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# A low frequency radio array for space

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**Summary.** At the lowest radio frequencies (< 30 MHz), the Earth's ionosphere transmits poorly or not at all. This relatively unexplored region of the electromagnetic spectrum is thus an area where high resolution, high sensitivity observations from space can open a new window for astronomical investigations. An array of free flying spacecraft which work as a coherent interferometer will be able to probe this frequency range. Operating from ~1 to ~30 MHz, such a telescope will extend astronomy from just above the ionospheric cutoff, where ground based observations can still be done, down to the fundamental physical limit where observations at still lower frequencies from within the Milky Way are impossible due to absorption by diffuse, ionized interstellar hydrogen.

The scientific rewards of such a space mission are likely to be great. Even without considering the serendipitous discoveries which have always accompanied the opening of a new realm of frequency, resolution, or sensitivity in astronomy, a low frequency telescope in space can map in detail the galactic background synchrotron emission; determine the distribution of diffuse, ionized interstellar hydrogen absorption along lines of sight to discrete background sources; study individual radio source spectra for energy production and absorption/loss mechanisms; search for fossil radio components in radio quiet objects; extend statistical cosmology studies of radio sources to the low frequencies where synchrotron lifetimes approach the age of the universe; study the impulsive low frequency emission from Jupiter and the Sun and search for similar radiation from other Solar System bodies; and search for the coherent plasma oscillations found from Solar System bodies but undetected so far in larger systems.

**Key words:** instruments – interferometry – radio continuum – radio telescopes – space vehicles

## 1. Introduction

Although radio astronomy started at the low frequency of 20.5 MHz (wavelength 14.5 m) just above the ionospheric cutoff (Jansky, 1933a–c), the major efforts of its workers quickly moved to higher frequencies where ionospheric disturbances are minimal and where good resolution can be obtained with reasonable sized telescopes. Only a few dedicated workers have continued to study the dekameter-hectometer wavelength radiation.

The most extensive investigations at the very lowest frequencies have been carried out with the Radio Astronomy Explorer (RAE) satellites 1 and 2 (Weber, Alexander, and Stone, 1971; Alexander and Novaco, 1974) in Earth and lunar orbit, respectively. They were launched at different dates and used as single survey antennas with their travelling wave V-antennas yielding only steradian resolution. Ground-based observations are normally confined to frequencies > 10 MHz during solar minimum or > 20 MHz during solar maximum, and only under special conditions at preferred locations does the ionosphere transmit radiation at frequencies as low as 2 to 5 MHz (Reber, 1968; Ellis and Hamilton, 1966). The Llanherne array in Tasmania has produced galactic surveys at 3.7 and 8 MHz, but with relatively low resolution [5°.6 at 3.7 MHz (Cane, 1975) and 2°.6 at 8 MHz (Cane and Whitham, 1977)]. At 10 to 30 MHz and above, several ground-based surveys exist (Bridle and Purton, 1968; Hamilton and Haynes, 1968; Caswell, 1968; Viner and Erickson, 1975; Braude et al., 1979), which would permit a connection of new results to earlier work and to higher frequency observations. However, even these higher frequency surveys have been carried out only with relatively low resolution.

The possibility for launching radio telescopes into space combined with the well developed techniques of Very Long Baseline Interferometry (VLBI) means that it is time to reconsider these relatively neglected frequencies and to pursue the high sensitivity, high resolution observations which have heretofore been impossible. These lowest frequencies represent a region of the electromagnetic spectrum that is essentially unexplored by astronomy but which, at $\sim 10^6$ Hz, is likely to display phenomena as different from those at centimeter radio wavelengths ($\sim 10^9$ Hz) as centimeter radio phenomena are from infrared ($\sim 10^{12}$ Hz), or infrared are from ultraviolet ($\sim 10^{15}$ Hz), or ultraviolet are from x-ray ($\sim 10^{18}$ Hz). Because of this large gap in our knowledge, even though many valuable projects can already be specified for a new instrument, the likelihood of discovering new processes and objects is great. Also, observing at frequencies as low as ~1 MHz extends astronomy to the lowest practicable physical limit for studying electromagnetic radiation from within our Galaxy. At still lower frequencies the diffuse, interstellar ionized hydrogen gives very high absorption over relatively short path lengths (Alexander et al., 1969), effectively cutting off our view of distant celestial objects.

