An Earth-to-Deep-Space Optical Communications System With Adaptive Tilt and Scintillation Correction Using Near-Earth Relay Mirrors[1]

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The performance of an Earth-to-space optical telecommunications system is degraded by distortion (scintillation and tilt) of the beam as it propagates through the turbulent atmosphere. Conventional approaches to correct distortions that are based on natural or artificial guide stars are useful in, for example, astronomical imaging, but have practical difficulties or are not adequate to correct the distortions important for Earth-to-deep-space optical links. A beam-relay approach that overcomes these difficulties is presented. A downward-directed laser near an orbiting relay mirror provides a reference source for measuring and correcting atmospheric distortion. The ground station preprocesses its uplink communications beam such that, after passage through the atmosphere, uplink propagation effects are removed, delivering a diffraction-limited beam to the mirror. The orbiting mirror then directs the corrected beam to the distant spacecraft. We discuss this system.

I. Introduction

Optical telecommunications will be the next technological step in Earth-to-space communication. However, propagation of an optical beam through the irregular atmosphere results in significant distortion of the signal, necessitating correction schemes for deep-space communications. Adaptive optics to correct for some atmospheric propagation effects have been used successfully in many astronomical [1] and military [2] applications. These correction schemes require the presence of a "glint"—an optical reference source—very near the target direction. In astronomical applications, for example, a laser-produced artificial guide star (AGS) in the upper atmosphere, nearby the target direction, has been successfully implemented to correct high-order optical distortions [3].

For optical telecommunications, adaptive optics will be necessary for high-data-rate downlinks and coherent communications applications. For the uplink, the low-order optical distortions—in particular the "tilt" or transverse gradient of the optical phase—are of particular importance, however. The tilt of the wave determines the instantaneous direction of the beam; if the tilt is too large, the beam is not pointed at the target and the link is degraded or lost completely. The situation is particularly acute for the

[1] A shorter version of this article appeared in *Optics Letters*, vol. 23, pp. 1087–1089, 1998.

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uplink in very long distance communication (e.g., Earth to Pluto) where approximately diffraction-limited beams are required to deliver adequate signal strength to the distant spacecraft.

The atmospheric tilt can be quantified [4,5] through the integrated phase structure function: $D_\phi(r) =$ the mean-square difference of the geometric-optics phase at a transverse separation, r, in the receiving plane. For isotropic Kolmogorov turbulence, $D_\phi(r) = (r/b_{coh})^{5/3} = 6.88(r/r_o)^{5/3}$, where r_o is the Fried parameter, over a wide range of scales. A typical refractive tilt is $(\lambda/2\pi)grad(\phi) \sim \lambda/(2\pi b_{coh})$. At 1 μm, r_o can be $\sim$10 cm at astronomical sites such as the Table Mountain Facility in California. Thus, a $D =$ 1-m telescope typically has $D >> r_o$ and, without compensation, has tilt errors that can be large compared with the diffraction limit.

In this article, we outline difficulties with conventional schemes for atmospheric correction as applied to long-distance (Earth-to-deep-space) optical telecommunications systems. We then describe a new approach that can overcome the problems for propagation through the irregular atmosphere. This new system will be able to provide precise adaptive tilt and scintillation correction for a deep-space communications link.

II. Difficulties With Artificial Guide Stars in Optical Telecommunications Applications

Given existing laser technology, the large distance between the Earth and a distant spacecraft at Pluto ($\sim$30 AU) requires the optical uplink between the Earth and the space probe to be near diffraction limited from, for example, a 1-m aperture. Both scintillation and tilt are problems. Turbulence-induced tilt of the wave, usually greater than the diffraction limit, becomes crucial; without tilt correction, the signal from Earth is degraded or could miss the targeted spacecraft completely.

Several methods have been suggested to correct for optical propagation through the atmosphere, particularly in an astronomical imaging context. These involve natural guide stars or producing one or more AGS reference sources at or near the desired uplink direction. These methods are in development, and their final performance will be application-dependent. AGS-based correction methods when applied to the uplink optical telecommunications problem (as distinguished from the imaging problem) present special difficulties. We outline these difficulties below in order to contrast these approaches with the beam-relay solution we propose here.

(1) A straightforward way to measure and correct the tropospherically induced tilt and higher perturbations is to use a natural star [6] nearby the desired uplink direction as the reference source. The requirements on such a natural guide star are severe, however. The star must be both bright (to get enough photons to sense the tilt in the $\sim$1 to 100 ms before it changes significantly [7]) and near the desired direction (to assure that the turbulence-induced distortion is highly correlated between the reference star and the uplink beam direction). This latter requirement can be stringent in the general case when high correlation of the two optical paths is necessary. Bright stars nearby a desired target direction are not usually available, so this natural-guide-star scheme is not practical for operational, high-availability communications systems.

