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THE FEASIBILITY OF AN ORBITING 1500-METER RADIOTELESCOPE

by William M. Robbins, Jr.

Prepared by
ASTRO RESEARCH CORPORATION
Santa Barbara, Calif.

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THE FEASIBILITY OF AN ORBITING 1500-METER RADIOTELESCOPE
—— A Summary Report ——

By William M. Robbins, Jr.
Astro Research Corporation

SUMMARY

Various investigations by the Astro Research Corporation concerning the development of an orbiting, 1500-meter radiotelescope are reviewed. The radiotelescope system utilizes a paraboloidal reflector formed by a network of aluminum ribbons and weighs only about 1300 kg in orbit. The fabrication, deployment, control, and long-term survival of such a system appear entirely feasible.

The various detailed investigations and analyses which have been carried out to date are documented in the reports referenced herein.

INTRODUCTION

Some of the most startling theories of modern cosmology have been developed only after the advent of radiotelescopes which could probe the universe with adequate spatial resolution. The earth-bound radiotelescope, however, is hindered by the thick atmospheric filter through which it must look and which limits observations to a "window" existing from 10 mc to 30,000 mc.

There is certainly much to be learned by extending the frequency range so that the celestial sphere can be examined in the region between 1 and 10 mc with a telescope capable of considerable resolution. Since the required aperature of a radiotelescope is proportional to the wavelength of observation and inversely proportional to the angular resolution, very large radiotelescopes orbiting above the earth's atmosphere will be required.

As "ground rules" for the present study it has been assumed that the system should operate between 1 and 10 mc but be optimized for producing a half-power beamwidth of 3° at a frequency of 4 mc (a wavelength of 75 meters). The system should orbit the earth at an altitude of 6000 km and should be capable of scanning the entire celestial sphere in a period of six months or less.

The environment in which the radiotelescope will operate is considerably different from that of most very large structures and it is therefore to be expected that the radiotelescope will be basically different from conventional structures. It will not experience the wind or gravity loads that determine the form of earth-based structures. Rather, it will be subjected to a very small difference in gravitational acceleration at various portions of the structure, to the geomagnetic field, to solar radiation, and to a flux of very high-velocity (but generally very small) micrometeoroids. Further, its size and mass at launch must be compatible with present or planned rocket launch vehicles.

It is not the function of this report to present detailed analyses of any of the major problems associated with the design of a very large orbiting radiotelescope but to bring together various results obtained elsewhere and to show, in a cursory manner, that a reasonable system solution exists if conventional ideas of design are discarded in favor of filamentary tension structures.

SYSTEM CONFIGURATION

Of the various possible forms of directive antenna, the paraboloid of revolution has been chosen for the large orbiting radiotelescope since it is the most generally useful in that it can operate over a wide band of frequencies, side-lobe responses are quite low, and the design is the simplest in most respects since the only distributed structure which is required is a surface. In order that a half-power beamwidth of 3° be achieved at a frequency of 4 mc, an aperature (reflector diameter) of 1500 meters is required. Since signals reflected from various portions of the paraboloid must arrive at the focus sufficiently in phase if the system is to operate as a high-gain device, the root-mean-square deviation of the reflecting surface from a true paraboloid must be no greater than about 1/16 wavelength, or approximately 2 meters for a wavelength of 30 meters (which corresponds to 10 megacycles per second).

An overall view of the system is shown in figure 1. It is composed functionally of the 1500-meter paraboloidal reflector, a radio receiver at the focus of the paraboloid, a radio link to earth-based receivers, and a system for making the telescope scan the celestial sphere or for commanding it to "look" in some desired direction.

The reflector is a paraboloidal annulus with a focal ratio of 0.5 , formed of aluminum ribbons, and maintained everywhere in tension by means of a central compression column and the centrifugal forces supplied by spin about the axis of symmetry. The required boundary forces are supplied at the inner rim by a system of fibers and at the outer rim by a system of fibers acting in conjunction with a distributed rim mass. This rim mass also serves to carry a rim current which reacts with the geomagnetic field to precess the spinning systems in scanning the celestial sphere.

A spin rate of one revolution in 16 minutes (6.54×10^{-3} rad/sec) has been chosen as a reasonable compromise between several conflicting requirements. A lower spin rate would provide insufficient tension in the reflector network while a higher rate would impose difficult design requirements on the compression column and would result in the use of a large rim current, and thus an undesirably large expenditure of power, in order to achieve the desired scanning rate.

