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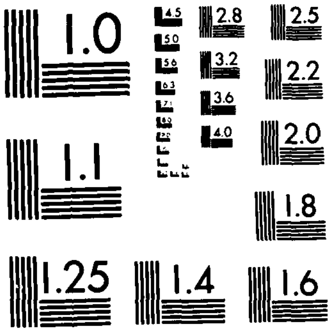
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ASTRO-ARRAY
A Space-Based, Coherent Radio Interferometer Array

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With the proven techniques of radio astronomy and the rapidly advancing technology of space science, it is clear that the expansion of radio astronomy arrays beyond the limits of the Earth's surface is called for. Therefore, a preliminary discussion of the design and capability of a purely space based array is presented. The science which can be done with such a high resolution, high sensitivity radio telescope array is discussed and a number of the parameters of a system are developed. A coherent interferometer array is possible with reasonable extensions of present technology and such a telescope will lead to major advances in the areas of astrometry, the study of radio stars and radio supernovae, the investigation of astronomical masers, and the determination of the properties of the Milky Way nucleus and the active regions of normal galaxies, radio galaxies, and quasars. It is clear that an array of high orbit radio antennas linked to the low orbit Space Station represents the next logical step in the progression to continually higher resolution and sensitivity for radio astronomy.

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CONTENTS

ASTRO-ARRAY
A SPACE-BASED, COHERENT RADIO INTERFEROMETER ARRAY

INTRODUCTION

Through employment of the techniques for Very Long Baseline Interferometry (VLBI) maximum radio interferometer baselines have now reached the physical limits of the diameter of the Earth. Additionally, construction has already started on a dedicated VLBI telescope, the Very Long Baseline Array (VLBA), and plans are being developed for extending Earth based instruments to higher resolution through the addition of a space antenna in a highly elliptical orbit. This last project, appropriately named Quasat, will give baseline lengths up to approximately 20,000 km for the principal objective of studying the active nuclei of galaxies and quasars (see ESA, 1984).

The Quasat will serve as an important first step into space and will be able to perform very important science during its operational lifetime. However, it is still useful to consider the next epoch of radio telescope configurations and technologies. A fully space-based array will offer great possibilities for very high resolution with excellent mapping capability in all directions, at high sensitivity, over an extremely broad range of frequencies. Therefore, we present here a preliminary discussion of the design and use of such a fully space-based radio telescope array employing numerous high orbit radio antennas linked to a correlator located on the Space Station.

Manuscript approved July 10, 1985.

SCIENTIFIC CAPABILITY

Although more detailed discussion of the proposed properties of Astro-Array will be reserved to the following Sections, a short synopsis is given here to aid consideration of its scientific capability. The array is to be entirely in space, with no ground based elements and with the correlator also in space on the low Earth orbit Space Station. The individual antenna elements will be large ($\sim$50m) with accurate reflecting surfaces to provide observing capability over all radio astronomy frequencies from $\sim$30 MHz to $\sim$300 GHz ($\sim$10 m to $\sim$1 mm wavelength). These antennas, chosen to be 30 in number, will be placed in orbits such that the array provides full sky coverage with good Fourier (u,v) plane sampling on baselines from a minimum of $\lesssim$1,000 km to a maximum of $\sim$200,000 km.

The general design goals are summarized in Table 1 with the resulting capabilities of the array given in Table 2. Interstellar scattering (ISS) will be an important effect for the telescope at lower frequencies, so this information is also included in Table 2 (Column 6) and discussed in more detail in a following Section.

Although the telescope is designed to have a maximum resolution of $\sim$1 microarcsecond (1 μas) at $\sim$1 mm observing wavelength (300 GHz), for reference the linear resolution of the array on a number of important astronomical objects is given in Table 3 for a more average frequency of 3 GHz (0.1 milliarcsecond (mas) angular resolution). The capability of the array is portrayed graphically in Figures 1 and 2. The resolutions of the Astro-Array, the Very Large Array (VLA) (maximum baseline $\sim$35 km) of the National Radio Astronomy Observatory (NRAO), the planned Very Long Baseline Array (VLBA) (maximum baseline $\sim$8000 km) of the NRAO, and the VLBA with Quasat (maximum baseline $\sim$20,000 km) are shown in Figure 1 along with size estimates or size limits for a number of astronomical objects. Correspondingly, the flux density and brightness temperature sensitivity for the Astro-Array, and the flux density sensitivities for the VLA and the VLBA are shown in Figure 2 together with the intensity and surface brightness for a number of astronomical objects.

Astrometry

Astrometry concerns itself with the establishment of a basic coordinate grid on the celestial sphere and the determination of motions with respect to that grid. For radio astrometry, which is now the premier technique for high accuracy position measurement, the work can be roughly split into three parts: 1) the determination of a reference grid for radio sources over the whole sky to as high an accuracy as possible with current technology (often called "absolute" astrometry); 2) the very high precision measurement of relative motions over only a very small part of the sky (often called "relative" astrometry); and 3) the determination of the relationship between the optical and radio reference frames (with subsets of the dynamical reference frame of solar system objects, the stellar reference frame of galactic stars, and the extragalactic reference frame of quasars and galactic nuclei). (For a brief discussion of the current status of the field, see e.g. Johnston, 1984).

What might be called the modern era of radio astrometry can be considered to have started with Ryle and Elsmore (1973) who achieved an accuracy of ~ 0".03 at $\delta = 45^{\circ}$ for "absolute" astrometry of a few objects with the conventional (connected element) 5 km interferometer in Cambridge, England. A number of other workers using connected interferometers at Green Bank, West Virginia and the VLA have more recently achieved similar accuracy ($\sigma \sim 0''.01$) for much larger numbers of sources (see e.g. Wade and Johnston, 1977; Ulvestad, et al., 1981; Perley, 1982).

However, with its much higher resolution and (theoretically) far superior positional accuracy, the forefront efforts in radio astrometry use VLBI techniques and are claiming an order of magnitude improvement in positional precision ($\sigma \sim 0''.001$) over that available with connected interferometers (see e.g. Johnston, 1983, 1984; Argue, et al., 1984).

The establishment of a precise relationship between the optical and radio reference frames is presently limited by the accuracy of optical position determinations and the question of the exact relationship between radio and optical emitting regions. The offset between the FK4 and radio reference frames in the northern hemisphere is only known to the ~0".1 level (Johnston, et al., 1985). However, the optical reference frame to be established by the HIPPARCOS satellite will be accurate to the $\sim$3 mas level at the epoch (1990) of observation and refinements in optical astrometry via optical interferometry may further increase the accuracy of the optical reference frame.

The accuracy of "relative" radio astrometry of the rapid internal motions within active radio sources, both sub- and super-luminal, (see a following Section on LFVs, AGNs, and QSOs and, e.g., Kellermann and Pauliny-Toth, 1983) is at the sub-milliarcsecond level and mainly limited by maximum resolutions (maximum baselines) available to current Earth-based VLBI. The same is true for relative positions of maser spots in galactic interstellar maser clusters (see a following Section on Interstellar Masers and, e.g., Genzel, et al., 1982) and a relative positional accuracy between two presumably unrelated radio sources in the antenna beam has been achieved at the level of 20 - 30 μas (Bartel, et al., 1984). These relative astrometric measurements will be directly improved by the increase in resolution of the Astro-Array. Also, the increased sensitivity of the Array will give not only a greater selection of radio sources sufficiently intense for study, but a greater precision in position measurement due to improved signal to noise.

The unique contribution to astrometry of the Astro-Array, however, will be in the area of "absolute" position measurements -- i.e., position and motion determination over large areas of the sky. Not only will the high resolution and sensitivity increase the astrometric precision available in the same manner as for relative astrometry, but also by maintaining communication links between antennas and to the

Space Station housing the correlator (see the Antenna Description Section) it will be possible to establish baseline lengths, orientations, and changes to high accuracy. This translates directly into high accuracy absolute astrometric positions in much the same manner that ground-based antennas are maintained phase coherent and are surveyed to establish their relative positions on the Earth for translation into a celestial coordiate frame (see e.g. Ryle and Elsmore, 1973; Wade and Johnston, 1977). The establishment of well determined baselines and the absence of perturbing effects such as the Earth's atmosphere and ionosphere for the Astro-Array means that absolute phase stability can be maintained, giving absolute positional accuracies equalling or exceeding those already demonstrated for relative astrometry -- i.e. $\lesssim$ 10 μas. (The structure of extragalactic radio sources will have to be monitored and taken into account for an absolute reference frame with such an accuracy, but this does not represent a fundamental problem.)

