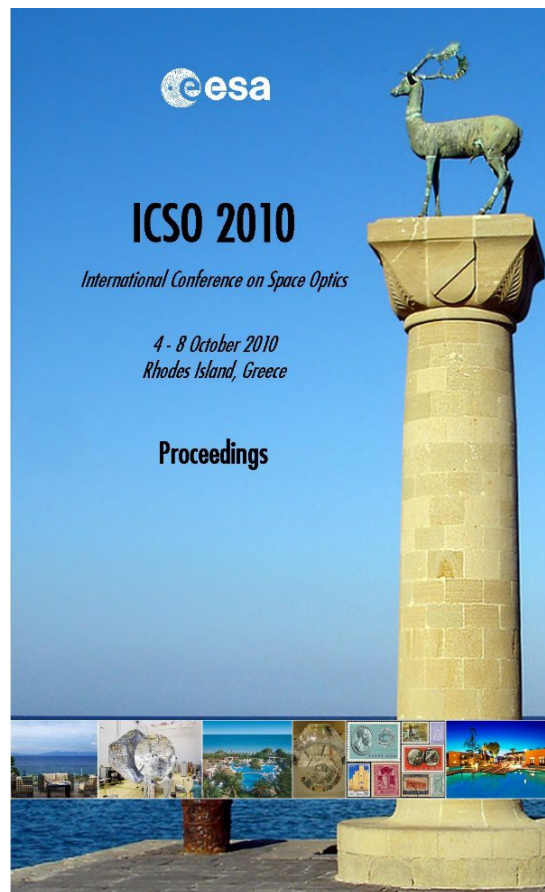


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TRANSCEIVER OPTICS FOR INTERPLANETARY COMMUNICATIONS

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I. INTRODUCTION

In-situ interplanetary science missions constantly push the spacecraft communications systems to support successively higher downlink rates. However, the highly restrictive mass and power constraints placed on interplanetary spacecraft significantly limit the desired bandwidth increases in going forward with current radio frequency (RF) technology. To overcome these limitations, we have evaluated the ability of free-space optical communications systems to make substantial gains in downlink bandwidth, while holding to the mass and power limits allocated to current state-of-the-art Ka-band communications systems.

A primary component of such an optical communications system is the optical assembly, comprised of the optical support structure, optical elements, baffles and outer enclosure. We wish to estimate the total mass that such an optical assembly might require, and assess what form it might take. Finally, to ground this generalized study, we should produce a conceptual design, and use that to verify its ability to achieve the required downlink gain, estimate its specific optical and opto-mechanical requirements, and evaluate the feasibility of producing the assembly.

II. MAIN CONSIDERATIONS

An interplanetary optical communication system must reliably overcome tremendous space losses to efficiently maintain communications. Between Mars and Earth, space losses of up to 370 dB are expected, requiring the transmission of high power or the use of large-aperture optical systems. Given the practical limitations of electrical power and mass on deep-space flight systems, the vast majority of the communications system burden is shifted to the ground segments. Nevertheless, a large, diffraction-limited flight transceiver aperture helps tremendously in overcoming this space loss; since the gain of the transceiver scales roughly as the square of the aperture diameter. Thus, it behooves the system designer to put the largest, most efficient optical system possible on the flight terminal. Unfortunately, as aperture increases, the mass of the system also increases.

In developing an instrument for deep-space operation, the launch vehicle's limited ability to loft the payload and the delta-V requirements for control of the spacecraft trajectory impose binding restrictions on the transceiver's total mass. Comparison with other instruments showed that the optical system generally only accounts for roughly 20% of the total mass of the instrument. This mass includes the main telescope optics (*i.e.* the primary and secondary mirrors, mirror mounts, optical bench, aperture baffling system, aft optics bench, aft optical components and mounts, *etc.*)

To be considered a primary interplanetary communications resource, an optical communications system must be capable of operating throughout the solar conjunction cycle. Long outage periods during the time surrounding solar conjunction would make the system much less attractive to mission designers. As a result, we require the system to operate down to within 3 degrees of the limb of the Sun. This limitation results in an outage (at Mars) of a period of less than two weeks roughly every year. Pointing so close to the Sun introduces considerable difficulty for high-performance optical instrumentation. Optical scattering significantly increases the background noise, which quickly becomes a limiting factor in the ability of the transceiver to observe the uplink beacon and decode the data imbedded in the modulated beacon. In addition, pointing close to the Sun introduces a very high, and unevenly-distributed thermal power input into the optics, threatening to cause differential expansion of optical mirrors and exacerbate the wavefront error. This can occur both by distorting the shape of optical surfaces, and by affecting the sensitive alignment of optical elements with respect to one another.

