Design Studies of Radio Telescopes

by J. W. Findlay

National Radio Astronomy Observatory
Post Office Box 2
Green Bank, West Virginia

February 11, 1965

LFSP/JWF/3

Dear Colleague:

The Largest Feasible Steerable Paraboloid

I have received a number of comments and replies to my first paper on the design study, and I am circulating these either in full or in abstract in the following documents:

a) Parts of a letter dated January 20, 1965, from Professor F. D. Drake, Cornell University

b) Parts of a letter dated January 21, 1965, from Dr. B. F. Burke, Department of Terrestrial Magnetism, Carnegie Institution of Washington, with a brief note added by me

c) A letter dated January 22, 1965, from Grote Reber

d) A paragraph of a letter dated January 29, 1965, from Mr. T. P. Wright, President of Associated Universities, Inc.

e) A letter and enclosures dated January 28, 1965, from Professor R. N. Bracewell of the Radio Astronomy Institute, Stanford University.

With my best wishes,

Sincerely yours,

John W. Findlay

John W. Findlay,
Deputy Director

a) Excerpt from a letter from Professor F. D. Drake, Cornell University, dated January 20, 1965:

"My suggestion, which you have heard before, is to consider the analog of the optical mirror cell. I think the presently most plausible form of this would employ an alt-azimuth mount, with the dish supported in many places by pairs of pistons in pneumatic cylinders, the cylinders being nearly at or at right angles. The total force exerted on each piston of a pair would be adjusted so that the resultant force generated by the two pistons is exactly vertical and equal to the weight of the portion of the dish bearing on that particular pair of pistons. As the dish is moved in altitude, the pressures in the two cylinders are varied so as to maintain the resultant force constant in magnitude and direction. This latter task can be done easily in an analog manner by having two master cylinders which feed all the cylinders, the forces in the cylinders being produced by weights on their pistons. These master cylinders move with the mount, and the pressure in their systems will be proportional to the component of the gravitational force of the weights along the axis of the cylinders. Obviously, if the master cylinders are parallel to their slaves, the variation in pressure in each system of cylinders with altitude will be just right.

"Something must take the wind force (also in Bowen's suggestion mentioned in the floating sphere document). I would suggest a wind screen just in front of and behind the dish, and connected by many rods to the same structure which carries the pneumatic cylinder system. The rods would penetrate the dish to reach the screen on the front side of the dish. The wind screen and basic supporting structure will then deflect considerably due to wind and gravity loads, but the dish will not deflect because it is supported with the required forces without self-deflection, and is protected from the wind. The wind screen is a cheap, small radome, carried on the instrument itself.

"The concept can be applied to the equatorial configuration with the addition of a third pneumatic system."

b) Excerpt from a letter from Dr. B. F. Burke, Department of Terrestrial Magnetism, Carnegie Institution of Washington, dated January 21, 1965:

"Thank you for sending along the first draft study on the floating sphere antenna. I have a few comments - mostly negative, but then negative criticisms are always easiest.

"1. Formula 10, page 3, is in error. If the area of section is taken normal to the surface of the sphere as in formula 9, the supporting force must be increased by the cosecant of the angle between the horizontal and the tangent to the sphere. This raises the stress by a factor of almost two which is still within the allowable stress limits for steel. The strain is of the order of 3×10^{-4} however, which is a fairly large elastic deformation.

"2. Dynamic properties of the sphere will certainly be considered in the future. One easy number to calculate is the resonant period of the sphere bobbing in the water. It is easy to see that if the sphere is submerged to the depth ℓ, its resonant period will be $2 \pi A \sqrt{\frac{\ell}{g}}$ which, except for the geometrical factor A, is the same as for a simple pendulum. $A \cong \sqrt{2}$ for the case of a sphere submerged to a small part of its diameter in an infinite bath tub. It is easy to calculate A for other configurations.

"The natural period will certainly be several seconds, an awkward period for a servo system that must compensate for wind pressures varying with similar periods. This point will surely have to be looked into carefully.

"3. Several people, including myself, have championed foam plastic as an unusually stiff material when only self-loads are considered. This morning we measured the ratio of elastic modulus to density, E/ρ, for polystyrene foam and find that it is approximately 60 times worse than steel. Upon reflection, this result is not surprising since one would expect foam steel (steel structures with many members) to be stronger than foam plastic."

Note by JWF:

I agree with BFB's comment 1. My mathematics are wrong. The bobbing action of the sphere I forgot, since it seems reasonable that one would never float all the weight of the sphere, but only about 90%, carrying the rest on wheels and rails for guiding and providing the rotational movements needed.

c) Copy of a letter from Grote Reber, dated January 22, 1965:

"C.S.I.R.O.
Stowell Avenue
Hobart, Tasmania
Australia

"Dear John:

"Thank you for your letter of the 13th and enclosure. I have always been interested in large dish type radio telescopes. They provide important astronomical data plus real engineering challenges. Much of my comments in the past have been critical because I thought both the designs and the methods of approach were poor. However, if the subject is to be taken up again in a rational and unhurried manner, I will try to offer constructive suggestions.

"Mirror Surfaces

"A very good theoretical disertation with experimental confirmation upon the effects of mirror roughness is entitled "Effect of Aperture Distribution Errors on the Radiation Pattern", by John Ruze, Antenna Laboratory Memorandum AFCRC, January 22, 1952. I recommend it as a starting point on mirror design.

