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Proposal for a High-performance, Large Aperture, Low Cost Radio Telescope

INTRODUCTION

This proposal describes a new approach to radio telescope design. The antenna described may be built with very large collecting area. Useful bandwidth is considerably larger than bandwidths provided by other non-parabolic systems. Sky coverage may, with ease, include almost all the sky visible from the latitude of Green Bank. Multiple beam operation may be achieved at very low additional cost. The physical structure of the system, although not placing any difficult requirement on the topography of the telescope site, is ideally suited to the topography of the NRAO. Satisfactory tracking times may be achieved. The entire telescope structure may be constructed from readily available components, even with very large apertures. There is no appreciable attenuation in the system before the antenna output connection, thus allowing the full realization of the high sensitivities provided by low-noise radiometers. Lastly, the cost to construct an antenna of given aperture is probably much lower than the cost of obtaining the same aperture by means of any other known antenna concept.

THE DESIGN CONCEPT

The telescope is a reflecting instrument in which the reflector makes use of the properties of Fresnel diffraction, and is, in fact, an axially asymmetric reflector version of the "zone plate" (cf. Jenkins and White, Fundamentals of Optics, p. 360). A two-dimensional version of the instrument is shown in Figure 1. The points A, B, C, and D have been chosen such that the ray path lengths OAF, etc., bear the relation

$$OAF = \frac{n\lambda}{2} \qquad OCF = (n + 2)\frac{\lambda}{2}$$

$$OBF = (n + 1)\frac{\lambda}{2} \qquad ODF = (n + 3)\frac{\lambda}{2}$$

where n is any integer.

Now, consider a vector representation of the incoming electromagnetic wave. Assume that the phase of the Huygen's wavelet reflected from point A is 0° at F. Then the phase angle of the wavelet from B will be 180°. The net vector sum of all the wavelets reflected from the portion of the reflector between A and B will be a wave of phase 90°. If the reflector were perfectly flat, then the phase of the wave from point C would be 360°. The vector sum of all waves reflected from the region between B and C would be 270°, and would destructively interfere with the wave from the region A-B. To make the zone reflector concentrate energy, we raise the surface of the reflector between B and C so that there is an overall change of 1/2 wavelength inserted in the net wave train from B-C. Then the phase of the vector sum of all wavelets from B-C is 90°, and there is constructive interference from the wave from A-B at F. The wave train from C-D will have phase 450°, and will constructively interfere. Again we raise the reflector surface in the region D-E, so that this region contributes an increase in intensity at F. The increase in surface height, where required, is of the order of 1/3 wavelength for reasonable systems, or about 3 inches at 1420 mc. The principle is carried on over the entire reflector surface. It is readily seen that the same principle can be applied to a three dimensional system.

It may be shown that such a reflector, even though made completely of flat elements, will have a gain which is 41% of the gain of a perfect parabola presenting the same cross section to the incoming wave. When the projection effect is taken into account, a reasonable system might have a gain which is 30% of the gain of a true parabola of the same aperture. Although this may seem an inefficient use of aperture, the cost of the flat zone reflector is so much less than that of a parabola that, economically, the zone reflector is very efficient.

It should be noted that the resolving power and sidelobe levels, the latter only to a good approximation, are the same as those of a parabola of same geometrical cross section to the incoming waves. Since resolution limiting and sidelobe effects are the factors of paramount importance in large reflectors, the loss in gain should be of minor concern.

Limitations on bandwidth and beam swinging will be discussed later.

PHYSICAL STRUCTURE OF A PRACTICAL ANTENNA.

The ability to pivot the zone reflector about the feed mast, while maintaining the reflector strictly flat, would be quite desirable, as it would allow extensive beam swinging. Both needs may be met by floating the reflector on a liquid. Such a liquid support provides a very inexpensive back-up structure which supports the reflector rigidly, positions it precisely in a plane, and still allows freedom of movement. A system employing such a liquid support is shown in Figure 2.

The system in Figure 2 has been drawn for the example of a 300-foot antenna giving a mean beam altitude of 45°, to be discussed quantitatively later. An inexpensive and effective reflector could be constructed of plywood, properly wax impregnated or sealed in another way. The reflecting surface could be made of aluminum foil, or wires cemented to the plywood. The raised portions of the reflector could be made from thicker plywood. Dimensional tolerances must be good in the vertical direction, but ordinary plywood floating in liquid would certainly provide more than enough precision in the surface. The pool surface probably should be a layer of oil, to damp waves and prevent freezing. Tolerances in directions parallel to the surface of the pool are not critical, removing any great demand on the quality of the carpentry employed. With proper design, the reflector could be walked on for construction purposes, maintenance, and inspection. There are obviously many simple ways to pivot the reflector around the feed mast.

