SAND 94-2002C
Conf-950226--43

Laser Beaming Demonstrations at the Starfire Optical Range

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

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

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

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

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

ABSTRACT

The ability to acquire, track, and accurately direct a laser beam to a satellite is crucial for power-beaming and laser-communications. To assess the state of the art in this area, a team consisting of Air Force Phillips Laboratory, Sandia National Laboratories, and COMSAT Corporation personnel performed some laser beaming demonstrations to various satellites. A ruby laser and a frequency-doubled YAG laser were used with the Phillips Lab Starfire Optical Range (SOR) beam director for this activity. The ruby laser projected 20 J in 6 ms out the telescope with a beam divergence that increased from 1.4 to 4 times the diffraction limit during that time. The doubled YAG projected 0.09 J in 10 ns at 20 Hz. The SOR team demonstrated the ability to move rapidly to a satellite, center it in the telescope, then lock onto it with the tracker, and establish illumination. Several low-earth-orbit satellites with corner-cube retro-reflectors were illuminated at ranges from 1000 to 6000 km with a beam divergence estimated to be about 20 μradians. The return signal from the ruby laser was collected in a 15-cm telescope, detected by a photomultiplier tube, and recorded at 400 kHz. Rapid variations in intensity (as short at 15 μs) were noted, which may be due to speckles caused by phase interference from light reflected from different retro-reflectors on the satellite. The return light from the YAG was collected by a 35-cm telescope and detected by an intensified CCD camera. The satellite brightened by about a factor of 30 in the sunlight when the laser was turned on, and dimmed back to normal when the 50-μradian point-ahead was turned off. The satellite was illuminated at 1 Hz as it entered the earth's shadow and followed for about 10 seconds in the shadow. In another demonstration, four neighboring GEO satellites were located and centered in succession with a 3.5-m telescope at a rate of about 16 seconds per satellite.

Keywords: Satellite illumination, power beaming, atmospheric propagation, active tracking, Starfire Optical Range, Beacon C, GEOS 1, Explorer 27, Explorer 29, scintillation

1. INTRODUCTION

Accurately beaming laser light to satellites has numerous potential applications. At low power, the beam can be used for high-bandwidth communication or high-accuracy ranging. At high power, electricity can be produced on the solar panels

DISCLAIMER

and this could be a potential means for reducing the cost of satellite power systems, extending the life of the satellite batteries, and augmenting space propulsion systems.[1] The key steps in the area of accurate illumination are (1) locating the satellite, (2) centering it in the beam-projecting telescope, (3) follow the satellite as it moves, (4) projecting a properly aligned laser beam to the target, and (5) overcoming atmospheric turbulence, which causes beam spreading. Past demonstrations began around 1965 with the launch of several satellites with corner-cube retro-reflectors (CCRs).[2-7] These pioneering efforts usually involved beams with a divergence of about 1000 μradians and yielded success rates of often only a few percent. More recent demonstrations with much improved equipment have projected beams with divergences of 30-90 μradians and a success rate of essentially 100%.[8] In order to assess and demonstrate the state of the art in these areas, a team consisting of personnel from the Air Force Phillips Laboratory's Starfire Optical Range (SOR), Sandia National Laboratories, and COMSAT embarked upon some laser beaming demonstrations.

First-order corrections for atmospheric turbulence can be overcome fairly simply on bright stars by fast tracking with a tip-tilt mirror. This technique is beginning to be used within the astronomical community.[9,10] But to obtain truly tight beams requires high-order corrections, and this involves the use of adaptive optics (AO) with a deformable mirror.[9-12] The SOR telescope has demonstrated the ability to overcome both the first-order and high-order terms in atmospheric turbulence in observing stationary stars by the use of AO.[13-14] But using AO on moving objects is more difficult. This paper will report on the use of fast tracking (tip-tilt) to help overcome the first-order term of turbulence, but it will not address the issue of overcoming higher-order terms on moving objects.

2. EXPERIMENTAL APPARATUS

The demonstrations used a ruby laser, a frequency-doubled YAG laser, and the 1.5-m diameter beam director at the SOR. The ruby laser beam had a wavelength of 694.3 nm, a nominal pulse length of 6 ms, and a total energy of 30 J (but because of losses in the optical train, only 20 J left the telescope). The laser was composed of two ruby rods, each 1.0 cm in diameter, arranged in an unstable-resonator configuration. The resonator used one flat mirror and one convex mirror separated by 2.1 meters. Figure 1 shows the divergence measured before and after the laser was moved from Sandia to the SOR and installed. The divergence in the first millisecond is near the diffraction limit; when it exits the 1.5-m diameter telescope its divergence should be about 0.8 mradians. The end of the pulse is about 3.5 times the diffraction limit; when this portion of the beam leaves the 1.5-m diameter telescope, its divergence will be about 2.1 mrad. Since the atmospheric turbulence causes a divergence of about 10 mradians, the first millisecond, and even the tail of the beam, can be used to determine the effect of atmospheric turbulence.

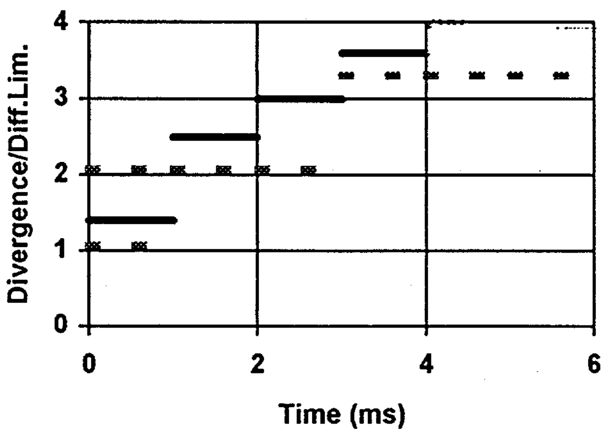

Figure 1. Beam divergence vs. time. Dashed lines are before the move to SOR. Solid lines are after.

Figure 2 shows the layout of the laser relative to the other optical elements in the SOR coudé room. (For more details, see Reference 14.) This configuration is a good example of what would be needed for an actual laser power-beaming system. The ruby laser is in the upper left of the figure. Light from it enters the SOR beam train on the optics bench on the right side of the figure. It reflects from an off-axis paraboloid (OAP) mirror to a deformable mirror which is configured to compensate for the atmospheric aberration at about 100 Hz. From there the ruby beam reflects off a fast steering mirror which corrects for jitter in the telescope and first-order atmospheric aberration (isoplanatic tilt). It then reflects off another OAP mirror and then a series of flat mirrors and is expanded to 1.5-meters diameter in the final beam-directing telescope (on the right side of the figure).

