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Final Report for the period June 1987 to March 1988

Holographic Solar Energy Concentrators for Solar Thermal Rocket Engines

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May 1988

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This is a Phase I Report on Holographic Concentrators for Solar Thermal Rocket Engines. The object of the work was to demonstrate that highly reflective holograms could be used as solar concentrators to heat liquid hydrogen for use as a propellant in satellite boost engines. The interest in this results from the need for a reliable, inexpensive alternate for conventional rockets.

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INTRODUCTION

This document is a report on the work performed by National Technical Systems (NTS) under the Phase I Contract, No. F04611-87-C-0015, entitled "Holographic Solar Concentrators for Solar Thermal Rocket Propulsion". The object of the work was to demonstrate that highly reflective holograms could be used as solar concentrators to heat liquid hydrogen for use as a propellant in satellite boost engines.

BACKGROUND

The interest in this technology results from the need for a reliable, inexpensive alternative for conventional chemical rockets. These rockets are used to boost satellites from Low Earth Orbit (LEO) where the Space Shuttle off-loads them to Geosynchronous Earth Orbit (GEO) where they perform their tasks.

In principle, the Solar Thermal Engine would make use of solar energy in space by using two large concentrators, each 700 square feet in area, to direct the energy onto a pressurized liquid hydrogen system. These concentrators would collect and focus solar energy at a concentration ratio greater than 10,000 to 1 over the majority of the solar blackbody spectrum, thereby heating the working fluid (hydrogen) in the engine to over 6000F°. This superheated hydrogen would be expelled as the rocket exhaust at very high velocities and low molecular weight, producing thrust from the working fluid at a low mass rate of expulsion.

NTS, as a major goal of the Phase I effort, has used a laser scanner to make strips of holograms more than five feet long. This technique can be used to produce 400-foot long strips of holograms that can then be joined together to form giant holoconcentrators. A five-foot long strip was produced as a proof of concept example of this unique and novel holographic technique. Fig. 1a shows a schematic of the experimental exposure setup used to produce this hologram. Fig. 1b shows the resulting optical density versus wavelength characteristics of the strip hologram. Fig. 2 shows a schematic of an automated holographic foil production system that could be used to manufacture very large holoconcentrators. As can be seen by the optical density spectrum for the five-foot long hologram (Fig. 1b), even though this example was meant only to show proof of concept of the exposure technique, an optical density of 3 was obtained with a bandwidth of 70 nm.

REPORT ORGANIZATION

The basic organization of this report is as follows:

Review of Holography

Basic holographic concepts are introduced including the recording and reconstruction methods used to produce simple reflection and transmission holograms, general Bragg plane diffraction theory, and general holographic concentrator principles. These holography concepts are discussed in the context of actually producing the holographic concentrators.

Review of Phase I Accomplishments

The Phase I effort is described in terms of the goals undertaken and the accomplishments achieved by NTS during the "Holographic Solar Concentrators for Solar Thermal Rocket Propulsion" contract. Topics

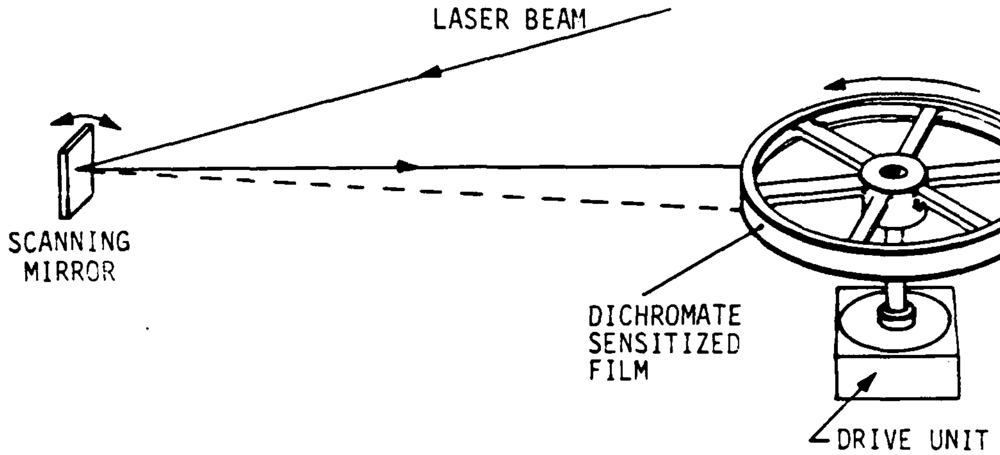


Figure 1a. Proof of concept holographic strip exposure experimental setup.

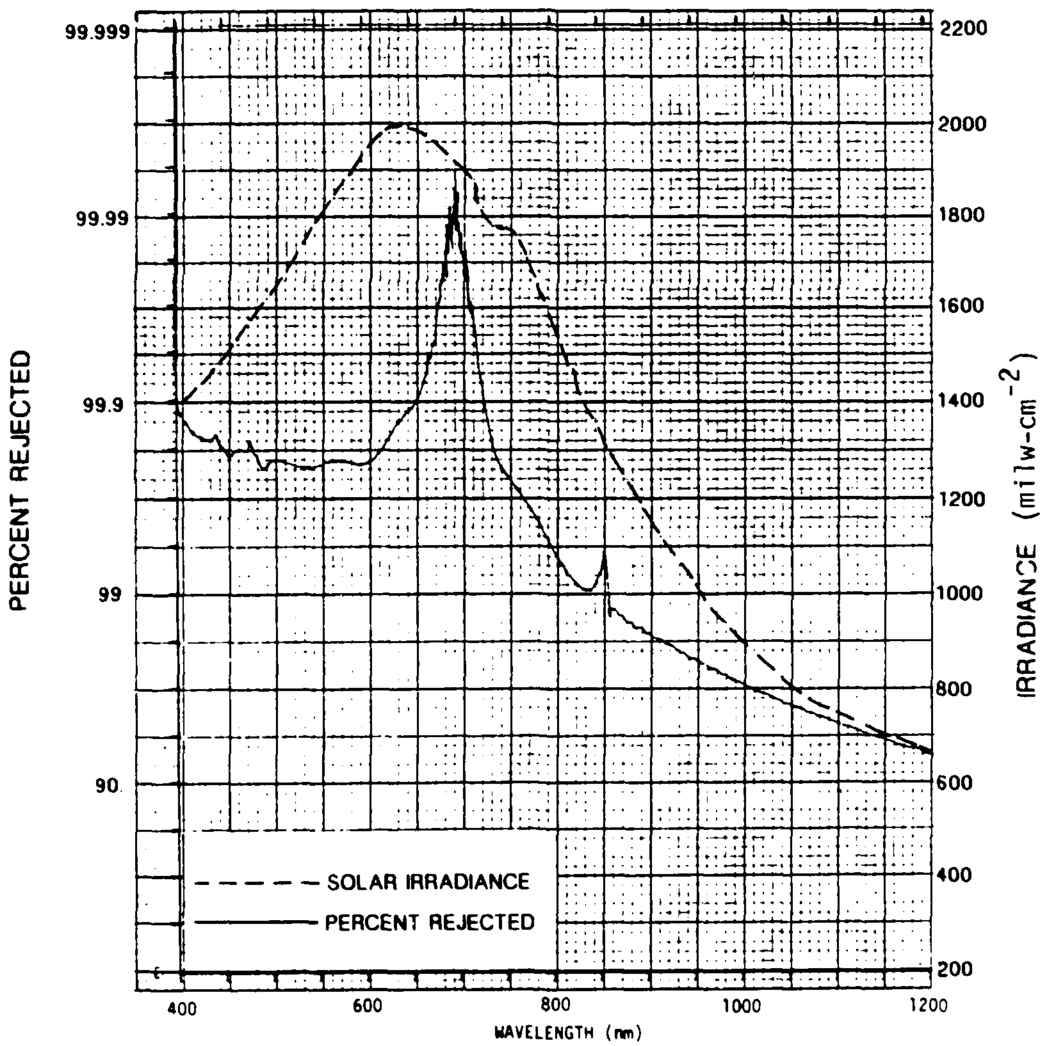


Figure 1b. Solar irradiance vs. wavelength for 5' holographic strip.

