SAND 78-1500-2
Conf-940142-- 13

Laser Beaming Demonstrations to High-Orbit Satellites

Ronald J. Lipinski, Dorothy C. Meister, and Stephenson Tucker
Sandia National Laboratories
P.O. Box 5800, Albuquerque, NM 87185-5800

Robert Q. Fugate, Phillip Leatherman, Carl Maes, W. Joseph Lange, and William Cowan
Air Force Phillips Laboratory/LIG
Kirtland AFB, NM 87117-6008

Andrew Meulenberg, Jr.
COMSAT Laboratories
22300 COMSAT Drive, Clarksburg, MD 20871

Richard A. Cleis, James M. Spinhirne, and Raymond E. Ruane
Rockwell Power Systems
1650 University Blvd NE, Albuquerque, NM 87106

Robert B. Michie
Mission Research Corporation
1720 Randolph Ave SE, Albuquerque, NM 87106

Donald F. Vonderhaar
Ball Systems Engineering
2901 Juan Tabo Blvd NE, Albuquerque, NM 87111

ABSTRACT

Laser power beaming to satellites and orbital transfer vehicles requires the accurate pointing of a low-divergence laser beam to its target, whether the target is in the sunlight or the earth's shadow. The Air Force Phillips Laboratory (AFPL) has demonstrated reduction in the image size of stars by a factor of 10 or more by using laser beacons and adaptive optics for atmospheric compensation. This same technology is applicable to reducing the divergence of laser beams propagated from earth to space. A team of Phillips Laboratory, COMSAT Laboratories, and Sandia National Laboratories plans to demonstrate the state of the art in this area with laser-beaming demonstrations to high-orbit satellites. The demonstrations will utilize the 1.5-m diameter telescope with adaptive optics at the AFPL Starfire Optical Range (SOR) and a ruby laser provided by the Air Force and Sandia (1-50 kW and 6 ms at 694.3 nm). The first targets will be corner-cube retro-reflectors left on the moon by the Apollo 11, 14, and 15 landings. We will attempt to use adaptive optics for atmospheric compensation to demonstrate accurate and reliable beam projection with a series of shots over a span of time and shot angle. We will utilize the return signal from the retro-reflectors to help determine the beam diameter on the moon and the variations in pointing accuracy caused by atmospheric tilt. This will be especially challenging because the retro-reflectors will need to be in the lunar shadow to allow detection over background light. If the results from this experiment are encouraging, we will at a later date direct the beam at a COMSAT satellite in geosynchronous orbit as it goes into the shadow of the earth. We will utilize an onboard monitor to measure the current generated in the solar panels on the satellite while the beam is present. A threshold irradiance of about 4 W/m^2 on orbit is needed for this demonstration.

1. INTRODUCTION

As long-duration, high-power lasers have come closer to reality, the interest in using them to beam power to space for various applications has increased. The prominent concepts proposed in this area include¹⁻⁶

- Extending the life of batteries on existing geosynchronous-orbit (GEO) satellites by illuminating them when they pass through the earth's shadow

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ydr

- Eliminating the need for batteries on future satellites by (reliably) illuminating them in the earth's shadow
- Increasing the output of future satellites tenfold by continuously illuminating them with a very high-power beam
- Supplementing power on the space station
- Powering orbit-transfer rockets which lift payloads from low earth orbit (LEO) to GEO
- Powering orbit-transfer rockets from LEO to low lunar orbits to support development of a lunar base
- Illuminating solar panels at a future lunar base during the 350-hour long lunar night, thereby reducing the size of the energy storage system
- Supplying power to a small rocket which launches payloads from earth to LEO
- Removing space debris with a ground-based laser

All of these applications require the accurate pointing of a low-divergence laser beam to its target, whether the target is in the sunlight or the earth's shadow. For geosynchronous orbit (GEO) satellites, the solar arrays are typically a few meters across, so the beam divergence and pointing accuracy needs to be less than one microradian (0.2 arc-seconds) to avoid wasting power that spills over outside the panels. Since typical atmospheric aberrations limit beam divergence to about 10 μ rad, efficient laser power beaming requires good compensation for atmospheric distortion. These stringent beam-control requirements have hindered serious consideration of laser power-beaming applications. However, recent advances in atmospheric compensation techniques at the Air Force Phillips Laboratory (AFPL) and elsewhere⁷⁻⁹ make power beaming much more achievable than before. A team of Air Force Phillips Laboratory, COMSAT Laboratories, and Sandia National Laboratories plans to demonstrate the state of the art in this area with laser-beaming demonstrations to high-orbit satellites.

