Strawman Optical Reception Development Antenna (SORDA)

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A strawman design of a ground-based station for receiving optical communications from deep space is presented. This strawman will serve as a basis for further study and design refinement. The recommendation to build rather than to use an existing facility is explained. Parameters of the design have been selected to postulate a workable system, starting with a 10-m-diameter, hexagonally segmented, f/0.5 primary mirror. The effects of variations of design parameters on performance and cost are discussed. Some design formulas are included. An electro-optical functional block diagram is presented and discussed. Cost calculations are based on a previous cost model for the hardware or on typical construction costs per unit area for several types of facilities. Other cost factors are included in the usual way for Construction of Facilities. The ratio of high and low reasonable values was less than a factor of 2,with a best estimate of under $16,000,000.

I. Strategy for Optical Reception Development

A long-range concept has been established for the development and deployment of optical communications for planetary use and beyond. The concept is based on a number of assumptions, and although it has been modified occasionally as required by new constraints such as mission launch-date changes, its basic ingredients have remained very stable for several years. Those key ingredients are (1) a ground-based optical reception development antenna by 1993, ready for the following item; (2) a mission-augmentation flight experiment package aboard Cassini, to be launched in 1995; (3) a spaceborne R&D optical reception station in conjunction with the space station by 1999; (4) a user spacecraft transceiver by 2000; and (5) an operational optical reception station in geosynchronous orbit by about 2015.

Other optical communications development concepts are possible. One could skip the ground-based optical reception development antenna and start directly with spaceborne optical reception. However, it is believed that before major resources will be committed for a spaceborne facility, substantial confidence in the utility and performance of optical communications technology must be established. Furthermore, it is believed that the spaceborne facilities will not be fully developed immediately but, like the current deep-space network, will continue to increase in capability long after they first become operational. Thus, the ground-based antenna will be a key beginning point in the development of deep-space optical communication.

Below, the strawman optical reception development antenna is introduced. A rationale is outlined which favors building the antenna over renting time on existing astronomical facilities. Various characteristics of a model facility that is adequate for the proposed experiments are then described. Values of some parameters have been selected as a starting point for further discussion and research. An electro-optical functional block diagram is presented and explained. Preliminary estimated costs with high and low ranges are also presented on the basis of a combination of several different methods of costing.

II. Introduction to the Strawman Optical Reception Development Antenna

A strawman optical reception development antenna based on the ground, together with the associated pedestal, observatory building, dome, sunshades, and signal processing, acquisition, tracking, and control systems, is postulated. It will support development of tracking and data acquisition for deep-space probes as communications frequencies are raised to the visible region.

Visible optical communication from deep space will initially be accomplished in spite of the disrupting effects of the Earth's atmosphere. The optical phase of the received signal will be ignored. Direct detection and photon counting will exploit the granularity of the optical signal to suppress noise. The optical coherence will not be wasted, however; a narrow-band optical predetection filter will allow discrimination against solar interference.

The optical reception antenna will be concerned primarily with photon collection. Costs will be reduced by accepting considerable blur. Coarse imaging of a portion of the received beam will permit acquisition and tracking of deep-space probes. Imaging of natural bodies will be no better than adequate to verify sufficiently accurate coarse pointing of the antenna to a preselected portion of the sky. Very fast[1] uncorrected primary optics will further sacrifice image quality for cost reduction by making the entire optical train fit within the sphere swept out by the motion of the primary collector. The primary collector will consist of low-mass, rigidly mounted, hexagonal reflecting segments.

Daytime communication to within a small solar elongation angle will present sunshading and convective airflow problems not previously encountered by astronomical observatories. The conventional pair of meridional external dome shutters will not be used. Instead, an aperture plate running in meridional tracks and a pair of zonal shutters, above and below the plate, will limit the dome aperture to the same size as the telescope aperture (see Fig. 1).

A solid cover will be selectable for mounting on the aperture plate to seal the dome against inclement weather, especially when high winds are expected. When the antenna is in use, the aperture plate may carry a selected sunshade. The sunshade will be rotated axially to prevent direct sunlight incidence on the primary mirror. A sunshade will be selected according to the solar elongation angle from the deep-space probe in order to shade sufficiently without being unreasonably long, unduly reducing the field of view, or unnecessarily obstructing the aperture. One sunshade will consist of a clear-aperture tube for use when the solar elongation angle is large. Two other sunshades, containing internal vanes with coarse or fine spacing, will be used when the solar elongation angle is intermediate or small. A control system will maintain alignment of the dome, aperture, sunshade, and telescope line of sight.

The dome design philosophy and observatory site selection criteria will differ from those usually applied by astronomers. Large seeing disturbances caused by the dome and sunshades, as well as by nighttime or daytime operation, will be tolerated along with considerable blur. Altitude and exceptional seeing will likewise be traded for high visibility and easy logistics.

III. Design Issues and Cost Drivers

A. The Decision to Build a New Facility or to Use an Existing Facility

A new facility should be built.

Concerns expressed below preclude the use of an existing facility. In summary, these are as follows: (1) only a few facilities have telescopes large enough to demonstrate optical communication at significant data rates over representative large distances; (2) no existing facility has the sunshades required for daytime reception, nor could any facility accommodate an adequate sunshade within its dome; (3) existing facilities were not designed to cope with the added heating from daytime operation, nor would they cool rapidly enough to avoid degrading the performance expected by nighttime users; (4) conflicts with other users might be avoided by obtaining exclusive use, but exclusive use is not available on any telescope that is sufficiently large for a convincing demonstration; and (5)

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[1] In optics, "fast" means that light passing through a lens converges to a focus in a distance that is short compared to the aperture diameter, and "slow" means the convergence distance is long. The focal ratio or f number is the ratio of the focal length F to the aperture diameter D, so the larger the f number, the slower the lens and the slower the beam produced by the lens. If the lens is used for photography, fast lenses allow rapid exposure of the film to the required density, and slow lenses make the exposure process slow.

short-term exclusive use of a large telescope might be obtainable for a crisis such as a flyby planetary encounter, but optical communications experiments are not being planned as crises.

