PROGRESS REPORT ON THE DESIGN OF THE LARGEST FEASIBLE STEERABLE TELESCOPE (LFST)

by

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LFST/8

January 1966

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I. INTRODUCTION AND GENERAL SURVEY

J. W. Findlay and M. M. Small

1. The LFST Study

The present study came about as described in earlier papers in the series with references LFSP/1 through 6. A minor change has taken place in the title of the study. Since other than parabolic dishes have proved of interest, the group believes it is now desirable to consider the largest feasible steerable telescope, and has so changed its cognomen.

Work has proceeded since March 1965 very much along the lines set out in the original plan. Attention has been directed to novel or "unconventional" designs by Faelten, Heine, and others, while work of Von Hoerner and Jennings is not specific to any particular design. The way of working has also followed the original plan. Work programs have been accepted by various group members. The results of these programs have been reviewed and the programs extended or modified at regular meetings.

So far there have been six meetings over the time interval between April 1 and December 6, 1965. Engineers from interested industrial firms, Lear Siegler (Defense Systems Operations), North American Aviation (Columbus Division) and ITT Federal Laboratories (Nutley) have attended group meetings to present their several ideas. Most meetings have been at Green Bank or Charlottesville, but the group spent two days studying the 1000-foot dish at the Arecibo Ionospheric Observatory and in meetings in San Juan. Future meetings are planned for the West Coast and for the Boston area to which local engineers and scientists with interest in the study will be invited.

Although the membership of the group is not restricted, the following have formed the nucleus:

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2. Summary of Progress

Work has tended to concentrate in three areas.

Chapter II of the report describes an attempt to find and apply first principles of design to large structures, as well as an attempt to minimize the basic limitations imposed on any structure such as a telescope by its weight, by wind effects and by temperature differences. This work is devoted to two end-points. First, to establish basic design principles; second, to develop from first principles the size and weight of an ideal structure. This chapter thus sets limits to the size of any proposed structure and then provides a yardstick against which practical designs can be tested. The concept of homologous deformation has been implicit in telescope design for some time, but as Chapter II shows it may be possible to design structures with such properties after a semi-analytic process. If so, the homology approach can be of particular importance in future large telescope design and of great significance to structural design in general.

Chapters III and IV describe the progress made in design approaches to specific types of telescopes which were outlined in earlier study group papers. In neither case can we yet be sure that these new approaches represent a major improvement on previous, more conventional designs. Their cost is high. However, it is not possible to reject them as unacceptable candidates for the LFST.

It will be noted that specific designs have been made usually at a 200 meter diameter. This is large enough to uncover engineering difficulties and allow order of magnitude cost estimates, but the use of specific diameter figures has been for these purposes and must not be taken to mean that a specific size of dish has been decided upon. In order fully to investigate the efficacy of concrete, a sphere diameter of 1080 feet is being studied by Lear Siegler.

Chapter V, by R. L. Jennings, describes the theoretical and analytical support given to other efforts by his group working at the University of Virginia. As is pointed out, our conclusions have been greatly aided by the availability of this group and the University computer to attack problems of specific importance to the study. In addition, both positive and negative conclusions have been and will continue to be of great interest to structural engineers in fields other than radio astronomy. A paper on homology will be presented to the ASCE, in Miami, February 3, and others on shell theory as well as homology will be presented to the appropriate societies as the work allows. Thus, the original plan is being followed to give wide publication of all useful, direct contributions to radio astronomy as well as all useful results of interest to other fields.

The 1000-foot reflector telescope at Arecibo is not described in this progress report. This type of instrument, despite its small sky-cover, may still be a strong competitor (if it could be built twice more) with other designs.

No very careful work has yet been done by the group on Luneberg lens telescopes because the basic questions of cost, dielectric scattering and dielectric loss for very large lenses as yet appear to remain unanswerable.

II. LARGE STEERABLE RADIO TELESCOPES

S. von Hoerner

The following summarizes four previous papers:

1. The Design of Large Steerable Antennas, June 20, 1965
2. Approach to a Structure with Homologous Deformation, August 20, 1965
3. Telescope Model for Homologous Deformation, November 5, 1965
4. Calculating Method for Homologous Solutions, November 17, 1965

These papers were written as contributions to the LFST Group; but most of the results are of a general nature, applicable to antennas in general.

1. Basic Design Principles

There are growing needs for building very large antennas for 10 to 20 cm wavelength reception and for observing at very short wavelengths with antennas of moderate size. Since both demands soon run into structural as well as financial limitations, a general survey was undertaken to find the basic principles involved in antenna design and the most economical designs based on them. We will deal only with the design of tiltable, round reflectors of conventional type.

a) Three Natural Limits

Elementary considerations show that the largest diameter of a conventional antenna must be limited in three ways. First, a maximum height is reached when the weight of the structure gives a pressure at its bottom which approaches the maximum allowed stress in the material used; this height is proportional to S/ρ, where ρ is the density and S is the maximum stress; we call this the stress limit.

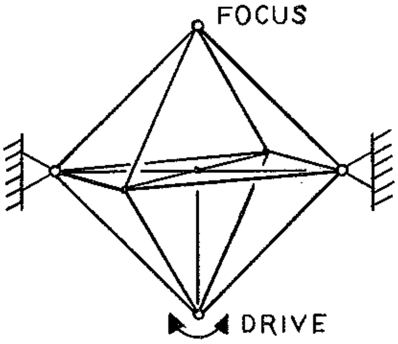
A second limit applies to any structure which, while being tilted, must maintain a given accuracy (1/16 of the wavelength), since the height h of a structure is compressed by its weight in an amount proportional to $h^2\rho/E$, where E is the modulus of elasticity; we call this the gravitational limit.

A third limit holds for any structure which must maintain a given accuracy while part of it is exposed to sunshine, since a temperature difference ΔT changes the length ℓ of a member by an amount proportional to $\ell\Delta T$.

These three limits are "natural limits," as opposed to technical or financial limits. The second and third limits depend on the shortest wavelength to be used, while the first one does not. Numerical values for these limits depend on the material used and on the shape of the structure. For reasonable construction materials, the maximum height turns out to be much larger than actually is needed. The gravitational deformations are the same for normal steel, high stress steel and aluminum, but are three times larger for concrete. The thermal expansion is twice as large for aluminum as for steel. Thus we arrive at <u>normal steel</u> as the best construction material.

As to the shape of the structure, an almost regular <u>octahedron</u> as its basic part will give the smallest gravitational deformations;

the feed supports become part of the main structure which then becomes as "round" as possible. The lower part of the octahedron will be filled with a framework supporting the surface. The surface diameter need be only about 1.25 the octahedron "diameter" to avoid long cantilevered parts.



Octahedron as the Basic Structure

An octahedron with diagonals of 100 m will support a surface which will deform under its own weight by 1.7 cm at most. The rms deformation of the surface will be about 0.5 cm. These values hold as long as any additional weight (bracings, surface, etc.) is neglected as compared to the weight of the main chords of the octahedron. Otherwise the deformations are multiplied by a factor K, with

$$K = \frac{\text{total weight}}{\text{weight of main chords}} .$$

The limit, K = 1, can be approached with infinite weight only. For an economical design we find K ≅ 1.5 for 100 m surface diameter, K

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REPORT NO.
CONTRACT NO.
PAGE OF
DATE Febr. 28, 1966

PROJECT: LFST

SUBJECT:

ERRATA

for

Progress Report on the Design of the
Largest Feasible Steerable Telescope (LFST)

Please make the following corrections on page 8:

	reads	should read
2. Gravitational Limit, ...	$\frac{m}{100\ m} = \frac{\lambda}{8\ cm}$	$\frac{D}{100\ m} = \left\{\frac{\lambda}{8\ cm}\right\}^{1/2}$
3. Thermal Limit, ...	$\frac{D}{100\ m} = \left\{\frac{\lambda}{2.4\ cm}\right\}^{2/3}$	$\frac{D}{100\ m} = \frac{\lambda}{2.4\ cm}$

S. von Hoerner

increasing slightly with the diameter. For the type of tiltable antenna as described, with antenna diameter D and shortest wavelength λ (16 times the rms deformation), we obtain for steel (and with $K = 1.5$) the values:

1. Stress Limit, defined by maximum allowed stress of material: $D \leq 600\ \text{m}$
2. Gravitational Limit, defined by deformations under own weight: $\frac{\text{m}}{100\ \text{m}} \leq \frac{\lambda}{8\ \text{cm}}$
3. Thermal Limit, defined by assuming temperature differences of 5°C within the structure: $\frac{D}{100\ \text{m}} \leq \left\{\frac{\lambda}{2.4\ \text{cm}}\right\}^{2/3}$

For our present needs the first limit plays no role. Antennas larger than 40 m are gravitationally limited; smaller ones are thermally limited. But the thermal limit is flexible and drops out at night, during cloudy days, and within a dome. The gravitational limit is fixed and thus is more important; details of the structure do not matter much (unless they make it worse), and even a floating sphere deforms by the same amount as a hanging octahedron. Figure 1 shows the three limits. The 36-foot NRAO telescope exceeds the thermal limit, but is protected by a dome. Some of the existing or designed telescopes come very close to the gravitational limit, but no tiltable antenna exceeds it.

b) The Weight of an Antenna

For investigations of economy and financial limits, formulae have been derived for the weight of an antenna as a function of diameter

D and shortest wavelength λ. The derivations assume a "near-to-ideal" design of the type described, and the results should be valid within ± 30%. It is shown that the weight can be defined by four items:

1. Minimum Structure: for any structure, no matter what its purpose, there is a minimum weight for stable self-support, which is proportional to D^2.
2. Survival Conditions (highest winds, snow, ice) define the weight for certain D,λ combinations; the weight then is proportional to D^3/λ, plus the minimum weight.
3. Wind Deformations during observations must be kept below λ/16. The weight then goes with D^4/λ for a solid surface and with D^4/λ^2 for wire mesh.
4. Gravitational Deformations are decreased by using heavier main chords. The gravitational limit, $\lambda_g = 5.2$ cm $(D/100\ \text{m})^2$, is approached with weight $D^2\lambda/(\lambda-\lambda_g)$.

Figure 2 shows which items dominate in which fields of the D,λ plane. Figure 3 gives the weight as a function of D and λ. The comparison with some actual telescopes shows that our estimates, although derived on general grounds only, are reasonable.

Antennas	D	λ	Weight from Fig. 3	Actual Weight
300-ft Green Bank	92 m	15 cm	300 tons	450 tons
120-ft Haystack	37	1	80	50
Bonn Design	80	7	305	350
210-ft Parkes	64	6	200	270

c) Economy

The question of getting a good telescope for the lowest possible price has been investigated from several aspects. The main conclusions are as follows:

1. There is a most economical wavelength for an antenna of given diameter, any other wavelength leading to a waste of either strength or rigidity.
2. No radomes should be used for antennas above 50 m diameter, and below 50 m the advantages of radomes are doubtful, at least for radio astronomy.
3. All longer members must be split (like towers) into 3 or 4 chords connected by bracings; very long members need multiple splitting. Extensive use of splitting reduces the total weight considerably, but the weight of bracings increases the gravitational deformations and a very careful compromise is needed.
4. The best basic structure seems to be an octahedron which includes the feed supports and yields a "round" shape.

5. The antenna surface should be only 1.25 the octahedron diameter. It should consist of wire mesh for $\lambda \geq 5$ cm (elastic mesh, to prevent permanent deformations).

6. Most economical seems an alt-azimuth mount with two corners of the octahedron supported by bearings at the top of two towers. The towers have three legs each, wide astride, two legs standing on wheels on a circular track, the third leg of each tower on a strong pintle bearing at the center of the circle, which takes all lateral forces. Uplifting forces are opposed by counterweights, leaving only downward forces on the tracks. Larger telescopes need special anchorings in a stow position.