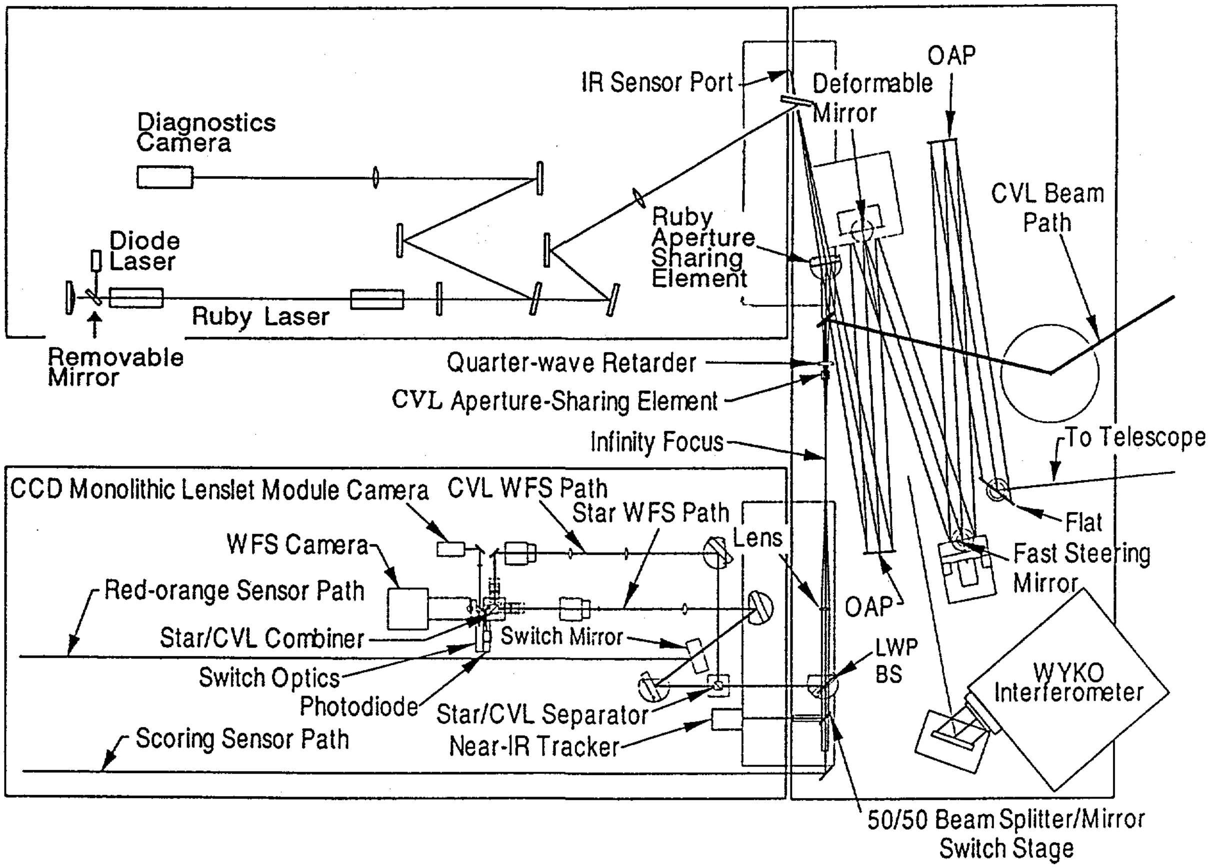

Figure 2. Layout for ruby laser at the Starfire Optical Range.

The system is complicated by the need to sense the satellite location (for first-order atmospheric correction) and the atmospheric aberration (for high-order correction in some future experiment) with many of the same optics used by the outgoing ruby beam. When a laser guidestar is needed (for high-order corrections), a 180-W continuous copper vapor laser (CVL) must share the beam path through the telescope. This all is achieved by using polarized filters, line filters, and beam splitters.

Light from the satellite (distorted by the atmosphere) is collected by the 1.5-m beam-directing telescope and enters the coudé room at the far right of the figure. It reflects off the off-axis paraboloids (OAPs), the fast steering mirror, and deformable mirror, sharing the same path as the ruby beam, but traveling in the opposite direction. The satellite light then encounters the ruby aperture sharing element which reflects the satellite light (but allows the ruby beam to pass through on its way to the telescope).

The satellite light then continues on to the red/NIR tracker at the bottom of the figure. This sensor determines the corrections needed for the fast steering mirror to compensate for telescope jitter and first-order aberrations of the atmosphere. Some of the light is split off and directed to the Shack-Hartmann lenslet array and wavefront sensor camera (WFS camera) near the bottom center of the figure. This sensor determines the higher-order aberrations caused by the atmosphere and allows calculations of the appropriate corrections for the deformable mirror. The phase measuring interferometer (built by WYCO, Inc.), in the lower right of the figure, views the deformable mirror and provides a real-time view of the mirror wavefront slopes and a means of accurately calibrating influence functions and flattening the mirror.

The satellite light can be imaged and monitored in either the infrared or visible. Two separate paths are provided for this. The infrared long wave pass beamsplitter (IR LWP BS) reflects wavelengths shorter than 1 μm and transmits wavelengths greater than 1 μm (out to the cutoff of 2.5 μm of the fused silica window--not shown). The long-wave-pass beamsplitter (LWP BS) reflects wavelengths shorter than 0.85 mm 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).

Unfortunately, most satellites are quite dim, so a laser guidestar may be needed for high-order atmospheric compensation. In these cases, a 180-W copper vapor laser (CVL) must be injected into the system and out the telescope. The CVL beam is brought in under the main optical path, and then steered upward, and injected into the main beam path (the regions with triple lines) at the CVL aperture sharing element. This reflects CVL light of a certain polarization. It passes through a quarter-wave retarder that rotates its polarization 90°. The CVL light then heads toward the ruby aperture sharing element where it is reflected and joins the ruby beam. The CVL beam is then reflected off and OAP, the deformable mirror, the fast steering mirror, and is sent out to the telescope.

When the beam passes through the atmosphere, some of it is scattered back to the telescope. This light forms an artificial guidestar and contains information about the atmospheric distortion. It must then pass through the beam train and be sensed by the wave front sensor (WFS) . To do this, it must not bounce off the mirror it used to get into the beam train. When it passes through the quarter-wave retarder on the return trip, its phase is rotated another 90°. This allows it to pass through the polarization-sensitive mirror and reach the wave front sensor. Separate paths are provided for the CVL light and satellite light (by use of filters) to allow comparison of the two different techniques for atmospheric compensation.

