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

Goddard Laser Systems and their Accuracies [and Discussion]

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Goddard laser systems and their accuracies

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[Plate 1]

Work on pulsed ranging lasers for satellite tracking started at Goddard about 1961/2. Its main purpose was to develop a high precision tracking system for 'future' needs. As it turned out it was in retrospect, a very fortunate step. As early as 1964, the first laser corner cube equipped spacecraft, Beacon Explorer-B, was launched into orbit and tracked with our laser ranging system. Tracking errors of several metres were obtained at this time. Over the last decade, considerable progress was made in reducing these errors. Today ten laser corner-cube equipped spacecraft are in orbit and routinely tracked by ultra-precision laser ranging systems whose ranging noise and accuracy are in the deci- and subdecimetre range. Laser ranging errors (bias and noise) were about 50–70 cm in 1971, 10–30 cm in 1973 and are now about 5–8 cm. Advanced studies of the Earth's gravity field, polar motion, and Earth rotation variations are now being pursued using these laser systems. This paper describes the latest Goddard systems, their uses for our Earth dynamics program, and further discusses the accuracies obtained using actual field data.

Introduction

During the past decade, development of pulsed laser systems for high precision satellite tracking has resulted in the design of a N.S.A. world-wide laser tracking network to support specific tasks of N.A.S.A.'s Applications Program. The accuracy of the laser systems developed increased by more than an order of magnitude in this time period. Our first laser system, in operation since 1964 had ranging errors to be counted in metres. Today's short pulsed systems have range errors in the subdecimetre range. Since that time ten spacecraft equipped with laser reflectors have been launched into orbit. Laser ranging data have been used for ultra-precision orbit determination (Smith *et al.* 1972), for the further improvement of the Earth gravitational field (Lerch 1975), for the determination of the Earth polar motion (Smith *et al.* 1973), for computing the distances between two laser stations with extreme high precision (Smith *et al.* 1973), and are at present further used to calibrate the Geos-3 radar altimeter (Vonbun 1971, Berbert 1973).

In this paper the Goddard laser systems are briefly described and special attention is paid to the performance of these systems which are most important for our geodynamics applications programs. These lasers can interrogate all presently orbiting corner-cube equipped spacecraft. They will further be able to track our Lageos spacecraft which will be launched in May 1976 into a 6000 km circular, 80° inclined orbit.

Brief history

Active work to construct laser systems for high precision satellite tracking started at Goddard around 1961/2 under the direction of H. H. Plotkin. At this time, considerations were given to advanced electronic satellite tracking systems in general, both for unmanned and manned spacecraft (Apollo). Thus, the time was proper to look even further ahead into the future use of precision tracking systems. It should be pointed out however that at this time no real 'requirement' was cited for a tracking system with the anticipated accuracies and precision achievable with pulsed laser systems (metres, at this time). Nevertheless, work was fortunately started and it can be stated today that it was done so with the proper foresight. Within the last few years, hard requirements for ultra-precision laser ranging to about 2–3 cm have been recognized and well documented (N.A.S.A. 1970, 1972; Vonbun 1972). Furthermore, work also went on simultaneously to construct laser corner cubes for future spacecraft needed to reflect the laser signals.

On 9 October 1964 the first satellite, Beacon Explorer-B, equipped with laser corner cubes was orbited from the Eastern Test Range at Cape Kennedy. The orbit had an inclination of 80°, a perigee of 940 km and an apogee of 1100 km. A short time later the first laser returns from space were actually obtained (Plotkin *et al.* 1965). Afterwards, rather rapid progress was made culminating in today's ultra-precision lasers already in operation at Goddard with range errors in the order of 4 to 8 cm.

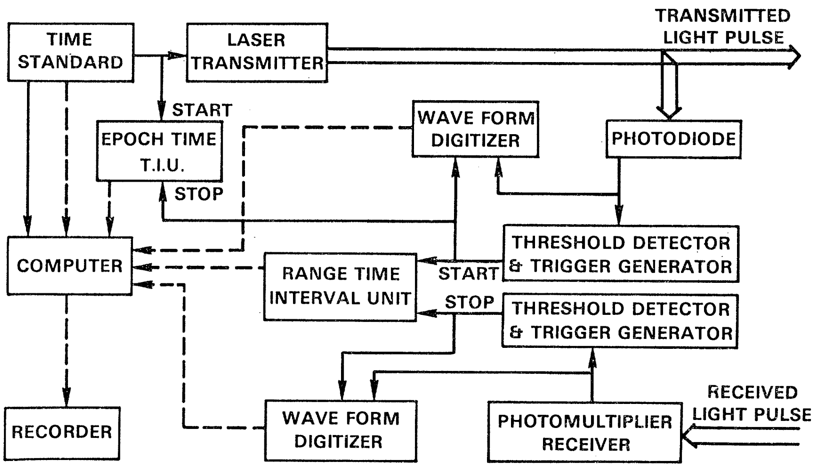

FIGURE 1. Schematic G.S.F.C. laser ranging system.