2. PAST ACCOMPLISHMENTS AND ISSUES

The major steps in beam directing are visual acquisition, tracking, atmospheric compensation, and feedback from the satellite. Visual acquisition of the satellite (that is., finding it with the telescope) involves consideration of the orbital angles, brightness of the satellite, lighting conditions, and a hand-off from an approximate track file or radar signal. (From here on, the term "acquisition" will mean visual acquisition by the site telescope). Acquisition is easiest when the satellite is in the sunlight and the telescope is in the dark of night. For LEO satellites at about 200-2000 km altitude this convenient situation occurs only during the few hours after sunset and before sunrise. In addition, for beaming sites in the U.S., the satellite must be in an inclined orbit and must be in the northern part of that orbit during the opportune twilight hours. These conditions do not happen often.

On the other hand, for geosynchronous orbit (GEO) at 36,000 km altitude, the satellite is almost always in sunlight and is visible continuously (provided it is stationed within about 60° longitude of the telescope). So nighttime acquisition with the satellite in sunlight is always available; however, because of the large distance, the satellite is quite dim, typically equivalent to a 15th magnitude star. For half-GEO orbits at 20,000 km altitude the satellites are typically in the sunlight for most of the time and are within sight about six hours per day. Acquisition of sunlit satellites during nighttime has been regularly accomplished for satellites from LEO through beyond GEO.

Acquisition of sunlit satellites during daytime is more difficult because of light scattered from the daytime atmosphere. It has been accomplished for LEO satellites, but GEO satellites present a challenging problem. Acquisition in the shadow of the earth may be possible with infrared detectors since the satellite retains its high temperature for some time. But it would be much easier to acquire it in the sunlight and then attempt to maintain tracking through the earth's shadow. Indeed, this is the problem that will be faced by most power-beaming applications and by the battery-life-extension mission in particular.

Tracking involves following the satellite with low enough wander and jitter that a laser beam projected through the telescope would dwell continuously on the satellite and not jitter so much that the effective beam diameter is increased. Since power beaming usually requires near diffraction limited beam projection, the jitter must be a fraction of the diffraction limit. For example, with a 4-m mirror and 0.694- μ m wavelength, the diffraction limit is about 0.2 μ rad, so tracking and jitter must be considerably less than 0.2 μ rad to maintain a high average power on the satellite. Since atmospheric turbulence creates image blur and jitter of about 10 μ rad, atmospheric compensation is necessary to achieve the required accuracy.

Turbulence in the atmosphere causes beam divergence to be 10 μ rad or greater, regardless of the telescope diameter. Without atmospheric compensation, the beam is so large at GEO that over 99.9% of the beam would miss the intended receiver, and the laser power requirements would be 1000 times larger than otherwise needed. Fortunately, extensive development sponsored by DoD has done much to overcome this difficulty. Accurate and rapid tracking of the satellite image is itself a form of atmospheric compensation. Atmospheric aberrations are categorized by various modes, with the lowest-order modes (x and y) called atmospheric tilt. Tilt causes the centroid of the satellite image to jitter with typically a 100-Hz frequency and 10- μ rad amplitude. With a fast tracking system and electronic feedback of the image centroid, this jitter can be removed. Removing the jitter from atmospheric tilt is a necessary, but not sufficient, condition for good atmospheric compensation.

Tracking of a satellite when it enters the earth's shadow becomes very difficult. The intensity level of infrared light emitted by the satellite will not be high enough for accurate tracking. An illumination laser will be needed. A power-beaming laser which is intended to replace sunlight is more than adequate for this task. However, for nearer-term experiments, other techniques must be used. If the satellite has a corner-cube retro-reflector, a much weaker laser will suffice.

For apertures much larger than the coherence diameter of the atmosphere (10 cm) the turbulence breaks up the beam so badly that there is no central peak. In this case even accurate tracking does little to improve the average power delivered to the satellite. It is therefore a crucial requirement to compensate the higher-order aberrations to create a bright central core in the beam using "adaptive optics." The performance of the adaptive optics determines the width of the central core and percentage of the beam power it contains. The adaptive optics requires a reference beacon above the atmosphere in the direction the laser beam is propagating. Sensors behind the beam projection telescope instantaneously measure the phase aberrations imparted to the reference beacon's wavefront by the turbulence. The phase information is used to distort the surface of a deformable mirror in such a way that it cancels out the aberration introduced by the atmosphere. The deformable mirror (a thin facesheet supported by an array of closely spaced actuators) must react several hundred times per second to keep pace with the changing aberrations. The deformable mirror puts an aberration on the outgoing laser beam that gets "undone" by the turbulence so that as the beam emerges from the atmosphere it is spatially coherent and has near diffraction limited divergence.