1. **Adequate diameter for a significant data rate.** Demonstration of optical reception from Saturn at a data rate of 100 kbps is part of the current concept. The minimum usable collector diameter is 10 meters, to provide something less than a 3-dB margin when receiving below the atmosphere under favorable weather conditions. If time on an existing 10-m facility were unavailable for this demonstration, one could still receive 25 kbps from Saturn with a 5-m telescope like the one at Palomar, or 6.25 kbps with a 2.5-m telescope like the 100-inch Hooker telescope on Mt. Wilson. With any of these telescopes, there is always a short enough range somewhere on the way to Saturn within which 100-kbps optical communication is possible. Nevertheless, it is important to demonstrate optical communication at a reasonable data rate all the way to Saturn in order to show the capability of coping with pointing problems and long loop delays.

Accepting data rates from Saturn as small as 6.25 kbps or even 25 kbps would be a disappointment, since it would mean discarding all potential for mission augmentation if the optical communication works well. Future missions are considering multispectral imagers and synthetic aperture radar science capabilities, sensors which generate enormous amounts of data. The current plan is to show that optical communication can bring those data home.

2. **The need for sunshades.** A convincing demonstration requires daylight reception as well as nighttime reception, because many people do not understand that a telescope with good filtering can look through the blue sky. The experiments must further demonstrate reception when the elongation of Saturn from the sun is relatively small, ideally as little as 3 degrees, in order to show capability comparable to that of radio.

In order to receive communications at small solar elongations, the optical antenna or telescope must be sunshaded. Direct sunlight on the primary mirror would produce intolerable scattering.

No existing astronomical facility of the required size can accommodate a sunshade of the required length within its dome. Astronomers do not use sunshades on the ends of their telescopes; they use the earth as a sunshade by observing at night. Domes are very expensive; they are not usually built larger than the size needed to clear the telescope as it swings.

Therefore, if an optical reception development facility is not constructed, one must obtain permission not only to rent time on an existing facility, but also to modify the facility. One would need to add sunshade mounting tracks and interior shutters to the dome and provide for storage of the sunshades during inclement weather. This modification of an existing facility would in itself be a large Construction of Facilities (C of F) project, but C of F money is rarely used to modify a rented facility. A request for funds to do that would be discouraged from the start.

3. **Thermal problems with existing facilities.** Large astronomical facilities keep their domes closed during the daytime. Opening them would cause heating of the interior and would set up turbulent convection currents. These would blur the images, require opening up the field of view, and degrade the communication link performance by forcing acceptance of extra background light. Most of the current analyses have made some allowance for such effects. However, the convection currents would not die out until several nighttime viewing hours were lost. One could not avoid schedule conflicts with other users by promising to use the telescope only during the day and to clear away all the equipment by nightfall. The next day the astronomical users would complain that the seeing during their viewing time was spoiled because the telescope was still hot.

Even worse, thermal shocks can distort the mirror. The old large mirrors (e.g., those on Mt. Wilson and Mt. Palomar) were made from Pyrex or even bottle glass. Pyrex has a huge thermal expansion coefficient (for glasses), and bottle glass is worse. It would take weeks for such mirrors to settle down after exposure to daytime temperatures if the dome were opened during the day. If the facility did not have a modern, relatively thermally insensitive mirror, it would be difficult to obtain permission for daytime use at all. Alternatively, one might have to retrofit the facility with a specially designed air-conditioning system.

4. **Exclusive use requires accepting a small diameter.** Conflicts with other users might be avoided, of course, by securing exclusive use of a facility. Any attempt to obtain exclusive use of an existing facility with a 10-m-diameter telescope, however, appears to be hopeless. If a small mirror size were accepted, it might be possible to negotiate exclusive use of some existing telescope facility (e.g., the Hooker telescope) along with permission to mount sunshades on it.

The sunshades would have to be built, retrofitted, and financed as special test fixtures to be discarded after the demonstrations. One would still have to determine if the degradation of the imaging (and of the signal-to-background ratio) due to thermal cycling would be tolerable for optical communications demonstration purposes.

The cost of following this procedure would be far less than that of the construction of a dedicated 10-m facility. However, it would force us to accept a limited aperture and a low data rate from Saturn. Additionally, the procedure would not provide a long-term development stepping stone for future optical reception systems.

5. **Scheduling problems for sharing a facility with adequate diameter.** The DSN could negotiate with any facility (including the new Keck 10-m telescope facility) to obtain viewing time for an event such as a flyby encounter. Cassini, however, is not a flyby. Some tests are also desirable on the way—say, between Jupiter and Saturn—but there would be no special time constraint to use as a crisis for negotiating purposes. There would also be no crisis event once the probe was in orbit.

Putting an experiment on an orbiter rather than on a flyby mission offers the advantage of flexibility in scheduling. This advantage is much less valuable than a crisis when bargaining for viewing time, however. Also, the managers of existing facilities will be reluctant to give time when they find out that the optical communications experimenters intend to modify the dome, temporarily disturb the viewing, and perhaps introduce an unknown, relatively long term thermal distortion into the optics.

B. Telescope

1. Aperture diameter

The aperture diameter was chosen to be 10 m.

In [1], it was shown that a 10-m telescope is at the knee of the curve of cost versus logarithmic communication growth, and it provides adequate optical channel capacity for many proposed mission requirements.

2. Primary–secondary spacing

The primary–secondary spacing was chosen as half the primary diameter.

