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The optical design of a system using a Fresnel lens that gathers light for a solar concentrator and that feeds into solar alignment optics

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ABSTRACT

The Marshall Space Flight Center (MSFC) has been developing a space deployable, lightweight membrane concentrator to focus solar energy into a solar furnace while remaining aligned to the sun. For an inner surface, this furnace has a cylindrical heat exchanger cavity coaligned to the optical axis; the furnace warms gas to propel the spacecraft. The membrane concentrator is a 1727 mm (68.00 in.) diameter, F/1.7 Fresnel lens. This large membrane is made from polyimide and is 0.076 mm (0.0030 in.) thick; it has the Fresnel grooves cast into it. The solar concentrator system has a super fast paraboloid reflector near the lens focus and immediately adjacent to the cylindrical exchanger cavity. The paraboloid collects the wide bandwidth and some of the solar energy scattered by the Fresnel lens. Finally, the paraboloid feeds the light into the cylinder.

The Fresnel lens also possesses a narrow annular zone that focuses a reference beam toward four detectors that keep the optical system aligned to the sun; thus, occurs a refracting lens that focuses two places! The result can be summarized as a composite Fresnel lens for solar concentration and alignment.

Keywords: Fresnel, solar concentrator, optical design, solar alignment, polyimide, thin membrane, cylindrical lens

1. INTRODUCTION

1.1 Background

Solar concentrators made from deployable thin membranes offer a significant size and weight savings as a propulsion power source for spacecraft upper stages. A membrane cast into a Fresnel lens can collect and focus the sun into a thermal cavity so that the energy absorbed there by a propulsive fluid creates a low thrust but a high initial specific impulse (ISP). MSFC is working on a demonstration of technology essential to the advancement of a Solar Thermal Upper Stage (STUS). The STUS goal is to employ solar energy to propel a spacecraft from an initial orbit to a higher one. A prime example is propulsion from a low earth orbit (LEO) to a geosynchronous orbit

1.2 Composite optical design

The overall optical system is illustrated in Figure 1. It is a composite design, concentrating sunlight into a heat exchanger and providing an optical pickoff for maintaining alignment to the sun for the spacecraft carrying the propulsion unit. Except as limited by scatter and chromatic aberration, the STUS plano-convex Fresnel lens sends all the light it receives, save a portion from a narrow annular zone, into the solar furnace. The furnace provides heat for the gas that propels the spacecraft. The Fresnel lens is a polyimide membrane. This lens uses a narrow annular zone, 10 mm (0.40 in.) across, to focus sunlight onto four symmetrically placed detectors that keep the optical system aligned to the sun. Each detector has a cylinder that reduces down the solar image size. The detectors are on a ring centered about the optical axis of the furnace system. One of these detectors and the optics associated with it are shown schematically in Figure 1 as a box labeled "Solar-Alignment Electro-Optics."

It must be noted that the optical design involves a *geometric Fresnel lens*, not a diffractive one. Geometric Fresnels are typically employed where size and weight matter more than optical resolution, such as in overhead projectors, car headlights, and theatrical stage lights. In such applications, they are often not modeled and tested rigorously as an optical element, but installed in the system and then operated, with the system performance being the acceptance criteria. This is also often the case for solar energy use.

1.3 Unique optical material for the manufacture of the geometric Fresnel lens

Very thin membranes are now available for space-qualified, large diameter optics.[1] One of the current optical materials is a polyimide referred to as CP-2. This polyimide developed by Langley Research Center can be cast into an ultra-thin, strong membrane tolerant of space environments. Work has been ongoing since 1988 at MSFC on fabrication and testing of membrane reflectors with CP-2.

The optical prescription for the Fresnel lens is optimized and converted into a groove pattern compatible with the tooling controller on the Moore M-40 diamond turning machine at the MSFC Optics Branch. An aluminum blank is attached on to the machine and the grooves cut in the blank to make the mandrel. The mandrel is used to cast the lens by pouring the dissolved polyimide onto the mandrel in a temperature and humidity controlled environment. After curing the membrane is released from the mandrel for mounting and testing.