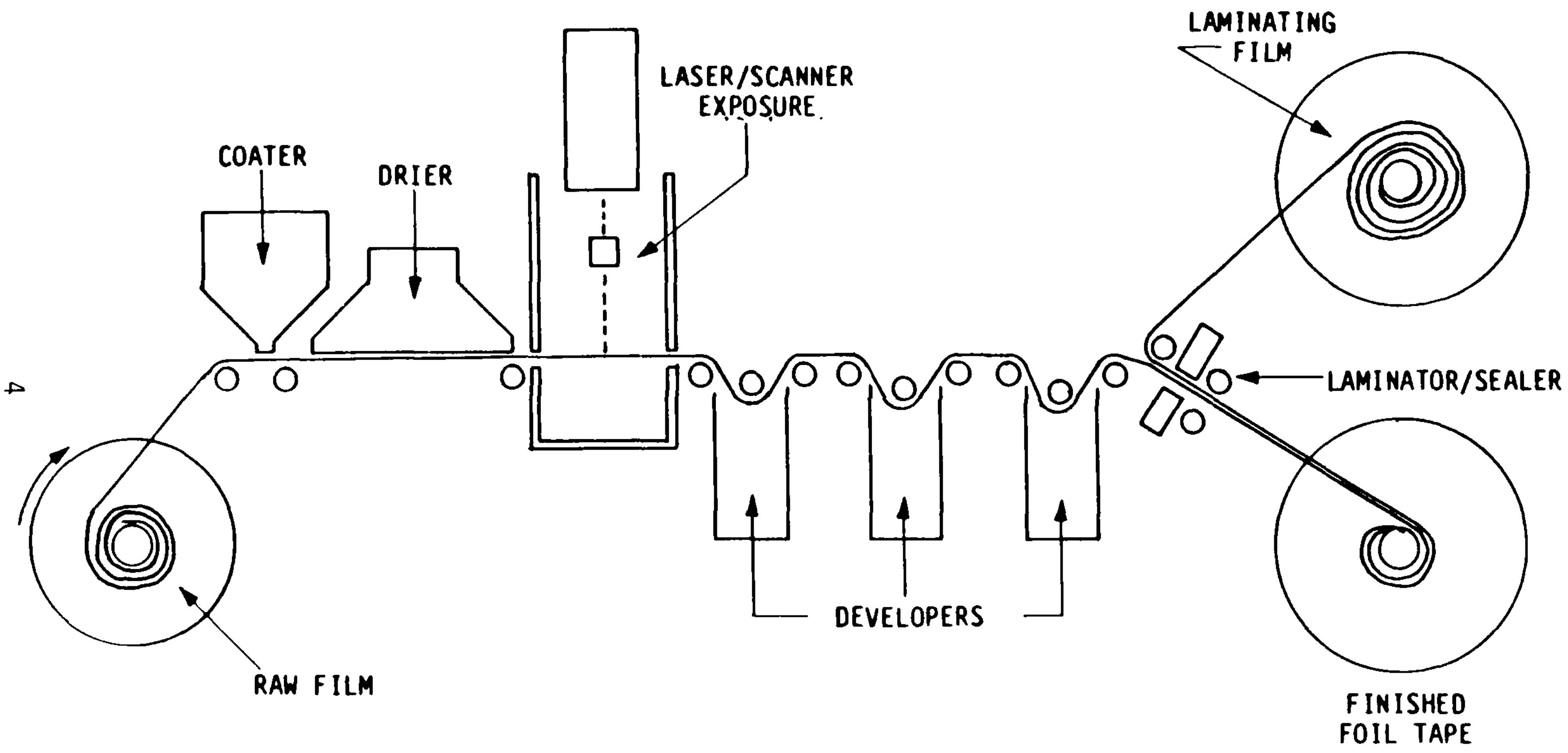


Figure 2. Automated holographic foil production.

such as giant size holograms, spectral dispersion compensation, broad bandwidth mirrors, space durability, manufacturing processes, structural support and deployment methods are discussed.

Conclusions and Recommendations

A summary of the results of this effort along with recommendations for further work on the development and application of holographic mirror technology is presented in this section.

REVIEW OF HOLOGRAPHY

Basic holographic concepts are introduced in this section including the recording and reconstruction methods used to produce simple reflection and transmission holograms, general Bragg plane diffraction theory, and general holographic concentrator principles. These holographic concepts are discussed in the context of actually producing the holographic concentrators.

BASIC HOLOGRAPHIC CONCEPTS

Holograms are recordings of interference patterns formed when two or more sets of waves strike and overlap each other. These waves most commonly are either optical (light) or acoustic (sound). In optical holography, a laser is used to provide a beam of monochromatic, coherent light. This means that the light is made up of one very specific wavelength, with the waves of light uniformly spaced.

To construct a hologram, the laser beam is split into a reference beam and an object beam (Figs. 3 and 4). The reference beam remains unchanged and goes directly to the photographic film. The object beam illuminates the scene or object, scattering from there onto the photographic film. As the beam is scattered off the object, the shape of its waves are distorted by the shape and texture of the object. This distorted object beam reaches the photographic film and overlaps the reference beam. The two beams interfere as the waves cancel and reinforce each other to form a fringe pattern on the film.

The two beams interfere in much the same way as water waves do, (i.e. two pebbles are dropped into a pond). In the case of the water waves, where two high points of the waves overlap there will be a

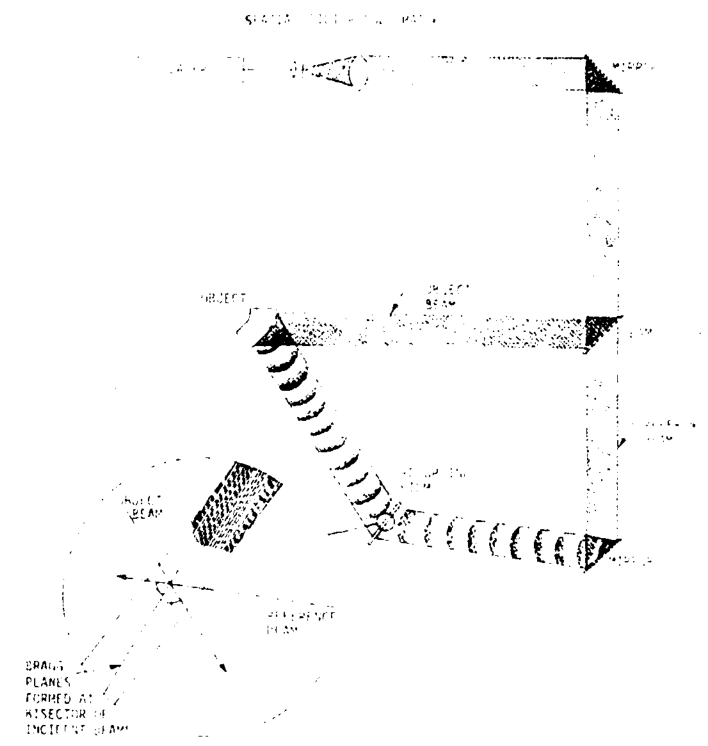


Figure 3. Basic setup for recording a reflection hologram.

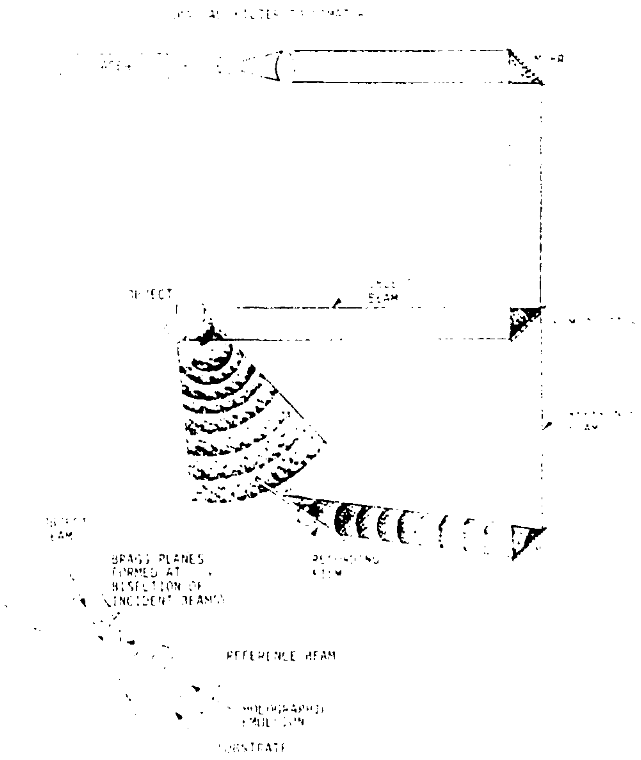


Figure 4. Basic setup for recording a transmission hologram.

doubly high amplitude in the wave pattern. Two low points overlapping form a doubly low amplitude. A high and a low point combine to form a flat region. In the case of the laser beams, the interference results in bright and dark fringes which are recorded on a photographic film. The hologram thus records the phase or wave front difference between two light beams. The resulting image in a hologram is a series of fringes that looks similar to the fringes formed by a couple of overlapping pieces of window screen.

Fig. 3 shows the basic setup for the formation of a "reflection" hologram. Note that in this arrangement the object beam and reference beam are each incident on different sides of the film. The interference pattern is formed by the combination of the two beams incident upon the film. Fig. 4 shows the basic setup for the formation of a "transmission" hologram. Note that in this arrangement the object beam and reference beam are incident on the same side of the film.

The three dimensional reconstruction of the object's image is achieved by placing the developed film in the same position and orientation (relative to the reference beam) that it occupied when it was exposed. This arrangement is illustrated in Figs. 5 and 6. The reference beam is then scattered off of the holographic fringes of the film in exactly the same way that the light was originally scattered off the object, and the full three dimensional view of the object is recreated.

HOLOGRAPHIC CONCENTRATOR PRINCIPLES

A holographic concentrator is a type of Holographic Optical Element (HOE). This means the optical properties that are characteristic of a lens or mirror have been recorded within the hologram. When incident

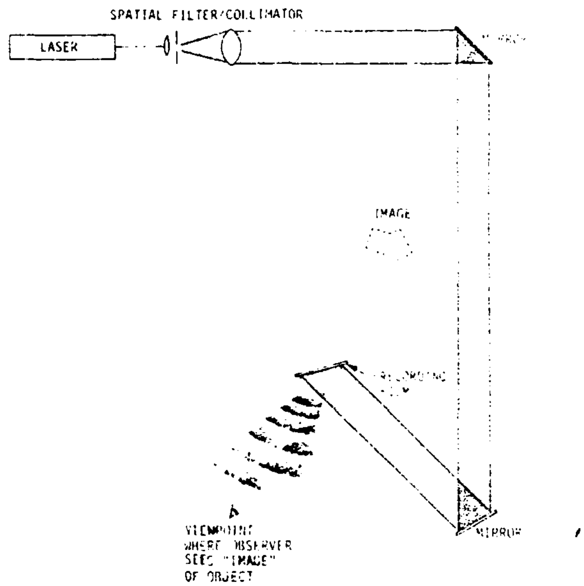


Figure 5. <u>Basic setup for reconstructing a reflection hologram.</u>

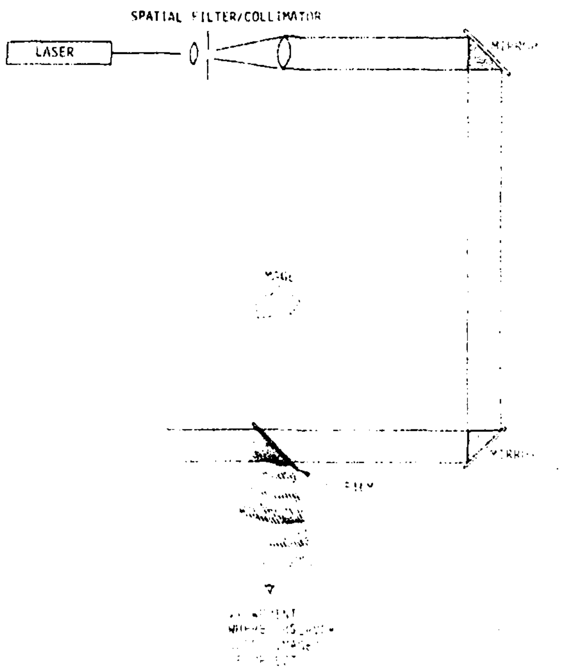


Figure 6. <u>Basic setup for reconstructing a transmission hologram.</u>

light falls upon the hologram, the light is redirected or focused exactly as it would be redirected or focused by the lens or mirror. Thus the hologram functions identically to lens or mirror-like optical elements.