Such an improvement, by more than two orders of magnitude, in astrometric precision will not only establish new coordinate systems suitably accurate for interplanetary and interstellar navigation, but will also permit the study of a number of important effects. E.g.:

1) measurement of the space motions of galactic objects such as Cyg X-3, SS433, RS CVn stars, pulsars, etc. ($\lesssim$10 mas/ year);

2) determination of which are "fixed" cores and which are "moving" components in compact extragalactic radio sources ($\gtrsim$ 1 mas/ year);

3) rapid determination of the solar motion in and perpendicular to the galactic plane (∼ 100-200 μas/ year);

4) measurement of the rotation of nearby galaxies (∼ 2 μas/ year at 1 Mpc);

5) measurement of the dynamics of the local group of galaxies (∼ 1 μas/ year);

6) statistical parallax to H_2O masers in the Virgo Cluster galaxies (∼ 0.6 μas/ year at 10 Mpc);

7) trigonometric parallax measurements to galaxies in the Virgo Cluster (∼ 0.1 μas at 10 Mpc).

Radio Stars

Many stars exhibit strong radio emission. This may be due to large flares in active binary systems such as RS CVn stars, Algol, β Lyrae and others which radiate principally at centimeter wavelengths, or by low frequency outbursts at meter wavelengths as is found in some dMe stars. Transient flares have also been reported from some supergiant stars such as α Ori, and α Sco A. All of these types of radio emissions are non-thermal in nature. Thermal emission associated with stellar winds has been detected from early type O stars, Wolf Rayet stars, and a few late type stars, but this radiation will probably not be of great interest at milliarcsecond resolutions unless it turns out to be partly of non-thermal origin (Abbott, *et al.*, 1984; Underhill, 1984).

The flux density variations of HR1099 (V711 Tau), an RS CVn star, have been reported extensively in the literature. Feldman, *et al.* (1978) have shown that during one interval the star showed daily flaring events at 10 GHz which ranged in flux density from 0.1 to 1 Jy. These are very high brightness temperature events since, for example, the sizes of emission regions for HR 5110 and Ux Ari are reported by Mutel, *et al.* (1985) to be ~ 1 and <0.4 mas giving brightness temperatures of 2×10^{10} K and $>1 \times 10^{10}$ K, respectively, at 5 GHz.

Flares from dMe stars were first reported by Lovell, *et al.* (1963) for UV Ceti. The dMe star YZ CMi has exhibited large flaring events, notably a three hour event in 1969 for which the flux density at 240 MHz was 80 Jy. This was a very steep spectrum event since its 408 MHz flux density never exceeded 6 Jy. The estimated brightness temperature for this flare was $\sim 2 \times 10^{15}$ K with a spectral index ranging from $-5 < \alpha < -1$ (Lovell, *et al.*, 1969). A very large stellar flare was detected by Slee, *et al.* (1969) which had a maximum brightness temperature $>10^{20}$ K associated with the nebular variables in the Orion aggregate. Flares on the dMe stars measured by Spangler, *et al.* (1974) have shown typical brightness temperatures of $\sim 10^{14}$ K with spectral indices of $\alpha \sim -4$. The timescales for these flaring events (at least for AD Leo) are on the order of seconds or less (Lang, *et al.*, 1983).

With the Astro-Array, radio sources such as the RS CVn and Mira variable stars within the Milky Way and in other nearby galaxies can be studied to determine the origin and distribution of radio emitting regions on their surfaces. Rotation periods and perturbations in the orbits of the stars caused by unseen bodies can easily be measured. Also, high precision astrometry on such objects will allow the accurate coupling of the stellar (optical) and extragalactic (radio) reference frames.

Flares on dMe stars appear to be large manifestations of processes similar to those seen on the Sun. Solar radio bursts occur most strongly at meter wavelengths but there is centimeter wave emission associated with coronal loops with brightness temperatures of $\sim 10^7$ - 10^3 K. With the very high sensitivity of the Astro-Array, detection and study of the brighter dMe stars, or even of common stars like the Sun, will be possible at low frequencies during their active phases. For example, during the maximum of the sunspot cycle, the Sun would be detectable below ~ 1 GHz even at a distance of 10 pc (see Figure 2) with resolution sufficient to map the structure of the emitting regions. The dMe stars could be studied to much greater distances. Such measurements will allow detailed comparison of solar-type stars in their radio emission and greatly enhance studies of the "solar-stellar connection."

Interstellar Scattering

Interstellar scattering (ISS) is, in effect, a "seeing" limitation for radio astronomy at long VLBI baselines and low frequencies (decreasing roughly as the square of the observing frequency). It arises in the scattering of the radio waves by the inhomogenities of the interstellar plasma and is, accordingly, greatest in the galactic plane and least towards the galactic poles. A recent review by Rickett (1977) fully develops a theoretical treatment of the subject.

The details of the actual distribution of the amount of ISS are, as yet, poorly determined. Duffett-Smith and Readhead (1976) (see also Readhead and Hewish, 1971, 1974) studied the problem at 81.5 MHz and concluded that they could roughly describe the scattering size limit as $\theta_{ISS} = 0''\!.15 \pm 0''\!.05$ at that frequency for $/b/ > 10^{o}$. As a general indication of the magnitude of the effect, this is the value shown for ISS size (scaled as ν^{-2} to other frequencies) in Table 2 and Figure 1.

There is considerable deviation from this value around the sky with Rickett (1977) predicting a factor of 4 smaller scattering size at the galactic poles and a number of authors finding much larger scattering sizes in the galactic plane, particularly in the direction of known HII regions (see e.g. Cordes, 1982; Dennison, 1982; Anderson, et al., 1972).

Dennison, et al. (1984) investigated this more fully and found that while some directions in the galactic plane show scattering consistent with the high latitude results extrapolated as $(\sin/b/)^{-0.5}$, other directions, particularly near the galactic center, show much stronger scattering. They also found that ISS varies significantly on angular scales $\lesssim 5^{\circ}$, supporting the earlier results that local inhomogeneties such as HII regions can have a large effect on the scattering. Cordes, Ananthakrishnan, and Dennison (1984) describe the high scattering regions as a disk $\sim$100 pc in thickness with clumpiness on a scale of 1 - 10 pc.

On average, it appears that at many galactic latitudes ISS will become the limiting factor on resolution for observations $\lesssim 3$ GHz (see Figure 1) but near the galactic poles this limit will be considerably relaxed and near the galactic center it will be much more severe. On the other hand, the relatively large effects of ISS mean that the Astro-Array will have sufficient resolution to carry out a detailed study of its origin, effects, spatial distribution, and variation at relatively high frequencies over the whole sky. Together with electron density and magnetic field data from pulsar dispersion measurements and from linear polarization Faraday rotation measurements, such data will allow the detailed modelling of the magneto-hydrodynamic properties of the ISM. Also, since the near field pattern of the telescope will extend for several kpc at high frequencies, more local cells of the scattering medium can be mapped in three dimensions.

Interstellar Masers

There are a number of molecules and radicals which are known to display masering processes in interstellar molecular clouds or in the circumstellar dust clouds surrounding late-type stars. In general, the apparent spot sizes of individual maser components are strongly related to their gain and it appears that masers associated with late-type stars have lower gains than masers of the same species in the interstellar medium. SiO masers (43 GHz) have only been observed in areas associated with late-type stars and the peculiar Orion IRc2 region and appear to be relatively large since VLBI observations have resolved the individual spots on moderate baselines. OH (1.6 GHz) and H_2O (23 GHz) masers are observed in both interstellar clouds and near late type stars with the clouds containing the stronger and more compact sources. In contrast to radio continuum sources, maser studies cannot obtain greater resolution by going to higher frequencies on the same baselines so that more detailed studies require larger interferometers.

Present studies of the galactic H_2O masers indicate there is considerable source structure on angular scales <0.3 mas (Genzel, et al., 1981b) and unresolved emission has been detected on baselines as long as possible on the surface of the Earth (12,100 km) (Batchelor, et al., 1976), indicating that such objects can only be studied in detail with a large space array. Other observations suggest that the apparent angular sizes of some H_2O masers are limited by interstellar scattering since the angular sizes appear to increase with distance (Moran, et al., 1973). This hypothesis must be checked by increasing the baselines to greater than the Earth's diameter and is important to study because all of our knowledge of ISS, at the present time, is based upon observations at much lower frequencies where little has been determined about the interstellar electron distributions and scale sizes.

Observations of extragalactic masers have been limited so far to spectroscopy by low resolution single antennas. Hence, we know nothing of their structure and dynamics. However, the potential for new knowledge is great. If proper motions of OH and H_2O maser complexes can be measured, as has been done for a few H_2O maser clusters in the Galaxy, their dispersion will give a direct measure of the outflow in extragalactic regions of star formation to be compared with other regions in the same galaxy and with similar regions in the Milky Way for information on the universal processes of star formation. Such compact radio sources as masers will also serve as reference points for measuring the rotation curves, inclinations, and distances to other galaxies.

For independent distance measurements, the technique of statistical parallax has been used with VLBI on several H_2O maser clusters in the Milky Way. These studies measure the small angular motions of the many maser spots in a complex and then compare those statistically with the radial motions obtained from spectroscopy to determine a distance. Using this technique Genzel, et al. (1981a,b) have determined independent distances to the Orion-KL complex and to the W51 H_2O maser complex (see also Schneps, et al., 1981). In each case, obtaining adequate proper motions required VLBI observations taken over about 2 years. However, with the relatively short lifetimes of maser spots of only a few years, the necessary tracking of individual spots places a severe limitation on the amount of time available for measurable proper motions to accumulate and, therefore, the maximum distance to which this technique can be used with current VLBI technology and Earth limited baselines (Reid, 1984). Clearly, the much higher resolution and sensitivity of the Astro-Array will allow utilization of this powerful technique to much greater distances.