MSFC has made 304.8 mm (12.00 in.) diameter models to test and prove the membrane Fresnel lens concept, specifically the mandrel fabrication technique and the optical performance. (These models are F/1.25 and one is a center section out an F/1.25, 1727 mm lens.) The lenses were produced and characterized. The models demonstrate just the solar concentration effects. Transmission losses from scattering through the grooves are larger than expected (~30%). The results of these models, along with related analysis, allows MSFC to scale up research and manufacturing to larger size lenses; however, any optical characterization of a Fresnel lens for a solar concentrator is "wind tunnel-type" (empirical) research.

The optical system's first element will be an ~F/1.7 Fresnel lens of CP-2. It will be a mere 0.076 mm (0.0030 in.) thick! Except for a few Fresnel grooves at the lens center, grooves are cut with a fluctuating pitch (reciprocal of frequency) such that all grooves are 0.051 mm (0.0020 in.) deep. Although the lens will have an aspect ratio of 22,700:1 before grooves (numbering a few thousand) are cut into it (a 34,000:1 average aspect ratio after grooves are cut), it seems adequately strong. A corresponding composite lens with classical surfaces (well-curved surfaces) would have drastic surface discontinuities and most likely could not be fabricated. Even a classical F/1.25 lens without an annulus for solar alignment is too fast (has too low an F/No.) to be fabricated into a lens with CP-2's index-of-refraction.

All 304.8 mm *model* lenses of the 0.076 mm thickness have been fabricated at MSFC with CP-2. Although CP-2 is strong, space qualified,[2] transmits pretty well (a little over 90% from 450 nm out past 1000 nm), and can be made extremely thin; it has a major drawback. It is very much a flint as far as glass type is concerned. Its index-of-refraction is 1.61 (at 587.6 nm) and its ν_d-number is 24. As can be seen from Figure 2, it cuts off fairly sharply near 400 nm. Figure 2 also shows the emission curve for a blackbody at 5800°K to simulate the sun and shows the combined effect of this blackbody curve with CP-2.

1.4 Computer programs for optical design and analysis; modeling the Fresnel surface

Optical analysis was performed originally on ZEMAX and OPTICAD (Focus Software, Incorporated, Tucson, AZ). In the past two years, all optical design and much optical analysis has been performed on CODE V (Optical Research Associates, Pasadena, CA). The Fresnel modeling can not be done completely on ZEMAX or OPTICAD, but these programs are handy for spot diagrams at various defocuses and for ray trace illustrations. CODE V simulates a Fresnel lens as an infinite set of infinitesimal Fresnel grooves. It refracts a ray at the Fresnel surface by obtaining the local slope of the Fresnel lens from the derivative of the standard CODE V sag equation for a high-order aspheric surface. (Only the derivative taken from this equation is significant; the sag is not.) Optical designs are obtained by employing 6th and 8th order aspheric coefficients, the conic constant, and what would normally be called the paraxial curvature. Within CODE V, ordinary paraxial ray trace is worthless and RMS wavefront error calculations are very inaccurate for the Fresnel lens; however, most other ray trace routines work well to model the Fresnel lens. The infinite set of infinitesimal grooves must be converted to a finite set of correct depth before manufacture.

1.5 Non-sequential surface (NSS) ray tracing

In order to model the travel of rays within a paraboloid and a cylindrical (image plane) surface (see Section 2.1), non-sequential surface (NSS) ray trace has to be used on CODE V.

1.6 Challenges

The overall project has several challenges. Casting a large, thin membrane that accurately replicates a Fresnel pattern is a challenging task. Fabricating the mandrel is tremendously difficult. The lens must concentrate light although it is made from a highly dispersive material. Groove shadowing and scattering are significant detriments. The lens must be "bi-focal," possessing a discontinuity, to create two images from a single element. The system's inflatable structure, secondary (discussed below), and heat exchanger are all quite challenging. The entire system must function properly after having been stowed, stored, and deployed in space.