The simplest HOE is a plane mirror. It is made by using a setup similar to that shown in Fig. 3. However, instead of receiving the object beam from a separate object, the reference beam is reflected back into the film emulsion by a mirror located behind the film plane (Fig. 7a). Thus the reference beam functions both as the reference beam and as the object beam. The two beams interfere to form a hologram of the mirror surface. Using this technique requires the coherence length of the laser to be slightly greater than the combined thickness of the recording film and the film substrate (i.e., approximately 25μm). This is in contrast to a coherence length on the order of meters necessary for true split-beam image holography.

Bragg Planes

Bragg planes are created when the bright fringes cause the emulsion consisting of Dichromated Gelatin (DCG) to form cross links between the gelatin polymers via chromate ions. When a light wave strikes these planes, it is reflected if the plane spacing is equal to some multiple of half wavelengths of the incident light. The desired spacing of these planes may be calculated using Bragg's law as follows:

$$m\lambda = 2d \sin \theta \qquad (1)$$

where

m = number of half wavelengths between planes

λ = wavelength of diffracted light

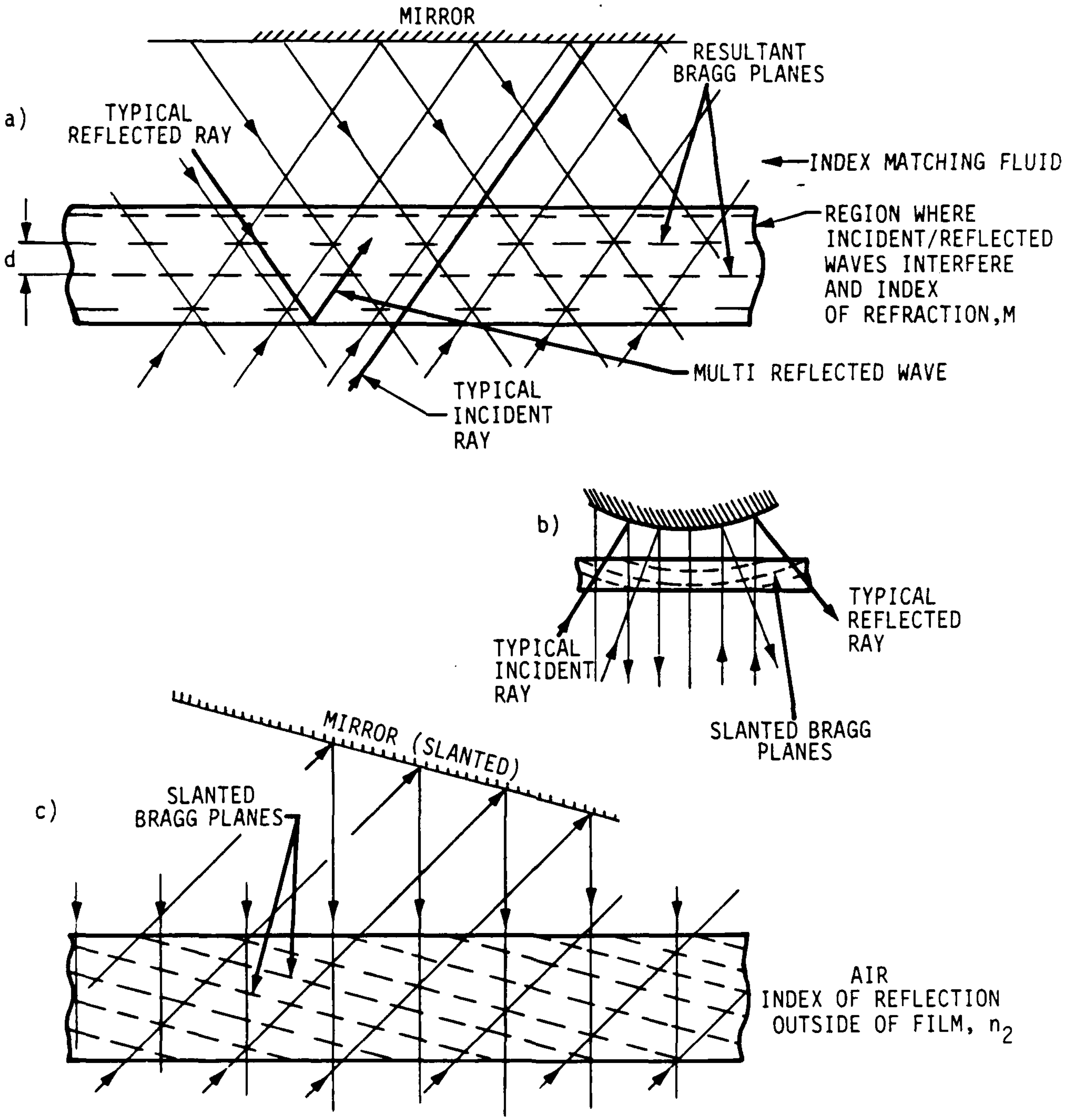


Figure 7. Hologram with (a) bragg planes parallel to surface, (b) concentrating HOE and (c) with slanted bragg planes.

d = the spacing between the planes

θ = the angle between the planes and the light beam measured from the horizontal

Since it is inconvenient to measure angles inside the hologram, Snell's law (Equation 2) can be used in conjunction with the trigonometric identity of Equation 3 to obtain the angle of incidence (from the normal) on the film as measured in air.

$$n \sin = n_1 \sin \phi_1 \quad (2)$$

where $$\theta + \phi = 90^{o} \quad (3)$$

ϕ = the incident angle of the laser beam on the Bragg plane measured from the normal

ϕ_1 = the incident angle in air of the laser beam on the film measured from the normal

n = the refractive index of the hologram film

n_1 = the refractive index of air

More than one wavelength can be reflected at any given angle, i.e., m=1 is the primary reflected color; m=2 is the second harmonic with 1/2 the wavelength of the primary; m=3 is the third harmonic with 1/3 the wavelength, etc.. Unfortunately, Equation (4) is only a theoretical approximation since a variety of other factors can affect the spacing of the Bragg planes such as emulsion shrinkage, humidity, temperature, etc. Consequently, Equation (4) becomes

$$d = \frac{m\lambda}{2\ K \sin\theta} \tag{4}$$

where K is an arbitrary constant determined by experiment.

Bragg Plane Locations/Arrangement

In principle, a HOE concentrator could be made up of thousands of Bragg planes or mirrors, each individually aimed; but this would be extremely difficult. It is preferable to develop the optical power of the concentrator on a flat film with the Bragg planes all of the same orientation. The setup for producing such a hologram is shown in Fig. 8. This arrangement is practical only for small size HOEs due to the need to have a master non-holographic optical element of approximately the same size as the HOE. This could be extremely expensive for large systems or for mirrors which must be off axis, that is, mirrors that are not rotationally symmetric.

NTS has developed a second technique for producing a HOE with optical power. The NTS system uses a rastor-scanning optical system that allows a hologram to be "written" similar to the way an image is "written" on a television screen. The laser beam is scanned across the film and is redirected back into the film by a slanted mirror. The film is translated orthogonally to the scan direction, allowing rolls of holograms to be fabricated hundreds of feet long. These rolls may then be joined side by side in order to form larger mirrors such as those needed for the concentrators (700 square feet in area).

The third technique for making a hologram is a combination of the first and second techniques. As shown in Fig. 7B, the off-axis portion of a HOE may be considered to be made up of slanted Bragg surfaces, i.e., Bragg surfaces that are not parallel to the surface of the film.