Excellent atmospheric compensation has been demonstrated at the Air Force Phillips Lab Starfire Optical Range in Kirtland Air Force Base, NM.^{7,8} This 1.5-m aperture adaptive optics system has formed images of stars having a full width at half maximum (FWHM) intensity of 0.6 μ rad (0.12 arcsec) and peak intensities 65% of the theoretical maximum (Strehl = 0.65) using the star itself as a reference beacon. But bright natural guide stars are not always where you want them, and they do not travel with moving satellites. So an artificially produced laser guide star formed by a low power laser beam focused high in the atmosphere is needed. This beacon must be formed slightly ahead of the satellite to allow for transit delays in the light. The Phillips Lab team has demonstrated this technique also. Peak intensities of 50% of the theoretical maximum have been achieved for a star using a laser beacon for the atmospheric compensation (again with a 0.6 μ rad FWHM image size). These results were obtained at a wavelength of 0.85 μ m (ideal for power beaming) and do not deteriorate for long exposures (>1 minute) indicating excellent tilt correction.

Figure 1 shows four images of a star made through the 1.5-m telescope at SOR at 0.88- μ m wavelength. The field of each image is 15 μ rad. The upper left image is uncompensated, and the other three are compensated to various degrees. The Strehl number is the ratio of actual peak on-axis intensity to the theoretical limit. A Strehl of 0.64 corresponds to a beam divergence of 1.25 times the diffraction limit. Figure 2 is a one-minute exposure of the binary star β -Del made at 0.85 μ m using laser beacon adaptive optics. The two stars (fourth and fifth magnitude) are separated by 1 μ rad. The individual star images are 0.6 μ rad FWHM.

Additional difficulties occur when attempting to combine tracking with adaptive optics using a laser beacon. For high-orbit satellites, the image from reflected sunlight (or from an illumination laser) is faint, so light from the laser making the beacon may interfere with the tracking. In addition, the high-power beam must be pointed somewhat ahead of the satellite to allow for the time-of-flight to the satellite. So the laser beacon must be formed a bit ahead of the satellite image. However, the light reflected from the satellite is being used for tracking to remove the atmospheric tilt. Unfortunately, the atmospheric tilt along the tracking path is different from the tilt along the power-beaming path. A laser beacon cannot detect tilt by itself since the outgoing tilt is canceled by reciprocity on the return. This tilt anisoplanatism problem is most

serious for power beaming to very high altitude satellites ($>1/2$ GEO) where the beam jitter needs to be considerably less than the diffraction limited beam size.

So far, tilt anisoplanatism is an unresolved issue. One proposed approach is to have a retro-reflector or beacon on the satellite to serve as a stable aim point. Unfortunately, this beacon must be stationed ahead of the satellite by 800 meters at GEO (linearly less when closer). Another possible solution is to use a second laser beacon to sharpen (and thus intensify) a nearby faint star for use as a guide to remove the tilt. A third is to use a multi-color laser beacon and utilize the variation in refraction index of air with wavelength.⁹

3. GOALS FOR A POWER BEAMING DEMONSTRATION EXPERIMENT

Most of the work to date with tracking and atmospheric compensation has been performed with satellites in LEO, but most of the power-beaming applications involve higher orbits (LEO to GEO to lunar). Beam divergences established at LEO will, of course, remain unchanged out to GEO and beyond. However, because of the lower light levels and longer times of flight to objects at those higher orbits, the techniques for acquisition, pointing, and atmospheric compensation (including overcoming pointing errors caused by anisoplanatic tilt) are much more difficult. This is especially true for tracking GEO satellites through the earth's shadow. In addition, a beaming demonstration to high orbit may allow a more accurate determination of beam divergence and jitter because of the much longer lever arms involved.

