NLSRT Memo No. 43

Possibly-Feasible Approaches to the Design of a Large Offset-Feed Radio Telescope.

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1. Introduction.

This memorandum and a previous one (NLSRT No. 29) are intended to start an investigation of whether an offset feed design is feasible for a large antenna to replace the 300-ft at Green Bank. Feasibility is here not just a technical matter, but includes the condition that the cost should be competitive with that of an on-axis design of similar size and frequency performance. If we use the usual cost relationship for large antennas, i.e. cost is proportional to aperture width to the power 2.7, then an increase in cost of 15% for the unblocked aperture would effectively cost 10% in aperture area, and an increase in cost of 50% would cost 35% in aperture area. One should get about about 5% of this area back because of the higher efficiency of the offset-feed design. Something like 30% is probably about as much aperture loss as anyone would be willing to trade for an unblocked aperture. Thus one condition of feasibility is that for a given aperture the offset feed design should not increase the total amount of steel by more than about 50%. In this memorandum the approach is to look for possibly-feasible offset-feed configurations for further evaluation and cost estimation, and to note any particular advantages or disadvantages.

The main reflector surface is a part of a paraboloid of revolution. For radio astronomical purposes we are mainly concerned with circular apertures, and thus with parts of paraboloids that are circular when projected normal to the direction of the beam axis. The part of the parabolic surface involved is conveniently defined in terms of the corresponding part of the generating parabola, that is by the section of the reflector surface in a plane through the center of the surface and the axis of the paraboloid. On the parabola in Fig. 1, such a part can be specified by the angle theta, the focal length, f, and the aperture, D. In all cases where the feed is at the focus of the paraboloidal surface, the axis of the main beam is parallel to that of the parabola. In many offset-feed designs the angle theta in Fig. 1 is small, and near the vertex only a small part that would be blocked by the feed is missing. The part of the parabola that is used in generating the surface extends outwards from the end near the vertex to a point determined by the the required aperture. In a few other cases theta is larger (say 60 deg. or more) and one is using a part of the parabola further away from the vertex.

A general problem with offset feed antennas is that the lack of circular symmetry results in higher cross polarization sidelobes than in off-axis designs. This effect gets worse as theta is increased and one moves out from the vertex of the parabola (Rudge and Adatia, 1978: see section III). When circular polarization is used the cross polarized component that is generated appears as a beam squint. Also, when a simple prime focus feed is used there is a gradient in the illumination over the aperture which can be a problem. This effect is discussed in VLSRT Memo No. 29 and for small theta becomes more serious as f/D is decreased. Both of these problems can largely be solved by the use of a secondary reflector, and special shaping of the two reflectors. However, for the Green Bank antenna use of prime focus feeds is seen as an important feature for low frequencies and at higher frequencies for multi-beaming. Also, shaping of the reflectors severely limits the possibilities for use of arrays of feeds. We are therefore interested here in antennas which give satisfactory performance with prime focus feeds, and also in the Cassegrain mode with unshaped (paraboloid-hyperboloid) reflectors.

Figure 2 shows the configuration of the focus and the beam direction for four different parts of the generating parabola, all with the same aperture size. In (a) theta is small and we are using a surface as close as possible to the vertex. As one moves out along the parabola further from the vertex the configuration becomes less compact, which tends towards structural difficulties in very large antennas. Also the polarization problems get worse, and a greater area of reflecting surface is needed for the same sized aperture. The main disadvantage of the system in (a) is that when the beam is pointed near the zenith the focus is high above the ground. Configurations (c) and (d) offer solutions to the focal height problem. The two most obvious directions to explore are configuration (a) with a small f/D ratio to reduce the height of the focus, and configuration (c) to take advantage of keeping the focus closer to the ground.