"Mirror Support

"General considerations applicable to any design will be found on first three pages of memorandum by me entitled "Large Mirror Design", 12 March 1955, Appendix A-14-1 of AUI report on Steerable Radio Telescopes. These points can be used as a criterion for comparison of widely divergent designs.

"Models

"I strongly urge more time, money and effort be expended on working scale models. Much of the past difficulties have been caused by reliance upon the opinions of consultants with low index of expertness. General considerations relating to models may be found in my comments published in Stenographic Transcript of NASA Conference on Large Aperture Antennas, Washington, D. C., November 6, 1959, pages 117 & 118. Chairman Wallace L. Ikard. On pages 115 & 116 appears some interesting description of design of spars to support focal apparatus.

"Reference LFSP/JWF/2

"Under conclusions should be an item (aa) Windage. This is only hinted at in section (c) item (b) page 4. A simple formula for wind pressure on a flat surface is $P = V^2/300$ pounds per square foot, where V is wind velocity in miles per hour. For long thin cylinders multiply by 2/3 and for spheres by 1/2. Not only will the wind forces be large but highly irregular in direction and magnitude due to gusts. This means large non-uniform horizontal forces must be dealt with. They will be high above the center of support. The idea has been studied somewhat by John M. Boyle, Naval Ordnance Testing Station memorandum TP2183 entitled "A proposal for a very large Antenna for Radio Astronomy, Space Communication and Long Range Radar", 17 February 1959. The design might be attractive on the back of the moon.

"Please keep me on the mailing list. I suggest that this letter be circularized to the whole group.

Best regards

S/ Grote

Grote Reber"

d) Excerpt from a letter from Mr. T. P. Wright, President of AUI, dated January 29, 1965:

"I received your letter of January 13 concerning the LFSP. On rereading this, I believe I have no additional comments to make other than I mentioned to you the other day, namely, that cost estimates be based not only on detailed calculations of the various components added up to give a total, but also a more general estimate based on extrapolation of actual costs which have maintained in the past on telescopes of a somewhat similar type. I found this was very useful in connection with estimating the costs of new types of aircraft which were under development during the past many years. As regards aircraft, it is interesting to note that we found quite consistently that the cost of larger aircraft was less than those of smaller on the unit basis, whether based on airframe weight or on wing area. The actual rule was that the cost of larger units went up as the cube root of the size factor.

"I was much intrigued by your discussion of "the floating spherical antenna." This seems like a very logical concept and one which might very well work out admirably in practice. If this should not prove a feasible scheme, then probably some more usual configuration such as that of the Jodrill Bank telescope will be indicated as desirable. I fear that the arrangement of the 140 ft. telescope at Green Bank is one that has just about reached its maximum in size in that instrument."

e) A letter and enclosures* from Professor R. N. Bracewell of the Radio Astronomy Institute, Stanford University, dated January 28, 1965, attached.

* Reprints not enclosed.

RADIO ASTRONOMY INSTITUTE

STANFORD, CALIFORNIA

January 28, 1965

Dr. J. W. Findlay
National Radio Astronomy Observatory
Green Bank, West Virginia

Dear John,

Thank you for sending LFSP/JWF/1 & 2 which represent the beginning of a worthy enterprise.

Here is a suggestion to add to the list of possible LFSP configurations: a number of parallel tiltable parabolic cylinders, each 600 feet long, or longer, mounted so as to be rotatable in azimuth.

Considerations leading to this arrangement are written up in the following references which are attached:

"Future large radio telescopes", Nature vol. 193, pp. 412-416, February 3, 1962. R. N. Bracewell, G. Swarup and C. L. Seeger.

"Proposal leading to future large radio telescopes", Proc. Nat. Acad. Sci., vol. 49, pp. 766-777, June, 1963. R. N. Bracewell.

A feed which has been developed for cylindrical reflectors is described in

"A dual-polarized line source for use at S-band", Microwave Journal, vol. 6, pp. 81-87, January 1963. W. A. Cumming.

In its existing form, this feed allows for linear polarization both horizontally and vertically and for circular polarization in either sense.

If this feed were scaled to 21 cm, it would have a bandwidth of 50 Mc/s, amply covering the protected band 1420-1427 Mc/s.

A cost advantage might result from replacing a cylinder with a line focus by a "scalloped" cylinder with multiple collinear point foci and accepting the extra structural complexity. The point foci would be interconnected as described by Thompson and Krishnan, "Observations of the six most intense radio sources with a 1.0' fan beam" (Ap.J. in press).

Design data and cost estimates on tiltable parabolic cylinders in the smaller sizes were obtained by Rohr Aircraft under Grant GP-440 from the National Science Foundation.

For some astronomical purposes the inability to point at the horizon will be disadvantageous, but for other astronomical purposes the configuration proposed is perfectly satisfactory. Therefore I think it certainly qualifies as a candidate for cost studies alongside other filled-aperture circular-beam radio telescopes.

In addition two particularly advantageous features should be noticed.

(a). The arrangement is well adapted to operation at the wavelength of 10 cm mentioned as a hope in Dr. Westerhout's report, or even less.

