NLSRT Memo No. 2

Telescope Consultation

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WHAT NEXT ?
Suggestions for Future Radio Telescopes

Summary

A discussion of existing telescopes and natural limits shows a lack of precise large single dishes, especially in the USA. For planning new telescopes, different design types are described and compared.

For conventional parabolic mirrors, the compromise beween gain losses from spillover and from strong taper reduces the aperture efficiency considerably. The blockage from support legs and feed (or Cassegrain) gives some more gain loss, but more important can be the scatter, raising the far-away sidelobes, and picking up ground noise which matters for future low-noise receivers. The only advantage of parabolic primaries is the possibility of prime focus observation.

A two-mirror system with shaped surfaces can transform a narrow feed pattern (negligible spillover) into a uniform aperture illumination (maximum efficiency), without any gain loss for geometrical optics. The axisymmetric case is not more expensive than the conventional parabola-hyperbola Cassegrain. But if pickup of ground noise shall be avoided, asymmetric systems can be designed which have clear view and no scatter. But their longer backup structure and legs will add some cost, and all surface panels are different from each other.

A spherical primary (alt-azimuth) can reduce the cost for very short wavelengths (one mold for all panels), putting all complications into one or two small auxiliary mirrors. Furthermore, with just a single axisymmetric Gregorian one can get already a much better efficiency than for a parabolic primary. And two shaped auxiliaries will again give uniform illumination for a narrow feed pattern. But the asymmetric case would need either a large secondary or a very long focal length, which is more expensive.

How to reduce thermal deformations is discussed. And homologous gravitational deformations can be approached in all cases. The total cost is mainly defined by survival winds if exposed, and by internal stability if shielded.

I.Existing Telescopes and Natural Limits

A comparison of radio telescopes is shown in Fig.1. There, No.1 is the Sub-Millimeter-Telescope (SMT), Reference [1], where design and funding exist, whereas the site, Mt.Graham, is still denied by environmentalists. For comparison, No.9 shows the NRAO 65-Meter design of 1972, worked out in all detail [2], but never funded. All others do exist.

The straight lines are natural limits for accuracy versus size, derived 1967 for simple conventional designs [3]. The shortest wavelength is defined as 16*rms(δz) of the surface deformations. When a telescope of diameter D gets tilted, gravity will cause deformations $\delta z \approx D^2$. This limit can be surpassed either by not moving the primary mirror, as at Arecibo, No.13. Or by designing a backup structure which deforms in a homologous way, from one parabola to another parabola, yielding a perfectly focussing mirror for any angle of tilt. An iterative mathematical method was derived 1965 for this synthesis [4], [5]. It has been succesfully used for telescopes No.3, 5, and 9. Another approch to the same goal is trial and error, a series of some successive designs and improvements, plus good engineering judgement. This was done at Effelsberg, No.11, and the SMT, No.1. and probably also for No.14. All other (older) telescopes are indeed below or close to this gravitational limit.

When the whole telescope warms up uniformly, it will expand uniformly, still having a parabolic surface with the feed exactly at its focus (provided all parts of the backup structure are made of the same material, which normally is done for this reason). But when some parts of the backup structure are warmer than others by δT degrees, they will expand more, and the surface will deform by $\delta z \approx D^* \delta T$. For exposed telescopes with good protective paint which is white for visible radiation (of the sun) but black for infrared radiation (of its own), the difference between sunshine and shadow will mostly cause δT = 5-6 °C, while at clear nights we get δT = 1-2 °C from the difference between cold sky and warm ground.

Another cause for deformations is thermal lag during fast changes of the ambient air temperature. The thermal time constant of structural members is proportional to their wall thickness. Thus thin-walled members will quickly follow the air, while thick-walled members will lag behind, causing thermal differences and thus deformations of the surface. During one or two hours after sunrise and sunset, the deformations from this lag can be even larger than those from strong sunshine, for exposed older telescopes. Since wind reduces thermal differences, exposed telescopes may have either strong thermal or wind deformations, but not both at the same time [1].

Thermal lag can be reduced by keeping the wall thickness of all members within certain limits (2.5 to 10 mm for the exposed 65-m design). Inside a radome, direct sunshine (and wind) are omitted.

Thermal deformations then are caused only by thermal lag, by air stratification, and thermal differences of ground, dome and air.

A middle course between exposure and radome has been adopted for No.3 at Pico Veleta [6]. It has no dome, but the whole backup structure is "put in a bag", enclosed within thermally well insulating light-weight walls fixed to the backup. This needs good ventilators inside, which produce so much heat that a good cooling system is needed as well. This method may sound a bit complicated, but it does work very well. Observers cannot detect the difference of the efficiency between sunshine and night; and they are not troubled either by absorption, shadow or scatter from a radome.

Thermal deformations can be practically omitted altogether, if the whole backup structure (and the surface) is made from material with a thermal expansion coefficient close enough to zero. This is the case at the SMT, No.1, using carbon-fiber members with invar joints [1]. The SMT is far above the upper thermal limit in Fig.1. The telescope is shielded in stow position against heavy weather by a (co-rotating) simple hut, which opens up its front and roof during observation, exposing most of the telescope to sunshine.

Regarding their thermal deformations, and their location in Fig.1, telescopes No.1, 3, 4 and 13 have the plotted location day and night. But all other telescopes plotted above the 5°C line will observe at this wavelength only during nights, while during sunshine they will move to the right-hand side of this line.

Wind deformations cause no natural limits because they can be reduced by "beefing up" some mebers (up to a financial limit).

II. Future Size and Precision

If a future radio telescope is to be planned, observers would mostly like it as large and as precise as possible. Thus, we first should discuss where to draw the line in Fig.1. The gravitational limit can be surpassed by a large factor with homologous deformations, as shown by No.9. We thus will disregard this limit.

Next to be considered are the thermal limits. Regarding costs, smaller telescopes can have more fancy designs, shielded at their backup structure or by a dome, or made from carbon fiber. Then the thermal limits can also be surpassed. Limits then are only given by cost (size), technology (surface), and atmosphere (absorption). Two such examples are already there, Nos.1 and 3 of Fig.1.

For larger sizes, it seems we should ask only for exposed telescopes, without any shielding, and from normal steel. This means that future designs can go up to the thermal limit of 1°C in Fig.1 (at night, and 5°C in sunshine). And that is also where a new telescope actually should go, making full use of our natural possibilities.

Since No.9 was never built, Fig.1 shows a well pronounced lack of large and precise telescopes. Nothing larger than No.3 comes close to the thermal limit. Thus it does make sense, world-wide, to consider a new large telescope along this limit.