THE G.S.F.C. LASER SYSTEMS

A block diagram of our laser ranging systems is shown in figure 1 (McGunigal *et al.* 1975). As can be seen, the principle used is more or less the same as that of a conventional radar. The laser systems consist of three major sub-systems, that is: (*a*) a tracking pedestal together with the transmitting and receiving optics; (*b*) a laser transmitter; and (*c*) a ranging and data control system. All our lasers are equipped with computer driven tracking mounts so that they are able to interrogate and track spacecraft even in daylight (Moss & Johnson 1971). The only practical difference between a laser and a radar is the frequency or wavelength employed as well as the fact that specific laser reflectors on board the spacecraft have to be used to insure a proper and strong enough return signal. In the radar case, either an active transponder on board the spacecraft or just skin tracking is used. Greater accuracies of modern laser systems in general result from the use of extremely short pulses and the fact that no variable transponder delay times are involved by using corner cubes whose exact point of light return can be determined to within say one cm or less dependent on the spacecraft cube array structure. Main emphasis to obtain high accurate tracking has to be placed on the system for measuring the time interval between the transmitted and received pulse centroid, its accuracy and dynamic stability, that is on the

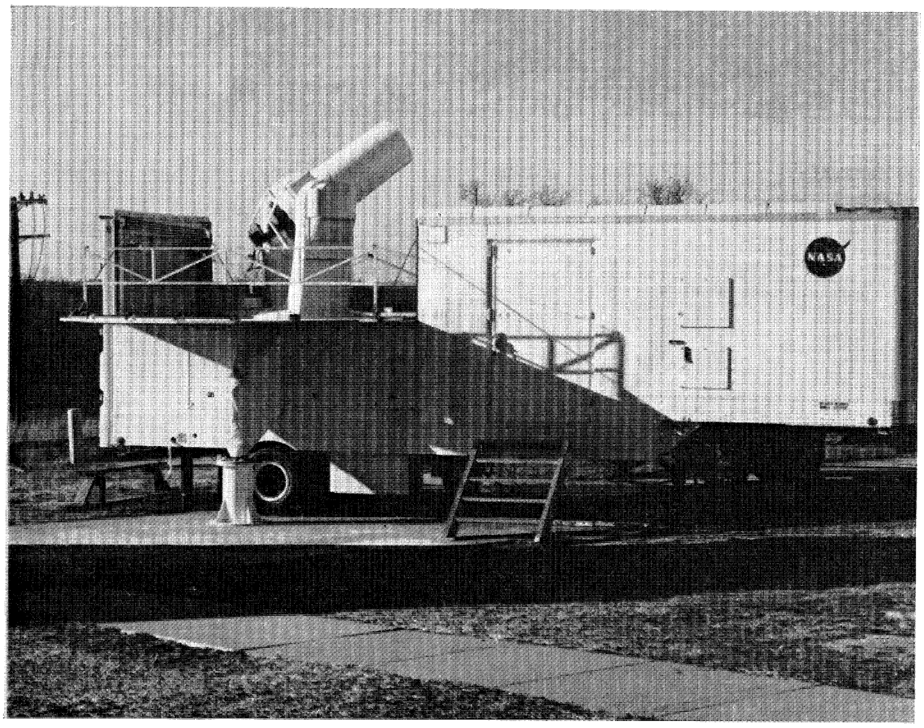

Figure 2. Goddard mobile laser ranging station.

(*Facing p.* 445)

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

system which actually measures the travel time of the laser pulse to and from the satellite. A timing error of only 1 ns, to quote an example, corresponds to 15 cm in spacecraft range which is already much too large for today's extremely tight Earth dynamics tracking requirements of 2–3 cm, as mentioned previously.