(b). In the size range from 600 to 1000 feet no structural barrier is likely to be encountered.

Sincerely yours,

RNBracewell

R. N. Bracewell

Encs.

RNB:msn

THE FLOATING SPHERE ANTENNA

J. W. Findlay
(December 1964)

INTRODUCTION

As a mount for a large parabolic dish, the floating sphere was considered by the CSIRO group in Australia when preliminary studies for the 210-foot were being made. The idea was not followed far because more conventional designs were clearly satisfactory for reflector sizes up to about 300 feet. The following simple note sketches some possible advantages and disadvantages of the floating sphere mount for much larger dishes.

GENERAL DESCRIPTION

Figure 1 shows the general idea. The dish is supported within a sphere which is partly rigid and partly completed by a radome. The sphere floats on water. The motion of the sphere may be controlled and its position indicated in a variety of ways. The general properties of such a design can be shown by a few simple "order of magnitude" calculations. For these, a sphere of 100 meters radius, which is about right to hold a 600-foot dish, will serve as an example.

SIMPLE PROPERTIES OF A SPHERICAL SHELL

For simplicity, consider a uniform complete shell of radius R and thickness t.

(a) How deep does it sink in water?

Let the density of the sphere material be ρ kgrms/m^3. For water $\rho_w = 10^3$; for steel $\rho \doteq 7.8 \times 10^3$; for concrete $\rho \doteq 2.7 \times 10^3$.

$$\text{Mass of sphere} = 4\pi R^2 t\rho \text{ kgrms} \tag{1}$$

Let the depth of immersion be D meters.

$$\text{Mass of displaced water} = \pi D^2(R-D/3)\rho_w \text{ kgrms.} \tag{2}$$

Equate (1) and (2) to give D.

Roughly neglecting D compared with 3R we get

$$D = (4Rt\rho/\rho_w)^{1/2} \tag{3}$$

For $R = 100$ $t = 0.1$ $\rho/\rho_w = 7.8$ $D = 17.7$ meters. A more accurate solution of the cubic equation for D gives a value of $D = 18.2$ meters.

(b) <u>What is the pressure of the sphere in water?</u>

The maximum pressure on the spherical shell is that arising from the hydrostatic pressure at depth D. From (3) approximately

$$\text{Pressure} = (4Rt\rho\rho_w)^{1/2}\, g \tag{4}$$

where the units are Newtons m^{-2}. In engineering units of lbs/sq. inch at 18.2 meters (60 feet) of water the pressure is about 26 lbs/sq. inch.

(c) <u>How thick should the sphere be?</u>

To illustrate the stresses in the sphere due to its own weight, imagine it first cut into two halves by a horizontal plane. The gravity forces across this plane are

$$\text{Force} = 2\pi R^2 t\rho g \tag{5}$$

The area of the surface of the plane is $2\pi Rt$ so that the force per unit area is

$$\text{Force/unit area} = R\rho g \qquad (6)$$

{Note that this stress is independent of the shell thickness.}

Using practical units, with R = 100 meters (3940 inches) in (6), we get

Aluminum:	ρ = 0.1 lbs/cubic inch	Stress = 394 lbs/sq. inch
Concrete:	ρ = 0.1 lbs/cubic inch	Stress = 394 lbs/sq. inch
Steel:	ρ = 0.28 lbs/cubic inch	Stress = 1100 lbs/sq. inch

These stresses are very small for the materials in question. However, consider the stresses in the steel at the water-line. It is floating with D submerged. For the sphere at the water surface we have

$$\text{Radius of surface section} = (2RD-D^2)^{1/2} \qquad (7)$$

The stresses at this section may be estimated by taking the total weight above this section and the area of the section.

$$\text{Total weight} = (4\pi R^2 - 2\pi RD)t\rho \qquad (8)$$

$$\text{Area of section} = 2\pi(2RD-D^2)^{1/2} \qquad (9)$$

$$\text{Stress} = \frac{(2R^2-RD)\rho}{(2RD-D^2)^{1/2}} = R\rho\sqrt{\frac{2R-D}{D}} \qquad (10)$$

Again, in lbs/sq. inch for steel, approximately, using D = 18.2 meters (718 inches)

$$\text{Stress} = 3.8 \times 10^3 \text{ lbs/sq. inch} \qquad (11)$$

As before, the stress is independent of t and is still a reasonable value.

It is clear that dead-load stresses in the shell are reasonable, but they do not lead to a choice of shell thickness when treated in this elementary way. The choice of shell thickness and material is obviously going to be determined by a proper structural analysis which considers

(a) extra loading imposed on the shell by the dish and its supports,

(b) wind loads,

(c) permissible deflections of the shell, and

(d) economics of fabrication and erection.

(d) What sky cover can be achieved with this design?

Fairly simple geometry shows that, for a sphere of 100 meters radius, carrying a 600-foot dish and floating to a depth of 18.2 meters, the open edge of the hole in the sphere touches the water when the zenith angle of the telescope is 77.6°. Thus it seems reasonable to hope that the design could reach the zenith angle requirement of 72° (which reaches below the galactic center at the NRAO).

FURTHER DESIGN SUGGESTIONS

(a) Location of feed.