7. As to foundations and tracks, it has been shown that standard railroad equipment, with normal roadbed, ties and rails, is fully sufficient for $\lambda \geq 8$ cm. The tower legs go on normal steel gondolas, filled with rock and gravel for counterweight. In this way, a lot of money can be saved in the foundations.

8. A cost estimate has been made for a special case. An economical antenna of 150 m diameter (500 feet) and $\lambda = 20$ cm should cost about 4 million dollars, including foundations and drives, provided that the design really uses optimization for every detail and that economy is the leading criterion.

2. Some Ground Supported Reflector Telescopes

a) Passing the Gravitational Limit

As we see from Figure 1, one of the most urgent questions is "How can we exceed the gravitational limit?" It seems that this can be done only in three ways: By

i. Avoiding the deformations by not moving in elevation angle,

ii. Fighting the deformations with strong servo motors in the structure,

iii. Guiding the deformations so they do not hurt the performance.

The first way leads to a limited steerability, but this is acceptable for many types of observations. The second way was tried in Sugar Grove; it will always be very complicated and expensive and is omitted in the present investigation. The third way leads to the concept of homologous deformations and will be discussed in the last section.

An extreme example of the first way is the Arecibo antenna in which the reflector does not move at all, but moving the feed moves the antenna beam by 20° from the zenith in any direction. This is a very economical design which could be extended at least to 10 cm wavelength. A radio source can be followed for two hours (integration time), and the complete sky could be covered if more similar antennas were located at different geographical latitudes; this possibility deserves more attention than it has received up to now. A second and more flexible example was suggested by J. Findlay and is being worked on by E. Faelten (see Section III). Here a spherical dish is mounted with a fixed elevation angle and is driven on circular tracks 360° in azimuth, while moving the feed allows 1 or 2 hours integration time. This telescope gives transit observations of a considerable part of the sky.

The price of this last type of telescope is defined by wind deformations. Suppose we pass the gravitational limit in some way or the other. The next natural limit then is the thermal one, but it holds only in sunshine. In Figure 4 we show the weight of a telescope if gravitational deflections are omitted. These weights are valid for telescopes where the height is comparable to the diameter (as is the case in the Faelten design). This weight increases very steeply for shorter wavelengths in the wind deflection region, especially so for larger telescopes. We might try a radome, place the antenna in a shielded valley, limit short-wavelength observations to lower wind velocities, or, finally, design a telescope which sits flat on the ground.

b) A Large Parabolic Mirror Flat on the Ground

A possible solution is sketched in Figure 5, using a parabola at 45° elevation angle with its focus at F. In a more conventional design, we would use part AB, where a large surface is high above ground. Now, we use part CD. It is 40% larger, but is never more than 40 m above ground and at no place more than 26 m in stow position. This parabolic mirror P (282 m long and 200 m wide) gives a round aperture of 200 m diameter and is mounted on wheels in a flat, cylindrical trough GHI (343 by 200 m) which has its center line through point M. Rotating the mirror in the trough by 10° around M yields about one hour of integration time. The trough sits on wheels on horizontal, circular tracks on the ground, giving 360° movement in azimuth around center point Z. The feed is mounted to move along track T, which is 50 m long and is 10° of a circle around M. This track can be rotated 360° around a vertical axis supported on a tower 200 m high.

The feed cannot be at the primary focus. In order to illuminate the antenna beam symmetrically, the feed would need an asymmetric pattern. This could be done, but then the feed could not be rotated for polarization measurement. This problem is resolved by using a small secondary reflector of Gregorian type; feed and Gregorian are moved together in one package along track T. If the secondary mirror has the right tilt, it just counteracts the asymmetries introduced by the primary mirror, and the feed illumination becomes symmetrical again. But for isotropic feed illumination, the aperture illumination becomes somewhat tapered.

Recent calculations have shown that there is a one-parameter family of symmetrical solutions for the secondary mirror. If we decide to have a feed illumination angle of 100° (best for simultaneous multifrequency observations), we get a taper of only 0.8 dB (17%) and the Gregorian ellipse has an eccentricity of 0.46.

This type of design will be the most economical one for telescopes above a certain critical diameter, if large sky coverage is wanted with a single transit telescope. But whether this critical diameter is below or above 200 m cannot be decided without an actual design and cost estimate. The shortest wavelength λ is not defined by natural limits, but will depend on the money available. A rough estimate showed that $\lambda = 5$ cm could be obtained without serious complications.

3. Homologous Deformation

The transit telescope is satisfactory if a large number of objects are to be observed in the same program. But full steerability is needed for all observations of a few, special objects, for lunar occultations and for line studies. Thus we try to pass the gravitational limit with full steerability. If the concept developed here is of practical use, then a new generation of fully steerable large antennas becomes possible.

a) General Concept

Gravitation lets a structure deform into a state of minimum energy, it must move down on the average, and the material constants ρ and E tell us the amount it must move. But no law of nature tells us that a paraboloid must deform into something different from a paraboloid. So, we look for a structure which deforms down whatever it must, but still gives some exact paraboloid of revolution for any angle of tilt, at least for a number N of surface points. A deformation of this kind, deforming one surface of a given type into another surface of the same type, we call "Homologous Deformation."

It can be shown that mathematical solutions exist. There is a family of solutions with 7N free parameters. But all cross-sections must be positive and finite for a physical solution, and a useful solution should have a convenient shape, not too much weight, and so on.

Mathematical solutions exist; but are there useful solutions, and how do we get them?

b) The Homologous Cell

We cannot play at random with 7N free parameters until hitting something useful; we need some logical principle to guide us, and a possible one is the following: We divide the space between bearings and surface into layers of decreasing thickness with an increasing number of joints, each layer being divided into cells by the joints, and all cells being topologically identical (same basic structure, but different sizes and cross-sections). Figure 6 shows an example with three layers.

The basic idea is to let the single cell fulfill a set of conditions such that the whole structure deforms homologously. Solving the problem for one cell will give a solution for the whole telescope, and the number of free parameters is reduced to the few in a single cell. Even if this principle did not yield exact solutions for the whole telescope, it still should yield good approximations.

For two dimensions, two types of cells were investigated analytically, and both gave exact solutions. But a structure composed of these cells would be exactly homologous only if it were infinitely long; otherwise we get "boundary distortions" consisting of pressure and torsion. The pressure term is removed by making the second type of cell pressure-stable (Fig. 6C). This cell is a very useful solution. It needs only 37% additional weight for fulfilling the conditions of homology. Three problems then are left: boundary torsion, extension to three dimensions, and constructing a telescope from cells.

c) Model of a Homologous Telescope

An attempt to solve these three problems yields the structure shown in Figure 7. It starts at two bearings which suspend the octahedron. The structure has 5 homologous points in the basic subsurface. Using two types of cells alternately, we reach 21 surface points with a single layer. With 21 homologous points, the gravitational limit can be passed at least by a factor of 10 in wavelength (or a factor of 3 in diameter). The boundary distortions are removed; first by using pressure-stable cells. Second, boundary torsions can come only from an upper layer. Their action will be to deform the subsurface under the upper layer into an S-type shape. However, the basic subsurface has not enough points for an S-shape, and the upper surface layer cannot be deformed because there is no layer above it. The result is a uniform tilt, which again is a homologous deformation.

R. Jennings has started to make the quite involved calculations. When he has numerical results, a model of about 10 m in dimension will be built. It need not have any surface. Model deformations during rotation in elevation angle may be measured with an optical interferometer. The model should show whether a numerically obtained homologous solution can be realized in practice.

If the model gives good results, the principle can be applied to telescopes of any size. It might be most important for millimeter wavelength antennas. Given one homologous solution, if each length is multiplied by one and the same but arbitrary factor, the result is again a homologous solution. The same holds independently for changing the cross-sections. The factor for the cross-sections is obtained from two conditions: First, that the wind deformations are never more than $\lambda/16$; second, that the structure can withstand the survival load. The first condition will dominate, if we pass the gravitational limit by a large factor.

d) Calculating Method for Complex Structures

When a good solution is found for the single cell, one may then design a telescope consisting of these cells as shown in Figure 7. Most probably, this structure will not be an exact solution but only a first approximation, to be changed by some steps of an iterative method until the approach to a true solution is close enough. The mathematical procedure for these iterations has been worked out in detail and in such a way that it can be applied to any type of complex structure.

The conditions of homology lead to a system of algebraic equations of very high order. The method regards the geometrical shape as being given, and it is linearized in the changes wanted for the cross-sections of members. It uses the means and notations of linear algebra, for which good subroutines are available at large computers.

The task of changing a first approximation into a homologous solution is not defined because of the free parameters. In order to make it uniquely defined, the missing number of equations is derived from the following demand:

> From all possible homologous solutions, choose the one which is most similar to the first approximation.

This definition has the additional advantage of making all changes as small as possible, which makes it as hopeful as possible that the linarized method will converge, and that the results then will be a useful solution if the first approximation has been. The method also contains several checks, giving failure indications if no solution exists for the geometrical shape used.

If all goes well, this method will yield a useful solution, but not necessarily the best one. The best solution I have defined is one which meets the following conditions with a minimum weight:

1. Exact homologous deformation of all surface points,
2. All cross-sections positive,
3. All deformations elastic in winds up to 100 mph,
4. All surface deformations due to winds up to 25 mph smaller than $\lambda/16$.

A minimum task cannot be solved with a linear method. A two-gradient procedure, in which I have had good experience in other similarly complicated cases, is now being developed.

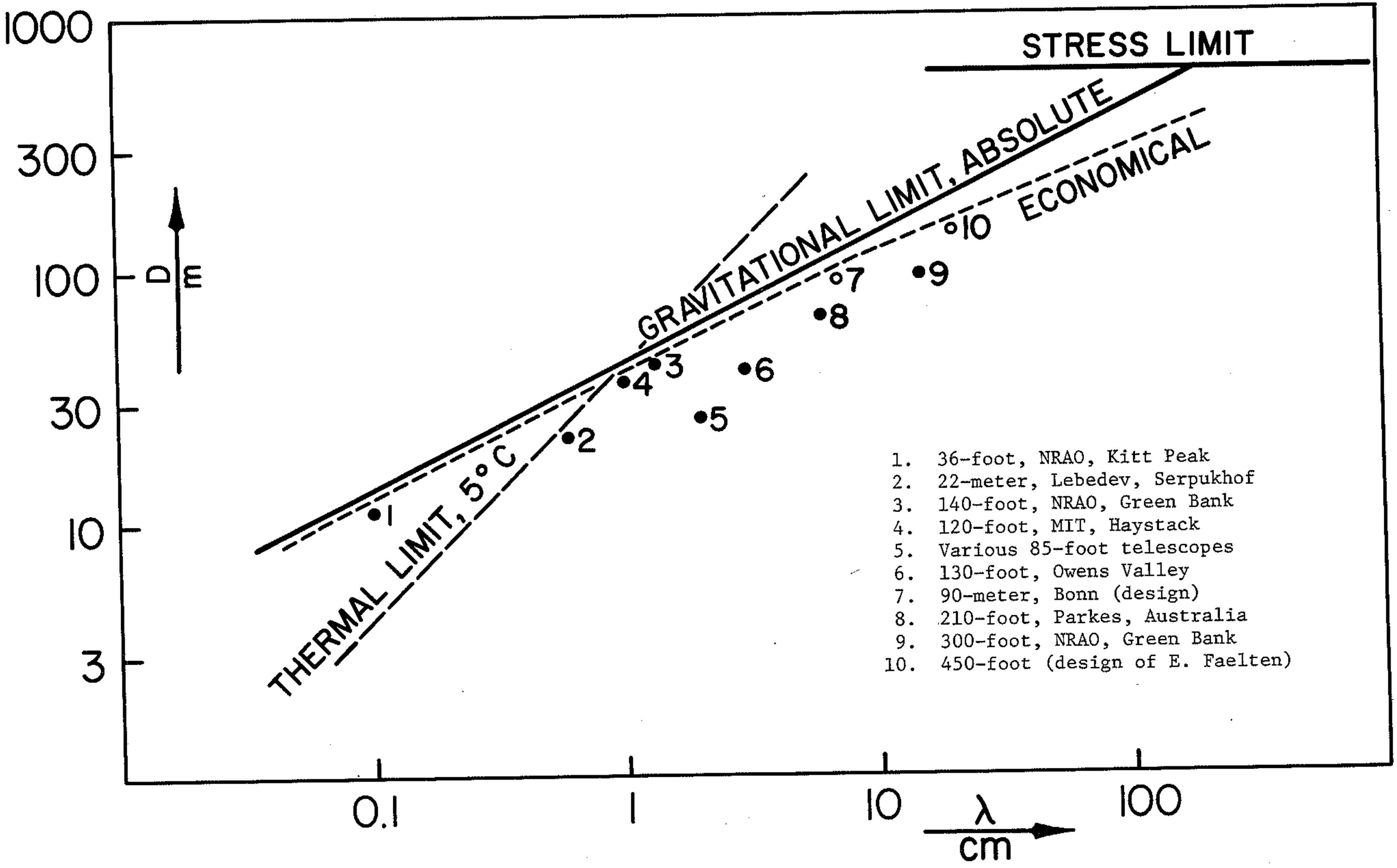


Fig. 1. Three natural limits for tiltable conventional telescopes.