An equipment package at the focus of the paraboloid consists of a dipole array for feeding the radiotelescope and an electronic equipment package for signal processing and for communication. A back equipment package at the opposite end of the column consists of solar cells and power supplies for the supply of current to the rim conductors and to electronic equipment.

The masses and moments of inertia of the various subsystems and the totals for the system are shown in Table I.

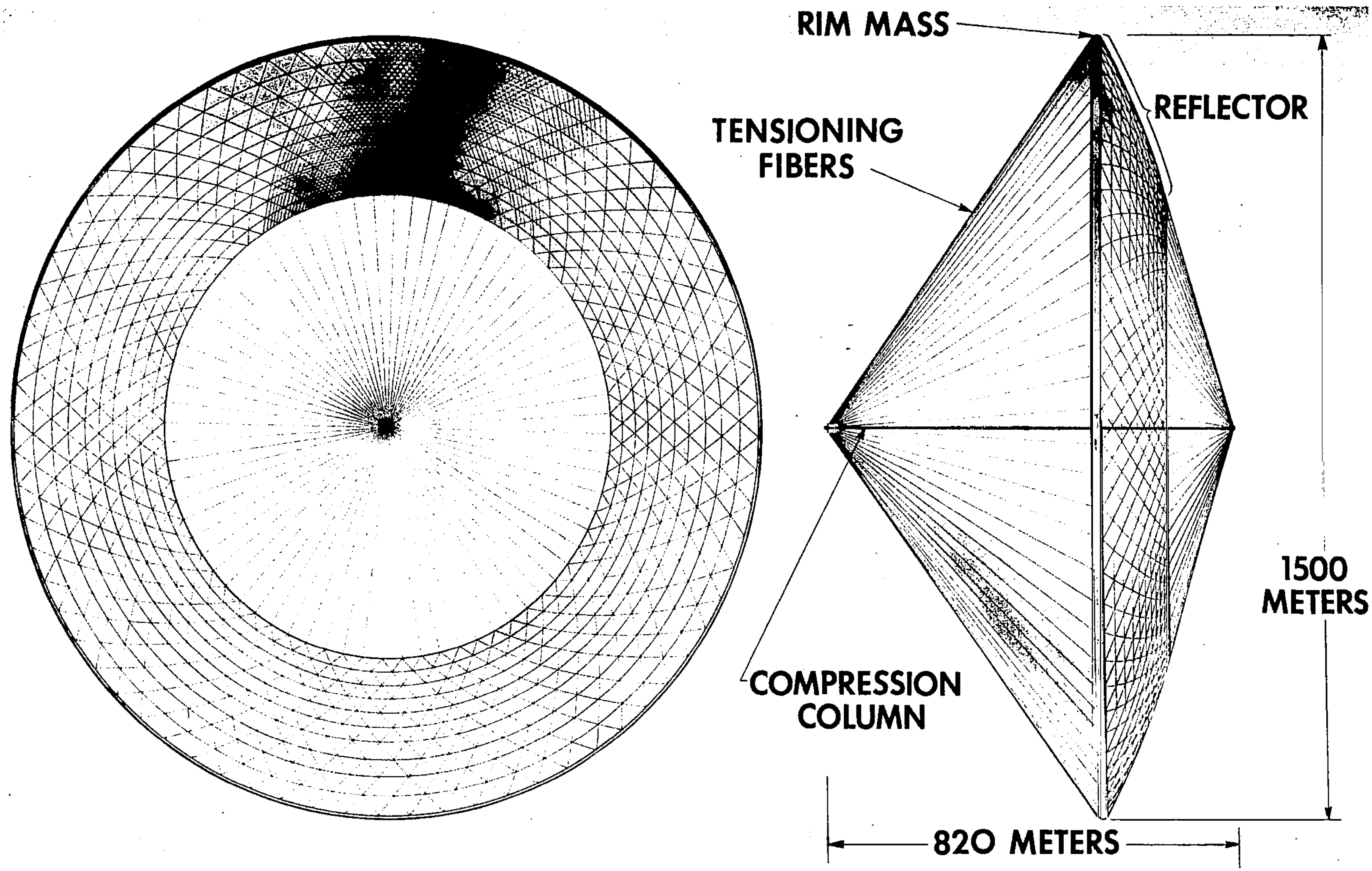


Figure 1. —— Overall View of Radio Telescope

TABLE I

SYSTEM MASSES AND MOMENTS OF INERTIA

Item	Mass (kg)	Polar Mom. of Inertia ($kg \cdot m^2$)	Transverse Mom. of Inertia ($kg \cdot m^2$)
Reflector Grid	498	183.3×10^6	96.5×10^6
Rim Mass	214	118.3×10^6	59.3×10^6
Central Column	227	0	15.7×10^6
Front Equip. Package	100	0	27.6×10^6
Back Equip. Package	140	0	12.2×10^6
Front Tensioning Network	77	14.4×10^6	14.2×10^6
Back Tensioning Network	39	2.6×10^6	3.4×10^6
TOTALS	M = 1295	$I_z = 318.6 \times 10^6$	$I_x = 228.9 \times 10^6$

Notes:

(1) c.g. location is 525 m aft of focus

(2) $I_z / I_x = 1.393$

THE PARABOLOIDAL REFLECTOR

The principal functional element of the large orbiting radiotelescope is its parabolic reflector which is 1500 meters in diameter and has a focal ratio of 0.5 . By truncating the paraboloid at an inner diameter of 900 meters, certain structural problems are overcome (as will be discussed later) and the performance of such a paraboloid is very little degraded by the removal of the central region, leaving an annular reflector, since its directivity is mainly a function of overall size.

The paraboloidal surface is formed by three families of aluminum ribbons, one family being along parallel circles, the other two being symmetrically placed spiral families which make an angle of 30° with the local meridian. The surface of the truncated paraboloid is thus covered with ribbon conductors which everywhere form equilateral triangles, the dimensions of which are proportional to the distance from the axis of symmetry. Such a system is analyzed in reference 1.