The shell is the primary support for the dish and the feed system. It seems fairly obvious to set the focal length so that the feed is either in the plane of the shell aperture (i) or at the center of the sphere (ii). In our case this gives focal lengths of

(i) $f = 2d + 300^2/4f$

Hence $f = 333$ feet $f/D = 0.56$

(ii) $f = d + 300^2/4f$

Hence $f = 230$ feet $f/D = 0.38$

A further alternative would be to use a Cassegrain system with the feed at either (i) or (ii).

(b) Deflection studies.

The concept may fail because the shell deflections are too great. However, it seems likely that the deflection pattern of the shell may be superior to that of a dish mounted on conventional bearings. The dish itself should be made as light as possible to give maximum stiffness under its own weight. Perhaps such novel structural materials as foam plastic might be considered.

Alternatively, the dish surface may be adjusted by an "open-loop" servo system. E. G. Bowen suggests (letter to JWF) air pressure differentials from the back to the front of the dish. A very few pounds per square foot could compensate for gravity loads on a light surface. Possible division of the surface into cells with independently adjustable pressure is worth thought.

None of these schemes can be considered quantitatively until the deflection pattern of the shell is known. This is thus a very important part of the study.

(c) Drive and position indicator systems.

Drives might be friction wheels (with say 95%) of the sphere weight resting on water and 5% on the wheels), racks, cables or gravity by driving two heavy trucks around the inside of the sphere. In the early stages of the study any reasonable system may be considered. The problems will lie in determining what the dynamic behaviour of the telescope will be. Some thought has to be given to the choice of the drive axes--for example, should a polar drive be attempted?

The system will have a large moment of inertia. About a diameter, a spherical shell of mass M has a M of I of 2/3 MR^2. For our sphere, made of steel 10 cm thick, this is 6.5 x 10^{11} MKS units. However, to give an angular acceleration (in the absence of friction) of 0.05 degrees/sec^2 requires equal forces at the ends of a diameter of the sphere of 325 tons weight. This shows that the drive problems may be a limitation to the design of the system.

For position indicating, gravity sensors and stabilized gyroscopes are obvious. The gyro drift could be corrected by an optical pointing device when needed.

CONCLUSIONS

The main problem areas, at first sight, appear to be:

(a) What are the deflections and the deflection pattern of the spherical shell?

(b) How can the sphere be driven?

THE LARGEST FEASIBLE STEERABLE FILLED-APERTURE TELESCOPE

J. W. Findlay

INTRODUCTION

Discussions of the possibilities and uses of a large filled-aperture radio telescope have taken place over many years, and have been referred to, for example, in the report of the Pierce Committee (summarized by Keller in the Astrophysical Journal, Vol. 134, p. 927, November 1961). More recently, a report entitled "Ground-based Astronomy, A Ten-Year Program" has been prepared by the Panel on Astronomical Facilities for the Committee on Science and Public Policy of the National Academy of Sciences. This report was published in 1964 by the National Academy and is often referred to as the "Whitford Committee Report" after the name of the chairman, Prof. A. E. Whitford of the Lick Observatory. The report recommends a quite detailed plan of development for astronomy generally, and specifically (pages 56-57) proposes that a design study for a very large steerable paraboloid be undertaken.

When it was evident that the present program at the NRAO for building and bringing into use large parabolic dishes (300-foot transit telescope, completed October 1962, 140-foot equatorial nearing completion, January 1965) was approaching the end of its first phase, the time was clearly ripe to consider the possibilities of designing a very large instrument. A meeting of a representative group of radio astronomers under the chairmanship of Prof. G. Westerhout of the University of Maryland was held at Green Bank on October 30, 1964. The report of the group (reproduced as Appendix A) was brief and to the point; it concluded:

> "Summarizing, the meeting gave the NRAO a mandate to undertake a feasibility study of a steerable instrument with a circular beam, a diameter of at least 600 feet, useful down to 18 cm, and hopefully down to 10 cm."

The present note is intended to outline a plan which NRAO might follow in undertaking such a feasibility study. It is naturally evident that such an outline cannot be definitive, but can serve as a framework for work and discussion.

FACILITIES AVAILABLE AT THE NRAO

Limited funds have already been provided to the NRAO from the National Science Foundation for studying new antenna designs and concepts. These funds are needed for the present study, but must meet in addition the task (to which both the Whitford and the Westerhout Committees attach a higher priority) of developing a major high-resolution instrument. However, requests for further funding for both tasks will be included in future NRAO budget requests in the hope that funding will be continued at a satisfactory level.

The staff at the NRAO, although limited, is able to provide immediately some scientific, engineering and administrative effort. This should be sufficient, when added to the help which is available from many in the field of radio telescope building, to make a start on the plan outlined. The study work at the NRAO would be very much helped if a young, versatile engineer could be found who would be willing to join the Observatory staff for this project. Such a man might have a bachelor's degree in mechanical or structural engineering; it is possible that a qualification in aeronautical or even ship-building might be equally useful. The task would need good scientific insight, and the ability to make good "order-of-magnitude" assessments in a fairly wide variety of engineering fields.

If any of the addressees of this note know of such a person, perhaps they would ask him to write to me at Green Bank, We could locate the design study work either at Green Bank or at Charlottesville in the first instance. After about December 1, 1965, it would definitely be at Charlottesville.