The ruby laser beam was adjusted until it matched the SOR beam train with regard to vertical and horizontal position, vertical and horizontal angle, divergence, and beam size. This was done by using a diode laser alignment beam reflected along the ruby path just before the first oscillator rod at the far left of the figure. (The diode-laser mirror was then removed before firing the oscillator.) Another light source at the base of the telescope (also removable) directed a beam toward the ruby laser. When the two spots met, the system was aligned. A second laser used for the beaming demonstrations was a frequency-doubled YAG laser, which replaced the ruby laser. The doubled YAG beam was 10 ns long at 530 nm, with 0.09 J per pulse at a rate of 20 Hz. The beam entered the optical path at about the same location as the ruby beam (with suitable replacement optics for the new wavelength).

Finally, to confirm successful illumination, a detector was needed for the light returning from the satellite. For the experiments using the ruby laser, a 15-cm diameter telescope was mounted piggy-back on the 1.5-m telescope to collect the light reflected back from the satellite. A photomultiplier tube mounted on the 15-cm telescope was used to detect the light. For the experiments using the doubled YAG laser, a 35-cm telescope was used to collect light, and the image was detected by a Xybion intensified CCD camera and recorded on videotape. The 35-cm telescope was attached to the 3.5-m telescope at the SOR[15] which is located 127 m (horizontally) northwest of the 1.5-m beaming telescope (at azimuth = 285.4°).

3. SATELLITE ILLUMINATION PROCEDURE

The procedures followed at the SOR during the illumination demonstrations are good examples of what would be done during an actual power-beaming operation. Satellite illumination with a laser beam requires written permission from the satellite owner. We obtained such permission for a number of satellites with corner cube retro-reflectors (CCRs). Additional constraints to beaming involve continuous monitoring of the skies for aircraft (both visually and with radar) and restricting the beam to greater than 45° above the horizon. The 45° limit is based on an agreement with the local offices of the Federal Aviation Authority and can be reduced to 30° for special events, with prior approval. In addition, the path of each target is checked by Air Force personnel responsible for tracking all satellites in orbit, and broad windows in time are established during which beaming is not allowed so as to avoid potential interference with other satellites (this is called "predictive avoidance"). Working within these constraints was not difficult, especially since the best beaming angles are higher than 30° because of atmospheric effects. The predictive-avoidance shutdowns were short and fairly inconsequential.

Laser beaming proceeds through a series of steps flowing from target acquisition, to laser beam projection, and then to confirmation of satellite illumination. The detailed orbital parameters for a satellite ("orbital elements") change fairly significantly over a few weeks for LEO satellites, and so fresh elements must be obtained within a few days of beaming.

The element set for a given satellite is used to determine when the satellite will be visible in the sunlight and above the allowed beaming angle (45°). For LEO satellites, this occurs only during early evening or early morning hours; for orbits 6000 km or higher, the satellite is usually out of the earth's shadow for more than 90% of the pass.

The orbital elements of the desired satellites are read into the acquisition program. The system is set up so that those satellites that will be overhead that night are shown on a computer screen, and those which are currently above the horizon are highlighted. At the chosen time, the acquisition operator selects the desired satellite from the list; the telescope is then automatically moved to the location where the satellite is expected to be and automatically follows the expected trajectory. A wide-field acquisition video camera mounted piggyback on the main telescope is used to search for the satellite. The acquisition camera field of view was 7 by 9 milliradians (0.4 x 0.5 degrees), and with fresh element sets, the satellite is found within this region. An operator searches the live video image for the satellite (which remains stationary against the background of moving stars as the telescope follows the predicted track). When the the satellite is found, the operator identifies it for the computerized tracking system by clicking on it with the computer mouse. This causes the telescope to center it in the field of view. (If the satellite is not found, the operator can manually scan the area around the predicted track.) This completes the target acquisition stage. The entire process (from selection on the computer screen to final centering) usually takes 10 to 20 seconds.

The next step is to lock onto the target with the fine tracker. After the image is centered, the light from the primary telescope is directed to the tracker sensors in the coudé room. A second operator there manually centers the image for the tracking sensors and adjusts the sensor integration time to maximize the signal-to-noise ratio while still obtaining a high enough re-fresh rate to keep up with atmospheric turbulence. This process removes the first-order term of atmospheric turbulence.[9-12] With a bright, stable object such as a star, the process is fairly simple and is beginning to be used in astronomical observatories. But with fast-moving, dim satellites, the process is much more challenging because sometimes there are not enough photons to do the job. Typically it takes about 200 detected photons in each 10-ms time interval to achieve tracking lock.[11] With a bright object, tracking lock is usually achieved in about 20 to 40 seconds. With a dim object, it can take several minutes, and sometimes it is not achieved. The limit of the tracking system for the 1.5-m telescope is a visual magnitude of V = 13 for a stationary star and good atmospheric conditions.[11] It could be less for a moving satellite and poorer conditions.

This paper will not report on higher-order atmospheric compensation while attempting laser beaming, but the next step in an actual power-beaming process would be establishing such compensation with adaptive optics. Adaptive optics (AO) removes the higher-order atmospheric disturbances that are not removed by the tracker.[9-12] If the object is bright enough, the light from it can be used for compensation. The AO step is performed immediately after tracking lock is achieved and is controlled by two more operators in the main control room. Some of the object light is directed to the Hartmann wavefront sensors. The sensor output is used as input to the AO computer, which rapidly adjusts the deformable mirror to compensate for the atmosphere. The AO algorithm has a few empirical parameters to allow for changing conditions from night to night. Indeed, the system is usually tuned up every few hours using a bright stationary star. With a moderately bright star, the two AO operators can achieve AO lock in about a minute.

If the object is not bright enough for AO lock, an artificial laser guide star (LGS) must be formed high in the atmosphere.[13,14] If the object is a satellite, the LGS must move with it. This requires permission to beam laser light from the telescope. So, while the satellite is being acquired and tracking lock established, a spotter is deployed to the roof adjacent to the telescope to watch for airplanes. Another person, the safety officer, watches a radar screen for incoming traffic, and also checks that there is no predictive-avoidance shutdown in effect at that time. The safety officer also is the central control and final authority for allowing the laser beam to be projected out of the telescope. When conditions are clear, he will grant permission for the laser to exit the telescope and form the LGS. (This same process is used for the satellite-illumination laser.) The communications to verify safe beaming conditions usually takes about ten seconds, and since the laser is prepared well in advance, getting the beam out takes only a few seconds more.