2 Modified Bell-System Horn Design.

In NLSRT memo no. 27, J.Lockman has suggested a design based on the Bell System horn design, which results in the the configuration of Fig. 2(c). The sides of the horn are omitted in the modification, but the paraboloidal surface and the feed location remain, as in Fig. 3(a). The object of this idea is to accomodate a fairly large f/D ratio by keeping the long focal dimension horizontal, rather than letting it point upwards. Because the distance from the feed to the opposite end of the antenna is about 2.5 times the width of the aperture, the suggested design includes separate structures for the main reflector and for the feed as shown in Fig. 3(b). Note that the part of the parabolic section that generates the main reflector is approximately centered on the intersection with the latus rectum. A serious problem with this design is that the line defining the elevation axis intersects the reflector surface, so that from structural considerations one would like to have two elevation bearings, one on either side of the reflector. However the clear aperture condition requires that the surface be supported from the back side only, in some manner such as that shown in Fig. 3(b). The surface must be kept clear of any support structure in the areas indicated in Fig. 3(a), and almost the only structure allowed would replace parts of the horn of the original design. Thus it is very difficult to envisage any support structure around the front side of the reflector that would not involve long and extended members. A large wheel at the back of the surface would be a possibility, as in Fig. 3(b), but this would add greatly to the amount of steel required. Thus the mounting of the main reflector appears to be a major problem in this design.

A second problem with the modified Bell System design is the high feed tower, approximately 50 m tall, which moves around the main reflector on circular rail tracks approximately 200 m in radius. The focus can be lowered to ground level as in Fig. 3(c), which would greatly decrease the size of the tower, and also decrease the width of the rail tracks and their foundation that are required for stability. One then needs to use a parabolic section that is a little further out along the parabola such that the latus rectum intersection is at the lower edge. If the focus is to remain in the same position when the main reflector is rotated to to provide the elevation motion of the beam, then the rotation axis must pass through the focus. Thus the axis must be tilted as indicated in Fig. 3(c), which means that the bearings must be designed to take a thrust component along the axis. Note that as the reflector is rotated about the axis in Fig. 3(c), the beam has a component of motion in azimuth as well as in elevation. This does not matter so long as the beam goes through the zenith, since it can be taken account of in the azimuth motion of the feed tower and reflector. The question of which of the two schemes, Fig. 3(b) with the high feed tower or Fig. 3(c) with the tilted "elevation" axis, would be the cheaper to construct needs the opinion of a mechanical engineer.

It may be possible to reduce the rail track for the feed tower to less than a full circle in the schemes in Fig. 3 if the pole can be reached by going "over the top" through the zenith. Indeed if the main reflector would go down close to the horizon in both directions of elevation motion, only a half circle of track would be needed for the feed. Larry D'Addario points out that the antenna would fulfill most of its requirements if the elevation motion were restricted to, say, 15 deg. to 75 deg. This should simplify the mount for the reflector. Overall, however, the systems in Fig. 3 look clumsy and expensive to me, and the feed tower and its rail track are items that significantly increase the long term maintenance load of the observatory.

3 The Small-Theta, Low f/D Approach.

As an alternative approach we start with the system of Fig. 2(a). Figure 4 shows four examples of the configuration of the focus and reflector for different f/D ratios, all for the case where theta in Fig. 1 is small and the reflector is cut off near the vertex so as just to avoid shadowing by structure at the focus. In the cases where f/D is large (1.0 or 0.75) it is obvious that a long arm or tower is required to support the feed or subreflector, and this will increase the cost. The longer the arm, the stronger and heavier the construction needed to obtain adequate stiffness. If the arm is attached to the reflector backup structure it will add constraints to the stiffness and balance of the whole antenna. On the other hand, Fig.4 shows that when f/D becomes as small as 0.35, the surface area for a given aperture begins to increase because the angle between the normal to the surface at any point and the direction of the main beam increases as f/D decreases. For f/D = 0.35, this angle is 54 deg. at the edge of the reflector. Thus there is a value of f/D that minimizes the overall size of the structure, and from Fig. 4 this value is probably not far from 0.5. Low values of f/D also lead to large beam squints and illumination gradients with prime focus feeds, so the overall optimum f/D may be somewhat greater than 0.5.

Figure 5 shows a comparison of reflector profiles and focus positions for an on-axis antenna with the conventional focal ratio of 0.35 and as off-axis antenna with focal ratio 0.5. Both of these antennas are drawn with the same aperture D, and in the stow position. Figure 6 is a sketch of an antenna of f/D about 0.5, with feed support attached to the main reflector structure. It is positioned with the main beam pointing to the zenith. Two possible directions for the elevation axis are shown, AB and CD. In the position shown the reflector has a plane of symmetry that is vertical and contains the line AB. If the antenna is rotated about the axis AB gravitational deformation will destroy the symmetry, but not if it is rotated about CD. CD may be preferable as the elevation axis, but this is a point for further study.