The feed mast would have to be rigid, and allow the rotation of the feed and radiometer front end components around a vertical axis. Since simple feeds only are necessary, no great engineering problems are envisioned. The vertical members of the two cranes employed in the 140-foot telescope erection are taller, more rigid, and stronger than the feed masts required for antennas up to about 500-foot effective diameter.

It should be noted that only a simple feed, such as a horn, is necessary. Thus many feeds could be mounted on the feed mast to give multiple beam operation at very low cost.

Another point of interest is that the feed point may be located well away from the nearest reflector edge. This provides the possibility, in a region like that of Green Bank, of mounting the feed on a hillside, below which the pool is located. Thus, the mast might be eliminated or greatly decreased in size.

EXAMPLE OF ACTUAL REFLECTOR DESIGN

As an actual example of what might be done with one of these reflectors, a design giving a 300-foot effective aperture, mean beam altitude of 45°, and

and center frequency of 1420 mc has been made. This design has been depicted in Figure 2. It may be shown that the optimum reflector design, where "optimum" provides maximum bandwidth and beam swinging, is achieved when the ray path lengths for the nearest and farthest points of the reflector are equal. This is intuitively obvious, of course. The design shown is optimum. The parameters given by this design are:

Declination coverage +83° to -7°

Number of Fresnel zones: 120

Greatest difference in ray path length: approx. 40 feet, or 60 wavelengths.

Bandwidth: Without movement of feed, the bandwidth will be of the order of 1/60 of center frequency, or about 24 mc. Movement of the feed can increase this.

Permissible change in beam altitude: undetermined.

Very rough cost estimate for antenna:

Reflector, 100,000 square feet, at cost of $.20/sq. ft.		$ 20,000
Pool retaining wall		30,000
Reflector drive		10,000
Feed Mast and drive		50,000
Contingency		40,000
	Total	$150,000

A design for a similar reflector giving a beam altitude of 60° has also been prepared. This seems to give no advantage over the 45° system, except for increased beam altitude swing. It requires a taller mast, and gives less declination coverage, and so is probably of little interest.

BANDWIDTH AND BEAM SWINGING IN ALTITUDE

No detailed study has been made of the increase in bandwidth and beam swinging in altitude that may be achieved by moving the feed point. This is because the computations, although straightforward algebra, are quite lengthy, and it was deemed advisable to pursue this step only if there is enthusiasm among the NRAO staff for the approach described here. However, it is possible to make a few remarks on the basis of simple approximations.

First, with regard to bandwidth, it should be noted that the zone plate has infinite bandwidth, which is unexpected intuitively. The focal length of a zone plate changes with frequency, making it undesirable for optical use, but being acceptable for radio use. We would expect that the same characteristics would apply to the zone reflector, although one probably would not expect infinite bandwidth. Consider the three axial ray paths passing through the nearest edge of the reflector, the middle of the reflector, and the farthest edge of the reflector. The middle path length is shorter than the other two, which are equal in the optimum design. There are two path length differences to be maintained equal to an integral number of half wavelengths when we change frequency. Changing the frequency will change all three path lengths, in terms of wavelengths, and will change both path length differences, if the feed is not moved. However, we have the freedom of moving the feed in two dimensions. Since we have two equations to preserve, and two free parameters, it is obviously possible to maintain the path length differences, measured in wavelengths, constant. Thus, by moving the feed, we can keep the nearest, farthest, and center sections of the reflector in consonance. In the first approximation, then, there is infinite bandwidth. This will break down for higher approximations, and precise computations will be required to determine how much the intrinsic bandwidth of the instrument can be increased by moving the feed.

With regard to beam altitude swinging, the situation is similar. Again, if we consider the same three ray paths as before, changing the altitude of the incoming rays will change both path length differences. But moving the feed in two dimensions will allow us to preserve the path length differences. Again, in the first approximation, large changes in beam altitude are possible.

