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## A VERY LOW FREQUENCY RADIO ASTRONOMY OBSERVATORY ON THE MOON\*

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Abstract

Because of terrestrial ionospheric absorption, very little is known of the radio sky beyond 10 m wavelength. We propose an extremely simple, low-cost very low frequency radio telescope, consisting of a large (approximately 15 by 30 km) array of short wires laid on the lunar surface, each wire equipped with an amplifier and a digitizer, and connected to a common computer. The telescope could do simultaneous multifrequency observations of much of the visible sky with high resolution in the 10- to 100-m wavelength range, and with lower resolution in the 100- to possibly 1000-m range. It would explore structure and spectra of galactic and extragalactic point sources, objects, and clouds, and would produce detailed quasi-three-dimensional mapping of interstellar matter within several thousand parsecs of the Sun.

Introduction

The spectral window through which ground-based radio astronomers can make observations spans about five decades of wavelength, from a bit less than a millimeter to something more than 10 m. The millimeter cutoff produced by molecular absorption in the Earth's atmosphere is fairly stable, but the long-wavelength cutoff caused by the terrestrial ionosphere is highly variable with sunspot-cycle, annual, and diurnal effects; scintillation on much shorter time scales is also present. Radiofrequency interference imposes further limits, making observations at wavelengths longer than 10 m normally frustrating and frequently impossible.

Consequently, the radio sky at wavelengths longer than 10 m is poorly observed and virtually unknown for wavelengths longer than 30 m, except for a few observations with extremely poor resolution made from satellites. Exploration of the radio sky at wavelengths longer than 30 m must be performed from beyond the Earth's ionosphere, preferably from the far side of the Moon, where physical shielding completes the removal of natural and manmade terrestrial interference that the inverse-square law has already greatly weakened.

The Long-Wavelength Radio Sky

What may we expect in the long-wavelength radio sky (apart from the unexpected, which experience often shows to be more important)?

First, nonthermal radiation from plasma instabilities in solar system objects is present in rich variety, especially from the Sun, Jupiter, Saturn, and Earth itself. This phenomenon was unexpectedly discovered by telescopes flown for other purposes.

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Second, the synchrotron radiation from the galaxy reaches a peak of intensity near a frequency of 4 MHz, or a wavelength  $\lambda$  of 75 m, then drops off as absorption by ionized hydrogen becomes important, and possibly for other reasons as well. This behavior has been seen by the low-resolution (20° beam) telescopes already flown.

Third, the plane of the Milky Way – already dimming at  $\lambda = 10$  m – becomes even more absorbed by ionized hydrogen, and many black blots of HII regions are seen in absorption against the bright radiation background. Such clouds, having emission measure that is too small to be noticed optically, would be obvious using a moderate- to high-resolution (1° to 0.1°) very low frequency (VLF) telescope. At longer wavelengths, our distance penetration becomes increasingly limited, decreasing with the square of the wavelength until, by 300 m, unit optical depth corresponds to only a few hundred parsecs.

Fourth, extragalactic discrete sources continue to be visible as wavelength increases (outside the gradually expanding zone of avoidance at low galactic latitudes), and their spectra can be measured, although their angular structure will be increasingly distorted by interstellar and interplanetary scattering. At these wavelengths, it is the expanded halo parts of such objects which are viewed, and inversions will be noted in the spectra of many. For wavelengths longer than about 300 m, HII absorption in our own galaxy will effectively prevent extragalactic observations, even at the galactic poles, and, at wavelengths longer than a kilometer or so, we will be limited to studying objects within a few tens of parsecs of the Sun.

Finally, there may be features of the sky which can be studied for the first time through the use of a high-resolution and high-sensitivity telescope at long wavelengths. These features include

1. Nonthermal emission from stars and planets or other such sources within a few parsecs (if any of these are significantly more powerful than the Sun and the Earth)
2. Radio emission of very steep spectra from new classes of galactic or extragalactic discrete sources that may have gone undetected to date in even the faintest surveys at short wavelengths, yet be detectably strong at 100 m
3. Nearby and compact gas clouds, visible in absorption, the presence of which has hitherto been unsuspected
4. Fine-scale structure in the galactic emission, which – given data at high resolution and multiple low frequencies – can be studied in depth as well as direction

The proposed telescope should provide a uniquely detailed and effectively three-dimensional map of interstellar matter in the galaxy to distances of thousands of parsecs.

### The Lunar VLF Observatory

As noted previously, the low-frequency telescopes flown to date have had very poor resolution, although they have been valuable for some studies on very bright sources; e.g., dynamic spectra of the Sun, the Earth, and Jupiter, and the cosmic noise spectrum. Significant advances, however, will require high resolution (say 1°, corresponding to 15 km aperture at 300 m wavelength) and high sensitivity (many elements). A lunar base offers probably the best location in the solar system for constructing an efficient low-cost VLF radio telescope.