III. OPTICAL SYSTEM TRADES

A. Aperture Size vs. Mass

In an effort to optimize the configuration of a flight transceiver, we undertook an extensive trade study, considering the size, form and materials for such a transceiver. We began with an estimation of the largest

flight transceiver aperture that might reasonably meet our 5 kg mass limitation. We analyzed a proprietary database of flight optical systems maintained by Optical Research Associates, and based on particular thermal, wavefront quality, alignment, a material considerations, derived the 'Top Down' parametric curves shown in Fig. 1. Two curves are shown: one for systems for which standard lightweighting practices were applied, and a second on which more aggressive lightweighting was used. The mass of our system was assumed to be bounded by these two curves, but was expected to come closer to the aggressive lightweighting curve shown. As a check of this 'top down' approach, we developed a component-based model, in which the various components of an optical communications transceiver were identified, and the size of each component was parametrically scaled to the instrument's aperture size. The mass of the component was then estimated based on a database of material parameters (including material density and allowable thickness-to diameter aspect ratios for flight systems). The calculated masses of all of the components were then summed to arrive at the particular masses shown at discrete points in Fig. 1. The envelope of these points closely matches the standard lightweighting curve, both in parametric form and absolute magnitude, which is not surprising since it was based on standard aspect-ratio rules-of-thumb for flight materials. Note that these data are specific for the application, constraints, and expected operational environment of a deep-space optical communications transceiver, and may not be appropriate for other types of optical instrumentation. The 5 kg mass allocation can be expected to limit the flight system's aperture to about 22 cm, given the use of aggressive lightweighting techniques.

B. On-axis vs. Off-axis configuration

We next set out to determine whether the transceiver should employ an on-axis or off-axis system. Telescopes usually make use of on-axis optical systems; the small areal obscuration of the secondary mirror and support structure is generally a small price to pay for the reduction in volume and concomitant reduction in mass afforded by having light traverse the same volume multiple times. A deep-space optical communications system is different from most telescopes though, in that the performance of the system is not simply related to the collection area of the aperture, as it is with most telescopes, but is more related to the ability of the optical system to efficiently concentrate the downlink signal on the target receiver. A central obscuration results in a diffraction pattern with a narrower central lobe [1], exacerbating the already daunting tasks of accurate pointing and platform jitter rejection, and throws more of the energy into the outer rings of the diffraction pattern, where it is not useful. Finally, the central obscuration removes the 'sweet spot' of the Gaussian downlink beam [2], completely removing it from the transmitted beam, and turning it into a potential liability by reflecting it back toward the laser system.