2. SOLAR FURNACE

2.1 Solar furnace optical system

The solar furnace system's first optical element is the huge, 1727 mm (68.00 in.) diameter Fresnel lens. It is a plano-convex lens with the Fresnel surface on the side toward the furnace. Recall that the design employs a *geometric Fresnel lens*, not a diffractive lens. The so called best focus, designated as the "circle of least confusion," is 2936 mm (115.6 in.) beyond this surface; therefore, MSFC designates this system to be F/1.7. Axial chromatic aberration, spherochromatism, and third-order coma (recall that the whole solar disk is being imaged) are essentially the only aberrations; their strength is reflected in the order listed. These aberrations are all significant with axial chromatic aberration from the high dispersion of CP-2 causing most of the blur. The circle of least confusion is expected to have a diameter of about 135 mm (~5.3 in.).

The solar furnace path, illustrated schematically in Figure 3, consists of all the F/1.7 beam (except the narrow annulus from the huge Fresnel membrane), followed by a super fast paraboloid (F/No. can be close to 0.2) near focus that behaves like and looks a little like a funnel. It collects a very wide bandwidth from the sun (400 to greater than 1100 nm) and also concentrates some of the solar energy scattered by the Fresnel lens. The paraboloid feeds the light into an immediately adjacent cylinder coaligned to the optical axis. (The paraboloid and the cylinder appear to be joined together in the schematic; they must not be in actual practice.)

Work by W. T. Welford and R. Winston[3] has been studied to better understand the handling of light by solar concentrators. In fact, Lewis Research Center (LeRC), Analex Corporation (Brook Park, OH), and DF Corporation (Brook Park, OH) have performed much research on the secondary related to this MSFC technology development program and on similar secondaries. They have recommended, instead of a reflecting paraboloid, a special type of concentrator called a compound parabolic concentrator (CPC)[4], "a solid single crystal refractive device." It depends upon total internal reflection to perform its collecting task.

The first models of an all-reflecting paraboloid collector and a CPC have not been fabricated. MSFC and LeRC, respectively, plan to make scaled down models and probably full scale models of these secondary concentrators. The CPC naturally costs considerably more but has certain advantages that LeRC, Analex, and DF have documented.[4] The CPC's heavier weight most likely will not be a problem for STUS projects.

2.2 Heat exchanger

Rays are absorbed when they hit the inner surface of the cylinder or at least after they bounce off of it a few times. The vast majority of rays directed into the cylinder from the secondary are visible or near IR solar spectrum rays. The cylinder is the innermost part of the gas-warming heat exchanger and is made of rhenium (Re). When the exchanger reaches the designated temperature of 2200°K (4000°R) due to the solar irradiance, N_2 gas is fed into the exchanger ducts. The gas passing through the exchanger absorbs the heat and rapidly flows out the nozzle, propelling/thrusting the spacecraft.

Much is yet to be done to combine the optical performance calculations with the engine cavity thermal absorption calculations.

3. SOLAR ALIGNMENT OPTICAL PATH

The Fresnel lens has a narrow annular zone, 10 mm (0.40 in.) across, to focus sunlight onto four symmetrically placed solar alignment optical systems. These solar alignment systems consist of four optical paths to four detectors. The systems are on a ring centered about the optical axis of the furnace system at 12:00, 3:00, 6:00, and 9:00.

Solar alignment electro-optics for one of the identical four optical paths are shown in Figure 4. (The detector location is where the rays cease to be drawn.) The electro-optics start 1864 mm (73.37 in.) beyond the Fresnel lens. Each solar alignment optical system optical paths starts from a narrow annulus 203 mm (8.00 in.) radially out on the Fresnel lens. Light travels from the Fresnel annulus (not shown) to a neutral density filter, then to a BK7 cylinder (~150 mm [~6.0 inches] in the powered direction by ~76 mm [~3.0 in.]), and finally through a bandpass filter (not shown) to the detector. The cylinder reduces the sun's image into a much smaller spot (~8 mm or ~0.3 in.) radially away from the optical axis.

Each detector's dimensions are 30.0 mm X 6.4 mm (1.18 in. X 0.25 in.), and the long ends are pointed radially away from the sun. As the sun gets out of alignment this spot appears to move directly toward or away from the optical axis on any detector on which it registers. Figure 4 shows five field points on a detector, if the sun were moving perfectly radially at this detector. Proceeding upward in the figure, one comes to (1) the lower limb of the sun at 0.00°, (2) the center of the sun at 0.00°, (3) the upper limb of the sun at 0.00°, (4) the lower limb of the sun at 2.50°, and the upper limb of the sun at 2.50 °. A detector traces the sun a little over 2.50° and has an accuracy of ~0.01° over the first 1.0°. This provides a total field-of-view of at least 5.0 °.