CONCLUDING REMARKS

The antenna described here seems to be a combination of the best aspects of array and reflector type antennas. It consists, in essence, of a number of discrete energy collectors, whose outputs are added in the proper phases for constructive interference, thus resumbling an array. But the paths along which the energy is carried to bring about the proper phase relations are all in free space, eliminating the very undesirable attenuation existing in standard arrays. The large bandwidth, low side lobe levels, and easy beam movement characteristic of the reflector antenna appear in this device. In addition to this distillation of good qualities, the device automatically is suited to very inexpensive construction.

This proposal has been prepared for study by the NRAO staff, obviously in connection with the 300-foot and 1000-foot antenna projects, and with a desire to obtain comments and criticism, both destructive and constructive.

If enthusiasm for this design is shown, and no major deficiencies are found, it is proposed that a detailed mathematical study of this system be conducted. If this produces promising results, as appears quite likely, it is proposed that a small working model of one of these antennas be constructed.

This might consist of an optimum 45° beam altitude reflector, operating on 10-cm wavelength, and with maximum reflector dimension of 30 feet. This would call for a mast height of about 11 feet, and would have only 16 Fresnel zones, giving a bandwidth of the order of 400 mc. It might be built next to the lab building, with the radiometer and feed inside the lab.

For the benefit of those who would like to try their own ideas, an appendix is included which contains a few of the basic formulae for the zone reflector antenna.

F. D. Drake
March 4, 1960

Appendix

With parameters as defined in Figure III:

Edge of Fresnel zone is defined by equation:

$$y^2 = x^2(-\sin^2 A) + x(n\lambda \cos A - 2a - 2\ell\cos^2 A) + \frac{n^2\lambda^2}{4} + \ell^2\cos^2 A - n\lambda\ell\cos A - b^2 - a^2 \quad (1)$$

where n is an integer.

For optimum antenna, with $b = c\ell$,

$$a = \frac{\ell}{2}\left(\cot A\sqrt{\sin^2 A + 4c^2} - 1\right) \quad (2)$$

Maximum path length difference for reflector ΔP is given by

$$\Delta P \approx \frac{\ell}{2}\cos A + \sqrt{b^2 + a^2} - \sqrt{b^2 + \left(a + \frac{\ell}{2}\right)^2} \quad (3)$$