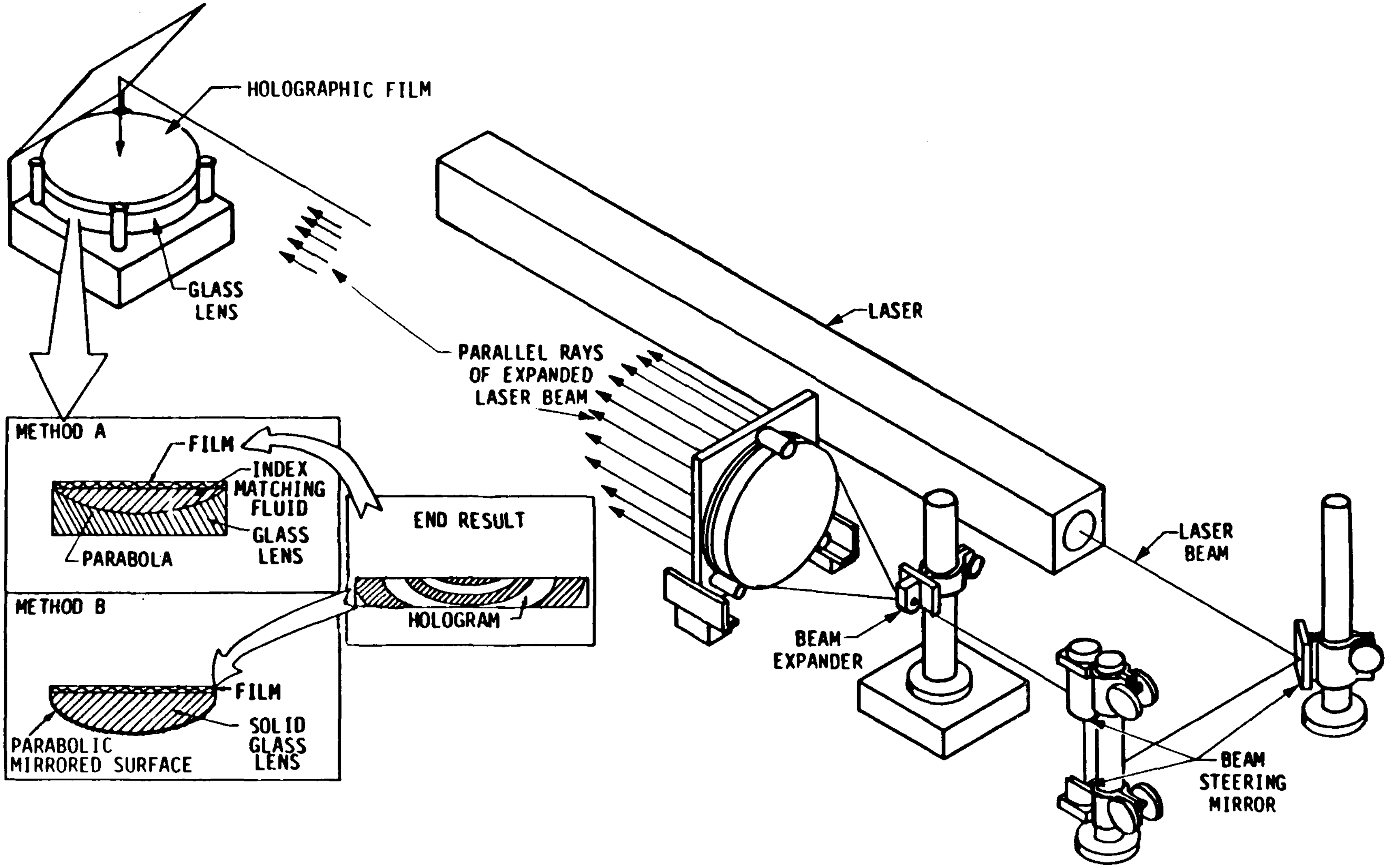


Figure 8. Setup for producing a parabolic hologram with optical power.

Fig. 7C shows the principle for making this type of hologram. Again, this technique is limited to the size of the mirror used as the master optical element to make the HOE.

HOLOGRAPHIC CONCENTRATOR CHALLENGES

There are two challenges associated with the production of concentrating HOEs. The first is making a hologram which is sufficiently broad in bandwidth to utilize the majority of the available solar blackbody spectrum. This is inherently difficult to achieve due to the wavelength selective nature of holograms. The second is achieving high (10,000 to 1) concentration ratios over this broad bandwidth. This is difficult for similar reasons: the nature of holograms tends toward narrow band selection, and diffractive optical systems tend to focus different colors at different locations. Fortunately, these problems have many potential solutions. Nature cooperates in this dilemma.

The sun behaves like a blackbody with most of its energy radiated around a wavelength of 0.5 microns; the near infrared and visible parts of the spectrum. Also, most photovoltaics operate in the region around 1.1 microns. Thus, the available solar energy can be efficiently used for heating and also for powering the electrical systems by using the solar band between 0.5 and 1.2 microns. See Fig. 9 for the solar emittance curves versus wavelength.

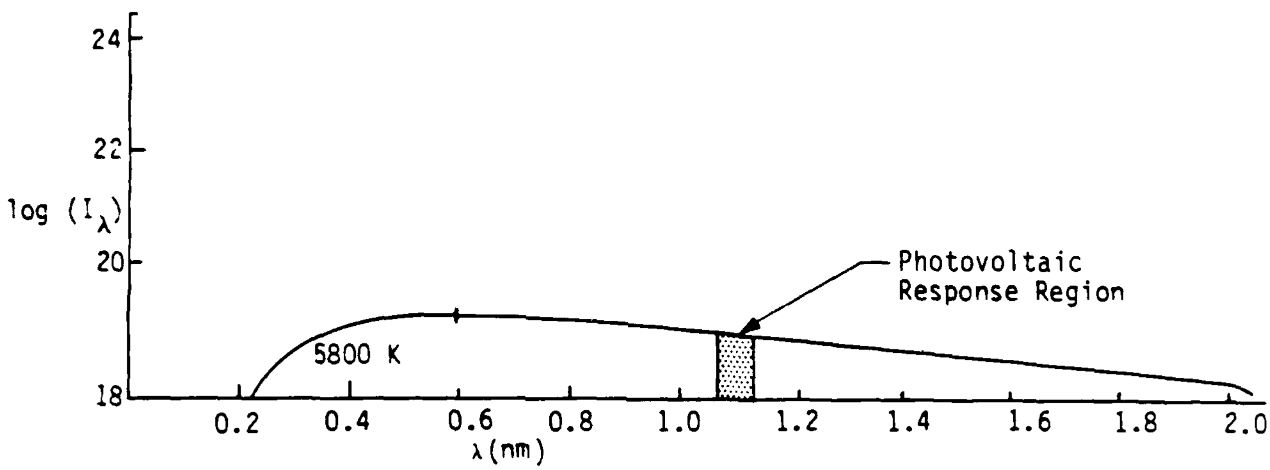


Figure 9. Solar emittance vs. wavelenoth.

REVIEW OF PHASE I ACCOMPLISHMENTS

The Phase I effort included the following task requirements as listed below in their original sequence:

A) Research and define optimum substrate materials based on space durability.

B) Fabricate holographic mirrors with optimum trade-off of bandwidth (400 to 1800 nm) and reflectivity (95%) with the aim of maximizing black body energy on target.

C) Fabricate holographic mirrors with concentration ratios of 10,000 to one or better.

D) Produce a one foot square sample demonstrating the above.

E) Research manufacturing methods which would allow production of 700 square foot mirrors.

F) Perform research into lightweight support concepts which could make full use of holographic parameters, allowing ease of storage, deployment and alignment.

NTS accomplished most of the goals it set out to achieve. The primary goal included producing an HOE concentrating mirror with the following characteristics:

- A concentration ratio of 10,000 to 1.
- A reflectivity of more than 95 percent.
- A broad bandwidth.

The accomplishments are listed in TABLE 1 and discussed in detail below.

HOLOGRAPHIC CONCENTRATION

Holographic concentrating mirrors were produced incorporating various converging geometries. Exposures were made in such a way that the concentrating effects of a concave mirror was reproduced by the hologram at approximately f/1, as shown in Figure 8.

Reflectivity was measured using NTS' Perkin Elmer Spectrophotometer, as well as a laser reflectometer thus making it possible to measure optical densities greater than O.D.5 (~99.999% reflection).

The concentration ratio, CR, of a holoconcentrator is determined by measuring the area of the focal spot and dividing it into the area of the HOE aperature, that is CR = (Area Focal Spot)/(Area HOE Aperature). The bandwidth of a specific HOE is determined by measuring the full width at an OD of 2 (ie. bandwidth at ~99% reflection), on a Wavelength vs. Optical Density plot.

Holographic concentrators were made in sizes ranging from 200 to 300mm (8 to 12 inches) in diameter with various bandwidths. The widest bandwidth obtained was 335nm (representing 24% of the desired bandwidth goal of 1400nm). This hologram had a concentration ratio of 6400. The peak optical density of this hologram was well over O.D.5 (~99.999% reflection). Recall that metal mirrors rarely have reflectivities exceeding 95%.

TABLE 1. Phase I Accomplishments

GOALS	ACCOMPLISHMENTS
Holograms that Exceed Coherency Length	Made holographic strip more than 5 feet long
10,000 to 1 Concentration Factor	Accomplished for laser bandwidths, not for full solar blackbody spectrum.
>95% Reflectivity	Better than 99% reflectivity.
Broad Bandwidth	Broadening of 335 nm accomplished.
Space Durability	5 years simulated w/o degradation.
Nitinol as a Space Structure	Shows promise - has been used for some small space applications - Lit. search performed vendors contacted.
Deployment Assessment	Deployment easier than inflatable structure. No forseeable problems.
Substrate	Mylar preferable for 1 - 2 month mission Aclar for multiple year missions.

Several holoconcentrators were made with bandwidths of 10nm. These holoconcentrators had concentration ratios of 40,000. The peak optical density of these holograms was well over O.D.5.

Thus, in conclusion, the broadest bandwidth holoconcentrator obtained had a 335nm bandwidth, a CR = 6400 and a 99.999% The highest concentration ratio achieved was approximately 40,000 in a holoconcentrator with a 10nm bandwidth and a 99.999% reflectivity.

SPECTRAL DISPERSION

One problem exhibited by the concentrating mirrors is spectral dispersion. Spectral dispersion is a phenomena, common to refractive and some reflective optics, whereby transmitted or reflective broad bandwidth light is focused into multiple, spatially-separated focal planes. When this occurs with light reflected from a holoconcentrator the focal spot is spread out over a larger area resulting in lower concentration ratios, see Fig. 10. A common example of spectral dispersion is exhibited by a prison which separates white light into the familiar rainbow spectrum.

Several parallel approaches were undertaken in order to overcome the problems of spectral dispersion and insufficient bandwidth in the proof of concept HOE. The methods used to optimize the bandwidth are discussed in Section 3.2. In order to reduce the large spot size caused by spectral dispersion, two methods of dispersion compensation were used and are discussed in the two following sections.