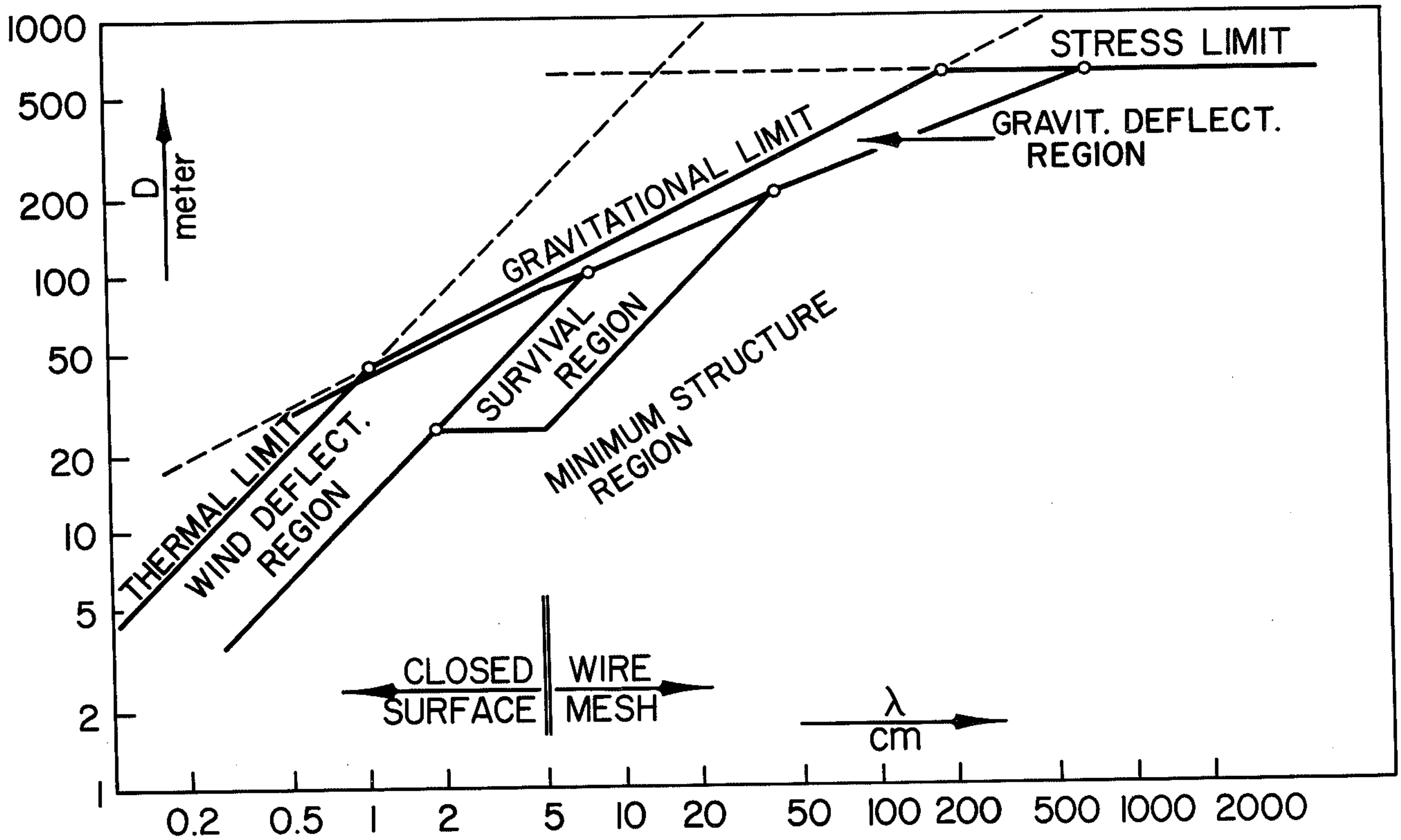


Fig. 2. Regions of diameter D and wavelength λ in which the weight of the structure is defined by different conditions and the three natural limits of antennas.

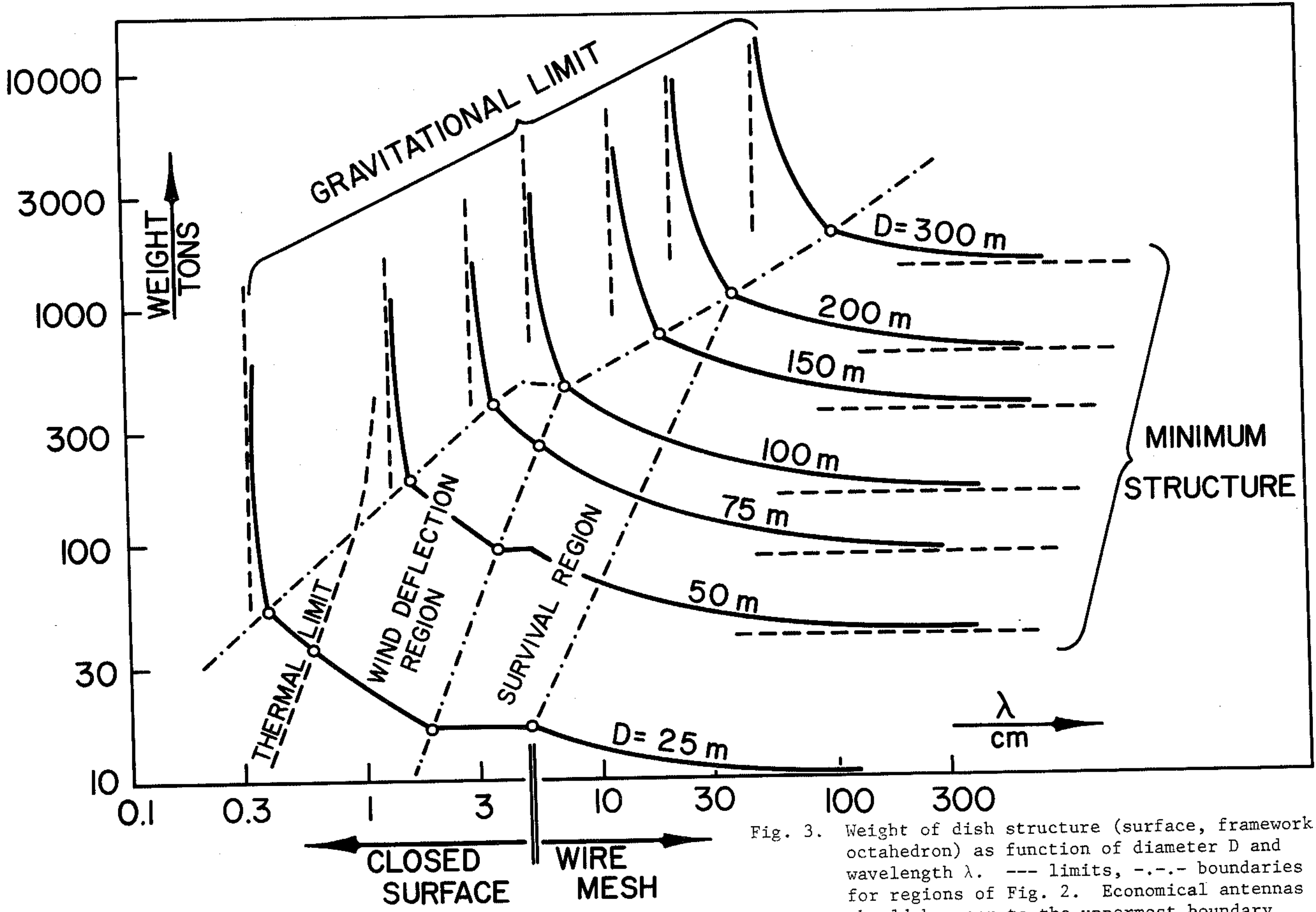


Fig. 3. Weight of dish structure (surface, framework, octahedron) as function of diameter D and wavelength λ. --- limits, -.-.- boundaries for regions of Fig. 2. Economical antennas should be near to the uppermost boundary.

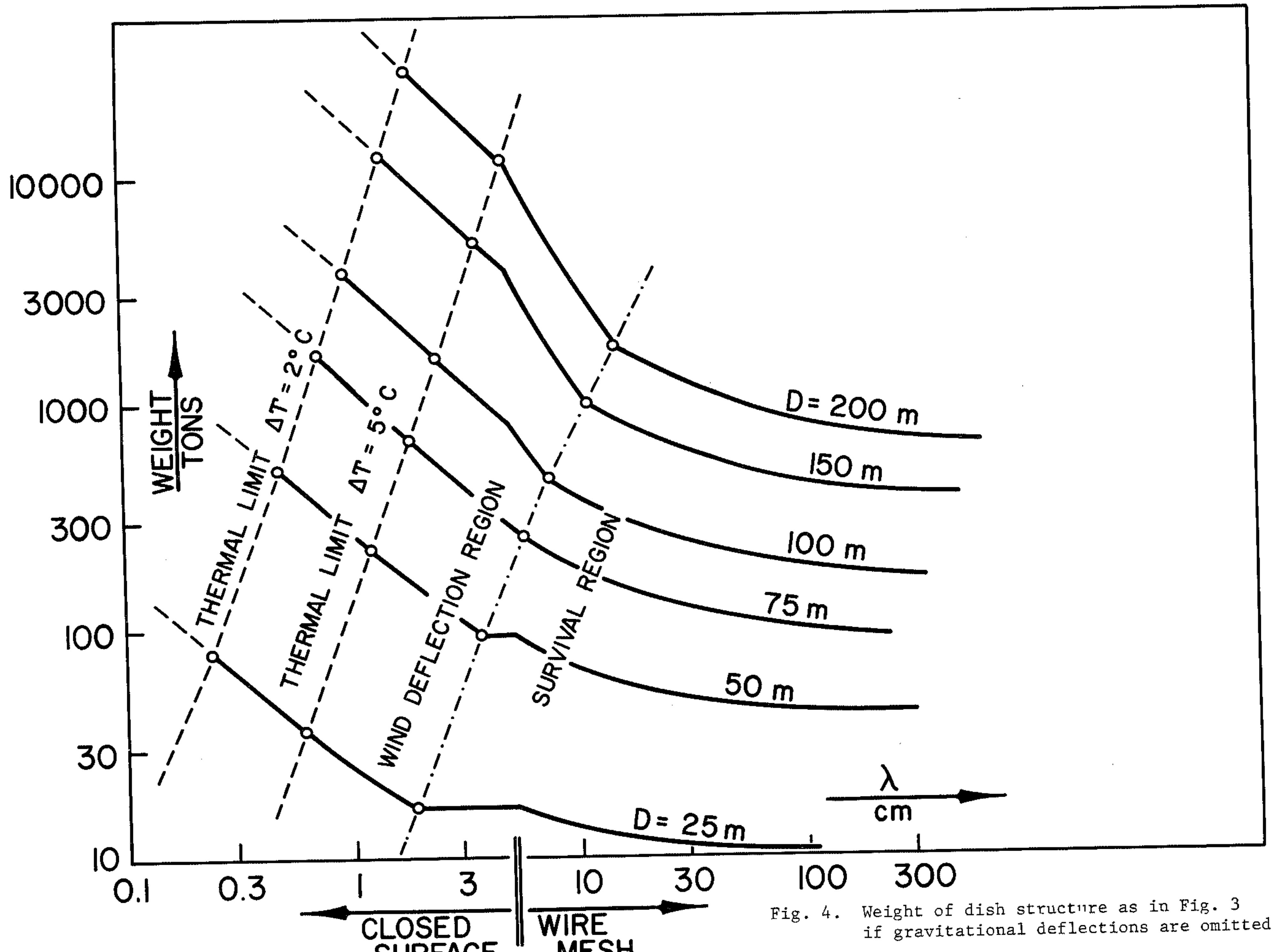


Fig. 4. Weight of dish structure as in Fig. 3 if gravitational deflections are omitted.