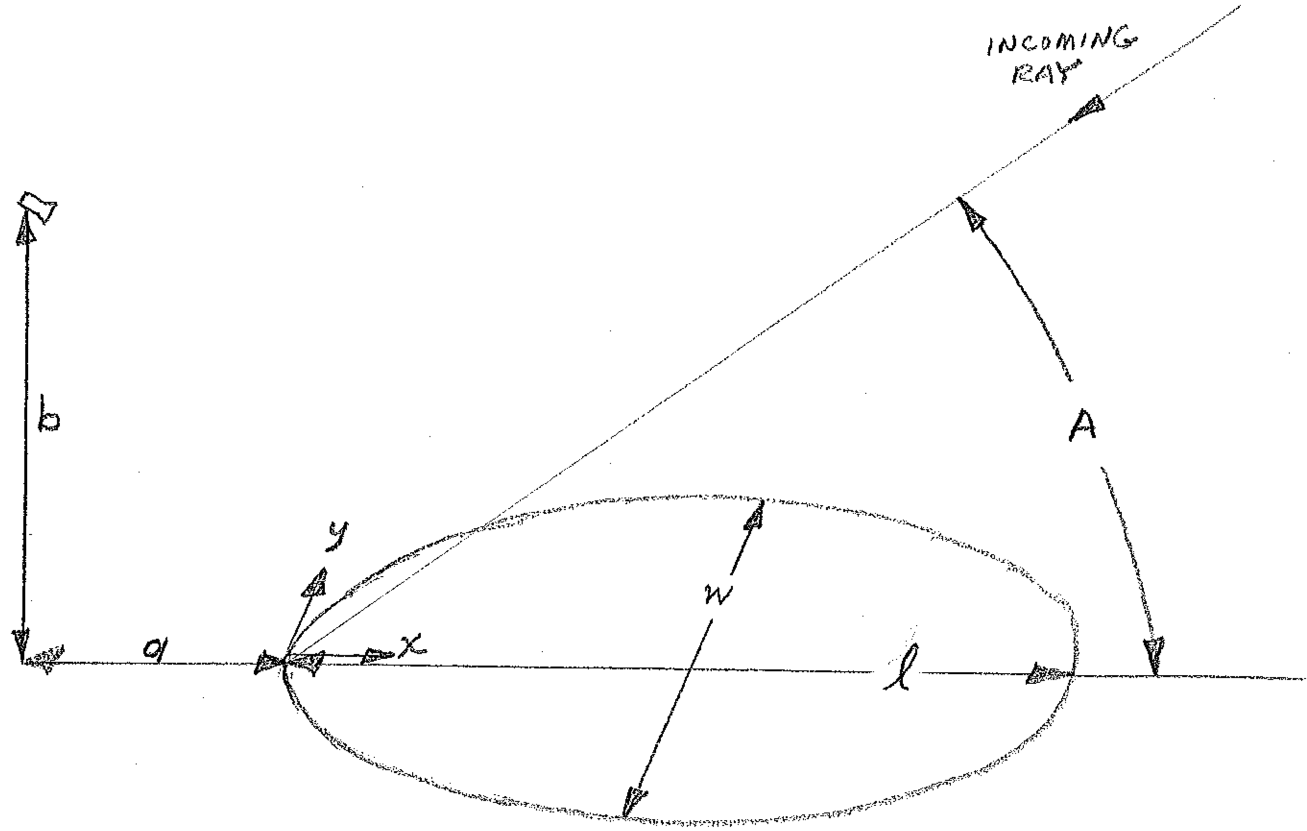


FIGURE III

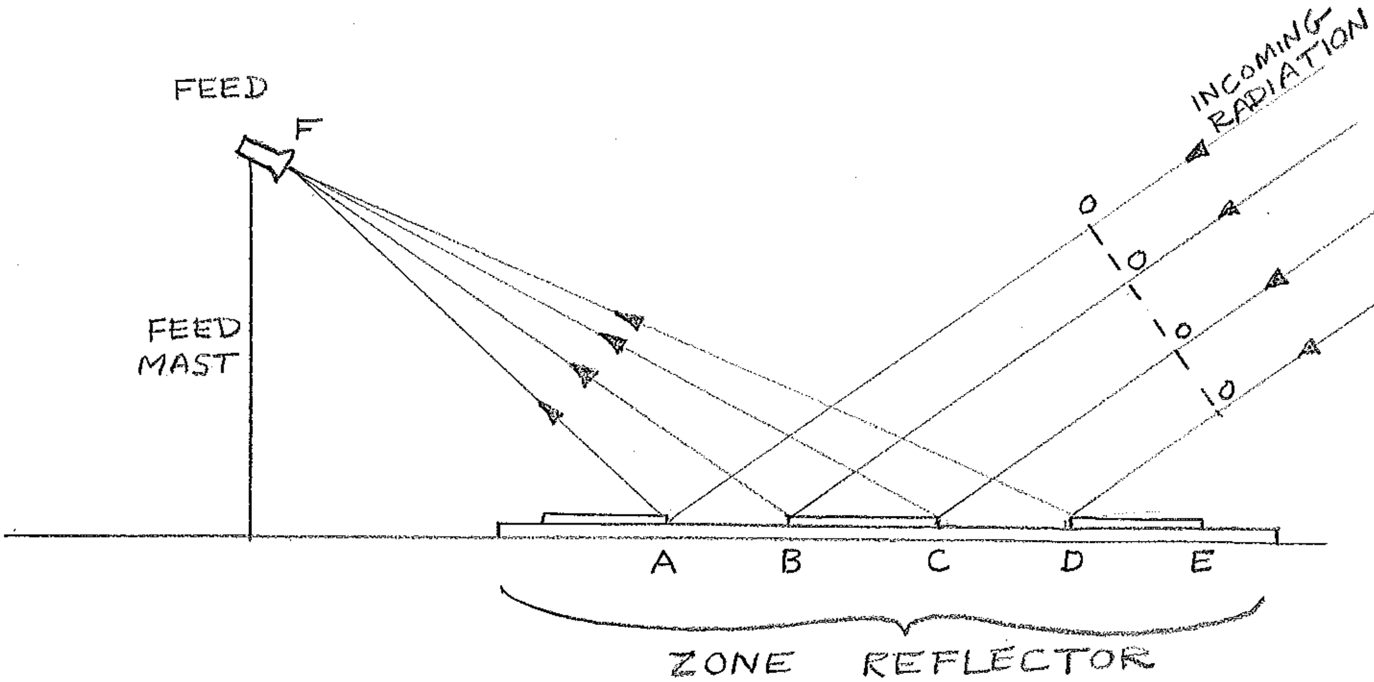