Radio Supernovae

Supernovae have long provided one of the most spectacular events in the universe. A single star, due to an internal explosion or implosion, increases over a period of days from obscurity to a brightness which rivals the combined luminosity of the other 10^{11} stars in a galaxy. During the brief span of a few weeks to a few months, the supernova releases $\sim 10^{51}$ ergs of energy before fading again into relative quiescence. The supernova's effects, however, linger on through the formation of a supernova remnant which, at least in our own Galaxy, remains visble for $\sim 10^{5}$ years and, perhaps, a pulsar with a lifetime of $\sim 10^{6} - 10^{7}$ years.

These catastrophic events, which occur every $\sim$25 years in a galaxy such as the Milky Way, are thought to be responsible for many of the most important galactic processes such as: 1) formation of heavy elements and return of these elements to the interstellar medium; 2) formation of neutron stars (and, perhaps, black holes) which are responsible for X-ray binary systems and pulsars; 3) stirring of the interstellar medium; and 4) perhaps, triggering of star formation. (For a comprehensive review of the subject see Trimble, 1983 and references therein.)

While the study of supernovae was for many years a subject only for optical astronomy, new instrumentation has allowed results to be extended into other wavelength ranges. Infrared (see Elias, et al., 1985), ultraviolet (see Panagia, 1984), and even X-ray (Canizares, Kriss, and Feigelson, 1982) results have been obtained.

Of particular concern to us here, however, is that supernovae have been found to frequently be powerful emitters of radio emission (Weiler, et al., 1981, 1985; Panagia, Sramek, and Weiler, 1985; Sramek, Panagia, and Weiler, 1984). While this radio work has met with a great deal of initial success with the development of a detailed description of the radio generation processes (Pacini and Salvati, 1981; Bandiera, Pacini, and Salvati, 1983, 1984; Chevalier, 1982, 1984) and the obtaining of estimates of the stellar progenitor types, evolutions, and winds (Chevalier, 1984; Sramek, Panagia, and Weiler, 1984), detailed radio study of the phenomenon is still very much instrument limited.

The one supernova event expected in a galaxy such as ours every quarter century is rapid by astronomical standards, but it is impossibly slow for human observers. Therefore, all modern supernovae (since AD1604) have been observed only in external galaxies where, in spite of their prodigious radio energy output for a single star ($\sim 10^{39}$ ergs s^{-1}), they are still relatively weak radio sources of, at most, a few mJy flux density. Thus, the study of these radio supernovae (RSN) has only developed since the completion of the VLA with its high sensitivity. However, even with the excellent maximum resolution of the VLA and with the RSN expanding rapidly ($\sim 10^4$ km s^{-1}), they remain unresolved point sources throughout their (radio) visible lifetimes of $\sim$1 - 20 years and the structure of the emitting regions cannot be studied. The present results, even though they have been fruitful (see references given above), have been almost entirely limited to the determination of radio light curves and spectra. The single exception to this has been the work by Bartel, et al. (1984, 1985) in using VLBI to slightly resolve one exceptionally bright RSN, SN1979c in NGC4321 (M100). However, low sensitivity and resolution of current VLBI arrays have so far limited the results to model dependent estimates of the sizes and angular velocities for this single case. Completion of the VLBA will aid this study significantly but will still be limited by low resolution when the supernovae are young, small, and bright and low sensitivity when they are older, larger, but weaker. As is illustrated in Figure 1, the Astro-Array can map all bright RSN as soon as they become optically thin after the supernova explosion and determine the (changing) details of their structures, their angular velocities, their accelerations or decelerations, and their spectral index distributions as they age. Such results will not only tell us much more about the mechanisms of supernova explosions and their relation to the development of remnants, cosmic rays, and the formation of active neutron stars, but they will give us detailed information on the properties of the interstellar medium and the local environment of the supernova, including estimates of the stellar winds from pre-supernova stars. Even simple structure measurements will be able to answer astrophysically important questions on the symmetry of the supernova explosion and whether the radio emission is internally (pulsar) or externally (shock) generated. Then without model assumptions, radio measurements on RSN can be used to obtain independent estimates of the Hubble Constant (H_0) out to the Virgo Cluster of galaxies and beyond (Bartel, et al., 1985). Finally, when young and small, RSN will provide compact reference points for obtaining astrometric information on external galaxies.

Giant Planets

Jupiter is known to emit very strong bursts of low frequency (<100 MHz) radio radiation (Brown, Carr, and Black, 1968; Dulk, 1970) from small regions in its belts and Clark and Erickson (1973), with transcontinental VLBI at 26.3 MHz, have shown that the radiation arises from a source which is <0"1 in size. It is not even clear whether the bursts originate by the incoherent synchrotron mechanism (as in most known radio souces) or by a coherent radiation process which could show a much smaller size and a much higher brightness temperature. To study the structure of such compact sources at the low frequencies where the Jupiter bursts are detectable is not possible with ground based arrays. However, such bursts would be easily detectable and, presumably, resolved with the Astro-Array and could be mapped in 3-dimensions for a better understanding of their location, mechanism, and evolution.

A second topic for possible study on the giant planets is the Saturn Electrostatic Discharges (SED). These have, so far, only been detected from the spacecraft Voyagers 1 and 2 but appear to emit broadband radio radiation of an impulsive nature over a frequency range from ∿100 kHz to ∿40 MHz (Evans, et al., 1981; Warwick, et al., 1982). The bursts are characterized by short impulses lasting from ∿30 ms to ∿250 ms and may extend in frequency above the 40 MHz upper limit to the spacecrafts' receivers. They are theorized, although not proven, to originate in electrostatic discharges in the ring system of the planet. Such emissions should easily be detectable with the Astro-Array, allowing, as with the Jupiter bursts, detailed study of their location, structure, and mechanisms.

Pulsars

Pulsars will constitute a class of objects which will probably be the only true "point" sources for the Astro-Array at most frequencies. If the pulsar emission arises at or within the light cylinder (see e.g. Goldreich and Julian, 1969) the size of the emitting region will be too small to be resolved except for, perhaps, the nearest and slowest examples. However, the Astro-Array will be able to provide important limits on emitting region sizes. Also, as unresolved sources the pulsars, with the high sensitivity and high resolution of the Astro-Array, will serve as important references for phase (position) calibration and their own intrinsic proper motions of up to ∿0".4/year (Anderson, Lyne, and Peckham, 1975; Backer and Sramek, 1976; Ables and Manchester, 1977; Hanson, 1979) will be detectable in a few hours or a few days time. With such accurate positional information, it will also be possible to search for accelerations or decelerations in pulsar motions due to the proposed "rocket" (Harrison and Tademaru, 1975; Tademaru and Harrison, 1975) or other effects.

Extragalactic pulsars, of which at least one has now been discovered in the Large Magellanic Cloud (McCulloch, et al., 1983) will provide reference points for determining the astrometric distances and motions of their parent galaxies (see the Astrometry Section).

Galactic Center

The center of the Milky Way is known to have structure on essentially all angular scales from large sizes easily resolved with single antennas (see e.g. Haslam, et al., 1982) though sizes available for study with connected interferometers (see e.g. Goss, et al., 1983) to VLBI size scales (see Balick and Brown, 1979). Even though the interstellar scattering (ISS) in the direction of the galactic center is poorly known and likely to limit the effective resolution possible with the Astro-Array at all but the very highest frequencies (see the ISS Section), with its high resolution, wide frequency coverage, and excellent mapping capability the Astro-Array will certainly contribute much new and valuable information on the active processes occuring in the center of the Milky Way and, by analogy, in the centers of other similar galaxies.

From astrometric measurements our distance from the galactic center can be easily measured with the Astro-Array by trigonometric parallax ($\sim$0.1 mas). Also, the rotational motion of the solar system around the galactic center ($\sim$13 mas/year) and the peculiar motion of the Sun perpendicular to the galactic plane ($\sim$0.15 mas/ year; Delhaye, 1965) can be determined (see the Astrometry Section).

LFVs, AGNs, and QSOs

One of the most intractible problems in modern astronomy is understanding the nature of the energy sources powering the non-thermal, compact extragalactic radio sources such as the Low Frequency Variables (LFVs), Active Galactic Nuclei (AGNs), and Quasi-Stellar Objects (QSOs). These sources contain an energy of $\sim 10^{61}$ ergs within small regions less than a few parsecs in size and, by poorly understood processes, often channel a portion of this energy into sharply focussed, relativistic beams which transport it to distant radio lobes which are tens of kiloparsecs or even megaparsecs from the central "engine."