4. CONCLUSIONS/SUMMARY

MSFC has made 304.8 mm diameter models to test and prove the membrane Fresnel lens concept, specifically the mandrel fabrication technique and the optical performance. The lenses were produced and characterized. Transmission losses from scattering through the grooves were higher than expected, because the scattering cannot be modeled. The models demonstrated just the solar concentration effects. Physical models of the paraboloid collector and sun centering electro-optics have yet to be made.

The results of test data from scale lens model measurements were compared and the design refined for improvement. Because many performance parameters are interdependent and cannot be clearly predicted, the intent of this technology development program is to learn, discover, and create mainly by building and testing instead of elaborate analysis. Since optical design and related software must be customized for this kind of Fresnel application, work will continue on software. There is a great need to combine optical performance analysis with engine cavity thermal absorption analysis. The struggle to create the new programming will pay off in subsequent STUS designs.

Any optical characterization of a Fresnel lens for a solar concentrator is very innovative and undefined. There are no standard, master, or control Fresnel lenses established for comparison. Testing will have to be improvised and customized in a trial and error basis. Several approaches will be needed with the best process becoming the standard. The discoveries will expand Fresnel characterization technology.

By making and testing a thin membrane Fresnel lens from the CP-2 polyimide, this investigation has expanded the database and developed better expertise to understand the solar energy concentration system.

5. ACKNOWLEDGMENTS

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6. REFERENCES

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Figure 1. Ray Trace of the Composite Solar Concentrator Fresnel Lens