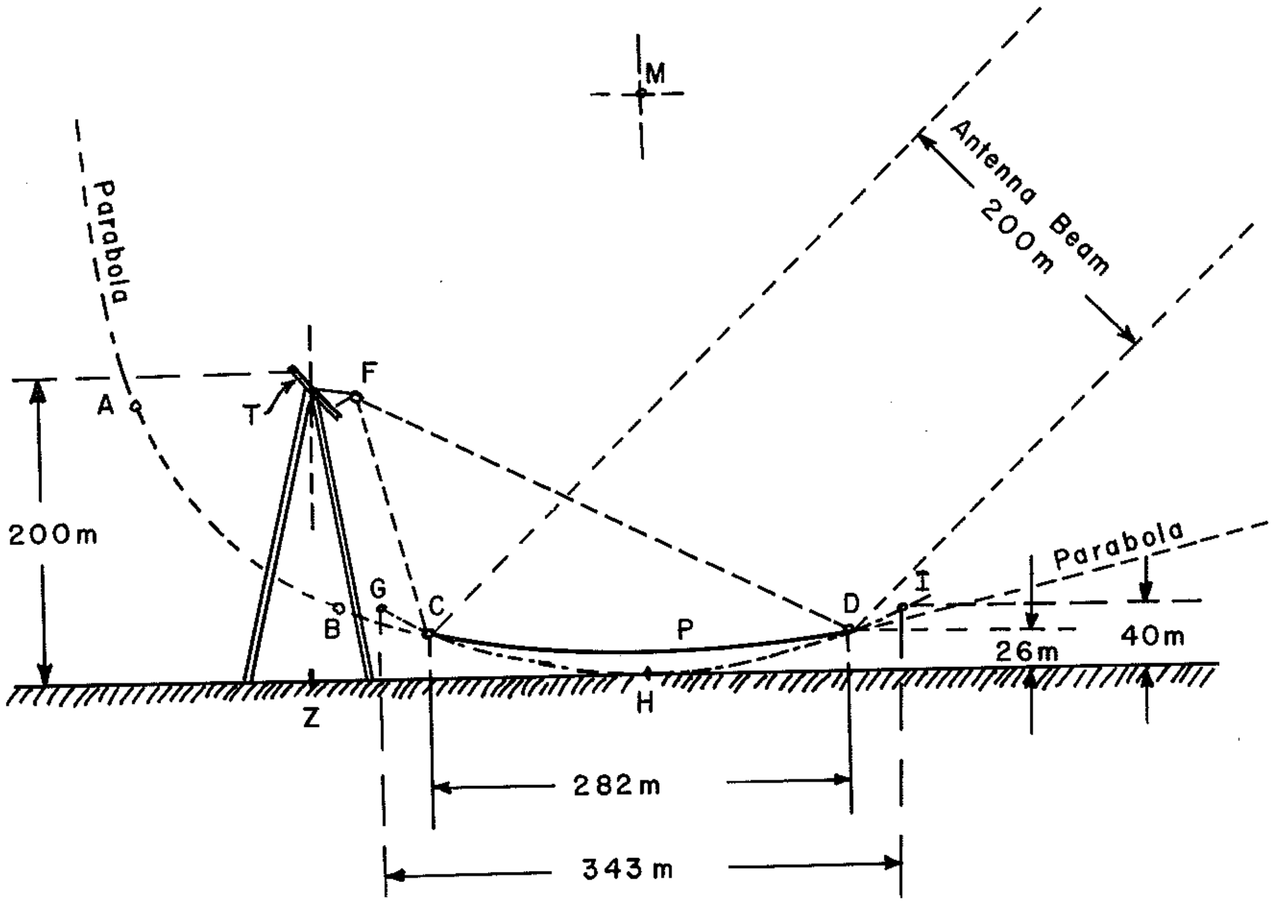


FIG. 5. Fixed-elevation transit telescope with large surface flat on the ground. The parabolic mirror CPD moves on wheels in a flat cylindrical trough GHI by 10° around M. The trough moves on horizontal circular tracks by 360° around Z. In stow position, the rim of the mirror is only 26 m above ground.

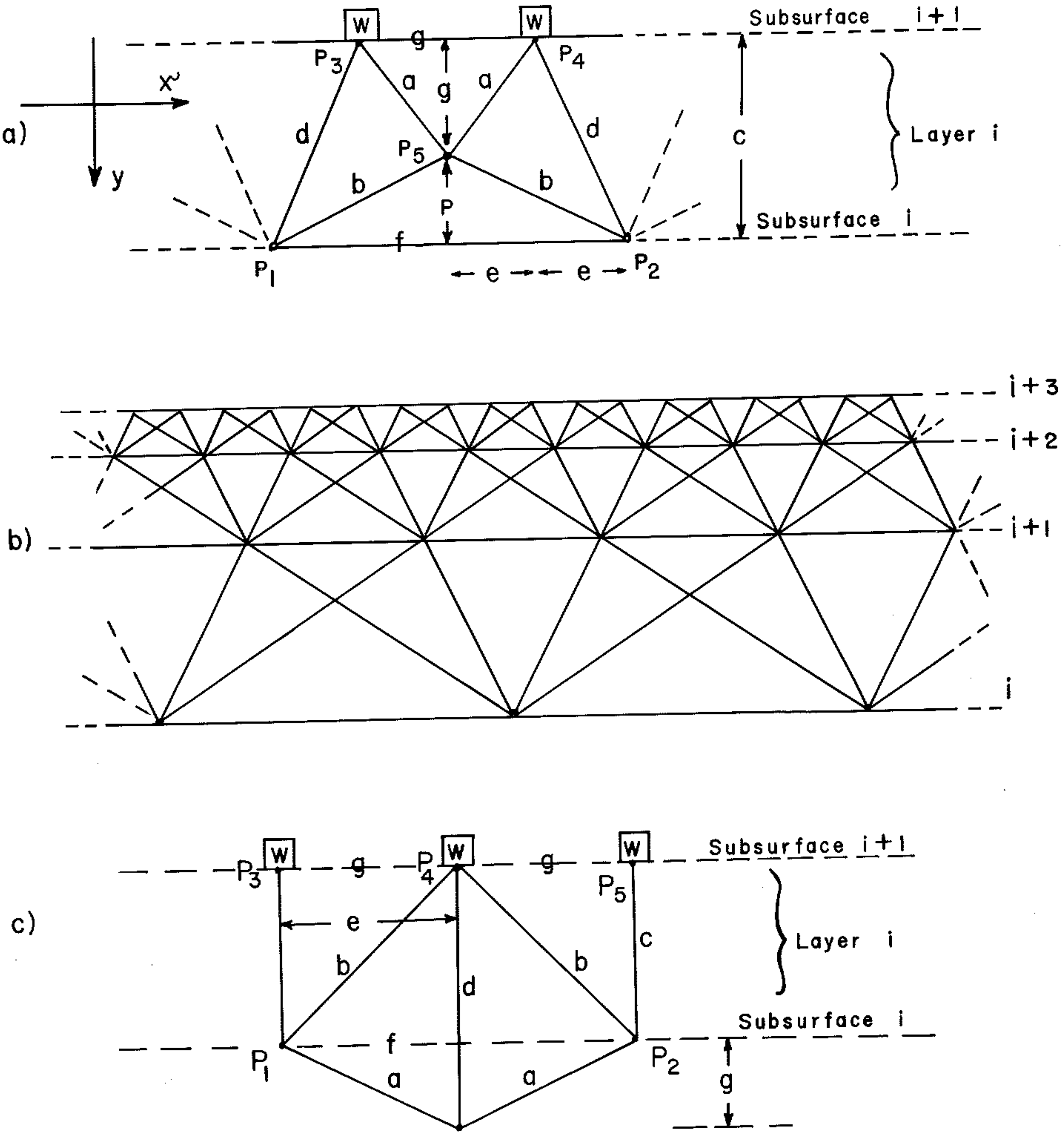
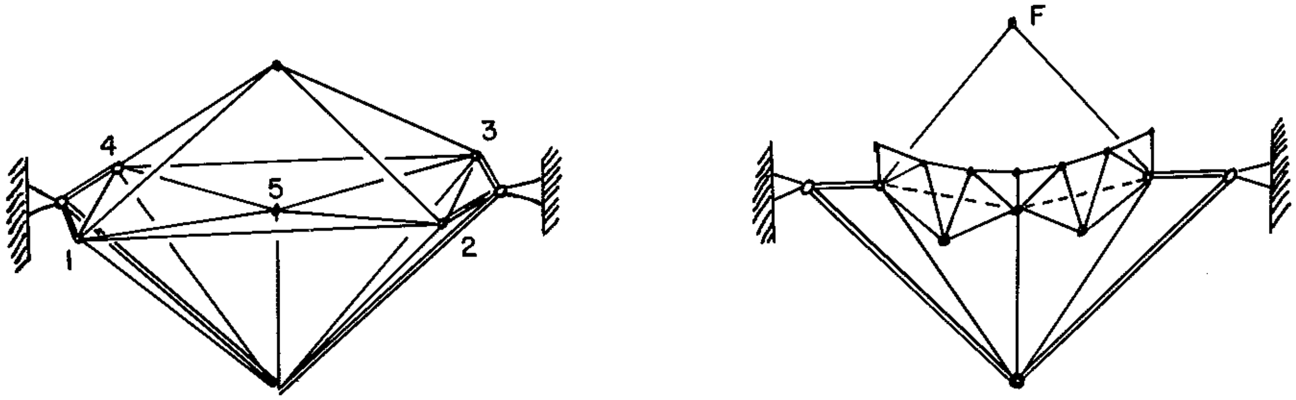


FIG. 6. Two types of cells, where layer i + 1 is parallel to layer i for any elevation.