The present high precision Goddard lasers are short-pulsed ruby lasers with a pulsewidth of about 4 ns ($\sim$ 120 cm), an energy of approximately 0.25 J, operating with a repetition rate of one pulse per second. In order to achieve this rather narrow pulse, the systems are operated in a *Q*-switched, cavity dump transmission mode (McGunigal *et al.* 1975). It should also be mentioned here that photomultiplier tubes within a spread in electron transit time of say less than 100 ps are further required. Otherwise, the detection device itself would introduce a rather large range noise error.

Figure 1, plate 2, shows one of our new mobile laser ranging stations. Typically, five vans are required for one of our future 'mobile' sites. A telescope and laser van, an electronics van, a radar van, a shop and storage and a comfort van. If commercial power is not available, an additional power generating van is needed.

Laser tracking errors

Studies to determine the actual field performance of the Goddard laser systems, went on in parallel with their development over the years. For the actual 'use' of the laser data only the total range errors are of importance to the analysts (geophysicists, geodynamicists, orbital analysts, etc.). These range or timing errors are due to: (*a*) the laser system itself; (*b*) the propagation medium (atmosphere); and (*c*) the reflecting corner cube assemblies. In the following these three cases are discussed briefly. Main emphasis will, however, be paid to the total errors and their possible estimation. All three major error sources are of complete different nature and thus usually analysed by different specialists.

The laser systems errors can be characterized by a number of factors. First, one has to calibrate the system using an exact known distance. This is in most cases a board or a corner cube separated by 3–5 km from the laser and measured to less than 1 cm in order to determine the fixed as well as the dynamic (pulse dependent) system delay time. Secondly, the system noise has to be estimated in order to determine the 'true' position of the pulse for exact pulse travel time determination (order of sub-nanoseconds). Further, the time drift of the system has to be kept within the same error limits. All these errors are under constant surveillance by the laser designers at Goddard and are further updated on a continued basis for proper 'use' by the data analysts. Since these system errors are best understood by the hardware people, analysts should not attempt to do their own laser systems (hardware) error analyses.

Station timing on a world-wide basis is further needed to 1 μs. This will introduce an approximate range error of 0.5 cm for a near-Earth satellite travelling with about 8 km/s.

An error budget for our laser system is shown in table 1 together with the atmospheric, array and station timing errors.

Atmospheric errors are reduced by using a special correction program developed for our laser tracking (Marini & Murray 1973). Correction of tracking data has been extensively studied and many different correction equations have been published (Freeman 1962; Hopfield 1969; Marini 1972; Rowlandson & Moldt 1969; Saastamoinen 1972*a*, *b*) paving the way to achieve the required accuracies stated. Marini's range correction equations seem to be good to about 1.0–1.5 cm for elevation angles of say larger than 10°. For this correction the satellite range and elevation angle has to be known together with atmospheric pressure, temperature and water vapour at each laser station at the time when tracking data are taken.

The influence of the reflecting corner cube assembly on the range determination has further to be known and thus analysed in some detail (P. O. Minott & M. W. Fitzmaurice 1975, private communications; Minott 1974). Figure 3 shows an example of the corner cube array range corrections by Minott & Fitzmaurice which are used for our Geos-3 spacecraft. The values are all negative by convention, meaning that the range measured to the 'centre of the spacecraft' is simply shorter by the amount shown. As can be seen, substantial corrections (up to 120 cm) have to be made to achieve a high ranging accuracy.

TABLE 1. G.S.F.C.-LASER ERROR BUDGET EXAMPLE

(4 ns pulse.)

	cm
calibration (ground target)	1.7
pulse position (pulse centre)	3.3
system stability (drift)	4.0
laser system: r.m.s.	~5.5
atmosphere (10° elevation)	1.5
corner cube array (different for each spacecraft)	1.5
station time	0.5
total r.m.s.	~6

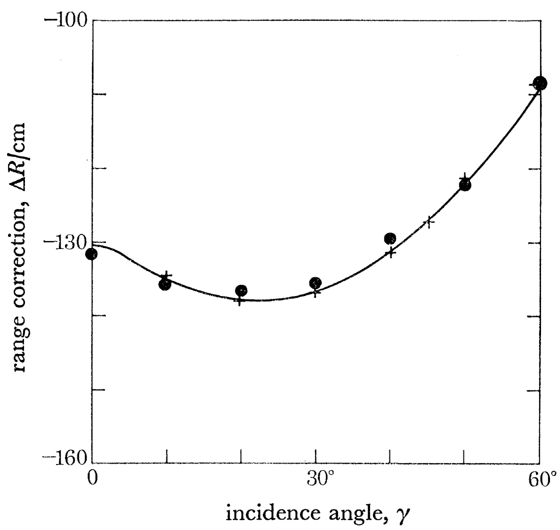

FIGURE 3. Laser range correction for Geos-3 (pulse length = 200 ps).