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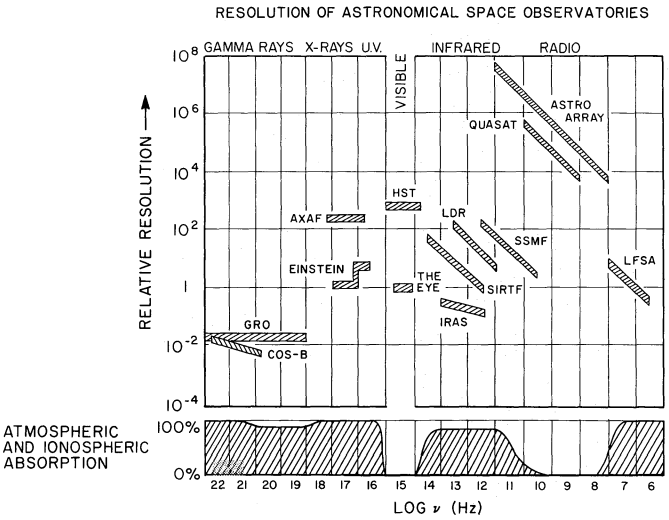


**Fig. 1.** Top – Schematic representation of some recent or planned space observatories showing their relative resolution (vertical axis; best resolution at top) vs. frequency. Bottom – Schematic representation of the average absorption by the atmosphere and ionosphere in per cent (vertical axis) vs. frequency. (Acronyms: AXAF = Advanced X-ray Astrophysics Facility; GRO = Gamma Ray Observatory; HST = Hubble Space Telescope; IRAS = InfraRed Astronomy Satellite; LDR = Large Deployable Reflector; LFSA = Low Frequency Space Array; QUASAT = QUAsar SATellite; SIRTF = Space Infrared Telescope Facility; SSMF = Space Station Millimeter Facility) An LFSA would provide unique capability at the inaccessible low radio frequencies

Let us consider, therefore, the need for and possibility of constructing and operating a low frequency array in space, a Low Frequency Space Array (LFSA), to form an entirely space-based synthesis interferometer for high resolution, high sensitivity sky surveying and source imaging over the frequency range from $\sim 1$ to $\sim 30$ MHz. [For a more detailed description see Dennison et al. (1986)]. The unique and complementary role which an LFSA would play with respect to other space observatories is illustrated in Fig. 1.

## 2. Scientific programs

A Low Frequency Space Array would be a powerful tool for investigating a broad range of known astrophysical phenomena. Study of the distributed background emission of the Milky Way is a rewarding task in all parts of the electromagnetic spectrum with different frequencies emphasizing different physical processes. For example, the COS-B survey of $\gamma$-ray emission is sensitive to the interaction of cosmic rays with the ambient interstellar gas; the well known optical Palomar Sky Survey emphasizes stars and ionized hydrogen (H II) regions; and the IRAS survey enhances visibility of the relatively cold interstellar dust. Radio frequency studies (see, e.g., Haslam et al., 1982 at 408 MHz; Wielebinski et al., 1968 at 151 MHz; Milogradov-Turin and Smith, 1973 at 38 MHz; Jones and Finlay, 1974 at 29.9 MHz) are most sensitive to the relativistic electron component of cosmic rays and the distribution of interstellar magnetic fields. Low frequency observations may be able to distinguish regions in the Galaxy with different spectral properties and provide clues to the relevant cosmic ray $e^-$ loss and injection mechanisms. Existing surveys do not have sufficient resolution or provide sufficient spectral range to do this.

By measuring spectral index values and distributions, it should also be possible to test the theories on whether the observed loop-like features are old remnants from nearby supernovae (Berkhuijsen, 1971) or loops of magnetic field and particles leaking out of the galactic plane (Parker, 1965). At the low frequencies which an LFSA would operate, the lifetime of the synchrotron electrons is a significant fraction of the age of the universe ($\sim 3\ 10^9$ yr at 1 MHz) so that electron distributions are relatively unaltered by evolutionary effects.

By observing a large number of extragalactic radio sources and determining their low frequency spectra as a function of galactic latitude and longitude, it would be possible to measure the changes due to absorption by the diffuse, interstellar gas in the Milky Way and thereby investigate its distribution. By combining the survey results at several frequencies and the low resolution, higher frequency maps from the literature, the thermal absorption and synchrotron emission components of the Galaxy could be separated to test models for a warm ($T_e \sim 10^4$ K) disk of ionized hydrogen imbedded in a hot ($T_e \sim 10^6$ K) galactic halo. A global picture of the free-free absorption could also be obtained for comparison with existing higher frequency pulsar dispersion and Faraday polarization rotation measurements and with the COS-B $\gamma$-ray measurements which are related to the local cosmic ray energy and interstellar gas density.

A complementary technique to studying the diffuse free-free absorption would be use of nearby ionized hydrogen (H II) regions, which are opaque at such low frequencies, to completely block the synchrotron radiation from more distant parts of the Galaxy. Any remaining emissivity is attributable solely to the radiation arising between the observer and the H II region, yielding measurements of the local cosmic ray $e^-$ and magnetic field components. This technique has, so far, been successfully employed only in a small number of cases but it could be extended by the superior sensitivity and resolution of an LFSA to many more lines of sight.