COMSAT has made available one of their communication satellites in GEO for use in a power-beaming demonstration. The Air Force and Sandia National Laboratories have allowed use of a ruby laser developed for the Air Force and presently operated by Sandia. The Phillips Lab has allowed use of the Starfire Optical Range (SOR) with a 1.5-m aperture telescope, adaptive optics, and an experienced team. Two power beaming demonstrations are being pursued utilizing these combined facilities. The goal of the first demonstration is to utilize corner-cube retro-reflectors left on the moon by the Apollo 11, 14, and 15 landings. We will beam light to them via the SOR optics and utilize the returned light to determine key beam parameters such as intensity, divergence, and random pointing error. This information will then be compared to existing models for beam propagation including atmospheric compensation. This work will be challenging because the retro-reflectors need to be in the lunar shadow (lunar night) to minimize background light. The demonstration will give a bottom-line indication of the state-of-the art for beaming to slowly-moving space objects.

The goal of the second demonstration is to beam sufficient light to a COMSAT satellite in GEO so that its onboard monitoring equipment can detect an increase in the power coming from the solar panels. It is presently uncertain whether the ruby laser is adequate for such a demonstration. The results of the first demonstration will be used to assess the likelihood of success for the second and whether it should be attempted. Success may depend on the ability to beam while the satellite is in eclipse when the panels are cold and the background noise is low. The main products of both of these demonstrations will be the operational experience and measurement of real-world beaming capabilities and limitations.

4. REQUIREMENTS AND OPTIONS

Ultimately, operational power beaming will require projection of light intensities about equal to that of the sun for durations of at least an hour at a time. Since most solar arrays of interest are about ten square meters with efficiency around 10%, this will require at least 100 kW of incident light. (Sunlight is 1370 W/m^2 .) Allowing for beam spill, atmospheric loss, and beam-train losses, the laser requirement could rise to hundreds of kilowatts. Because high-power lasers are expensive, a more accurate estimate of the required power is useful.

The shape of a diffraction-limited circular beam at range R is a central (Airy) disk surrounded by concentric rings. The central disk has 84% of the beam power and has a radius of $r_A = 1.22 \lambda R / d_t$, where λ is the transmitted wavelength and d_t is the diameter of the beam-director telescope. Since satellite solar arrays are usually much smaller than the beam size, it is the on-axis intensity that is most relevant. The on-axis intensity is $I_c = 3.7 P_b / (\pi r_A^2)$. Laser imperfections, beam jitter, and atmospheric turbulence usually spreads the beam well beyond diffraction; so a more realistic estimate of the time-averaged beam size and shape is a Gaussian intensity distribution:

$$I = I_0 \exp(-r^2/r_b^2) \quad (1)$$

where I_0 is the on-axis intensity and r_b is the Gaussian beam diameter. A convenient feature of a Gaussian distribution is that the on-axis intensity is equal to the total power divided by πr_b^2 , and r_b is the beam radius at $1/e$ times the on-axis intensity.

Including other sources of loss and beam spread, the beam intensity distribution at range R is:

$$I = \frac{f_o f_a \cos \theta P_L I_{rel}}{\pi r_b^2} \exp(-r^2/r_b^2), \text{ where} \quad (2)$$

$$r_b = \frac{2 \lambda R \beta}{\pi d_t} \quad (3)$$

and where f_o is the fraction of beam energy transmitted through the beam-director optics, f_a is the fraction of beam energy transmitted through the atmosphere vertically, θ is the beaming angle off vertical, P_L is the total laser power, β is the laser beam divergence relative to diffraction limited divergence, and I_{rel} is the Strehl ratio from high-order terms in atmospheric turbulence, anisoplanatic tilt, tracking noise, and point-ahead errors.

A typical Strehl ratio is 0.5 on a good night. There is uncertainty at present as to the precise effect of imperfect atmospheric compensation and tracking. The light is not entirely lost; on the other hand, Figure 1 shows that over brief intervals it is not spread out uniformly. So, statistically, the laser intensity on the target occasionally will be larger than equation (2) indicates, but when averaged over time the intensity on target should be as indicated. In addition, the time-averaged distribution of the beam off-axis will be larger (in diameter and intensity) than equation (2) indicates, but it is difficult to predict by how much.

Typical beam directors have around ten to twenty reflective surfaces in the beam train which results in $f_o = 0.5$. But for power beaming, f_o must be increased to around 0.9 so that the lost power does not damage the optics. (This will be done with high-reflectance coatings). The efficiency for converting monochromatic light to electricity peaks at about 840 nm for silicon and GaAs cells. At this wavelength, the efficiency is about twice that of sunlight for both materials. In addition, $f_o = 0.8$ at that wavelength. An average beaming angle off vertical is about 45° (beyond 60° the Strehl number drops strongly). The largest existing mirror with adaptive optics and an optical train suitable for laser beaming is the 1.5-m mirror at the SOR in New Mexico.⁷ A 3.5-m mirror has been installed recently there and will soon be linked to an atmospheric compensation system. The largest telescope in the world is the Keck in Hawaii with a diameter of 10 meters. It also may have atmospheric correction capability in the future, but it is not a likely candidate for power beaming demonstrations.