Choosing the primary–secondary spacing at half the primary diameter fixes the primary *f* number close to *f*/0.5. Actually, if the central obstruction is one hexagon in a four-ring system, the primary *f* number may be *f*/0.56. Making the spacing any shorter would decrease the *f* number, worsen the uncorrected imaging unnecessarily, and worsen the departure of the paraboloidal figure from sphericity. Lengthening the primary–secondary spacing would mean that the telescope could not swing within the sphere swept out by the primary diameter. The common diameter of the observatory building and dome would then have to be increased at very substantial cost. Whether the uncorrected image quality produced by such a fast primary beam will be sufficient for the derivation of adequate pointing, acquisition, and tracking information remains to be analyzed in detail.

3. Post-secondary focal point

The post-secondary focal point was chosen as the primary mirror center.

Just before the focus, a tertiary lens collimates the beam to a convenient diameter. The optical train from there must fit behind the primary mirror within the sphere swept out by its radius for the cost reasons given above. This and the secondary mirror diameter set the post-secondary *f* number.

4. Primary mirror segmentation

Segmentation was chosen over a single-piece mirror.

A 10-m-diameter single-piece mirror is too large and heavy to fabricate, coat, or swing in a telescope. For glass mirrors, the thickness must be about one-sixth the diameter to maintain the polished optical figure. If the specific gravity of the chosen glass were only 2.5, the mirror mass would be 327,000 kg, and the weight would be 360 tons.

Segmentation was chosen over multiple mirrors.

Multiple mirrors and multiple detectors would add detector noise without increasing the signal. This could be serious at very low light levels when space probes are very far from earth.

Multiple mirrors and a single detector may require extra light-collection mirrors, each with its own alignment requirements. If energy collection were the sole issue, this would not be much worse than the alignment requirements of multiple segments. However, some imaging capability is also necessary for the acquisition and tracking of the deep-space probe. Image quality from a collection of mirrors may be much worse than that from a segmented mirror. This trade must be reevaluated after the imaging requirements have been better determined.

Segment substrates were chosen to be honeycomb rather than solid panels.

A hexagonal glass substrate whose width w across the flats is 1.11 m, whose thickness is $w/6$, and whose density is 2500 kg/m^3 has a mass per unit area of 462 kg/m^2. Panels with similar stiffness and thermal stability, but using honeycomb core construction,[2] can be made with mass-to-unit-area ratios of less than 10 kg/m^2.

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[2] P. N. Swanson, *A Lightweight, Low-Cost Deployable Reflector (LDR)*, JPL Publication D-2283 (internal document), Jet Propulsion Laboratory, Pasadena, California, June 1985.

Segment alignment was chosen to be manual rather than automated.

It is assumed that gravitational distortion will not be problematic as the telescope is turned in different directions because of the low mass of the segments. and because the truss rigidity need not be compromised by such space-flight requirements as low mass and deployability.

Segmentation was chosen as hexagonal with four rings and 60 segments.

The Keck telescope has three rings and 36 segments. Segment width across the flats is calculated from the number of rings n and the overall aperture diameter D as $w = D/(2n + 1)$. For the 10-m Keck telescope w is 1.43 m, and for the SORDA w = 1.11 m.

As the number of rings increases, the segment size, weight, and departure of a spherical segment figure from the overall paraboloidal figure all decrease. Complexity, alignment problems, and residual alignment errors and their contribution to blur all increase as the number of rings increases. The designers of the Keck telescope chose three rings rather than four in order to reduce the complexity of their active segment alignment system. They feared that aligning 60 segments rather than 36 would represent a control problem too difficult to encounter on the first model. Other users might profit from their experience, however, and use a larger number of rings in the future [2]. With SORDA there is no control problem. However, the alignment has been made more difficult by the use of four rings instead of three.

The segment figure was chosen as paraboloidal rather than spherical.

The departure of an $f/0.5$ paraboloid from sphericity at the farthest points of a segment from the innermost ring amounts to about 1200 waves, or 0.6 mm. This is far too much to correct by polishing, so paraboloidal segments were chosen at considerable increase in cost. One spherical tool (the mold that forms the segment substrate) might cost $50,000, and it would serve for all 60 segments. If the segments are to be paraboloidal, symmetry permits dividing the segment number by no more than 6. The SORDA design will require 10 tools, each of which might cost $250,000 because of their nonspherical shape. Thus the tools for making a segmented paraboloidal mirror cost 50 times more than the tool for making multiple spherical mirrors mounted on a paraboloidal frame.

Options to be studied also include using best-fitting spherical mirrors at each segment location, for which the tools would cost 10 times more than the one for making multiple spherical mirrors, or best-fitting spherical mirrors for each ring, for which the tools would cost four times as much.

The outside diameter circle was chosen to be tangent to the corner hexagon's outer edges (see Fig. 2).

Other options make the circle pass through the points of the midlateral hexagon neighbors (Fig. 3), through the point of the midlateral hexagon (Fig. 4), or through the outer end of the joint between the midlateral hexagon and its neighbor (Fig. 5). The option chosen requires negligible trimming of any hexagon and provides the smallest width across the flats for a given diameter, at a cost of the loss of the unfilled irregular area at the edges. Some of this area might be obstructed in any case by the tripod or hexapod that supports the secondary mirror.

For an aperture of diameter D = 10 m, the segment width w across the flats for various options is

$$w = \begin{cases} 1.11\ \text{m} = D/9 & \text{tangent to the outer edge of the corner hexagon} \\ 1.20\ \text{m} = D\sqrt{39}/52 & \text{through the points of the midlateral hexagon neighbors} \\ 1.24\ \text{m} = D\sqrt{3}/14 & \text{through the point of the midlateral hexagon} \\ 1.32\ \text{m} = D\sqrt{129}/86 & \text{through the joints between the midlateral hexagon and its neighbors} \end{cases}$$

in order of increasing aperture filling and increasing number of trimmed hexagons. The last option cuts all the outer ring hexagons substantially and completely fills the aperture.