It is generally accepted that small scale ($\sim 10^9$ cm) fluctuations in electron density in the interstellar medium can diffractively scatter radio waves from a background source (Dennison et al., 1984). Less clear, yet of considerable importance, is the ability of somewhat larger irregularities ($\sim 10^{13}$ cm) to refractively focus and defocus radio waves. Such refractive scintillation has been proposed as the origin of some low-frequency variability observed in compact extragalactic sources (Shapirovskaya, 1978; Rickett et al., 1984). It is likely that interstellar plasma irregularities, in fact, occur on many spatial scales and Rickett (1977) characterizes them by a power spectrum. Some major questions remain concerning interstellar scattering such as:

1. the correct form of the irregularity power spectrum, the values of its power law index, and the inner and outer size scales;
2. the isotropy of the irregularity spectrum and of the scattering;
3. the origin of the turbulence and how is it distributed throughout the Galaxy; and
4. the relationship between the turbulence and the known phases of the interstellar medium (ISM).

Because the scattering and refraction angles scale roughly as $\lambda^{2.2}$, these effects would be quite large at low frequencies (see Table 1), causing measurable angular broadening of many of the discrete sources in the all-sky surveys at $\leqq 10$ MHz. From the appearance of the broadened images, it would also be possible to evaluate refractive effects. If present, refraction should produce a patchy or even multiple image (Goodman and Narayan, 1985) and would be evidence for quite large (0.01–1.0 pc) refracting

structures in the ISM. On the other hand, if the broadening is dominated by diffraction, the images should appear smooth.

Very little is known about the properties of individual radio sources at low frequencies. However, the capability of an LFSA would be such that thousands (see Table 2) of discrete sources would be detected and the brighter ones could be studied for such properties as integrated spectrum, surface brightness and spectral index distribution, and source counts ("$\log N - \log S$"). For this last, since the relativistic electrons which an LFSA would detect are generally far older than those normally studied by radio astronomy, the possible appearance of "fossil" steep spectrum sources not observable at higher frequencies would impact theories for the evolution and lifetime of radio sources and of the universe.

It has long been known that the spectral index $\alpha$ describing the change of flux density $S$ with frequency $\nu$ ($S \propto \nu^{+\alpha}$) is a function of frequency $\alpha(\nu)$ and that measurement of this frequency dependence is important for understanding the physics of the emission and absorption processes in the sources. Determination of $\alpha(\nu)$ requires measurements of source flux densities at all frequencies and, in particular, at low frequencies where a number of absorptive and emissive processes become prominent. At present, very little in known about source spectra at frequencies as low as 20 MHz and practically nothing has been measured for $\nu < 10$ MHz. It is thus an important capability of an LFSA to provide such information at multiple frequencies throughout this poorly explored range and to investigate the complex physical processes involved.

Enhanced emission from sources at the lowest frequencies and thereby new classes of radio sources can be anticipated due to a number of phenomena. The possibility of new "fossil" electron components becoming visible has already been mentioned and there is already known to exist a class of sources with steeply declining spectra ($\alpha < -1$) which are only detectable at low frequencies (Baldwin and Scott, 1973). These last display no peak in their spectra and appear to increase monotonically in flux density to the lowest measured frequencies.

Some low frequency sources are quite large ($\sim 1$ Mpc) and are associated with clusters of galaxies. Apparently, such sources are rare (Jaffe and Rudnick, 1979) and the conditions under which they occur are not well understood. At present only a small number of these cluster halo sources are known, with the Coma Cluster providing the best example. Because of their typically quite steep spectra, they are best studied at very low frequencies to determine the physical conditions which give rise to this cluster halo emission. If the relativistic electrons have leaked from radio galaxies in the cluster, then they must propagate with speeds in excess of the local Alfven speed in order to reach the periphery of the halo source in less than a radiative lifetime (Jaffe, 1979). Models have been proposed in which electrons are formed (Dennison, 1980) or are accelerated in the intracluster medium (Roland, 1981) and an LFSA, which would sample a very old population of electrons, would be able to test such models.

Many radio sources display a spectrum which peaks in flux density at some intermediate frequency and declines both above and below that. For extended sources the frequency of peak flux density is usually quite low and in some cases this turnover is presumed to occur at frequencies below present observational limits. Since the emission process is assumed to be synchrotron radiation with a constant power law index, a decline at low frequencies is usually attributed to one of three absorption processes: 1) external, ionized hydrogen, free-free absorption; 2) internal free-free absorption, and 3) synchrotron self absorption. Additionally, while not strictly an absorption process, the Razin-Tsytovich effect can suppress low frequency emission.

**Table 1.** Estimated scattering diameters for galactic latitude $|b| > 30°$

| Frequency (MHz) | Scattering Diameter (arcsec) | Max. Useful Baselines (km) |
|---|---|---|
| 1.5 | 300–1800 | 20– 130 |
| 4.4 | 50– 150 | 100– 300 |
| 13.1 | 6– 20 | 300–1000 |
| 25.6 | 1– 3 | 1000–3000 |

**Table 2.** Estimated capability of a low frequency space array (LFSA)

| Freq. (MHz) | $T_s$ (K) | $t$ (sec) | $A_e$ ($m^2$) | $\sigma$ (Jy) | $N_{det}$ | Appx. Resol. [a] |
|---|---|---|---|---|---|---|
| 1.5 | $3\ 10^7$ | $7.5\ 10^6$ | 2400 | 40 | 1300 | $\sim 0\overset{\circ}{.}1$ |
| 4.4 | $5\ 10^6$ | $3.8\ 10^6$ | 1000 | 9 | 5000 | $\sim 1'$ |
| 13.1 | $3\ 10^5$ | $1.5\ 10^6$ | 400 | 3 | 6000 | $\sim 0\overset{'}{.}3$ |
| 25.6 | $3\ 10^4$ | $\sim 10^6$ | 175 | 1.5 | 10000 | $\sim 10''$ |

[a] The maximum resolution is generally limited by the interstellar scattering (see Table 1).

