Report 31

Feb. 24, 1970

The Choice of a Cassegrain System for the 65-m Telescope

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Summary

A discussion of several arguments leaves only one crucial reason for a secondary mirror: a large cluster of many feeds needed for a survey of the whole sky at shortest wavelength (which would take 25 - 900 years at the prime focus). A removable Cassegrain is suggested, to be used for 3.5 mm $\leq \lambda \leq$ 3.8 cm, while longer wavelengths must be observed at the prime focus (excessive horn length at secondary focus), using a spillover shield. The Cassegrain mirror should be mounted at three feed legs, on computer-controlled jacks, allowing ± 1 inch movement in all directions with an accuracy of ± .002 inch up and ± .010 inch sideways.

For structural reasons, the secondary focus is located only 5 ft above the vertex. The cabin is 10 x 10 ft wide, and 12 ft long. The maximum feed cluster is 9 x 9 ft. There should be two exchangeable cabins.

Two lower limits and four upper ones are derived for the diameter d of the secondary mirror, resulting in d = 12 ft. The magnification, then, is 15.7; the longest wavelength at the Cassegrain focus is 3.8 cm; the first side lobe is 22.8 dB, and the coma lobe is lower than 15 dB at the corner of the feed bluster for all wavelengths; the maximum number of feeds is 965 for λ = 6 mm, and larger for smaller λ; the weight of the secondary mirror is about 900 lb, and its lowest dynamical frequency is 4.5 cps (sufficient for fast corrections of the pointing, bypassing the dynamical lag of telescope and towers).

I. General Considerations

1. Reasons for Planning a Cassegrain System

Table 1 lists the six reasons mostly given in favour of a secondary mirror, plus one more connected with our special pointing system. They are listed in the order of increasing importance regarding the 65-m telescope (zero means no difference, positive is in favour of a secondary, negative is against it).

Table 1. Reasons for a secondary mirror.

Reason	Remarks for 65-m design	Estimated importance (-5 to +5)
1. Easy access	Service tower for prime focus is planned anyway. Access, then, is even easier there.	-2
2. Heavy equipment	Feed legs rest on most basic points of back-up structure. Additional weight at prime focus gives less surface deviation than at vertex (factor 3.4).	-2
3. Scanning ability	Telescope is fully steerable.	0
4. Reduced spillover	A spillover shield at prime focus (Report 3, 1965) is just as good but cheaper; usable for $\lambda \leq 20$ cm for 65-m. Needs to be tested at 140-ft.	0
5. Multiple feed for alternative observations	Important for short wavelength and weather changes. But can also be done with rotating bottom of prime focus cabin, see Parkes telescope.	1
6. Improvement of pointing accuracy	Bypassing the lowest dynamical frequency of the whole telescope (1.5 cps) with a fast-correcting secondary mirror. Estimated 20-30% improvement of pointing accuracy; to be known better after O. Heine's platform experiment.	3
7. Cluster of many feeds for simultaneous observations.	Survey of whole sky at short wavelength. Completely impossible at prime focus because of long duration.	5

Regarding item 2, an experiment was run on the computer. It shows (1) that almost any load (up to 30 tons, say), if known in advance and not to be changed later, can be taken care of in our homology program by small changes of bar areas, such that no

additional rms surface deviation results. (2) Once the telescope is built for a given load, any additional load at the prime focus then gives additional rms surface deviations of 1.66×10^{-4} inch/ton, and 5.67×10^{-4} inch/ton at the vertex (factor 3.41). This is tolerable up to about .002 inch; which allows up to 12 tons additional load at the prime focus, but only up to 3.5 tons at the vertex.

There is only one really crucial reason for a secondary mirror: a cluster of many feeds needed for a survey at shortest wavelengths. For $\lambda = 3.5$ mm, the beamwidth is only 13.3 arcsec. The observable 3/4 of the whole sky then contains 2.89×10^9 beam areas. With an integration time of 10 sec per beam area, a complete survey then would take 983 years with a single feed, or still 25 years with 1 sec integration and four feeds at the prime focus (where a large number of feeds is prevented by coma lobes). The only way out seems to be a cluster of 100 - 1000 feeds at a secondary focus. According to S. Weinreb, receivers will get better in the future only down to some "natural limit" of noise temperature, and from then on they will get cheaper, and multiple feeds (and receivers) of several hundred may become feasible. For a wavelength of a few millimeter, a high number of bolometers in a common dewar may be considered.

Even if this reason were the only one, it still is important enough to decide on a secondary mirror. The system, thus, should be designed especially with regard to its use at shortest wavelengths. But for longer wavelengths, the prime focus must be accessible, too.

Whether to plan a Cassegrain (hyperbola below prime focus), or a Gregorian (ellipse above prime focus), seems not to be an important decision. Since a Gregorian needs a higher feed support sturcture, which is already rather high and slender in our design, and since Cassegrains are better understood, several discussions at NRAO resulted in planning a Cassegrain.

2. Mount of Cassegrain Mirror

The mirror should be mounted at three of the four feed legs. Removing and accurately remounting must be fast, with a design goal of 1 hour, say, and a maximum of 1/2 day. It should be mounted on computer-controlled precision jacks, allowing the following movements:

(a) ± 1 inch parallel up and down, z; for homologous changes of focal length;

(b) ± 1 inch parallel sideways, x; for homologous changes of axial direction;

(c) ± 1° rotation about prime focus, x and y; for alternating observations (1.5 feet off-axis at vertex), and for on-off source observations; needs ≈ ± 1 inch movement sideways for Cassegrain mirror;

(d) ± 5 arcsec fast tilt about its center, x and y; for fast pointing corrections.

In summary, all three mounts must be able to move in all three directions by ± 1 inch, with a precision of about ± .002 inch up and down, and about ± .010 inch sideways. Therefore, it is highly desirable to keep the secondary mirror as small and as light-weight as possible. If its weight goes with $d^{2.5}$, its moment of inertia even goes with $d^{4.5}$.

3. Feed Movement Needed ?

(a) Secondary focus. A feed movement sideways is never needed because of the high flexibility demanded for the secondary mirror. But a feed movement along the telescope axis could be needed regarding the homologous change dF of the focal length. If F changes by dF, then the prime focus, the secondary mirror, and the secondary focus, all must move in parallel by dF. If the feed does not move, it then is axially displaced by $\Delta z = dF$. With dF = 1 inch, and $\lambda = 3.5$ mm, the feed is displaced by

$$\Delta z = 7.26\,\lambda. \tag{1}$$

According to equation (17) of Baars (1966), the relative gain loss, $L = 1 - \frac{G}{G_o}$, is for a parabolic illumination

$$L = \frac{1}{18}\left[2\pi\,\frac{\Delta z}{\lambda}\,(1\cos\varphi)\right]^2 \qquad \text{for} \qquad L \ll 1, \tag{2}$$

which holds for a feed at the prime focus, and where φ is the illumination angle, see Fig. 2. For a feed at the secondary focus, we must use φ_0 instead of φ, where (for M >> 1)

$$\cos\varphi_0 \approx \frac{f}{\sqrt{f^2 + D^2/4}} \approx 1 - \frac{1}{2}\,(D/2MF)^2 = 1 - 0.685/M^2 \tag{3}$$

which gives

$$L = \frac{\pi^2}{18} (D/2F)^4 \ (\Delta z/\lambda)^2 \ M^{-4} = 1.03 \ (\Delta z/\lambda)^2 \ M^{-4} \tag{4}$$

and with (1)

$$L = 54.6 \ / \ M^4. \tag{5}$$

If we demand, for example, $L \leq 2\%$, then

$$M \geq 7.23. \tag{6}$$

Since we will see later that $M \approx 15$, we have only $L \approx 0.1\%$. This means that a feed movement is <u>not</u> necessary at the secondary focus.

(b) <u>Prime focus</u>. From equation (2) and $dF = 1$ inch one can derive that an axial movement of the feed is needed for $\lambda \leq 14$ cm if $L \leq 2\%$ is demanded, and for $\lambda \leq 9$ cm if $L \leq 5\%$. This means that we certainly need an axial movement.