Increasing the segment width also increases the paraboloidal departure from sphericity at the extreme points. This may increase costs depending on the method of forming and polishing tools for the panels. The worst departure is at the outer points of the inner ring hexagons. There the departure, as measured parallel to the telescope line of sight, is

$$2fD - \frac{19w^2}{48fD} - \sqrt{\left(2fD - \frac{19w^2}{48fD}\right)^2 - \frac{469w^4}{2304f^2D^2}}$$

where f is the focal ratio or f number. For the four options mentioned above, with an $f/0.5$ primary mirror, the respective departures are 0.63 mm, 0.86 mm, 0.97 mm, and 1.26 mm.

5. Primary mirror figure tolerance and surface quality

The root-mean-square figure tolerance and surface quality should be 2 μm.

The use of low-mass honeycomb panels for low cost and mass reduction requires accepting a currently achievable figure tolerance and surface quality. This means accepting considerable blur from this source as well as others, but the main purpose is just light collection. A budget of blur, aberrations, diffraction, and seeing must be prepared and analyzed to determine how much disturbance from each source is tolerable.

The most important cost driver after the diameter of the primary aperture is the amount of blur accepted for the telescope. The major driver of blur is the surface quality of the primary mirror, when a rough reflector is accepted. (It is assumed that the panels will remain in accurate alignment.) The root-mean-square surface roughness σ accepted is about 4λ, with an estimated correlation distance $T_c = 0.25$ m, approximately one-fourth of the distance across the segments. This would give a blur of $\theta = 9.33''$ (i.e., all but $e^{-2} = 13.5$ percent of the light collected from a point source would be scattered into a cone of angle $\theta = 4\sqrt{2}\sigma/T_c$, according to [3]). Studies to date have shown that blur circles this size will not overly compromise the quality of deep-space communication links [1].

6. Secondary mirror diameter

The secondary mirror diameter was chosen to fit within one hexagon.

This arrangement makes the primary beam as slow as possible, given the primary–secondary spacing, without requiring cut hexagons in the primary mirror. The fractional area obstructed centrally is 1/61.

C. Dome

1. Diameter

The dome diameter was chosen to be 12 m.

The telescope primary diameter is 10 m. Allowing 1 m on either side for clearance and wall thickness, the dome diameter is 12 m (39 ft). This size is within the upper range of commercially available standard sizes, at least for hemispherical domes. However, if the lowest telescope elevation angle $e_{\min}$ to be used is less than 56.5 degrees, the dome required will exceed hemisphericity. The fraction of a sphere required will be (156.5 degrees − $e_{\min}$)/180 degrees, or 0.87 for a telescope that can look horizontally.

Alternatively, a much larger hemispherical dome could be used, with the telescope center mounted above the hemisphere center. A 10-m-diameter telescope mounted 5 m above the center of a hemispherical dome, with 1 m of clearance above the telescope, would have an unobstructed horizontal view if the dome diameter were 22 m (72 ft). The observatory building cost would increase by a factor of $(22/12)^2 = 3.4$. The dome size would probably require custom fabrication.

2. Thermal design

Special thermal requirements are imposed by operation at all hours.

Astronomers do their observing at night using the Earth as a sunshade. Domes are ordinarily kept closed during the day in order to prevent thermal shocks to monolithic mirrors that would not rethermalize for weeks. The present requirements call for a dome and sunshades that will exclude direct sunlight on any part of the telescope, especially the primary mirror, but also on the mount and the back of the secondary mirror.

3. Automatic dome positioning

The dome will be positioned automatically by the telescope pointing system.

Automatic positioning of the dome relative to the telescope line of sight is desirable for reception of lengthy communications from the deep-space probe. It is assumed that this positioning will be controlled by the same system that acquires and tracks the deep-space probe and points the telescope. See Fig. 6 for a block diagram of the systems.

D. Sunshades

1. Location

The sunshade location was chosen to be external to the dome.

Precise alignment between the sunshade and the telescope optics is not required. The spacing between the primary and secondary mirrors, for example, is critical for focusing, but the sunshade may be made large enough to tolerate small parallel displacements of its optical axis from the telescope line of sight. Small angular displacements will have no effect on the system performance as long as the sunshade has a clear aperture somewhat larger than the telescope aperture. A sunshade with internal vanes would produce extra obstruction when displaced angularly, however.

The dome is the most expensive ingredient in the observatory building, and its cost increases rapidly with diameter. Mounting the sunshade externally rather than at the end of the telescope reduces the required observatory and dome diameter to the telescope swing diameter plus clearance.

2. Strength

The dome will have to be stronger than usual to support sunshades.

Telescope domes have to be strong to survive high winds at mountain sites. An additional strength requirement, yet to be analyzed in detail, arises when a sunshade of considerable weight is to be positioned at various elevation angles for operation during moderate wind conditions. A counterweight may be required, and the position or mass of the counterweight may require dynamic adjustment.

Either the dome or the telescope structure must bear the weight of the sunshade. One or the other will therefore require additional strength at extra cost. Putting the sunshade on the dome rather than on the telescope increases the required precision of the automatic dome positioning. The required precision is still not as stringent as that required for pointing the telescope.

3. Aerodynamic design

The external sunshade will require redesign of dome aerodynamics.

Good seeing–the maintenance of high image quality unperturbed by atmospheric turbulence–usually requires special dome design to ensure that airflow around the dome is as nearly laminar as possible. The presence of one of several sunshades of varied internal vane configurations will alter the aerodynamics of the dome considerably and will present special design challenges.

4. Length

The sunshade length was chosen to be 9 m.

Making the external sunshade length equal to 3/2 of the dome radius R produces a structure that looks like a ball with a short protruding shaft (see Fig. 1). This is not too unwieldy for pointing, given the wind loads to be borne during operation.

5. Removable mounting

Sunshades will be removable.

Table Mountain Observatory reports logging winds of 90 m/s (200 mi/h), and their domes survived. An external sunshade would probably add too much wind load to a dome of reasonable strength, so the sunshades will be removed and stored safely when inclement weather is expected.

6. Interchangeable mounting

Sunshades will be interchangeable.