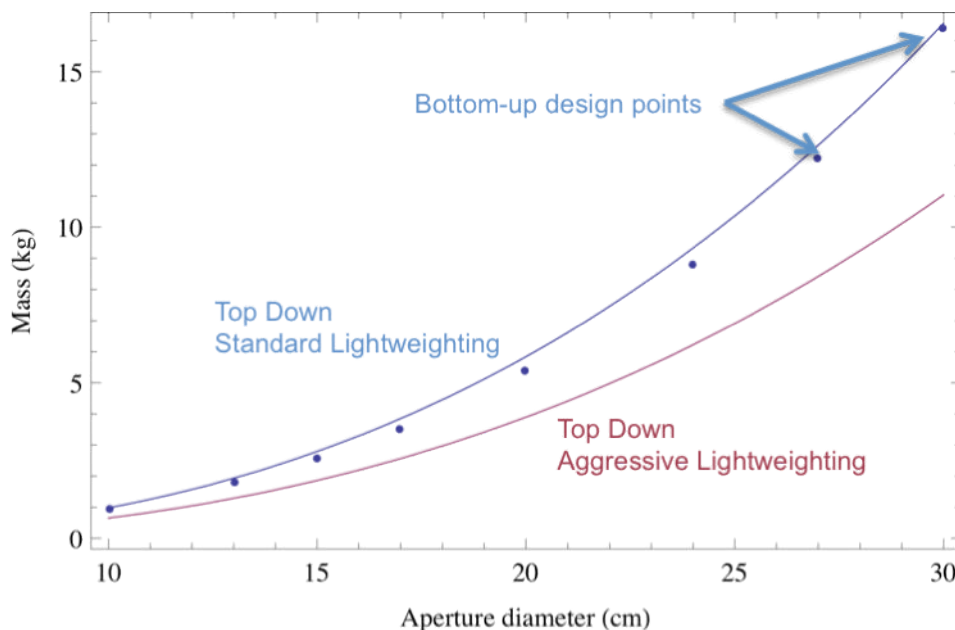


Fig. 1 Comparison of top-down parametric study of flight system mass as a function of aperture (continuous curves), 'bottom-up' component-based model (discrete points)

If the central obscuration were a very small fraction of the aperture, the on-axis advantages of mass and volume might still dominate the aforementioned effects; however, an optical communications transceiver is also different from most telescopes in that it must maintain operation while pointing near the Sun. This requires extra shielding and baffling to protect the transceiver and prevent significant amounts of stray light from overwhelming the faint pointing beacon transmitted from Earth. This extra baffling generally results in a relatively high linear obscuration ratio ($D_{\text{secondary}}/D_{\text{primary}}$) of 30-35%. Given this, and the antennal gain analysis for a Gaussian beam laid out in [3], the trade can easily be performed, as shown in the nomogram of Fig. 2.

This analysis uses the effective far-field gain and mass analysis summarized in Fig. 1 to demonstrate that a near-Sun-pointing optical communications transceiver would have to grow in aperture by over 22% to compensate for the large obscuration, resulting in a total mass increase of almost 70%. This mass increase is roughly 3 times larger than the estimated mass savings afforded by an on-axis system. Inverting the analysis, we estimate that for the trade to favor the on-axis system, the linear obscuration ratio would have to be less than 0.23, a difficult task for a near-Sun operational system.

C. Cassegrain vs. Gregorian form

Cassegrain-type telescopes in which the secondary mirror is a negative element placed before the telescope's prime focus are more common than Gregorian systems where the positive secondary mirror is placed beyond prime focus because they provide a significantly more compact system. This compact system results in significant cost savings for ground-based telescopes because the telescope dome can be much smaller and the telescope's superstructure can be much smaller and lighter. These same advantages generally apply to a space-based flight transceiver architecture as well.

However, once again the requirement to point close to the Sun alters the trade considerably. The accessible focus of the telescope's primary mirror provides an ideal location for an early field stop, the advantages of which are difficult to overstate. This field stop completely prevents illumination of the secondary mirror by direct sunlight, down to angles far below the minimum operational angle of the system. While the primary mirror is still subjected to full-Sun exposure, this exposure is not nearly as critical as exposure of the secondary mirror to sunlight is.