(2) An alternative to natural guide stars for astronomical imaging is to form a monochromatic AGS, produced from a transmitter site co-located with the telescope. Such a system cannot be used to measure and correct the tilt of the wave front, however. This is because the atmospheric tilt is *common* to both the laser beam propagating up through the atmosphere and the back-scattered light from the AGS. The result is that the tilt cannot be sensed—thus, cannot be corrected—by such a system.

(3) More elaborate artificial *polychromatic* guide star systems, which exploit the dispersion in the refractive index of air between the ultraviolet and the infrared, have been proposed for tilt measurement. The idea is to break the symmetry of the upward-going and downward-going paths by exciting mesospheric sodium with laser beams at 589 and 569 nm. When the atoms relax, they fluoresce at wavelengths between 0.33 and 2.3 μm. The dispersion of the refractive index causes the tilt to be different at different wavelengths; observation of the angular offset of the AGSs at different wavelengths allows the tilt to be determined [8]. This approach is under development, and a challenge for a practical implementation will be generating sufficient laser power to allow for diurnal and seasonal variations in the sodium column density.

(4) Two or more monochromatic AGSs produced by laser transmitters physically separated from the main telescope have been proposed. In suitable circumstances, the tilt in the target direction can be deduced. The technical difficulties with a practical implementation of this idea have been discussed in the literature [9].

(5) The optical downlink from the spacecraft itself cannot, unfortunately, be used as an AGS reference source for two reasons. First, the optical downlink from a distant spacecraft will be weak and will not give adequate signal-to-noise ratio (SNR) to estimate and correct the distortions of the beam in an adaptive optics system. Second, and more fundamentally, the downlink photons in general will be arriving from the wrong direction. Because of aberration introduced by the relative velocity of the ground and spacecraft, the downlink and uplink directions are separated; the difference between the apparent direction of the downlink and the required pointing direction of the uplink will be $2\Delta v/c$, where Δv is the relative transverse velocity of the ground station and spacecraft. Typically, Δv for a deep-space probe will be dominated by the Earth's orbital speed, $\approx$30 km/s, so that the typical aberration angle will be $\approx$200 μrad. This is far larger than the isoplanatic angle for observations in the visible (but comparable to the isoplanatic angle in the near infrared [10]).

We propose here an alternate, fundamentally different way to communicate from the ground to a distant spacecraft in the presence of atmospheric distortions of the optical beam that avoids these difficulties with conventional guide stars.

III. Beam-Relay System

Since optical propagation in interplanetary space is distortionless and since there is negligible uncertainty in the location of the spacecraft relative to a near-Earth point outside the Earth's atmosphere, a correctly pointed diffraction-limited optical beam can be sent from a point outside the Earth's atmosphere to the spacecraft without scintillation or tilt error. This diffraction-limited beam could be formed either by a transmitter above the atmosphere or by a *mirror* that redirects a suitably corrected beam that passed through the atmosphere from the ground.

The essence of the idea is that a relay mirror is located in Earth orbit, above the distorting atmosphere. A reference beam providing the information necessary for the ground-based adaptive optics to correct for the atmosphere and thus deliver a diffraction-limited beam to the orbiting relay mirror is produced from a small laser source. The reference source is slightly physically offset from the relay mirror to allow for aberration caused by relative velocity of the ground and the relay mirror. The relay mirror directs the uplink communications beam towards the distant spacecraft with the required pointing accuracy. A sketch of this relay system is provided in Fig. 1. An essential feature of this system is that it has a bright reference source, generated *above* the atmosphere, and at the same angular position where the uplink beam must go through the atmosphere. Under this condition, adaptive optics on the ground can be used to correct the uplink beam for the propagation-induced distortions generated by its passage