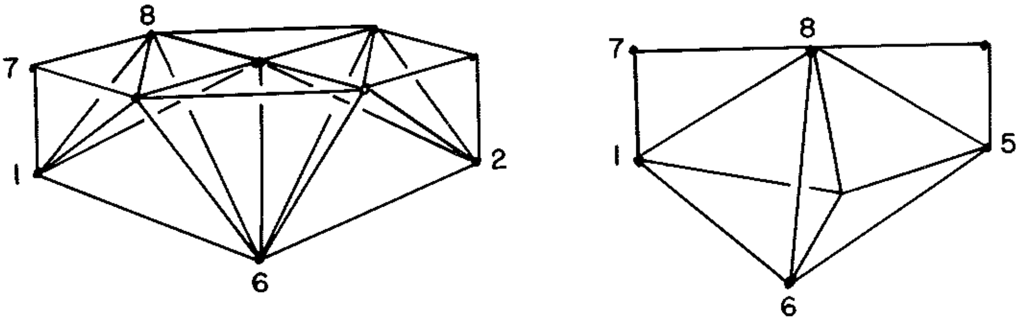
a) Most simple type, general solution.

b) Particular solution (c = 2e = 3q) of same type, three layers.

c) Cell which keeps height constant if P_1P_2 is compressed.


suspension (═════)
and octahedron (─────) :

with layer added:


cell A:

cell B:

21 surface points (•)
5 basic points (O) :

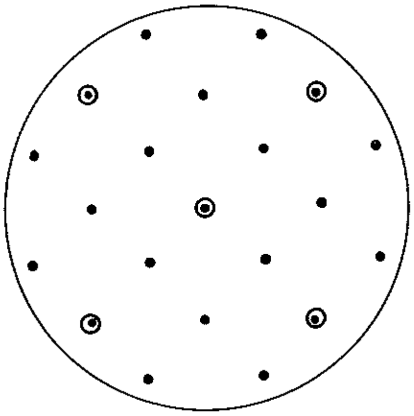


FIG. 7. Antenna structure for homologous deformations;
with suspension, octahedron, one layer, and 21 surface points.
(Identical numbers mean identical points in the structure)

III. DESIGNS FOR AZIMUTH-ELEVATION INSTRUMENTS WITH LIMITED ELEVATION MOVEMENT

E. R. Faelten

When the design of a parabolic dish reaches diameters of several hundred feet, the deflection of the structure under its own weight becomes of over-riding importance. Such deadweight deflections would, of course, be unimportant if the moving structure did not change its relation to the force of gravity, since the deadload deflections would be constant and could be allowed for in design and erection. Deflections due to wind loads and thermal inequalities still of course remain, but for very large structures are of less importance.

With these principles in mind, one aspect of the LFST study has been to consider types of Az-El telescopes in which the elevation range is limited to ± 10°. Two ways of achieving this are being considered; the first proposes a fairly conventional parabolic dish whose axis can move through the desired range of elevation angle; the second proposes a fixed elevation spherical reflector and a moving phase-corrected feed.

The parabolic dish concept has been worked out and is the subject of a lengthy study which is summarized in Section 1 of this report. The work on the spherical dish continues, and its present status is given in Section 2.

1. A Telescope with a Parabolic Surface

a) The General Design

Even in the 200 meter (660 feet) size chosen for study, preliminary estimates suggested that the changes in deflection as a result of moving such a dish through a 20° elevation angle might still permit operation down to $\lambda = 10$ cm. Accordingly, the design shown in Figure 1 was developed in some detail in order to arrive at first figures for the probable weight, performance and estimated cost for such a telescope concept.

The chosen design isolates the feed support system from the parabolic dish. The feed is carried on a fixed steel tower 640 feet in height. The feed system itself must rotate and move so as to always point at the apex of the dish. Details of the 6 degrees of freedom mechanism for achieving the requisite pointing and position control of the feed have not been worked out.

The 660-foot diameter parabolic dish is adjusted in elevation on a set of curved tracks which in turn are supported on the main azimuth carriage structure. This azimuth carriage travels in a circular path around the center of the feed support tower. Although full 360° rotation of the azimuth carriage is not essential, it has been provided in this first design.

The parabolic dish is counterweighted by concrete blocks suspended by cables, and it is moved along the curved tracks over the elevation (of the telescope beam) range from 30° to 50° above the horizon. Motion in elevation is achieved by a string of guided hydraulic rams, which move the paraboloid on wheels on the tracks.

The azimuth carriage is supported on trucks and is driven by a number of geared, eddy-current clutch drives. Circular guidance and wind shear resistance are provided by servo controlled rollers on hydraulic rams pushing laterally against massive steel-faced inner and outer annular concrete rings.

The main structural and mechanical design of the telescope has been worked out sufficiently to give the following features and quantities:

Dish diameter - 660 feet

Focal length - 561 feet

f/D - 0.85

Tower material - steel

Tower weight - 550 tons

Tower height - 641 feet

Paraboloid material - aluminum

Paraboloid weight - 2100 tons

Azimuth carriage material - steel

Azimuth carriage weight - 10,000 tons

Weight of machinery and trucks - 2491 tons

Moment of inertia of total mass about vertical axis through center of feed tower - 2.39×10^{11} slug feet^2

Moment of inertia of the paraboloid about an axis through the focal point - 4.26×10^{10} slug feet^2

Foundations are assumed soil-bearing concrete pads and rings

b) Cost Estimate

An outside cost estimate for the structure, including drive machinery and foundations, is $60 million.

c) Performance

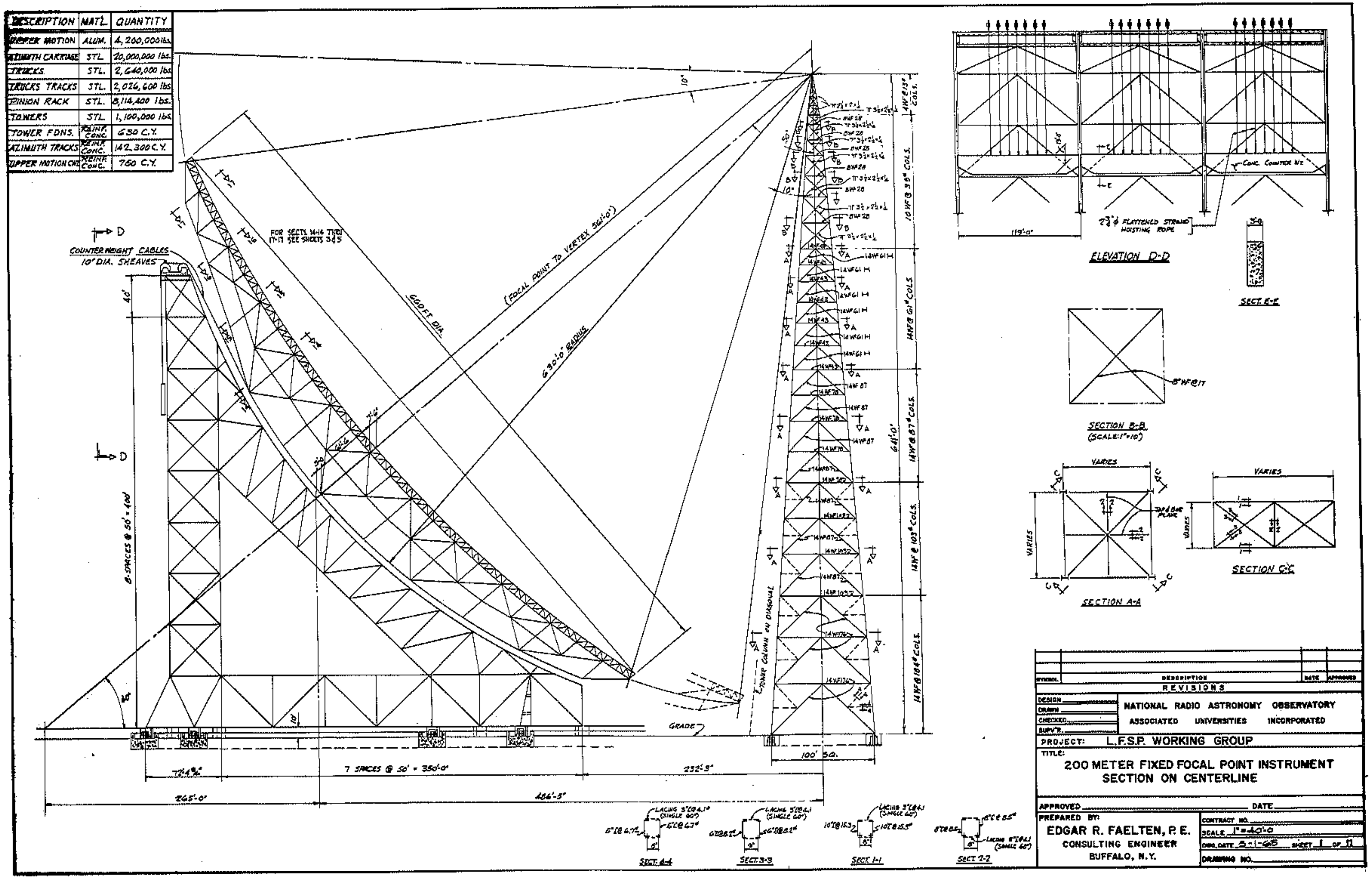
Although a full deflection analysis of the structure has not been carried out, the deflections of some of the main trusses have been calculated by graphical methods. The results suggest that the gravity deflection changes over the 20° of elevation motion would permit satisfactory 10 cm operation over the entire range.

The feed support tower will shift with wind and temperature. This motion is disturbing since it is necessary to keep the phase center of the feed within about 1 cm of the dish focus and to keep the feed correctly pointed. These requirements indicate that a fairly sophisticated servo-mechanism would be called for.

2. A Telescope with a Spherical Surface

The alternative to moving a parabolic surface is to use a spherical surface. A surface which is a segment of a 600-foot radius sphere and which has dimensions of 600 feet by 840 feet is sufficient to give a beam movement of 20° in elevation. This surface will be mounted so that the telescope beam will move from 30° to 50° in elevation above the horizon. A possible mounting is shown in Figure 2. The reflector surface and a feed support structure are supported on an azimuth rotating support, which in turn is carried on rails and wheels and which is stabilized by a central pintle bearing.

The design of this instrument has not yet proceeded to the point of engineering conclusions or estimates. There are indications that this concept will require less steel than the parabolic surfaced telescope, hence will be less costly. Further study will continue until an appraisal similar to that of the parabola can be made.



DESCRIPTION	MAT'L	QUANTITY
UPPER MOTION	ALUM.	4,200,000 lbs.
AZIMUTH CARRIAGE	STL	20,000,000 lbs.
TRUCKS	STL.	2,640,000 lbs.
TRUCKS TRACKS	STL.	2,026,600 lbs.
PINION RACK	STL.	8,114,400 lbs.
TOWERS	STL.	1,100,000 lbs.
TOWER FDNS.	REINF. CONC.	630 C.Y.
AZIMUTH TRACKS	REINF. CONC.	142,300 C.Y.
UPPER MOTION CW	REINF. CONC.	760 C.Y.

SYMBOL	DESCRIPTION	DATE	APPROVED

REVISIONS

DESIGN
DRAWN
CHECKED
SUPV'R.

NATIONAL RADIO ASTRONOMY OBSERVATORY
ASSOCIATED UNIVERSITIES INCORPORATED

PROJECT: L.F.S.P. WORKING GROUP

TITLE:
200 METER FIXED FOCAL POINT INSTRUMENT
SECTION ON CENTERLINE

APPROVED DATE

PREPARED BY:
EDGAR R. FAELTEN, P. E.
CONSULTING ENGINEER
BUFFALO, N.Y.

CONTRACT NO.
SCALE 1"=40'-0
DWG. DATE 5-1-65 SHEET 1 OF 11
DRAWING NO.