The aluminum ribbons are one-half mil thick and a tenth of an inch wide ($12.7\mu \times 2.54$ mm) and the spacing of each of the three sets is 0.8 meters at the rim, the above dimensions being selected to meet the requirement for adequate electromagnetic reflectivity in the frequency range from one to 10 megacycles. The choice of thin and relatively wide tapes was made to decrease vulnerability to micrometeoroid fracture, and to decrease the shortening and the compliance due to creases.

The number of ribbons in each spiral set is 5100 and the number of parallel-circle ribbons is 516. The total number of ribbon elements is thus 7,900,000 , the number of nodes is 2,635,000 , and the total length of ribbon in the reflector network is 5.7×10^6 meters. The mass per unit area at the rim is 327 kg/km^2 and the total reflector mass is 498 kg.

In reference 2 the geometric and ohmic reflection coefficients of networks of ribbons are derived. The data therein shows that the network under consideration has a geometric reflection coefficient of 0.986 and an ohmic reflection coefficient of 0.992 for the spacing at the rim at a frequency of

4 megacycles. These values seem more than adequate but a detailed verification, especially at longer wavelengths where the geometric reflection coefficient is less, will be the subject of subsequent investigations.

As was shown in reference 3, thin-walled tubes and ribbons are much less subject to fracture by micrometeoroids than are solid conductors of the same cross-sectional area. The choice of ribbons rather than tubes is discussed later. From figure 5 of the above reference the expected fracture rate is 4.3×10^{-5} fractures/meter-year which yields a total of 245 fractures per year or one fracture in each 32,200 members per year. This appears to be a very acceptable situation but a determination of the actual total number of tolerable fractures will be given additional consideration.

In reference 1 it is shown that the distribution of stresses in the spinning network of three families of fibers depends upon the spin rate and upon the force supplied by the central column, and that the minimum radius at which tension in the parallel-circle fibers remains positive is thus determined. This stress distribution is defined in terms of a dimensionless characteristic parameter Ω_f which is here chosen to be 4.0 . This value assures that the tension in all ribbons remain positive to a dimensionless inner radius $r/f = 0.6$ or $r = 450$ meters. The parameter Ω_f is defined to be

$$\Omega_f = \frac{\rho \omega^2 f^2}{\sigma_{c(r=f)}}$$

where:

ρ = density of ribbons

ω = spin rate of antenna

f = focal length of paraboloid

$\sigma_{c(r=f)}$ = stress in spiral ribbons where $r = f$

As shown in reference 4, the shortening of a ribbon due to a crease (which may have occurred while the network was in its folded condition) as well as the effective tensile modulus of the ribbon depends upon the direct tension in the ribbon. As the required tension is reduced by using a minimum thickness of tape and a minimum yield stress, the material for the ribbons was chosen to be 0.5-mil, commercially pure, fully annealed aluminum with a yield stress of approximately 5000 psi. A spin rate of one revolution in 16 minutes ($\omega = 6.54 \times 10^{-3}$ rad/sec) has been chosen which yields a value of $\sigma_{c(r=f)}$ (the minimum stress which occurs in the network) of 2.36 psi. This value appears to be sufficiently high if care is taken to minimize the number of sharp creases allowed. The manner in which the reduced effective tensile modulus effects the vibratory modes and amplitudes is discussed in reference 5.

In order that the correct boundary forces be supplied at the inner radius of the reflector, the rear tensioning network, which is taken to lie in a conical surface, must lie tangent to the reflector surface at the point of attachment. There is more freedom in choice of the front tensioning network, with the restriction that the correct rim mass be supplied for a given angle that the tensioning network joins the reflector. However, it is desired that a fixed point be provided at the focus of the paraboloid for supporting the antenna feed system, or primary radiator. For this reason, the front conical tensioning net is assumed to join the front end of the compression column at the focus of the paraboloid. This results in a column length of 820 meters.

From the results of reference 1, it can be shown that the rim mass must be 214 kg and the column load is 2.065 newtons or 0.465 lbf.

THE CENTRAL COMPRESSION COLUMN

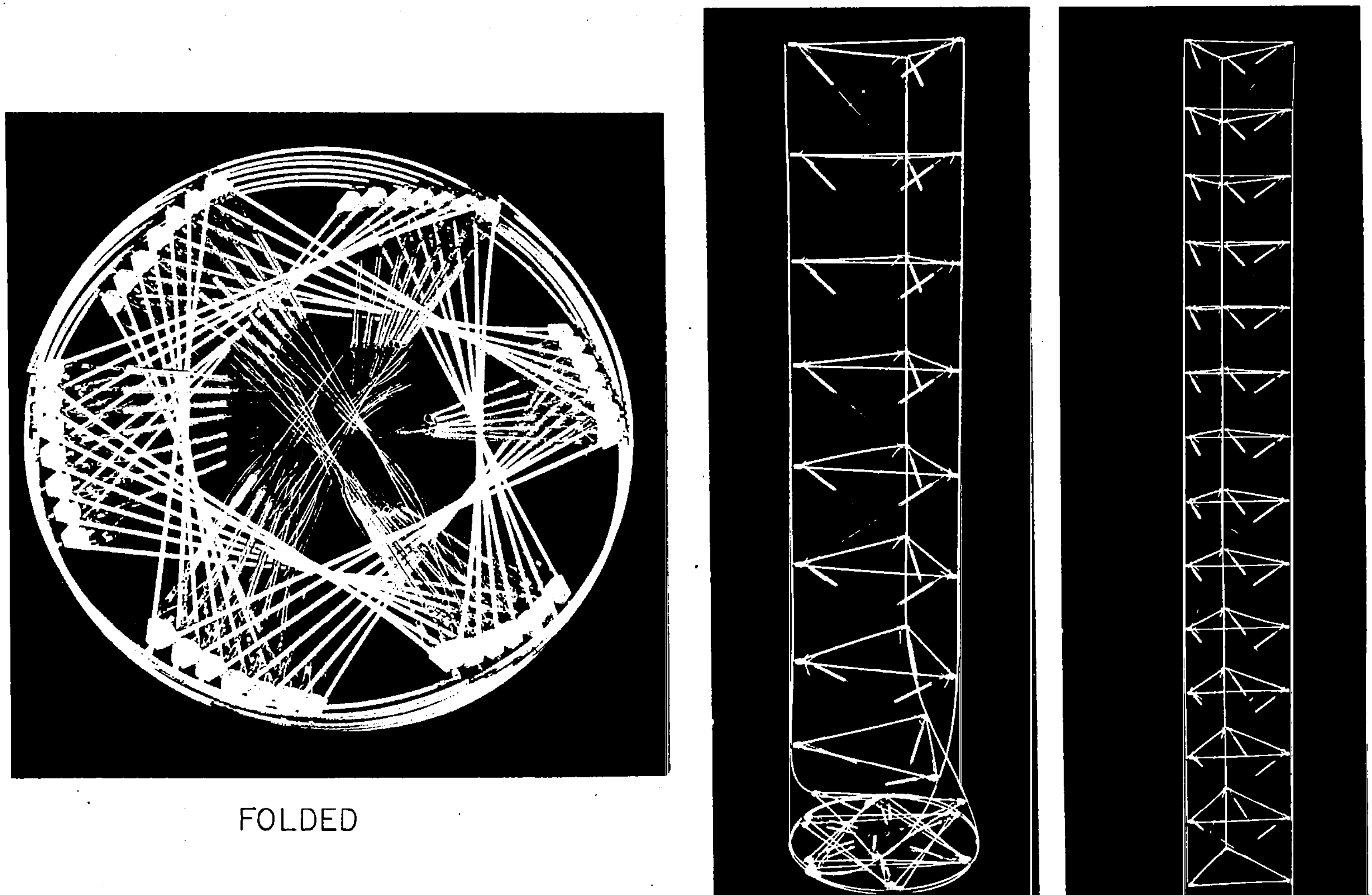
A number of possible concepts for the required central compression column have been considered but analysis has shown that most of them have features which are objectionable enough to eliminate them from further consideration (see reference 6). However, one of these concepts appears to be entirely feasible and is described herein.