Investigation of the "cores" of AGNs and QSOs by the techniques of VLBI has proceeded rapidly for a number of years (see, e.g., a recent review by Kellermann and Pauliny-Toth, 1981) and has revealed very compact and high surface brightness components. The phenomenon of LFV which is present in many sources (see Fanti, *et al.*, 1979, 1981, 1983) but should not occur under standard models (and may yet have an extrinsic explanation - Rickett, Coles, and Bourgois, 1984) has been shown, in some cases, to be associated with similarly compact and high surface brightness regions (Romney, *et al.*, 1984). Additionally, many of these compact extragalactic radio sources show a phenomenon known as "superluminal" motion or changes in their structures which imply movements of radio emitting components at velocities several times faster than the speed of light ($\sim 2 - 10c$) (Unwin, *et al.*, 1981; Cohen, *et al.*, 1979). While a number of models have been proposed to explain this phenomenon (see e.g., Kellermann and Pauliny-Toth, 1981, and references therein) none appears to yet be completely satisfactory.

More detailed study of these types of objects is, in fact, one of the principal scientific goals of the planned Very Long Baseline Array (VLBA) (NRAO, 1982) and its extension with Quasat (ESA, 1984). While these new telescopes will make major advances in the study of such high energy and enigmatic phenomena, the best resolution of the VLBA at its highest planned observing frequency (or the VLBA plus Quasat at its somewhat lower maximum frequency) of ~0.1 mas will still be insufficient to resolve the most compact inner structure of these objects. For example, the current record resolution for an Earth based VLBI interferometer of ~0.2 mas ($1.1*10^9\lambda$ or ~3700 km at 89 GHz), even with the relatively low sensitivity available, still shows unresolved structure in 3C273 (Backer, *et al.*, 1984). Thus, the ability to obtain resolutions of a few hundred AU with the Astro-Array, rather than the several parsec sizes currently possible or proposed, will be an important advance for the study and understanding of these complex phenomena.

ANTENNA DESCRIPTION

Interferometry

From the wave nature of electromagnetic radiation, it is impossible to study details (obtain a resolution) finer than $\sim\lambda/D$ where λ is the observing wavelength and D is the diameter of the instrument. Since when studying an object in any given frequency band λ is essentially fixed, the only solution to obtaining better resolution is to build instruments with larger diameters. Assuming a circular aperture, this correspondingly increases the photon collecting area of the instrument so that fainter objects can also be studied.

For radio astronomy, where λ is very long ($\sim 10^5$x) compared to that of visible light and radio sources are copious producers of relatively low energy photons, filled aperture telescopes with arcsecond or better resolutions are neither possible nor necessary. For example, to equal the theoretical resolution of the Mt. Palomar 5 m optical telescope at 5000 Å, a radio telescope at 5 cm wavelength would have to be 500 km in diameter. However, since the entire filled aperture is not needed for sensitivity, it turns out that a large radio telescope can be approximated by combining many widely separated, "small" (usually 25 m to 100 m in diameter) radio antennas in pairs to form interferometers. Mathematically, the result from each of the interferometers provides information on the Fourier transform of the radio source structure being studied and all interferometers can be combined to provide an approximation to the complete Fourier transform of the radio source. Only a straight forward mathematical transformation is then needed to obtain the desired picture of the object under study.

In principle, all possible separations and orientations of the two antennas in the interferometer (all possible baseline lengths and orientations) must be obtained to give an accurate estimate of the Fourier transform. This would be an endless process for maximum interferometer baselines more than a few hundred meters in length. However, through the use of multiple antennas to give multiple simultaneous interferometers ($N = n(n-1)/2$ where N is the number of interferometers which can be formed with n individual antennas), and, at least on the Earth, through the Earth's rotation to change the baseline orientations with respect to the source being observed, large numbers of independent samples of the Fourier transform can be obtained rapidly. Also, within limitations, an acceptable picture of a radio source can usually be obtained with only partial sampling of its Fourier transform.

The quality of the sampling of the Fourier transform is usually expressed as a plot of the positions where data samples will be obtained in the Fourier (u,v) plane and a number of these are illustrated in the next Section. Briefly stated, a completely blackened circle in the u,v plane is equivalent to having observed with a filled aperture radio telescope of that diameter, but, realistically, the goal for an array is to obtain a relatively dense and uniform filling of the u,v plane within some maximum radius. Such filling can be enhanced if the individual antennas can be moved respect to one another by more than the relative motion the rotation of the Earth provides. For example, the 27 antennas of the VLA can be moved to concentrations within 4 different maximum baselines and all 4 configurations can be added, if desired, to obtain the final picture of the radio source. The VLBA, on the other hand, will not have moveable antennas and will have, at any given frequency and point on the sky, a fixed filling of the u,v plane. The addition of Quasat to the VLBA will then provide not only a longer maximum baseline but a mobile antenna to give denser and more uniform coverage in the u,v plane.

A second factor for consideration in interferometer arrays is that, while the entire collecting area of the equivalent single dish antenna is not needed, sensitivity is an important consideration and, assuming that all modern telescopes have approximately the same quality of low noise receivers available, goes directly as the total collecting area in the array (i.e. the number of antennas times the collecting area per antenna).

Astro-Array Performance

The Astro-Array will have many advantages for all of these factors. Because all of its antennas are in orbit, they are all in motion with respect to one another, giving a rapid and uniform filling of the u,v plane (providing quick mapping and good image quality), even to quite short minimum baselines (providing a wide field of view). This filling of the u,v plane to short baselines is particularly important for allowing the study of relatively large objects and the uniform filling of the u,v plane will lead to a high dynamic range in the maps.

With a purely space-based array, the maximum baseline is no longer limited by the diameter of the Earth and has been chosen to be 200,000 km (orbital radius 100,000 km) to provide a resolution of ~1 μas at 1 mm observing wavelength (300 GHz). While there is, in principle, no limitation of the maximum baseline, this represents a compromise with such difficulties as placing large structures in high orbits, providing sufficient numbers of antennas to give good u,v plane coverage with rapid source mapping, and remaining within a justifiable and reasonable expansion (approximately an order of magnitude) of the planned maximum baseline of the VLBA plus Quasat.

Without the limitations of the Earth's atmosphere (at high frequencies) and ionosphere (at low frequencies), the Astro-Array can be used at all radio frequencies and without the gravity and wind loading of antennas on the Earth's surface it can have large (~ 50 m) antennas as array elements for improved sensitivity. Additionally, with interferometric discrimination against, and antenna pattern suppression of, terrestrially generated interference, large (~ 10%) receiver bandwidths can be used for good sensitivity. For an initial conceptual design, the number of antennas has been chosen to be 30.

These telescope parameters are listed in Table 1 with the resulting array capabilities listed in Tables 2 and 3 and shown in Figures 1 and 2. Examples of possible u,v plane coverages for several simple orbital configurations and relatively short observing times (6^h) are described in the next Section and shown in Figures 3 to 6.

To avoid the limitations imposed by the need for direct communication with the Earth's surface, all elements of the array will be space based as will the correlator, with this last placed on the Space Station. The communication links between antennas and to the correlator will be through broadband (perhaps laser) transmissions. Performing correlation and averaging on the Space Station means that transmission of the results to the ground will require minimal bandwidth. Antenna to antenna communication will be maintained to provide high accuracy determination and monitoring of the many interferometer baselines for precision absolute astrometry and to provide data relay, avoiding information losses due to Earth blocking of some lines of sight to the low orbit Space Station.

With all elements placed in space and without the disturbing effects of the Earth's atmosphere and ionosphere, the Astro-Array will have sufficient phase stability that coherence can be determined and maintained, removing restrictions on minimum averaging times and the problems of orbital "smearing" of the data. A coherent array will also provide large gains in dynamic range and astrometric precision.

Orbital Considerations

With a large number of antennas and full 3-dimensional space in which to place them, there are many free orbital parameters. To reduce the number of degrees of freedom, we have made the simplifying assumptions that: 1) the orbits are all circular with the same radii (100,000 km); 2) only the simplest, most symmetric arrangements of orbital planes will be considered; and 3) the satellites will be equally spaced around the orbits. These assumptions can be justified to some extent and, in any case, provide a conceptually easy first look at the u,v plane coverages obtainable. Also, we have selected a short (6^h) mapping time as the basic unit for these first estimates to avoid undue "blackening" of the u,v plane. For this same reason, the Hermitian conjugate points have not been plotted; i.e., the density of points obtained in the u,v plane is actually twice that shown in Figures 3 to 6 and actual mapping would have a point symmetric through the origin for every point shown.

With the above constraints, the minimum number of symmetric, independent orbital configurations for 30 satellites are: 1) 10 satellites in each of 3 planes, 2) 7, 7, 8, and 8 satellites in each of 4 planes, and 3) 5 satellites in each of 6 planes. No ground stations are used, but real time telemetry to the Space Station (via other satellites if necessary), provides continuous data acquisition except for Earth blockage of the source being observed, which is small (~23°) for these large orbits. The orbital planes were selected using the appropriate regular polyhedrons to orient the angles uniformly in three dimensions.