After acquisition and tracking lock (and AO lock in future experiments) are achieved, the system is ready for laser beaming to the satellite. The telescope is pointed ahead along the flight track by an angle of $\theta = 2v/c$ (where v is the satellite speed, and c is the speed of light) to allow for the time it takes for the satellite light to reach the tracker, and for the laser light to reach the satellite. This is achieved automatically by the tracking telescope once the correct offset is entered into the computer. For a LEO satellite, the point-ahead angle is about 50 μradians as it passes overhead; for a GEO satellite it is about 20 μradians.

The safety officer verifies with the spotter on the roof and the radar that there are no approaching aircraft and that there is no predictive-avoidance shutdown, and the laser beam is allowed to exit the telescope. If conditions are good, and if the safety team is already deployed, the whole process from the start of the acquisition process to the moment the laser beam reaches the satellite takes about 30 to 60 seconds (without AO). Based on experience with stars, adding LGS AO will require an additional 60 seconds or more. However, in many cases all this can be done before the satellite reaches the allowable beaming altitude (45°), so the loss in available beam time can be as small as a few seconds. Unfortunately, with dim satellites there often is not enough light until it is high in the sky, and the tracking lock also takes longer. So there is a definite time advantage in having a bright object for beaming.

If the intent is to detect light returned from corner-cube retro-reflectors (CCRs) mounted on the satellite, then one must be sure the detector is within the diameter of the returned spot. The typical divergence of CCRs is 30 to 100 μradians. So for a LEO satellite 1000 km overhead, the return spot is about 30-100 m in diameter; for a GEO it would be about 1-4 km, depending on the CCR. The receiving telescope must be within this distance of the transmitting telescope. The beam is returned in the precise direction it came from (in the rest frame of the corner cube), so the center of the return spot will be offset from the beaming telescope by a distance $d = 2\, v_r R / c$, where v_r is the relative velocity between the satellite and the telescope. For a LEO satellite passing overhead at 1000 km, the displacement is about 46 m along the direction of travel; for GEO it is 650 m. If the transmitter and receiver are colocated, the full divergence angle of the corner cube must be greater than $4v_r/c$, which is about 100 μradians for LEO and 35 μradians for GEO. (But for GEO it would be possible to move the receiver 650 m to the east to remove this constraint.)

4. SATELLITE ILLUMINATION DEMONSTRATIONS

Over a period of about a year, we successfully illuminated three different satellites on several different occasions. These are summarized in Table 1. The first satellite illuminated was Lageos 2 (Laser Geodynamics Satellite, NORAD #22195). Lageos is a 60-cm diameter, 405-kg sphere covered with 426 CCRs.[16] Each CCR is 3.8-cm in diameter and returns light with a divergence of about 25 μradians. Lageos was launched in 1987 for laser ranging purposes and to study continental drift. It orbits at an altitude of 5610-5950 km, with an inclination of 52°. Because it is small and distant, and sunlight is reflected back to the sun, Lageos-2 is fairly dim. It was about equivalent to about a 10^{th} magnitude star, which is almost as dim as a geostationary-orbit (GEO) satellite. Nonetheless, the satellite was acquired and tracked by the 1.5-m telescope system within a few minutes. The photomultiplier tube (PMT) mounted on the 15-cm telescope detected return signals from this satellite at a distance of about 6100 km and an elevation of 70° above the horizon. The laser continued to fire at 15-second intervals, and we continued to detect return light on all the shots as we tracked the satellite for several minutes. Unfortunately, the data acquisition system failed at this time, so we do not have digitally recorded data. We scanned the beam across the track, and from this we estimated that the beam divergence was about 20 μradians wide.

On our next opportunity, Beacon C (also called Explorer 27, NORAD #1328) was available. Beacon C is about 1 meter tall and its nose is covered with 360 CCRs arranged in an approximate hemisphere about 30 cm in diameter.[2-5] It was launched in 1965 for laser ranging and development of navigational techniques. It orbits at 932-1309 km altitude, with an inclination of 41°. It has a permanent magnet which stabilizes the satellite's attitude with respect to the earth's magnetic field. The CCR array is on the north-seeking end, and the full divergence of the CCRs is 100 μradians.

The satellite was about as bright in the sunlight as Lageos-2. It also was moving more rapidly across the sky (24 deg/min near apogee, compared with 3 deg/min for Lageos). We were able to acquire Beacon C, obtain tracking lock, and fire the ruby laser beam within a few minutes, even though it was fairly dim. (However, on the second pass of Beacon C for the evening, it was dimmer and we were not able to achieve tracking lock at all.) We obtained very strong return signals in the PMT and recorded the data digitally. We continued to fire at 10-second intervals for a period of just over a minute with a 100% hit rate (8 shots total). Although the beam diameter was not measured during this run, we believe it to be about 15-20 μradians in divergence (at 1/e peak intensity), based on measured beam quality in the coudé room, the optical configuration, and atmospheric conditions.

Table 1. Satellites with Retro-Reflectors used in Laser Beaming Demonstrations

Satellite	NORAD Number	Perigee (km)	Apogee (km)	Orbital Incl. (deg.)	Date (MST)	Bright-ness	Beaming Range (km)	Beaming Time (min.)	Comment
Lageos 2	22195	5610	5950	52.6	12/6/93	Dim	6100	3	Successful illumination detected
Beacon C (Explorer 27)	1328	932	1309	41.2	3/9/94	Dim	1480-1600	1.3	Successful illumination, data recorded
GEOS 2 (Explorer 36)	3093	1079	1572	105.8	3/9/94	Dim	None	0	Illumination attempted, no return detected
Lageos 1	8820	5837	5945	109.8	3/9/94	Very dim	None	0	Track lock failed, no illumination attempted
Beacon C (Explorer 27)	1328	932	1309	41.2	3/9/94	Very dim	None	0	Track lock failed, no illumination attempted
GEOS 1 (Explorer 29)	1726	1114	2273	59.4	12/14/94	Mod-erate	2260-2350	1.5	Successful illumination recorded on videotape
Beacon C (Explorer 27)	1328	932	1309	41.2	12/14/94	Dim	1480-1550	2.5	Successful illumination, recorded on videotape as sat. entered earth's shadow

Figure 3 shows a typical result recorded from the PMT. The first 6-ms pulse is light from the outgoing beam reflected from the atmosphere. The second 6-ms pulse is light returning from the satellite CCRs. The return signal is nearly strong enough to saturate the detector. The spiked nature is partly due to the laser beam itself being spiked because it is free-running and lases on its own when enough upper level states have been pumped. (The flat-top of the first pulse is lower than the spikes of the second because the PMT responds differently to steady signals than to spiked ones because of its AC-coupling.) Analysis of these data will be presented in a later section.