The requirements for replacing sunlight at GEO are given below in the second column of Table 1. With a moderately sized beam director of 4 meters, the beam radius at GEO is 6 meters and the required laser power is 300 kW. Note that without atmospheric compensation, the beam radius would be about 185 meters, and the laser would need to be almost 300 MW! This illustrates the crucial importance of atmospheric compensation for power beaming to GEO and beyond.

Table 1. Requirements and options for laser power beaming to GEO.

Symbol	Parameter	GEO Power	GEO	Lunar
		Beaming	Demo	Demo
P	Laser power (kW)	300	50	5
λ	Wavelength (μm)	0.84	0.6943	0.6943
β	Laser divergence/diffraction	1.2	1.3	1.3
d_t	Beam director aperture (m)	4	1.5	1.5
f_o	Beam director transmission	0.9	0.4	0.4
f_a	Vertical atmospheric transmission	0.8	0.7	0.7
θ	Beaming angle ($^\circ$)	45	45	45
I_{rel}	Atmospheric turbulence Strehl	0.5	0.3	0.3
R	Range (Mm)	37	37	384
r_b	Total beam radius with atmospheric comp. (m)	5.9	14.2	147.
	(Beam radius without atmospheric comp. (m))	185.0	185.0	1920.0
I	On-axis beam irradiance (W/m^2)	690	4.71	0.0044
	Fraction of sunlight (thermal)	0.504	0.0034	3.19E-06
	Photovoltaic enhancement for laser vs. sunlight	2	2	
	Fraction of sunlight (electrical)	1.00	0.0069	
r_{cc}	Radius of retro-reflector (m)			0.019
θ_{cc}	Full angle of return (μrad)			25
N_{cc}	Number of retro-reflectors			300
r_r	Radius of receiver (m)			0.75
t_p	Laser pulse length (s)			0.006
N	Returned photons in receiver			380,000
	Returned photons without atm. comp.			2200

In spite of the benefit of atmospheric compensation, the amount of laser power needed is still quite large. Unfortunately, there is no steady-state laser presently available at the optimum power-beaming wavelength of 840 nm with anywhere near 300 kW of power. So near-term demonstrations must be content with brief moments of high power. There is a ruby laser at 694 nm available from the Air Force and Sandia National Laboratories with a 6-ms pulse length and power possibly as high as 50 kW during that pulse. At that wavelength, $f_a = 0.7$. With the 1.5-m SOR beam director, $f_o = 0.4$ and the best I_{rel} expected is 0.3 because the characteristic size of the atmospheric aberration cells is smaller at shorter wavelengths and the required bandwidth of the correction is higher. The beam quality of the ruby laser was improved to $\beta = 1.3$ by using an unstable resonator for the oscillator. With these conditions, the beam radius at GEO would be 14 meters, and the beam would produce electric power equivalent to 0.7% of sunlight (as shown in the third column of Table 1).

The satellite proposed for use by COMSAT is COMSTAR-4 (D-4), which is in GEO orbit at 76° west longitude. The onboard diagnostics system samples the output current of each solar panel every 500 ms for a sampling duration of 1 ms each. This information is telemetered continuously to earth along with other diagnostic information. It is estimated that the diagnostics could detect about 0.5% of sunlight on the panels when they are in the earth's shadow. This corresponds to about $3.4 \text{ W}/\text{m}^2$ at 694 nm. The ruby laser and beam director would need to exceed this amount for at least 1 ms to assure detection. Since the ruby pulse length is only 6 ms correct timing is essential. (Indeed, only the first 1 ms of the pulse may be good beam quality because of thermal effects in the ruby rods.) Because of these concerns, it would be wise to gain experience using another space object with a more sensitive feedback on beam conditions.