The sunshade limits the largest field of view of the telescope. It should therefore be removable when it is not needed.

The dome itself provides some sunshading. If the aperture of the dome is a circle of the same diameter as the primary mirror, the dome radius is 6/5 of the primary mirror radius, and the primary mirror is situated in its swing sphere as far back as possible from the dome aperture, then direct sunlight will be excluded from the primary mirror as long as the angle between the telescope line of sight and the solar direction line is greater than 71.65 degrees. The dome aperture circle and the primary mirror rim will lie in parallel planes separated by $\sqrt{R^2 - (D/2)^2} = 3.32$ m.

Operation will often require looking closer to the Sun than 72 degrees. Sunshades will be provided that will not unduly limit the telescope field of view. An open tubular sunshade mounted on the dome aperture circle and extending from there by 3/2 of the dome radius, or 9 m, will exclude direct sunlight at a solar elongation angle from the deep-space probe of 39.07 degrees.

The present Deep Space Network can communicate with a deep-space probe within about 1 degree of the Sun. An open-tube sunshade to permit operation at that angle is too long. Instead, a second sunshade will be provided, at the performance cost of the introduction of a small amount of additional obstruction and diffraction. Eight equally spaced parallel-plate vanes extending from the end of a similar tube down to the dome radius (6.32 m) would permit looking to within 10 degrees of the rim of the Sun. If the number of vanes is $n = 8$, the vane spacing is $D/(n + 1) = 1.11$ m.

To look within 2 degrees of the rim of the Sun (solar elongation of 2.25 degrees), another sunshade would have 45 parallel plate vanes with a spacing of 22 cm. This introduces considerably more obstruction than the other sunshade. However, it will usually be needed only for tracking missions to the terrestrial inner planets, as the giant planets and Pluto spend little time at such small conjunction angles.

E. Site Selection

The site will be chosen for high visibility and easy logistics rather than for good seeing.

The signal attenuation of the clear atmosphere and the image-degrading effect of turbulence both decrease as elevation increases. Elevation is not as important to optical reception as it is to astronomy, however, because there are ways to increase the signal strength, and because optical reception does not rely on clear images. On the other hand, visibility (freedom of skies from cloud cover) is essential to this operation, and the site will be selected accordingly.

Proximity to other Deep Space Network sites, which would simplify the logistics of maintenance and operation, is desirable but not mandatory.

IV. Optical Functions, Signal Processing, and Control Systems

Figure 6 shows the electro-optical functional block diagram. Between the blocks the laser beams are shown as broken lines, natural-light beams as thick solid lines, and electrical cables as thin solid lines.

A. Optical Functions

The telescope primary and secondary and the beam-steering mirrors will be coated for high reflectivity in the extended visible region.

Coating for high reflectivity at only the laser wavelength would increase the signal power while reducing background interference significantly. Solar incidence and the need to provide some verification of correct pointing relative to the stars or planets prevent optimizing the reflectivity at the laser wavelength.

If the primary mirror substrates were transparent and nonabsorbing (or absorbing but very stable thermally), it would be possible to coat the mirror segments to reflect the laser wavelength with high efficiency over a narrow spectral region of 10 or 20 nm. The remaining natural light could be transmitted by the coating and substrate to a cooled, absorbing screen on the back of the primary mirror. In this way it might be possible to avoid the need for sunshades. However, the ability to see any natural objects in the sky (except the very brightest) would be lost. This loss might not be inconvenient if the objects were to be viewed only occasionally for the purposes of checking calibration of the altitude and azimuth setting circles. However, if a planet or guide star is to serve as a beacon for locating the spacecraft, then it has to be detectable.

The tertiary collimator will be coated for broadband low reflectivity in the extended visible region.

Once again, the antireflection coatings could be optimized only for the laser wavelength, but the transmission of natural light would suffer.

Beam steering will be provided on two axes for both natural and laser light.

Beam steering will first be used in acquiring the laser signal and centering it on the direct laser photodetector. Once the signal is acquired, the beam-steering mirrors will provide fast reactions to remove pointing errors due to atmospheric disturbances and telescope vibrations.

An optical filter with a tunable notch for the laser signal will separate laser light from natural light.

The optical filter bandwidth will be as large as 1 nm or as small as 0.1 nm. If it is very narrow it must be tunable to accommodate Doppler shifts of ±53 GHz (±0.05 nm) in the received signal from a distant spacecraft. Very narrow bandwidths are usually achieved by combining in series a multilayer dielectric narrowband filter and an etalon. These two elements may be separated. The multilayer dielectric filter may be placed at an angle on a beamsplitter so the natural light (minus a narrow notch) can be sent one way through a focusing lens to a planet/star detector, while the narrowband light is filtered further by an etalon.

A selectable power splitter will separate some of the laser signal for the acquisition and tracking system.

About half the laser signal will be separated in the acquisition mode. Later, once the signal is acquired, only about 5 to 10 percent of the laser light will be used for tracking. The rest will be detected for communications. A selectable power splitter is therefore required.

The field stops will be adjustable for operating mode and conditions.

During acquisition the field stops must be larger than they are during tracking. Also, the direct laser photodetector field stop may be adjusted according to the amount of background present.

B. Signal Processing

Once the signal is detected directly by the laser photodetector, it will receive very little immediate processing before being recorded and transmitted for signal processing at the telescope site. The important information to be fed back to the systems controller immediately is just that the signal has been acquired.

C. Control Systems

The operations processor receives commands to locate, acquire, and track spacecraft. Localization is first achieved by prediction according to past tracking data and the epoch. Pointing of the telescope and dome is done through appropriate controllers and is verified by detection of nearby stars and planets. Once the acquirer/tracker reports acquisition of the spacecraft the operations processor follows it, receiving feedback from lines and sensors not shown on the diagram in Fig. 6.