4 Some Questions to be Pursued.

(1) Is the modified Bell System design in section 2 a serious possibility? (I think it is not.)
(2) Is the performance of the design in section 3 with f/D = 0.5 satisfactory with respect to polarization and uniformity of illumination ? If not, what is the smallest acceptable f/D?
(3) Is an antenna of the design in section 3, with the minimum satisfactory f/D a serious possibility in a 100 m size?
(4) Are there other approaches besides the two discussed above that are feasible for a very large offset-feed antenna?

5 Reference.

Rudge, A.W. and Adatia, N.A., Offset-Parabolic-Reflector Antennas: A Review, Proc. IEEE, 66, 1592-1618, 1978.

6 Erratum.

In Fig. 2 of VLSRT Memo No.29, $y = 4x^2$ should be $y^2 = 4x$.

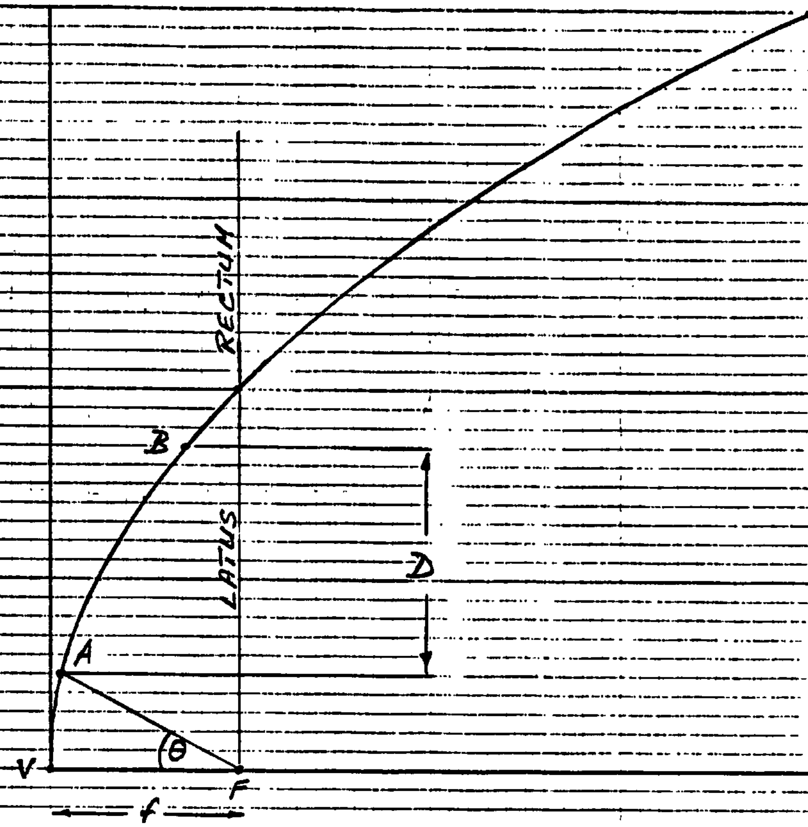

Figure 1. Parabola from which paraboloid is generated. V is the vertex, F is the focus, f is the focal length, D is the aperture. A section such as AB can be defined by specifing f, D, and theta.