The retro-reflectors left on the moon by the manned landings of Apollo 11, 14, and 15 would be suitable for such a demonstration. The retro-reflectors return beamed light to its source regardless of incident angle and thus can provide a good return signal for determination of beam intensity on the moon. The Apollo 11 and 14 sites each have an array of 100 reflectors, and the Apollo 15 site has 300. Each reflector is 3.8-cm in diameter and has a divergence of about $25 \mu\text{rad}$ (< 2 times diffraction). They are aimed at earth, which always remains in the same part of the sky when viewed from the moon.

The number of returned photons collected by the receiving telescope is approximately

$$N = \frac{I t_p}{E_\lambda} \pi r_{cc}^2 N_{cc} f_a \cos \theta \frac{\pi r_t^2}{\pi (\theta_{cc} R/2)^2} \quad (4)$$

$$= \frac{4 \pi I t_p N_{cc} f_a \cos \theta r_{cc}^2 r_t^2 \lambda}{h c \theta_{cc}^2 R^2} \quad (5)$$

where I is the beam intensity on the moon, t_p is the pulse length, E_λ is the photon energy, h is Planck's constant, c is the speed of light, r_{cc} is the radius of the corner cube reflectors, N_{cc} is the number of corner cubes facing the beam, r_t is the radius of the receiving telescope, and θ_{cc} is the full-angle divergence from the corner cubes.

The expected return from site 15 in the 1.5-m telescope is 4×10^5 photons per 6-ms pulse with adaptive optics (or 2200 without adaptive optics) as shown in the bottom rows of Table 1. The return from sites 11 or 14 would be three times smaller. Avalanche photo diodes can detect individual photons with 40% efficiency, so this return is adequate for diagnosing the beam on the moon. The outgoing beam can be made tight by using the laser beacon. However, we probably will not be able to perform tilt correction for the outgoing beam because the retro-reflectors will be in the lunar night. So this will be very much like beaming to a GEO satellite in eclipse. Stochastically, we expect to see an occasional direct hit where the on-axis beam intensity can be measured. An additional opportunity for direct measurement of on-axis intensity and beam diameter may arise if the retro-reflectors are near the terminator and there is a sunlit mountain peak in the field of view. The mountain then can be used to remove the atmospheric tilt and permit reaping the full benefit of atmospheric compensation. The beam diameter could be measured directly by steering the beam by known angles off axis and mapping the intensity.

An additional benefit of this demonstration may be a better determination of the retro-reflector location relative to lunar features than is currently known. Once the reflector locations are known in the coordinate system of the telescope to better than atmospheric resolution, other key features on the moon can be tied down with similar accuracy using the telescope as a long-range theodolite. Finally, this demonstration may be the tightest beaming to the moon yet achieved and an indication of the potential for power beaming to a future lunar base.

5. EQUIPMENT

The demonstration will utilize a ruby laser and the adaptive optics system at the SOR. The laser is flashlamp pumped with a 6-ms pulse length. It is composed of two ruby rods and flashlamp heads in the oscillator and two more rods and heads as amplifiers. Only the oscillator rods are needed for the lunar demonstration, so only they and their power supplies will be moved to the SOR for that phase. Near-diffraction limited performance is needed from the laser for at least one millisecond so that an accurate assessment of the adaptive optics performance can be made. The oscillator as originally configured had a beam divergence of well over ten times diffraction limit with 30 J in the pulse. The oscillator was modified by using a convex mirror and 2-m long path to make an unstable resonator.

The beam quality in this configuration was measured by comparing it with a (low-power) near diffraction-limited HeNe laser. The measured divergence was 1.2 ± 0.2 times diffraction limit for the first 1 ms of the pulse with a power level of 5 kW. The divergence became worse over the rest of the pulse. Averaged over the first 3 ms, the normalized divergence was 2.3; averaged over the last 3 ms, the normalized divergence was 3.6. Apparently, the rod was heating with time. Fortunately, 1 ms is sufficient for the demonstration. With a 1.5-m aperture, the diffraction-limited full angle divergence is about $0.5 \mu\text{rad}$, while the divergence from atmospheric turbulence is about $10 \mu\text{rad}$ (at 693 nm wavelength). So even at 3.6 times diffraction, the beam quality is good enough to demonstrate the effect of atmospheric compensation. However a

Strehl of 0.3 corresponds to a beam divergence of 1.8 times diffraction, so the good quality of the first millisecond of beam is needed to demonstrate the true potential of the atmospheric compensation system.