$T_s$ = Effective system temperature (determined by the galactic background emission)
$t$ = Integration time = (0.5 data loss factor) × 1 year/antenna directivity
$A_e$ = Total effective array aperture = 4 × effective aperture per antenna
$\sigma$ = Rms error (assuming 2 polarization channels, 50 kHz bandwidth per channel, and a sensitivity constant of 2)
$N_{det}$ = Number of detectable sources [extrapolated from the Clark Lake survey (Viner and Erickson, 1975)]

External free-free absorption modifies the observed spectrum by the factor $e^{-\tau}$ while for an internal mixture of emitting and absorbing regions, the factor is $(1-e^{-\tau})\tau^{-1}$. Thus, for a simple case one can choose between mechanisms on the basis of the observed spectrum, calculate the optical depth $\tau$, and estimate the integral electron density ($N_e$) and temperature ($T_e$) along the path (l) through the absorbing medium at frequency $\nu\,[\tau \propto \int N_e^2\, dl/(\nu^2\, T_e^{1.5})]$.

When the apparent brightness temperature of a source approaches the equivalent kinetic temperature of the relativistic electrons, part of the synchrotron emission is reabsorbed. In the approximation of an optically thick relativistic electron gas, the flux density below the turnover would be $S \propto B^{-0.5}\,\theta^2\,\nu^{2.5}$ where $\theta$ is the source angular size, $B$ is the magnetic field strength, and $\nu$ is the observing frequency. Therefore, an observed decrease in the flux density below turnover with the power $\nu^{2.5}$ indicates synchrotron self absorption and, if the source size is known, allows the estimation of the internal magnetic field strength.

If the plasma density is sufficiently large that the index of refraction of the medium must be taken into account, the synchrotron emission is no longer concentrated along the electron trajectories and the higher harmonics are suppressed. This Razin-Tsytovich effect cuts off the spectrum very sharply below $\nu \sim 20\, N_e/B$ MHz and is easily recognizable compared to absorption processes.

Therefore, observations of turnover spectrum sources at low frequencies will provide important astrophysical information on thermal electron densities, temperatures, and distributions as well as on magnetic field strengths and relativistic particle densities and lifetimes.

A number of loss processes can affect the energy of relativistic electrons and these alter the observed spectrum in different ways. For example (Longair, 1981), if $\gamma$ is the power law index of the relativistic electron energy spectrum $N(E) \propto E^{-\gamma}$ [N.B.: It can be shown that this cosmic ray energy index $\gamma$ is related to the radio spectral index $\alpha$ by $\gamma = (1-2\alpha)$.] and ionization losses dominate, then $N(E) \propto E^{-(\gamma-1)}$ (i.e., the observed spectral index $\alpha$ is flatter by 0.5). If bremsstrahlung or adiabatic losses dominate, then $N(E) \propto E^{-\gamma}$ (i.e., the spectral index $\alpha$ is unchanged) and if inverse Compton or synchrotron losses dominate, then $N(E) \propto E^{-(\gamma+1)}$ (i.e., the index $\alpha$ is steeper by 0.5). Thus, if an estimate can be made of the dominant energy loss processes and magnetic field strengths, detection of breaks in the radio spectrum permits the determination of the approximate age of the relativistic electrons being observed.

Since the number of relativistic electrons increases very rapidly with decreasing energy ($\gamma \sim 2.5$), at some point acceleration mechanisms must cease in order to avoid an infinite energy content for radio galaxies. Searches have been made (Hamilton and Haynes, 1968; Erickson and Cronyn, 1965; Roger et al., 1973) but such a cutoff has never been clearly identified and the accurate determination of radio source spectra down to the lowest frequencies is required.

Since an LFSA would have resolution ($<1'$) which is typical for source studies made at much shorter wavelengths, the detailed mapping of supernova remnants, normal galaxy disks, normal galaxy halos, radio galaxies and quasars, radio tails, component bridges, and distributed emission from clusters of galaxies to deeper levels and greater extensions would permit the accurate determination of spectral index distributions across extended objects and searches for evolutionary effects in component motions and/or electron distributions. Perley and Erickson (1979) have done this for a few giant radio galaxies and Winter, et al. (1980) have studied the bridges in Cygnus A. Such information helps to identify relativistic electron injection, acceleration, diffusion, and evolution processes which are still only poorly understood. Also, high resolution studies at low frequencies would allow direct comparisons with other wavelength bands such as optical, x-ray, and $\gamma$-ray where surveys and individual source studies with comparable resolution exist.