A lateral movement is not needed if $L = 5\%$ can be tolerated at $\lambda = 2$ cm. But if wavelengths $\lambda \leq 2$ cm are to be observed at the prime focus, too, then a lateral feed movement of 1 inch must be also provided (for homologous changes of axial direction).

4. Location of Secondary Focus, Cabin Size

Long feed horns can be avoided by placing the secondary focus higher above the vertex, closer to the secondary mirror. Fig. 1 shows the Goldstone antenna, with a vertex tower reaching 41 feet above the vertex, reducing the horn length by almost a factor of four as compared to a horn at the vertex.

This solution cannot be applied to our 65-m telescope because of the high surface precision needed for millimeter wavelengths. A long and heavy tower gives a large moment at its base when pointed at horizon, which is extremely difficult to counteract in the telescope structure. It was thus decided to mount the feed cabin right at the vertex, where it adds only a weight but no moment.

We need a feed cabin each at the prime focus and the secondary focus. For the latter, S. Weinreb suggested to have two exchangeable cabins, one to work with and one to work at. These cabins should be small enough for being removable; but they should be wide enough for housing two independent experiments, alternating with weather changes, and they should be long enough for the feed horns at the longest Cassegrain-wavelength, λ_m. As a compromise we agreed on

$$\left.\begin{array}{l}\text{10 x 10 feet wide}\\ \text{12 feet long}\end{array}\right\}\ \text{Cabin size} \tag{7}$$

for both secondary and prime focus. Whenever this length is not needed, a higher second floor can be mounted inside.

Regarding the length of 12 feet, we then decided to have 5 feet above the surface and 7 feet below it. The distance b between vertex and secondary focus in Fig. 2 then is

$$b = 5 \text{ feet.} \tag{8}$$

5. Longest Wavelength λ_m at Secondary Focus

A large distance between primary and secondary focus, a finite cabin length, and the desire for a small secondary mirror, all tend to result in a small λ_m (above which the prime focus must be used). Formulas for λ_m will be given later. Here, we ask only: how small a λ_m can be accepted from the future user's point of view?

First, there should be a certain overlap with existing or future large, high-precision telescopes which are shown in Table 2. This comparison results in a smallest value of about $\lambda_m = 3$ cm, because for $\lambda \geq 2$ cm there are two telescopes larger than 65 m (= 213 ft) available.

Table 2. Existing and future large telescopes.

Telescope	D feet	λ_{min} cm
NEROC	410	2
Bonn	330	2.5
Goldstone	210	5
Arecibo	1000	10

Second, we try to imagine how the scheduling might be done with $\lambda_m = 3$ cm. This is shown in Table 3, assuming a good telescope site with 7 good months, say, and 3 bad ones like a rain season, and two intermediate ones in between. It is assumed that the scheduling always plans an alternate observation at longer wavelength to accompany any short-wavelength observations, changing from one to the other with changes of atmospheric conditions (and with day and night for the very shortest wavelengths). These changes, however, should not include a change between Cassegrain and prime focus.

Table 3. Example of scheduling, with $\lambda_m = 3$ cm.

Period/Year	λ (cm)		Focus
	shortest	alternate	
7 good months	0.3	$3 = \lambda_m$	Cassegrain = 7 months
2 intermediate months	2	6	Prime } = 5 months
3 bad months	5	20	Prime } = 5 months

Since $\lambda_m = 3$ cm seems reasonable with respect to both overlap and scheduling, whereas a longer cut-off still would be more convenient, we conclude

$$\lambda_m \geq 3 \text{ cm.} \tag{9}$$

II. Magnification, Blocking, and Horn Size

1. Magnification

Definitions are given in Fig. 2. We call

$$m = D/d = \text{diameter ratio of mirrors,} \tag{10}$$

$$M = f/F = \text{magnification} = \text{ratio of focal lengths.} \tag{11}$$

If we neglect the difference in curvature between primary, secondary, and equivalent mirror (valid for $m \gg 1$), we obtain from Fig. 2

$$m = D/d = F/a = f/g, \tag{12}$$

and, with

$$g = F - b - a = F - b - F/m, \tag{13}$$

we derive in general

$$M = m\,(1 - b/F) - 1. \tag{14}$$

Using $F = 91$ ft and $b = 5$ ft for the 65-m telescope, we have

$$M = 0.945\,m - 1 \tag{15}$$

or

$$m = 1.058\,(M + 1). \tag{16}$$

2. Blocking

The geometrical blocking is $(d/D)^2 = 1/m^2$. Since the blocked area is illuminated, too, we get a factor of two for constant illumination, and another factor of about two for a tapered illumination where the center counts highest. In terms of signal/noise, the blocking then is

$$B = 4 / m^2. \tag{17}$$

For example, we may demand

$$m \geq 14.1 \quad \text{for} \quad B \leq 2\%. \tag{18}$$

3. Minimum Horn Length

Definitions for the feed horn are given in Fig. 3a. We use a paper of A. P. King (1950) about horn optimization. The shortest horn for a given gain is defined by

$$\ell_s - \ell = 0.3\ \lambda$$

which, for $\lambda \ll \ell$, gives a horn length of

$$\ell = 0.417\ h^2/\lambda. \tag{19}$$

The half-power beamwidth β for this optimized horn is $1.221\ \lambda/h$ for the magnetic plane, and $1.047\ \lambda/h$ for the electric plane, with an average of

$$\beta = 1.134\ \lambda/h. \tag{20}$$

4. Tapered Illumination of Cassegrain Mirror

We demand that the illumination is 3 dB down at 1/2 the Cassegrain radius:

$$\beta\, g = d/2. \tag{21}$$

With equations (10) to (14), we find in general the horn width as

$$h = 2.27\ \frac{F}{D}\ M\ \lambda. \tag{22}$$

Selecting the same $F/D = 0.427$ as at all our NRAO telescopes,

$$h = 0.969\ M\ \lambda. \tag{23}$$

Insertion of (22) into (19) yields the horn length in general as

$$\mathcal{L} = 2.15 \left(\frac{F}{D} M\right)^2 \lambda. \tag{24}$$

Or, with F/D = .427,

$$\mathcal{L} = 0.391 \, M^2 \lambda. \tag{25}$$

Demanding $\mathcal{L}$ = 12 ft and $\lambda \geq 3$ cm, we find

$$M \leq 17.6. \tag{25a}$$

5. Multiple Feed Cluster

We use a square feed cluster as shown in Fig. 3b. With respect to the cabin size of 10 x 10 feet, we adopt a maximum cluster size of, say,

$$c_m = 9 \text{ feet}. \tag{26}$$

In general, we have

$$c = h \, (\sqrt{n} - 1), \tag{27}$$

with n = number of feeds, and using h from (23) we find for F/D = .427

$$n = (1 + 1.032 \, c/M \lambda)^2, \tag{28}$$

and with c_m = 9 ft = 275 cm finally

$$n_m = (1 + 283 \text{ cm}/M \lambda)^2. \tag{29}$$

Demanding, say, $n \geq 1000$ for $\lambda = 3.5$ mm, we obtain $M \leq 26.5$, and with (15) we find a maximum diameter ratio of

$$m \leq 29.1. \tag{29a}$$

III. The Coma Lobe

The tolerable scan angle (off-axis feed displacement) of a Cassegrain system is limited by gain loss and/or by coma lobe increase. Both are caused by two effects. First, a one-sided spillover occurs beyond the rim of the primary mirror as shown in Fig. 4b. Second, the difference in path length between various rays yields phase errors. From the first effect, the gain loss is more harmful than the coma increase; in addition, any spillover toward the ground increases the noise temperature. From the first effect, the coma increase is more harmful than the gain loss. These distinctions are not clearly seen in many published papers.