For the 3 plane case there are 2 polar orbits and 1 equatorial. The u,v plane coverage for a source at 40° declination at a longitude perpendicular to one of the polar orbits for a 6^{h} observation is shown in Figure 3. The coverage is a uniform ellipse from the equatorial plane satellites superimposed on a cylinder from the two polar planes. While the coverage is fairly uniform, there is a concentration of data points along the apparent tangents to the cylindrical surface. Observation with the same parameters of a source which has been shifted by 3 hours in right ascension will have the u,v coverage shown in Figure 4.

The u,v plane coverage becomes more uniform as more orbital planes are added. The case of 4 orbital planes is shown in Figure 5 where 7 satellites were placed in each of 2 planes and 8 in each of the other two. While it is best to have an odd number of satellites in a circular orbit for most uniform coverage of the u,v plane, these numbers were chosen to maintain a constant number of 30 satellites. As is apparent from inspection of Figure 5, a very uniform coverage of the u,v plane is now obtained.

By the time that the 30 satellites are spread among 6 orbital planes, there are more planes than there are satellites in a given plane. This makes the patterns that the individual planes define more difficult to see in the u,v sampling, shown in Figure 6. For 30 satellites it appears that 6 orbital planes are approaching the effect of random orbits and there does not seem to be a need to explore more orbital planes at this time.

Based on these simulations, it is clear that excellent u,v plane coverage, and, therefore, excellent beam shape, field of view, and dynamic range can be obtained for the number of satellites being considered in this report, even with the relatively short observing time of only 6^h. (This time is comparable to that needed ($\sim 8^h$) for full mapping with the VLA.) This is especially true since the u,v coverages represented by Figures 3 to 6 would actually be twice as dense as shown if the Hermitian conjugate points were plotted.

Although the excellent mapping capability of the Astro-Array has been demonstrated with these simple simulations, with the large number of free parameters available more detailed studies to determine the optimum orbital arrangement are obviously needed.

SUMMARY

We have presented here the concept of an entirely space based radio telescope array which will enhance the capability of radio astronomy to study the energetic, non-thermal phenomena in the Universe by more than 2 orders of magnitude in both resolution and sensitivity. It will provide detailed mapping capability of both galactic and extragalactic radio sources with a stability not attainable when observing from the Earth's surface. Because of its large physical size it will make possible, at the highest frequencies, the three dimensional holography of our local region of the Galaxy and the direct measurement of trigonometric parallax distances and intrinsic motions throughout the Galaxy and in our local part of the Universe. Nevertheless, all components of the telescope are conceivable extrapolations of current technology and numerous objects for study can be specified as needing such an array at the present time. New discoveries are always found by such a great advance in observing capability and those are, of course, beyond our conception.

Non-astronomical uses are also likely to be important. Establishing precise coordinate systems for the navigation of manned planetary missions and monitoring the positions and motions of interstellar probes are two of the most obvious of these.

TABLE 1: Assumed System Parameters

Number of Antennas	30
Antenna Size	50 m
Antenna Efficiency	0.5
Frequency Coverage	30 MHz to 300 GHz
Wavelength Coverage	10 m to 1 mm
Bandwidth	10%
System Temperature	50 K
Maximum Baseline	$2 * 10^8$ m (200,000 km)
Minimum Baseline	$<1 * 10^6$ m (<1,000 km)

TABLE 2: Array Capability

Observing Frequency	Observing Wavelength	Flux Den. Sensitiv.[a] (1σ)	FWHM Resolu.[a]	Brightness Sensitiv.[a] (1σ)	IS Scatter. Size Limit[b]
300 GHz	1 mm	0.12 μJy	1.0 μas	1.2 E 6 K	11 nas
100 GHz	3 mm	0.21 μJy	3.0 μas	2.1 E 6 K	100 nas
30 GHz	1 cm	0.38 μJy	10.0 μas	3.8 E 6 K	1.1 μas
10 GHz	3 cm	0.65 μJy	30.0 μas	6.6 E 6 K	10 μas
3 GHz	10 cm	1.19 μJy	0.1 mas	1.2 E 7 K	0.1 mas
1 GHz	30 cm	2.06 μJy	0.3 mas	2.1 E 7 K	1.0 mas
300 MHz	1 m	3.78 μJy	1.0 mas	3.8 E 7 K	11 mas
100 MHz	3 m	6.52 μJy	3.0 mas	6.6 E 7 K	100 mas
30 MHz	10 m	11.92 μJy	10.0 mas	1.2 E 8 K	1.1 sec

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[a] Based on the system parameters of Table 1, a correlator efficiency of 1.5, and an integration time of 6^h.

[b] Galactic latitude /b/ > 10^o.

TABLE 3: Linear Resolution for a 0.1 mas Array[a]

Object	Distance	Linear Resolution
Sun	1.0 AU	70 m
Mercury	0.6 - 1.4 AU	40 - 100 m
Venus	0.3 - 1.7 AU	20 - 130 m
Mars	0.5 - 2.5 AU	40 - 180 m
Minor Planets	1.8 - 3.8 AU	130 - 280 m
Jupiter	4.2 - 6.2 AU	310 - 450 m
Saturn	8.5 - 10.5 AU	620 - 760 m
Uranus	18.2 - 20.2 AU	1.3 - 1.5 km
Neptune	29.1 - 31.1 AU	2.1 - 2.3 km
Pluto	38.4 - 40.4 AU	2.8 - 2.9 km
UX Ari	50 pc	2.5 E -8 pc = 7.4 E 6 cm
Mira	80 pc	3.9 E -8 pc = 1.2 E 7 cm
Orion Nebula	500 pc	2.5 E -7 pc = 7.4 E 7 cm
NP0532	2 kpc	9.8 E -7 pc = 2.9 E 8 cm
SS433	5 kpc	2.5 E -6 pc = 7.4 E 8 cm
Galactic Center	10 kpc	4.9 E -6 pc = 1 AU
LMC-SMC	50 kpc	2.4 E -5 pc = 5 AU
M31	600 kpc	2.8 E -4 pc = 6 AU
M87	11 Mpc	5.3 E -3 pc = 1,100 AU
Virgo Cluster	11 Mpc	5.3 E -3 pc = 1,100 AU
3C273	500 Mpc	2.4 E -1 pc = 50,000 AU

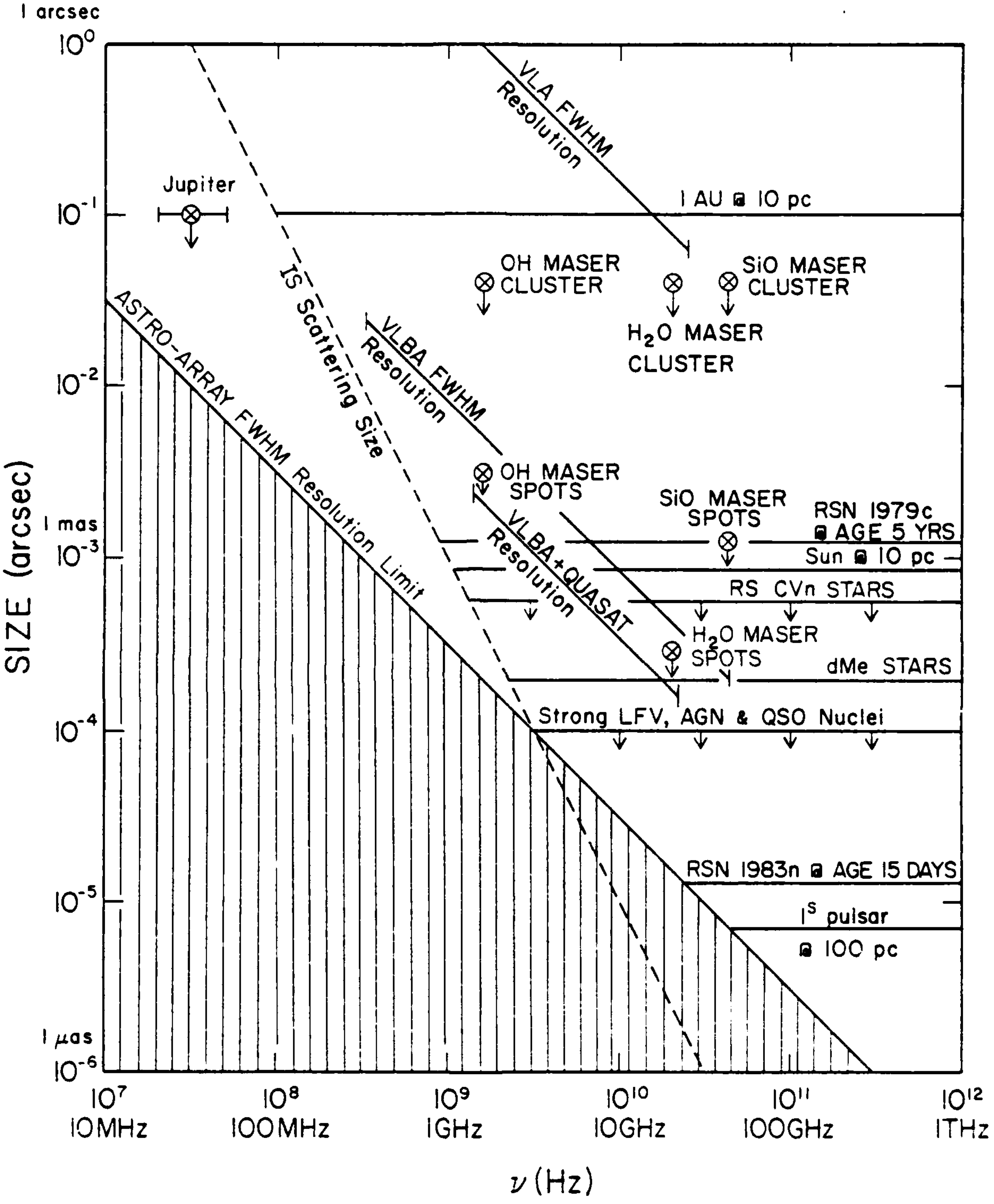
[a] The resolution of the Astro-Array at 3 GHz.