The chosen concept is a built-up column with three symmetrically placed compression-resistant longerons, triangular transverse frames, and one tension-resistant diagonal tie in each exterior rectangular section. The diagonal ties are maintained in tension by a spring in each exterior diagonal position not occupied by a tension tie. The system is folded by flexure of the longerons and simultaneous deflection of the springs so as to roll each longeron into a helical coil. A section of 1/10 - scale model has been fabricated and is shown in its deployed, partially deployed, and folded conditions in figure 2.

The main features of the column are its very large length-to-width ratio, its extremely small structural index (i.e. its load divided by the square of the length), and the very small cross-sectional dimensions resulting from limitations on storage space and from the requirement for minimum weight.

In the proposed design the critical failure mode is a general instability but of a more complicated nature than that which occurs in columns designed for a large structural index because the individual longeron members are themselves very long compared with their diameter. Thus, initial imperfections in the longerons cause them to deflect further under load and exhibit a greatly reduced longitudinal stiffness, this stiffness approaching zero as the load in the element reaches the Euler buckling load of the element. It is thus quite apparent that local buckling can never be limiting since the reduced longeron stiffness leads to general instability long before the local Euler load is reached.

Graphical methods have allowed a detailed analysis of the proposed column when given initial imperfections in the



FOLDED

PARTIALLY DEPLOYED

DEPLOYED

Figure 2. —— Deployable Column Folded by Flexure of Longerons

individual elements and in the overall column are assumed. However, no precise optimization technique has, as yet, been found and the design procedure has been carried out by making a number of simplifying assumptions.

The column is required to carry a nominal load of 0.465 lbf over the distance of 820 meters (2690 ft). It must also withstand a spin rate of one revolution in 16 minutes. The effects of subcritical spin (as is the case here) upon the initially bent column are very similar to the effects of end load but have turned out to be considerably smaller. The design analysis has been carried out under the assumption of an end load of 1.47 lbf at failure in the absence of spin.

Certain limitations have also been placed upon the design by the requirement for coiling the longerons for storage since local crippling of the tubular longerons will occur if the longeron diameter becomes too large or if the tube wall becomes too thin. This limit on longeron diameter, in turn, is the major factor which determines how straight the elements must be if they are to have a given effective longitudinal stiffness.

It is also of interest to note that the diagonal tension members must be in the form of ribbons to afford sufficient protection against fracture by micrometeoroids and that minimum-gage limitations on the ribbons results in a cross-sectional area large enough that shear compliance of the column is almost negligible.

The details of the preliminary design which meets the system requirements, as thus far studied, are given in Table II.