The spectra of most pulsars turn over in the 100 to 500 MHz range, but a few, interesting, fast pulsars have spectra which are very steep and flux densities which continue to increase down to the lowest observed frequency of $\sim$10 MHz. Two examples are the Crab Nebula pulsar (PSR 0531+219) (Bobeiko et al., 1979) and the millisecond pulsar (PSR 1937+214) (Erickson and Mahoney, 1985). These pulsars are among the strongest sources in the sky at 10 MHz so that LFSA observations would be able to discover other, similar objects. Also, to avoid radiating infinite power, the spectra of these pulsars must turn over at some frequency below 10 MHz and measurement of this turnover frequency would provide information on the spatial structure of the coherently radiating electrons in the pulsar's magnetosphere.

A very exciting possibility at low frequencies is the detection of coherent radiation. There are valid physical reasons to anticipate that the smaller distance between individual radiating electrons measured in terms of the electromagnetic wavelength is likely to amplify collective radiative modes. In such a plasma, the ratio of stimulated emission to spontaneous emission could be very high, varying as $\nu^{-3}$. If an inverted energy level population can be established and is sufficiently long lived, there are numerous collective modes which can be excited by instabilities in the magnetoactive plasma. Enhanced radiation should be generated at critical frequencies such as the plasma and gyro resonances and, in an inhomogeneous medium or in the non-linear case, coupling between modes can occur to produce wave amplification. In fact, the occurrence of coherent emission at low frequencies appears to be the rule rather than the exception for solar system objects such as the Sun, the major planets, and the magnetosphere of the Earth. Since objects such as the Crab Nebula, Seyfert galaxies, and quasars typically have densities of $\sim 10^4$ to $10^5\,\mathrm{cm}^{-3}$ and magnetic fields $<1$ Gauss, one may anticipate an analogous situation leading to coherent plasma phenomena in the 1 to 3 MHz range.

In the 1 to 10 MHz frequency range, the effective surface of the Sun ranges from 3 to 30 $R_\odot$ and, from the active corona, intense emission is to be expected at low frequencies. For the long lived emission centers, an LFSA would allow mapping of the propagation of electron streams through the corona (Type III emission) and propagation of coronal shock waves (Type II emission).

Extensive Earth-based and spacecraft-based observations have revealed the rich phenomenology of Jupiter's nonthermal emission (Carr et al., 1983). However, owing to disturbance by the Earth's ionosphere, no direct information exists on its location within the jovian magnetosphere. In a major review of the field, Goldstein and Goertz (1983) stress the importance of position determinations for theoretical understanding of the emission processes. Even such very basic questions as in which hemisphere the various emissions originate and possible association of the emission with the jovian aurora or the satellite Io still need to be answered in order to understand the physical processes involved.

At the relatively unexplored low radio frequencies, new processes and phenomena which we cannot now predict may be encountered, even in apparently well studied objects. For example, supernova remnants are thought to be well understood globally even though many details remain elusive. Shell-type

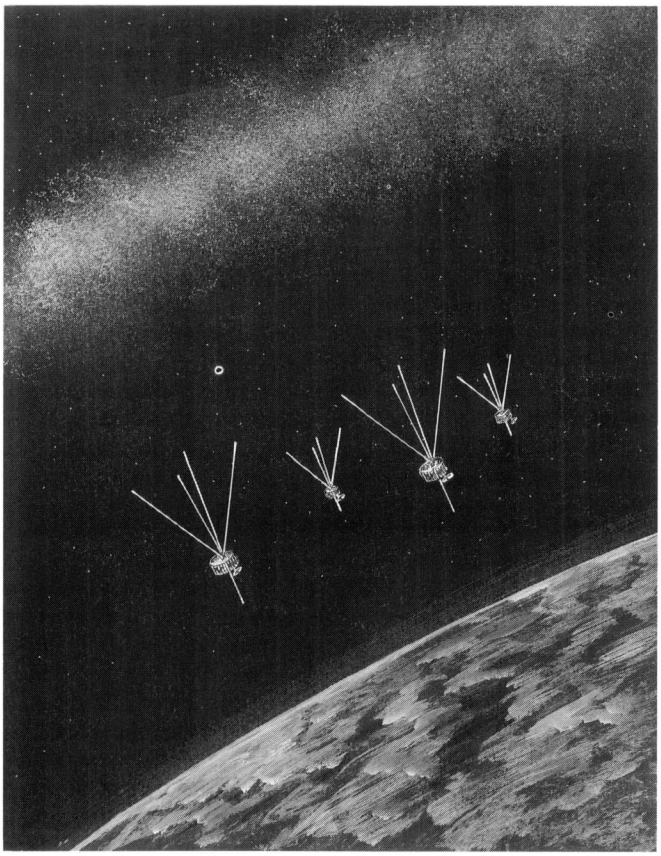

**Fig. 2.** Artist's conception of a Low Frequency Space Array (LFSA) with four array elements

remnants arise from shock waves expanding into and interacting with the interstellar medium and generating radio emission through Rayleigh-Taylor instabilities accelerating relativistic electrons (Gull, 1973a, b). Therefore, a remnant like Cassiopeia A (SN ~ 1670) is expected to decay slowly in flux density due to adiabatic energy losses (Shklovsky, 1968) and a decrease of roughly the proper magnitude has been observed at high frequencies (Baars et al., 1977). However, this tidy picture may need to be modified. A series of observations by Erickson and Perley (1975) show that Cas A *increased* in flux density at 39 MHz at a rate of ~1.5% per year between 1967 and 1975. This may represent observation of the shock acceleration process in action, but it remains unusual in that it appears to only occur at low frequencies. Unexpected low frequency phenomena occurring in "normal" objects is thus a tantalizing possibility.

