NLSRT Memo No. 62

Prime-Focus and Cassegrain Operation, and the Focal Ratio of the Green Bank Telescope.

A. R. Thompson.

June 6, 1989.

A number of important considerations concerning the choice of feed location and f/D ratio (focal length/reflector diameter) for the Green Bank telescope have been discussed by Rick Fisher in NLSRT Memo. 59, which calls attention to the calculations of Minnett and Thomas (1968) on the performance of paraboloid reflectors with ideal hybrid-mode feeds at the prime focus. I fully agree with Rick's conclusions, and present some further discussion in this memorandum.

Figure 1 shows the theoretical maximum aperture efficiency for a paraboloid reflector antenna as a function of f/D, for prime focus operation with a dual hybrid-mode feed. The curve is defined by five points taken from Fig. 13 of Minnett and Thomas, for $U_a = 0.7$ which corresponds closely to the radius of a dual hybrid-mode horn. This feed design is about the most efficient available with current technology. In the Cassegrain mode the effective focal ratio as seen by the feed is about a factor of 10 greater than the f/D value of the main reflector, and the corresponding efficiency is taken to be the value of approximately 0.91 that the curve in Fig. 1 approaches at large f/D. Note that the results in Fig. 1 represent theoretical calculations based only on the diffraction from an unblocked circular aperture, and do not include the effects of scattering, blockage or other losses. In NLSRT Memo 59, Rick emphasizes this point, and notes experience at Green Bank with single-mode hybrid feeds for which the measured efficiency is typically 80% of the calculated value. Thus in this memo the values of efficiency should be regarded as indicating only the relative behavior as a function of f/D or other parameters.

Figure 2 shows how I visualize the probable performance of a 100 m symmetrical paraboloid as a function of frequency, based on the results in Fig. 1. In the frequency range below about 600 MHz, operation would be from the prime focus, and two efficiency levels, corresponding to f/D ratios of 0.3 and 0.42 are shown. The value of 0.3 is that tentatively recommended by Larry D'Addario for optimization of performance in the Cassegrain mode. 0.42 is the value commonly regarded as close to optimum for prime focus operation, and is about the lowest f/D that can be easily accommodated by the dual hybrid-mode design. From Fig. 1 the value of 0.42 is seen to be a compromise, between maximizing the efficiency and keeping the focal length fairly short. Increasing the focal length necessitates using larger feeds and feed support structures, resulting in increased scattering and decreased rigidity. In the range above about 5 GHz the operation would mainly be in the Cassegrain mode, and here I have taken the efficiency to be 0.91 for f/D = 0.3, and 0.88 for f/D = 0.42, on the assumption that the blockage would be about 1.5% lower for the smaller f/D. The lower scattering resulting from lower blockage would also be expected to result in a lower system temperature by something like 4-5 K. The thermal limit for a 100 m diameter antenna, which is the frequency at which temperature variations of 1 K result in surface deviations of one sixteenth of a wavelength, has been estimated by von Hoerner in NLSRT Memo 2 to be 60 GHz. At this frequency the efficiency should have fallen by a further factor of 0.5. The thermal limit for the inner 50 m of the antenna may be about twice that for the full antenna, and this possibility is the basis for the point at the highest frequency shown in Fig. 2.

The shaded area in Fig. 2 represents a region of crossover between prime focus and Cassegrian operation, where either focus location may be used depending upon the details of the system involved. The lowest practicable frequency for Cassegrain operation is approximately 600 MHz. At 1.4 GHz, Cassegrian operation is fairly easy to implement, but prime focus operation has it advocates. For receiving systems with array feeds prime focus operation offers some advantages up to about 5 GHz, since the total area blocked by the feed cluster is smaller than with Cassegrain feeds. Factors affecting the choice between prime focus and Cassegrain operation include considerations of the size and weight of feeds, and are thus likely to differ for single-beam and array-feed systems. It is probably not possible, or even desirable, to specify a single crossover frequency that would apply to all systems.

When considering the choice of mode of operation or value of f/D for the main reflector it is of prime importance to bear in mind the astronomical requirements for the telescope. These are described in the NRAO Report "A Radio Telescope for the Twenty-First Century", Table 1 of which lists four categories of observations as follows: (1) pulsars and stars, (2) neutral hydrogen, (3) spectroscopy, and (4) continuum studies. The first category calls for observations down to approximately 50 MHz in frequency, and an aperture of "150 m class". The second category calls for observations down to approximately 100 MHz, and in NLSRT Memo No. 59, Rick Fisher has emphasized the importance of 10-15% factors in (gain)/(system temperature) for neutral hydrogen observations. Thus in the first two categories there is a clear call for the highest effective apertures at frequencies as low as 100 MHz or thereabouts. For the third and fourth categories, frequencies as low as 400-500 MHz are mentioned, galactic polarization being a specific low-frequency interest in continuum studies. However in these last two categories the emphasis is more on frequencies above 1 GHz.