1. Spillover and Critical Displacement

A critical scan angle Θ_{cr} is defined by White and DeSize (1962): for $\Theta \geq \Theta_{cr}$ all incoming rays, after reflection at the primary, miss the secondary mirror, see Fig. 4a. The authors plot Θ_{cr} for various F/D ratios as a function of M. For M >> 1, the critical angle approaches $\Theta_{cr} = 0.72/M$, in radians, for F/D = 0.427. The critical angle then can be transformed into a critical displacement, r_{cr}, using Baars' (1966) values of the beam deviation factor, BDF, for small M (using BDF as a function of f/D instead of F/d):

$$r_{cr} = \frac{F\,\Theta_{cr}\,M}{BDF} \,. \tag{30}$$

Of course, one cannot go until r_{cr}. From computer data about beam patterns published by Nihen and Kay (1963) it can be derived that a 3 dB gain loss is reached at about 0.4 r_{cr}, while a 15 dB coma lobe is reached at about 0.3 r_{cr}. But since the noise increase from spillover seems more serious, we suggest to regard

$$r_o = 0.1\, r_{cr} \tag{31}$$

as a desirable limit. At this limit, the spillover is about 10% of the illuminated area, but the power spillover is considerably less, depending on the illumination taper. Fig. 5 then shows the maximum feed displacement r_o for the 65-m telescope.

For $M \gg 1$, we find $r_o = 6.5$ feet; this is just about the maximum feed cluster size adopted in (20) giving $r = 9/\sqrt{2} = 6.37$ feet. This means that within a cluster size of 9 x 9 feet, the spillover creates a tolerable noise increase, and negligible gain loss and coma increase.

2. Coma Lobe from Phase Errors

Nihen and Kay (1963) have calculated beam patterns for 18 different combinations of m, F/D, b, D/λ, with 3 scan angles each. The results are shown graphically in detail, but are only poorly discussed: (a) the spillover effect is introduced in their description of the computer program, but is hardly ever mentioned regarding the results, although the vast majority of their cases is severely spillover-limited (mostly $D/\lambda = 200$ only), see the discussion of their Figs. 38 and 39. (b) They define the maximum scan angle by a 3 dB loss, although coma lobes up to 7 dB are much more severe for many applications. (c) They seem not to see that for a Cassegrain system it is mostly $f/D = MF/D$ which matters and not F/D itself. But 4 of their graphs are essentially free of spillover effects and are used in the following.

We measure the scan angle Θ in terms of the half-power beamwidth β and define

$$k = \Theta/\beta. \tag{32}$$

We call γ the level of the coma lobe (in dB, defined positive) at scan angle Θ, as compared to the main lobe at $\Theta = 0$, because this is what matters for mapping or confusion problems. From Nihen and Kay's beam patterns we can derive approximately

$$k = 4.6\, M\, 10^{(15-\gamma)/20} \qquad \text{for} \qquad \gamma \leq 20 \text{ dB}, \tag{33}$$

or

$$\gamma = 15 - 20 \log (k/4.6\, M) \qquad \text{for} \qquad k \geq 2.6\, M. \tag{34}$$

For $k \to 0$, γ approaches quickly γ_0 of the first sidelobe, which is given by Baars (1964) as a function of the illumination taper and of the blocking by the secondary mirror. The limits given in (33) and (34) apply to $m \geq 7$; they are $\gamma \leq 22$ and $k \geq 2.1\, M$ for $m \geq 15$.

Next, we use $\Theta = r/f = c/(MF\sqrt{2})$ and $\beta = 1.2\ \lambda/D$ in (32) and obtain, in general and for $F/D = .427$,

$$k = 0.589\ \frac{D}{F}\ \frac{c}{M\lambda} = 1.38\ \frac{c}{M\lambda}. \tag{35}$$

With (27) for c, and (22) for h, we then have in general

$$k = 1.33\ (\sqrt{n} - 1). \tag{36}$$

With (35) and (36) we thus can obtain the coma lobe from (34), for any given cluster size c, or given feed number n.

Demanding the full use of the cabin size at shortest wavelength, $c = 9$ ft and $\lambda = 3.5$ mm, with a tolerable coma lobe of $\gamma \geq 15$ dB, we obtain

$$M \geq 15.35. \tag{37}$$

IV. Dynamical Properties

The total pointing error of the telescope consists of two parts. The first part is unknown, like thermal and wind deformations above the pointing platform, and reading errors. The remaining part is known but cannot be corrected fast enough because of the dynamical lag of the telescope structure. This second part is in proportion to $\nu^{-\alpha}$, where ν = lowest dynamical frequency of combined structure, and with $\alpha = 1$ for slow perturbations, $\alpha = 2$ for fast ones, and about $\alpha = 1.5$ in the average. The combined structure (from ground to focal cabin) has $\nu = 1.5$ cps.

This second part of the pointing error can be reduced if the secondary mirror can be tilted with more than 1.5 cps. A considerable reduction by a factor of ≥ 5, say, then demands a dynamical frequency of the secondary mirror of $\nu \geq 1.5 \times 5^{2/3}$, or

$$\nu \geq 4.4 \text{ cps}. \tag{38}$$

The mirror itself will be very stiff because of its small size. What matters, then, is the bending stiffness of the long feed legs where the mirror is mounted. Scaled down from Report 22, for D = 213 ft, we have for the feed legs:

Unguyed length	610 inch	
Prime focus - secondary mirror ...	160 inch	
Chord area (3 chords)	5.88 $inch^2$	
Weight length	3.28 lb/inch	(39)
Radial width	46 inch	
Radial moment of inertia	2770 $inch^4$	
Tangential width	21 inch	
Tangential moment of inertia	433 $inch^4$	

From these values, using formula (5) of Report 20, the dynamical frequencies from dead load only (neglecting the mirror weight) are

$$\text{Radial} \qquad \nu_{rd} = 13.0 \text{ cps}, \tag{40}$$
$$\text{Tangential} \qquad \nu_{td} = 5.13 \text{ cps}.$$

The dynamical frequencies from the mirror weight W only (neglecting the dead load) are found from formula (6) of Report 20 as

$$\text{Radial} \qquad \nu_{rw} = 11.8 \text{ cps } (W/\text{kip})^{-1/2}, \tag{42}$$
$$\text{Tangential} \qquad \nu_{tw} = 9.3 \text{ cps } (W/\text{kip})^{-1/2}. \tag{43}$$

Radial oscillation of the feed leg means a parallel translation of the mirror, where in (42) the full weight W is applied to a single feed leg (worst case, with three-point mount). Tangential oscillation of the leg means a rotation of the mirror about the telescope axis, where for (43) only W/3 is applied to one leg.

Both radial oscillations give rather high frequencies which we neglect. The combined rotational frequency, ν_t, is found from

$$\nu_t^{-2} = \nu_{td}^{-2} + \nu_{tw}^{-2} \tag{44}$$

as

$$\nu_t = \frac{5.13 \text{ cps}}{\sqrt{1 + 0.303 \text{ W/kip}}} . \tag{45}$$

Demand (38) then leads to

$$W \leq 1190 \text{ lb.} \tag{46}$$

For deriving a limit of the diameter d of the secondary mirror, we use $W = 4100$ lb and $d = 22$ ft from the Goldstone antenna, and we assume that $W \sim d^{2.5}$, which gives

$$W = 571 \text{ lb } (d/10 \text{ ft})^{2.5}, \tag{47}$$

and (46) finally results in

$$d \leq 13.4 \text{ ft.} \tag{48}$$

V. Size of Secondary Mirror

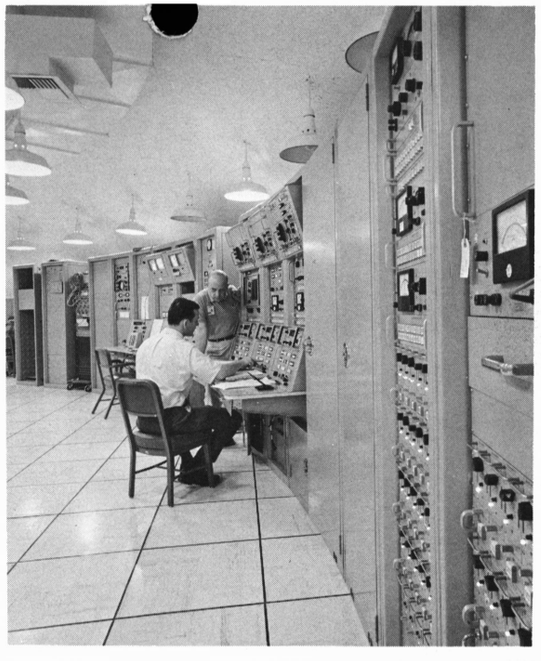
In the previous sections we have derived a total of 6 limits for M, m, or d. With (10) and (16), we convert the former limits into limits for d; this results in two lower limits and four upper ones. They are listed in Table 4.