The SOR beam director system uses a 1.5-m telescope with atmospheric compensation being performed on a 0.113-m diameter deformable mirror backed with 241 active actuators.⁸ A 180-W copper vapor laser (CVL) generates a laser beacon at an average range of 10 km by Raleigh scattering of the beam. The beam is time-gated into 16- μ s (2.4-km) long samples. (A laser for creating a laser beacon in the atmospheric sodium layer at 90 km also is available, but is not needed for these demonstrations). The controlled areas on the 0.113-m diameter deformable mirror map onto the 1.5-m primary mirror as 92-mm square subapertures. The achieved Strehl ratio depends strongly on the ratio of subaperture size (d_{sa}) to the Fried coherence length¹⁰ of the atmosphere (r_0). With infinitely fast actuators, $I_{rel} = \exp(-(d_{sa}/r_0)^{5/3})$. At 693 nm, a typical r_0 at the SOR is about 7 cm (r_0 varies as $\lambda^{6/5}$) but can vary from 3 to 14 depending on atmospheric conditions.

The SOR system is capable of about 100 Hz atmospheric correction rate (loop closure frequency, f_c) with the CVL beacon. The rate of change in the atmospheric conditions is called the Greenwood frequency^{8,11} (f_g), and the performance of the compensation system depends strongly on the relation between that and the loop closure frequency. With an infinite number of actuators, the atmospheric Strehl is $I_{rel} = \exp(-(f_c/f_g)^{5/3})$. Typical Greenwood frequencies at SOR are 40 Hz, but they can range from 10 Hz to 200 Hz. Considering both these effects, with nominal conditions of $r_0 = 7$ cm and $f_g = 40$ Hz, the Strehl with atmospheric correction should be about 0.2 at 694 nm, but could be 0.3 on a good night.

Figure 3 shows a schematic of the SOR optics system with the ruby laser installed. The coude feed to the telescope is at the far right. The off-axis paraboloids (OAP) and lens image the entrance pupil of the telescope on the deformable mirror and Shack-Hartmann lenslet arrays in the copper vapor laser (CVL) and star wave-front sensor (WFS) paths. The phase measuring interferometer provides a real-time view of the mirror wavefront slopes and a means of accurately calibrating influence functions and flattening the mirror. The infrared long wave pass beamsplitter (IR LWP BS) reflects wavelengths shorter than 1 micrometer and transmits wavelengths greater than 1 micrometer (out to the cutoff of 2.5 micrometer of the fused silica window--not shown). The long wave pass beamsplitter (LWP BS) reflects wavelengths shorter than 0.85 μ m into the star/CVL separator where light is subsequently directed into the WFS or auxiliary red/orange sensor path (if the switch mirror is installed). the CCD 'MLM' camera is an unintensified camera switched into the focal plane of the lenslet arrays as an aid to registering the wavefront sensors to the deformable mirror actuators. This camera is used only with the source simulator in the pier. All light passing through the LWP BS goes either to the tracker alone (if the 100% reflecting mirror is installed) or to the tracker and scoring camera if the 50/50 beamsplitter is installed. The CVL beam is brought in under the main optical path and injected into the coude path at the aperture sharing element.

6. PROCEDURE

The main 1.5-m telescope will be used for four nearly simultaneous functions: observing the satellite in sunlight to establish a track file and update tracking at a high enough rate to eliminate atmospheric tilt jitter, directing the CVL to form the laser beacon slightly ahead of the satellite, directing the ruby laser to illuminate the satellite, and receiving the return light to diagnose the beam size at target. The ruby laser will be joined to the system by an aperture sharing element as shown in Figure 3. The sensors measuring the optical return signals from the moon will be shuttered mechanically during the firing of the ruby beam and opened after the appropriate time of flight (2.5 s).

Once the satellite has been acquired and the active track loop closed, we will fire the ruby laser and measure the return signal intensity. The beam director system has a feature in which the telescope can be pointed away from the nominal centerline of closed-loop tracking by a fixed amount horizontally and vertically. We will use this feature to map out the beam intensity versus position utilizing the return signal from the retro-reflectors. From these data the Gaussian beam radius will be determined. This process will be repeated with the adaptive optics on and off, and if possible, with the active track loop on and off, so as to determine the effect of all these components of beam control.

We will then attempt to beam to the satellite as it enters the earth's shadow. We may have some difficulties here since we will not have light with which to track it. This means that eventually the beam will drift off the target. With a good enough track file established by prior tracking in sunlight, and with a good enough model for the telescope pointing behavior, this limitation could be overcome and we should continue to hit the satellite. However, there is another, potentially more

difficult problem. Without light coming from the satellite, we will lose information on the atmospheric tilt. A laser beacon can remove higher order effects of the atmosphere but cannot remove the lowest order (tilt) because it is a differential measuring process. In essence, we lose the benefit of active (millisecond scale) tracking. So the beam intensity on target is expected to go down and we will measure the size of this effect, as well as search for ways to overcome it.