In order to test all these, side-by-side ranging calibration experiments were and still are performed at Goddard. This means that two independent but co-located laser systems are operated at the same time using the same target satellite. Employing short arc (few minutes) orbit computations and taking the separation distance (~ 25 m) of the two lasers into account, their noise values can be determined quite accurately together with their possible range biases by differencing the ranges and assuming that these errors are not correlated and equal.

Figure 4 shows graphs of the laser range bias errors as determined from two Goddard laser systems tested (McGunigal *et al.* 1975). Each point is the result of a separate satellite track taken

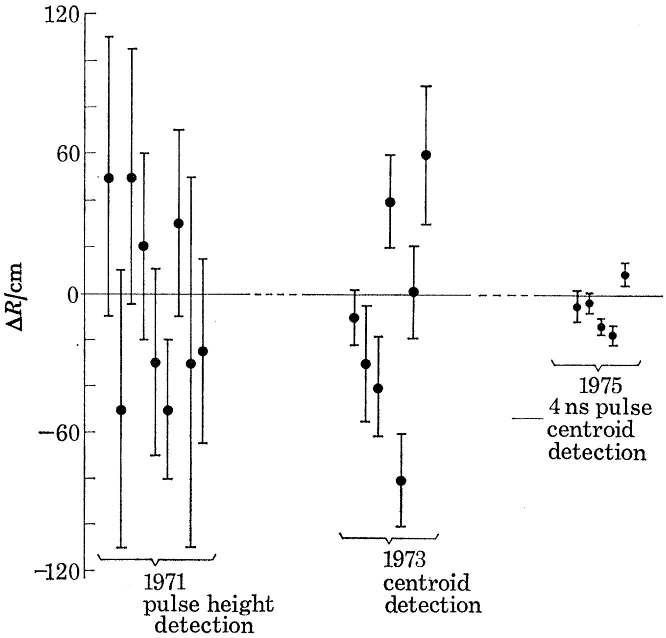

FIGURE 4. G.S.F.C.-laser ranging two station intercomparison range bias errors.