This lack of a large precise telescope gets rather drastic if we look at those within the USA. They are all at least a factor of five less precise than possible. They are far off below and to the right of their thermal limit. Nothing in the USA can compete with the precise telescopes overseas, in Spain, Japan, Russia and in Germany. And even better ones than these could now be designed.

> In summary, Fig.1 suggests a new radio telescope of 60 to 100 m diameter, its precision at the upper thermal limit for exposed steel structures, and located in the United States, or maybe in the southern hemisphere.

III. PARABOLIC PRIMARIES

Radio telescopes with a reflecting surface were originally just built for prime focus observation, and the surface thus had to be a paraboloid of revolution. Later on secondary mirrors were added, which then had to be a hyperboloid (Cassegrain, below prime focus) or, more rarely used, an ellipsoid (Gregorian, above prime focus). The secondary moves the receiver to a more accessible place which also can carry more weight, and it moves the feed spillover from warm ground to cold sky, reducing the system noise. If a telescope is designed for a secondary, then there is no need any longer for the primary to be parabolic, at least not for short wavelengths.

But diffraction at the smaller secondary reduces the efficiency for longer wavelenghts, and since telescopes were wanted for both short and long wavelengths, we mostly have now parabolic primaries with a removable hyperbolic Cassegrain.

The present situation is different, however, insofar as the large telescopes usable for long wavelengths do already exist. Missing are the large more precise telescopes, which may be confined to shorter wavelengths (up to 21 cm, say). The secondary then can be fixed, and the primary does not have to be parabolic.

The main disadvantage of a parabolic primary is the inability to have a good aperture illumination and a low spillover as well. A low spillover demands a strong taper, which means a narrow and less effective illumination. While an effective broad illumination calls for a small taper, which reduces the efficiency by a strong spillover. Thus a compromise is needed, with reductions from both sides. The efficiency can be improved to some extent by using specially designed feed horns, illuminating a broader maximum surrounded by a steeper decrease, but they are mostly more limited in bandwidth, and a real steep cutoff is not possible anyway.

Conventional telescopes are axisymmetric. The support legs of feed or Cassegrain cast shadow, which also reduces the gain; first by a reduction of receiving surface, and second by having the lost parts still illuminated. A small secondary with very slender legs will have at least 4% of geometrical shadow, yielding

$$\text{gain} = (1 - \text{shadow})^2 = 0.9216. \qquad (1)$$

In addition to shadow, we have scatter which picks up ground noise, mostly 5 to 10 K, which can be more important than the gain loss for present and future low-noise receivers. We also have increased far-away side lobes, decreasing the dynamical range, which is very important for extended mapping.

Fig.2 shows the gain losses from shadow according to (1); and, as a function of the taper, the losses from illumination and spillover. We have assumed a feed giving a Gaussian illumination I(r) across the aperture. With an edge taper of t (dB), we call $T = 10^{-t/10}$ the illumination at the rim. We then obtain the gain, or efficiency, from illumination, E_I, and from spillover, E_S, as

$$E_I = \langle I \rangle^2 / \langle I^2 \rangle = (8.686/t)*(1-T)/(1+T) \qquad (2)$$

and

$$E_S = 1 - T \qquad (3)$$

where ‹ › means average, and 8.686 = 20/ln 10. The total aperture efficiency then is the product of (1), (2) and (3). This holds for medium wavelengths, below diffraction but above surface errors.

The maximum efficiency thus is 61%, at 8 dB taper, for the Gaussian illumination which is a good approximation to most feeds. Special feeds can increase the efficiency somewhat, with a maximum at somewhat stronger taper. But normally one wants still more taper, 13 to 15 dB, and even with special feeds it is then very difficult to raise the efficiency above 61%. This is the basic disadvantage of parabolic primaries, with or without a secondary.

The largest disadvantage of axisymmetric systems is the pickup of ground noise, 5 to 10 K, which must be compared with receiver noise and natural background, shown in Fig.3. The ground noise does not matter for wavelengths which are very short (atmosphere), or very long (galactic noise). But in the range

$$2 \text{ cm} \le \lambda \le 40 \text{ cm} \qquad (4)$$

the addition of ground noise from scatter will <u>double</u> the system noise, for telescopes with best reveivers. Which, for the signal to noise ratio, is the same as loosing half the telescope surface.

In summary, for the Parabolic Primary,
we have at best about
Effciency = 61%, Ground Noise = 5-10 K. (5)

IV. SHAPED TWO-MIRROR SYSTEMS

1. Axisymmetric

A single condition, equal pathlength (exact focus), can be met by choosing a single proper surface, the paraboloid. If we demand a second condition, broad aperture illumination from narrow feed pattern (high gain but low spillover), both can be met with two surfaces, "shaped" in a special way. This was investigated already 1962 by Kinber [7] who found a shaping procedure for axisymmetric systems, improved by Galindo [8] and others, see [9].

Solutions are obtained by the integration of a differential equation. In the extreme case, one can use a very narrow feed pattern (negligible spillover) and still obtain a uniform aperture illumination (maximum gain), if a sidelobe level of 17.6 dB can be accepted. Otherwise a certain aperture taper must be chosen. With uniform illumination (efficiency 100%), a feed taper of, say 20 db (spillover 1%), and shadow from equation (1), we find at medium wavelengths for geometrical optics:

Shaped and Axisymmetric,
we have at best about
Efficiency = 90%, Ground Noise = 5-10 K. (6)

2. Asymmetric

The need to omit the ground noise for good receivers was early realised, and an offset parabola-hyperbola system of 7 m diameter has been built by Bell Lab on Crowford Hill. But for the shaped systems, Kinber had given a proof that no soluions exist [7].

However, in 1978 we described an iterative relaxation method which gave good solutions for all cases tried, even for the most asymmetric systems without a plane of symmetry [9]. The pathlength condition was always fulfilled exactly, while the illumination condition (uniform, 100% efficiency) was approached in only eight iterations. The remaining error was never more than $1.4*10^{-4}$ for the efficiency, which may have been the accumulation of numerical errors. The feed pattern chosen was Gaussian, with 25 dB feed taper at the rim of the secondary (0.3% spillover).

An asymmetric shaped system is sketched in Fig.4, with F/D=0.5 as used in the iterations. Elevation drive and feed cabin are indicated, but support legs and azimuth mount are omitted. There is no shadow or scatter, with a clear view from feed to secondary to primary to sky. But diffraction from the mirror edges may still give abou 1 K of ground noise, depending on wavelength. Adopting a feed taper of 20 dB (1% loss), we find for medium wavelengths:

Shaped and Asymmetric,
we have at best about
Efficiency = 99%, Ground Noise = 1 K. (7)

3. Polarization

If we demand a third condition, zero cross-polarization (and zero beam squint), we would need a third shaped surface. But as it turns out, we seem to get away without it. This is exactly true for all axisymmetric systems.

