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Future Developments in Lunar and Satellite Laser Ranging

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Future developments in lunar and satellite laser ranging

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Most laser ranging systems operating today are first-generation systems using either cavity dumped or *Q*-switched ruby lasers and time-interval counters and are capable of an accuracy of 10–100 cm. Second-generation systems using mode-locked Nd: YAG lasers and epoch timers are being developed and compact, largely automated, fully mobile stations can now be built which are capable of ranging to both high satellites and the Moon with an accuracy of a few centimetres. Even higher accuracy is possible by using streak tubes as detectors and using measurements at two wavelengths to compensate for variation in atmospheric transmission.

The use of CO_2 lasers and heterodyne detection, which has the advantage that both range and velocity can be measured, is also discussed.

A laser ranging system consists essentially of a laser, transmitting and receiving optics, a detector, pulse processor and some means of measuring the round trip time to the target and back. For accurate predictions some means of providing a world-wide distribution of epoch is also required and this can now be done with sufficient accuracy with atomic clocks.

First-generation satellite ranging systems used *Q*-switched ruby lasers giving about 1 J in 20–30 ns although in many cases this pulse length was later shortened to about 2–5 ns using cavity dumping or pulse-chopping techniques. The ruby laser operated multimode and, as a result, the beam divergence was quite large and the pulse was irreproducible both temporally and spatially. The photomultiplier detectors used had a rise time and jitter of the order of 1 ns and timing was by means of a stop–start interval counter which also had a resolution of about 1 ns. A variety of techniques such as leading-edge amplitude discriminators, zero crossing and constant fraction discriminators and centroid determinators were used to derive time from some characteristic of the pulse shape. The more sophisticated systems used computer control and automatic pointing from orbit predictions whereas others used visual tracking. The very best systems attained an accuracy of ~ 10 cm but more often the accuracy obtained was closer to 100 cm.

Early lunar laser ranging systems were similar except that they used larger telescopes and operated with single photoelectron (or less) detection.

Second-generation systems are now appearing which use mode-locked lasers with a pulse length of ~ 100 ps and epoch timing systems with a time resolution of the same order and these should be capable of a ranging accuracy of < 3 cm. These lasers are more efficient, give near diffraction limited output, and can be operated at a higher average power enabling smaller and more compact systems to be built for both satellite and lunar ranging. Photomultiplier jitter has been improved slightly but at *ca.* 300 ps at the single photoelectron level is now one of the main obstacles to higher accuracy.

The general consensus of opinion favours a mode-locked Nd: YAG laser with type II second harmonic conversion to 0.53 μm which can be as efficient as 80 %. A single pulse is selected from the mode-locked train using an electro optic switch and then amplified. The laser can be mode-locked either actively or passively. In active mode-locking an acousto optic device, for example, introduces a loss modulation at a frequency corresponding to twice the round trip transit time in the oscillator producing a continuous train of mode-locked pulses. The energy of any one of these is, however, small – of the order of 1 μJ – and has to be amplified in a regenerative multipass amplifier up to ~1 mJ before final amplification in a number of single pass amplifiers. Alternatively, the laser can be passively mode-locked using a saturable absorber which gives a short train of pulses each of which has an energy of ~1 mJ and there is thus no need of a regenerative amplifier. Such passively mode-locked lasers are therefore cheaper than actively mode-locked lasers but have not been as fully developed and engineered. They also offer the possibility of multipulse operation (e.g. a train of up to 10 mode-locked pulses could be used instead of a single pulse) which would reduce the number of ranging shots required to obtain a given accuracy.

The energy obtainable in a single mode-locked pulse with either of these systems is about 200 mJ at 0.53 μm, the output being limited by available rod size and the energy storage capacity and non-linear refractive index of the material. This is quite adequate for satellite ranging but for the moon the return signal is considerably less than the optimum of one photo-electron per shot and for lunar ranging it is therefore necessary to operate at as high a repetition rate as possible to obtain the necessary accuracy. Stress birefringence is likely to place an upper limit of about 10/s on the repetition rate but fortunately this should be sufficient to enable lunar ranging data accurate to a few centimetres to be obtained in a time varying from about 10 s to 10 min, depending upon atmospheric conditions and pointing accuracy, and multipulse operation, mentioned earlier, could reduce this time by up to an order of magnitude.

The Haleakala lunar laser ranging station is the only second-generation system operating at the present time but Sylvania are marketing a complete mobile mode-locked laser ranging system and the University of Texas plans to build a mobile sub-nanosecond lunar laser ranging station.

Improvements that may be expected in the short term are:

(i) Improvements in the reflectivity of large mirrors at the laser wavelength (enhanced metal or all dielectric coatings) to improve the optical efficiency of the receiver.

(ii) The possibility of higher laser output from new host materials, such as lanthanum beryllate, which can be fabricated in larger rod sizes and have lower gain and therefore better energy-storage capacity than Nd:YAG.

(iii) Reduction in detector jitter by the use of cross field photomultipliers or channeltrons.

(iv) Improvements in pointing accuracy and more extensive use of computer control and absolute, or offset, pointing.