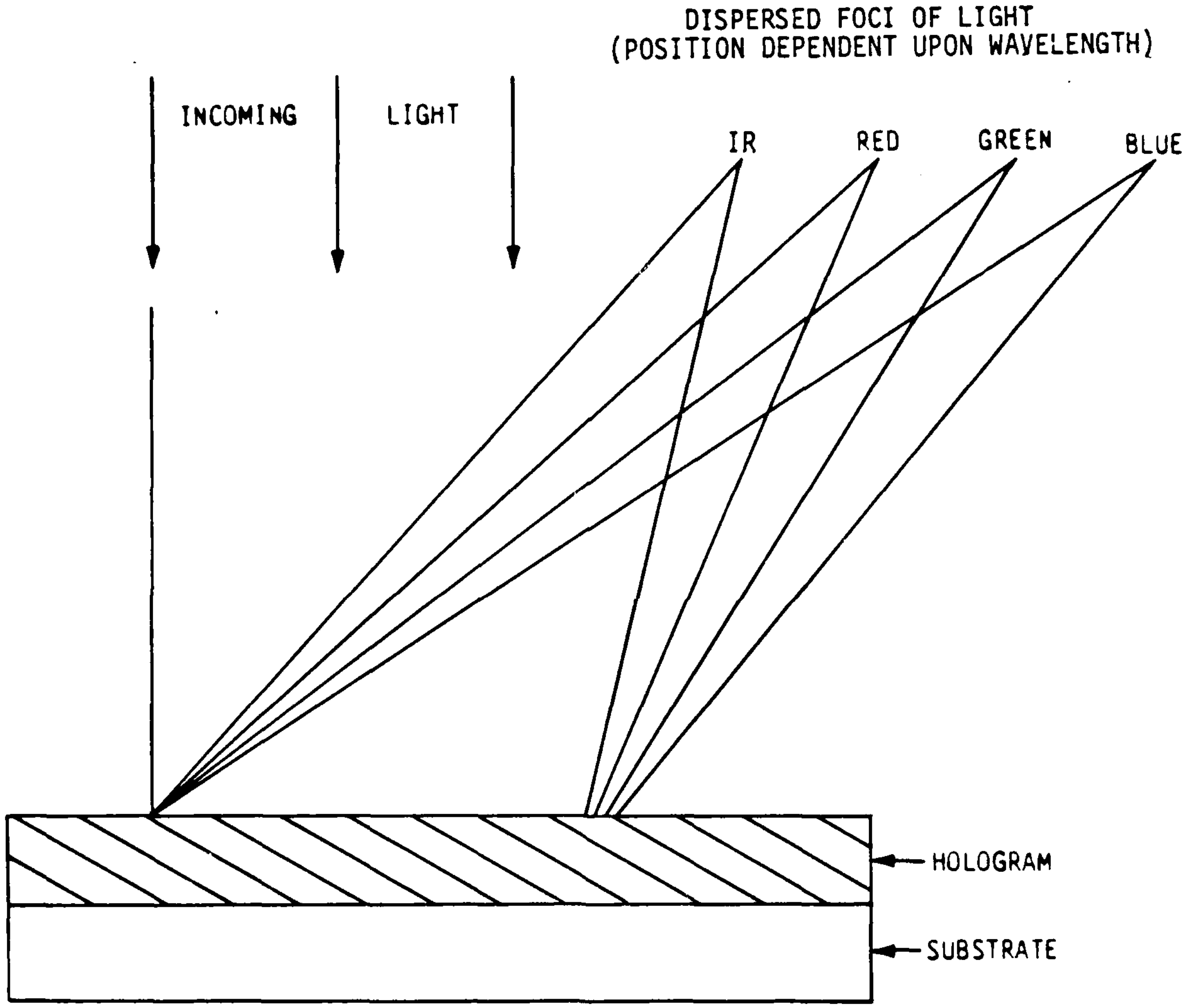


Figure 10. Diffractive dispersion inherent in holographic optics.

Laminated Dispersion Compensation Holograms

The first method of dispersion compensation is a technique which was originally used for image holography. It consists of a correcting transmission hologram in contact with the concentrating (primary) hologram to counteract the spectral dispersion (prismatic effects) (Figs. 11 and 12). This approach proved difficult to achieve in Phase I due to the precision necessary to make a correcting transmission hologram. This type of hologram can be made using the NTS laser scanner technology, but requires a computer program to optimize the Bragg plane orientation for maximum correction over the entire area. Continued effort was outside the scope of the Phase I effort.

Separated Dispersion Compensation Holograms

Dispersion compensation may also be achieved by using a second compensating hologram separated from the primary hologram (Figs. 13 and 14). This forms a Cassegrainian-style telescope in which each element has opposite chromatic dispersion effects. Preliminary experiments were performed using combinations of converging/diverging and converging/converging HOEs. Results were promising in that the dispersive and focal effects were improved. Further effort was outside the scope of the Phase I effort.

BROAD BANDWIDTH CHARACTERISTICS

Broad bandwidth research was included in Phase I. The combination of broad bandwidth and high reflectivity were to be optimized in order to maximize the blackbody spectra reflection.

Broad bandwidth mirrors are achievable by several methods, namely:

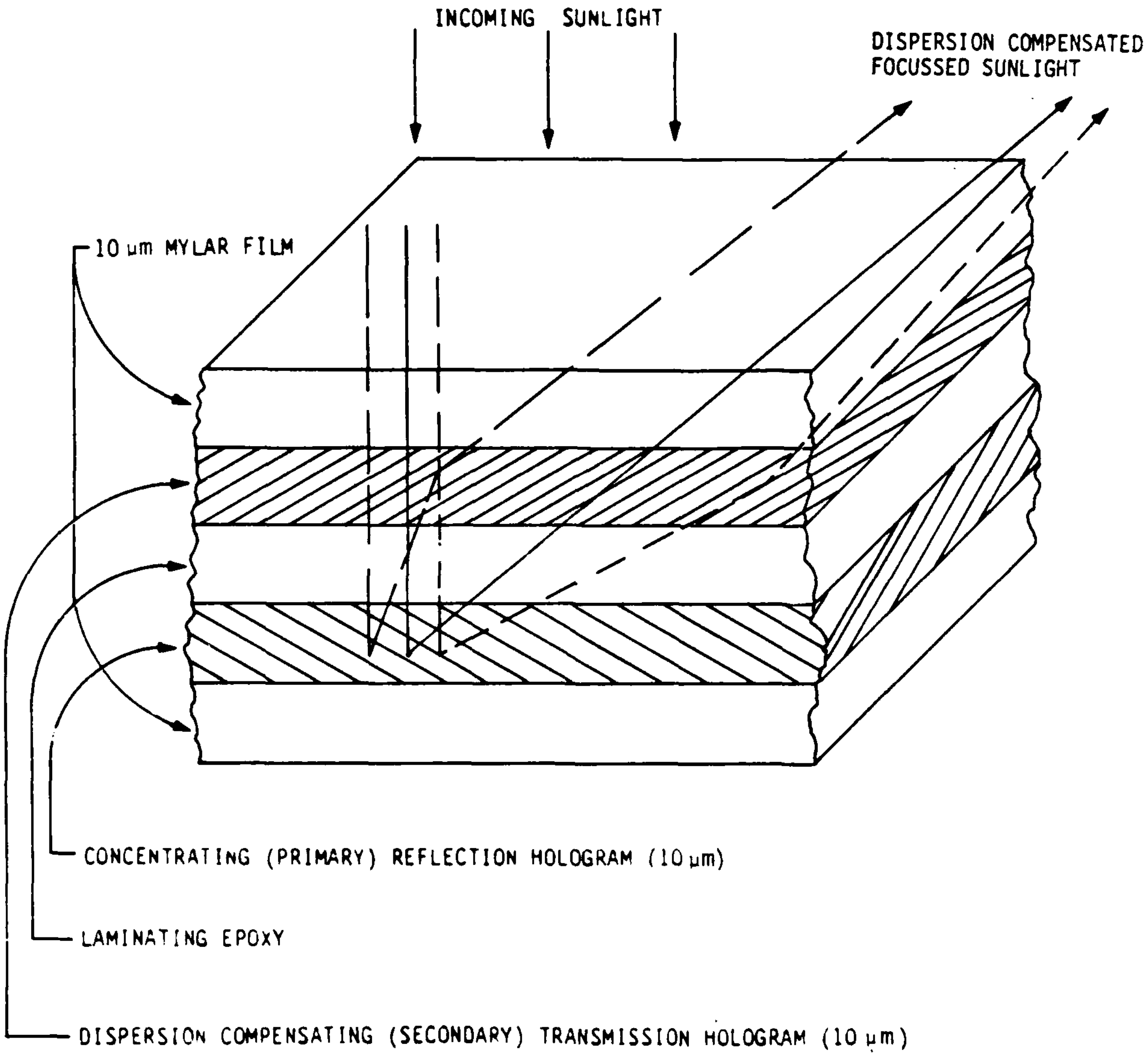


Figure 11. Dispersion compensation hologram in contact with the concentrating hologram (expanded view).

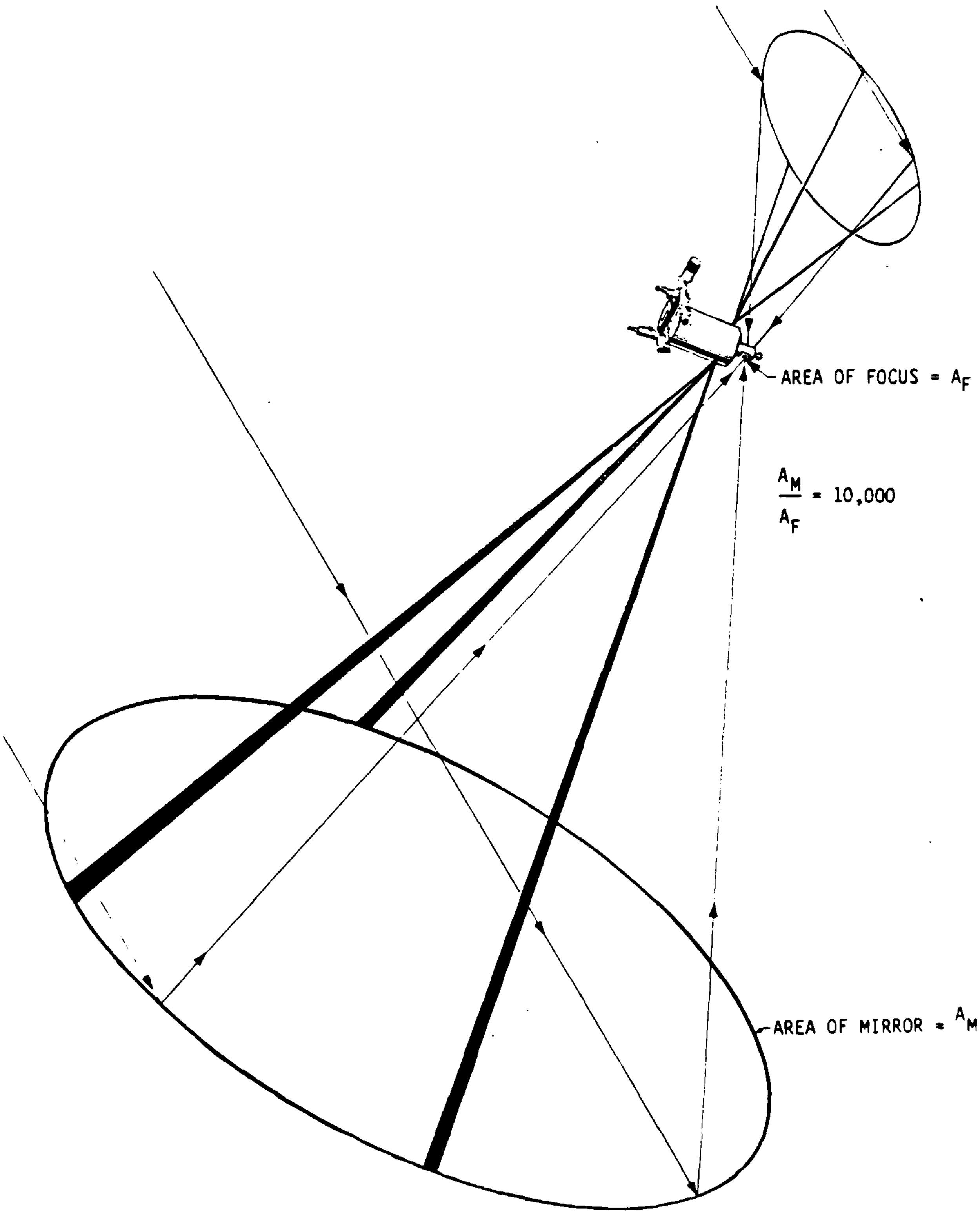


Figure 12. Laminated dispersion compensation hologram.