Fig. 1 — Full Width at Half Maximum (FWHM) resolution vs frequency for an array with a maximum baseline of 200,000 km. The figure also shows an average interstellar (IS) scattering size limit outside of the galactic plane (/b/ > 10°) (also see the Interstellar Scattering Section). The current Very Large Array (VLA) maximum resolution (Hjellming, 1982), the planned Very Long Baseline Array (VLBA) resolution (NRAO, 1982), and the proposed Quasat resolution (ESA, 1984) are given for the frequency ranges over which they are expected to operate. For reference, the known sizes or size limits for a number of compact, non-thermal astrophysical objects are also shown. For example, the Earth-Sun distance (1 AU) seen at 10 pc distance can be resolved by the VLA while the separation of galactic clusters of interstellar masers into individual spots requires at least VLBI resolution. Separation of extragalactic maser clusters into individual spots will require a factor of $10^2 - 10^3$ more resolution and will only be possible with the Astro-Array.

The emission regions on galactic flare stars such as the RS CVn and dMe stars are difficult to impossible to resolve with the VLBA, even with Quasat, and need the high resolution (and sensitivity) of the Astro-Array to permit study in detail.

The extragalactic radio supernovae (RSN) become large enough to resolve with current or planned telescopes only after several years of expansion and study of the critical early development phase of the supernovae requires the much higher resolution of the Astro-Array.

The Low Frequency Variable sources (LFVs), the Active Galactic Nuclei (AGNs), and the Quasi-Stellar Objects (QSOs) have structure on many size scales from < 0.1 milliarcseconds (mas) to arcseconds and even to arcminutes. For these, all telescopes, from the large single dishes (e.g., the Effelsberg 100 m telescope), to the connected interferometers (e.g., the VLA), to the Very Long Baseline Interferometers (e.g., the VLBA and Quasat), to the Astro-Array complement one another with the increasing capability for observing smaller size scales. For studying the intrinsic energy generation mechanisms of these powerful and poorly understood objects, the highest resolution at the highest frequencies is needed.


1 arcsec
1 mas
1 μas
SIZE (arcsec)
ν (Hz)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
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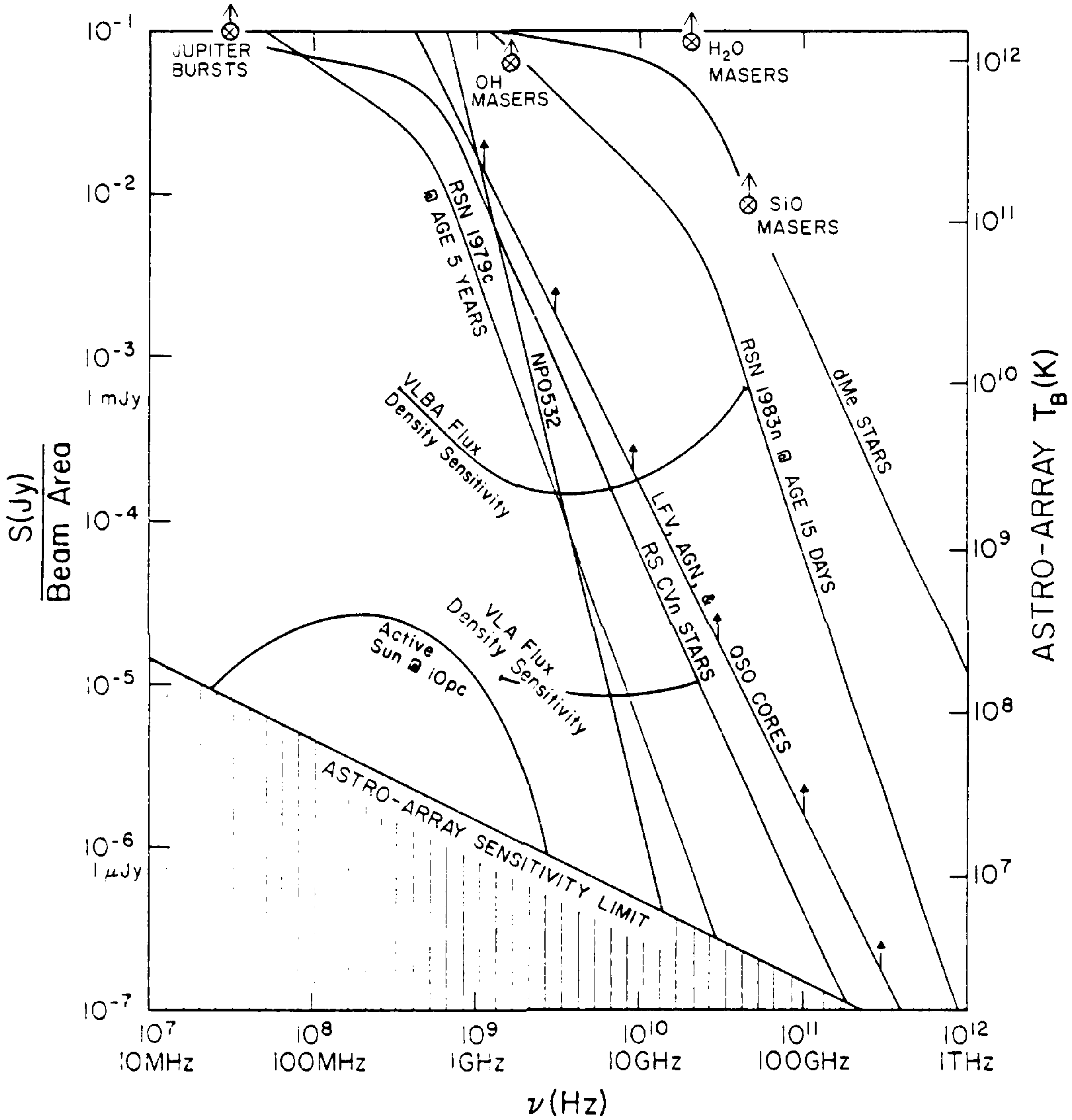
10^7 10MHz
10^8 100MHz
10^9 1GHz
10^10 10GHz
10^11 100GHz
10^12 1THz
VLA FWHM Resolution
Jupiter
1 AU @ 10 pc
OH MASER CLUSTER
SiO MASER CLUSTER
H2O MASER CLUSTER
IS Scattering Size
ASTRO-ARRAY FWHM Resolution Limit
VLBA FWHM Resolution
OH MASER SPOTS
SiO MASER SPOTS
RSN 1979c @ AGE 5 YRS
Sun @ 10 pc
VLBA+QUASAT Resolution
RS CVn STARS
H2O MASER SPOTS
dMe STARS
Strong LFV, AGN & QSO Nuclei
RSN 1983n @ AGE 15 DAYS
1^s pulsar @ 100 pc

Fig. 2 — Flux density (left scale) and brightness temperature (right scale) sensitivity vs frequency for the Astro-Array with the system parameters from Tables 1 and 2. For comparison, the VLA flux density sensitivity (Hjellming, 1982) and the planned VLBA flux density sensitivity (NRAO, 1982) are shown. (N.B.: While the flux density (left) scale applies to all telescopes, the brightness temperature (right) scale is *only* applicable to the Astro-Array. Brightness temperature sensitivity is dependent on the telescope resolution as well as on its flux density sensitivity.) The flux density sensitivity for the VLBA with Quasat will not differ significantly from that for the VLBA only.

With the large collecting area per antenna, large number of antennas, and wide receiver bandwidths at high frequencies, the Astro-Array will have 5 to 10 times more sensitivity than the VLA and approximately 2 orders of magnitude more than the VLBA. The Astro-Array will be able to detect even steep spectrum objects like pulsars (e.g., NP0532) up to high frequencies and provide detailed study of extended objects such as the cores of LFVs, AGNs, and QSOs and the young and rapidly evolving Radio Supernovae (RSN). Emission regions on flare (RS CVn and dMe) stars will likewise have sufficient surface brightness to be mapped at the higher frequencies and not only will the galactic masers (shown) be strong sources but the most intense extragalactic masers will be detectable (even though 10^6 times weaker) out to the distance of the Virgo Cluster.