THE OUTLINE PLAN FOR THE FIRST YEAR

The following list of tasks should be undertaken. These are not in strict chronological order, although they probably should be done in about the order listed. We have also, under each task, sketched some of the things to be done.

(a) Uncover all reasonable possible configurations for the antenna.

These can be listed fairly well by considering existing instruments, designs already made, or ideas already discussed. In making such a list, the exact letter of the suggested telescope performance criteria will not be adhered to, to avoid, for example, rejecting too soon a good practical design for perhaps its one poor performance feature. Table 1 is a first attempt at such a list of possible configurations.

(b) Evaluate a selected number of the configurations listed.

The first emphasis should be on making a first-order comparison between the probable performance and cost of the best-looking "unconventional" designs. The object of this should be to find, if it exists, at least one unconventional design which is generally superior to the others. Tests of superiority should rest on applying uniform standards to the estimated performance of the instrument -- sky cover, upper frequency limit, beam shape uniformity, polarization performance -- and its estimated cost.

At this stage the problems of cost-estimating arise. In a first-order study they can be met by setting up a basic cost list against which all instruments are priced. Such a list would give information of the following kind:

Cost of simple, light structural steel, erected up to k feet above the ground	\$A per ton
Cost of similar steel above k feet from the ground	\$B per ton
Cost of machinery steel	\$C per ton
Foundation costs -- reinforced concrete in the ground	\$D per c. yd.
Foundation piles	\$E per ft.
Earth moving	\$F per c. yd.
Drive machinery	\$G per H.P.

Special items, such as control and indicator equipment, in any design would have to be priced separately, but a schedule of the kind outlined would give a good first impression of the relative costs of the various concepts.

The end of (b) should be that hopefully one or more of the unconventional designs are found to be reasonably feasible.

(c) Study and evaluation of the conventional designs.

Some of these designs exist as telescopes; some like Sugar Grove were designed in detail and would repay a very close study. The NRAO and others have carried out considerable design work of fully steerable dishes up to 100 meters diameter. Before undertaking any further design, a uniform comparison of existing designs, giving performance and estimated costs, must be made.

(d) Ancillary information needed.

At this state of the preliminary study several items of information become necessary. For example, for radomes:

(i) What is the feasibility, performance and cost of large radomes?

(ii) To what extent is the design of the more conventional instruments dictated by wind and weather?

(iii) Is the radome worth its cost?

Such radome studies are already being undertaken by the New England group, and the results of these studies will be needed in the present work.

Considerable work and study have gone into the effects of wind on large structures (New York Academy of Sciences Conference 1964), but the results need review and there may well be a need for further experimental work.

The present information of the gravity deflection patterns of dishes needs to be unified. The accuracy of good deflection analysis by STAIR and FRAN programs has been proven, for example, on Haystack. It would be even better if a cheaper method could be found and checked against other methods and against measurements. This analysis should be applied to various dish designs to:

(i) Confirm that we can make a reasonably optimum design

(ii) Determine at what size and upper-frequency limit the need for control of the surface shape becomes critical

(e) First draft of performance specifications.

By this stage one or more of the unconventional designs should still be in the race, and it seems certain that at least one of the conventional designs will be still practicable. In the light of the information available, it should be possible to prepare performance specifications which both satisfy the astronomer and which the engineer can reasonably be expected to meet. These specifications would state the size for the dish and indicate the cost/size relationship at and above 600 feet. To get this, parametric studies are needed, but since these are expensive they would only be done for a limited number of concepts.

By this stage the study should begin to converge onto a design concept and a size and a first performance specification. Although it is difficult to determine the time scale of the study precisely, there seems reasonable hope that this stage could be reached by the early summer of 1966.

THE EVALUATION WORKING GROUP

If the plan outlined can be followed, we should be ready in the summer of 1966 to evaluate the study and to prepare the first design contract. A suggestion of how to do this would be to use an evaluation working group.

For 6-8 weeks in the summer of 1966, a group of scientists and engineers might be assembled at the NRAO. They would be drawn from those who have shown strong interest in the study phase. Their task would be:

(a) To choose the concept to be designed

(b) To make the first choice of size, upper-frequency limit, sky cover, etc., for the instrument

(c) Investigate and recommend on the choice of a suitable design contractor

(d) Prepare a report on the work, including first construction cost estimates for submission to the NSF.

J. W. Findlay

Reference LFSP/JWF/1

Green Bank, W. Va.

January 14, 1965

Table 1. Possible LFSP Configurations.

Conventional		Unconventional	
Type	Example	Type	Example
Dish on wide-based towers	Jodrell Bank 250-ft.	Spherical fixed reflector	Arecibo 1000-ft.
Dish on many large elevation wheels	Sugar Grove 600-ft.	Parabolic cylinder fixed reflector	U. of Illinois 400 x 600 ft.
Dish on floating towers	Ashton 300-ft. design for AFCRC	Kraus type antennas	Ohio State and Nancay
Dish on alidade	Rohr/JPL 210-ft.	Steerable plate antenna	AFCRC multi-plate antenna
Dish on small-hub mount	CSIRO 210-ft.	Zone plate antenna	Concept only at NRAO
Tensioned member dish and mount	Preliminary design by S. von Hoerner at NRAO	Floating sphere antenna	CSIRO suggestion--several years ago
Dish within a radome	Haystack	Luneberg lens antennas	Many military examples
		Fixed elevation az-rotating transit with spherical dish	North American Aviation proposal for Sugar Grove modification, but use spherical dish and corrected feed to give $\pm$ 1 hour of track