In contemplating any lunar-based experiment, the question must first be asked whether it is preferable to perform the work in free space. For the proposed VLF observatory, the Moon offers a number of advantages.

1. It is an excellent platform, capable of holding very large numbers of antenna elements in perfectly stable relative positions over tens or even hundreds of kilometers' separation. (This configuration would be excessively difficult and expensive to achieve in orbit.)

2. The initial telescope can be modest, though still useful, and can be expanded to include thousands of antenna elements added in the course of traverses of lunar terrain undertaken at least in part for other purposes.

3. The dry dielectric lunar regolith permits simply laying the short thin-wire antenna elements on the surface. No structures, difficult to build and maintain, are required.

4. Lunar rotation provides a monthly scan of the sky.

5. The lunar far side is shielded from terrestrial interference, although even the near side offers orders-of-magnitude improvement over Earth orbit because of the inverse-square law, and because of the much smaller solid angle in the sky presented by the Earth.

### Limiting Factors

Various natural factors limit the performance of a lunar VLF observatory.

Long-wavelength limits. - The following limits on long wavelengths apply.

1. Interplanetary plasma at a distance of 1 AU has about 5 electrons/cm<sup>3</sup> corresponding to a plasma frequency ( $f_p$ ) of 20 KHz, or a wavelength of 15 km.

2. The Moon may have an ionosphere of much higher density than that of the solar wind;  $10^{-12}$  torr corresponds to about 40 000 particles/cm<sup>3</sup>, if the mean molecular weight is 20. If such an atmosphere were fully singly ionized,  $f_p$  would be around 1.8 MHz, usefully but not vastly better than the typical values for the Earth of around 9 MHz. However, ground-based observations of lunar occultations suggest that electron density  $N_e$  is actually less than 100 electrons/cm<sup>3</sup>. In this case,  $f_p$  would be less than 90 KHz (wavelength 4 km), and would set no practical limit to very low frequency lunar radio astronomy. It will clearly be very important for detailed planning of the lunar VLF observatory to have good measures of the lunar mean electron density and its diurnal variations.

Scattering. - Performance limits introduced by scattering and scintillation are as follows.

1. The interstellar medium produces scattering and scintillation, which result in the angular broadening of sources; e.g., the angular size of an extragalactic point source would be about 8 arcsec if observed at 30 m wavelength. The size grows with wavelength to the 2.2 power, becoming 20 arcmin at 300 m.

2. Interplanetary scintillation is more important. Obeying essentially the same wavelength dependence as interstellar scintillation, it ranges from about 50 arcsec at 30 m to a few degrees at 300 m (1 MHz). However, it is still worthwhile to design the telescope with higher resolution than 2° at 1 MHz, since techniques analogous to speckle interferometry may recover resolution down to the limits set by interstellar scintillation, which will be relatively small especially for nearby sources in our galaxy.

Interference. - Natural interference factors limiting performance include the following.

1. Solar: The intensity of the cosmic background radiation is on the order of  $10-20 \text{ W m}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$ . The Sun is already known to emit bursts stronger than this by an order of magnitude in the VLF range; therefore, the most sensitive observations may have to be performed during lunar night.

2. Terrestrial: Near-side location will always expose the telescope to terrestrial radiations. Consider two known types: auroral kilometric radiation is strong between 100 and 600 kHz; an extremely strong burst would produce flux density at the Moon of about  $2 \times 10^{-15} \text{ W m}^{-2} \text{ Hz}^{-1}$  - far stronger than the cosmic noise we are trying to study. Fortunately, it is sporadic and limited to low frequencies. Also, it probably comes from fairly small areas in the auroral zones, so that its angular size as seen from the Moon will be small. Lunar VLF observations below 1 MHz will therefore be limited unless the telescope is highly directive with very low side lobes or built on the lunar far side.

Terrestrial radio transmitters may leak through the ionosphere in the short-wavelength portions of the spectrum of interest. If we assume a 1-MW transmitter on Earth with a 10-kHz bandwidth, the flux density at the Moon would be about  $5 \times 10^{-17} \text{ W m}^{-2} \text{ Hz}^{-1}$  without allowing for ionospheric shielding. This would be a serious problem; much weaker transmitters with some ionospheric shielding would merely be an occasional nuisance. Again, this is an argument in favor of a far-side location, particularly for frequencies above 4 MHz or so.

#### Considerations of Telescope Design

It would be futile to perform a detailed telescope design at this point; however, some general considerations can be addressed.

Frequency range. - The telescope should be broadband, but it should be capable of observing in very narrow bands over the broad range to deal with narrow-band interference. The upper limit of frequency should be around 10 MHz ( $\lambda = 30 \text{ m}$ ). Even though this wavelength can be observed from the ground, it is extraordinarily difficult to do so. The initial normal lower limit should be about 1 MHz ( $\lambda = 300 \text{ m}$ ), although the capability for extending observations with reduced resolution to substantially longer wavelengths should be retained.

