N71-17878
NASW-2014
NASA CR-116423

A HIGH-RADIANCE LASER SYSTEM FOR LUNAR RANGING

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December 1970

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011-67A

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Abstract

A transportable laser system for lunar ranging is described. It can be used at any astronomical observatory where a 1.5-m telescope is available. Since this telescope is used for the returned signal only, its use for other purposes is not affected significantly.

The transportable system uses a high-energy, single-mode, neodymium-glass laser whose frequency-doubled wavelength is 530 nm. Because the laser's divergence is very low, an atmospherically limited beamwidth can be achieved with optics only 0.2 m in diameter.

An initial phase of the program, concerned with ranging to near-earth satellites, will be described. For this application, a 5-cm coudé system is used to point the laser beam. There is also a separate 12-cm receiving telescope.

1. Lunar Ranging with Ruby Lasers

The first laser return from the moon (Ref. 1) was achieved with a 50-J ruby laser. In this experiment a 0.5-ms laser pulse was transmitted over the 384-mm distance between earth and moon, reflected from the moon's surface, returned to earth, and detected after a round-trip travel time of about 2.6 s. Only a few photoelectrons were generated by the returned signal. Hence the structure of the returned pulse was not defined and the error of the measurement corresponded to about half the pulse duration, or to about 40 km.

The accuracy of lunar range measurements was increased once short-pulse, Q-switched lasers became available. Using such a laser, range measurements to the moon's surface were made to an accuracy of about 200 m (Ref. 2). This error is not related to the pulse duration; it corresponds instead to surface variations in the lunar surface intercepted by the laser beam. The beam is about 10 km in diameter when it reaches the moon.

When a retroreflector was placed on the moon in 1969, the accuracy corresponding to the pulse duration of a Q-switched laser was realized. The error in this case is about 1 m. Two organizations in the United States have made lunar range measurements with Q-switched ruby lasers. They are the National Aeronautics and Space Administration, at the McDonald Observatory, Texas (Refs. 3, 4), and the Air Force Cambridge Research Laboratory, at the Catalina Observatory, Arizona (Ref. 5). The characteristics of these systems are given in Table 1. They both use large telescopes for the transmission and reception of the laser beam.

Table 1. Characteristics of ruby-laser systems for lunar ranging

Laser	NASA	AFCRL
Pulse duration (ns)	4	10
Wavelength (nm)	694	694
Energy (J)	5	10
Repetition rate (min^{-1})	20	12
Divergence (arcmin)	5	3
Beam diameter (mm)	20	15
Transmitting telescope		
Aperture (m)	2.7	1.5
Beamwidth (arcsec)	2	4
Receiving telescope		
Aperture (m)	2.7	1.5
Quantum efficiency of photomultiplier tube (%)	7	6
Received signal (photon counts)	1	2 to 4

This work was supported in part by contract NASW-2014 from the National Aeronautics and Space Administration.

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2. The Use of a High-Radiance, Neodymium-Glass Laser

When ranging to the moon, one wants to maximize the amount of the transmitted energy that reaches the retroreflector, to receive as much as possible of the returned energy, and to detect this energy as efficiently as possible. To maximize the amount of energy incident on the retroreflector, one must transmit as much energy as possible, but one must also confine this transmitted energy into the narrowest possible beam. As a practical matter, the beamwidth cannot be reduced below a few arcseconds because of the effect of turbulence in the earth's atmosphere. As Table 1 shows, the divergence of a ruby laser is measured in arcminutes. It is for this reason that a transmitting telescope of large aperture is required to collimate the beam to arcseconds. The receiving telescope should be as large as possible so as much of the returning signal as possible is collected. However, the strength of the detected signal depends also on the quantum efficiency of the photodetection system. An increase of a factor of 3 in quantum efficiency is equivalent to an increase of 1.7 in the diameter of the receiving telescope. It can be seen, therefore, that the ideal laser should have a low beam divergence and a wavelength in the region where the quantum efficiency of phototubes is high.

A recent development in a neodymium-glass laser meets these two requirements very well (Refs. 6,7,8). Its output beam divergence is only 1/2 arcmin and its wavelength of 530 nm is in the region where photomultiplier tubes can be made with efficiencies of about 20%. This laser is shown in Figure 1 along with a ray diagram showing how 60 J of I-R energy is obtained at 1.06 μm and converted to 20 J of visible energy at 530 nm. The beam from such a laser can be reduced to the atmospheric limit with a transmitting telescope whose aperture is only 20 cm in diameter. An instrument for this purpose is currently being fabricated. It will first be used at the Agassiz Observatory in Massachusetts. Then it can be moved to any observatory where a large instrument is available for receiving the returned signal. This instrument can be used with very little modification. The reason is that the reception of a laser signal puts far less stringent requirements on a large telescope than does the transmission of the signal. The received signal is very weak; it cannot possibly damage the optics. And the field can be opened up to reduce the required tracking accuracy without reducing the strength of the received signal. The background noise will be increased as the field is made larger, but the increase is not significant when the lunar retroreflector is in shadow.

Table 2 presents the characteristics of the glass-laser system at the SAO Agassiz Observatory. These characteristics can be compared to the corresponding values in Table 1. The low pulse-repetition rate of the glass laser prevents thermal distortion of the glass rods. Even very small distortions can increase the divergence of the beam.