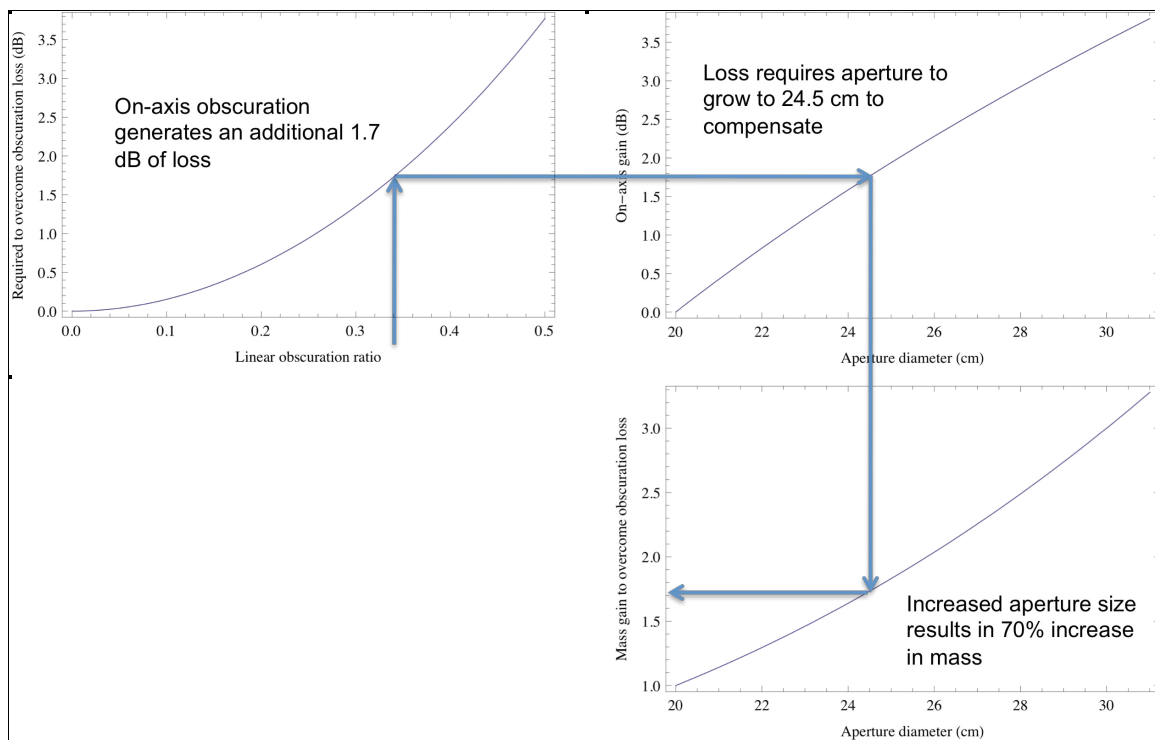


Fig. 2 Nomogram for computing mass effects of on-axis system's obscuration. The obscuration generates a system loss, which requires an aperture increase to compensate, resulting in an overall mass gain of 70%.

The secondary mirror of a telescope pointing near the Sun is subjected to significantly higher irradiances; while the primary mirror may be exposed to approximately 0.014 W/cm^2 from direct Sun at 1AU, the focusing power of the primary mirror will result in irradiances as much as 25-100 times higher on the secondary mirror. This level of irradiance can result in significant thermal distortion to the secondary surface, rapidly resulting in significant aberration to the observed uplink beacon and the finely-tuned downlink. Given the tight wavefront error requirements, it is imperative to prevent Sunlight focused by the primary mirror from depositing significant amounts of heat in the secondary mirror.

A second reason to avoid direct illumination of the secondary mirror with light focused by the primary mirror is that this light will result in significantly more scattering at the uplink sensor detector than that produced directly by the primary mirror. Though the primary mirror is generally considerably larger than the secondary mirror, the concentration of the light by the primary mirror generates roughly the same amount of total scattering from both surfaces. However, the secondary mirror is optically much closer to the detector than the primary mirror, resulting in a significantly larger effective solid angle presented by the detector. We estimate that for a typical optical transceiver system, scattering from the secondary mirror generates approximately 25 times the amount of scattered light at the detector as the same total amount of light scattered from the primary mirror.

Introducing a field stop prior to the secondary mirror almost completely eliminates secondary mirror scattering, thus enabling near-Sun operations. It also acts as a first line of defense against damage produced by accidental direct-Sun pointing. A deep-space optical communications terminal can operate with a required field of as little as 1 mrad, approximately $1/10^{\text{th}}$ the angular subtense of the disk of the Sun when observed from 1 AU. Implementing a Gregorian collecting telescope with a 1 mrad field stop in a transceiver can therefore limit the total amount of sunlight transmitted on to the remaining optical channels to about 1% of the power collected by the primary mirror, even during direct-Sun pointing.