AD HOC MEETING OF RADIO ASTRONOMERS:

Largest feasible steerable filled-aperture telescope

Green Bank, October 30, 1964

Present:

R. N. Bracewell	A. E. Lilley
B. F. Burke	E. F. McClain
F. D. Drake	R. B. Read
J. W. Findlay	M. S. Roberts
D. S. Heeschen	G. W. Swenson
G. Keller	H. F. Weaver
J. D. Kraus	G. Westerhout

The main aim of the meeting was to discuss the question of whether this is the time to start thinking about a design study for a very large steerable telescope. The meeting was unanimous in its positive answer. A very much larger steerable telescope than those now in existence or in the design stage is certainly needed. Since the time between initial studies and the completed instrument is long (8 years?), the next step in large telescope design should be started now. The N.R.A.O. is willing, and the meeting considered the staff able, to undertake a feasibility study. It was emphasized that the studies for a very large array should not in any way suffer from this new undertaking.

After some discussion, it was decided that in order to make the telescope as universal as possible a more or less circular beam would be preferable. Thoughts will have to be concentrated mainly on some form of single-focus antenna, so that equipment from different observers can be easily interchanged. The steerability question was discussed at length and it was decided that a very considerable declination coverage would be most necessary. In particular, it was felt that both the Galactic Center and the Andromeda Nebula should be reachable, if at all possible. This requires a declination coverage of at least 70°, which in essence means a full declination coverage. The minimum coverage in right ascension should be at least one hour, in order to reach reasonable integration times. It was felt that a complete azimuth coverage was not necessary. One of the few fields in which complete sky coverage would be necessary is that of occultations. It has been shown that these can be more profitably observed at wavelengths longer than those for which the large telescope will be mainly used, and therefore would be better observed with an inexpensive special-purpose telescope.

The telescope under discussion here should still be reasonably efficient down to 10 cm. and in any case it should be fully operable at 18 cm.

The main discussion centered around the question of size. The Whitford Committee Report states that a design study should be made of the largest feasible, movable telescope; the present meeting was called to implement this point. Within the next 10 years, several telescopes with diameters of the order of 300 feet will be available. It is clear that with the present-day techniques, telescopes up to 450 feet are feasible. In fact, the initial studies of designs for this kind of diameter have been made. We are dealing with a feasibility study; therefore, our limits should be considerably higher. Although every increase in size is a step forward, the astronomers at the meeting were agreed that a step of at least a factor of 2 is a minimum for the largest instrument. Possible research projects for this telescope range through the entire field of radio astronomy and might even include a limited amount of planetary radar. In every single field, the highest possible resolution is required. It was therefore decided that the feasibility study should be of a telescope with a minimum diameter of 600 feet. This may well lead to completely new concepts in the construction.

As was said before, this study is secondary to the study of a very large array, which was the highest priority item in the Whitford Committee Report. Also, it has been assumed throughout the meeting that at least two steerable telescopes of the order of 300 feet would be available within the next five years, built either by groups of universities on the East Coast and the West Coast, and/or by the N.R.A.O.

Summarizing, the meeting gave the N.R.A.O. a mandate to undertake a feasibility study of a steerable instrument with a circular beam, a diameter of at least 600 ft., useful down to 18 cm. and hopefully down to 10 cm.

The Fixed Elevation Transit Telescope

1. Concept

The idea of a transit telescope consisting of a parabolic dish mounted at a fixed elevation angle, yet capable of rotating about an azimuth axis, is not new (1,2). Its main advantage is that a very large reflector surface of high accuracy may be built since gravity deflections are constant and can be allowed for in the design and construction.

It suffers the disadvantage of all transit radio telescopes, that of giving only two (in this case) opportunities to observe any given object in a day. Only a very limited track capability is possible if the reflector is parabolic. The sky cover is also somewhat limited.

However, an obvious way to increase the tracking time for a given source is to provide limited ability to move the beam in elevation. This can be done (3) by using a spherical dish and a phase corrected feed (4,5). All the required techniques are known and developed, so that before considering the practical construction aspects in detail, let us examine the requirements for sky cover and for azimuth and elevation motion of the beam.

2. Astronomical Requirements

(a) Sky cover

Let the dish be built so that the altitude angle of the beam may be varied from h to h + s (Fig. 1). Thus h is the minimum altitude angle which can be observed, and the beam may move through an altitude scan angle s above h.

In a practical telescope the choice of h will be governed by many considerations. One of these will be the amount of atmosphere which it is permissible to look through; another will be the desire to see, from a chosen site, the most interesting objects in the sky. For simplicity, we will choose $h = 30°$ since, although it is obviously desirable to keep h small to increase sky cover, at 30° we already commit ourselves to making all observations through twice the zenith atmospheric depth.

If the telescope is at north latitude = ϕ, then no sources can be seen at declinations south of

$$\delta_s = h + \phi - 90° \tag{1}$$

For example, at NRAO (ϕ = 38°26') with $h = 30°$ this declination limit is -21°34'.