Table 4. Limits for diameter d of secondary mirror.

No.	Problem	Adopt	Demand	Equation	Limit
1	multiple feed, cluster size	$c = 9$ ft $\lambda = 3.5$ mm	$n \geq 1000$	(29a)	$d \geq 7.3$ ft
2	limited cabin length	$\ell = 12$ ft	$\lambda_m \geq 3$ cm	(25a)	$d \geq 10.8$ ft
3	full use of cabin width	$c = 9$ ft $\lambda = 3.5$ mm	$\gamma \geq 15$ dB coma	(37)	$d \leq 12.3$ ft
4	improved pointing accuracy	$W \sim d^{2.5}$	$\nu \geq 4.4$ cps dyn. freq.	(48)	$d \leq 13.4$ ft
5	blocking by secondary mirror	$B = 4/m^2$	$B \leq 2\%$ gain loss	(18)	$d \leq 15.1$ ft
6	homologous dF, fixed feed	$dF = 1$ inch $\lambda = 3.5$ mm	$L \leq 2\%$ gain loss	(6)	$d \leq 22.4$ ft

Table 5. Secondary mirrors of various size.

d	m	M	λ_m	Side + Coma Lobe			Number n_m of feeds, in 9 x 9 ft cluster		W	ν_t
				axis	6.37 ft off-axis, γ_c					
				γ_0	$\lambda =$ 6 mm	$\lambda =$ 3.5 mm	$\lambda =$ 6 mm	$\lambda =$ 3.5 mm		
ft			cm	dB	dB	dB			lb	cps
8	26.6	24.1	1.6	23.4	23.1	21.4	424	1192	327	4.89
10	21.3	19.1	2.6	23.1	21.9	18.6	661	1875	571	4.74
12	17.7	15.7	3.8	22.8	19.8	15.3	965	2753	901	4.55
14	15.2	13.4	5.2	22.5	17.3	12.6	1312	3758	1324	4.33
16	13.3	11.6	7.0	22.2	14.8	10.1	1738	4992	1849	4.11
18	11.8	10.1	9.2	21.9	12.4	7.7	2278	6561	2482	3.87



Located inside the pedestal building is the electronic equipment required to operate the antenna and to transmit and receive radio signals to and from the spacecraft. Signals received through the Cassegrainian cone are further processed for recording purposes and for transmission to the JPL command center located at Pasadena, California.

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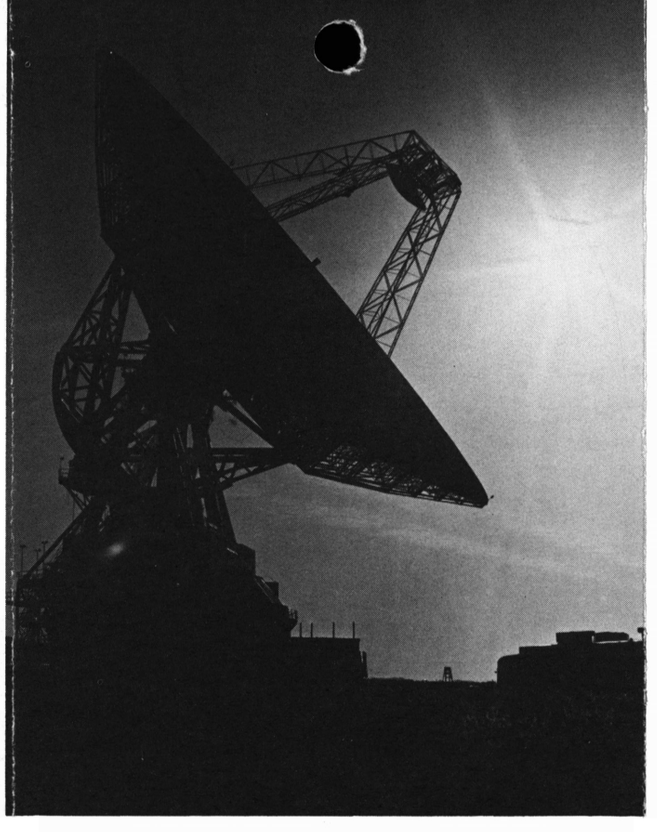


Welcome to the Mars Deep Space Station

VISITORS GUIDE

The Mars Deep Space Station, located at the Goldstone Deep Space Communication Complex near Barstow, California, is the site of the world's largest and most sensitive automatic tracking antenna. The antenna is the newest addition to the Deep Space Network (DSN), which is operated by the Jet Propulsion Laboratory for the National Aeronautics and Space Administration. The DSN is responsible for tracking unmanned lunar and planetary spacecraft missions and maintains and operates a network of tracking stations located at Goldstone, California; Cape Kennedy, Florida; Ascension Island; Woomera and Canberra, Australia; Johannesburg, South Africa; and Madrid, Spain.

JPL was responsible for establishing the performance and operational requirements of the antenna and directed the prime contractor, the Rohr Corporation of San Diego, California, and dozens of subcontractors and firms across the nation in the construction of the giant antenna. Construction at Goldstone was started in October 1963, and dedication ceremonies commemorating the antenna's completion were held at the station on April 29, 1966. Since then, all performance and operational objectives have been successfully achieved in tests and in actual tracking operations.

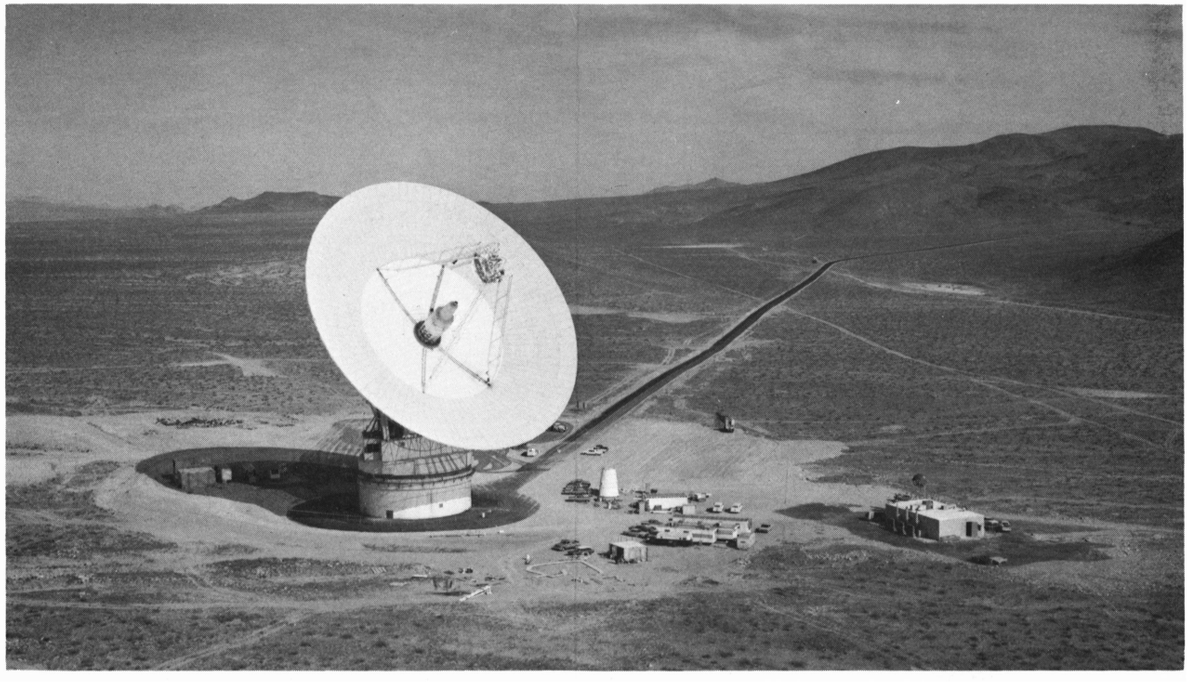
The Mars Station represents a major step forward in antenna design, reflector size, and instrumentation for deep space missions. The aluminum reflector, or "dish," is 210 feet in diameter, and the overall height of the structure, from the pedestal base to the apex, measures 234 feet, or the equivalent of a 21-story building. The entire structure, including the massive pedestal, weighs 8,000 tons. Despite its great size and weight, the "210" can be maneuvered as easily and precisely as the smaller 85-foot antennas used by the DSN.