D. Telescope Materials

Achieving light weight optical designs which can operate over the wide range of thermal loading conditions to which a deep-space optical transceiver will be subjected requires careful consideration and selection of candidate materials. To that end, we considered several different candidate materials for inclusion in the system.

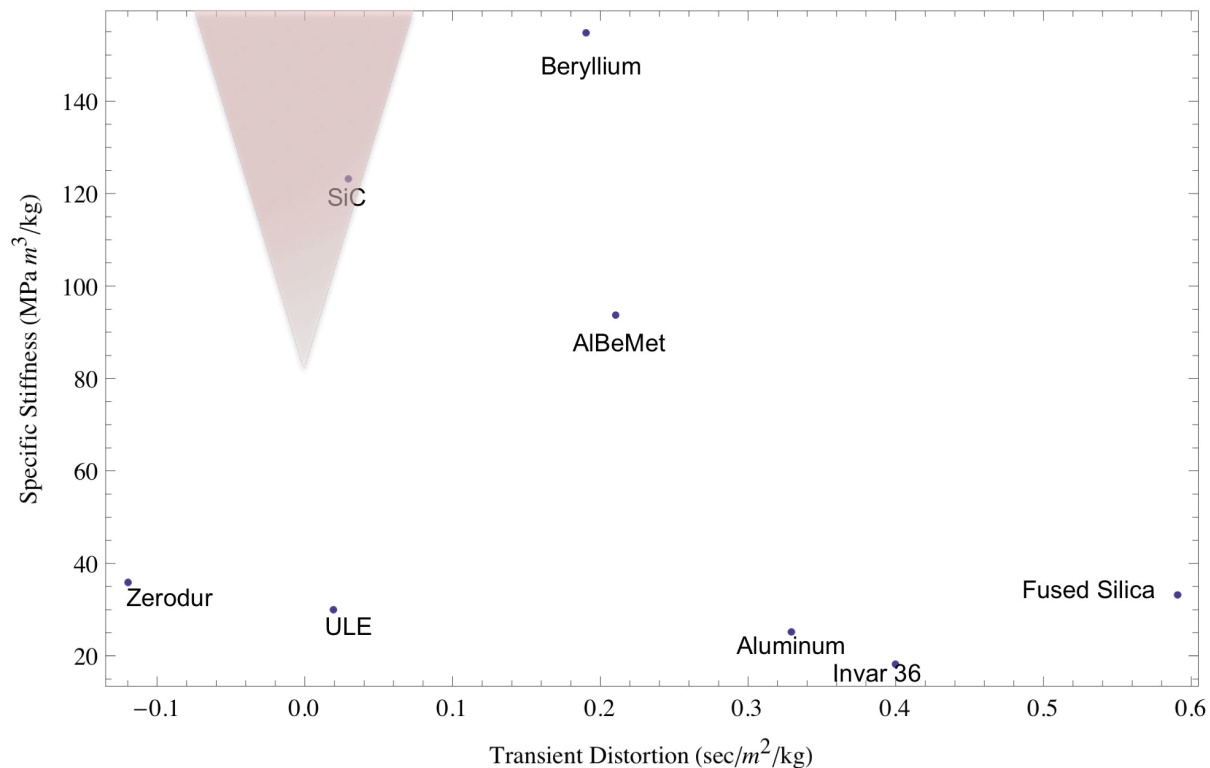


Fig. 3 Specific stiffness and transient distortion plotted for various candidate materials. The system requirements drive the choice of materials within the magenta triangular region.

The choice of material was driven largely by the two overriding concerns repeated throughout this paper: system mass and near-Sun operation. Reducing system mass (while maintaining optical alignment and optical wavefront requirements) requires material with very high specific stiffness (ratio of Young's modulus to density). Maintaining operations under different solar loading conditions requires low transient thermal distortion. These parameters for various optical materials are shown in Fig. 3. Ideal candidate materials would fall within the triangular region shown at the upper-left portion of the graph. While ULE is slightly better in transient distortion, and Beryllium is better in specific stiffness, SiC is the best material for meeting both requirements simultaneously.