Asymmetric systems may indeed have strong cross-polarization. But even without a third surface, we have some small freedom left (with the two surfaces used-up for pathlength and illumination). We are free to choose the locations of secondary and feed, within limits. For the asymmetric two-mirror systems of Ref.[9], cross-polarizatioin was very small when the feed axis pointed about parallel to the beam. And a similar result was now found for the Arecibo Upgrade, where the spherical primary shall have two shaped asymmetric auxiliaries: secondary and tertiary, both Gregorian.

V. SPHERICAL PRIMARIES

For very short wavelengths, the precise surface can require a considerable part of the total cost. Thus, it could make sense to ask for the cheapest most simple kind of surface for the large primary, moving all complications to a smaller secondary which then can be shaped on a large milling machine in one piece (the LOG in Tucson, up to 8 m diameter). And the most simple kind of curved surface is the sphere. All surface panels can be formed on the same single mold. Also, their quality-controll can be done in a simple way at the same setting, reflecting a modulated laser beam from their center of curvature.

1. Single Gregorian, Axisymmetric

The spherical aberration from the primary can be corrected with a secondary of either type, and since a Cassegrain gets too large for reasonable F/D ratios, we consider only the Gregorian type (above the caustic primary focus at R/2). The feed cabin shall be at the primary center. All is axisymmetric. The shape of the Gregorian is easily calculated by analytical equations.

As it turnes out, this most simple two-mirror system has a much better efficiency than the old parabola-hyperbola Cassegrain. The two mirrors give an "inverse taper", which nicely counteracts the feed taper, thus raising the efficiency, as shown in Fig.5 for a typical case (F/D=0.575, d/D=0.150, z_o/F=0.04). We have some freedom in the choice of the parameters, if a different illumination curve is wanted.

The connection between these parameters is shown in Fig.6. We see the basic problem of spherical primaries: we need either a large secondary (shadow, cost), or a very long focal ratio (support legs, rigidity, scatter). This is best for small z_o, but the secondary must have a certain distance above the paraxial focus of the primary, otherwise diffraction "smears out" the focussing property at the secondary's center where the ray density is very high (found by P.S.Kildal for the Arecibo Upgrade). If a future large telescope is built for short wavelengths, not above 21 cm, then it seems that the smallest acceptable distance is about

$$z_o/F = 0.02. \tag{8}$$

Also, Fig.6 shows that still smaller values do not help much. This limit, and the relations of Fig.6, should be almost the same, with or without a tertiary.

Now the other choices must be made. For example we want to keep F/D small, but we decide that the secondary shall not shadow more than 2% of the aperture, thus $d/D = \sqrt{0.02} = 0.1414$. Then F/D follows from Fig.6, and the feed taper is chosen for maximum efficiency. This case is shown in Fig.7. The aperture efficiency (from shadow, legs, spillover, inverse taper) then is 80%. A good deal more than the 61% of the parabolic primary. Another choice is to use all freedom for optimizing the efficiency. This gives d/D = 0.09, F/D = 0.70, 12 dB feed taper, and the performance:

Sphere, with One Symmetric Secondary,
we have at best about
Efficiency = 81%, Ground noise = 5 - 10 K. (9)

2. Two Shaped Auxiliaries, Axisymmetric

A spherical primary with two shaped auxiliaries, completely axisymmetric, would be difficult to design, since the (large) receiver cabin would then be blocking the tertiary mirror, which should be a small one.

But a symmetrically located secondary is possible, whose shape then could be almost symmetrical, if the tertiary is located at the axis, below the primary, tilted 45° with the feed sideways, as indicated in Fig.7. Assuming again 20 dB feed taper, leg shadow from (1), and the same geometry as in Fig.7, we find:

Two Shaped Auxiliaries, Secondary on Axis,
we have at best about
Efficiency = 87%, Ground Noise = 5 - 10 K. (10)

3. Asymmetric

The asymmetric one-sided case, without shadow or scatter from the support legs, has been investigated by Watanabe and Mizugutch [10], for a special application. They describe a good shaping procedure for this three-mirror system, and they have built and tested a model with very good agreement between expectations and measurments. A similar system with smaller offset is now prepared for the Arecibo telescope [11] and a small version has been built.

But for the application to general radio telescopes, Fig.6 says that we must have either a very long focal length, or an extremely large secondary. If we demand again (as in Fig.7) that the area of the secondary shall not exceed 2% of the primary, we obtain the system shown in Fig.8. Efficiency and ground noise would be just as good as for the two-mirror system:

Two Shaped Asymmetric Auxiliaries,
we have at best about
Efficiency = 99%, Ground Noise = 1 K. (11)

But we have now the focal length F/D = 1.11 , which calls for very long support legs, difficult to make rigid without making them heavy. Also, diffraction will be very strong at the right-hand edge of the secondary, where the ray density is high.

VI. GENERAL CONSIDERATIONS

1. Homologous Deformations

In Section I we desribed how the surface errors resulting from gravitational deformations can be made negligibly small. But the algorithm of this method assumes that the desired surface shape is expressed in analytical form, in order to find the "best-fitting" one. It worked well for parabolic primaries, see telescopes No.3 and 9, Fig.1. It would work just as well for spherical primaries, with one or two auxiliaries.

This is different for the shaped two-mirror systems, where the primary shape is only approached numerically. Instead of using the mathematical algorithm, one could fall back on "trial and error", as used for telescopes No.1 and 10. This will be good enough an approach for smaller telescopes, as it was for No.1, and maybe up to 20 m diameter.

For larger telescopes, we suggest a few iterative alternations of homologizing and shaping. This should work well, because the shaping, applied to a paraboloid, does not change the primary surface much, as shown in [9]; thus it will also not change much the deformations of the backup structure.

We suggest to start out with a parabola-hyperbola system of the wanted geometry. First, apply the algorithm for homology. When the approach is satisfactory, apply the shaping procedure until the illumination demand is approached well enough. Then ask for the best-fitting paraboloid (no constraints), use this structure, and make it homologous again. Then shape it again. We think that a few steps of this kind should approach homology for a shaped system almost as well as for the analytical paraboloid or sphere.

The homology algorithm, as used for the 65-m design, changed bar areas but not joint coordinates, keeping the total weight constant. This was the easiest way, to see whether it worked at all. And then there was never time to start again a better method: let all bar areas be defined by survival stability only, and change the joint coordinates for homology.