FIG. I

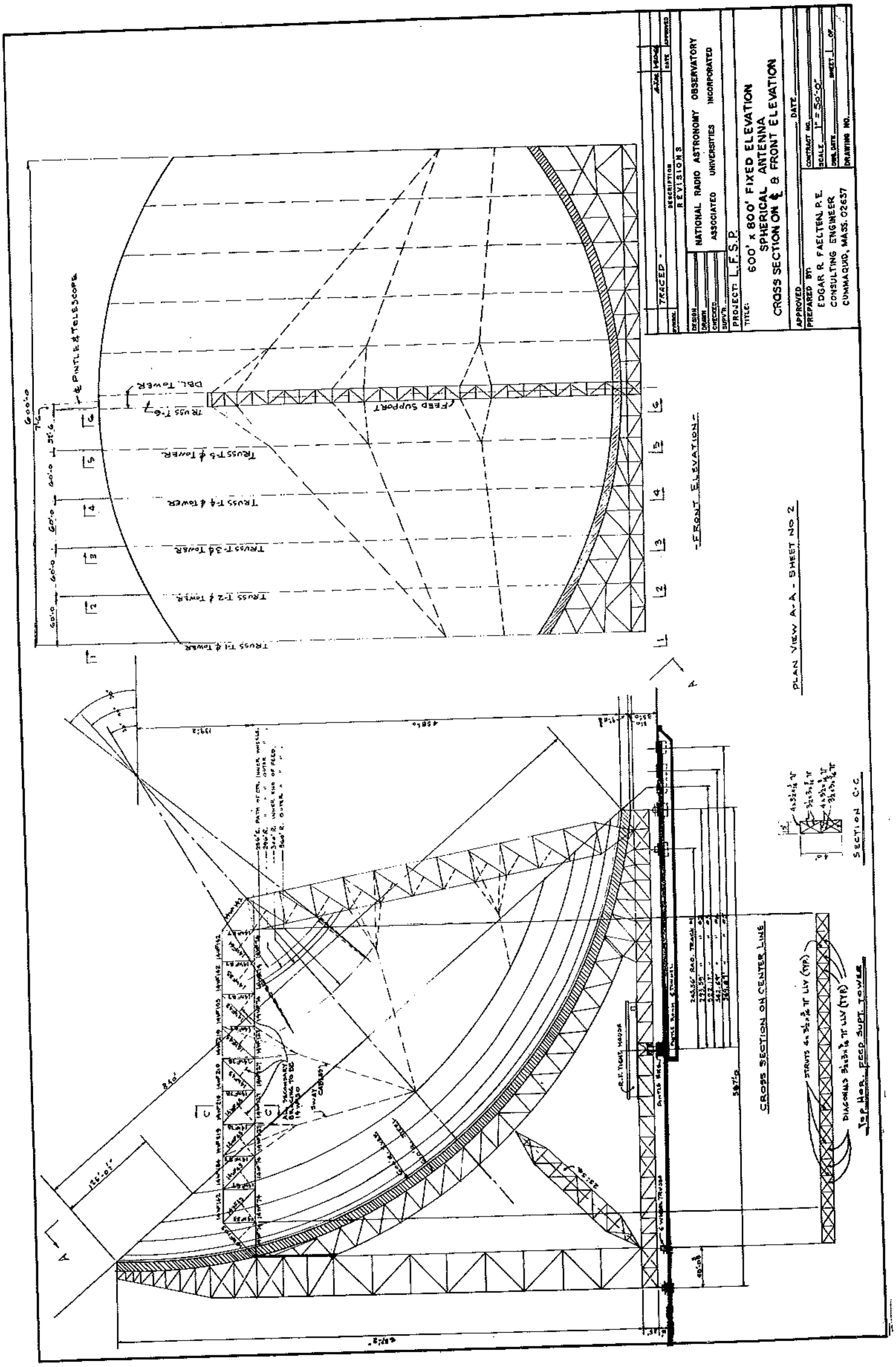

NATIONAL RADIO ASTRONOMY OBSERVATORY
ASSOCIATED UNIVERSITIES INCORPORATED
PROJECT: L.F.S.P.
TITLE: 600' x 800' FIXED ELEVATION SPHERICAL ANTENNA
CROSS SECTION ON ℄ & FRONT ELEVATION
PREPARED BY: EDGAR R. FAELTEN, P.E.
CONSULTING ENGINEER
CUMMAQUID, MASS. 02637
SCALE 1" = 50'-0"
SHEET 1 OF
TRACED
REVISIONS
DESIGN
DRAWN
CHECKED
SUPV'R.
APPROVED
DATE
CONTRACT NO.
DWG. DATE
DRAWING NO.
-FRONT ELEVATION-
TRUSS T-1 ℄ TOWER
TRUSS T-2 ℄ TOWER
TRUSS T-3 ℄ TOWER
TRUSS T-4 ℄ TOWER
TRUSS T-5 ℄ TOWER
TRUSS T-6
DBL. TOWER
FEED SUPPORT
℄ PINTLE & TELESCOPE
60'-0
600'-0
PLAN VIEW A-A - SHEET NO 2
CROSS SECTION ON CENTER LINE
SECTION C-C
TOP HOR. FEED SUPT. TOWER
STRUTS
DIAGONALS
SWAY CABLES
R.T. TIGHT HOUSE
A
C

FIG. 2

IV. A FULLY STEERABLE TELESCOPE MOUNTED IN A FLOATING SPHERICAL SHELL

O. R. Heine

1. Forward

The development of a large, steerable radio telescope with maximum obtainable sky coverage, narrow beam width, high pointing accuracy and low initial cost necessitates the consideration of unique design approaches.

Among other concepts being studied by the LFST group, the concept of a floating spherical shell telescope is being investigated. It appears to offer fulfillment of all above requirements, because of the simplicity of the concept and the fact that foundation, bearing and external load variations (due to geometrical unsymmetry) problems are greatly minimized.

Conventionally designed large radio telescopes require massive and evenly strained foundations, which are not easily obtainable due to varying supporting soil properties normally experienced on foundations of large structures.

The floating sphere concept eliminates the need for such a massive and often unpredictable foundation, offers excellent and easily compensated wind and thermal load characteristics and provides, in addition, natural hydrostatic bearing support for either azimuth and elevation or X-Y controlled tracking motions.

The purpose of this study is to establish by means of reasonable and economic methods the feasibility, performance characteristics and approximate development and construction cost of a large diameter, hollow, spherical shell mount, floating in a fluid medium and supporting a parabolic reflector of 200 m approximate diameter.

2. General

It was recognized by the LFST group early in the study effort that the feasibility of two major systems components had to be investigated, namely:

a) The stability, strain and stress relation of a single-walled floating spherical shell support, and

b) The type, feasibility and achievable pointing accuracy of the drive system.

It was assumed that to use water as the supporting fluid would be the most practical approach and that a simple azimuth-elevation gear train would provide the most accurate and conventional means of directing the floating mount.

3. Investigation of Spherical Shell Stability

a) Studies by O. Heine and W. Blythe

After studying the available technical literature on spherical shells, it became evident that simplified manual analytical techniques considering membrane stresses and strains in a single-walled spherical shell with cutout, floating on a body of water, would not yield reliable results. An existing computer program entitled "Computer Analysis of Asymmetrical Deformation of Orthotropic Shells of Revolution" was found, and a first analysis of a 1-foot thick concrete shell of 711 feet diameter having an opening of 656 feet (see Figure 1) diameter to accommodate the 200 m reflector was performed, considering the zenith-pointed load condition only. The results were encouraging and indicated a rim deflection on the order of 8 inches with maximum stresses of about 4000 PSI in the shell. The next analysis was performed on 60° off zenith position on the same shell. Results indicated that the shell was not stable under this load condition. The cause of the structural instability was determined to be the unsymmetrical bending of the shell opening due to distribution of necessary counterweight in this area, and it was concluded that an increase in wall inertia and application of a stiffener ring around the reflector opening was necessary. Several double-walled spherical shells with stiffener rings of various cross-sections were subsequently analyzed and yielded more reasonable stresses and strains, but were still not satisfactory.

It was then concluded that a material with a higher stiffness/density ratio would have to be used in order to obtain a more reasonable shell stability. In order to check the beforementioned results of the computer program, a parallel stress/strain investigation of the first two cases was conducted manually by developing the necessary equations for membrane and bending stresses. The results thus obtained were in good agreement with the computer results, thereby establishing the reliability of the numerical analytical method previously applied.

Concrete was known to be the least costly construction material and was therefore given first attention. Steel, being the most common, was second choice due to its higher cost. Aluminum was considered to be the least desirable because of its high initial fabrication and construction cost. However, comparing the ratios of stress/density and stiffness/density of only the three construction materials considered, concrete appeared to be the poorest choice, while aluminum would be best from this point of view.

Material	Stiffness/Density	Stress/Density
Concrete	33,300	44.4
Steel	61,300	62.5
Aluminum	58,000	116.0

From all points of view, steel appears to be the logical choice.

Consequently, the next analyses were of a double-walled concentric steel shell with wall thickness of one inch, spaced 20 feet apart and balanced by a 2.5 ft x 34 ft steel ring. The results of these analyses indicated reasonable stresses and strains in the shell(s).

In order to investigate the stiffening effect of a space-frame type of radome covering the reflector area supported by the spherical shell structure, a computer analysis of the second harmonic (bending mode) was performed. The results were compared with the results of the second harmonic analysis of the previously studied steel shell. The evaluation of this effort indicates that use of a radome contributes no significant reduction of stress in a relatively heavy and stiff shell structure, but that reduction in supporting ring deflections are obtainable. It is possible that the effect of a relative stiff radome upon

These investigations were based on membrane stress calculations assuming a zenith pointed position only.

In a companion study, Lear Siegler is applying an existing computer program to investigate unsymmetrical bending deflection and stresses occurring in a feasible concrete shell having a 656-foot diameter cut off for mounting a 200 m diameter reflector.

It is expected that the results of these investigations will permit determination of the practical feasibility and approximate cost of a floating spherical concrete shell.

c) Effort by Other Companies

North American Aviation will also study the feasibility of a spherical floating radio telescope. They will analyze a 750-foot diameter shell constructed with 6 inch thick expanded steel honeycomb panels having a skin thickness of only .1 inch.

In contrast to the approach followed by the LFST group, North American pursues the idea of floating this structure on an air pressurized bearing arrangement. The use of slightly compressed air to support the shell has the advantage of providing constant distributed support pressure. The hydrostatic pressure on a structure floating in water will increase with the depth of submersion. There would, however, be a distinct load discontinuity at the rim of the air bearing, while the hydrostatic pressure of the water bearing is zero at this point. North American believes that the power required to keep the structure floating on the air would be only a few 1000 HP and that the uniform bearing pressure would minimize bending stresses in the spherical shell.

The drive system proposed by this Company is entirely different from the one studied by the LFST group, but is not necessarily exclusive for this design. It is also believed by North American that a load-carrying radome can be designed as stiff as the supporting shell and that, consequently, the shell could be extremely light.

Further, more detailed, studies of this concept are required to substantiate its feasibility. If a more accurate shell analysis proves that it is indeed theoretically feasible to utilize a thin walled honeycomb shell as support for say a 200 m reflector, a comparison of economy and practicality of high cost/low weight honeycomb panels versus low cost/high weight ship plate construction will determine which type of construction will be more desirable.

4. Reflector

The desired rms surface accuracy for the primary reflector is .5 cm (1-δ limit).

Two possibilities for mounting the primary reflector are available with the spherical shell design: a) Mounting the reflector inside the shell, and b) Mounting the reflector on the supporting ring. Since internal mounting of the reflector would require additional counterweight distributed at the supporting ring, the second approach only was considered to date.

In order to minimize the effect of supporting ring distortion, a four point reflector suspension was assumed, each of the four bearing points at 90° to each other. These points were assumed to follow the elliptical deflection contour of the ring support without constraint. Two diagonal points would be fixed bearing points while the remaining two would be guided to follow the deformation of the support. Again, an existing computer program entitled "Stress," developed by M.I.T., was used to analyze the above structure.

In order to eliminate the differential expansion problem, a steel spaceframe reflector with a solid single surface was analyzed within the above conditions. It was found that peak deflections would not exceed 7.5 cm. Since sufficient support behind the reflector is available, it is assumed at this time that the contour of the reflecting surface can be controlled to closer tolerances by means of programmed loading of key members of the reflector in various positions to obtain the desired surface accuracy. The "Homology Principle" could also be successfully applied since the reflector weight is not of primary importance.