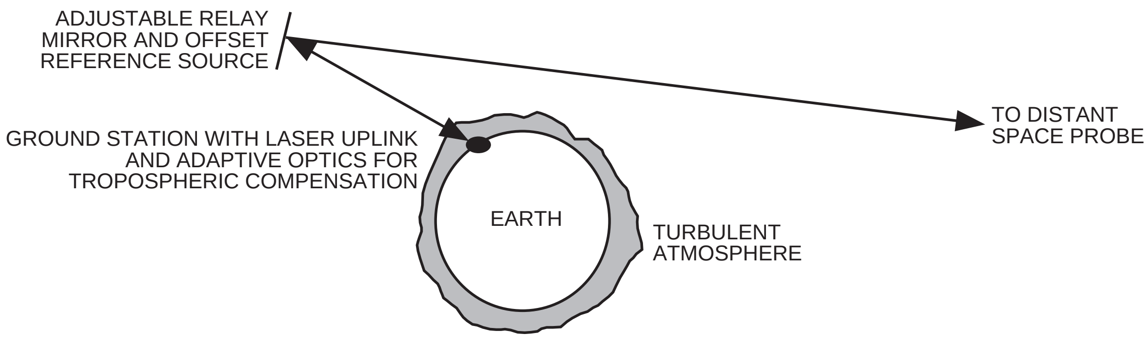

Fig. 1. Schematic, not-to-scale diagram of the optical telecommunications beam-relay system. The beam from a laser slightly offset from the relay mirror (to compensate for aberration) propagates down to the Earth, giving a reference for the adaptive optics on the ground station. The atmospherically compensated uplink communications beam is transmitted to the orbiting relay mirror and then directed to the distant deep-space probe.

through the atmosphere. Unlike other atmospheric compensation approaches, the beam-relay approach offers the ability to monitor in space the degree of compensation achieved on the uplink. By placing optical detectors in the interstices between mirror segments, one can monitor and map the optical power distribution across the aperture. These data could be relayed to the ground station along with metrology data on the mirror segments. With appropriate registration of the detectors, they could provide real-time information on the irradiance pattern at the relay mirror and of the beam directed to the spacecraft.

IV. Some Design Considerations of a Relay System

The beam-relay system proposed here fundamentally solves the principal problem: The laser reference source for the adaptive optics is above the atmosphere, the tilt is estimated from a wave that makes only *one* passage through the troposphere, and the reference beam can be used to produce a diffraction-limited communications beam that can be aimed accurately at the relay mirror.

Some system design considerations are discussed below.

A. Reference-Beam Power

The orbiting laser that provides the reference should be bright enough for very rapid (∼ms) tilt and higher-order corrections. This can be accomplished with a modest-power laser using small optics. The SNR for the adaptive optics system will be limited by some combination of sky background (which can be made small with appropriate filters) and receiver noise. The shot-noise-limited receiver SNR is $\eta P_R/(2h\nu B)$, where η is the quantum efficiency, P_R is the received power, h is Planck's constant, ν is the photon frequency, and B is the receiver bandwidth. An order-of-magnitude calculation for the farthest Earth-relay distance that we might contemplate: If the light from a 1-mW laser at $\lambda \sim 0.5$ μm on a spacecraft at geosynchronous orbit were transmitted to the Earth through ∼10-cm optics, a 1-m telescope on the ground would collect $P_R \approx 30$ nW of the transmitted power. Taking $\nu \approx 6 \times 10^{14}$ Hz and $B \approx 1000$ Hz gives a shot-noise SNR of ≈70 dB. (Practical receivers do not achieve the shot-noise limit but still are adequate for high-SNR operation. Daytime operation should be possible with the SNR reduced owing to sky background noise. Even for observations at 0.5 μm—with a 100-μrad field of view, a filter bandwidth of $\Delta\lambda \approx 1$ Å, and looking ≈10 deg or farther from the Sun—the sky background would contribute only about 1 percent of the power received from the spacecraft reference beam.) Thus, modest-power reference beams provide an SNR adequate for rapid, high-quality estimation and correction of atmospheric tilt and scintillation.

B. Relay Mirror

The reflector need not be a single mirror (there may be practical reasons to synthesize the aperture from smaller, cheaper, easier-to-control segments). The relay mirror (or mirror segments) could be flat—

no special figuring of the mirror(s) is necessarily required. System engineering trade-offs (e.g., the size of reflector/number of segments versus distance to the orbiting mirror; the complexity of tracking low-Earth orbiters; and the number of relays required) can be made. As an example, suppose the relay were in relatively low orbit with a typical ground-station-to-relay distance of $\sim$1000 km. A diffraction-limited beam from a 1-m aperture with $\lambda/D \sim 0.5 \times 10^{-6}$ rad propagating a distance of $z \approx 10^6$ m to the relay would have a spot size of $\approx$1.5 m. Restricting operations with a given relay spacecraft to intervals when the angle of incidence on the mirror was $\lesssim$45 deg means that the mirror would have to be $\approx$2 m in size. (Moving the relay to geosynchronous orbit would require fewer relay spacecraft and might have operational advantages, but would require a larger structure in space. Having a smaller propagation distance to the mirror by putting the relay in near-Earth orbit obviously is desirable to minimize mirror size.)