2. Adaptive Optics

For large optical telescopes one has learned to measure the surface shape during or in-between observations, and to correct it automatically with servo-motors. This allows modern telescopes to become much larger and more precise than before.

But application to large radio telescopes is difficult. Our surface panels are limited in their maximum size by specifications for their own thermal and gravitational deformations. For precise telescopes, they must be small. For large telescopes, their number will then be very large. And each pannel has four (at least three) adjustment srews, to be measured and corrected. The 65 -m design had 2912 surface plates of 1.22 m² average, with 11.648 adjustment srews. For a large radio telescope, this would mean to rely on (and to maintain) many thousand servo-motors, which are high up, exposed to snow and ice, and which must be strong enough to withstand survival wind pressure.

However, we may have a different possibility, which I will call adaptive reception. Suppose that in the future good receivers can be uncooled, and made on chips. With correlators again on chips. For not too short a wavelength, we then may have a very large number of dipoles plus receivers in the focal plane; like charged devices, but now with phase in addition. The central one is correlated to all others. By phase closure, we could then, between observations, have all surface and atmospheric errors measured and calibrated at a nearby point source, and the next observations could be phase-corrected in the receivers.

3. Comparing Costs

Once the need for a new large telescope has been established, and its purpose and size have been agreed on, we need good cost estimates of the different types described, for comparison with their performance, and for the final selection. At present, only some general remarks will be mentioned.

The weight of a telescope in a dome is not defined by its purpose but only by Parkinson's Law: by buckling stability of all members holding up each other against dead loads. Which takes already a lot of steel: the Haystack 120-ft was designed for dead loads only; but without its dome, it would already withstand a wind of 136 km/h. For an exposed large telescope, additional steel is defined by survival winds. If strong enough for survival, it is usually stiff enough for observations in moderate winds as well.

When scaling a design to other sizes, different members scale with different exponents of the telescope diameter D. Omitting all details: the many small members keep the bar area fixed and just go with D. Longer ones without much load keep the slenderness fixed and go with D^2. All those which carry the main loads of survival winds (ice, snow) keep the stress fixed and go with D^3. If a few members must be beefed-up for observational winds, they keep the deformation fixed and go with D^4. Altogether, we found from some examples an exponent of about 2.6 for the whole telescope.

Asking for a backup structure with homologous deformations will increase the cost only a few percent, since it is mainly just a re-distribution of weight and stiffness. But it takes time, effort and skill with the computer. The thermal backup-shielding of No.3, described in Section I, has increased the cost by 10% [6] but has doubled the observing time for short wavelengths (night plus day).

As compared to the old parabola-hyperbola Cassegrain, the axisymmetric shaped two-mirror system has exactly the same cost, but raises the efficiency from 61% to 90%. And the shperical primary with a single symmetric Gregorian has a cheaper surface and still 81% efficiency. This can be raised to 87% by a shaped tertiary and (almost symmetrical) secondary, which is somewhat more expensive. All symmetric designs have the same ground noise.

For low-noise receivers, the 5 to 10 K of ground noise would double the system noise for wavelengths of 2 to 40 cm of (4). This can be avoided by the asymmmetric designs. The spherical primary of Fig.8 has a cheap primary surface with all complications in two small auxiliaries. But it has awkwardly long support legs and some diffraction problem. Whereas the shaped two-mirror system of Fig.4 looks much better in these respects, but has a more expensive surface, each panel having a different shape from all others.

The asymmetric systems have an aperture efficiency of almost 100%, but their tilt needs more surface. The two-mirror system of Fig.4 has F/D = 0.5 and is tilted by 32°. This increases the surface length by 18%, thus needing 18% more steel (but not more labour) in the backup structure. The asymmetric spherical case of Fig.8 has a longer F/D = 1.11, thus a smaller tilt of 13°, which inreases the surface by only 3%. For both systems, shorter F/D ratios need larger surfaces, and a compromise should look for the minimum total cost of backup, surface, legs and secondary.

A very rough comparison showed that the asymmetric structure of Fig.4 may cost 20-30% more than a symmetric one of same aperture, and in addition we have the more expensive surface. But this cost increase must be compared with the increase of the signal/noise ratio: the aperture efficiency divided by the system noise.

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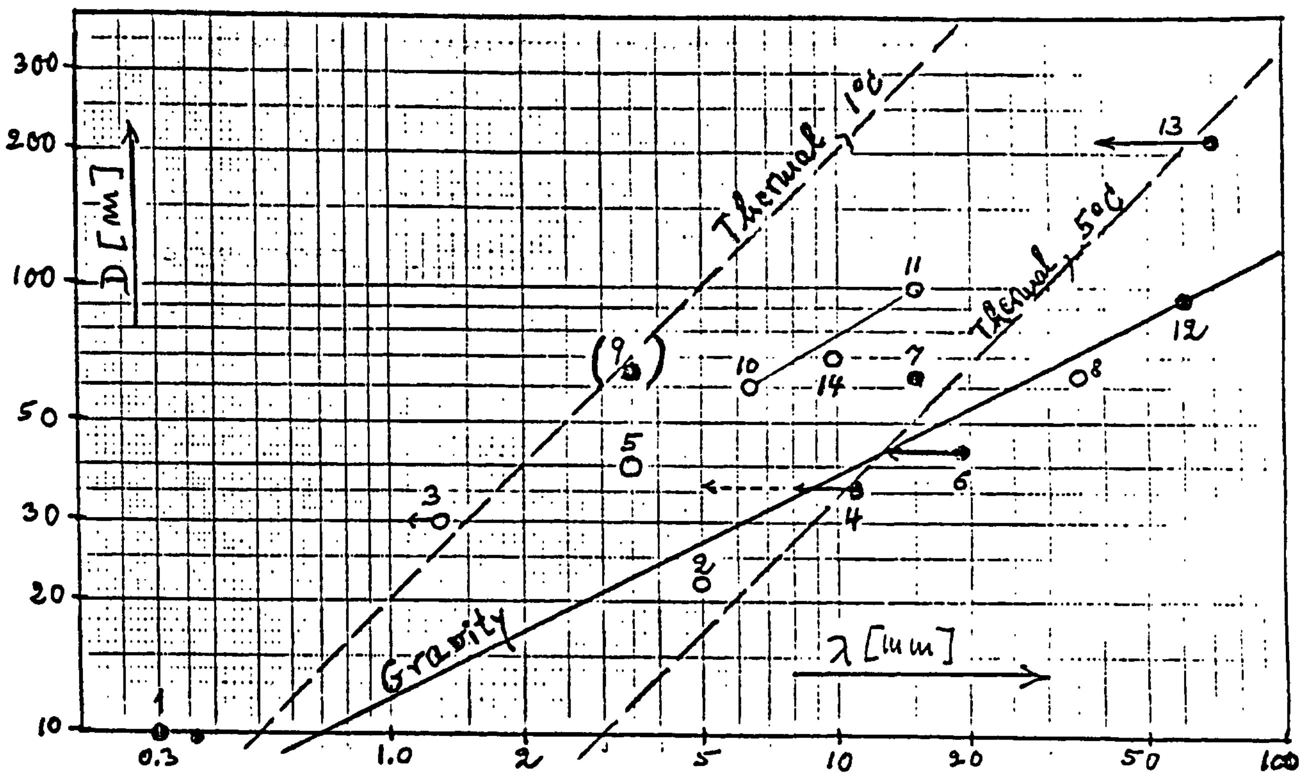