At the lowest frequencies, the structure of the non-thermal bursts in the magnetosphere of Jupiter can be studied and the radio emission from active solar-type stars can be detected out to several parsecs.


JUPITER BURSTS
OH MASERS
H$_2$O MASERS
SiO MASERS
RSN 1979c @ AGE 5 YEARS
NP0532
RSN 1983n @ AGE 15 DAYS
dMe STARS
VLBA Flux Density Sensitivity
LFV, AGN, & QSO CORES
RS CVn STARS
VLA Flux Density Sensitivity
Active Sun @ 10pc
ASTRO-ARRAY SENSITIVITY LIMIT
10^{-1}
10^{-2}
10^{-3}
1 mJy
10^{-4}
10^{-5}
10^{-6}
1 μJy
10^{-7}
S(Jy) / Beam Area
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
ASTRO-ARRAY T$_B$(K)
10^{7} 10MHz
10^{8} 100MHz
10^{9} 1GHz
10^{10} 10GHz
10^{11} 100GHz
10^{12} 1THz
ν(Hz)

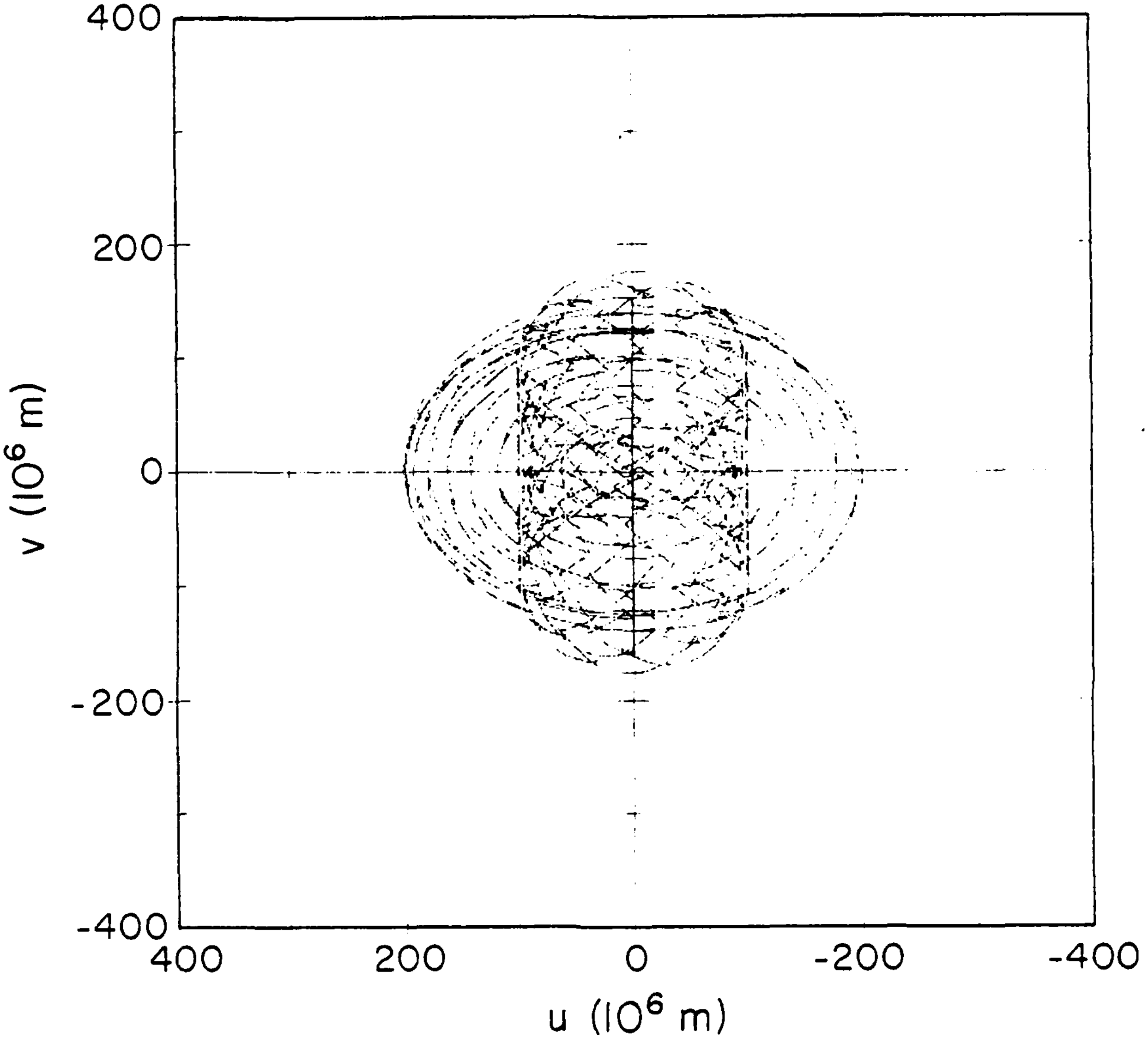


Fig. 3 — The coverage of the Fourier transform (u, v) plane by an array of 30 telescopes arranged 10 each in 3 perpendicular orbital planes for a source lying at 40° declination perpendicular to one of the polar orbital planes. All three orbits, one equatorial and two polar, are circular with equal radii of $1 * 10^8$ *m* (100,000 km). The 10 antennas in each orbit are equally spaced.

(N.B. The Hermitian conjugate tracks are NOT shown.)

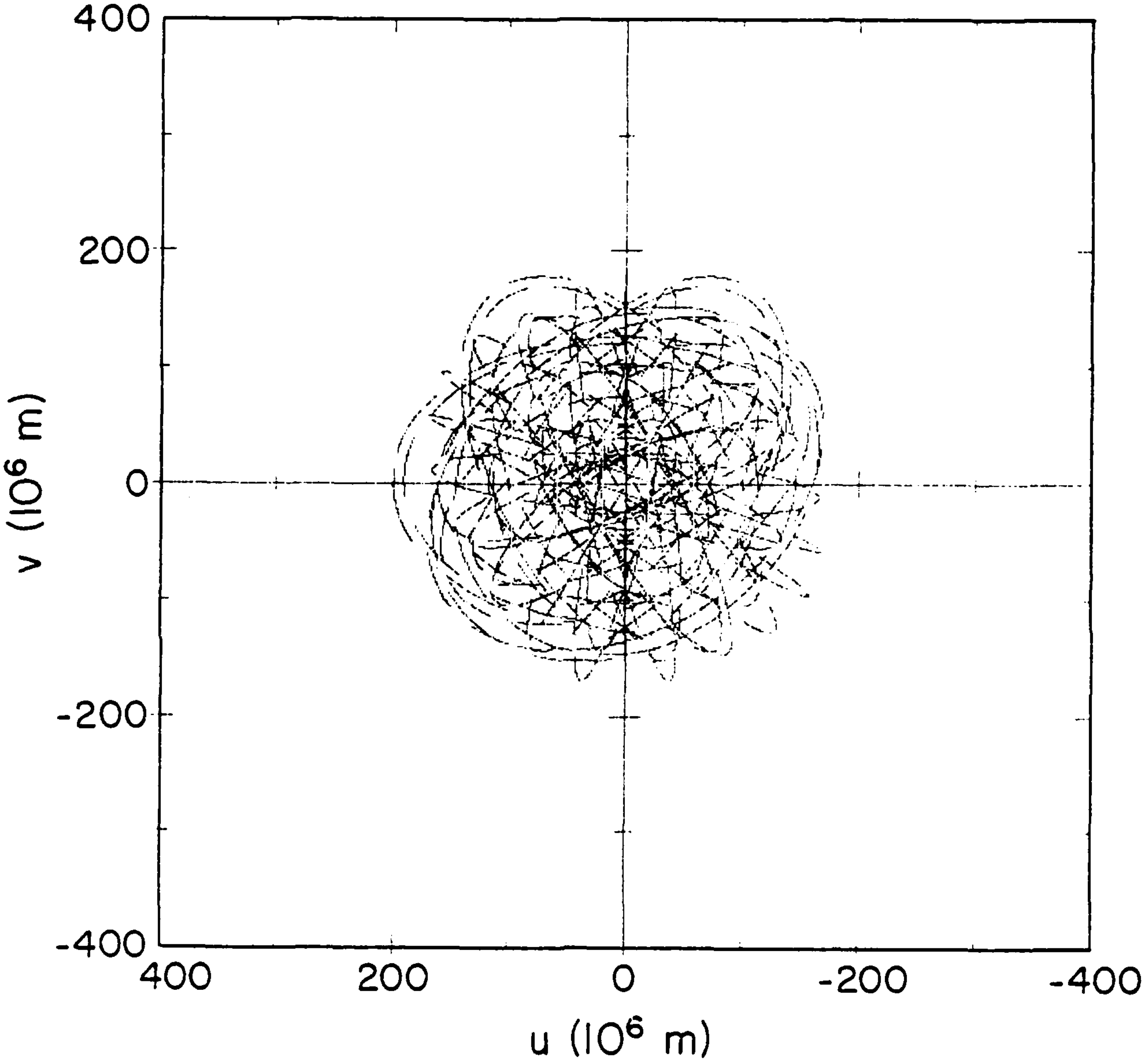


Fig. 4 — The same configuration as Figure 3 but with the source shifted by 3^h of right ascension. (N.B. The Hermitian conjugate tracks are NOT shown.)