(v) Improved data analysis; a least-squares analysis should improve the accuracy by about a factor of 2 and a much greater improvement could be obtained by using independently timed detector channels.

(vi) Development of a cheap aircraft-detection system to replace the lock-out radars which are sometimes required at present and which greatly increase the overall cost of the system.

In more general terms it is obviously desirable to try to build cheaper and more compact mobile systems if only to increase the number of observations that can be made. As the ranging requirements for some of the new higher satellites such as Lageos are not too different from that of the Moon there is also a case for more dual purpose stations.

In the longer term streak tubes with either o.m.a. or c.c.d. digital output and having a time

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
THE ROYAL SOCIETY A
PHILOSOPHICAL TRANSACTIONS OF

resolution of a few picoseconds could be used as detectors. The laser pulse duration could easily be reduced to 20 ps (indeed, it has to be deliberately lengthened to obtain longer pulses) and timing circuits are already potentially capable of comparable performance. Very high accuracy ranging measurements of the order of a few millimetres accuracy could then be carried out in situations where the atmospheric correction is a constant and can be ignored.

With an accuracy of a few picoseconds two wavelength measurements could be made to check the atmospheric correction and enable an accuracy of better than 2 cm to be obtained for lunar ranging.

So far we have only considered pulsed systems and direct detection of the return signal. In heterodyne detection a local oscillator is used to illuminate the detector simultaneously with the signal and one detects the difference frequency. The signal-to-noise ratio for heterodyne detection is:

$$S/N \approx \eta P_s/h\nu B,$$

where η and B are the quantum efficiency and bandwidth of the detector and P_s and ν are the signal power and frequency of the radiation respectively. Heterodyne detection is particularly useful in the infrared where detectors are noise limited. For $\lambda = 10.6\,\mu m$ (CO_2 laser) and $\eta = 0.5$ the above formula gives a noise equivalent power for heterodyne detection of 4×10^{20} W/Hz, which is many orders of magnitude less than can be achieved with direct detection at this wavelength.

The use of heterodyne detection has, however, certain implications not applicable to direct detection. Thus, there is a requirement on the frequency stability of the local oscillator and the signal, and the difference frequency must lie within the detector bandwidth. Further, the signal and local oscillator wavefronts must coincide at the detector and this imposes a limitation on the field of view given by $\theta \approx \lambda/D$ where D is the diameter of the receiver; for $\lambda = 10.6\,\mu m$, $D = 100$ cm, $\theta \approx 10\,\mu rad$ or 0.2″.

Line of sight velocity of the target is seen as a Doppler shift in the frequency of the return signal. For the CO_2 laser at 10.6 μm the Doppler shift is $\sim 200\,m^{-1}\,s^{-1}$ and a detector bandwidth of ~ 1 GHz allows detection of a velocity of ~ 6 km/s (*ca.* 1500 mi/h). The accuracy of the measurement depends on the frequency stability of the laser over the observing time, a stability of ~ 10 Hz corresponding to an accuracy of ~ 0.1 mm/s (*ca.* 10^{-4} mi/h).

In order to determine range it is necessary to modulate the transmitted beam in a way that can be recognized by the receiver so that the time delay can be measured. A common technique used in microwave radar is to use a frequency scan, known as chirping, with the return signal detected by a matched filter. The width of the central peak of the matched filter output is of the order of the reciprocal of the chirp bandwidth which thus determines the timing accuracy. By using an up chirp pulse sequence followed by a down chirp pulse sequence range and velocity can be determined separately.

For a transmitter/receiver of radius r and a diffraction limited transmitted beam of power P the return signal P_s from a retroreflector of echoing area A (where A is defined as the equivalent area scattering uniformly into 4π) at a distance R is:

$$P_s \sim \frac{r^4 A P}{\lambda^2 R^4}.$$

For $A \approx 10^3$ m and $R \approx 10^6$, corresponding to Geos 3, $r = 1$ m, $\lambda \approx 10^{-5}$ m and a transmitted power $P = 1$ kW we have $P_s \sim 10^{-9}$ W, which should be readily detectable. For the Moon,

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

however, $R \approx 4 \times 10^8$ m and $P_s \approx 10^{-19}$ W, which is too small to detect when one takes into account other factors such as atmospheric attenuation, optical losses and limitations imposed by atmospheric turbulence, laser stability and instrumental effects. The main reason the c.w. CO_2 laser with heterodyne detection falls behind visible pulsed lasers with direct detection is the λ^2 factor in the divergence of the transmitted and reflected beams which amounts to a difference of *ca.* 10^5 between the two cases for the Moon.

Powers of the order of 1 MW and pulse lengths of a few microseconds can be obtained with good mode control and frequency stability using compact hybride or injection schemes in which a c.w. CO_2 laser is used to control a t.e.a. CO_2 laser and using these it may be possible to build smaller, more compact, CO_2 laser ranging systems. For high ranging accuracy very large chirp bandwidths are, however, required and while the technique is unlikely to compete with the very high precision available with mode locked Nd:YAG lasers it does have the advantage of providing line of slight velocity as well as range which may be of use in some applications.

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