V. Projected Costs

Preliminary estimates of Construction of Facilities costs for the strawman design are shown in Table 1, which shows best, low, and high estimates in order to provide a feeling for the error ranges involved. The rationale for these items will now be explained line by line.

The midpoint of construction year is the midpoint between the award and completion of the construction contract. The earliest this could be is 1993 based on present cycles for approval of Construction of Facilities requests. The latest pessimistic reasonable estimate is 1994, in order for the facility to be tested and available to support the proposed optical communications flight experiments on the Cassini mission.

The annual inflation factor is used together with the midpoint of construction year to update projected costs for the telescope, sunshade, and dome as well as construction costs per unit area to the midpoint time of construction. Costs also vary according to the contingency factor chosen and the percentage of total costs paid for architectural and engineering overseeing.

The telescope, pedestal, and pointing and control system costs are then calculated according to [1], with inflation from 1985, contingency, and overseeing costs included. Values in the cost estimate tables reflect the supposition that surface roughness is the major contributor to blur.

Present sunshade cost, plus the cost of strengthening either the telescope pedestal or the dome to bear the sunshade weight and the cost of sunshade positioning controls, was coarsely estimated at $500,000 per meter of length in 1987 dollars. When the sunshade is mounted on the telescope, the length was found by considering a single bounce within vanes spaced 2 cm apart when looking within 3 degrees of the Sun. The present cost was then extended in the same way as the telescope cost.

The location and mounting of the sunshade affect the common diameter of the observatory and dome. From the diameter, costs are obtained in two different ways. The observatory floor area is multiplied by a high cost of construction per unit area because of the reinforced concrete necessary and the foundation required for the pedestal. The dome cost was obtained by scaling down the cost of the Keck telescope dome according to the same exponent factor, 2.6, as has been used for telescope diameter. (This factor agrees well with off-the-shelf costs of domes up to 40 feet in diameter.)

Costs for a modest-sized companion building were also included. The area of the signal-processing building was doubled to account for the cost of the full plenum. The site conditioning cost, the preliminary engineering report cost, and the final design cost were taken as percentages of the total cost, but the study and the environmental assessment were considered to be fixed costs. The costs are based on certain models that include scaling studies of recently experienced costs, and typical costs of construction per unit area for various types of construction. A subjective estimate was used only for the cost of one component (the sunshades), and this cost is less than ten percent of the total cost.

VI. Conclusion

A workable model of a ground-based optical reception facility has been presented. The facility is needed to support development of optical communication from deep-space probes. No existing astronomical facility is available and suitable. Reasonable choices of design parameters, design issues, cost drivers, and cost estimates with optimistic and pessimistic limits were included. Several trade-study areas were identified which deserve further analysis. These included the adequacy of uncorrected images for providing pointing, acquisition, and tracking information; the use of multiple mirrors instead of segmented mirrors; the use of segments with spherical instead of paraboloidal figures; the amount of blur to be accepted from mirrors with low surface quality; the location and configuration of the sunshade; dome aerodynamics and thermal design; and visibility and convenience at the site.

References

[1] J. R. Lesh and D. L. Robinson, "A Cost-Performance Model for Ground-Based Optical Communications Receiving Telescopes," *TDA Progress Report 42-87*, vol. July–September 1986, Jet Propulsion Laboratory, Pasadena, California, pp. 56–64, November 15, 1986.

[2] J. Nelson, *The Design of the University of California Ten Meter Telescope*, University of California Draft UC TMT Report No. 90, University of California at Berkeley, p. 5-5, December 1984.

[3] V. A. Vilnrotter, *Optical Receivers Using Rough Reflectors*, JPL Publication 85-25, Jet Propulsion Laboratory, Pasadena, California, pp. 2-3–2-4, May 1, 1985.

Table 1. Preliminary estimates of facility construction costs

Item	Approximate*		Low range†		High range††	
	Value	Cost	Value	Cost	Value	Cost
Midpoint of construction year	1993		1993		1994	
Annual inflation factor	4%		4%		6%	
Contingency factor	20%		15%		30%	
Architectural and engineering overseeing	2%		2%		2%	
Aperture diameter	10 m		10 m		10 m	
Blur circle or minimum field of view	9″		10″		8″	
Telescope, pedestal, pointing, control		$9,240,000		$8,020,000		$13,800,000
Primary *f*/number	*f*/0.5		*f*/0.5		*f*/0.5	
Primary focal length	5 m		5 m		5 m	
Sunshade length	9 m		9 m		1.3 m	
Sunshade, mount strength, positioning		$1,010,000		$960,000		$1,300,000
Sunshade: 0 = on dome, 1 = on telescope end	0		0		1	
Swing radius of telescope	5.7 m		5.7 m		6.2 m	
Clearance swing to outside wall	1 m		1 m		1.5 m	
Observatory diameter	44 ft		44 ft		50 ft	
Observatory floor area	1521 ft^2		1521 ft^2		1963 ft^2	
Observatory building cost/unit area	$360/ft^2		$350/ft^2		$460/ft^2	
Observatory building cost up to dome		$550,000		$530,000		$900,000
Dome (2.6 power scaling from Keck)		$700,000		$680,000		$1,250,000
Signal processing building, full plenum	2500 ft^2		2500 ft^2		3000 ft^2	
Control room, facilities/utilities	750 ft^2		750 ft^2		1000 ft^2	
Construction cost/unit area	$230/ft^2		$220/ft^2		$290/ft^2	
Cost of companion building		$1,320,000		$1,270,000		$2,030,000
Site conditioning costs		$1,420,000		$1,270,000		$2,140,000
Total for construction of facilities		$14,240,000		$12,730,000		$21,420,000
Preliminary engineering report (PER)		$280,000		$250,000		$430,000
Design (final)		$850,000		$760,000		$1,290,000
Other: study, environmental assessment		$200,000		$200,000		$200,000
Total cost		$15,570,000		$13,940,000		$23,340,000

*To be considered the best values between high and low ranges.
†To be considered an optimistic reasonable estimate.
††To be considered a pessimistic reasonable estimate.

