REPORT OF HYDROGRAPHIC RESEARCHES No.12, March, 1977

AN EXPERIMENTAL SYSTEM FOR SATELLITE LASER RANGING

Minoru Sasaki*

Received 15 December 1976

Abstract

A satellite laser ranging system has been made under cooperation with the Hydrographic Department and the Geographical Survey Institute. The receiving telescope is of a Cassegrain type with 40cm diameter installed on 3-axes type mountings which are driven by pulse motors in combination with encorders in three different tracking modes: manual, programing and automatic. A 0.1 nsec-resolution counter is prepared for measuring flight time. The system has a 500 MHz oscilloscope with a remote controlled camera which makes it possible to study the shapes of the transmitted and received light for accomplishing high ranging accuracy. According to the test operations the transmitted laser energy attains to 3.3 Joules and the pulse width is 21 nsec. These correspond to 160 MW at peak. In the case of using an electro-optical shutter which is adopted for sharpening the transmitting light, those values become 0.2 Joule, 6 nsec and 43MW, respectively. It has been definitely shown by some experiments and test operations that the developed system is valid for precise ranging.

Key words: laser ranging system

1. Introduction

Since the first launching of artificial satellite in 1957, researches on application of satellites to geodetic work have been conducted at the Hydrographic Department of Japan (JHD), as are reported, for example, by Yamazaki (1971) and Yamazaki et al. (1972). JHD has also continued an investigation on the design of satellites for geodetic uses with the Geographical Survey Institute (GSI) of Ministry of Construction. One of such satellites has been planned to be a balloon of 10m in diameter which can be observed by photographing and laser ranging so that its direction and distance can be determined simultaneously with high precisions. The body of the satellite is a hard spherical hull coated by aluminum leaf. Some thousands of corner-cube prisms are sticked on the surface uniformly for laser ranging. Since the satellite keeps spherical shape and shines brilliantly by reflecting the solar rays, it is possible (i) to photograph the trailed image of the satellite while images of reference stars in background are taken as fixed dots on the photographic plate (equatorial mode), and (ii) to evaluate the geometrical relation between the reflection point and the center of the satellite's mass. Hence, the direction of the satellite can be measured on the photographic plate with the same accuracy as that of ordinary astrometry. On the other hand, since the pattern of laser reflection does not change with the satellite's attitude but is constant, the distance of the center of the sate-

* Astronomical Division, Hydrographic Department.