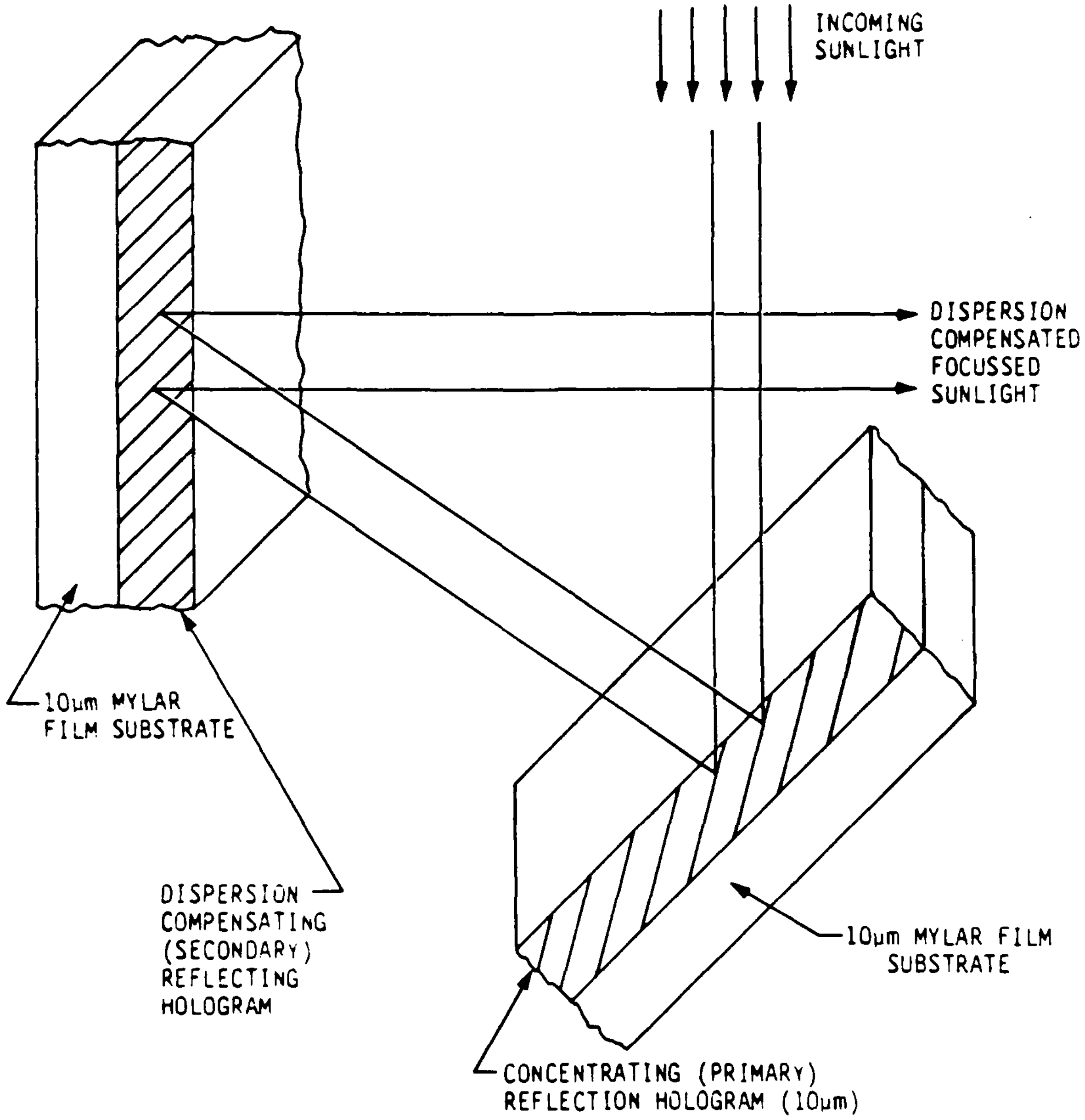


Figure 13. Dispersion compensation hologram separate from the concentrating hologram (expanded view).

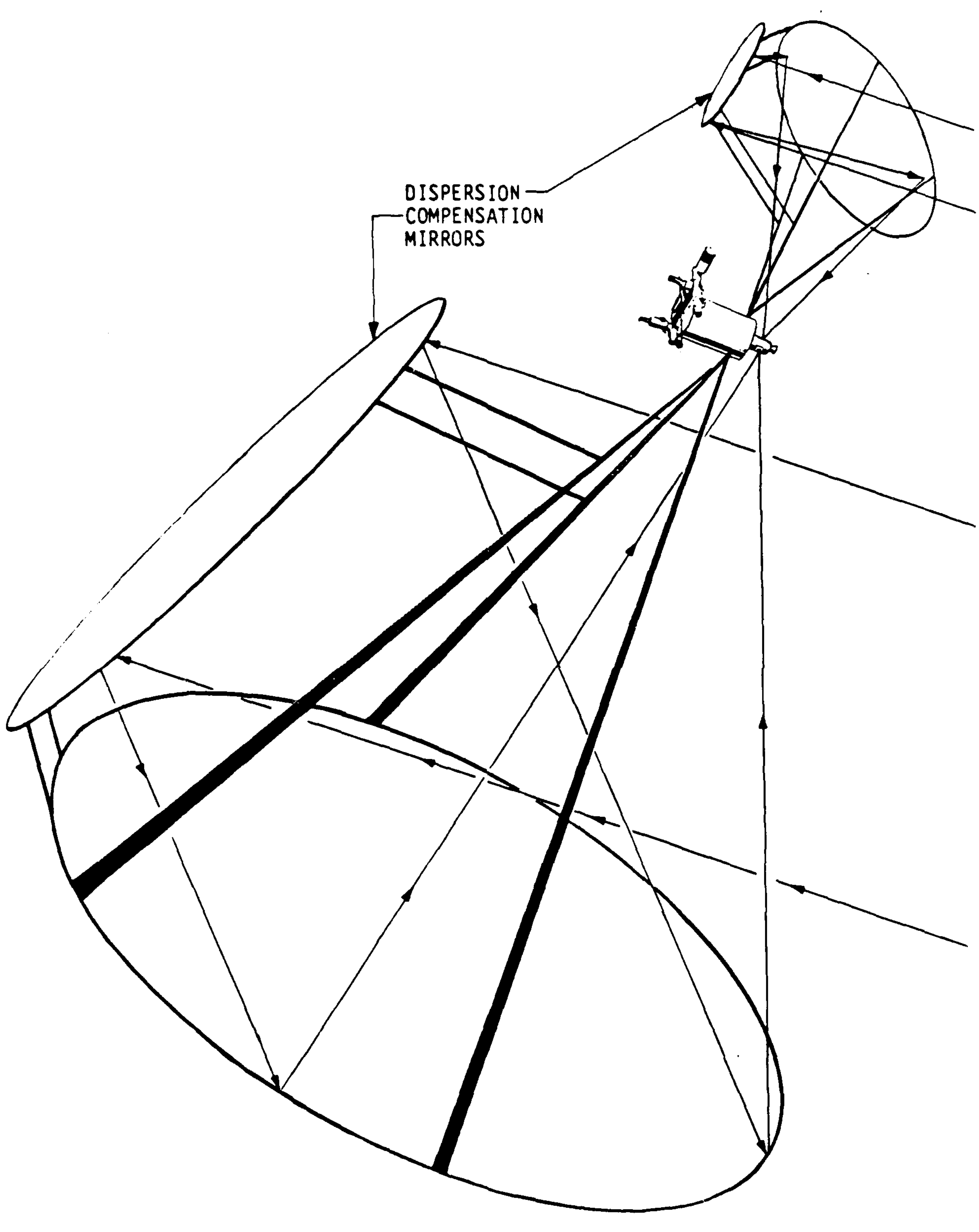
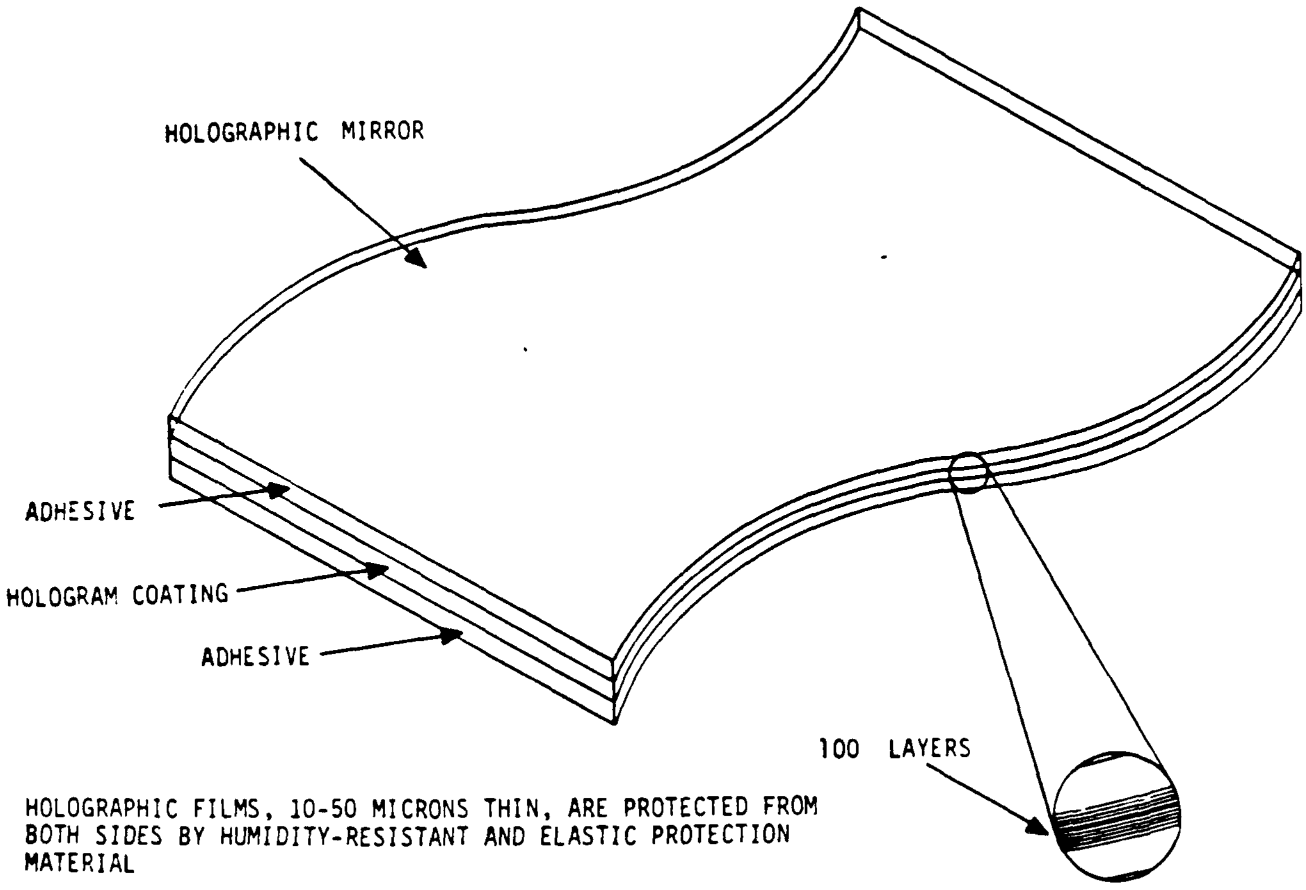