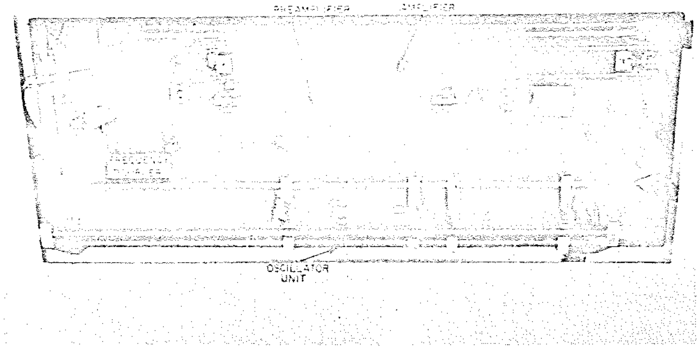

Figure 1. Photograph and ray diagram of the glass laser.

Table 2. Characteristics of a neodymium-glass laser system for lunar ranging

Laser	SAO
Pulse duration (ns)	20
Wavelength (nm)	530
Energy (J)	20
Repetition rate (min^{-1})	0.2
Divergence* (arcmin)	1/2
Beam diameter (mm)	20
Transmitting telescope	
Aperture (m)	0.20
Beamwidth (arcsec)	4
Receiving telescope	
Aperture (m)	1.5
Quantum efficiency (%)	20
Received signal† (photon counts)	2 to 8

*Between the half-energy points of the beam.

†Scaled from the return signals of the ruby laser systems.

3. An Initial Experiment

A temporary optical system was built to test the operation of the high-radiance laser under observatory conditions. This system is shown in Figure 2. It was designed for the tracking of near-earth satellites (i.e., up to ranges of about 4 Mm). In operation the transmitter and receiver are each pointed to the predicted direction of the satellite. The laser is then pulsed at the appropriate epoch. In this case, the transmitting telescope increases the divergence of the laser beam sufficiently to compensate for errors in the predicted satellite positions. When better predictions become available, mirrors or prisms will still be required to point the beam in the proper direction, but the telescope itself may no longer be necessary.

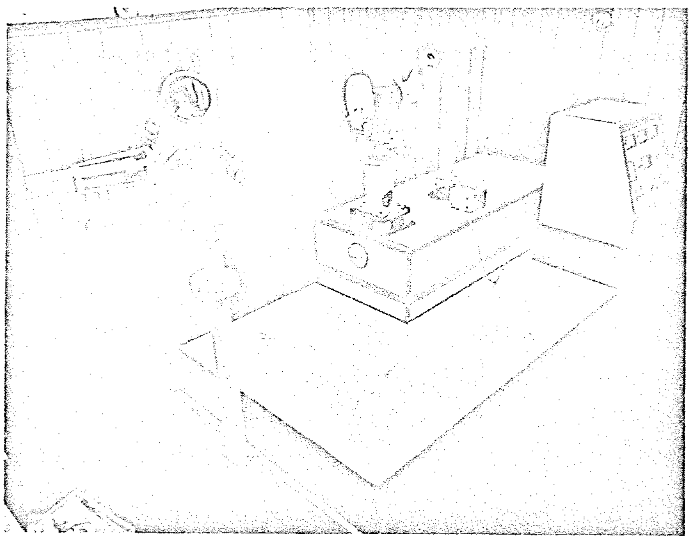

Figure 2. The temporary optical system for ranging to near-earth satellites. (The transmitting telescope is on the right and the receiving telescope is on the left.)

As shown in Figure 2, the laser remains fixed. The beam is pointed by a coudé optical system having prisms on the azimuth and elevation axes of the small transmitting telescope. The receiving telescope, shown beside the transmitter, has a 12-cm aperture. Its small size is made possible by the relatively high quantum efficiency of the photomultiplier tube at 530 nm. The green laser light scattered by the atmosphere along the path of the beam is quite visible when the sky is dark. It is shown in Figure 3.

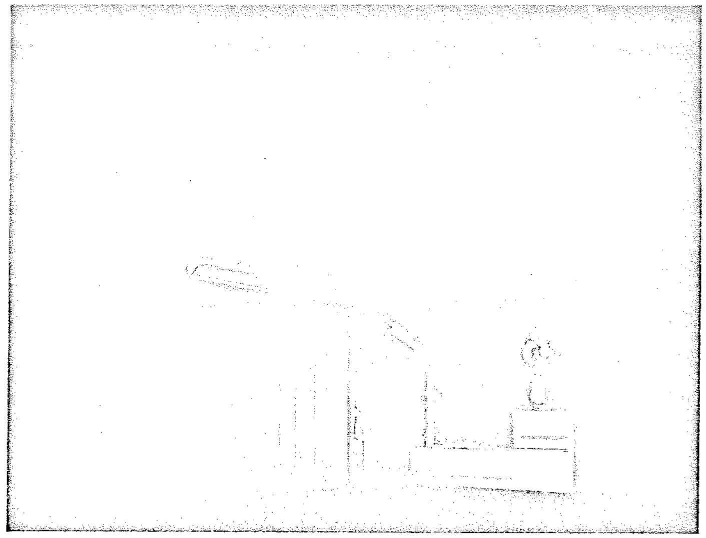

Figure 3. The temporary optical system in operation (showing the transmitted laser beam).

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