Fig. 1. Radio telescopes, and natural limits for simple design.
D = diameter,
λ = shortest wavelength (16 times surface rms),
Arrows = improvements.

Limits from:
Gravitational deformations for conventional backup.
Thermal deformations for steel and white paint, unshielded, for rms temperature differences at night (1°C) and in sunshine (5°C).

Telescopes:

1 Bonn-Arizona	6 NRAO 140-ft	10 Effelsberg, center
2 Crimea	7 Goldstone	11 Effelsberg, all
3 Pico Veleta	8 Parkes	12 NRAO 300-ft
4 Haystack	9 NRAO 65-m design	13 Arecibo
5 Nobeyama		14 Usuriisk

(● USA, o Overseas)

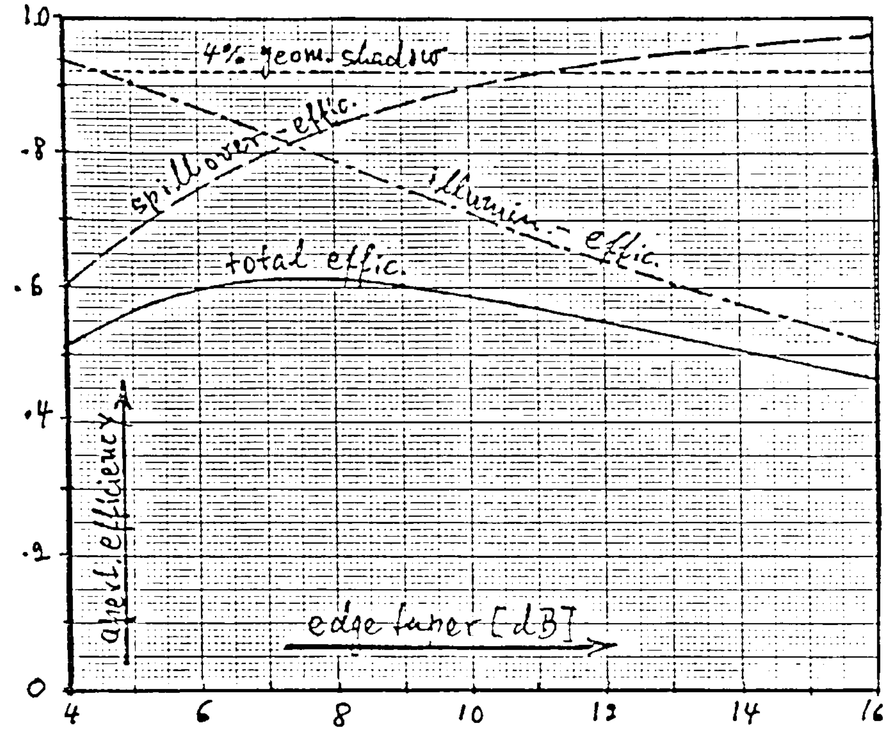

Fig. 2. Aperture efficiency of parabolic mirror.
(For simple feed with Gaussian pattern)

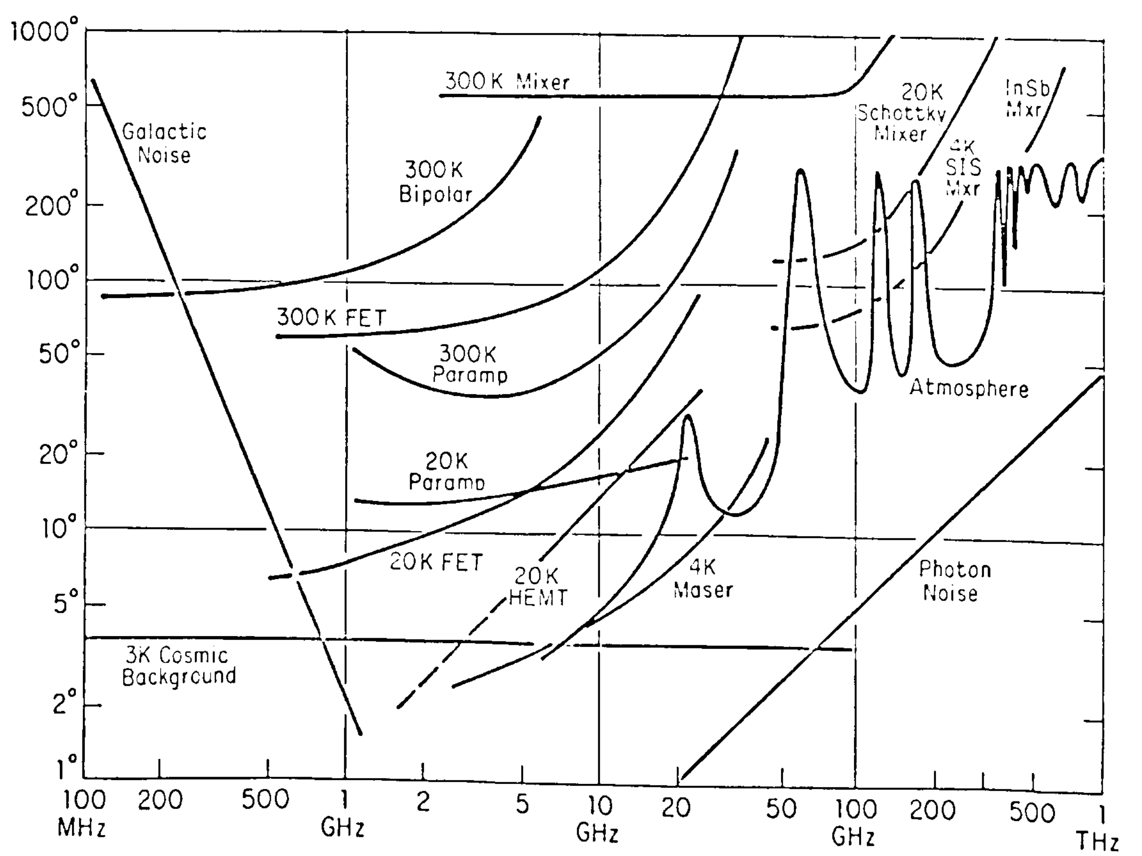

Fig. 3. Noise temperatures [°K] and natural limits (S.Weinreb, NRAO)