The north declination limit δ_N is given by

$$\delta_N = 90 - \phi + h + s \tag{2}$$

Clearly, when observing δ_s the telescope azimuth is south, and when observing δ_N it is north. As an example, at NRAO, if $h = 30°$ and $s = 8°26'$ all positive declinations can be observed.

(b) <u>Hour angle tracking</u>

By moving the telescope in azimuth (Z) and in altitude over the range h to h + s we can track a source as it moves in hour angle. The maximum extent of the tracking range required in LHA can be taken to be 2 hours. The following table, which is only approximate, shows the azimuth and elevation motions needed to give this hour angle range for an instrument located at NRAO with $h = 30°$.

Table 1. Ranges of azimuth and elevation motion needed to give from 1 to 2 hours track for sources at various declinations. Telescope at $\phi = 38°26'$ and $h = 30°$. Table compiled from NRAO conversion tables (H.A.,Decl.) to (Alt.,Az.).

Declination of source	Azimuth and elevation at start of observation		Azimuth and elevation at end of observation		Hours source tracked	Altitude Range S
	Z	h	Z	h + s		
-20°	164°	30°	196°	30°	1 hr 52 min	1°34'
-10°	136°	30°	170°	41°	2 hrs	11°
0°	118° 118°	30° 30°	150° 132°	47° 40°	2 hrs 1 hr	17° 10°
+10°	101° 101°	30° 30°	128° 113°	51° 41°	2 hrs 1 hr	21° 11°
+20°	87° 87°	30° 30°	109° 97°	53° 41.5°	2 hrs 1 hr	23° 11.5°
+30°	74° 74°	30° 30°	91° 82°	54° 42°	2 hrs 1 hr	24° 12°
+40°	61° 61°	30° 30°	71° 66°	52° 41°	2 hrs 1 hr	22° 11°
+50°	48° 48°	30° 30°	55° 52°	48° 39°	2 hrs 1 hr	18° 9°
+60°	36° 36°	30° 30°	40° 38°	45° 37°	2 hrs 1 hr	15° 7°
+70°	22° 22°	30° 30°	26° 24°	41° 34°	2 hrs 1 hr	11° 4°
+80°	6° 6°	30° 30°	10° 8°	34° 32°	2 hrs 1 hr	4° 2°

Table 1 shows that to get a full 2 hours track h must be about 24°. However, an h of 12° gives always at least one hour of track and more at some declinations.

(c) Drive rates

A study of Table 1 shows that the drive rates for tracking are very modest, only at most 17° per hour in azimuth and 12° per hour in elevation.

Higher slewing rates will, of course, be needed.

(d) Choice of site

It is probably generally agreed that the telescope should observe the galactic center, so that cover to $\delta = -30°$ is needed. At NRAO this represents rather a low value for h (21°34'). It may be desirable to keep h about 30° and consider a lower latitude site; Texas, Florida, or Hawaii are all attractive.

3. Structural Suggestions

The reflector should be of the shape sketched in Fig. 2. The width W and the length L are simply related to the choice of h and of the feed. The feed illuminates with correct phase and a suitable amplitude taper a circle of diameter W. If W and L are measured along the curved reflector surfaces

$$L = Rh + W \tag{3}$$

where R is the radius of curvature of the spherical surface and h is now measured in radians. Table 2 shows some choices of L R h and W as examples.

Table 2. Some possible sizes for the reflector. The approximate height of the structure $H \doteqdot .866\ L$ (for $h = 30^\circ$) is also given.

W	R	h	L	H	Remarks
1000 ft. 1000 ft.	1000 ft. 1000 ft.	11.4° 22.8°	1200 ft. 1400 ft.	1040 ft. 1220 ft.	R-W relation Similar to Arecibo
1000 ft. 1000 ft.	1500 ft. 1500 ft.	11.4° 22.8°	1300 ft. 1600 ft.	1130 ft. 1400 ft.	Rather tall Taller
600 ft. 600 ft.	600 ft. 600 ft.	11.4° 22.8°	720 ft. 840 ft.	620 ft. 730 ft.	

The general form of the structure should be to get the loads to the horizontal bearing surface as directly as possible. Fig. 1 suggests the feed might be carried on a vertical feed tower, not by structure connected to the dish. The aim should be to remove as many as possible of the variable loads from the dish support structure. Various structural questions come to mind. Is not a lot of the dish support structure mainly in compression? Is concrete a possible structural material? If so, how is the bearing done? Is this a place for a high vicosity hydrostatic bearing system? Or floatation again?

4. The Feed

Problems of feeds for spherical dishes still exist, but very considerable work has been done for Arecibo and more is planned. Although the line feed still looks best for Arecibo, the shaped reflector feed should still be considered, despite the illumination and aperture blocking difficulties (6). A few questions arise here. Would it be worth considering a parabolic/ spherical shape for the main reflector? A line feed would not make sense for such a shape, but in fact phase correction and steering is only needed in elevation, and in the other plane the reflector shape might be parabolic.

5. Brief Summary

This is a possible telescope within our present structural and electronic capabilities. It is not in the least esoteric and might be cheap. Heavy steel could easily go in for 50 cents a pound erected. Precise work would only be needed at the surface, the bearings, and the feed.