Resolution. - It is probably useless to attempt resolution at any given frequency better than the limit imposed by interstellar scintillation; e.g., about 20 arcmin at 1 MHz. A reasonable initial target resolution for the observatory might be  $1^\circ$  at 1 MHz. Although this is somewhat better resolution than the limit normally set by interplanetary scintillation, it is probably attainable using restoration procedures. This choice of target resolution implies antenna dimensions of 15 by 15 km for a square filled array, or of 30 by 15 km for a T configuration.

Filling factor. - A  $1^\circ$  beam may be synthesized from a completely filled aperture (100 by 100 elements, for a total of  $10^4$ ) or by a T, one arm of which has 200 elements, the other 100, for a total of 300 elements - far less than the completely filled aperture. Many other ways of filling a dilute aperture also exist, including a purely random scattering of elements over the aperture. The filled array has far greater sensitivity, but, what is also important in this context, it has much better dynamic range and a cleaner main beam. This will be of great benefit in mapping the galactic background, particularly in looking at the regions of absorption, which will be of much interest at these frequencies. The sensitivity of the filled array is also decidedly better: a  $1^\circ$  beam produced by a filled aperture at 1 MHz with a bandwidth of 1 kHz and an integration of 1 minute has an rms sensitivity of 1 Jy; the same sensitivity would require an integration of 1 day with the dilute array of 300 elements. The most sensible approach is probably to begin with a dilute aperture and work

toward the filled one and thus to increase the power of the system as more antenna elements are set out.

Telescope construction.- The telescope would be an array of many elements. Each element should be thought of as a field sensor, or a very short dipole, rather than as an ordinary beam-forming antenna. The inefficiency of such devices can be great before noise of the succeeding electronics becomes a factor, in view of the high brightness temperature of the cosmic background radiation. An analog-to-digital converter at each element would put the telescope on a digital footing immediately. The exceedingly low power requirement at each antenna element could be met with a tiny solar-powered battery large enough to carry its element through the lunar night.

Communication with the telescope computer at lunar base via radio or perhaps by individual optical-fiber links would bring all elements together for correlation. Bandwidth of the links need only be about 1 kHz per element if only one frequency is to be observed at a time, although maximum bandwidth consistent with economics will produce maximal simultaneous frequency coverage. In any event, the central computer will produce instant images of a large part of the visible hemisphere with the  $1^\circ$  resolution, at one or many frequencies, which can be processed for removal of radiofrequency interference and bursts prior to long integrations for sky maps at various frequencies in the sensitivity range of the system.

Short-wavelength operation.- Operation at the short-wavelength boundary of the telescope range will be a different proposition. Element spacing for 1 MHz is very dilute indeed for 10 MHz; some portion will have to be more densely filled, and operated against the rest of the system as a dilute aperture. At 10 MHz, the system would have a resolution of about  $0.1^\circ$ . In this way, an extremely powerful telescope for work both on extragalactic sources and on galactic structure would result.

### Establishing the VLF Observatory

The individual antenna elements – short wires – will probably each weigh about 50 g. Their associated microminiaturized amplifiers, digitizers, transmitters, and solar batteries can all be on several tiny chips in a package of similar weight. Allowing for packaging for shipment to the Moon, the initial array should still weigh less than 50 kg! Materials for the entire filled array would only need about a ton of payload. If individual optical-fiber couplings to the central computer are used, each of these should add only a few tens of grams to the total and thus should not appreciably affect the extraordinarily small cost of transporting the system to the Moon.

Of course, to process the full stream of digital information continuously, a powerful computer is required. Some on-base short-term storage of processed data is probably also desirable, but such data would presumably be dumped back to Earth at frequent intervals. Again, with the increasing miniaturization yet steady growth in power of computer hardware over the next 20 years, the required computer facilities also may be expected to weigh less than a hundred kilograms. It thus seems clear that at least the initial, and quite possibly the ultimate, VLF observatory system could be carried to the Moon as a rather modest part of the first scientific payload.

Laying out the initial system of several hundred antenna elements on the lunar regolith should require only a few days of work with the aid of an upgraded lunar rover having appropriate speed and range. (Such vehicles will be an essential adjunct of any lunar base for exploration, geological and other studies, and general service activities.) The elements need not be placed in accurately predetermined positions, but their actual relative positions need to be known to a precision of about a meter. This determination can easily be made, as the layout proceeds, by surveying with a laser geodimeter. The conspicuous tire marks produced by the rover vehicle will delineate the sites of each

of the antenna elements for future maintenance or expansion of the system. A concentrated month using two vehicles each carrying teams of perhaps three workers would probably suffice to lay out the full proposed field of 100 by 100 elements.

These estimates, although necessarily rough at this preliminary stage of planning, strongly suggest that because of its extreme simplicity and economy, its almost unique suitability for lunar deployment, and its high scientific promise, the VLF observatory is a major contender for being the initial lunar observatory – perhaps even the first substantial scientific project that should be undertaken from a lunar base.