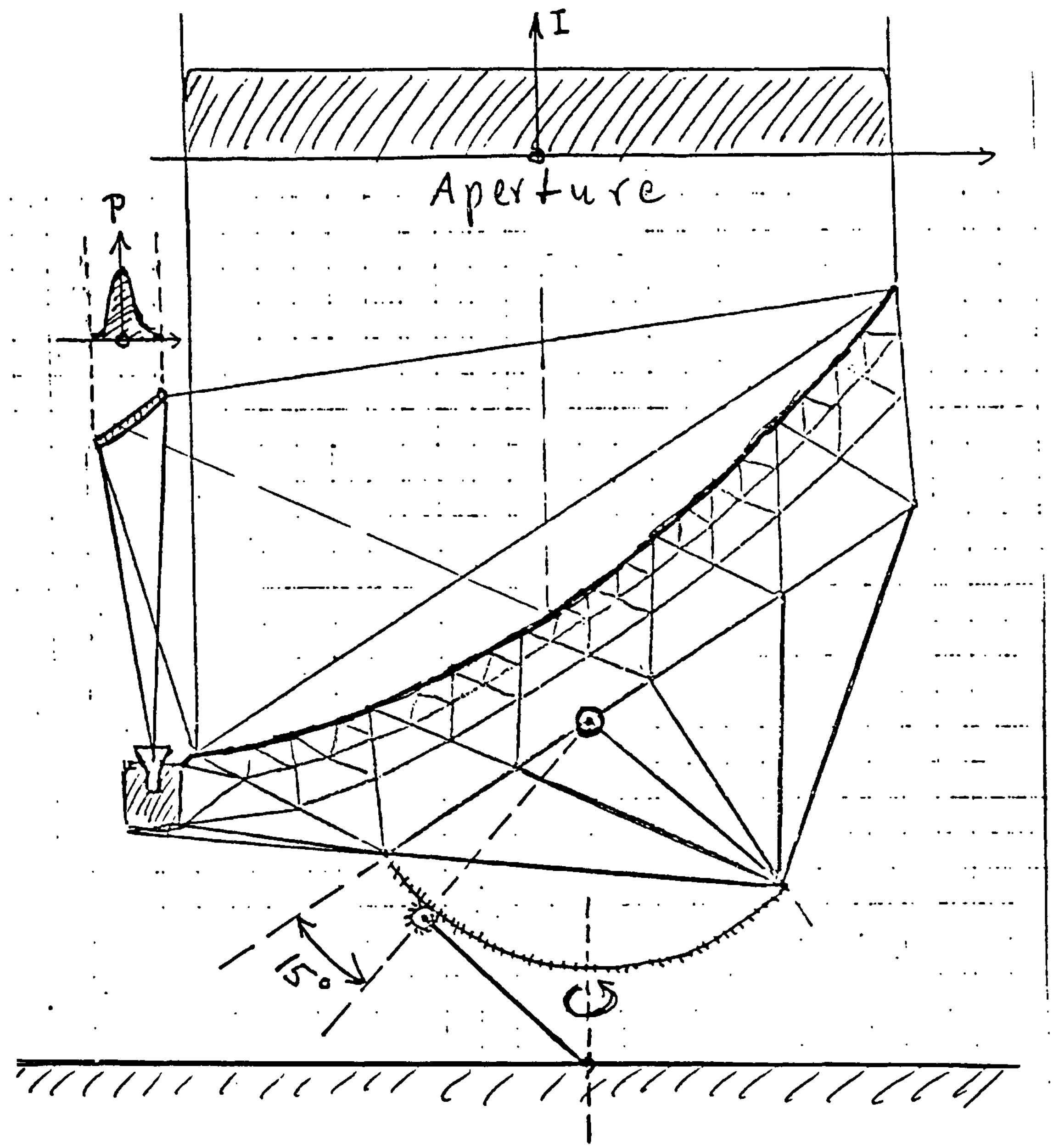

Fig. 4. Asymmetrical shaped two-mirror system, pointing at zenith.
(Elevation drive from horizon to 15° beyond zenith)

Shaped surfaces transform narrow feed pattern, P, into uniform aperture illumination, I. No gain loss from spillover or taper.

Asymmetry prevents any blockage and scatter from secondary or legs. No pickup of ground noise.