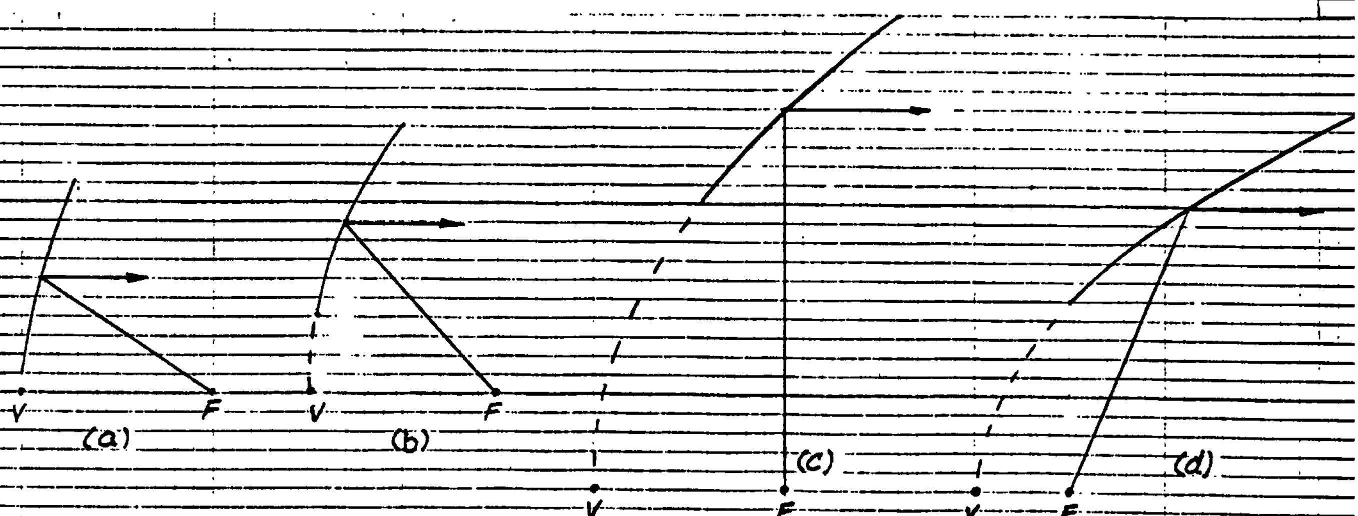

Figure 2. Four different parts of a parabola showing relative positions of the vertex and focus as the part that generates the antenna reflector is moved away from the focus.