TABLE II

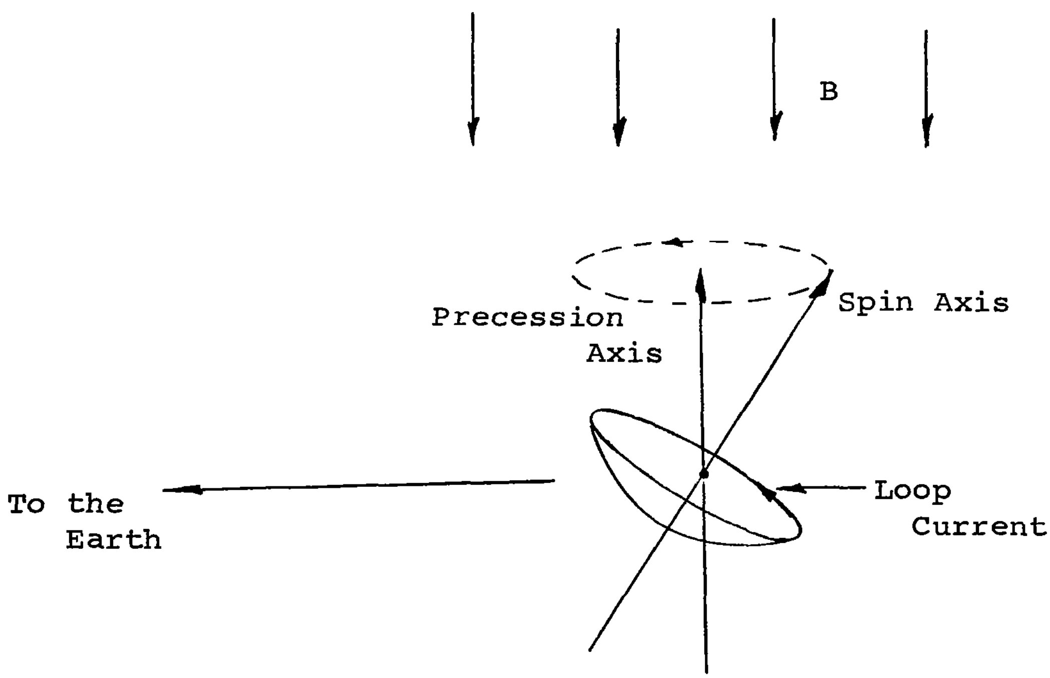
DETAILS OF CENTRAL COLUMN

Overall length	2690 ft
Failure load	1.47 lbf
Storage diameter	120 in.
Distance between longerons	100 in.
Distance between cross-members	57.8 in.
Longeron material	aluminum
Transverse-member material	aluminum
Longeron diameter	0.4 in.
Longeron wall thickness	0.012 in.
Diagonal material	glass-fiber ribbons
Diagonal dimensions	0.4 in. by 0.002 in.
Initial imperfection of longeron element at center	0.1 in.
Initial imperfection of overall column at center	130 in.
Total weight of column	500 lbm

SCANNING

For the purposes of preliminary investigation, it has been assumed that the earth's magnetic field is fixed so that the magnetic axis coincides with the earth's axis of rotation. Under this assumption, the orbiting radiotelescope, which is in an equitorial orbit, experiences a fixed magnetic field which is always normal to the orbit plane. Subsequent analyses will include the effects of the wobble of the earth's magnetic field.

Scanning of the antenna over the celestial sphere will be accomplished by means of a loop current about the rim of the reflector. This produces a torque which will cause the axis of symmetry to precess conically around the magnetic polar axis as shown in the following sketch.