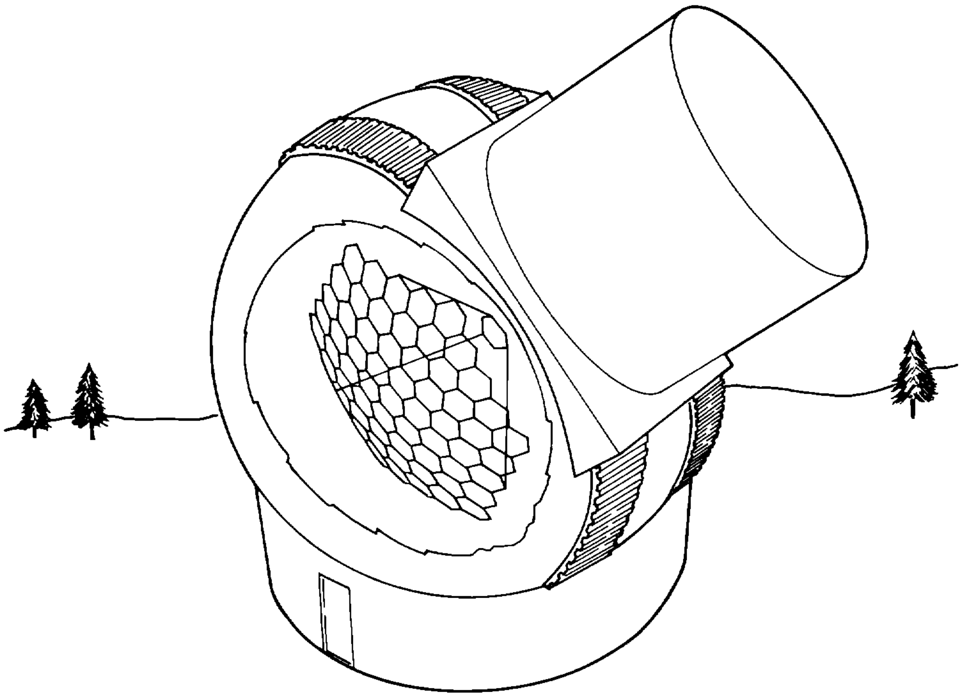

Fig. 1. Optical reception development antenna, observatory building, dome, and sunshades

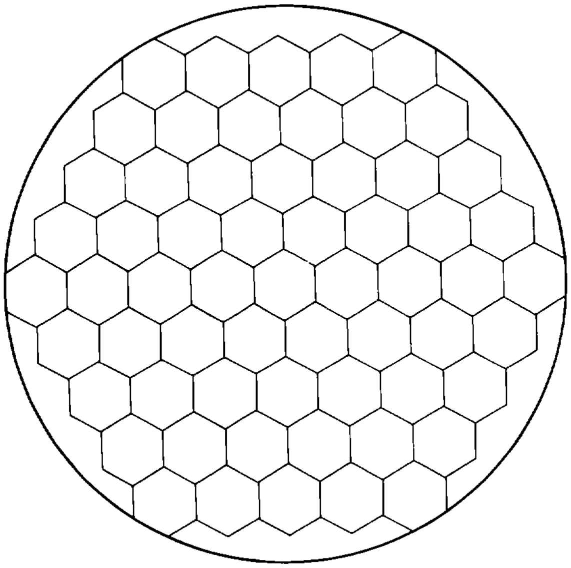

Fig. 2. A four-ring hexagonal segmentation pattern with the outside diameter circle tangent to the corner hexagon outer edges

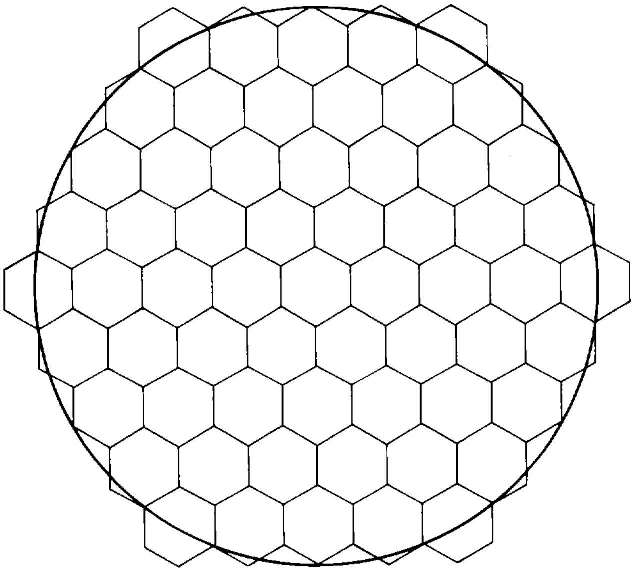

Fig. 4. A four-ring hexagonal segmentation pattern with the outside diameter circle passing through the point of the midlateral hexagon

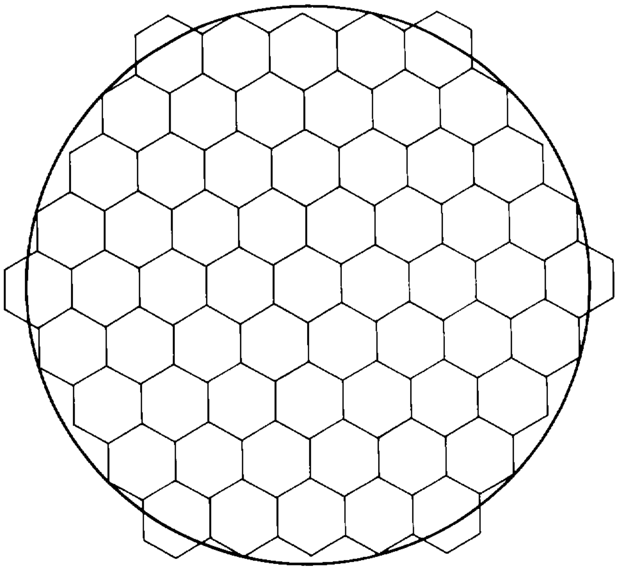

Fig. 3. A four-ring hexagonal segmentation pattern with the outside diameter circle passing through the points of the midlateral hexagon neighbors