Fig. 1 indicates that for prime-focus operation the value of 0.3 for f/D decreases the aperture efficiency by a factor of 0.87 relative to that for f/D = 0.42. Thus the lower f/D is equivalent to providing only a 93 m antenna from the viewpoint of the low frequency observer. The observational advantages of the lower f/D are the small improvements in aperture efficiency and system temperature in the Cassegrain mode, which apply to observations in the centimeter wavelength range. The considerations involved in the choice of f/D are not likely to be much influenced by further studies of the precise performance of the antenna with types of feeds within the current state of the art. Rather, the choice involves a judgement on how NRAO should meet the needs of different areas of astronomy, and does not fall within the domain of engineers.

Array feeds used on the Green Bank antennas have up to this time been prime focus systems operating in the 1-5 GHz range. Development of array feeds is still in the early stages, and it seems premature to predict how it is likely to progress during the lifetime of the new telescope, and whether prime focus or Cassegrain systems will predominate. When choosing parameters such as the f/D ratio for the new telescope, it would thus be a good principle to try to minimize constraints on future designs. For example, an f/D ratio strongly biased towards prime focus or Cassegrain operation should be avoided so long as good performance can still be obtained. It also seems worthwhile remarking that one of the principal advantages of the Cassegrain configuration is the ability to place heavy or bulky equipment, or a room with good working environment, at the feed location. This advantage becomes less important for an antenna of the 100 m size, which can be equipped with a prime-focus cabin and a tower to provide access from the ground.

A final point concerns observations at the highest frequencies. It has been pointed out that these can be made in Cassegrain operation, using a smaller and more accurate subreflector than is needed at centimeter wavelengths. However, it is worthwhile to mention the possibility of going back to the prime focus for such observations. No special subreflector is then needed, and the only surface errors involved are those of the main reflector. If only the central part or the dish is being used, the effective f/D ratio is increased and is likely to be satisfactory whatever the choice of f/D for the full surface. The unused outer part of the dish would act as a shield to prevent increased system temperature from spillover towards the ground. Beam switching could be performed by a mirror system, as shown in Fig. 3. The mirror M2 must be rotated back and forth through 90°, but its size need only be a few centimeters on a side for operation near 100 GHz. Although the mirror is moved through a much larger angle than a beam-switching subreflector, its inertia is much less, so a scheme of this type should be feasible. However, prime focus operation at high frequencies will not be possible if a deformable subreflector is used to compensate for the first-order gravitational deformation of the main reflector. This possibility was suggested by S. von Hoerner (during discussions in Charlottesville on May 22 1989) as a means of minimizing the range of travel required for the active surface positioners of the main reflector.

Reference.

Minnett, H.C. and Thomas, B.MacA., Fields in the image space of symmetrical focussing reflectors, Proc. IEE, 115, 1419-1430, 1968 (October).

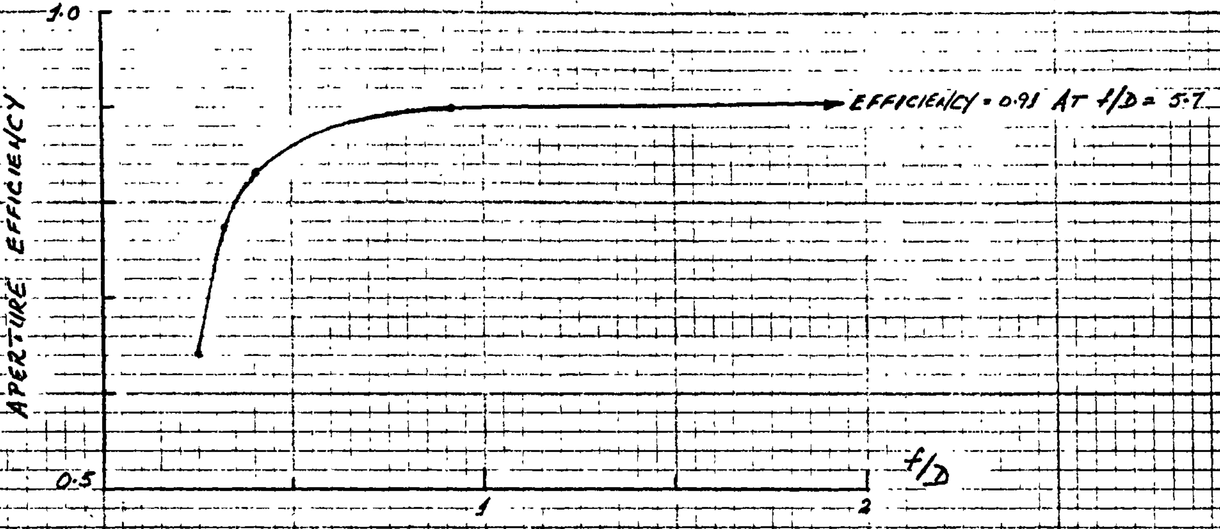

Fig. 1. Theoretical aperture efficiency of a paraboloid reflector antenna with a dual hybrid-mode feed at the prime focus. Data are taken from Fig. 13 of Minnett and Thomas (1968).