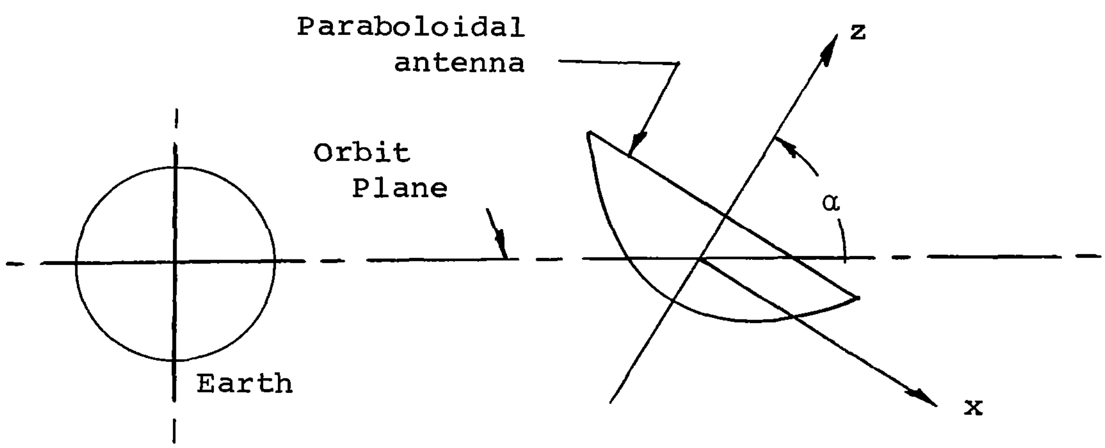


During the course of each scan around the precession axis, the size of the "coning angle" is changed by a relatively small space-fixed loop current which is normal to the rim current and which is maintained fixed in space by commutation between a number of body-fixed loops.

The Gravity-Gradient Torque

One of the major perturbing influences in maintaining the desired orientation of the "look axis" of the antenna (which is coincident with the spin axis) is the gravity gradient.

It has been shown by a number of authors that when an axially symmetric body is orbiting the earth, there is a gravity-gradient torque on the body which has a steady-state component about the transverse axis (y - axis)



which lies in the orbit plane and which is

$$M_y = \frac{3}{4}\cdot\omega_o^2\left(I_z - I_x\right)\cdot\left[2\cdot\sin\alpha\cdot\cos\alpha\right]$$

where:

ω = orbital angular velocity

α = angle between orbit plane and axis of symmetry (z - axis)

The maximum value of M_y occurs when $\alpha = 45°$ and is

$$M_{y(max)} = \frac{3}{4}\cdot\omega_o^2\left(I_z - I_x\right)$$

There are also oscillatory moments about both transverse axes but these are of relatively high frequency compared with the time required to make one scan about the precession axis and will not be considered here.

For an orbital altitude of 6000 km (a geocentric distance of two earth's radii) the orbital period T_o is

$$T_o = (84.4 \text{ min})\cdot(2)^{3/2} = 238 \text{ min} = 14{,}300 \text{ sec}$$

and the angular velocity is

$$\omega_o = 4.39 \times 10^{-4} \text{ rad/sec}$$

Then $M_{y(max)}$ becomes

$$M_{y(max)} = \left(\frac{3}{4}\right)\cdot(4.39 \times 10^{-4})^2(342.3 - 240.8)10^6$$

$$= 14.7 \text{ newton}\cdot\text{meter}$$

The Control Torque

Of the 214 kg of rim mass, it is assumed that 100 kg can be allocated to circumferential aluminum strips forming a conductor around the rim. A total rim current, I , can be made to flow at the expense of dissipating the power, P , in ohmic loss and for an aluminum loop 1500 meters in diameter, the two are related by

$$I = 0.231 \sqrt{P}$$

where I is in amperes and P is in watts. This current will interact with the earth's magnetic field to produce a torque which is normal to both the axis of symmetry of the antenna and to the magnetic field. At an altitude of one earth radius in the equatorial plane the magnetic field is approximately 10^{-5} webers/m^2 (see ref. 7). The maximum torque occurs when the axis of symmetry is perpendicular to the magnetic field and is

$$M_{c(max)} = \frac{\pi}{4} \cdot D^2 IB = 17.7 \times I \quad \text{newton} \cdot \text{meter}$$

or

$$M_{c(max)} = 4.08 \sqrt{P}$$

The allocation of power to the production of control torque is a problem affecting the entire system performance and the optimum value cannot, as yet, be chosen. However, 1000 watts does not appear prohibitive and leads to

$$M_{c(max)} = 129 \quad \text{newton} \cdot \text{meter}$$

When the loop is rotated away from the position of maximum torque, the torque will be decreased by the cosine of the angle of rotation. When the angle is 45° (the position of maximum gravity-gradient torque) the control torque is

$$M_{c(45°)} = 91.2 \quad \text{newton·meter}$$

and compares favorably with the maximum gravity-gradient torque of 14.7 newton meters. In fact, more detailed analysis shows that a torque of at least $100 \cdot \cos\alpha$ newton·meters is always available in the desired direction in excess of that required to overcome gravity-gradient torque.