The next satellite (13 minutes later) was GEOS 2 (Explorer 36, NORAD# 3093). It was built by the Applied Physics Laboratory for NASA for the National Geodetic Satellite program.[6-7] It was launched in 1968, orbits from 1079 to 1572 km altitude at a (retrograde) inclination of 106° and is gravity stabilized with the CCRs facing the earth. Explorer 36 also was dim, but the tracking team successfully locked onto it and the ruby was fired at 10-second intervals. We saw no return signal at all. We are not sure why.

Lageos 1 came over next. It is nearly identical to Lageos 2, but it was dimmer (it was launched in 1976). We were not able to achieve track lock on it, and so we did not beam to it. Beacon C returned for another pass an hour and a half later. It was dimmer than before and heading for the earth's shadow. Our plan was to keep firing the ruby laser as it entered the shadow. Unfortunately, we did not obtain tracking lock before it entered the shadow and so did not fire the ruby laser. These experiences point out the need for adequate light (> magnitude 13) to achieve tracking lock,[17] and also point out that we were fortunate that Lageos 2 and the previous pass of Beacon C were bright enough for beaming.

On a later night we performed some more experiments, this time with the frequency-doubled YAG laser replacing the ruby laser. The first target was GEOS 1 (Explorer 29, NORAD# 1726). It was launched in 1967, and orbits from 1114 to 2273 km altitude at an inclination of 59°, and like GEOS 2, it is gravitationally stabilized.[6,7] It has 400 CCRs with a total reflecting area of 2250 cm^2. At normal incidence, 50% of the light will be retroreflected within a cone 100 μradians in diameter.[7] We achieved acquisition and tracking lock, and then beamed the YAG laser through the 1.5-m telescope. We simultaneously observed the satellite with the nearby 35-cm telescope mounted on the 3.5-m telescope, and saw the image brighten considerably when the YAG beam was initiated. (Rooftop observers had reported observing the brightening with the naked eye on a previous night.) This demonstrates the importance of CCRs; without them, the predicted light return would have been about a million times weaker. We turned the laser off and on again and verified the effect. Then we turned off the point-ahead correction, and the satellite dimmed back to normal. The tracker lost lock for a few minutes at this point.

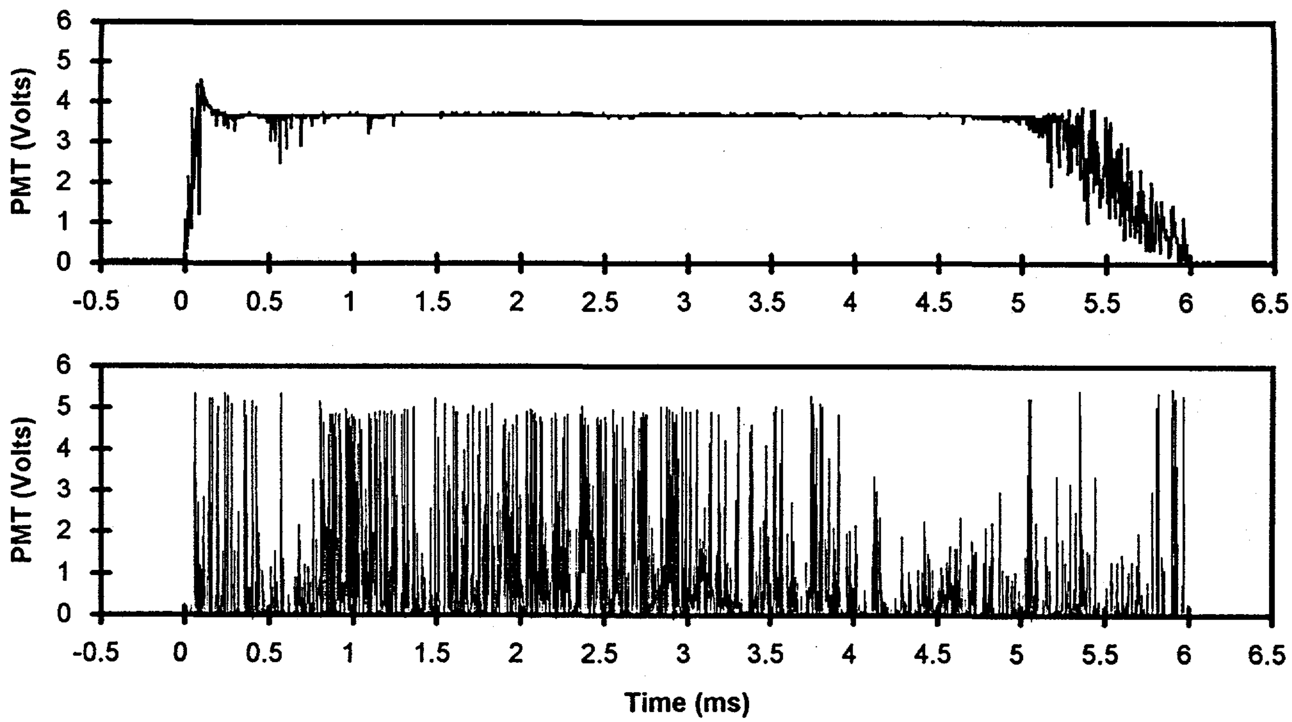

Figure 3. Typical return from Beacon C retro-reflectors. The top trace is the Rayleigh-scattered light from the atmosphere and saturates at about 3.7 V. The bottom trace is for reflected light from Beacon C and saturates at about 5 V.

The orbital path was later plotted against the star background, and the passage of the satellite in the video record was compared with star charts.[18] Positive identification was made on many of the passing stars, and by comparing the brightness of these stars with the satellite, we concluded that the satellite brightened in visual magnitude from about 8.7± 0.5 to 5.0±0.5 (time averaged) when the laser was turned on. This is an increase in brightness of a factor of about thirty. (An increase of 1 in visual magnitude corresponds to a decrease in brightness by a factor of 2.51.) A reduction of thirty in beam intensity occurs at 3.4 Gaussian radii. If we assume that the beam was Gaussian and that the beam was centered on the satellite when the 50-μradian point-ahead was active, then these data suggest that the 1/e full divergence of the beam was less than 30 μradians. (Unfortunately, a systematic scan of the beam point-ahead angle was not made during this brief pass.) We expect the divergence to be about 20 μradians.