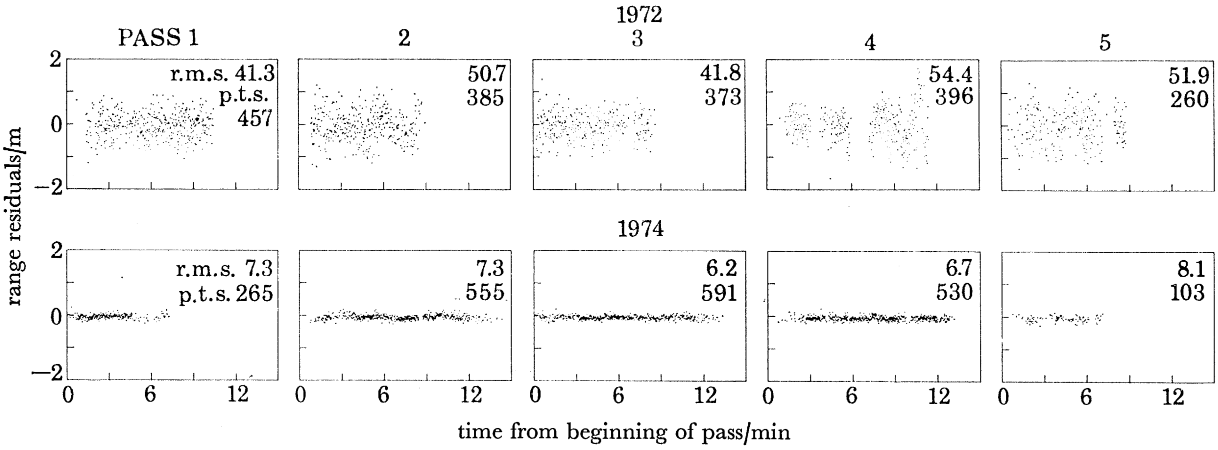

FIGURE 5. Laser residuals from five pass orbits for BE-C in 1972 and 1974

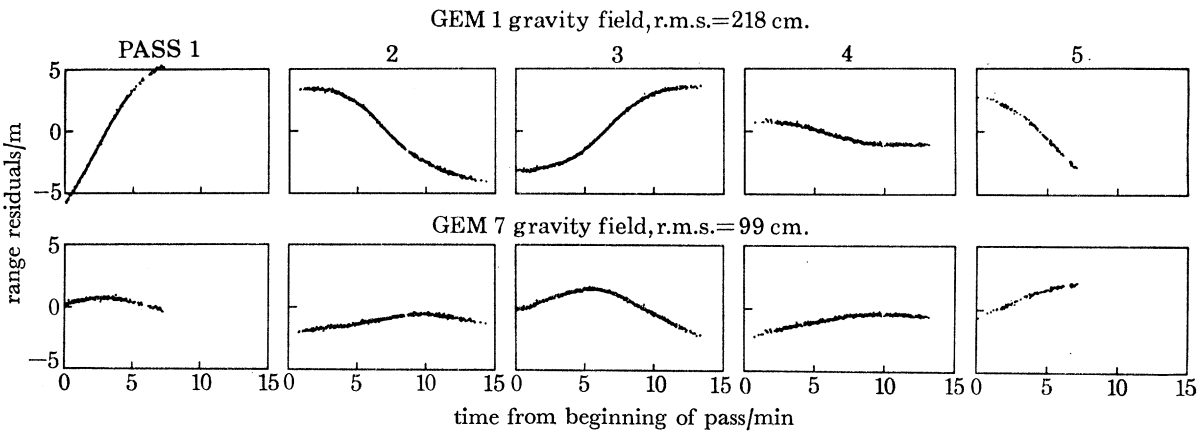

FIGURE 6. Laser residuals from five pass orbits in 1974.

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

by these lasers. The bars present the estimated errors of each bias value itself. Figure 5 depicts laser noise values for BE-C for 1972 and 1974. Both graphs clearly show the improvements in the ranging errors we were able to achieve over the last few years. Further improvements underway at present will bring these values shown for 1975 even further down. Our latest test results indicate total errors in the order of 5–8 cm as mentioned.

Figure 6 depicts improvements due to a better gravity field just to indicate its influence on laser range residuals (bias in this case).

Using the range equation $R = \frac{1}{2}c\tau$ or better its normalized variation $\delta r/r = \delta c/c + \delta\tau/\tau$, where c is the velocity of light, τ the two-way travel time and the δ's indicate the variation, it can easily be seen that the value $(\delta c/c)$ starts to play a role if the accuracy requirements come down to the cm ranges. This means that: either this value has to be improved to say $\delta c/c \leqslant 10^{-8}$ for an average satellite slant range of 2000 km ± 2 cm since $\delta r/r$ is for this case of the same order as $\delta c/c$, or one has to assume that light velocity c as a known constant and recompute the appropriate natural constants used in the Earth dynamic analyses.

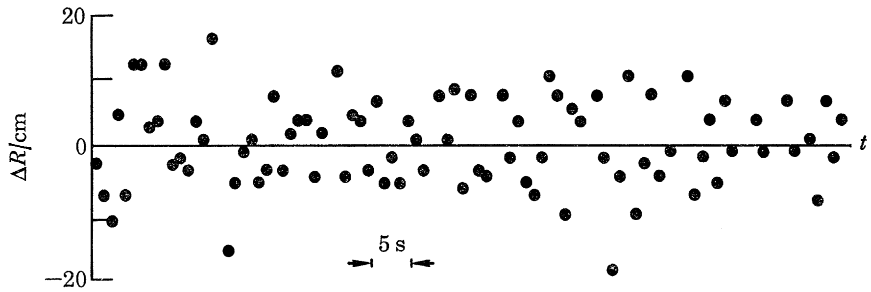

FIGURE 7. Laser range residuals (15th degree polyn). Starlette, 20 April 1965 (noise ± 7.5 cm).

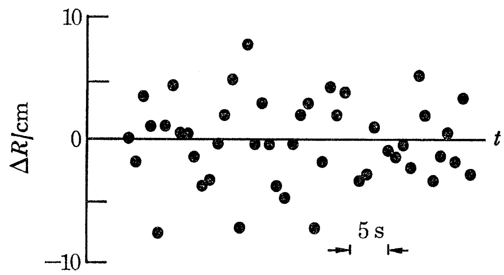

FIGURE 8. Laser range residuals (15th degree polyn). Geos-3, 22 April 1975 (noise ± 3.6 cm).