Scanning Rate and Time

A net torque of 100 newton·meters will cause a precession rate of

$$\dot{\varphi}_{max} = \frac{M_{c(max)}}{I_z \omega} = 4.47 \times 10^{-5} \text{ rad/sec}$$

where

$$M_{c(max)} = 100 \text{ newton·meters}$$

$$I_z = 342.3 \times 10^{6} \text{ kg·m}^2$$

$$\omega = 6.54 \times 10^{-3} \text{ rad/sec}$$

The total time to make one circular scan in the plane of the orbit is then

$$\tau = \frac{2\pi}{4.47 \times 10^{-5}} = 1.404 \times 10^{5} \text{ sec} = 39.0 \text{ hours}$$

Since both the total angle to be covered in one scan around the polar axis and the control torque vary as $\cos\alpha$, the time of one scan is not dependent on the coning angle. It is assumed that the conical scans are placed 3° (the half-power beamwidth) apart and that a conical region about each pole with a half angle of 10° is not scanned. The total number of scans about the polar axis is then (180-20)/3, or approximately 53 scans to cover the complete celestial sphere (except for the two small cones about the polar axes). The total scan time is then

$$\tau_{tot} = \frac{(39.0)\cdot(53)}{(24)\cdot(365)} = 0.236 \text{ years}$$

and four nearly complete scans of the celestial sphere can be accomplished per year.

STRESSES AND DEFORMATIONS

Static and dynamic distortions of the radiotelescope are important design considerations since they directly effect the gain and directivity of the radiotelescope. The stresses produced by environmental loads are not likely to be significant from the view point of structural integrity, with the possible exception of fatigue stresses in sharp creases. The permissible displacements of points in the reflector grid are relatively large. If it is assumed that a distortion equal to one-sixteenth of a wavelength is acceptable, then the permissible displacement from a paraboloidal surface at a frequency of 10 megacycles is about 2.0 meters or about 1/750th of the diameter of the reflector.

Due to the spin of the antenna about its axis, environmental loads that would normally be considered to be static for a non-rotating body produce dynamic effects that are subject to resonant amplification. A static-load distribution in a non-rotating coordinate system becomes a traveling wave in a coordinate system that rotates with the antenna. Details of the transformation between the non-rotating and rotating coordinate systems and identification of the important parameters for resonant amplification are discussed in reference 5.

No attempt has been made as yet to determine the magnitudes of the distortions due to dynamic loads, since this phase of the dynamic analysis of the orbiting radiotelescope has not yet begun. Order-of-magnitude estimates of the more obvious sources of dynamic loads have been made in reference 5 in order to indicate the need for dynamic analysis. The sources considered therein are gravity gradient, thermal gradient, photon pressure, mass unbalance, and transient control forces.

The homogeneous equations describing motions of an elastic axisymmetric body were written as partial differential equations in a cylindrical coordinate system. These equations were tailored for investigation in the SADSAM IV computer program of the MacNeal-Schwendler Corporation, and the normal-mode frequencies and mode shapes of the radiotelescope were computed for several values of n (the number of circumferential waves) for both forward and backward traveling waves (traveling waves rather than standing waves are the normal modes of a rotating elastic axisymmetric body).

The results of the calculations show the existence of potentially serious resonance conditions for all harmonic orders greater than the second. Resonance can be avoided for the lower harmonic orders, but not for the higher ones, by increasing the extensional stiffness of the reflector network. Once higher-order resonances are detected, however, they can be avoided by small changes in the rotational speed.

FABRICATION, PACKAGING, AND DEPLOYMENT

The reflector network and the front and back tensioning networks will be manufactured and packaged in a machine of reasonable dimensions which precisely meters the length of the elements, fabricates the joints, and lays the networks into the launch package as they are completed. The entire network structure is, of course, too large to ever be deployed except in space.

One possible deployment scheme calls for imparting spin momentum to the networks in the manner of the "yo-yo" despin device which has been successfully used on several satellites. This places the reflector and tensioning networks into two flat discs joined at the peripheries. Subsequent deployment of the central column then produces axial expansion and provides the final form to the system.

Other possible means for deployment include interaction of loop currents in the structure with the earth's magnetic field to supply radial expansion to the system.

CONCLUDING REMARKS

Some of the more critical aspects of the development of an orbiting 1500-meter radiotelescope have been investigated in a study undertaken by Astro Research Corporation and are documented in a series of Technical Reports. Those results which bear directly upon the feasibility of the system concept which has grown out of the study are summarized in this report.

None of the results thus far obtained indicate any basic obstacle in the development of the proposed system.

Astro Research Corporation
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