The satellite was traveling almost due northeast at 7.35 km/s at an elevation of 60°, so the center of the return spot is predicted to be about 200 m east (N80°E) of the 3.5-m telescope. Since the divergence of the CCRs is 100 μradians,[7] the spot radius in that direction is about 125 m. This suggests that at the center of the spot, the return signal was about 5 times larger than we observed at the 3.5-m telescope (assuming a Gaussian return beam) and equivalent to a magnitude 3.3 star.

The next target that night was Beacon C (Explorer 27) again. This time we programmed the YAG to fire at a 1-Hz rate. We acquired the satellite, achieved track lock, and projected the beam. Observing through the 3.5-m telescope, we saw a strong 1-Hz pulsing in the light. We continued to beam to the satellite as it entered the earth's shadow. The image vanished between pulses as it entered the shadow, but was very distinct during the pulse. The tracker lock failed because of the lack of light, and after about ten seconds in the shadow the beam fell off the satellite. However, the brightness of the image when the laser was on suggests that laser illumination of a satellite with CCRs on it could enable tracking of that satellite through the earth's shadow.

We then proceeded to practice acquiring (finding and centering) GEO satellites with the new 3.5-m telescope at SOR near to the 1.5-m telescope.[14] This telescope is not presently set up for tracking lock or laser beam projection, but this will give some indication of how rapidly a large telescope can acquire the very dim GEO satellites. We acquired Comstar-4 and three of its neighbors Satcom-K1, Satcom-K2, and Telstar-3C, all in a span of 3 minutes, stopping to center each one. The full span was about 12°, and it took about 16 seconds each to move and center. This shows that moving from one GEO satellite to another as they approach the earth's shadow will take a negligible amount of time. We also (on a previous night) followed Comstar-4 with the 3.5-m telescope as it entered the earth's shadow. About 31 minutes later, it emerged from the earth's shadow about 20 μradians from where it was expected to be. The 1.5-m system is able to develop a very accurate track file as it follows a satellite when the tracker lock is on. If such a system were on the 3.5-m telescope, we believe that an even smaller error (than 20 μradians in 31 minutes) could be achieved for a GEO satellite with blind tracking in the earth's shadow.

5. ANALYSIS OF THE RETURN SIGNALS FROM BEACON C

The data from seven shots on Beacon C were analyzed. In each case, the Rayleigh back-scattering from outgoing pulse saturated the detector at about 5 V for most of the pulse. Regrettably, there was not time to redo the runs and obtain less saturated data. However, the last millisecond of each trace is unsaturated for both the outgoing beam and the return signal and provides ample data for comparing the relative strengths of the two signals.

The laser was in free-running mode and generated a train of non-uniformly spaced pulses. Specifically, the flashlamps continuously pump the ruby rods; when the rods reached a threshold value, a brief laser burst depleted them of the stored energy. The burst lasts for about 1-2 μs and the interval between pulses is somewhat random, but has an average of about one every 6-10 μs. This pulse structure appears in the return light from the satellite, but the Rayleigh pulses are 8 μs wide, which is about 3 times wider than the CCR pulses. This may be due to scattering from different portions of the atmosphere. (8 μs equals about 2.4 km of travel for the 0.6-km long pulselet.)

Figure 4 shows the unsaturated tail of two of the pulses. The dashed line is the Rayleigh return, and the superimposed solid line is the CCR return from the satellite. To make a fair comparison, the retro signal has been averaged over 8 μs, as the Rayleigh pulse appears to be. Inspection of the data shows that there is a moderate correlation between the <u>timing</u> of the somewhat randomly spaced spikes of the two signals, but the <u>amplitudes</u> are strongly different. The ratio of CCR to Rayleigh signal varies from 0.1 to 2 in a span as short as 15 μs. Inspecting the retro signal during the bulk of the pulse (Figure 3) also shows that there are expanses of low return lasting up to a few tenths of a millisecond or more.

It is certainly possible that the fluctuations are an artifact of the detector or data acquisition system, but we have some evidence that this is not the case. The Rayleigh signal in Figure 4 reflects the expected variations in the outgoing laser pulse and these fluctuations are not more than a factor of 2 in intensity. But the retro signals vary by a factor of 10. So it seems likely that the retro signals are actual fluctuations in light intensity on the detector.

Possible sources of the fluctuation were considered and rejected. We considered jitter from the telescope tracking updates. But the tracking was being updated at a rate of about 50 Hz, which is much slower than the observed fluctuation rate, so it probably is not the cause of the fluctuations. We considered telescope pointing jitter, but the divergence of the outgoing beam was about 10 mradians, and the stability of the SOR mirror system is much better than that. We considered jitter in the laser itself. But measurements of the beam quality of the ruby laser in place on the optics bench in the coudé room at SOR show diffraction-limited stability (for a 1-cm aperture) over 1-ms intervals. This corresponds to angular stability of about 70 μradians, but when the beam is expanded into the 1.5-m telescope, the angular jitter decreases proportionately down to less than 0.5 μradians. So laser jitter is not likely the source of the fluctuations. Atmospheric distortions would be sufficient to account for the size of the fluctuations, but the frequency is too high. Atmospheric fluctuations typically occur in about 10 ms, not 10 μs.