The working group will look over the general concept, but, unless obvious difficulties emerge, it is worth some effort.

6. Question

The big question is whether the sky cover and tracking abilities are good enough to satisfy astronomers. We would welcome comments particularly on this point.

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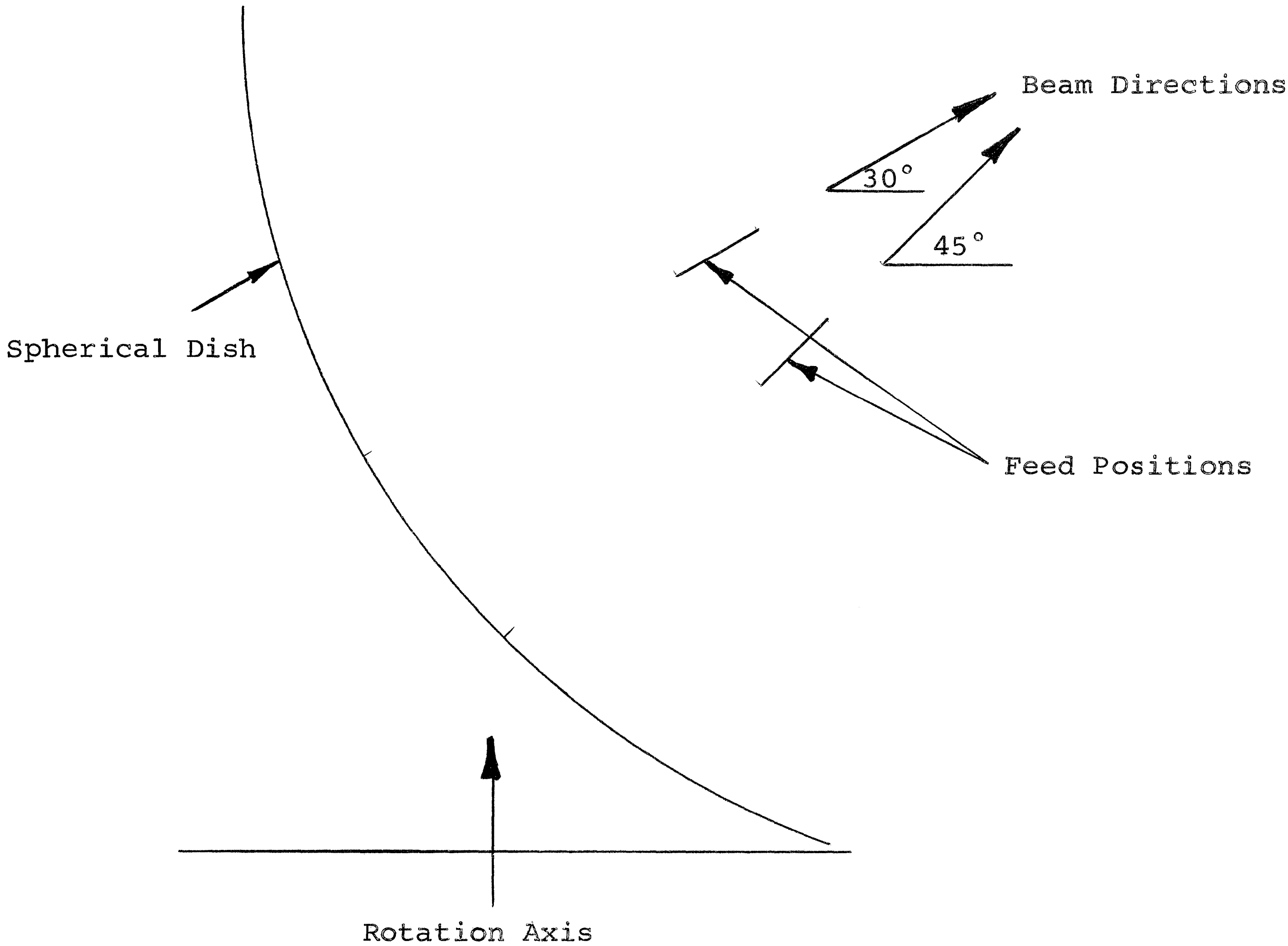

Figure 1

The fixed elevation transit telescope, showing feed positions for an elevation angle (h) of 30° and a scan angle (s) of 15°.

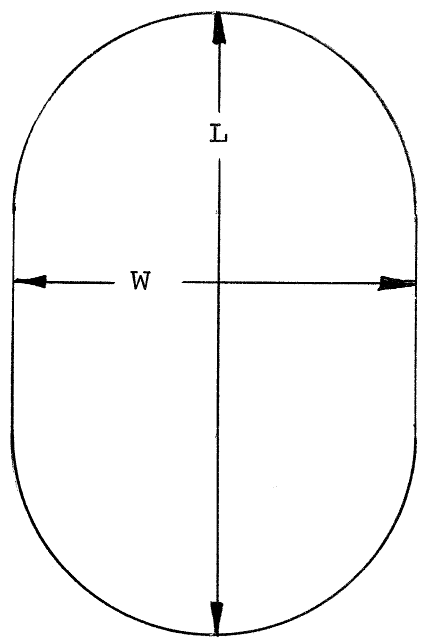

Figure 2

The suggested outline shape of the dish.