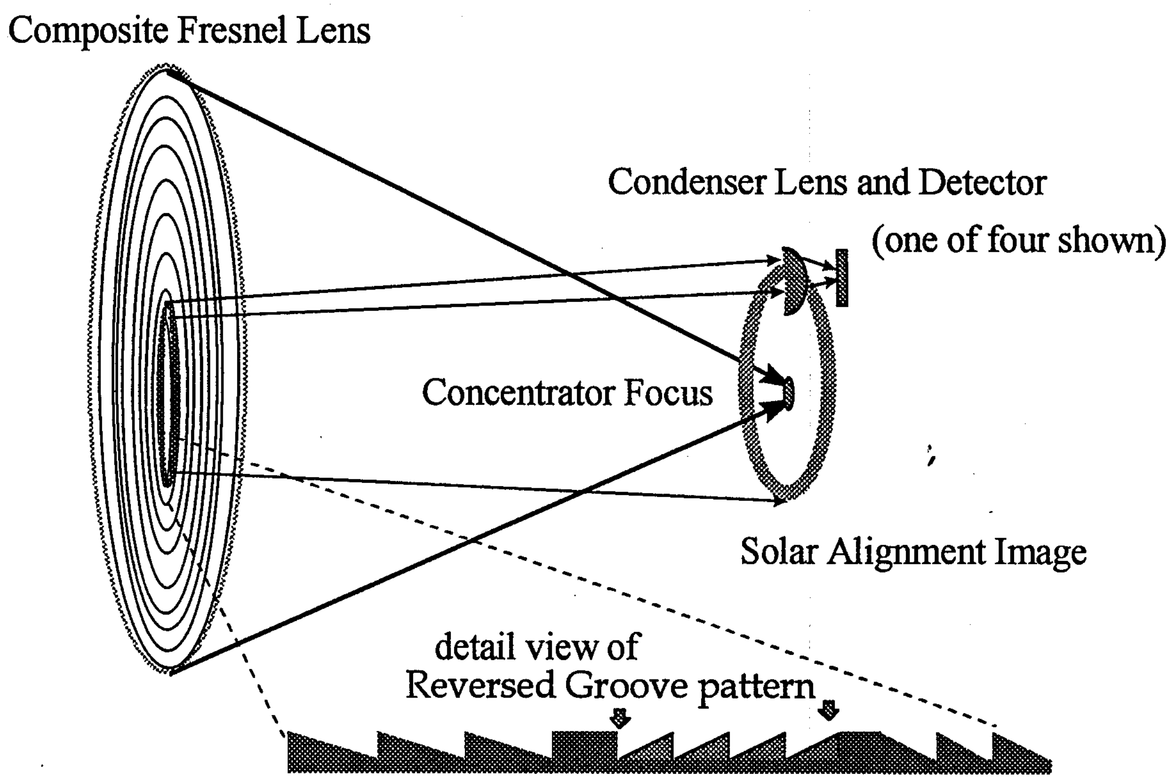

Figure 2. Black Body Curve, Transmittance of CP-2 Polyimide, and Combined Effect

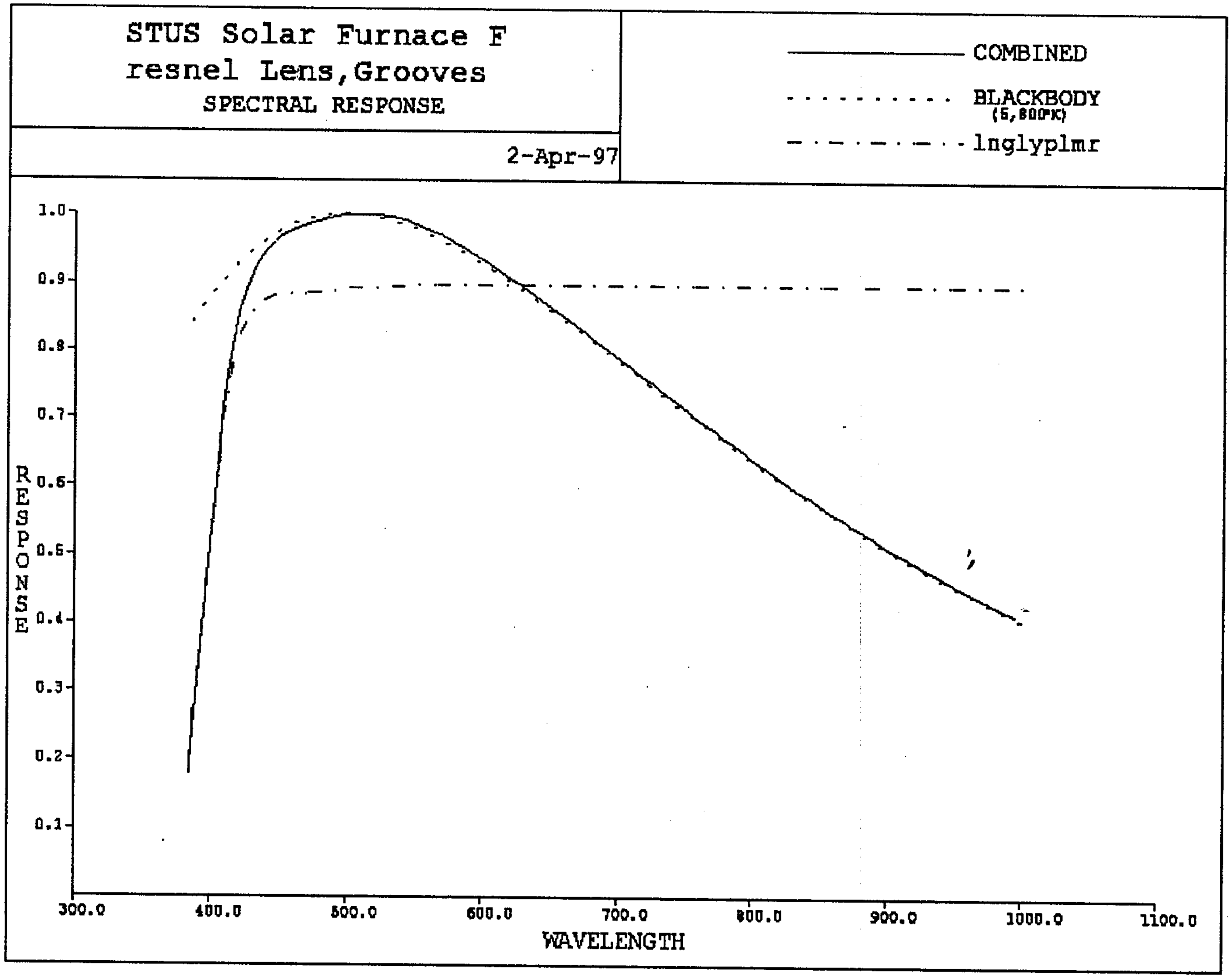

Figure 3. Solar Furnace Area after Fresnel Lens: Paraboloid Interfaced with Cylinder