To achieve the desired focal length a Cassegrain reflecting system was considered best for this application. The secondary reflector and supporting trusses were analyzed and deflection calculations indicate that position actuation of the secondary reflector, to maintain a true focal distance and axial line up, will be necessary. Position correction could be programmed as a function of the elevation angle or could be controlled by means of a feed-back system.

Present calculations indicate that uncompensated focal point movements will be less than 2 inches.

5. Drive System

A drive system for the azimuth-elevation motion could consist of four equally spaced trolleys, each provided with opposed elevation and azimuth drive gear to eliminate backlash. The elevation gear is mounted directly on the spherical shell by pinion drives on the track mounted drive trolleys.

Azimuth motion is achieved in similar fashion. The drive trolleys are in contact with the spherical shell through guide rollers and rotate the floating structure by traveling on circular tracks mounted to the foundation. They transmit drive torque through an azimuth gear. (See Figures 2 and 3.)

The drive systems can be powered by either electrical (eddy-current clutch) or hydraulic propulsion. Positioning feedback can be obtained by driving a precision encoding and re-transmission system off each trolley.

The wind up and achievable position accuracy were based on disturbing windloads acting on the structure at 25 mph wind velocity and on the desirable angular acceleration of $.01°/\mathrm{sec}^2$. Present investigations indicate that a pointing accuracy of 10 sec of arc is obtainable with this system. The maximum power requirement for achievement of a slewing velocity of .10°/sec is calculated to be less than 1000 HP per axis.

6. Foundation

A circular, reinforced concrete foundation will be required to provide support for the drive trolley tracks. The water pool needed for floating the spherical shell will require a minimal concrete wall for a thickness to depend upon the porosity of the encountered soil only. A preliminary analysis of the foundation indicates that total bearing loads will be less than 4000 PSF.

7. Conclusion

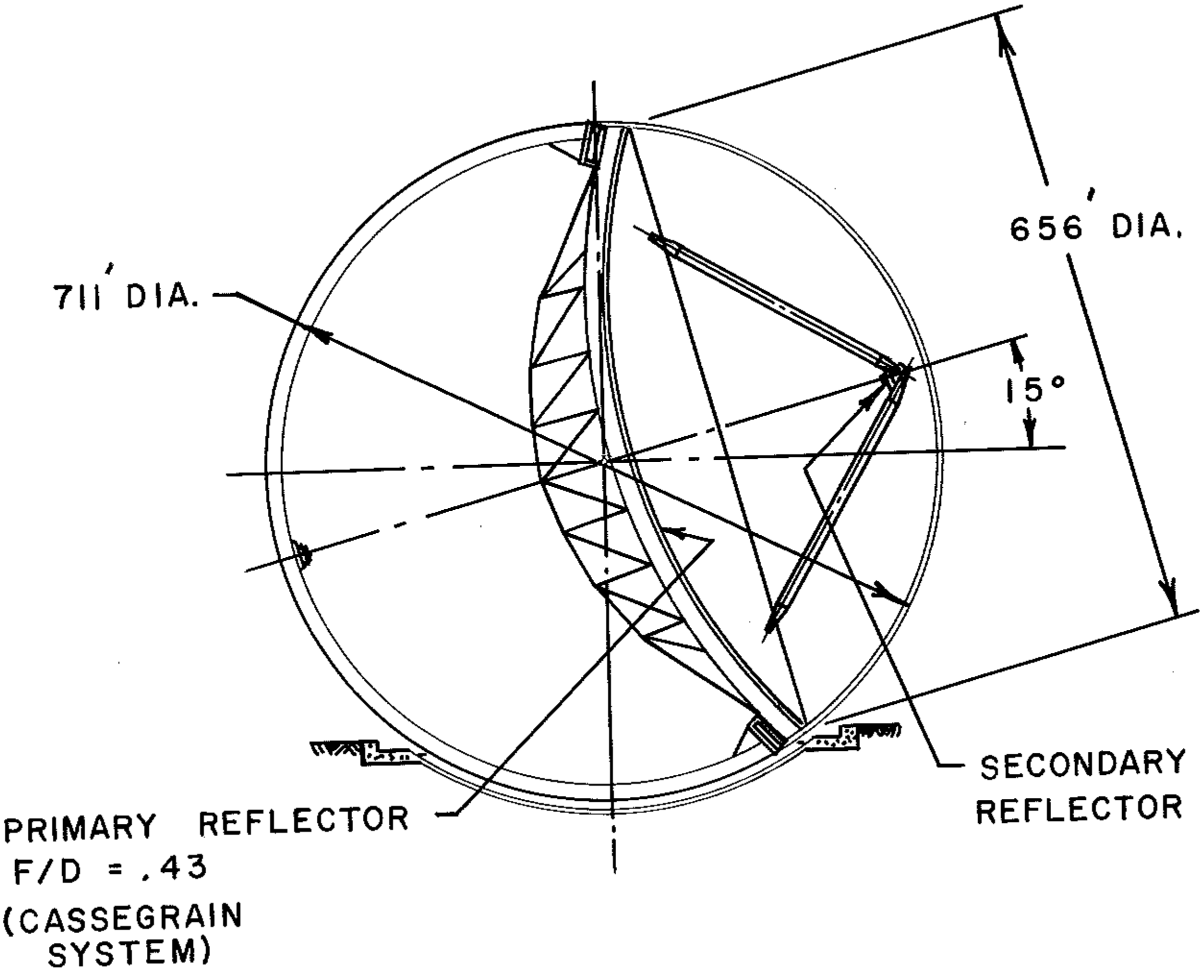
Based upon the investigations so far, it appears that the spherical floating-shell concept offers a feasible, practical and economical solution to the problem of constructing a large, precise, fully steerable radio telescope with maximum sky coverage. More detailed investigations in regard to the most economical and practical supporting shell structure will be performed in order to establish the minimum construction cost. The construction cost for the 711-foot diameter 1/2 inch steel shell is estimated at present to be within $50,000,000.

8. Summary of Parameters

1.	Diameter of floating shell	711 ft
2.	Diameter of primary reflector	200 m
3.	f/D ratio of system	.43
4.	Type of reflecting system	Cassegrain
5.	Desired reflector surface accuracy (rms)	.5 cm
6.	Desired pointing accuracy	8 sec of arc
7.	Type of drive	Azimuth-elevation
8.	Desired minimum acceleration	$.01°/sec^2$

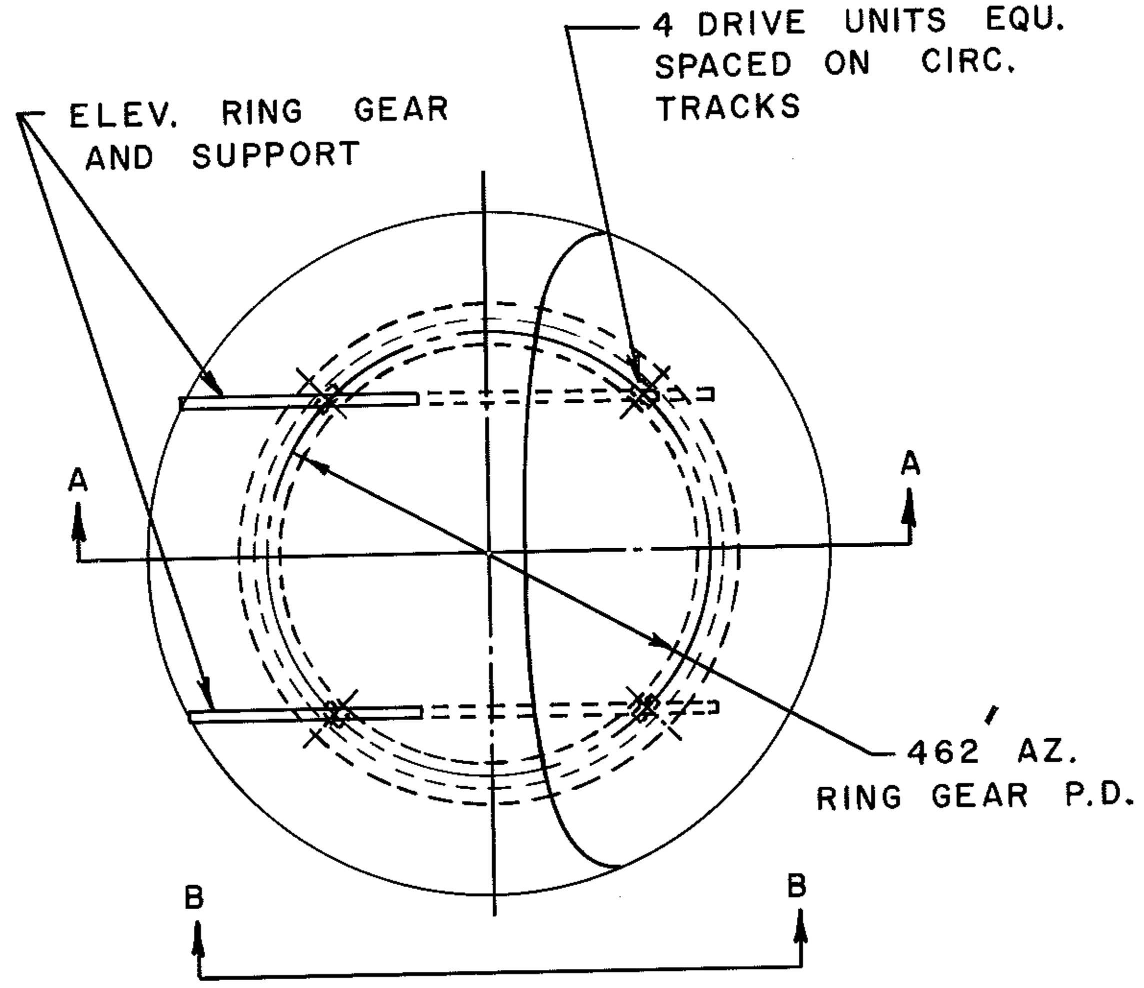
9.	Desired slew velocity	.1°/sec
10.	Sky coverage*	Full to 15° above horizon
11.	Depth of submersion*	55 ft
12.	Input HP per axis*	800 HP
13.	Distance between inner and outer shell	20 ft
14.	Rim deflections of supporting ring*	8 in max
15.	Maximum deflection of reflector	3 in max
16.	Total weight of telescope*	120 x 10^6 lbs