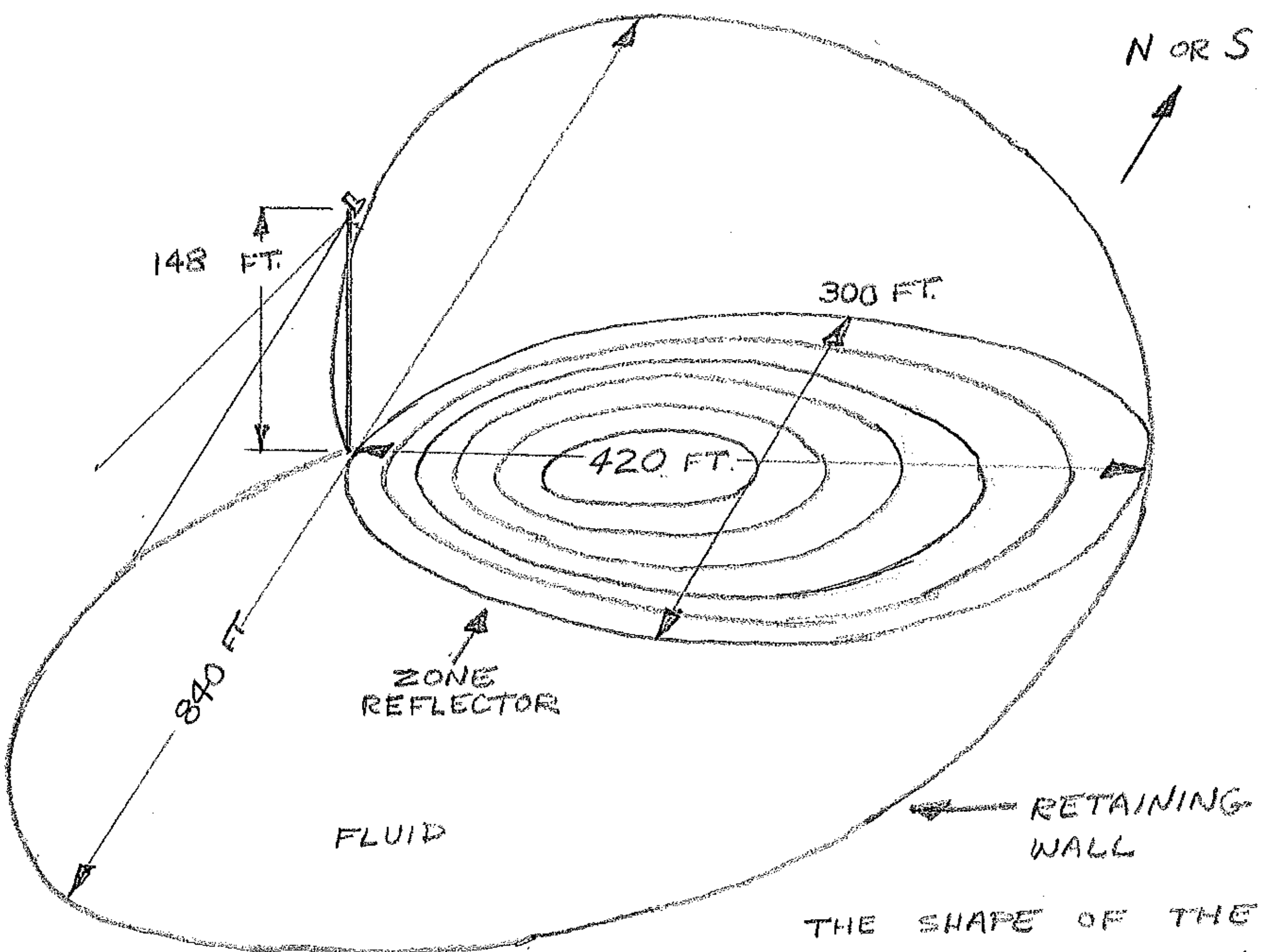


FIGURE 1



THE SHAPE OF THE ZONE OUTLINES IS NEARLY CORRECT.

FIGURE 2