## 3. Spacecraft description

A possible instrumental concept for an LFSA is that a single spacecraft bus places a number of free-flying antennas (array elements) into circular orbits at an inclination of ~100° to ~120° with a semi-major axis of ~8,000 to ~10,000 km. The orbits would be chosen with small differences so that the array elements travel in a pulsating and slowly changing formation to give a coherent, multiple baseline interferometer. A minimum of 4 array elements would be needed to provide a basic instantaneous mapping capability and, more importantly, for permitting the use of such data correction and calibration techniques as phase and amplitude closure. The bus itself would play no role other than providing final orbit injection.

The array elements would all be identical spacecraft with gravity gradient stabilized, outwardly pointing, broad beam, wide bandwidth antennas and full polarization capability. Travelling wave "*V*" antennas (Balinas, 1982; Iizuka, 1967) such as those used on the Radio Astronomy Explorer (RAE) satellites (Weber et al., 1971; Duff, 1964; Iizuka and King, 1965), but with shorter and stiffer arms of ~85 meters length, are a possible antenna form, using crossed "*Vs*" to give full circular polarization capability. Travelling wave "*Vs*" provide numerous possible operating frequencies with good efficiency, large beamwidth, and significant effective collecting area.

No spacecraft active stabilization or pointing capability would be needed, the antennas being pointed radially outward and stabilized by the gravity gradient. In this manner, the whole sky would be covered by the orbital sweep and nodal precession of the spacecraft. An artist's conception of how an LFSA might look in orbit is presented in Fig. 2.

Because the system temperture would always be dominated by the galactic background radiation (see Table 2), the receiver temperature is relatively unimportant. State-of-the-art components would be used, but no cooling or special developments are likely to be needed.

Initial receiver configurations might be near 1.5, 4.4, 13.1, and 25.6 MHz with individual bandwidths of ~50 kHz. These receiver center frequencies would cover the range from the lowest possible above the diffuse interstellar ionized hydrogen cutoff (~1 MHz) to the point where ionospheric limitations become much less severe for ground based observations (~30 MHz), with steps no larger than factors of 2 to 3 between bands. Additionally, near 25.6 and 13.1 MHz there exist protected radio astronomy bands which, as far as possible, would be utilized to reduce problems with man-made interference. Receiver bandwidths of 50 kHz are suggested as a compromise between the susceptibility to interference of wide bandwidths and the poor sensitivity of narrow bandwidths. Because of the presence of powerful bursting emission from the Earth's magnetosphere (Auroral Kilometric Radiation – AKR) of $\sim 10^9$ W at $\nu \leqq 700$ kHz, sharp suppression ($\sim -70$ db at $\nu \leqq 700$ kHz) of frequencies below 1.5 MHz would be needed in front of the first system pre-amplifier.

The full signal received, after suitable digitization and the addition of monitor and control information, would be recorded and transmitted periodically to the ground from each array element for archiving, correlation, and analysis. Clock stability aboard each array element would be sufficient for full array coherence at all times. With its very large Half Power Beam Widths (HPBW) at 1.5, 4.4, and 13.1 MHz (see Table 3), Sun synchronous precession of the orbital plane, and slow array expansion, an LFSA would image the entire sky to high resolution over the course of about 1 yr. Because it would be maintained in phase coherence, this also would provide a very long effective integration time and (with the assumed antenna properties of Table 3) give the very good sensitivities and consequent very large number of detectable sources shown in Table 2.

## 4. Satellite orbits

Since the array elements would all be independent free flyers in slightly different orbits, the array would pulsate during each revolution. The orbital radii ($A$) would be large enough to minimize magnetospheric plasma effects on the array but small

**Table 3.** Possible antenna parameters
*Assumed properties*
Antenna type: Crossed Travelling Wave "Vs"
Ohmic Resistance = 600 ohms
Antenna Length = $L$ = 68 m
Termination Length = 17 m
Total Boom Length = 85 m

| Frequency: | 1.5 MHz | 4.4 MHz | 13.1 MHz | 25.6 MHz |
|---|---|---|---|---|
| $L/\lambda$: | 0.3 | 1 | 3 | 6 |
| HPBW: | ~220 × 160 deg | ~180 × 100 deg | ~22 × 54 deg | ~15 × 30 deg |
| Directivity: | 2.1 | 4.1 | 10.0 | ~15 |
| Radiation Resistance: | 60 Ω | 125 Ω | 190 Ω | 230 Ω |
| Radiation Efficiency: | 0.09 | 0.17 | 0.24 | 0.28 |
| Effective Aperture: | 600 $m^2$ | 250 $m^2$ | 100 $m^2$ | 45 $m^2$ |

