signals.

4.2 Netherlands-China Low-Frequency Explorer

The Netherlands-China Low-Frequency Explorer (NCLE) is a joint development by ASTRON, Radboud University, ISIS, and the National Astronomical Observatories, Chinese Academy of Sciences (NAOC). NCLE will fly on the Chang' e-4 relay satellite at Earth-Moon L2, 6.4 km from the Moon. Science targets include high-redshift 21-cm lines, cosmic Dark Ages signals, planetary auroral radiation, radio background intensity at L2, and Earth’ s ionosphere. NCLE uses three 5 m monopole antennas co-located on the relay satellite exterior. For frequencies 1-80 MHz, dipole configuration provides optimal sensitivity. KHz-level signals can be detected with reduced sensitivity. Software-controlled science modes enable fast Fourier transforms for averaged spectra, triggering of brief radio events, and retrieval of arrival direction information.

4.3 Lunar Orbit Ultra-Long Wavelength Astronomy Microsatellites

Developed by Harbin Institute of Technology, two microsatellites form a lunar orbiting interferometer for ultra-long wavelengths. By observing 1-30 MHz radio signals, they will obtain all-sky ultra-long wavelength images and full-sky radio spectra, while monitoring solar and planetary ultra-long wavelength radio activity. The antenna configuration uses three orthogonal dipoles (1 m long), achieving 2° spatial resolution at 15 MHz center frequency with 1000 kHz spectral resolution. The microsatellites will be delivered to lunar orbit by the Chang’ e-4 relay satellite launch vehicle, enabling interferometer baselines of 1-10 km.

The Chang’ e-4 lander on the lunar far side avoids human radio interference and experiences minimal ionospheric effects, providing an ideal platform for low-frequency radio source detection. However, galactic background noise and instrument self-noise remain strong interference sources. To improve interference resistance and obtain fine radio images, future plans may employ interferometry, combining the lander spectrometer, NCLE, and orbital microsatellites into a long-baseline space interferometer array.

Technical challenges include: (1) Positioning and distance measurement between lander, relay satellite, and microsatellites, as interferometric imaging quality depends critically on baseline accuracy—errors exceeding one wavelength make measurements impossible, with microwave ranging currently the best solution; (2) Data storage and transmission, as even after preprocessing, the data volume is substantial for limited bandwidth.

Conclusion and Future Prospects

VLF radio astronomy development is closely tied to technological progress. Early ground-based arrays were limited by ionospheric cutoff, enabling observations only at select sites like Australia and the UK. Space technology enabled VLF satellites to obtain signals below 10 MHz. Lunar-based programs leverage the Moon’ s unique advantages to detect weaker VLF sources.

Ground-based VLF observations remain important. For high-resolution observations above the ionospheric cutoff frequency, expanding interferometer arrays and international cooperation are key, as demonstrated by Europe’ s LOFAR. Ground arrays face challenges in data storage and processing, with increasing demands on antenna design, data reception, sensitivity, and resolution as research deepens.

Space VLF satellites have achieved excellent results in solar wind, space plasma, and space weather research. STEREO/WAVES has provided data on solar Type III bursts, Type II bursts, auroral kilometric radiation, and discovered new periodicities in Jovian decametric radiation, providing direct data for understanding our environment. Coordinated multi-satellite observations represent the future direction for VLF radio astronomy.

Lunar-based VLF astronomy, benefiting from the radio-quiet far side, may enable breakthrough discoveries. Current plans use lander-orbiter interferometry as a precursor to future lunar arrays. Projects like the Radio Observatory on the Lunar Surface for Solar studies (ROLSS) will use Y-shaped configurations for high-sensitivity, high-resolution observations of solar burst mechanisms and electron acceleration in prominence eruptions. The Chang' e-4 lander spectrometer, NCLE, and lunar orbit microsatellites will be important scientific payloads for VLF research, taking the first step into the underexplored VLF domain using the radio-quiet lunar far side.

Future VLF radio astronomy, combining ground, space, and lunar-based facilities, will gradually achieve lower frequencies, higher sensitivity, and higher resolution. These data will address major scientific questions about the early universe, planetary meter-wave radiation, and solar radio bursts.

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