The dish is carefully contoured to an accuracy of less than ¼ inch. It is designed to operate in winds up to 50 miles per hour and to withstand winds up to 120 miles per hour in a stowed position.

The reflector and its supporting structure, weighing nearly 5 million pounds, rotate on a pressurized oil film about the thickness of a sheet of paper, by the use of three main hydrostatic thrust bearings. This great mass can be turned automatically or manually at desired tracking rates by drive motors with a combined capacity of 400 horsepower.

The pedestal supporting the antenna is 34 feet high and weighs more than 10 million pounds. The

The Mars Station 210-foot antenna is the largest operated by the Jet Propulsion Laboratory's Deep Space Network for NASA. It is one of six tracking stations located at Goldstone, including the Pioneer, Echo, and Venus Stations of the DSN; the Manned Space Flight Network Apollo tracking station; and the Space Tracking and Data Acquisition Network station.



Workmen are dwarfed by the Cassegrainian feed cone and surrounding aluminum dish surface of the "210" antenna. The signals received from a spacecraft are reflected from the main dish to a subreflector (out of view) mounted on a truss-type support (partially visible). The subreflector focuses the signal into the feed horn of the Cassegrainian cone, where it is amplified through a maser system.

walls are 42-inch thick reinforced concrete, and the footings extend 11 feet underground. Within the pedestal are rooms for machinery and tracking equipment, electronic and data-handling facilities, offices, and maintenance shops. (A permanent display describing the function and role of the station is located on the second floor of the pedestal.)

Through the pedestal's center—but completely isolated from it—rises a 106-foot tower which provides a stable, vibration-free platform for the sensitive angle-data master equatorial system. This unique system serves as the reference for antenna beam position and provides antenna pointing information in polar coordinates.

The Mars Station is capable of operation 24 hours a day, 365 days a year. Its transmitting and receiving capability provides six and a half times more power and sensitivity for the DSN than is available with 85-foot-diameter antennas, increasing the range of the present DSIF system on the order of two and a half times. This capability is a basic requirement for the extension of the space exploration effort. It allows spacecraft designers to increase the information-gathering capability of spacecraft for future missions. Because of the antenna's capability, scientific experiments aboard the spacecraft can be designed to yield a greater amount of and more precise data.

It is anticipated that facilities with the capabilities the size of the Mars Station eventually will be constructed at other Deep Space Network stations around the Earth.

Antenna Dimensions

Diameter	210 feet
Focal length	88.941 feet
Focal length/diameter ratio	0.4235
Surface area	37,491 square feet (0.85 acre)
Depth of paraboloid	31 feet
Pedestal wall thickness	3.5 feet
Outside diameter of pedestal	83 feet
Overall height of instrument tower*	139 feet
Total concrete	2500 cubic yards

*Height of concrete section, 68 feet, including 33 feet below grade.

Antenna Weights, lb

Overall	16,000,000
On elevation bearings	2,530,000
On azimuth bearings (including bearings)	5,000,000
On soil	16,000,000
Total rotating	5,000,000
Total tipping	2,500,000
Component	
Hyperboloid	4,100
Feed cone and equipment	62,000
Quadripod	39,000
Primary reflector surface	58,000
Reflector assembly (including reflector, wheels, and elevation counterweight)	2,370,000
Alidade and buildings	2,200,000
Azimuth bearings	400,000
Pedestal and foundation	10,000,000
Instrument tower (including wind shield)	
Steel	96,000
Concrete	1,151,000

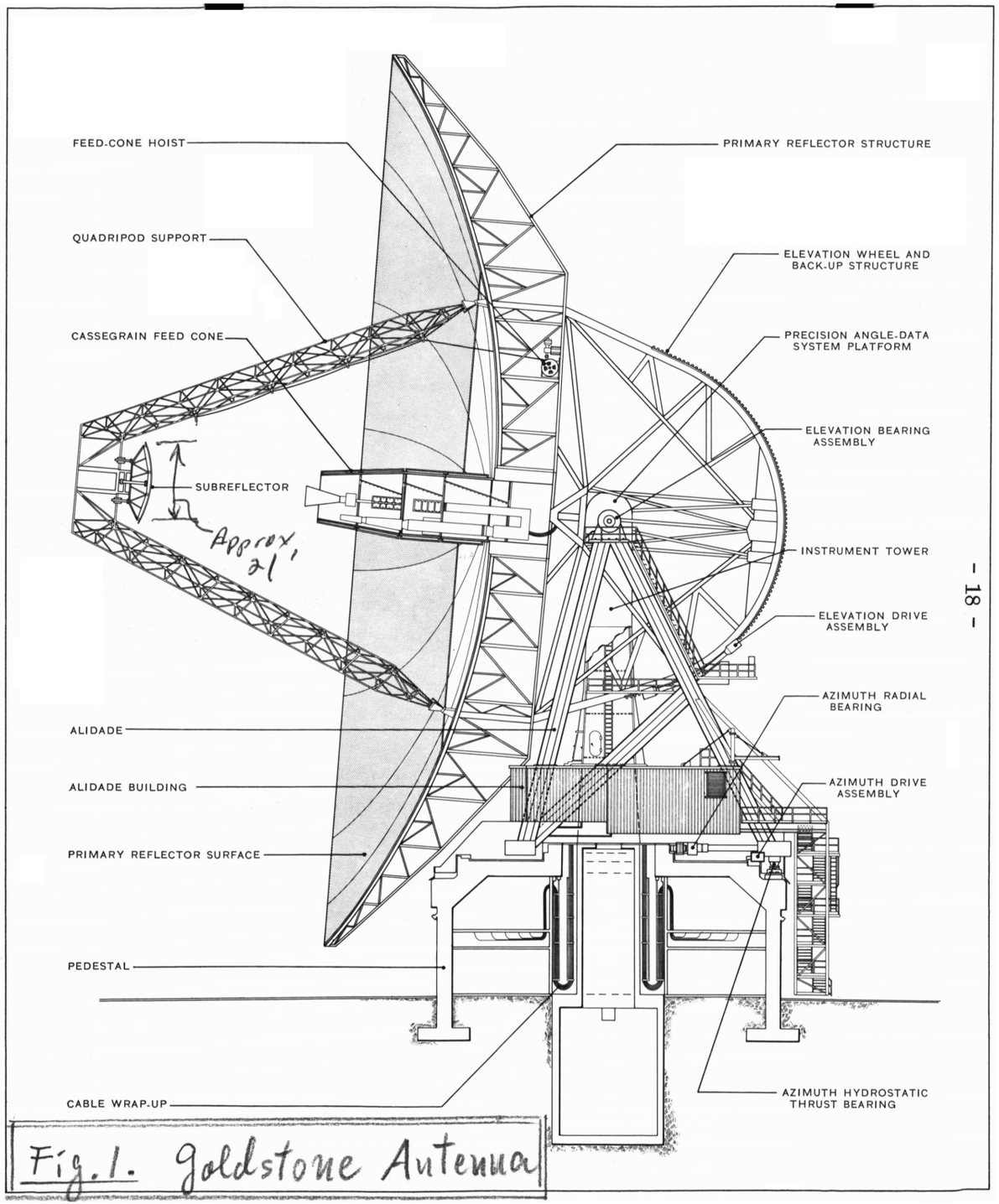


Fig. 1. Goldstone Antenna

Table 4 results in 10.8 ft $\leq$ d $\leq$ 12.3 ft. We suggest to regard

$$d = 12 \text{ ft} \tag{49}$$

as the best choice, yielding for the longest wavelength at the Cassegrain focus

$$\lambda_m = 3.8 \text{ cm}. \tag{50}$$

For other choices, Table 5 gives several quantities for comparison. The first side lobe level γ_0 (feed on axis) is taken from Baars (1964), and γ_c is a combination of γ_0 and the coma lobe γ from (34) and (35), at the corner of the feed cluster of c = 9 ft. The lowest rotational mode of the secondary mirror, ν_t, is found from (45).