**Table 4.** Orbital elements for sample LFSA orbits

| Orbiter | A (m) | E (°) | I (°) | $\theta$ (°) | $\bar{\omega}$ (°) | $\tau$ (°) |
|---|---|---|---|---|---|---|
| Orbit 1 | 9,500,000 | 0.0 | 114.005 | 0.0 | 90.0 | 0.000 |
| Orbit 2 | 9,500,005 | 0.0 | 114.000 | 0.0 | 90.0 | −0.005 |
| Orbit 3 | 9,500,000 | 0.0 | 113.995 | 0.0 | 90.0 | +0.005 |
| Orbit 4 | 9,499,990 | 0.0 | 114.000 | 0.0 | 90.0 | +0.020 |

enough to avoid the severe radiation background of the Van Allen Belts and to provide adequate gravity gradient stabilization (~10,000 km). The orbits would also be chosen such that differential dynamical forces cause the pulsations to slowly increase in amplitude providing, without active adjustment, an increase in the maximum interferometer baselines from an initial value of <1 km to a final value of >300 km during a period of ~1 yr. An orbital precession of ~1° per day and a high inclination would insure constant exposure to the Sun for operating power and minimal thermal effects from rapid transitions between sunlight and the Earth's shadow. Although investigation of orbital parameters is continuing, a possible set of orbits is given in Table 4.

Such a combination of array pulsation and expansion and orbital revolution and precession would provide the dense coverage of baseline lengths and orientations needed for high quality synthesis mapping at all 4 frequencies. Each array element should also have minor orbit adjustment capability (micro-thrusters) both for correction of non-classical orbital effects and for recompression of the array after reaching maximum desired baselines to repeat the all-sky survey for error and consistency checks. For illustrative purposes, the baselines covered by an LFSA in one sample orbital configuration observing a radio source at Right Ascension = $06^h$ and Declination = 45° are shown projected on to the aperture (u, v) plane in Fig. 3.

## 5. Data correction and processing

The entire digitized IF data streams for all array elements would be unloaded periodically from onboard recorders to ground stations for permanent recording and archiving. Since existing correlators could be modified to process these data streams, the VLBA video tape format presently coming into use for VLBI observations at a number of stations throughout the world appears to be a natural data archiving medium. A single tape can store about 7 Tbits which would be sufficient capacity on a single reel of tape for several days of operation of an entire LFSA.

Excising interference would obviously be important. However, techniques such as splitting the main bandwidth into numerous small subbands and either clipping or rejecting disturbed channels appear adequate to the task.

It would be necessary to correct for propagation variations due to the residual magnetosphere at the array altitude and above. These consist of "local" effects which occur between array elements and "global" effects which accumulate over the entire ray path through the magnetosphere. At the lowest frequencies, significant differential phase delay would occur between the array elements, but phase closure and phase referencing on bright, relatively compact sources should reduce or eliminate the problem. Significant Faraday rotation could also occur between array elements, leading to a loss of correlation for singly polarized antennas. However, through the use of two orthogonally polarized antennas on each spacecraft and correlation of full polarization information for each baseline, it would be possible to combine the output channels to recover the true total intensity information.

At the lowest frequencies, significant refraction would affect the incident rays from various parts of the sky. Preliminary estimates indicate that even poor modelling (~30% residuals after correction) would reduce the smearing in the final maps at all frequencies to the level of that caused by interstellar scattering. The birefringent splitting into orthogonally polarized images would be even less of a problem since it is considerably smaller than the refraction and could be modelled equally well.