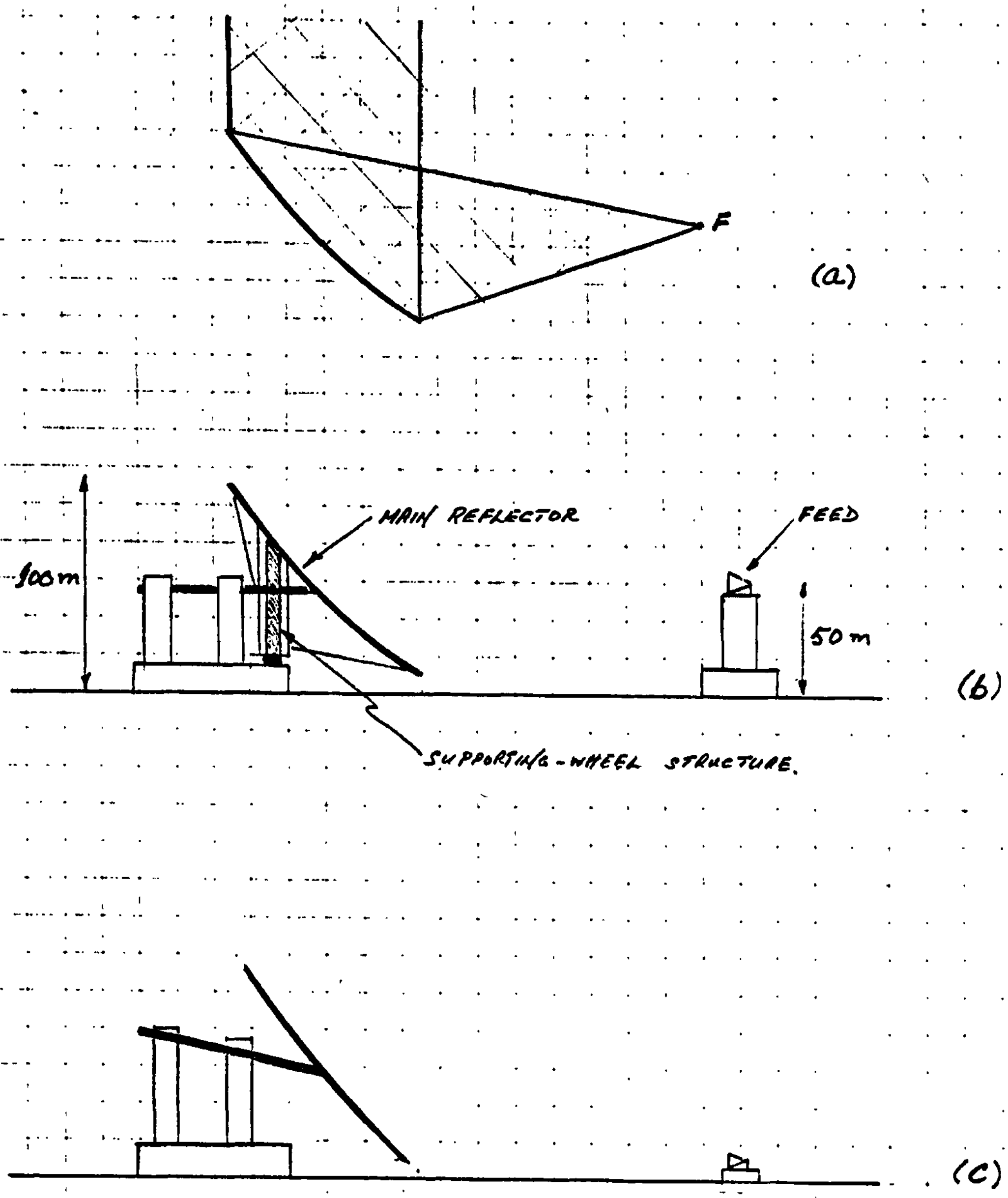

Figure 3. (a) Positions of main reflector and focus for modified Bell System design. The cross hatching indicates areas where the aperture must remain unblocked. (b) Possible mechanical implementation of (a). The main reflector is on a turntable to provide azimuth motion, and the feed tower is on a rail track that circles the main reflector. (c) Modification of (b) to reduce height of feed tower.