The upper limit of d is not so much given by ν_t, which varies only very slowly; nor is it given in a strict way by the side lobe level γ, since the number of feeds actually used will probably be much less than n_m, which decreases the cluster size and thus the coma lobe. At it seems, the upper limit of d is mostly given by the demand for having the secondary mirror just as small and as light-weight as possible, for easier handling and servo-control. With respect to all quantities, d = 12 ft seems to be a good choice. But this question is still open for discussion and will be decided later.

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A. P. King, 1950: Proc. IRE, p. 249.

J. F. Nihen and A. F. Kay, 1963: RADC-TDR-63-318.

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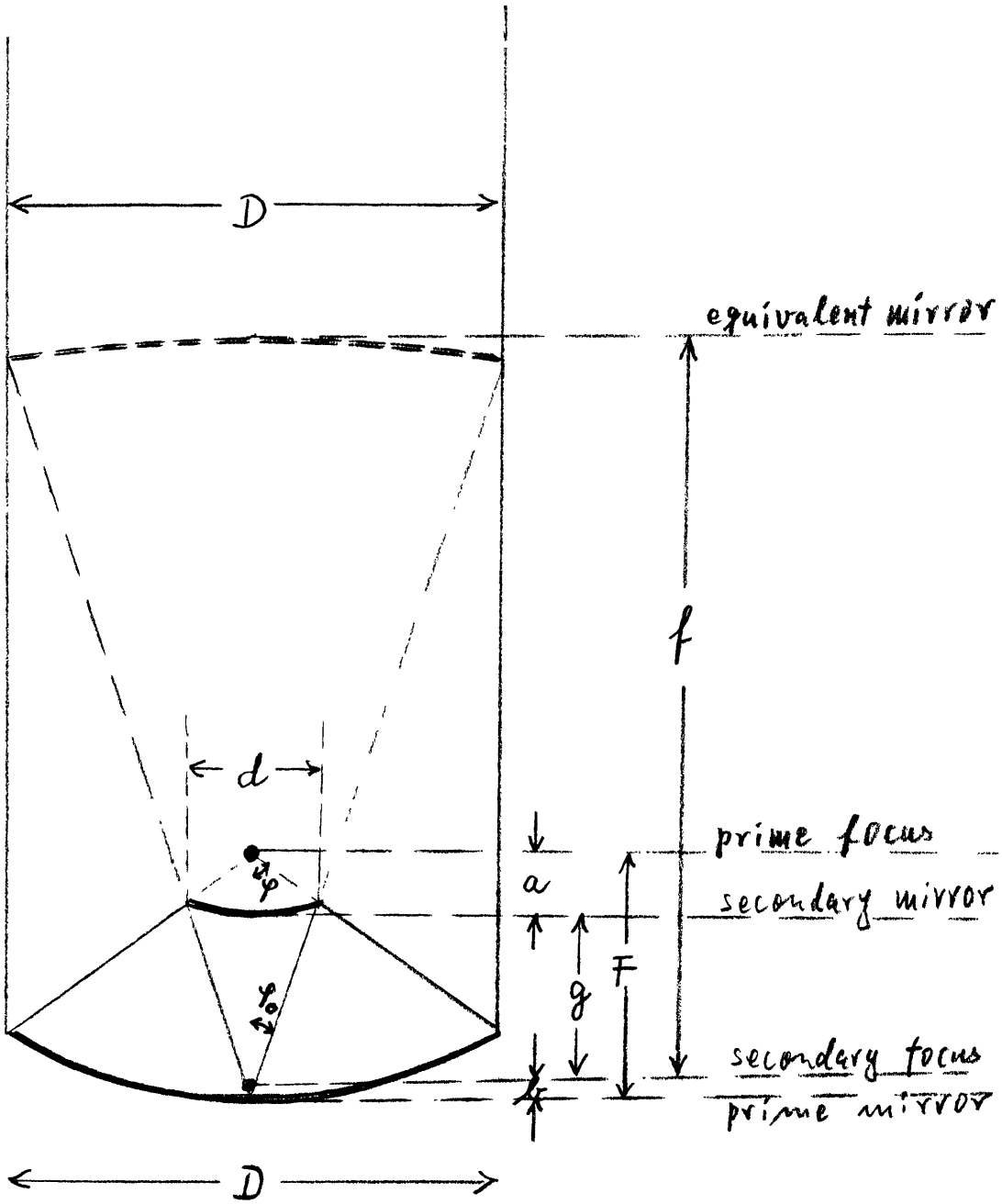


Fig. 2. Cassegrain system, definitions and geometry.

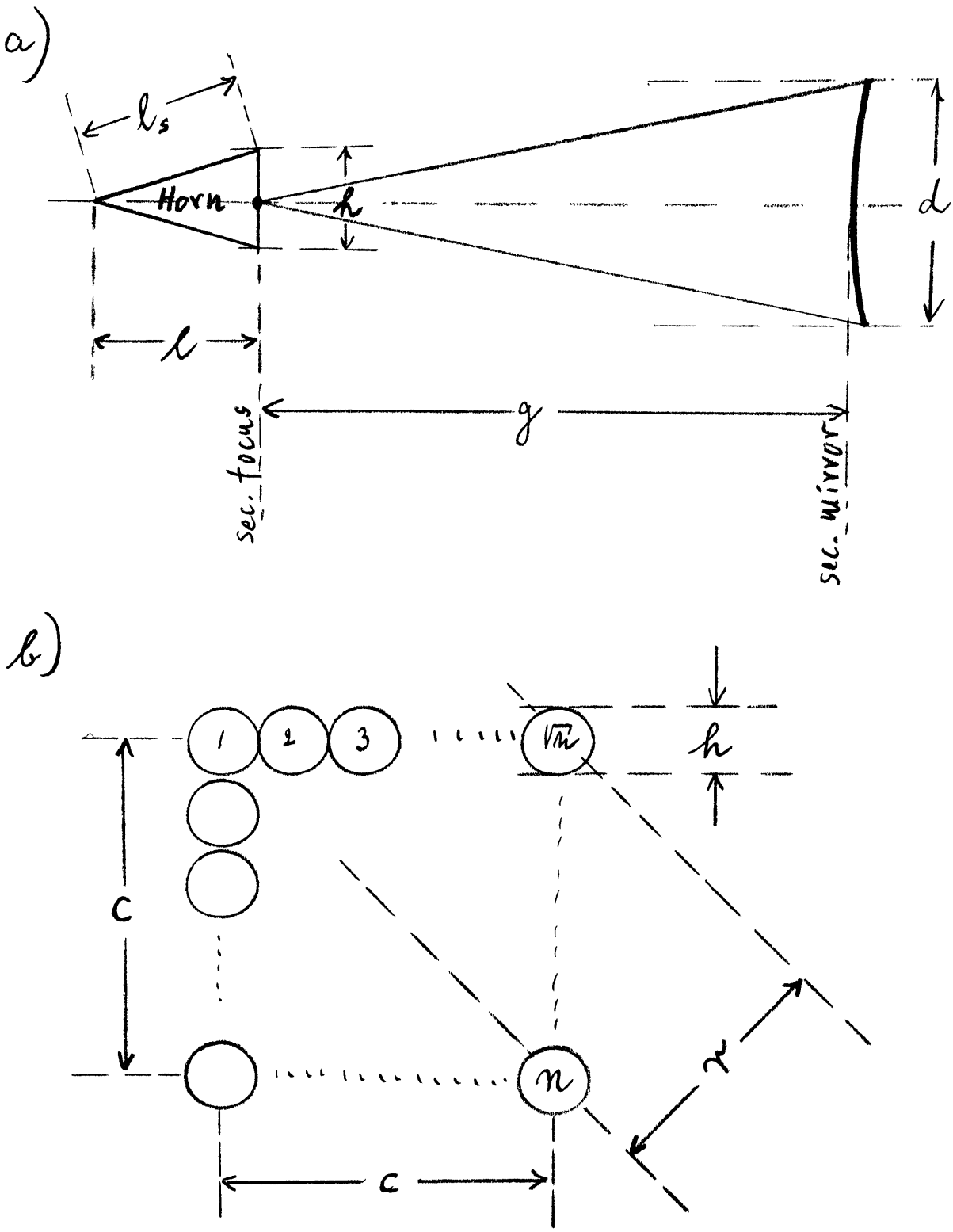


Fig. 3. Geometry and definitions for:
a) single feed horn, side view;
b) multiple feed cluster, top view.