In its simplest form, this approach involves one reflection off a relay mirror. For some geometries, relay to a second orbiting mirror, which then directs the radiation to deep space, may be desirable.

C. Uplink Pointing

Consider the case where the relay mirror is in near-Earth orbit. Owing to aberration of $2\,\Delta v/c \lesssim 8\,\mu$rad (here Δv is set by the orbital speed of the relay and Earth rotation speed), the reference beacon will have to be offset from the mirror by $\lesssim$8 m. The uplink then is pointed at the apparent position of the reference beam in order to hit the orbiting relay mirror. For a near-Earth relay spacecraft, the transverse velocity will change as it passes over the ground station. Thus, provision must be made to produce the reference beam at the appropriate (time-dependent) position with respect to the mirror. (If the relay were in geosynchronous orbit, the reference source might be on a separate small spacecraft $\approx$600 m away from the relay mirror.)

D. Atmospheric Heating by the Uplink Beam

The uplink communications beam must have relatively high power for communications throughout the Solar System. Some fraction of this power will be absorbed by the atmosphere, resulting in temperature gradients that will contribute to refractive steering of the beam. The extent of this heating depends on the opacity of the atmosphere at the wavelength of the uplink radiation and the beam power. Any tilt variations produced by beam heating will, however, be largely common with the downlink reference beam, thus sensed and corrected by the adaptive optics system.

E. Focus Anisoplanatism

There is little or no focus anisoplanatism in this realization. Laser AGSs are produced at altitudes less than or about 95 km. The backscattered AGS light thus senses atmospheric perturbations in a roughly conical volume, with the cone's apex at the AGS position and the base at the ground-station mirror. The actual optical path to the distant spacecraft (a cylinder through the atmosphere) is different, however. The reference source in our proposed method will sample almost the same atmosphere as the communications beam.

F. Relay-Mirror Pointing

The relay mirror is a space-borne structure with a characteristic dimension of $\gtrsim$2 m, depending on the orbit chosen. To relay the uplink communications beam accurately to a distant spacecraft, the relay mirror should be oriented in space to better than 10^{-6} rad (the whole structure need not be oriented to this accuracy, only control points defining mirror-surface positions). The spacecraft target position would be determined within a reference frame of relatively bright stars. After acquiring these guide stars, the structure then would be oriented to the correct position for beam relay; the desired orientation also would have to be continuously controlled as the ground-station-relay spacecraft geometry changed. In support of near-future optical interferometry/astrometry in space, there is interest in assembly and control for structures in space of comparable size to what is proposed here. Building a beam-relay spacecraft with the required capability and at an acceptable cost clearly will benefit from these and other technology developments (vibration isolation, thermal control, and laser metrology to measure positions of optics) for this type of structure in space [11].

G. Astronomical Applications

The system proposed here is for uplink telecommunications. By appropriately choosing the reference source position, the system could, in principle, also be a diffraction-limited receiver of light reflected from the relay mirror. However, any astronomical use would be severely limited, if only by the very small field of view of the aggregate system. The relay mirror subtends an angle only equal to the diffraction limit of the ground station. Thus, only a very small part of the sky would be instantaneously "visible" in the relay mirror. This limited field of view could effectively be enlarged by scanning the relay mirror, but at the expense of much longer integration times.

V. Summary and Conclusion

Uncompensated propagation through the Earth's turbulent atmosphere fundamentally degrades optical communications with distant spacecraft. Of particular concern are scintillation and tilt of the uplink wave front. We summarized various available or proposed guide-star methods to correct for tilt and scintillation in the optical communications problem. We then proposed a fundamentally different beam-relay system that can provide essentially perfect tilt and scintillation correction. Our proposed system employs an orbiting spacecraft with a bright laser reference source (used for precise adaptive tilt and scintillation correction of the communications beam) and a relay mirror. The atmospherically corrected communications beam is transmitted to the relay mirror and there directed to the distant target. The system requires a space platform providing precise, dynamic beam aiming via a relatively large ($\gtrsim$2-m) flat mirror surface. General requirements for such a system were addressed. These requirements are stringent but apparently can be met using current and near-future technologies.

The beam-relay system described here could serve the communications requirements of many future missions and would guarantee precise tilt and scintillation correction for high-power Earth-to-deep-space optical communications. This general approach also could be employed for Earth-to-Earth optical communications via space-borne mirror relay.

Acknowledgment

We thank Dr. Wilbur P. Brown of the University of New Mexico and Phillips Laboratory for stimulating comments.

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