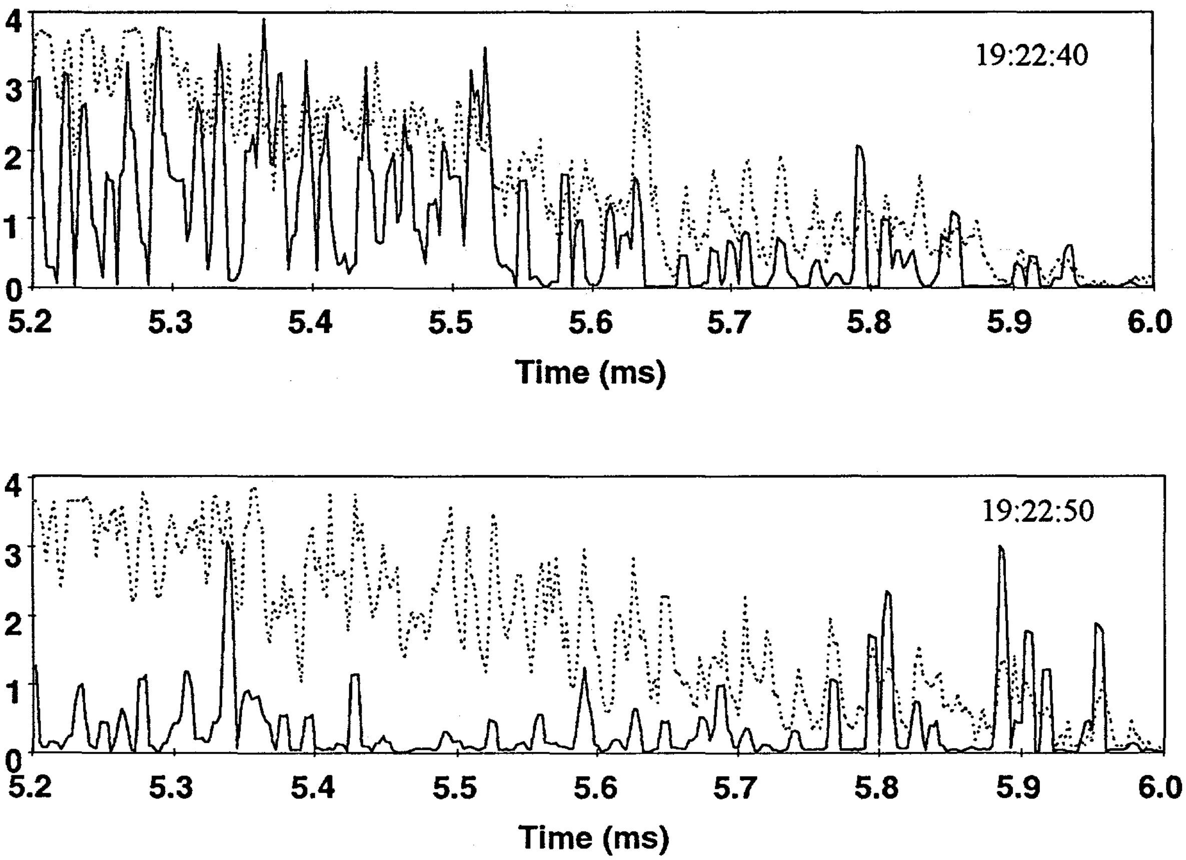

Figure 4. Enlarged view of shot 19:22:40 and 19:22:50 from 5.2 to 6.0 ms. Retro signal has been smoothed by averaging three bins together to make it similar to the Rayleigh signal .

One possibility is that the variations are caused by interference patterns from the reflected laser light, as suggested in other beaming experiments by previous researchers.[4,7] The light impinging on the satellite is close to a plane wave. The diameter (at 1/e of peak intensity) of a diffraction-limited spot at the range of the satellite (1500 km) would be about 0.9 m for a 1.5-m aperture. But our beam is even bigger than that. The typical atmospheric cell (r_0) is about 5 cm across at a 0.7 μm wavelength, so our beam (which was not compensated) was about 20 m across at the satellite. Since the CCRs on Beacon C span about 0.3 m, they see a plane wave coming from the laser.

The path length into and out of a single CCR is the same for all locations on the cube so the reflected light also is a plane wave. This is true even if the coherence length of the laser is only a few microns. The reflected beam from a single reflector on Beacon C diverges 100 μradians and is about 150 m in diameter when it hits the top of the atmosphere. This size spot would not be distorted much as it passes through the atmosphere. So the reflected beam from a single reflector forms a disk about 150 m in diameter on the ground offset from the transmitting (and receiving) telescope by about 140 m ($= 2v_rR/c$).

For a single retro, a simple rotation or translation does not cause a shifting of the pattern from it because the outgoing light always retraces the path of the incoming light. So simple satellite rotation or translation would not yield a moving speckle pattern from a single retro. But Beacon C has a large array of retros, and the reflected beamlet from each of them interferes with all the others. Each pair of retros would yield a different speckle pattern, but the smallest speckles would come from the largest separation (about 0.3 m). These would yield the fastest variations in signal as they move across the receiver.

The satellite is magnetically stabilized via the earth's field[4] with the nose pointing north. If the satellite were rotating about its axis, the speckles would sweep across the earth from east to west or west to east. To obtain one shift in speckles in 15 μs, the extreme reflectors (separated by about 30 cm) would need to move one wavelength relative to each other. This would require a rotational period of P = 2 p d t / l = 40 seconds (where d is the distance between the retros, t is the time for one fluctuation, and l is the laser wavelength). This seems like a reasonable rate. So it is plausible that the observed fluctuations in the return signals are caused by moving speckles coming from multiple CCRs and a slowly rotating satellite. Previous researchers also have seen rapid variation of the return signal from this satellite, but not in such detail.[4,5] Lightsey[7] noted scintillation in beaming experiments to the Relay Mirror Experiment (RME), but it was dominated by atmospheric scintillation on the uplink, and it fell off sharply above a few hundred Hz.

These results also may impact plans for using CCRs and illumination lasers to help in tracking satellites. In this application, it may be better to use one large CCR than an array of many. Tracking is done on a 1-ms time scale, and a very slow satellite motion may cause speckle changes on this time scale. This could confuse the tracker. For example, if there were two retros on a GEO satellite separated by 10 cm, the speckle pattern on earth would shift by one speckle in 1 ms if the satellite wobbled at a rate of 0.4°/s (24°/min).

6. CONCLUSIONS

The purpose of these demonstrations was to assess present capabilities for laser beaming. Several low-earth-orbit (LEO) satellites with corner-cube retro-reflectors (CCRs) were illuminated repeatedly and with high reliability at ranges from 1500 to 6000 km with a small beam divergence (20 μradians). One satellite with retro-reflectors brightened by about a factor of 30 when illuminated. Another was illuminated for ten seconds after it had entered the earth's shadow. The reflected light from one satellite showed large fluctuations ranging from 1 to 70 kHz. It is speculated that these high-frequency variations are due to interference patterns from separate CCRs on the satellite. Four neighboring geostationary-orbit (GEO) satellites were located and centered in succession with a 3.5-m telescope at a rate of about 16 seconds per satellite.