Figures 7 and 8 show the range noise errors obtained from the French Starlette and our Geos-3 spacecraft. The reason for the almost 2 to 1 difference is that the signal level of the return pulse is much stronger from Geos-3 than for the smaller Starlette. The values shown in figures 4 and 8 are simply computed using a 15th order polynomial as an orbit arc over a short time interval of say 1 min which turned out to be adequate for the estimation of the range noise only. Obviously no bias estimates can be made with this method.

Figure 9 depicts the variation of the signal level of the laser pulse from Geos-3 as a function of the laser pulse from Geos-3 as a function of the zenith angle. Also, this fact has to be taken into account under the array correction procedure.

In summary it can be stated however that for the Goddard lasers presently in operation the noise and bias values seem to be approximately equal. This is important when one has to compute orbital and other dynamic errors in advance.

As is known, the bias errors are unfortunately those which are the dominant ones influencing geodynamic computations since they do not decrease with the number of measurements taken (inverse square root law).

Table 2 lists the performance of our Goddard lasers using the Geos-3 spacecraft. As can be seen, actual range residuals are in the order of 5–7 cm for this special case. It also shows that the calibrated values taken before and after each pass are almost the same as those computed using the real Geos-3 orbit, an encouraging fact.

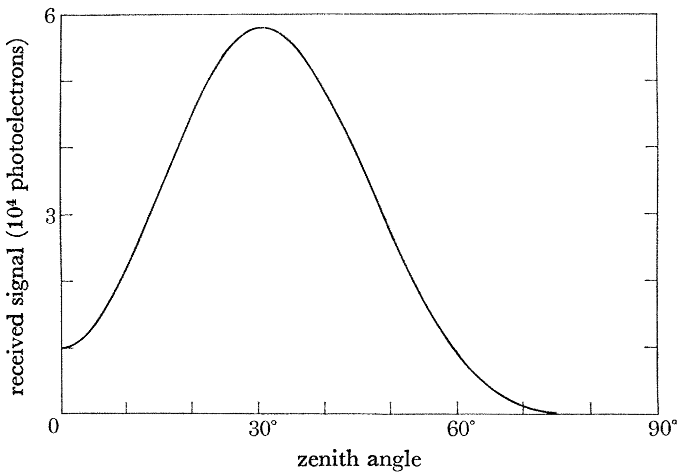

FIGURE 9. Received Geos-3 signals against zenith angle

TABLE 2. PERFORMANCE OF LASER RANGING SYSTEMS ON GEOS-3 (MAY–JULY 1975)

system	total no. of passes	average cal. range residual (cm)	average pass range residual (cm)	average number of hits per pass
Moblas 1	27	5.4	6.3	114
Moblas 2	51	5.9	5.7	133
Stalas	90	4.6	5.2	119

CONCLUSIONS

In summary it can be stated that the present Goddard ruby lasers can track spacecraft to an accuracy of about 8 cm. Further, all our experience as of today indicates that one can assume that the noise and bias errors of these lasers are approximately equal. Also, atmospheric errors will be corrected to about 1 cm in the near future or better for elevation angles above 10°.

From table 1 it is evident that in order to improve future lasers, pulse position and systems stability errors have to be improved.

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Discussion

J. A. Weightman (*Geodetic Office, Elmwood Avenue, Feltham, Middlesex*). If the returned laser signal shape is imperfect because only relatively few photons get back, it seems at first sight surprising that the centroid of the wave shape should give the best results: if a signal is deformed purely by subtracting information then surely the true peak would be displaced to a false peak in a direction which was towards the centroid of what was received and to use that centroid could take one even further away from the true position ?

F. O. Vonbun. This is true for a few photons; all our lasers have enough power so that the returned signal from our low altitude satellites produce about 200 to 2000 photoelectrons.

P. Wilson (*Institut für Angewandte Geodäsie, Frankfurt/M.-Sindlingen, Germany*). There appears to be some confusion in the discussion material presented, between the accuracies of clock times expressing the epoch of measurement and those of clock times used to register the round trip time of the signal from laser to receiver. Would Dr Vonbun kindly explain how and with which systems it is proposed to measure the epoch of measurements to be conducted for the Lageos network? What are the accuracies anticipated for these measurements?