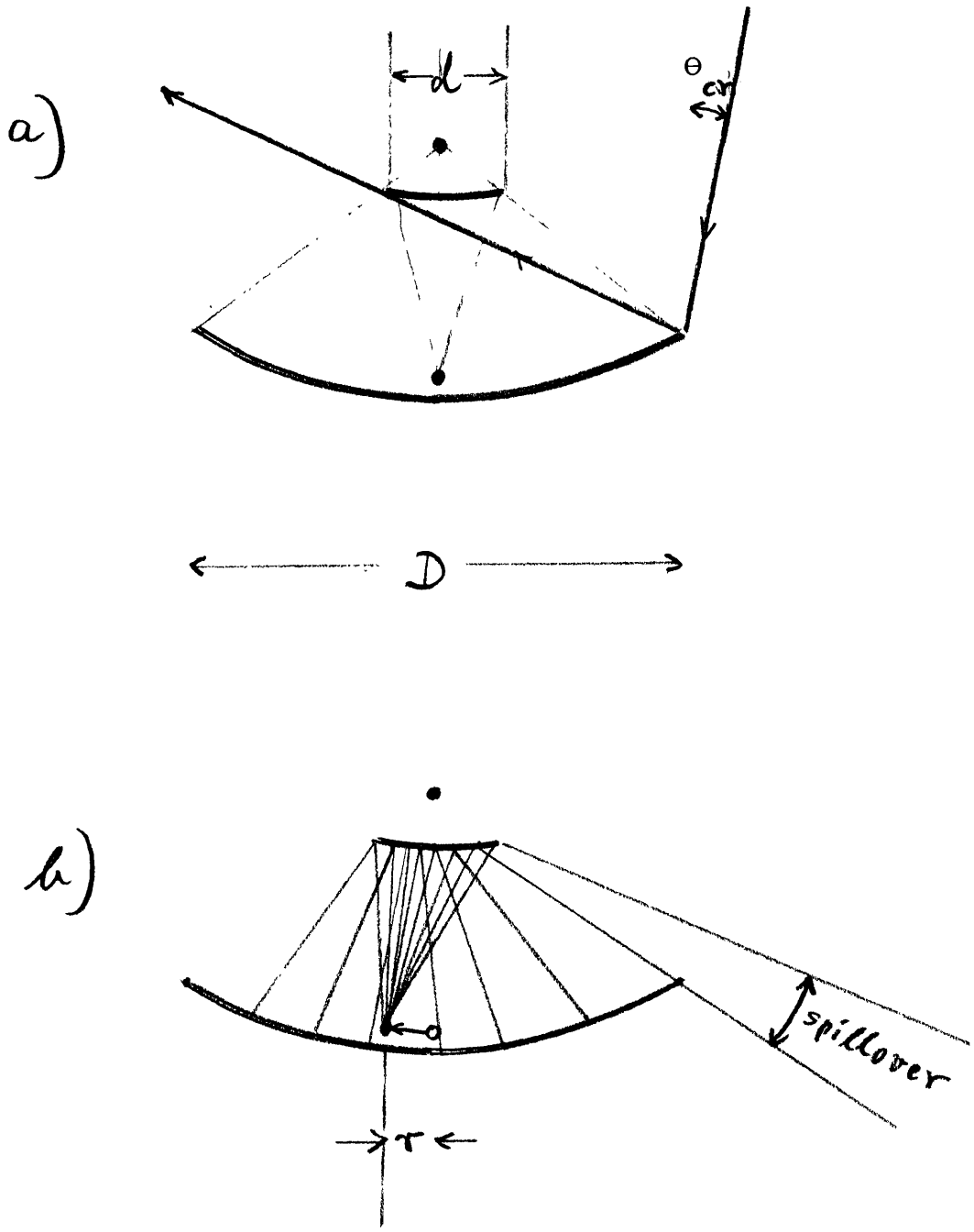


Fig. 4. Limit for scan angle Θ, from spillover.

a) Definition of the critical scan angle Θ_{cr}: all incoming rays, after reflection at primary, miss secondary mirror.

b) One-sided spillover for $\Theta \ll \Theta_{cr}$. (The spillover is 100 % for $\Theta = \Theta_{cr}$.)

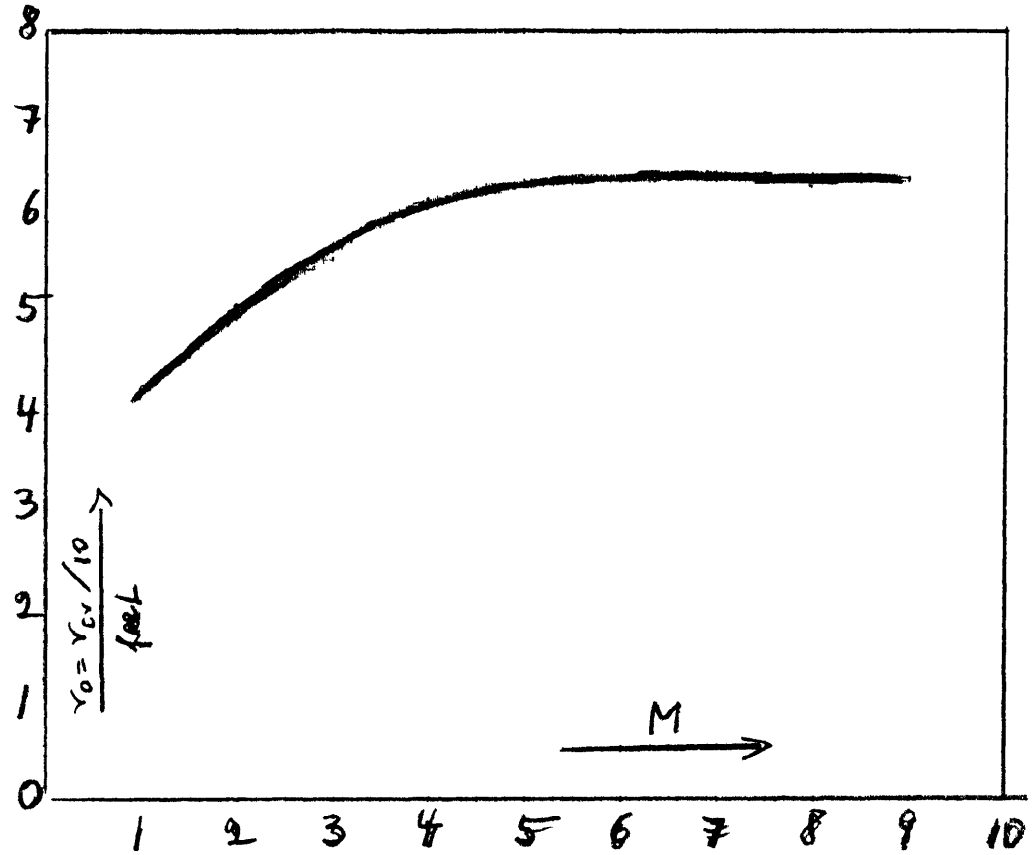


Fig. 5. Limiting feed displacement, $r_o = 0.10\ r_{cr}$, as a function of the magnification M; for F/D = 0.427.

NRAO Memorandum
Oct. 25, 1969

Spring-Support for the 140-ft Panels

S. von Hoerner

1. Principle

When tilted from zenith to horizon, the 140-ft structure deforms by about 10 mm, which increases the rms surface deviation from 1.2 mm to 4.5 mm. A new surface adjustment could decrease the zenith deviation from 1.2 mm to 0.7 mm, and it is at present discussed whether the gravitational sag under tilt should be removed by computer-controlled jacks at the adjustment studs of the surface panels. Fred Crews asked me whether there might be some easy way of making the deformations nearly homologous, by some automatical means. This seems indeed possible.