* Based on one inch wall thickness



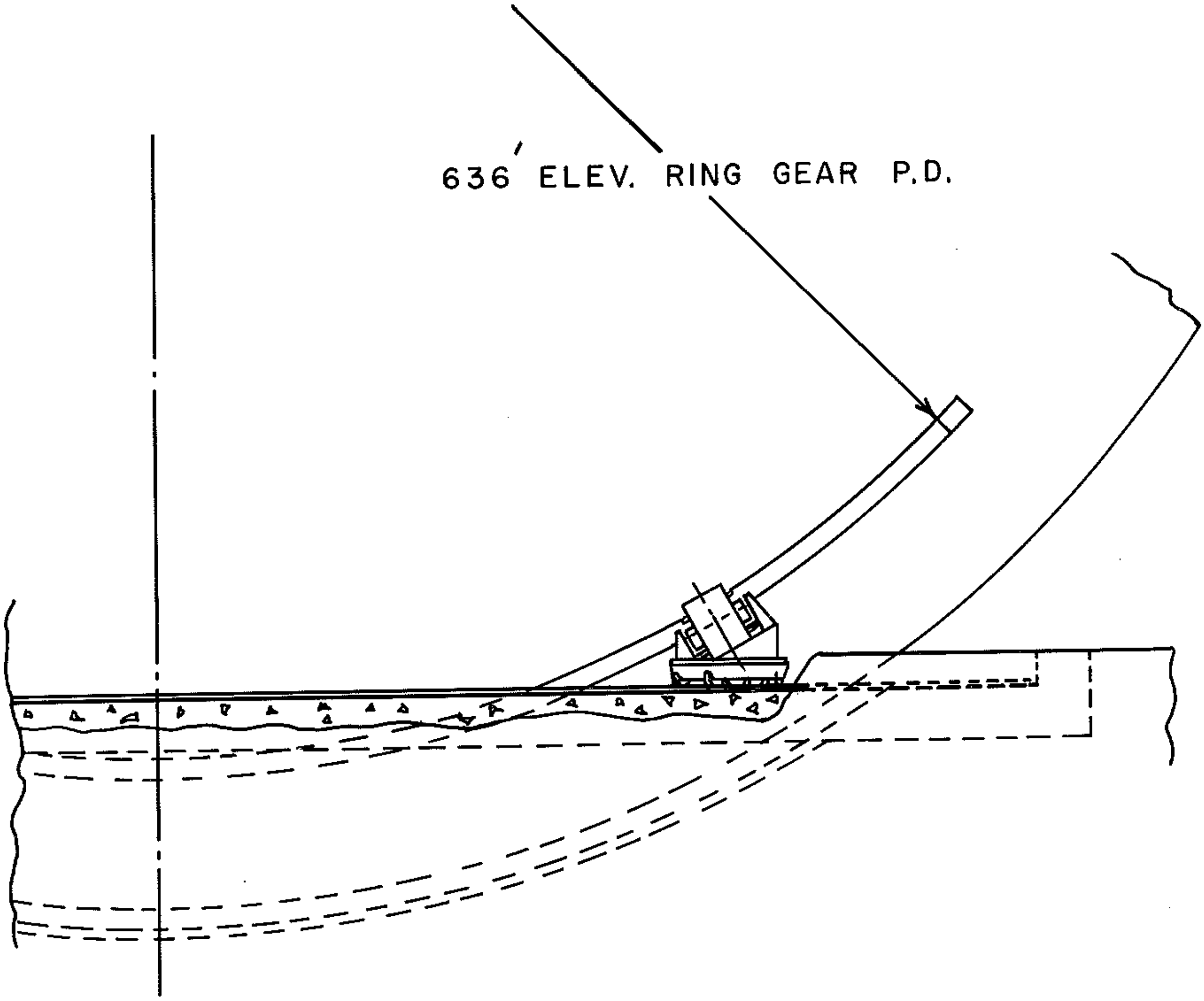
SECTION A-A
Scale: 1" = 200'

FIG. 1



TOP VIEW
Scale: 1"=200'

FIG. 2



VIEW B – B
Scale: 1"=50'

FIG. 3

V. STUDIES OF STRUCTURAL STRENGTH AND DEFLECTION

R. L. Jennings

1. Introduction

The effort by the University of Virginia in the overall LFST study has followed two major areas of investigation:

a) A theoretical investigation of the stresses and deformations in a large (700 feet diameter) thin spherical shell with a circular cutout at the apex. The work in this area complements and verifies a similar study undertaken by O. Heine.

b) An evaluation and application of the "Homologous Structure" concept developed by S. von Hoerner.

The results to date of these two studies are included in three separate reports which have been submitted previously. No part of them is reproduced here because their complexity is not germane.

The conclusions and plans for further study in these two areas follow.

2. Conclusions Concerning the Analysis of a Large Spherical Shell with Cutout

A thin spherical shell with a circular cutout has many advantages as a possible support configuration for a large diameter radio telescope. From a structural engineering viewpoint the major difficulties involved in such a support configuration would be: a) potentially high stress levels in localized areas such as in the vicinity of the cutout, b) excessive deformations in the shell wall which would destroy structural integrity of the system, and c) buckling of the shell wall due to inadequate structural support at the circular cutout.

A first order approximation theory used to predict stress levels in the shell wall indicates the necessity of using the complete bending theory (as opposed to use of the approximate membrane theory) for a reliable prediction of shell stresses.

The University of Virginia is currently in the process of developing this exact theory and developing the corresponding computer program to study specific loadings on the shell. The pertinent theory is described in Report C. Although the computer program is essentially complete, no results are available for presentation at this time.

This phase of the overall investigation will be continued for the following reasons:

a) The concept of a large spherical shell as a support configuration for a radio telescope still appears to be a practical solution for the support of such a telescope. Although generalized computer programs are available to predict thin shell behavior, none will be as efficient to use as the presently developing program <u>since it is especially written for the specific problem at hand</u>. Only details pertinent to the specific problem are retained, and thus the computer time is shorter and the accuracy is greater than any presently available "general shell" program. The net result, of course, is a dollar saving by use of the computer in this area.

b) The stress behavior of a thin structural shell with a cutout is a phenomenon not well understood by practicing stress analysts. Results and conclusions of this study, when published in trade journals, will be of significant value to analysts in civil and aeronautical fields. Such information is extremely useful to designers of pressure vessels, fluid containers, aircraft, etc. Thus it is apparent that this phase of the investigation has an importance far beyond the scope of the radio telescope application, and if continued would make an important contribution to fundamental understanding of a difficult engineering problem.

3. Conclusions Concerning the Concept of "Homologous Structures"

The efficiency of a radio telescope degenerates rapidly with structural deformations of the antenna. The structural deformations of a conventionally designed large radio telescope (500 to 1000 feet diameter) would be excessive and destroy the effectiveness of the instrument.

Structural deflections due to wind effects, thermal gradients, icing, etc., can be combatted or eliminated by placing the telescope in a protective environment such as a radome. However, the gravity deflections cannot be eliminated by such a construction.

Gravity deflections can be reduced, to a degree, by constructing a very massive, rigid back-up structure for the telescope. This is an extremely expensive solution to the problem, and introduces related difficulties due to the need of moving such a large, massive system.

An ingenious attempt to solve this problem is to introduce into the structural design of the telescope the concept of "Homologous Design." This concept, first developed by S. von Hoerner, is based on the idea that by a proper geometric arrangement of the structural framework supporting the dish the structural deformations can be controlled and caused to occur in a predetermined pattern. For example, if the surface of a radio telescope in one position has a true paraboloidal surface and for a different orientation of the telescope can be controlled to deform into a different paraboloid, then the only change to be accounted for is the variation in the paraboloidal focal length which can be accomplished by moving the feed mechanism in the appropriate fashion.

There are basically two avenues open for the theoretical development of the above concept, referred to as the "Homologous Structure" concept.

a) Work a conventional structural deformation problem backward. By this we mean specify in advance what the structural deformations are to be, then solve the resulting equations for the geometric properties of the structure necessary to effect such a solution.

b) Develop a theory for the calculation of structural deformations including free parameters to be adjusted in the process of the problem solution, such that the resultant structure approaches a truly "Homologous" structure.

Method (a) conceptually will work, but practically has severe limitations since the resultant equations are non-linear in nature. The solution to these equations frequently results in imaginary values for the geometric properties of the desired structure. Due to this liability, the method is unreliable and in any particular situation one cannot predict in advance whether the solution will be useful or not.

Method (b) will also work from a conceptual viewpoint. In addition, it appears that the method will produce useful, meaningful results.

The University of Virginia group is presently programming for the digital computer S. von Hoerner's development of method (b). One cannot state absolutely at this stage that this method will produce meaningful results in every situation, but it is our expectation that such may be the case.

Effort will be continued in this area since the results of this study can be applied to all radio telescopes, regardless of the mode of support. This appears to be one concept which can unify all the variations of telescope design in the future due to its power and obvious cost-saving potential. The continuing effort also is justified by the usefulness of this concept in the design of structures other than radio telescopes. The need for such a tool to be made readily available to structural designers in all fields is overwhelming. With such a design tool available, designers of movable structures could effect sizeable cost-savings due to elimination of massive, overdesigned structures to reduce structural deformations.

VI. SUMMARY AND FUTURE PLANS

J. W. Findlay and M. M. Small

In summary it is pleasant to report some progress in the study of a Largest Possible Feasible Telescope. Our approach has been informal. Our concern has been to examine all ideas contributed from within and without the group. There have been many.

We believe we have separated the chaff and are now in motion toward a definition of an LFST. Since arrays are not being considered, the largest feasible, supportable diameter dish with least degradation over a useful sky coverage at least possible expense is our objective.

It is too early to make choices, but feelings are germane and at this juncture we believe the following to be the status of the work.

a) Either of the limited elevation concepts set out in Chapter III could be built now at a cost in the vicinity of $60 million. We do not recommend that either brute-force design be built unless there is a clear-cut need for such a telescope on a crash basis. In such case we have two concepts which quickly could satisfy the need. The maximum diameter possible for least cost in either concept could be determined by optimization techniques now available, should this need arise. The first, and soon the second, conceptual design is thus on the shelf against such contingency--others may follow if the same cost range can be maintained.

b) The floating sphere concepts of Chapters IV and V are novel. We are titivated by them, particularly since here we may have a break-through. Heine believes his concept can be built for less than $50 million and is continuing to refine the design to pull the cost lower. Jennings is working to the same end, as are North American Aviation and Lear Siegler. Occasionally the cost criterion distresses us, but as engineering groups we recognize that there is no justification for a design simply because it can be built without regard for its cost. The sphere offers the possibility of high performance for a reasonable price, and the several aspects of it have been pressed for this reason. The prospects for its front-running emergence are good.

c) Homology, as discussed in Chapters II and V, may already be a breakthrough in structural design. Von Hoerner's fundamental approach is certainly the most original that has appeared in structural design in half a century. The mathematical model that he has proposed now is being reduced to a computer routine, following which a model will be built. Even if no further work were done toward large structure design, this contribution already has excited the Civil Engineering field to an extent to fully justify our support of this effort.

Future effort is planned as follows:

a) E. Faelten will continue his reduction of unconventional concepts to workable designs and estimates in order that we may increase our number of "on the shelf possible" designs against the possibility of a requirement for one. His effort will continue to be to optimize performance for minimum cost.

b) The 600-foot Sugar Grove experience will be thoroughly examined to determine what went wrong and to extract what remains that is right. Access to the job record has been arranged by the Navy through the National Science Foundation and this review will be started.

c) The floating sphere, on air and/or on water, will continue to be investigated by O. Heine and others in concrete, steel and core material until it can be disposed of as a concept, or put on the shelf as a possible priced design. One or the other conclusion is certain, but perhaps equally important will be the papers to be contributed to various disciplines as a result of these continuing investigations in shell and sphere design theory.

d) Ground-bound reflectors, such as Kraus antennas, Schell or Bracewell tilting antennas, or Von Hoerner's parabola shown in Chapter II, Figure 5, will be looked at in competition with other configurations. All of these types have performance limitations more serious than other types now being studied. However, since the cost of such instruments can be significantly lower than that of large, high structures, and since cost may prove to be the significant criterion in this exercise, it is possible that a largest feasible steerable telescope could come from this group. A front-runner in this comparision, of course, is the Arecibo instrument, multiplied by two or three, advantageously located for best sky coverage. An attempt at a quantitative evaluation of the worth of such a plan will be attempted.

e) The homology approach by Von Hoerner and Jennings will continue to be supported until the principle can be demonstrated or abandoned. The specific worth to radio astronomy and the general contribution to structural design theory both justify the continuation of this effort. Assuming the successful translation of Von Hoerner's mathematical models into satisfactory computer programs, a model will be designed and then built for test measurements by J. Hungerbuhler at the NRAO.

Conclusion

The group will continue at the present level of funding. Its objective is to determine the LFST. It is tempting to offer such this year or next, but that prediction is not possible. We will continue the investigations outlined above and welcome, in fact solicit, the suggestions of others and their participation in this study. From our efforts, hopefully augmented by those of others, we will continue to stockpile feasible designs with certain performance characteristics for predictable expenditures, but do not expect to propose a specific design until it is obviously the LFST.