F. O. Vonbun. The Navy's Navigation Technology Satellite will be used to assure a 1 μs station time synchronization of the Goddard lasers. The time associated with a specific range reading is the time of laser pulse reflexion from the satellite.

B. Elsmore (*Cavendish Laboratory, Cambridge*). I am surprised by the high accuracy of ± 1.5 cm which you claim for the uncertainty in the delay introduced by the atmosphere. Can you explain how this knowledge is achieved?

F. O. Vonbun. The use of pressure, water vapour and temperature measurement at the station indicates errors of about this value at an elevation of 20° (Hopfield 1969; Marini 1972).

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

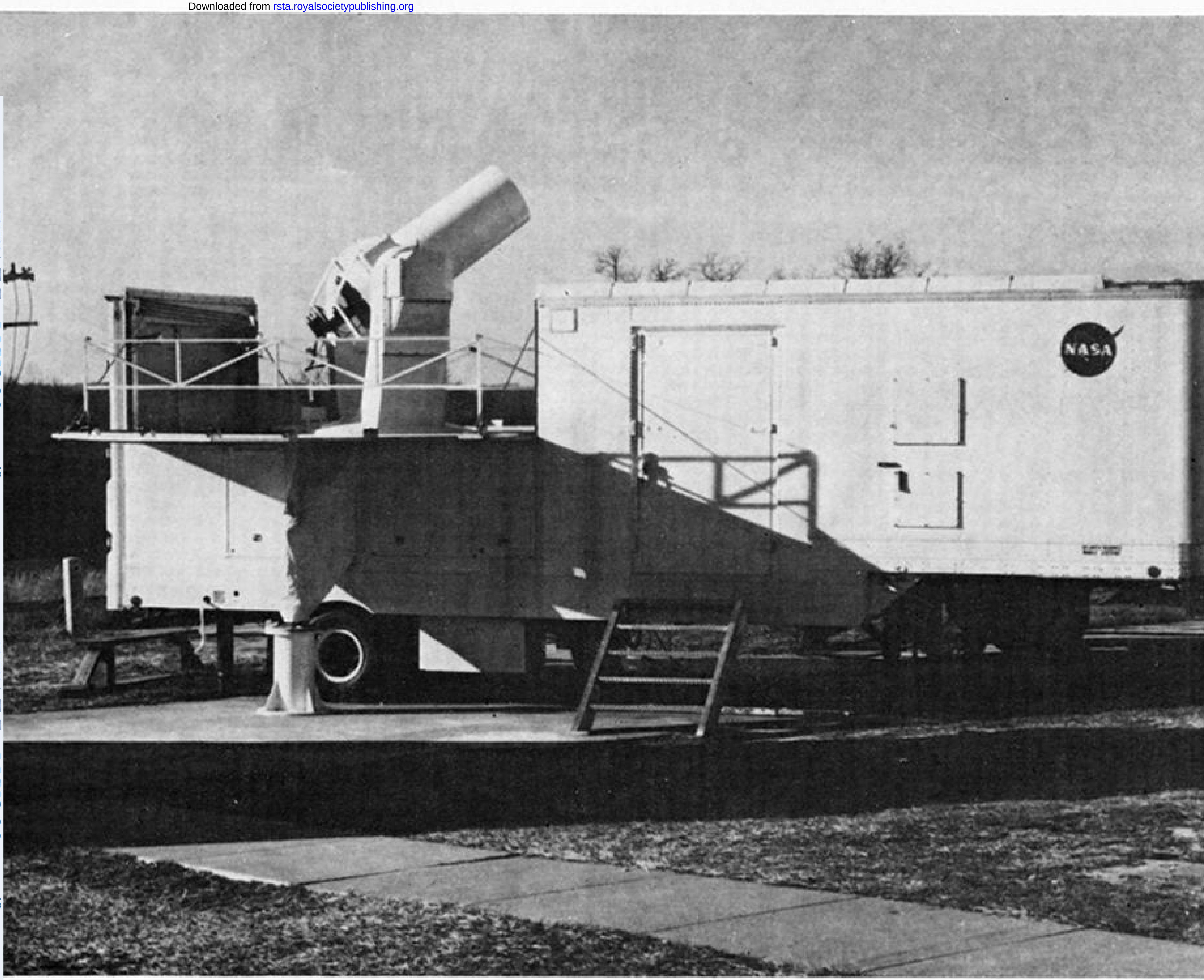

Figure 2. Goddard mobile laser ranging station.