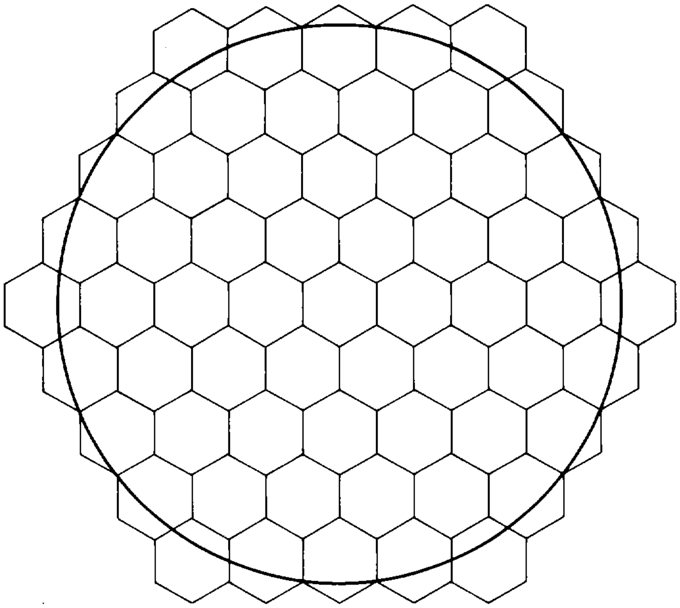

Fig. 5. A four-ring hexagonal segmentation pattern with the outside diameter circle passing through the outer end of the joint between the midlateral hexagon and its neighbor

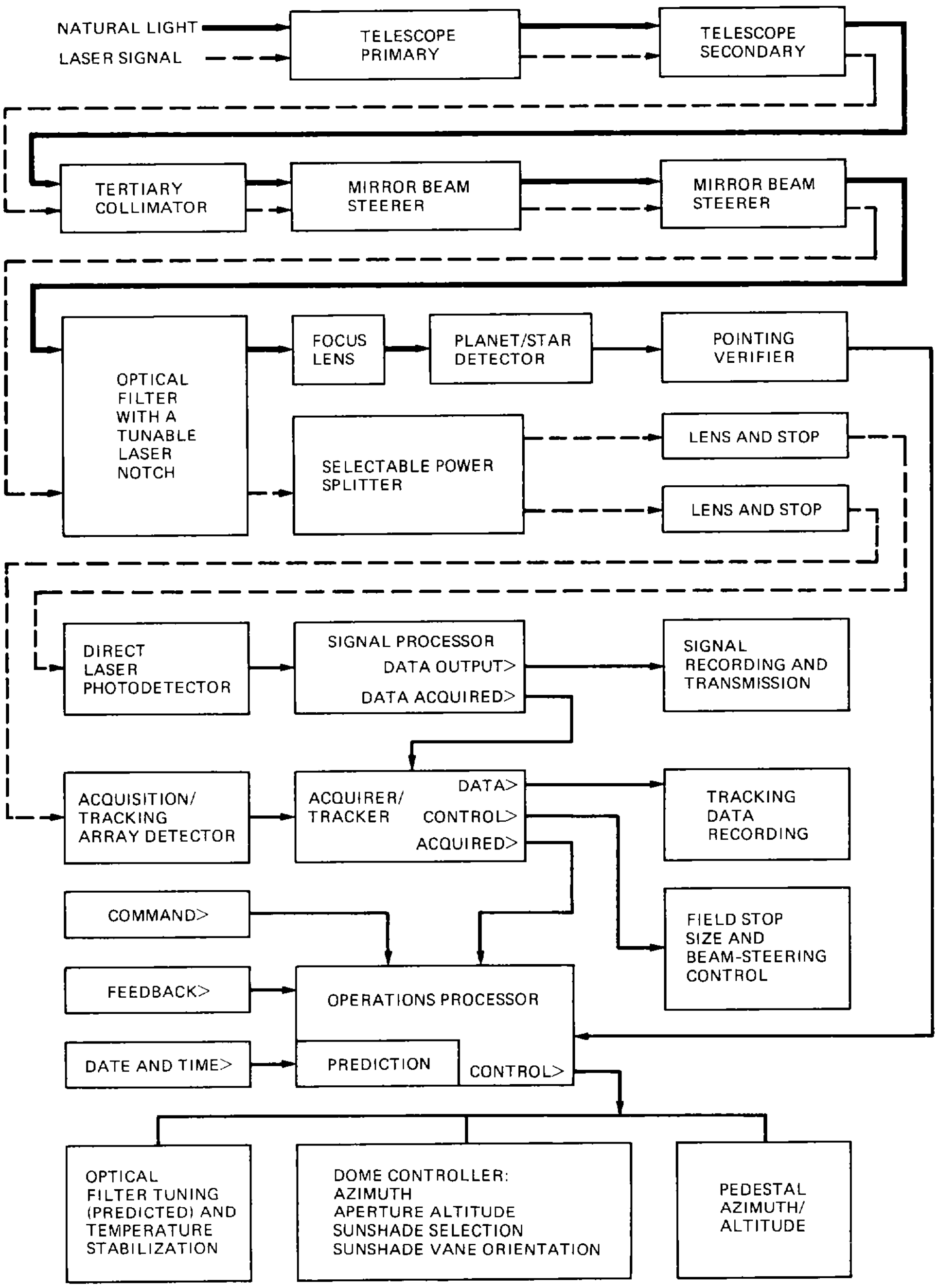

Fig. 6. An electro-optical functional block diagram of systems associated with the optical reception development antenna