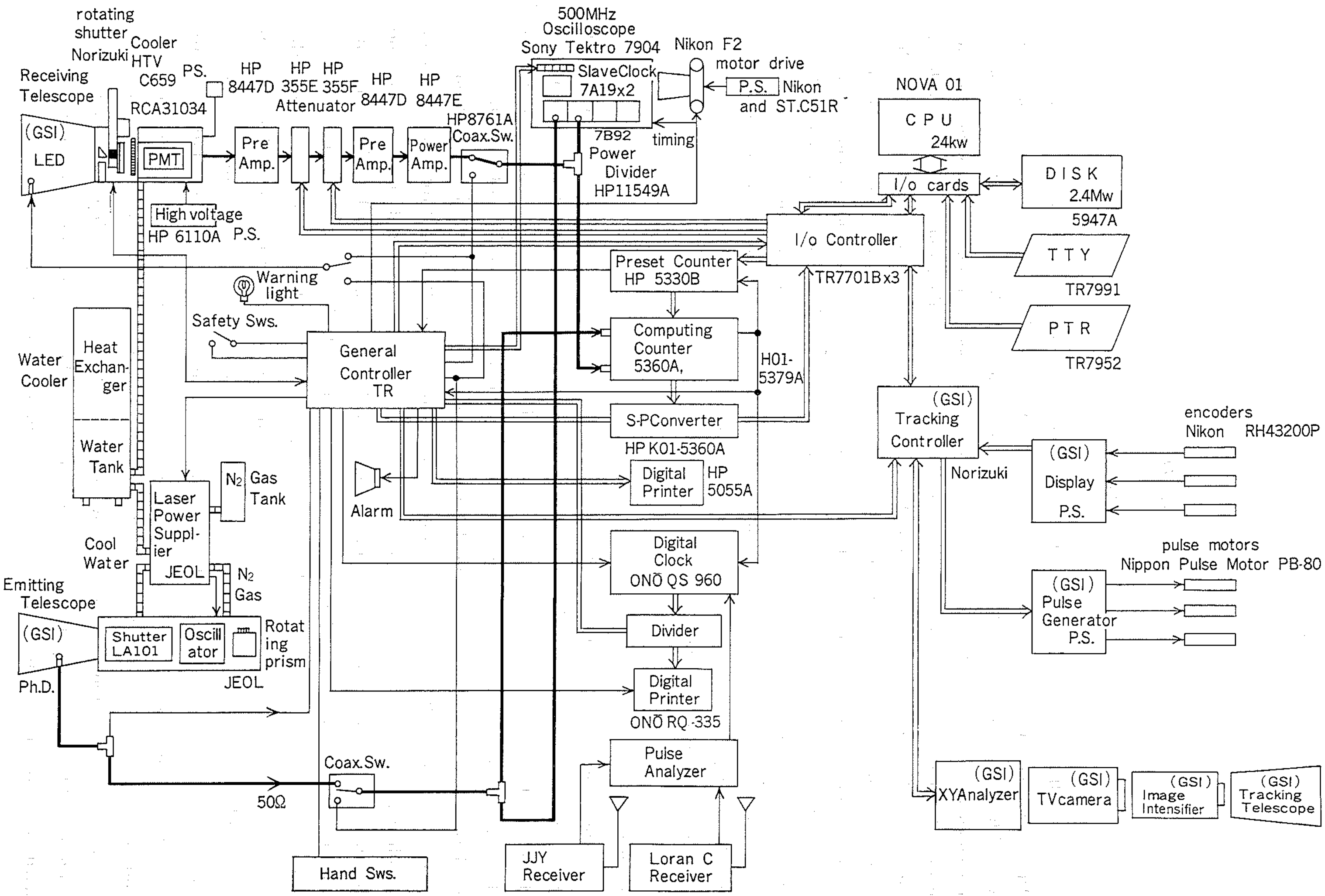


Fig. 1 Block diagram of the experimental satellite laser ranging system

llite's mass from the observer can be measured with a sufficient accuracy by comparing shapes of returning light pulses with transmitted ones.

The satellite is planned to be launched for the purpose of practical use to rectify the national geodetic net of Japan and to extend it to the ocean areas. Since the equipment for photographic observation of this satellite can be manufactured by some slight modifications of an apparatus which was designed by Ono (1966 and 1968) and has been verified its utility in practical observations in these ten years, it had been concerned mostly to develop the apparatus for distance measurement. In accordance with the launching project of the satellite, JHD and GSI have been cooperating to develop a satellite laser ranging system on an experimental basis.

The principal object of the development of this laser ranging system is various experimental investigations for designing a system to be employed practically for the observation of the geodetic satellite mentioned above. Main features of the present system are;

(i) Since sharpness of the transmitted wave is indispensable for obtainning high accuracy of distance measurement, an electro-optical shutter is attached to the transmitter as a trial for this purpose.

(ii) A high resolution oscilloscope is linked on line to investigate fully the forms and patterns of transmitted and returning lights.

(iii) Because of the high brilliancy of the satellite, tracking by optical method can be easily applied. If precise tracking would be realized, the beam width of the transmitted rays would be made extremely narrow. Such a narrow width would contribute in making the whole system smaller in size and higher in performance of its function. Since development of tracking system of simple mechanism and of high precision is one of the subjects of the present research equipments for automatic optical tracking has been manufactured.

Research on laser ranging system was undertaken already in 1967 at the Tokyo Astronomical Observatory (TAO) and valuable works have been performed with an experimental device at its Dodaira station. It is remarked that the results and various experiences of the researches were availed fully to start present research.

The present research is now under way, scheduling the practical observation in near future. In the present paper, a construction of the system and some results of experiments are described laying emphasis on the part which the JHD-team has been charged.

2. Instrumentation

The present system is composed of optics and tracking system, which are in charge of GSI, laser transmitting system, detecting system, measuring system and control system, which are in charge of JHD. See Fig. 1.

(1) Optics and tracking system

The system has four telescopes: a transmitting telescope, $\phi=7$cm, f$=27$cm; a receiving Cassegrain type telescope, $\phi=40$cm, f$=660$cm (effective); a guide telescope for automatic tracking, $\phi=12.5$cm, f=60cm; a guide telescope for visual and manual trackings, $\phi=8$cm, f=120cm.

These telescopes are set on a 3-axes type mounting which is driven in altitude-, azimuth- and tracking modes by three independent pulsemotors with 1.8 deg/step resolution. The maximum driving speeds of them are 30′/sec for altitude and azimuth axes and 65′/sec for tracking axis. The rotation angles per an input pulse are 2″.2 for altitude and azimuth axes and 0″.9 for tracking axis. The angles of these axes are read out in three photoelectric encoders, respectively. The reading resolution is 0′.1/pulse after five-time enlargement.

(2) Laser transmitting system

The laser oscillator is a ruby rod of 1.25cm in diameter and 10cm in length with a rotating prism as Q-switch and a herical Xenon lamp as the pumping source. The oscillator is cooled by a water cooling unit of circulation type. The light pencils have a divergence of 5mrad. They are emitted at a rate of 0.2Hz and then pass to an electro-optical shutter (LA-101, Japanese Electron-Optics Laboratories) for regulating the shape. The shutter is composed of two polarizers, of which polarization planes make a right angle with each other, and a Pockels cell is laid down between them. The light pencil is cut off to about 5nsec width by an abrupt rotation of the polarization direction of the Pockels cell. The part for the abrupt rotation is in need of nitrogen gas of about 10atms.