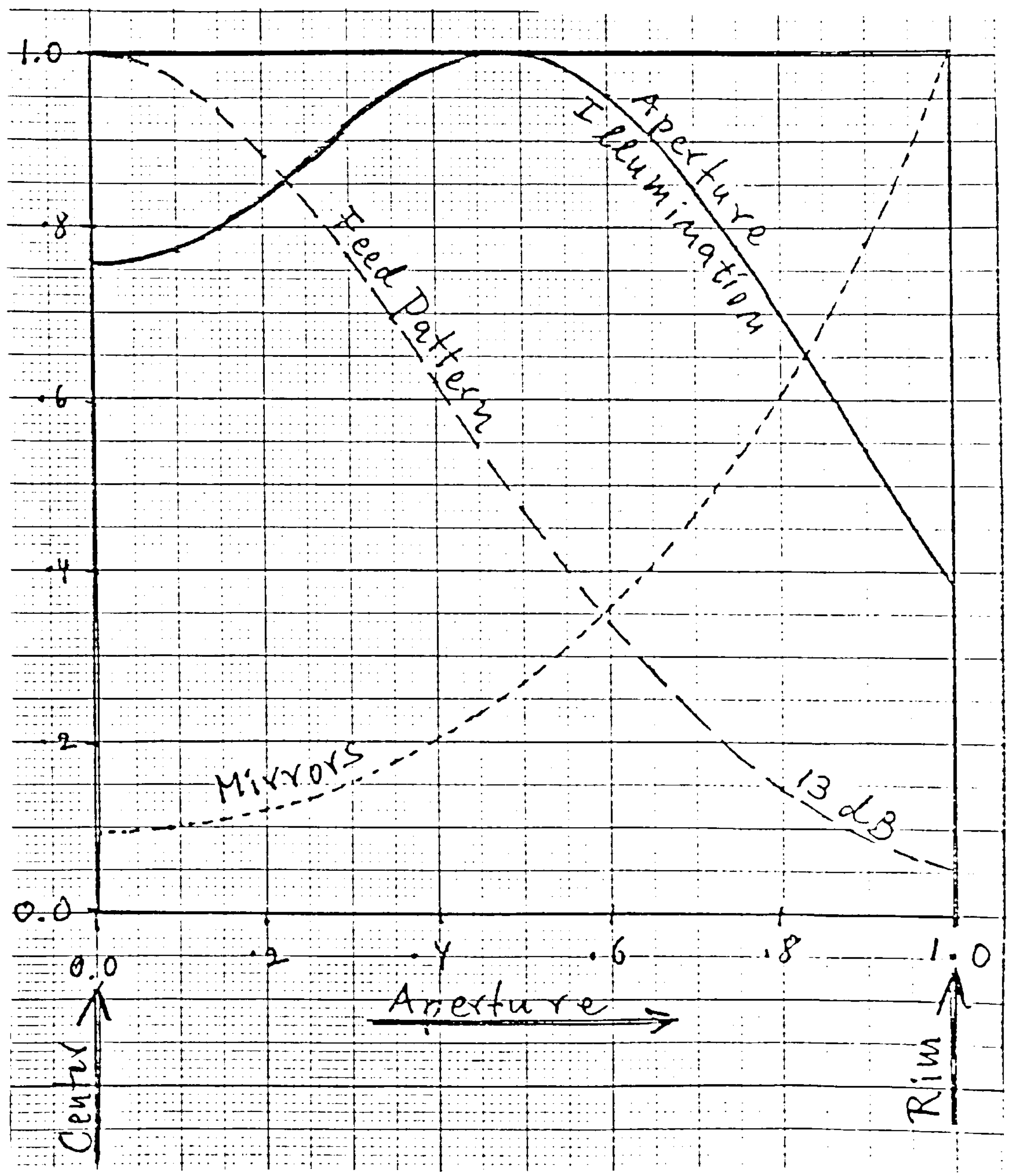

Fig. 5. Spherical Primary, Gregorian Secondary, Aperture Illumination. (Without a tertiary)

Aperture Illumination = product of Feed Pattern across secondary, times Inverse Taper produced by the two mirrors.

The inverse taper raises the efficiency.

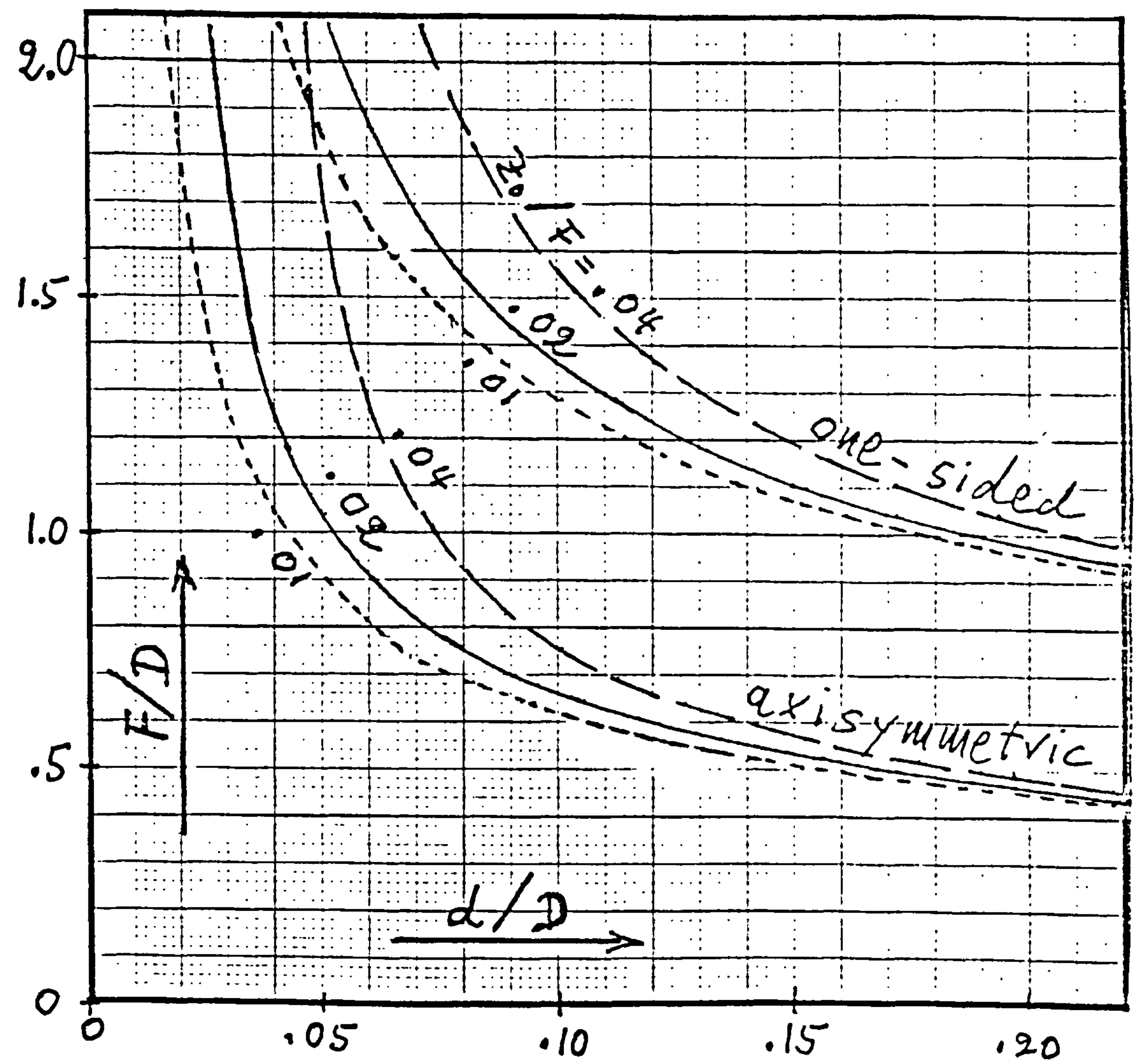

Fig. 6. Spherical Primary, Gregorian Secondary, Focal Ratio versus Diameter Ratio. (With or without a tertiary)

D = aperture diameter
d = secondary diameter
F = R/2 = primary paraxial focus
Z_o = height of secondary above F

Radius Primary Curvature = 1000 ;   Case 2 : Symmetrical
Aperture from x=-456.2 to 456.2 ;   POINTS= 61   Rays= 5
Focus ♦ at Xt= 0 , Zt=-500 ;   Height Secondary Zs= 10
F/D=0.5480   d/D=0.1414   β =15.17 degrees