IV. CONCEPTUAL FLIGHT TRANSCEIVER

An image of the optics and optical bench of the resultant flight transceiver concept is shown in Fig. 4. The system employs a lightweight but stiff SiC space frame structure with a fundamental resonance of 160 Hz. The structure holds a 22 cm aggressively-lightweighted SiC primary mirror. This mirror focuses light from an uplink beacon through a 1.4 mrad field stop (not shown), from which the light diverges toward the secondary mirror in the aft optics compartment. All aft optics are housed in a single plane imbedded within the long portion of the space-frame structure.

The aft optics section comprises three separate channels; (1) an imaging channel which allows high-resolution imaging of an uplink beacon from Earth to provide a stable pointing reference, (2) a transmit channel which directs a 4-Watt 1550 nm laser off of a piezoelectric point-ahead mirror, and then folds the beam into the field of view by reflecting from a flat dichroic beamsplitter, and (3) a reference channel in which residual transmit laser light transmitted through the dichroic beamsplitter is reflected into the receive channel as a reference for downlink pointing calibration and verification.

This conceptual design includes all optics, optical mounts, optical structure and optical baffles. For protection of the system, it uses a lightweight carbon composite outer shell (not shown) with internal baffle rings to prevent glancing reflections. Also not shown is a one-time use aperture cover with heritage previous flight systems. The entire system is covered in MLI, and is expected to require no additional heat beyond the 10 W emitted by the on-board flight processor. The entire system, including all optics, mounts, baffles and structure is expected to weigh just under 4.9 kg.

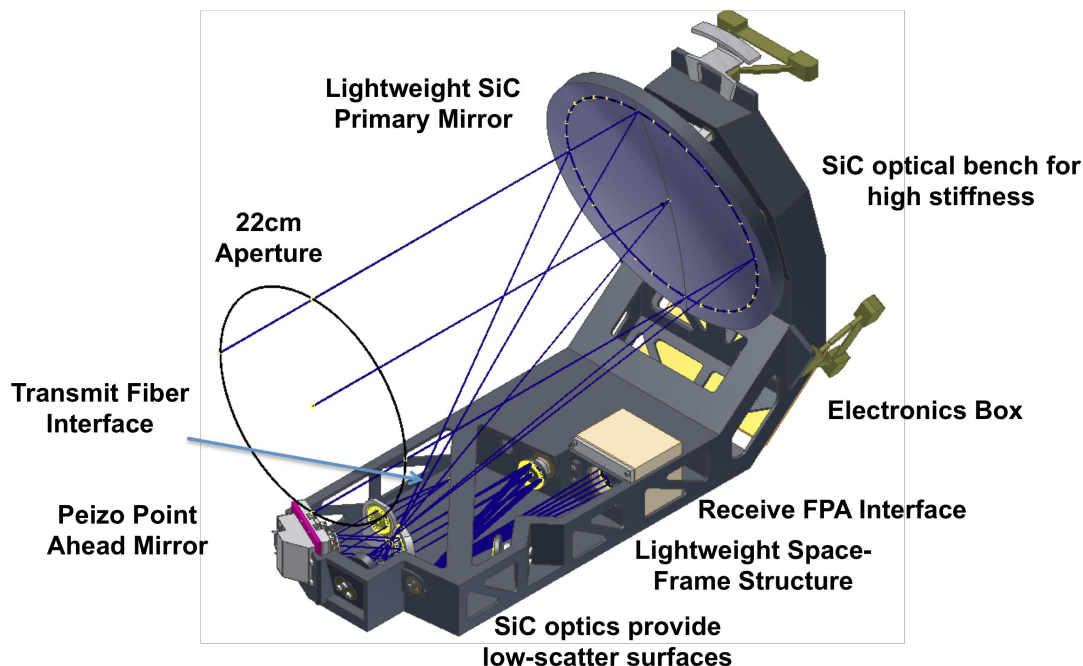


Fig. 4 Resulting point design for the optics and optical bench for a bi-directional deep space laser communications transceiver.

V. REFERENCES

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VI. ACKNOWLEDGEMENTS

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