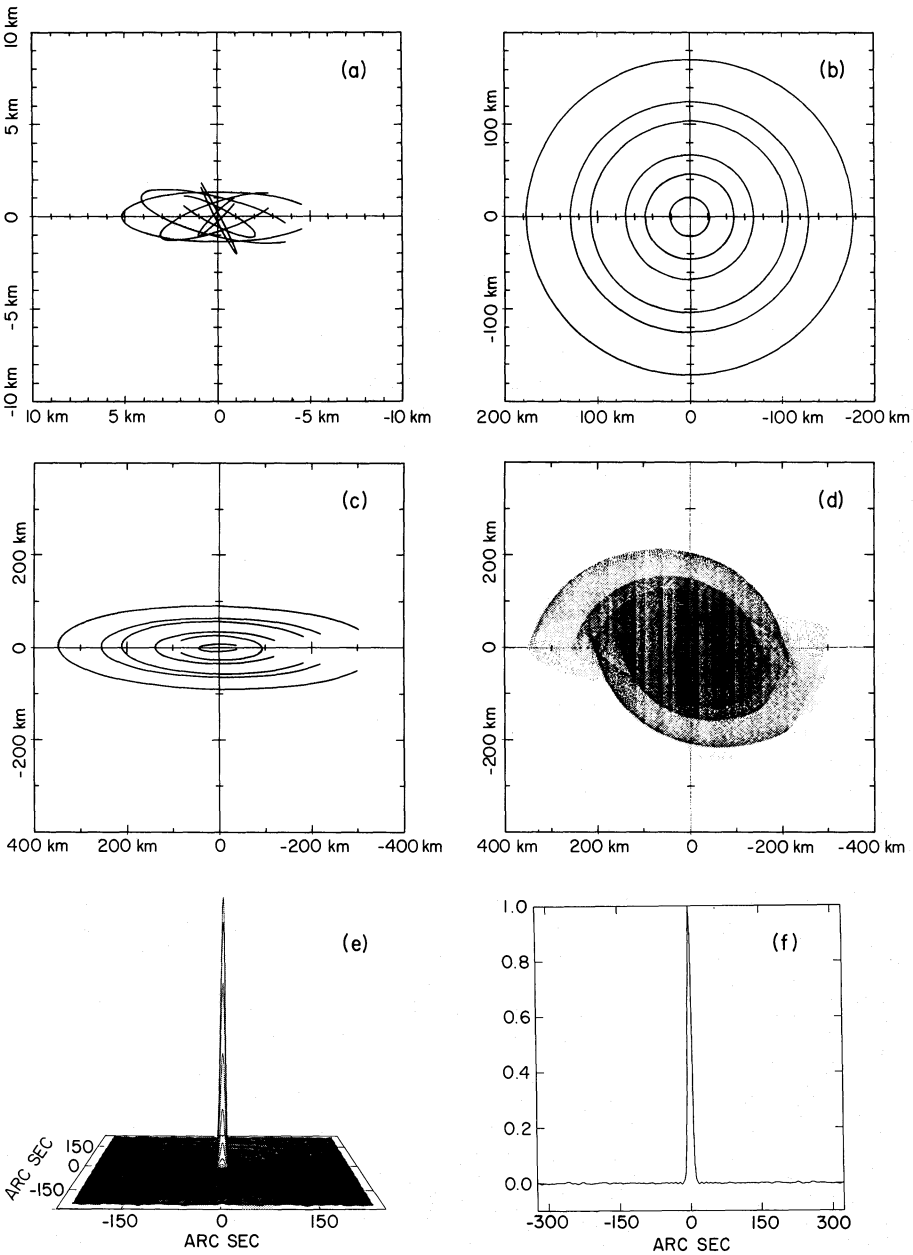


**Fig. 3.** Aperture (Fourier; u, v) plane coverage by a 4 element Low Frequency Space Array (LFSA) for a source at Right Ascension $=6^h$, Declination $=45°$ during a typical orbit on the day of launch (Day 1; Fig. 3a), ~6 months later (Day 180; Fig. 3b), and ~1 year later (Day 360; Fig. 3c). The total aperture plane coverage for all orbits during 1 year by the slowly expanding and precessing array is given in Fig. 3d and its Fourier transform (i.e., the resulting point spread function) at 10 MHz is shown in Fig. 3e. A cross cut through the point spread function which better illustrates the resulting sidelobe levels is given in Fig. 3f. (N.B.: The scales are different for different figures.)

Once the individual data streams were corrected and correlated, the image forming problems would be great but not beyond the limits of current technology. The large beams of the individual antennas in combination with the planned orbital scanning would result in extremely good sampling of the aperture (Fourier transform) plane so that the final point spread function would have very small sidelobe responses (see Fig. 3) and the required image deconvolution to remove errors caused by spurious responses from bright sources in the field of view should be tractable.

None of the techniques needed for mapping with the LFSA are fundamentally new although dealing with such large images projected on to a curved surface would create some computational difficulties. However, a discrete Fourier transform on to a spherical surface by a massively parallel computing machine should be well suited to the task. Such problems are already being studied for particular cases with the Astronomical Image Processing System (AIPS) of the National Radio Astronomy Observatory (NRAO). The major new complexity foreseen for processing LFSA images would be incorporation of calibration factors which vary as a function of time for each point of the image.

## 6. Conclusions

There is a wealth of new astronomical information yet to be found in the relatively (or totally) unexplored low frequency range below 30 MHz and to exploit it will require a space-based telescope. At such long wavelengths only interferometry is practicable and, for a Low Frequency Space Array, orbits, hardware, and systems exist

which can yield the high sensitivity, high resolution observations needed to fully investigate this frequency range. The additional possibility of unusual discoveries when opening up a new realm of frequency, resolution, and sensitivity make construction of an LFSA an exciting chance to explore one of the last frontiers of the electromagnetic spectrum.

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**Note added in proof.** Studies of spacecraft designs are continuing and that described here is only one possibility. Present evolution is in the direction of simpler, more numerous, unstabilized array elements with shorter, omnidirectional antennas. Circular orbits with much larger radii are also being considered. In collaboration with other interested groups the most effective design which can be built, launched, and operated for minimum cost without compromising the science to be done is being actively sought.