From this experience we draw the following conclusions:

1. Large telescopes (1.5 to 3.5 meters) can accurately locate, center, and follow satellites. The difficulty increases for smaller and more distant satellites. A 1.5-m diameter telescope can locate satellites down to a visual magnitude of about 15 (V=15). If computerized, the time required to locate, center, and follow a satellite is 10-20 seconds.
2. If the satellite is bright enough, fast-tracking optics in the beam train can follow the image and remove the first-order atmospheric distortion (tilt). For a 1.5-m telescope the brightness must exceed about V = 10 to 13. Achieving fast-tracking lock takes about 10 to 30 seconds unless the brightness is marginal.
3. A laser beam with a divergence of about 20 μradians can be projected to satellites with high reliability and consistency if there is enough light for the fast tracker (V>10 to 13 for a 1.5-m telescope).
4. The beam must be pointed ahead of the observed location of the satellite by 2v/c, which is about 50 μradians for LEO and 20 μradians for GEO.
5. Laser beaming presently requires about five people to run the telescope, the laser, the tracking electronics, and the active safety functions. This could be reduced with better automation and remote monitoring. Atmospheric compensation would require an additional 1 to 3 people.
6. Corner-cube retro-reflectors (CCRs) on the satellite and a small illumination laser on the ground can be used to make tracking much easier by increasing the brightness of the satellite. Without CCRs, the return intensity would be a million times less. We shined a 2-W laser on a LEO satellite and made it equal to a fifth-magnitude star. Scaling these results, a 100-W laser and 4.3-cm (2.5-inch) square CCR should yield a V = 13 beacon at GEO if the return divergence is 100 μradians. Putting such a CCR on all new GEO satellites would make accessing them for later power beaming much easier.
7. The return spot from a CCR on a satellite is displaced relative to the transmitter in the direction of travel by 2vR/c, which is about 50 m for a LEO satellite, and 650 m for a GEO satellite. If the transmitter and receiver are colocated, the full divergence angle of the corner cube should be greater than $4v_r/c$, which is about 100 μradians for LEO and 35 μradians for GEO.
8. A single corner cube may be better than an array because an array might yield fluctuating interference patterns that could confuse the fast tracker.

9. Satellites are often in the earth's shadow and essentially invisible (especially LEO satellites). Blind tracking of a LEO satellite is very inaccurate, but GEO is feasible. We demonstrated blind tracking of a GEO satellite through the earth's shadow and accumulated an error of only 20 μradians over 30 minutes. This could be improved by establishing a more accurate track file just prior to entry into the shadow.
10. Laser illumination of a satellite that has a CCR on it could overcome these difficulties and enable tracking at high accuracy through the shadow of the earth.

In general, we have found that the technology for projecting tight laser beams to satellites is maturing rapidly. Thirty years ago, satellite illumination required a beam with a 1000-μradian divergence, and even then the reliability was marginal. We now can achieve essentially 100% reliability with a divergence of only 20 μradians. This 50-fold decrease in divergence translates into a 2500-fold increase in intensity at the satellite, or a 2500-fold decrease in laser requirement. Atmospheric compensation offers the hope of decreasing the divergence by another order of magnitude or more. Such strong progress in beam directing lays the foundation for beaming power to satellites in the near future.

7. ACKNOWLEDGMENTS

This work was supported by the U. S. Department of Energy under contract DE-AC04-94AL85000, by the United States Air Force, and by COMSAT Corporation. The authors thank Air Force Lt. Col. John Anderson at the Air Force Phillips Laboratory, Army Lt. Col. James Felty at DOE, and Mr. Walt McKee at COMSAT for their steadfast support. We also thank Don Vonderhaar, Dean Dixon, Dan Neal, and Dave Monroe for their technical support.

8. REFERENCES

1. J. V. Walker and E. E. Montgomery IV, Chairmen, *Laser Power Beaming, SPIE Vol. 2121,* (1994).
2. J. A. Strasser, "Laser's second chance," *Electronics, 38, (1),* Jan. 11, 1965, pg 42 (1965).
3. G. L. Snyder, S. R. Hurst, A. B. Grafinger, and H. W. Halsey, "Satellite Laser Ranging Experiment," *Proc. of the IEEE, 53,* pp. 298-299 (1965).
4. H. H. Plotkin, T. S. Johnson, P. Spadin, and J. Move, "Reflections of ruby laser radiation from Explorer XXII," *Proc. IEEE, Vol. 53,* pp 301-302 (1965).
5. P. H. Anderson, C. G. Lehr, L. A. Maestre, H. W. Halsey, and G. L. Snyder, "The two-way transmission of a ruby laser beam between earth and a retroreflecting satellite," *Proc. of the IEEE, 54,* pp426-427 (1966).
6. D. G. Abby and T. E. Wirtanes, "Photomuliplier Reception of Satellite Beacon Flashes," *Appl. Optics, 8, (3),* pp. 627-631 (1969).
7. "Geos satellite will calibrate C-band sites," *Aerospace Technology,* Jan. 15, 1968, pp. 49-50 (1968).
8. P. A. Lightsey, "Scintillation in ground-to-space and retroreflected laser beams," *Optical Eng., Vol. 33, No. 8,* pp. 2535-2543 (1994).
9. N. Hubin and L. Noethe, "Active Optics, Adaptive Optics, and Laser Guide Stars," *Science, 262,* p. 1390 (1993).
10. L. A. Thompson, "Adaptive Optics in Astronomy," *Physics Today,47 (12),* pp. 24-31 (Dec. 1994).
12. R. Q. Fugate, "Laser beacon adaptive optics--boon or bust?" to appear in *Trends in Intern. Optics,* Academic Press, London (1994).
13. R. Q. Fugate, D. L. Fried, G. A. Ameer, B. R. Boeke, 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).
14. R. Q. Fugate, et al., "Two generations of laser-guide-star adaptive-optics experiments at the Starfire Optical Range," *J. Opt. Soc. Am. A, Vol 11, No. 1,* pp 310-324 (1994).
15. R. Q. Fugate, B. L. Ellerbroek, E. Stewart, D. Colluci, R. E. Ruane, J. M. Spinhirne, R. A. Cleis, and R. Eager, "First observations with the Starfire Optical Range 3.5-meter telescope," *Adaptive Optics in Astronomy, SPIE-2201,* March 17-18, 1994, Kona, Hawaii, U.S.A., pp. 10-21 (1994).
16. A. Wilson, Ed., *Jane's Space Directory 1993-94,* Jane's Information Group Limited, Surrey CR5 Wnh, UK, pp. 62-63, 96, 126, (1994).
17. R. Q. Fugate, "Observations of faint objects with laser beacon adaptive optics," *Adaptive Optics in Astronomy, SPIE-2201,* March 17-18, 1994, Kona, Hawaii, U.S.A. (1994).
18. W. Tirion, B. Rappoport, and G. Lovi, *Uranometria 2000.0,* Willman-Bell, Inc., Richmond, VA, 23235, USA (1987).