Most of the gravitational deviations arise from the difference between hard and soft surface points, and a good approximation to homology is an equal-softness structure, where each point sags by the same amount. Since one cannot make the soft points hard, one must make the hard points soft, which can be done by springs under the panels, using the panel weight as the active force.

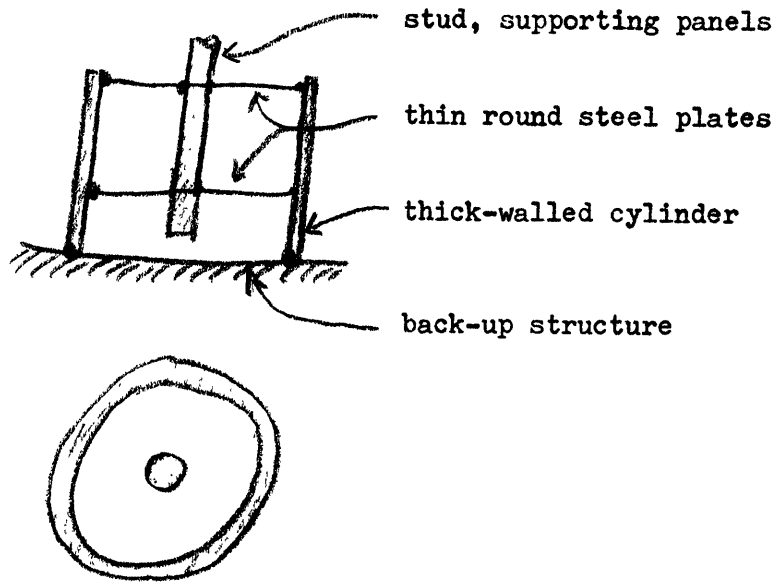
There are several problems. First, the telescope gets softer for wind deformations, and it must be checked whether this can be tolerated. Second, the springs must give enough movement from the panel weight, but should not be over-stressed from survival loads. Third, demanding exact homology for each support point for zenith and horizon imposes two conditions per point, while a spring yields only one degree of freedom (its stiffness); thus, exact homology cannot be achieved in the general case. It can be achieved, if the deformation component perpendicular to the surface, of each support point, is in proportion to cos ϑ, where ϑ is the angle between the vertical and the surface normal at this point (because that is exactly what a spring-supported panel will do). This condition will not be fulfilled exactly, but it should hold in a good approximation, since the back-up structure, too, is something like a spring. Thus, the spring-supported panels should give a good improvement. It can be calculated from the available deformation data.

2. Method Suggested

The support should be flexible perpendicular to the surface, but very stiff against tangential movements and all rotations. It might be done with the stud moving up and down in some gliding bearings, but this would certainly give serious problems in horizon position, from friction and stiction. One should look for some frictionless mount, like a leaf-spring:

This arrangement has the following advantages:

1. flexible up and down;
2. very stiff otherwise;
3. no friction or stiction.



3. Wind Deformation

We use 20 mph of wind, giving 1.03 lb/ft^2 pressure. This is to be compared with the panel weight of about 10 lb/ft^2 which must yield 4.5 mm rms movement on the springs, when the telescope is tilted. Thus the rms wind deformation is 1/10 of 4.5 mm. or 0.45 mm. This increases the (new adjusted) surface deviation from 0.70 to 0.83 mm, which can be tolerated.

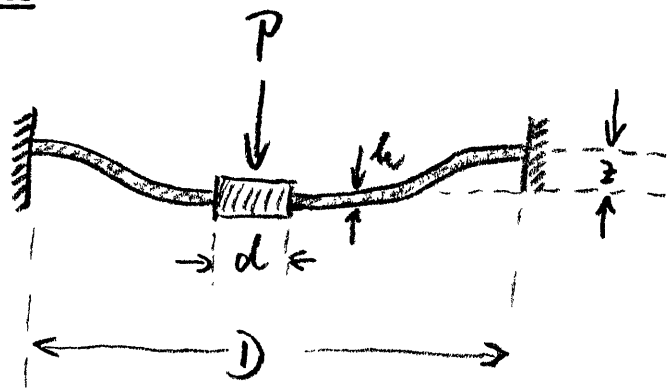
The same calculation would apply to any other telescope. Call w = weight/area of the panels, p = wind pressure, s = gravitational sag of the telescope to be corrected by the springs, and δ = desired rms surface accuracy. The demand then is

$$s\, p/w \ll \delta. \qquad (1)$$

This is fulfilled for the 140-ft. But not for the 300-ft (w too small), not for our new 65-m design (δ too small). In general, spring-supported panels will work for any telescope with large, heavy panels and for a moderate accuracy, yielding improvement factors of up to 10 but not much higher.

4. Plate Thickness from Survival Stress

We use the formulas for a circular flange, where the outer edge is fixed and supported, and the inner edge is fixed; with a uniform load along the inner edge.



The maximum stress at the extreme fiber, occurring at the inner edge, then is

$$S = \frac{3\,P}{2\,\pi\,h^2}\,K_1 \qquad (2)$$

with

$$K_1 = 1 - \frac{2\ln\alpha}{\alpha^2 - 1} \qquad \text{and} \qquad \alpha = D/d\,. \qquad (3)$$

α	K_1	K_2
10	.956	.778
15	.976	.861
20	.985	.907

Some values of the correction term K_1 are given in the table. We see α does not make much difference as long as $\alpha >> 1$. For the following estimates we adopt

$$\alpha = 15\,. \qquad (4)$$

The stress then is

$$S = .466\,P\,/\,h^2. \qquad (5)$$

For the survival load we use 20 lb/ft^2, and for a panel size of $12 \times 20 = 240$ ft^2, the load is 4800 lb. We add the panel weight of 2500 lb, and we divide by 2 since the load goes on two plates, yielding a survival load P_s on each plate of

$$P_s = 3650 \text{ lb.} \qquad (6)$$

The thickness h then is given by

$$h \geq .683\sqrt{P_s\,/\,S_m} \qquad (7)$$

where S_m is the maximum allowed stress of the steel used. Since it turns out that the diameter D would get unconveniently large for normal steel, we choose high-stress

steel with, say, $S_m = 75\ 000$ lb/inch^2. The minimum plate thickness, for the softest springs, then is

$$h = 0.150 \text{ inch} . \tag{8}$$

5. Cylinder Diameter from Deformation

The central deformation of the circular flange is

$$z = \frac{3}{16\pi}(1 - \nu^2)\frac{P D^2}{E h^3} K_2 \tag{9}$$

with

$$K_2 = 1 - \alpha^{-2} - \frac{4 (\ln \alpha)^2}{\alpha^2 - 1}, \qquad \alpha = D/d, \tag{10}$$

and with $\nu = .25$ = Poisson's ratio. Using again $\alpha = 15$, and $E = 3 \times 10^7$ lb/inch^2, we get

$$z = 0.0500 \frac{P D^2}{E h^3} . \tag{11}$$

In order to have a deformation z, the cylinder diameter then must be

$$D = 4.47 \sqrt{E z h^3/P} . \tag{12}$$

The load P on each plate is $P = 1250$ lb = 1/2 the panel weight, and the softest spring must move by $z = 10$ mm = .394 inch. With h from (8) we obtain

$$D = 25.3 \text{ inch} = 2.11 \text{ ft} . \tag{13}$$

In general, if the loads are given, $D \sim z^{1/2} S_m^{-3/4}$. The diameter would decrease if still better steel would be used for the plates, which is possible. Also, we have used for z the maximum deformation, which would be decreased by using the maximum deviation from a proper best-fit paraboloid. But even a diameter of two feet is not excessively large, and this method thus looks possible.

6. Various Stiffness

For the softest spring, h is given by (8) and D by (13). Any higher stiffness can be achieved by either increasing h, or decreasing D, or both; whatever is more convenient for the manufacturing.

If there is an actual interest in this method, I would volunteer to derive the formulas, for obtaining the needed spring stiffness at each panel support from the measured or calculated deformation data.