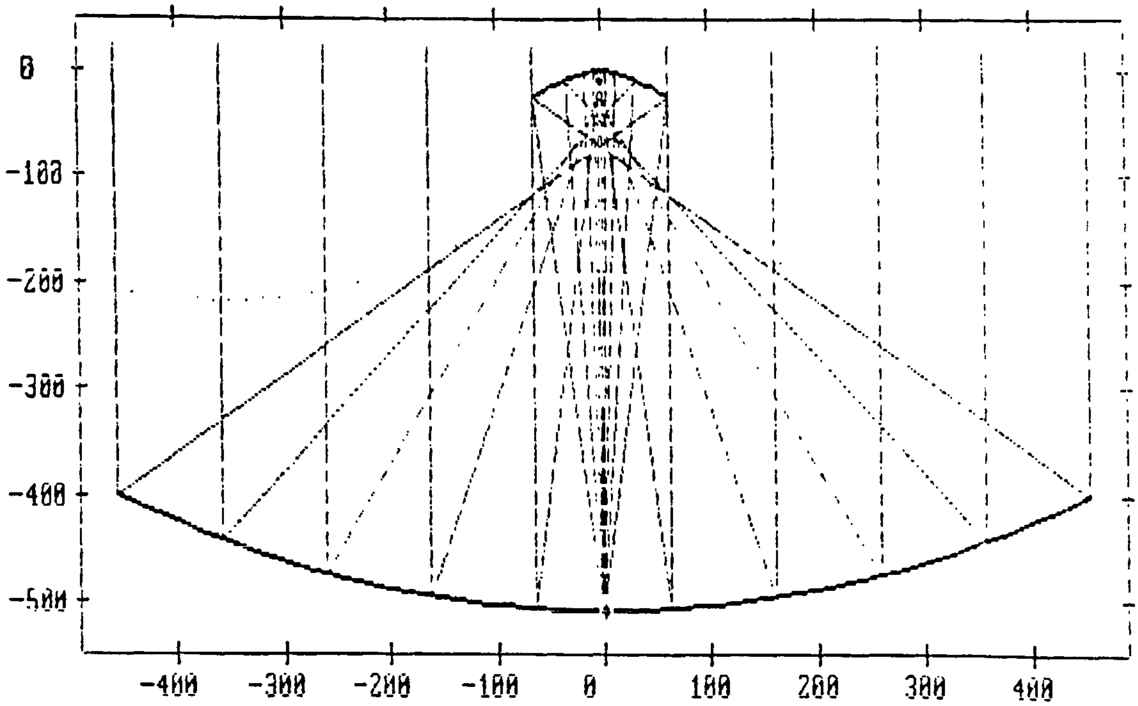

Fig. 7. Spherical Primary with Gregorian Secondary; Smallest F/D, but d/D limited to 2% shadow.

For <u>single</u> secondary as shown, with the feed at ♦, maximum efficiency is 80%, at 13 dB feed taper.

For <u>two shaped</u> auxiliaries, the tertiary could be below ♦, probably tilted 45°, with feed sideways. Maximum efficiency, with 20 dB taper, is 87%.

Beta is the angle from feed or tertiary to the secondary. The dotted curve is the caustic.

Radius Primary Curvature = 1000 ;   Case 3 : Asymmetrical
Aperture from x= 0 to 450.3 ;   POINTS= 51   Rays= 7
Tertiary ♦ at Xt=-25 , Zt=-515 ;   Height Secondary Zs= 10
F/D=1.1104   d/D=0.1414   ß = 7.23 degrees

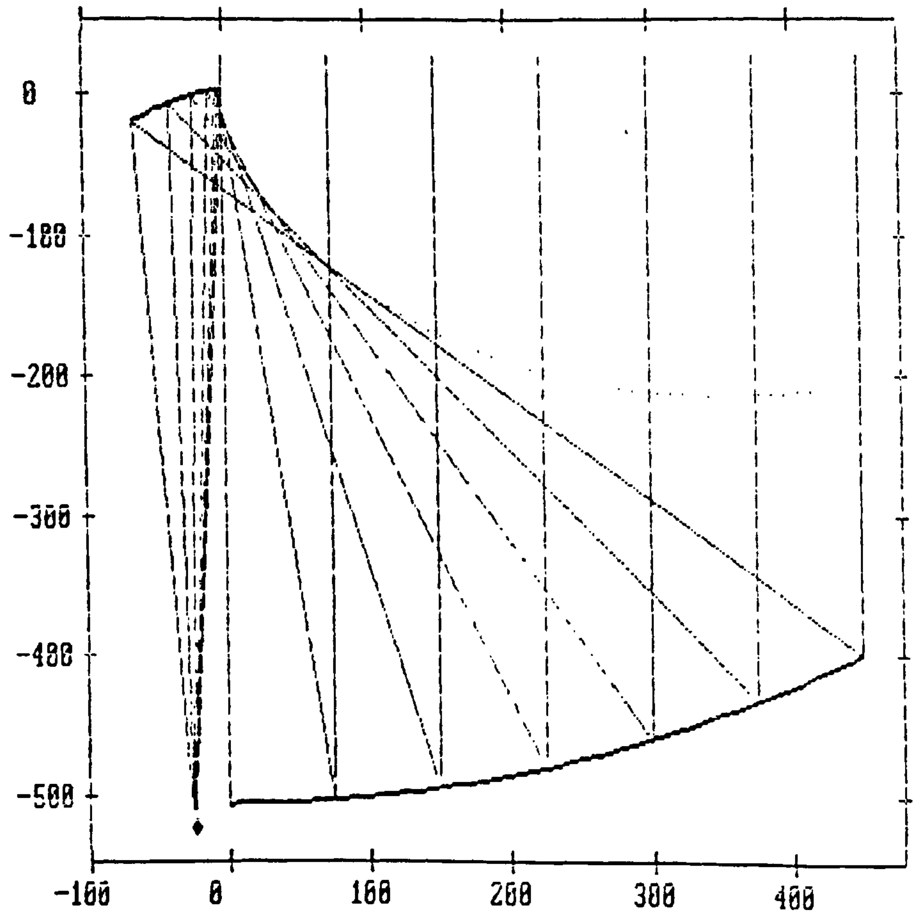

Fig. 8. Spherical Primary with Two Shaped Auxiliaries, Tertiary at ♦ (45° tilted, feed sideways).

For same diameter ratio as in Fig.7.

Efficiency 99% for 20 dB feed taper; but long F/D, and strong diffraction at right edge of secondary.