For the GEO satellite this difficulty may exist even in the sunlight: the image for a GEO satellite is so dim that tracking may be overwhelmed by the fluorescence of beam-train optics caused by the CVL light, so that tracking while compensating may not be possible. These measurements will help determine which is better, tracking without compensating, or compensating without tracking.

7. SUMMARY

Although very impressive progress has been made in overcoming the distorting effects of the atmosphere, beaming laser power to satellites with diffraction-limited divergence still requires considerable development. There are numerous engineering and procedural difficulties that must be overcome. We will attempt beaming laser energy to two orbital bodies (the moon and COMSTAR-4) to make accurate measurements of the state of the art in capability, identify the major areas of present difficulty, and explore ways of overcoming those difficulties.

8. ACKNOWLEDGMENTS

This work was supported by the U. S. Department of Energy under contract DE-AC04-94AL85000 and by the United States Air Force. The authors wish to thank D. Dixon and N. Blocker for their technical assistance, D. Monroe and D. Bodette for their technical advice, and Army Lt. Col. James Felty at DOE and Air Force Lt. Col. John Anderson at the Air Force Phillips Laboratory for their steadfast support.

9. REFERENCES

1. R. J. DeYoung, editor, *Second Beamed Space-Power Workshop, Hampton, VA, Feb. 28 - March 2, 1989*, NASA Conf. Publ. 3037 (1989).
2. E. P. Coomes, editor, *Power Beaming Workshop, Pacific Northwest Laboratory, Richland, WA, May 14-16, 1991* (1991).
3. A. Brown, editor, *First Annual Wireless Power Transmission Conference, WPT '93, San Antonio, TX, February 23-25, 1993* (1993).
4. J. D. G. Rather, "Laser Power Beaming for Space Development: An Example of an On-going Advanced Research Technology Project at NASA", *Proc. of the SELENE Advocacy Briefing and Progress Review, Marshall Space Flight Center, AL 35812, July 16, 1992* (1992).
5. G. A. Landis and L. H. Westerlund, "Laser Beamed Power: Satellite Demonstration Applications," *43rd Congress of the International Astronautical Federation, Aug. 28 - Sept. 5, 1992, Washington, DC, (IAF-92-0600)*.
6. D. K. Monroe, "Space Debris Removal Using a High-Power Ground-Based Laser," *Proc. of the AIAA Space Programs and Technologies Conference, Huntsville, AL, Sept. 21-23, 1993*, paper No. AIAA 93-4238 (1993).
7. R. Q. Fugate, D. L. Fried, G. A. Ameer, B. R. Bocke, S. L. Browne, P. H. Roberts, R. E. Ruane, G. A. Tyler, and L. M. Wopat, "Measurement of Atmospheric Wavefront Distortion Using Scattered Light from a Laser Guide-Star," *Nature*, 353, p. 144 (1991).
8. R. Q. Fugate, et al., "Two generations of laser guide star adaptive optics experiments at the Starfire Optical Range," to be published in January 1994 feature issue of *J. Opt. Soc. Amer.-A on Atmospheric Compensation Technology* (1993).
9. N. Hubin and L. Noethe, "Active Optics, Adaptive Optics, and Laser Guide Stars," *Science*, 262, p. 1390 (1993).
10. D. L. Fried, "Least-square fitting a wave-front distortion estimate to an array of phase-difference measurements," *J. Opt. Soc. Amer.*, 67, p. 370 (1977).
11. D. P. Greenwood, "Bandwidth specifications for adaptive optics systems," *J. Opt. Soc. Amer.*, 67, p. 390 (1977).

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Figure 1. Ten-millisecond star images made with 1.5-m aperture telescope at SOR with various amounts of atmospheric compensation. Field of each image is 15 μ rad.

Image through turbulence
Intensity = 384

Image with laser beacon AO
Intensity = 3260, raw data

Figure 2. One-minute exposure of binary stars β -Del made at 0.85 μ m with and without laser-beacon adaptive optics. The star separation is 1 μ rad.

Figure 3. Schematic of the SOR optics system with the ruby laser installed.

END

DATE
FILMED

3 / 16 1944