Figure 14. Separated dispersion compensation holograms.

(1) Multiple exposures - creates superimposed sets of Bragg planes in the film volume; (2) Swelling - enlarges and permanently distorts the micro-cracked and crosslinked DCG so that the period of sinusoidal refractive index is a function of the holographic film depth; (3) Laminations - consists of stacking several thin holographic films, each of which reflects its own characteristic spectrum (Fig. 15). This is essentially a multilayer film, each layer of which reflects a specific band. The drawback of this method is that the laminate may represent excessive film thickness in some cases; (4) Harmonic effects - a method of making a hologram in a single exposure that reflects multiple wave bands. This harmonic effect is due to the ability of the hologram to reflect any wavelength for which the Bragg plane spacing is some half wavelength multiple of the hologram's fundamental reflecting wavelength as previously discussed in Section 2.2.

Multiple Exposures

Superimposed holograms were produced by exposing a single photo-emulsion a number of times. This can be visualized as a Fourier series of sine waves each of which reflects a particular frequency. Variation of the angle of incidence was also tried so that cosine effects generated different Bragg plane spacings. This could allow for the possibility of forming large mirrors from a mosaic of smaller collimating mirrors. Difficulty arises in trying to make experiment match theory due to mechanical and chemical constraints of the photo-emulsion. This multi-exposure approach resulted in holograms which were broader in bandwidth than holograms produced by a single exposure but not nearly as broad bandwidth as theory predicted. Also, when attempts were made to swell these multiply-exposed holograms, the reflectivity and bandwidth were much worse than for swelled, single exposure holograms. This result was completely unexpected. However, since the resolution properties of DCG are very high and broad bandwidth holograms



HOLOGRAPHIC FILMS, 10-50 MICRONS THIN, ARE PROTECTED FROM BOTH SIDES BY HUMIDITY-RESISTANT AND ELASTIC PROTECTION MATERIAL

Figure 15. Schematic of laminated hologram based on NTS holographic foil technology.

have been achieved in the image holography industry, we are confident that better multiple exposures can be obtained.

Swelling

Swelling studies were performed on exposed plates by changing the processing times and chemical concentrations of the NTS' proprietary development process. The best results were obtained by swelling singly exposed plates, giving a bandwidth of 335 nm around the central frequency on the visible portion of the spectrum. Recall that the entire visible spectrum extends from 400 nm to 700 nm, or a bandwidth of 300 nm. Larger bandwidths ($\Delta\lambda \sim$1000nm) will be required to cover the near-infrared portion of the spectrum.

Laminations

Lamination tests were successfully performed on one foot square pieces of polycarbonate and mylar of 0.060, 0.010 and 0.001-inch thicknesses with no significant difficulties, such as bubbles or non-uniformities. This was achieved by using degassed epoxy of low viscosity inside a vacuum bag. Excess epoxy was forced out with a roller/squeegee while protective sheets kept the epoxy from adhering to the outer surfaces of the hologram laminates.

Harmonics

Holograms were made at the IR end (1800 nm) of the desired bandwidth to produce harmonics at 1/2, 1/3 and 1/4 of the prime wavelength, i.e. 900, 600 and 450 nm (Fig. 16). By swelling these 'harmonic holograms', a broad bandwidth may be achieved thus avoiding multiple exposures and multiple layer holograms (Fig. 16). If it is assumed that each specific band (i.e., 450, 600, 900 and 1800 nm) can be broadened to bandwidths

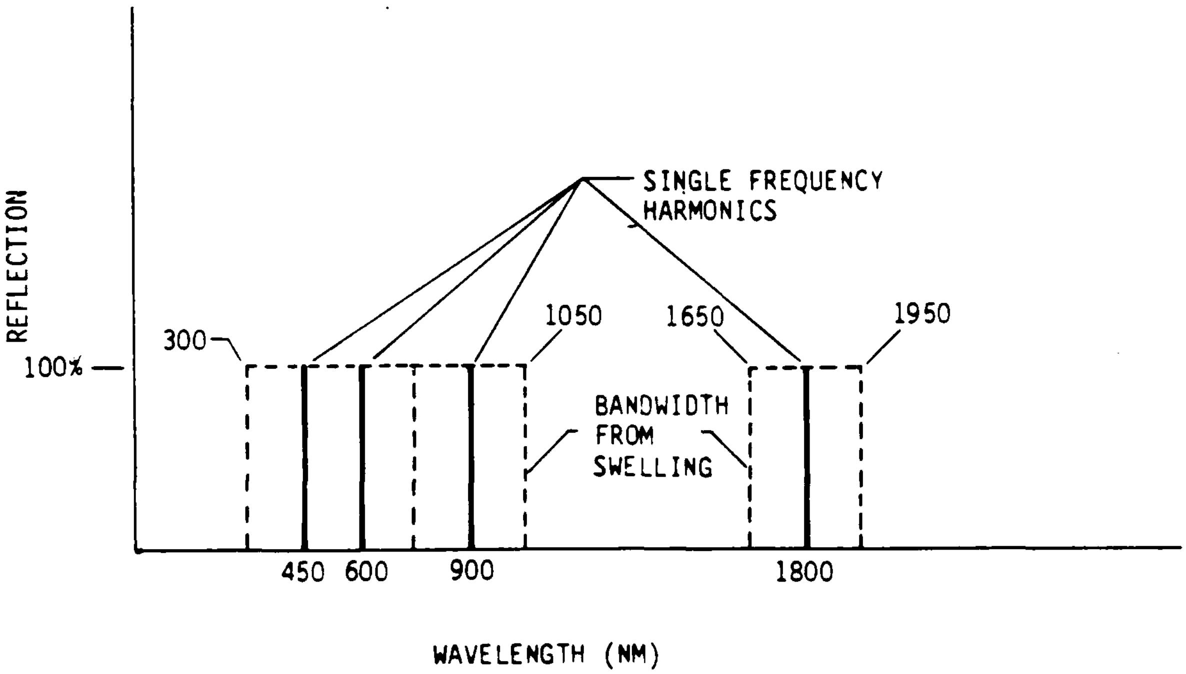


Figure 16. Combination of harmonic and swelled hologram.

TABLE 2. Environmental Simulation Tests for HOE Space Survivability

ENVIRONMENT SIMULATION	FIVE YEAR SIMULATION AT JPL	PERFORMED	
		YES	NO
Vacuum (100μ 5 days)	X	X	
Atomic Oxygen (Flowing)	X	X	
Cold Temperature (32°F)		X	
High Temperature (302°F)	X	X	
Ultra High Temperature (approx. 10,000 suns)			X
Thermal Gradient			X
Micrometeorite			X
Solar Pressure			X
Proton Flux (9MeV, .4MeV)	X	X	

300 nm wide, then two major areas of the spectrum, 300 to 1050 nm and 1650 to 1950 nm, are covered. This represents 60% of the total spectrum of interest. This technique of swelling harmonic holograms was not attempted. It was felt that the funding for Phase I was insufficient to properly investigate this process. However, the process of swelling single wavelength holograms indicates that harmonic swelling is definitely feasible.

SPACE DURABILITY

Phase I included a task to determine the optimum substrates for space-based holograms and to ensure sufficient longevity to support the planned missions. A literature search and tests of materials in the presence of various thermal conditions and ionized gases that may be encountered in a space environment were conducted. TABLE 2 shows the results of environmental simulation tests performed at JPL to investigate the HOE's space durability.

Due to the light weight and thinness of the holoconcentrators, one can be deployed while others are stored in a safe container. When the first mirror lifetime is exceeded, another one can be deployed to replace it.