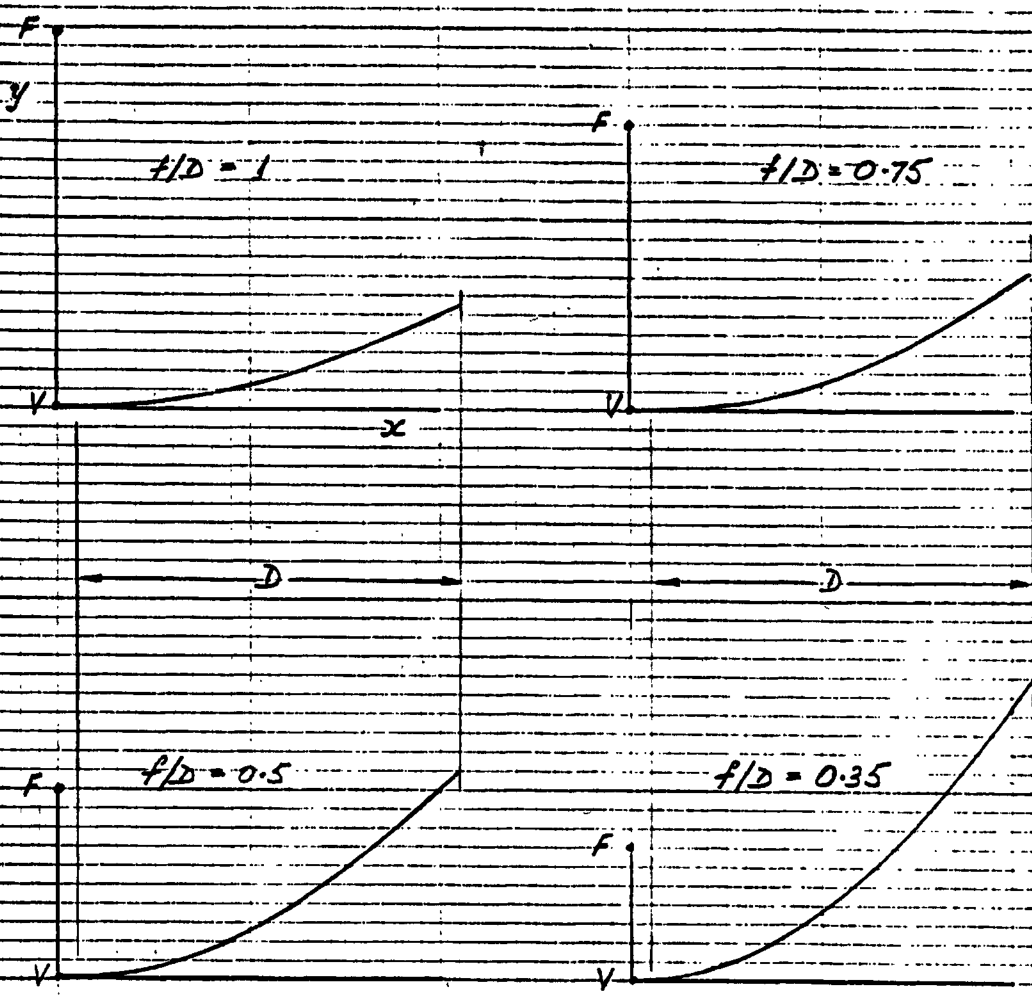

Figure 4. Relative positions of focus and main reflector for four values of the focal ratio f/D. These correspond to the small-theta case in Fig. 2(a).

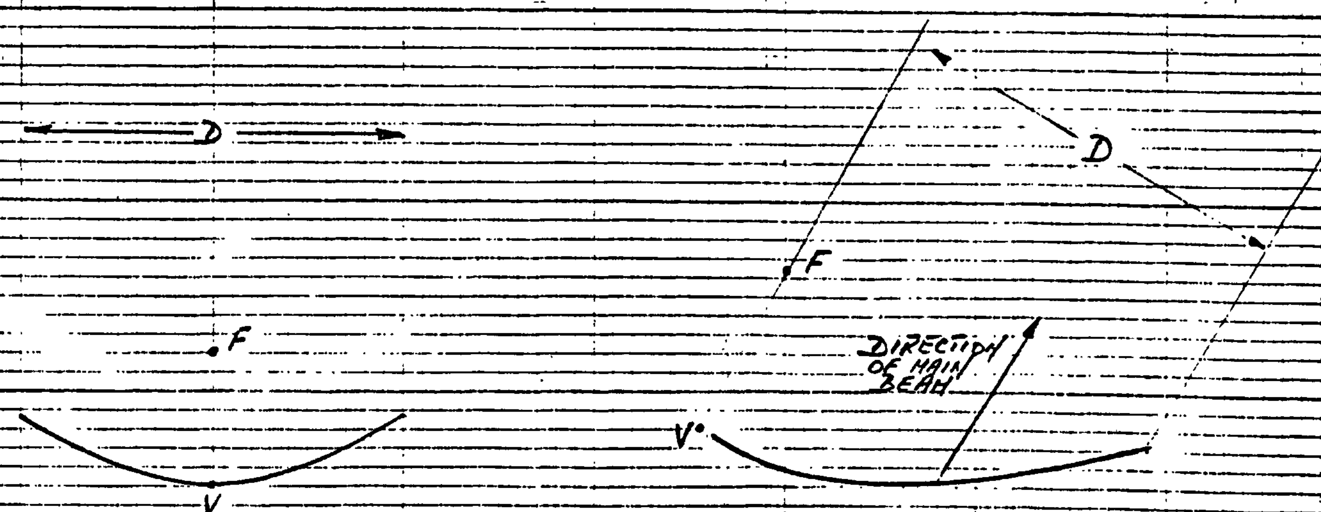

Figure 5. Comparison of positions of focus and vertex, and of size of main reflector, for an on-axis antenna with f/D = 0.35 and for an offset feed antenna with f/D = 0.5. The aperture D is the same in both cases.

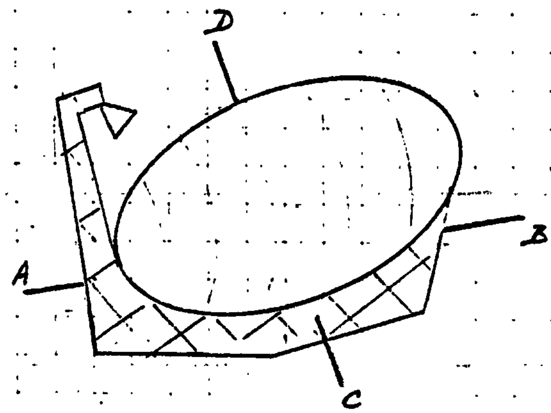

Figure 6. Offset feed antenna showing two possible locations for the elevation axis.