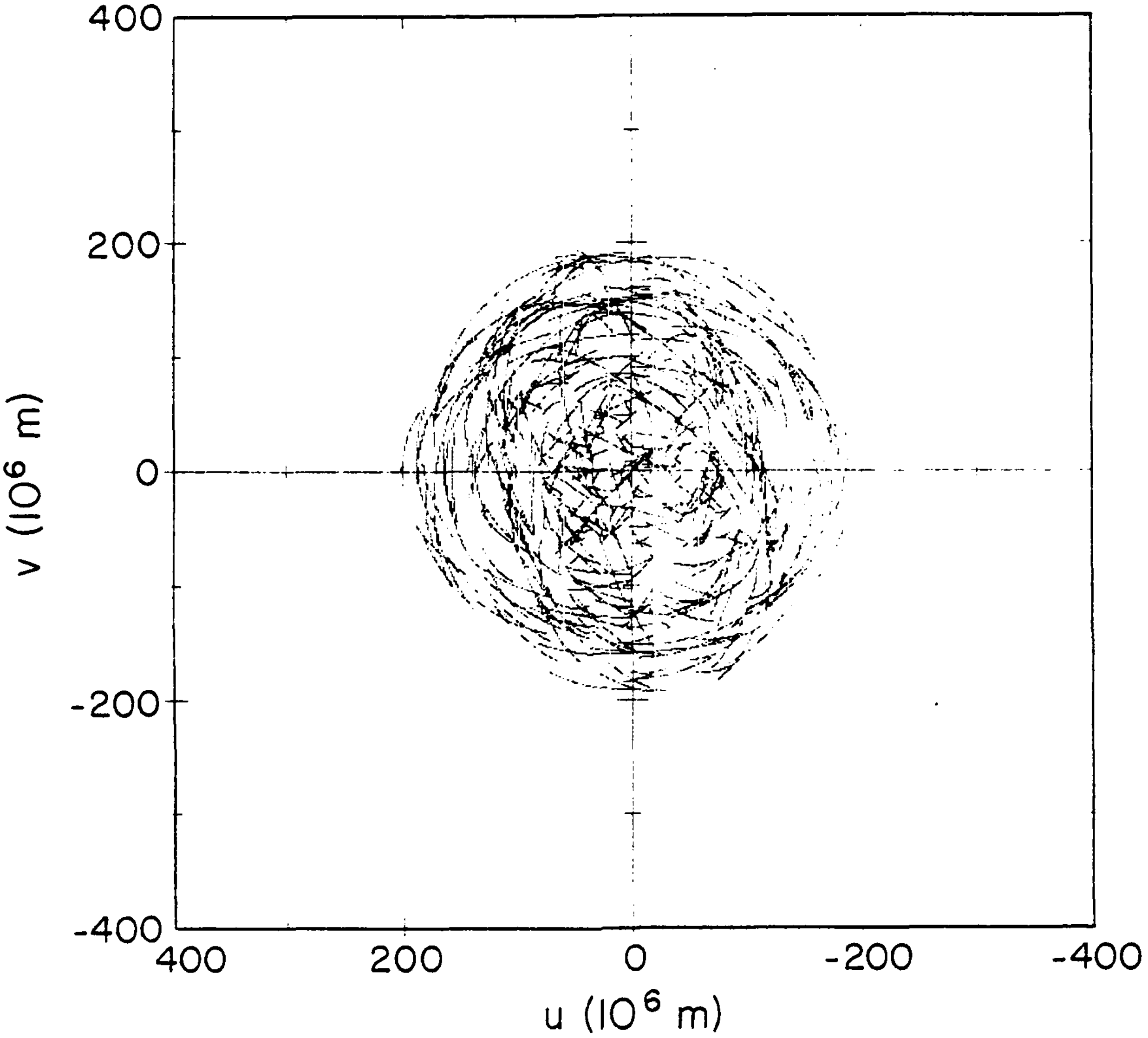


Fig. 5 — The coverage of the Fourier transform (u,v) plane by an array of 30 telescopes arranged in numbers of 7, 7, 8, and 8 in 4 orbital planes for a source at 40° declination. As the only arrangement of 4 independent planes the orbits pass through the points of a regular tetrahedron with one orbit in the Earth's equatorial plane. All orbits are circular with equal radii of 1 * 10^8 m (100,000 km) and the antennas in each orbit are equally spaced.

(N.B. The Hermitian conjugate tracks are NOT shown.)

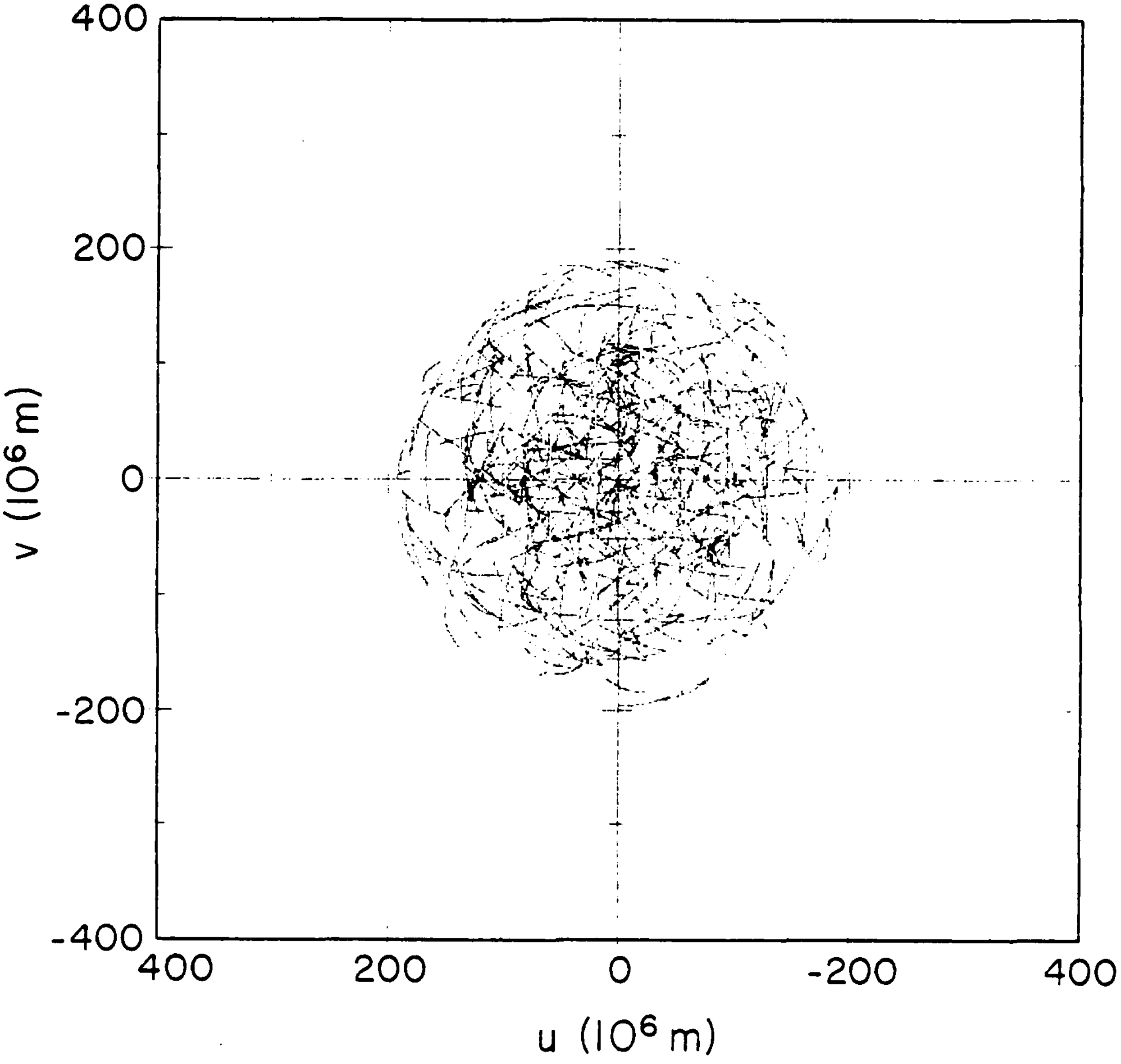


Fig. 6 — The coverage of the Fourier transform (u,v) plane by an array of 30 telescopes arranged 5 each in 6 orbital planes for a source lying at 40° declination. As the only arrangement of 6 independent planes, the orbits pass through the points of a regular duodecahedron with one orbit in the Earth's equatorial plane. All orbits are circular with equal radii of 1 * 10^8 m (100,000 km) and the antennas in each orbit are equally spaced.

(N.B. The Hermitian conjugate tracks are NOT shown.)

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