Substrates

Numerous materials were considered for use as holographic substrates. The final candidates were Aclar, Kevlar, Mylar and Teflon. Mylar appears to be acceptable for space use if the mission is short (1 to 2 months). Absorption of ultraviolet (UV) radiation can cause undesirable degradation in longer missions. Aclar exhibits much lower degradation due to UV absorption as well as having very low outgassing and chemical reactivity. Kevlar would at first appear to be a desirable substrate due to its puncture and tear resistance. However, if a micrometeorite strikes the hologram, the puncture and tear resistance could allow a small but significant portion of the meteorite's force of impact to be transmitted throughout the mirror structure. These forces could deflect the mirrors focus onto the spacecraft resulting in catastrophic damage. A full analysis of this scenario should be performed. Teflon is a very desirable space material, however it is presently very difficult to have holograms bond to a Teflon film. Some effort should be made to resolve this problem. Aclar represents the best trade-off of UV resistance, lack of outgassing and chemical reactivity, and acceptable adhesion to holographic films. Mylar will probably be used for prototype and lab work due to its lower cost and similarity to Aclar.

Emulsions

Degradation studies of the holographic emulsion involved exposure of the emulsion to a vacuum, solar wind proton flux, and atomic oxygen. There was no significant degradation after simulated exposures of five years. This was achieved by using simulation equipment at JPL.

The space environment poses two potential problem areas. However, these two problem areas should have a very low probability of occurrence. The first problem is that the hologram will fade if its temperature rises above 150 degrees Celsius (302° F). This is not predicted to occur during the mission lifetime. The second problem is the hologram's extreme sensitivity to moisture. This should not occur provided that the mirrors are manufactured in a clean room with dehumidified air, and then stored in a dry nitrogen-purged bag, which is standard for most space instrumentation. Alternate holographic materials with reduced moisture sensitivity would allow greater ease of handling and storage after manufacturing.

MAÑUFACTURING PROCESS

Preliminary evaluations were made of the most appropriate manufacturing methods. At present it is believed that the most cost-effective technique is to form large holograms on roll film which would then be joined in panels. For the 3 meter diameter mirror, the roll width would be 10 to 30 cm (4 to 12 inches) in order to allow the use of smaller, more easily removed, breadboard type equipment. For mirrors 30 meters (100 feet) in diameter, strips would be made approximately 1.5-meters (5 feet) wide by 3- to 30-meters (10- to 100-feet) long. Some considerations to be reckoned with are the availability of large, 3 meter (5 feet) wide film handling and processing equipment and the adaptability of silver halide film processing equipment to meet DCG requirements.

STRUCTURAL SUPPORT

In order to effectively utilize the advantages of HOEs, a method of compactly transporting, easily deploying and accurately aiming the system is necessary. This requires a structural support system that is lightweight, rigid, compact, reliable, and does not damage the mirror or spacecraft. In addition, a support system incurring minimal expense is desirable. Several deployable support systems were considered and are discussed in the following sections.

Nitinol (Memory Metal)

Nitinol has potential for use in space structures due to its "memory" capability, that is, it can be formed in a desired shape, then cooled and compressed into a small package. Later, upon heating the structure restores itself to its original shape. Nitinol also has the properties of being very ductile in its cold state, yet being extremely hard and rigid above its hotter transition temperature. This allows nitinol to be cut and stored easily (even crushed) at the lower temperature. At warmer temperature it has enough strength and rigidity (even in small wires) to support substantial loads and be nearly impervious to abrasion.

A literature search was performed on nitinol to determine if it had been evaluated as a structural material for the space environment. Several references were found which described nitinol being used as a structural joint, as an actuator, or as active structural control. This suggests that an entire structure made of nitinol might be feasible for space use. Conceptually, the structure might consist of an expanded wire mesh that would deploy when heated by sunlight (Fig. 17). Several FIGURE 17 manufacturers were contacted regarding price and availability. Prices range from $600 to $800 per pound dependent on quantity, form (wire, plate, bar, etc.) and whether it is a stock or custom item. Delivery ranges from 8 to 16 weeks dependent on the same factors.

Inflatable Structures

A literature search was performed on inflatable structures for space application. Several approaches have been tried which make this approach the oldest concept. However, it has not yet received wide acceptance due to such problems as micrometeorite penetration.

Piezo-Plastics

Another new structural material considered is a class of plastics called piezo-plastics. They may be shaped and controlled by application of high voltages to their surfaces. While of interest, it is not yet

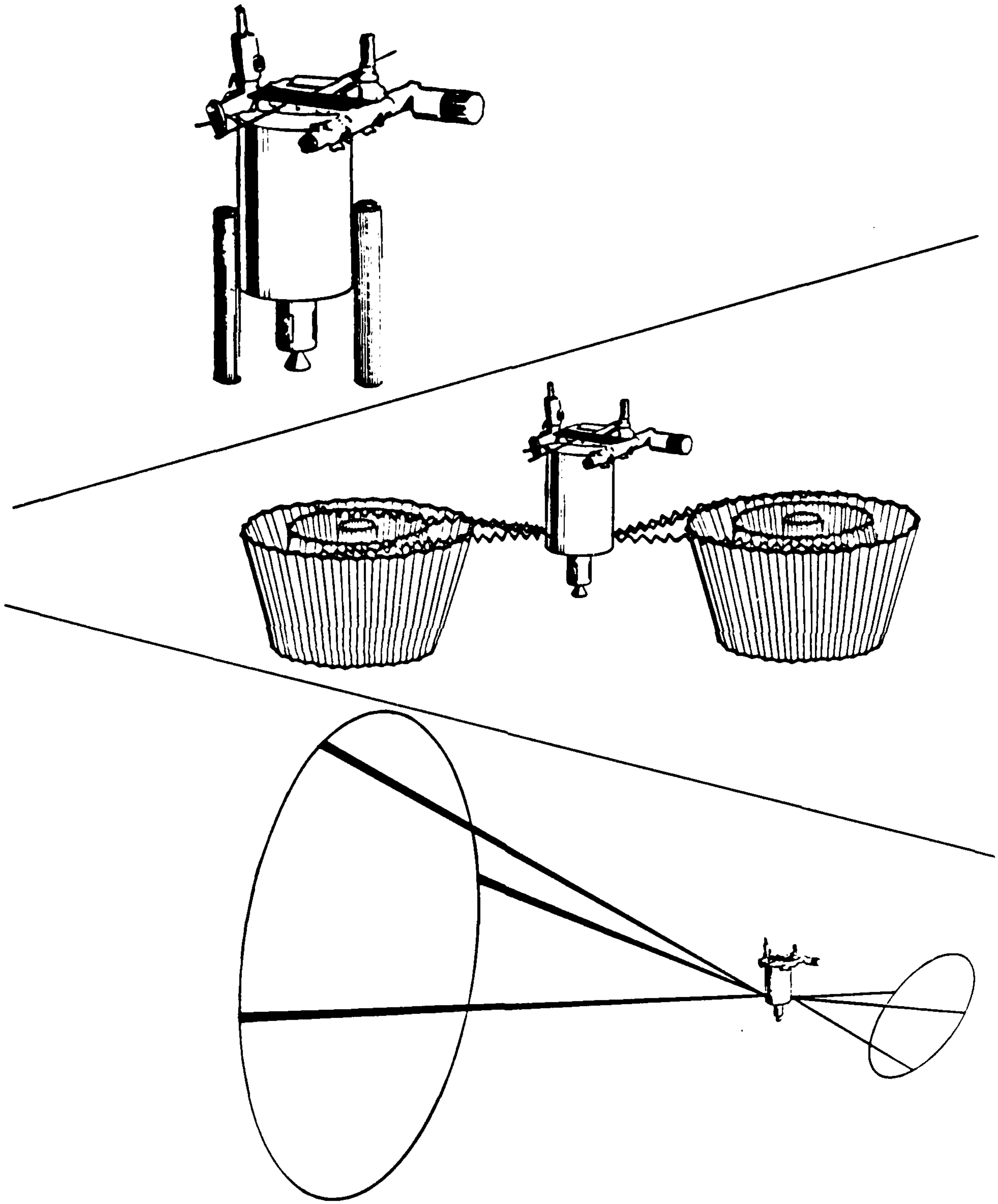


Figure 17. Deployment technique utilizing nitinol.

clear that this material is available in sufficient quantity and with sufficient strength to be a viable alternative. Also, obtaining the very high (20kv) voltages required to actuate the plastic is difficult.

DEPLOYMENT

Although orbital deployment of large HOEs was not a major aspect of the Phase I effort, consideration was given in order to determine an ideal method of deployment. The primary goal of this investigation was to identify any significant structural and methodological problems associated with deploying large HOEs in space. Potential problems including non-uniform, too rapid, and accidental HOE deployment were studied briefly. The deployment of inflatable structures involves slow, gentle inflation/deployment. Using non-inflatable, expandable nitinol memory metal for deployment and support should provide equally slow and graceful deployment of the HOE, although ensuring that the mirrors deploy without a snag and/or damage is obviously a major concern.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

This effort has demonstrated Holographic Optical Element (HOE) mirror technology as a viable alternative to other mirrors such as inflatable, lenticular mylar gas bags, or electrostatically deformed plastic for use as solar energy concentrators.

The scientific studies performed in Phase I demonstrate that HOE technology has great potential for use in producing solar energy concentrators. These studies have also demonstrated that NTS has the engineering skills required to develop a viable functioning prototype system that can be efficiently evaluated using the available AFAL test bed.

NTS' HOE mirror and concentrator technology has many anticipated benefits and potential commercial applications including the use of the HOE technology in solar arrays, thermal insulating glass (for use in buildings, homes, automobiles) and solar generators. Also the HOE technology could be used to manufacture head up displays, laser hardening devices, and lightweight refractive/reflective optics.

RECOMMENDATIONS

Based on the successful results realized from Phase I, a prototype system should be tested at AFAL and compared with alternative systems. The prototype system would consist of a holographic concentrating mirror approximately 3 meters in diameter that could be installed in place of the current AFAL segmented concentrator. The tests will provide both quantitative data evaluating the merits of the (HOE) mirror technology, and data for the analysis of the necessary structural support technology.

Areas in need of further research and development include dispersion compensation, expansion of the reflective bandwidth, moisture sensitivity and adhesion to substrates. Long range goals would involve the scaling up of the roll film processing technology through either existing or innovative designs. Also, a structural support system and an orbital deployment methodology need to be defined.

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