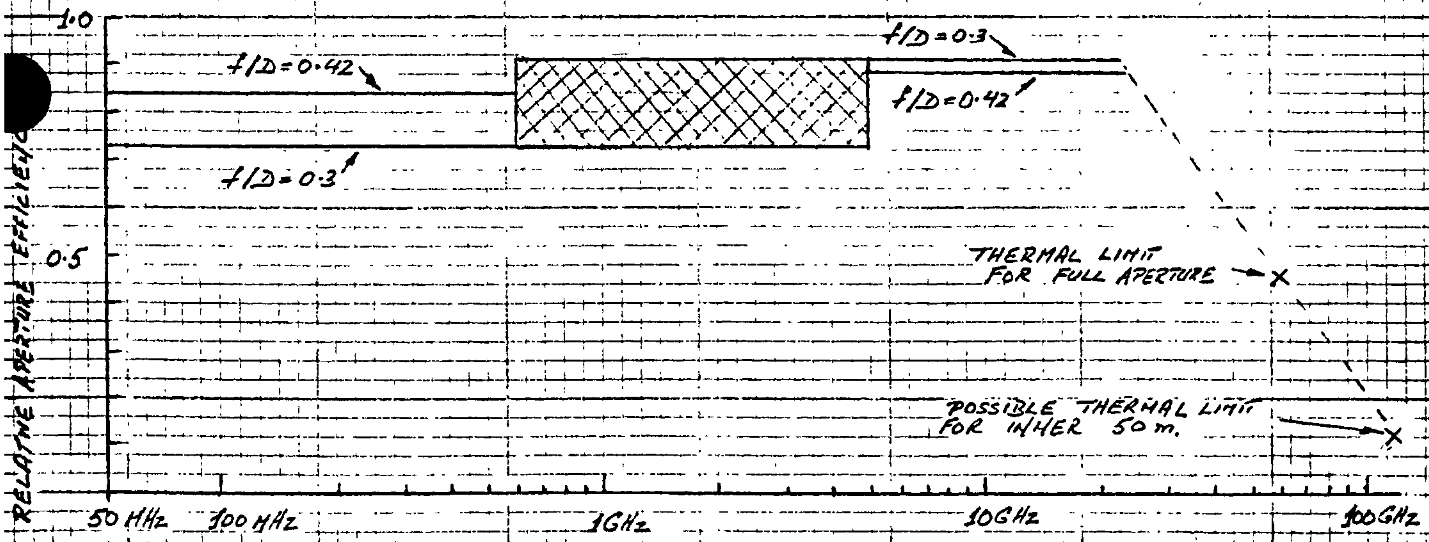

Fig. 2. Approximate performance of 100 m paraboloid antenna, for two values of f/D. Efficiency values are theoretical, and indicate only the relative performance as a function of frequency.

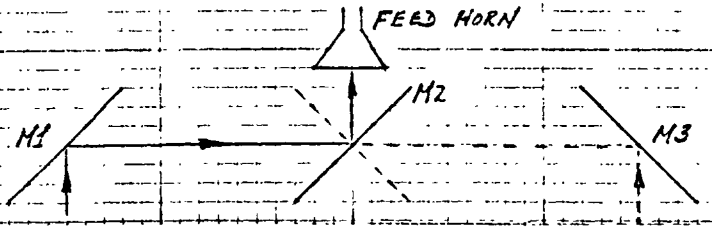

Fig. 3. Possible beam switching scheme for a prime-focus feed. Mirror M2 is rotated back and forth through 90°. M1 and M3 remain fixed, and their spacing determines the beam switching angle. For operation at 3 mm wavelength, the aperture of the feed would be less than 2 cm, so the mirrors could be quite small.

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ADDENDUM TO NLSRT MEMO NO. 62.

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June 13, 1989

As Rick Fisher has pointed out to me, the beam switching scheme in Fig. 3 of NLSRT Memorandum No. 62 will not work for a prime focus feed. The reason is that the angular width of the beam from the feed is greater than 90°, and in practice one cannot handle such a diverging beam with plane mirrors in the manner shown in the figure. The large beam angle seems to preclude any such scheme using plane mirrors at the prime focus. This objection does not apply at the secondary focus where the beam angle is that subtended by the Cassegrain subreflector, and is not likely to exceed 30°. However, the feed aperture would be larger than for the prime focus, and thus the moving mirror would also be larger and more difficult to move quickly through 90°.It seems that we have not yet found a good alternative to the vibrating subreflector.