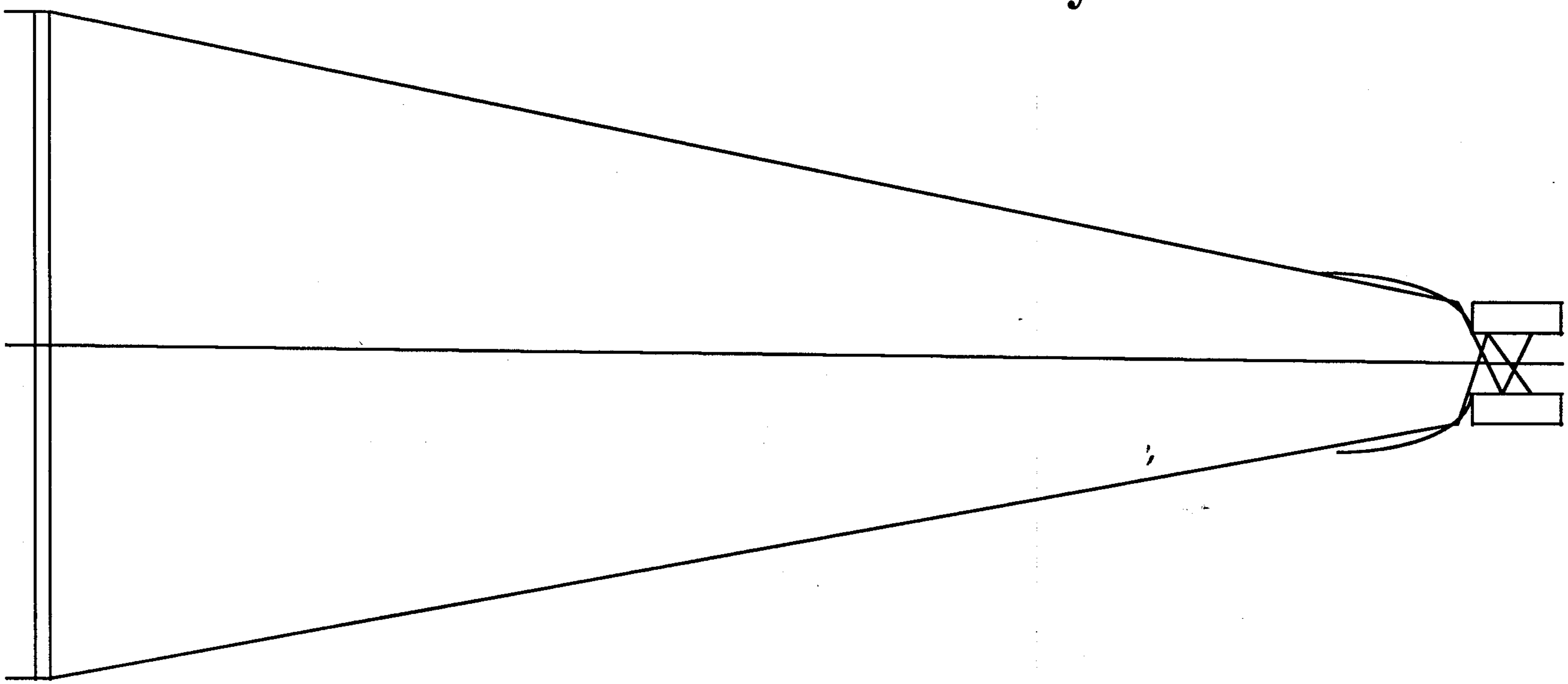

Figure 4. Solar Alignment Electro-Optical Area