(3) Detecting system

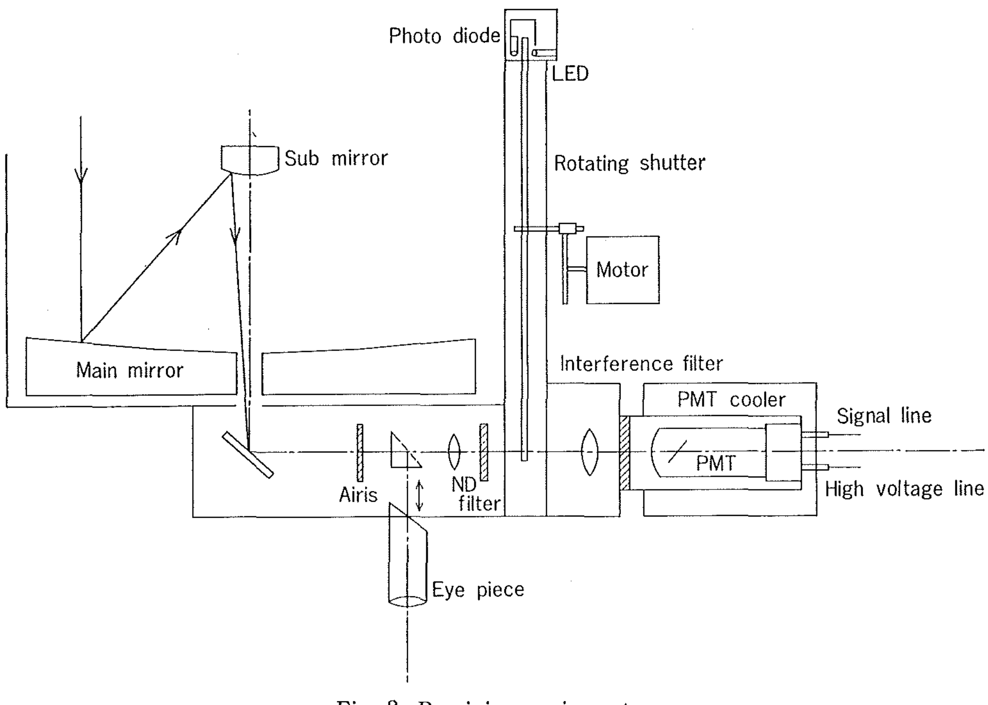


Fig. 2 Receiving equipments

The transmitted laser light is detected by a high speed photodiode. The signal is devided by two power-deviders into three equipments. One is led to a digital clock and it makes record the laser firing time. The other one starts a counter for flight time measurement of laser light pencil. The last one is sent to a high resolution oscilloscope and is photographed for analysis of the wave form of transmitted light.

The light reflected by the corner-cube prisms on a satellite surface is collected by the main telescope and it passes an iris and an interference filter ($\pm$5A in band width at 6943A) which decreases light noises before it reaches a photomultiplier (PMT). It can also be brought to the eyepiece through a bascule-prism attached in front of the PMT, as shown in Fig. 2. PMT in the system is RCA 31034. Its gain is 10^7 at the maximum voltage of 2200V. A part of circulating water to cool the laser oscillator is utilized for heat emission from electronic-cooler for PMT.

A rotating shutter, of which rotation is synchronized with the firing, is also attached for protecting the PMT against the scattered light of the emission.

(4) Measuring system

Two pre-amplifiers with a gain of 26dB and a range of 100k$\sim$1.3 GHz and a power-amplifier with a gain of 22dB and a range of 100k$\sim$1.3 GHz are prepared to amplify the signals from PMT. In order to analyze wave form at nearly the same wave height for any signals, the signals have to be decreased to almost the same levels. For this purpose two attenuators with a range of DC$\sim$1 GHz, which is controlled by computer in every 1dB step from 0 to 132dB, are combined with the amplifier. The amplifyed signal is devided by a power devider. One is led to the flight time counter to stop counting and another is led to the oscilloscope for investigation of the wave form.

As flight time counter a computing counter, Hewlet Packard (HP) 5360A, is adopted. This counter has following specifications ; 0.1nsec in timing resolution, 1 nsec in timing accuracy, 5×10^{-10} a day and 5×10^{-11} for 1 sec averaging in time base accuracy and 300mV in minimum sensitivity. For precise measurement of time interval HP H01-5379A which is a plug-in option of 5360A is used. This has a gate circuit called arming circuit. When an external arming signal is on, the counter can t operate. This circuit prevents miscounting caused by light noises within the time interval from a laser firing to just before the returning of the light. The external signal is made by a preset counter driven in computer control.

A digital clock integrates the standard frequency of 1MHz sent from the computing counter and keeps time. The time is calibrated by Loran-C using a comparison unit. Such a system was developed ten years ago at JHD and has been in practical use.

An oscilloscope of 500MHz (Tectronix 7904) has been adopted as the oscilloscope for wave form analysis. Its technical data are ; 0.8nsec of rise time, 0.5nsec/div in writing speed and 10mV/div in maximum sensitivity.

(5) Control system

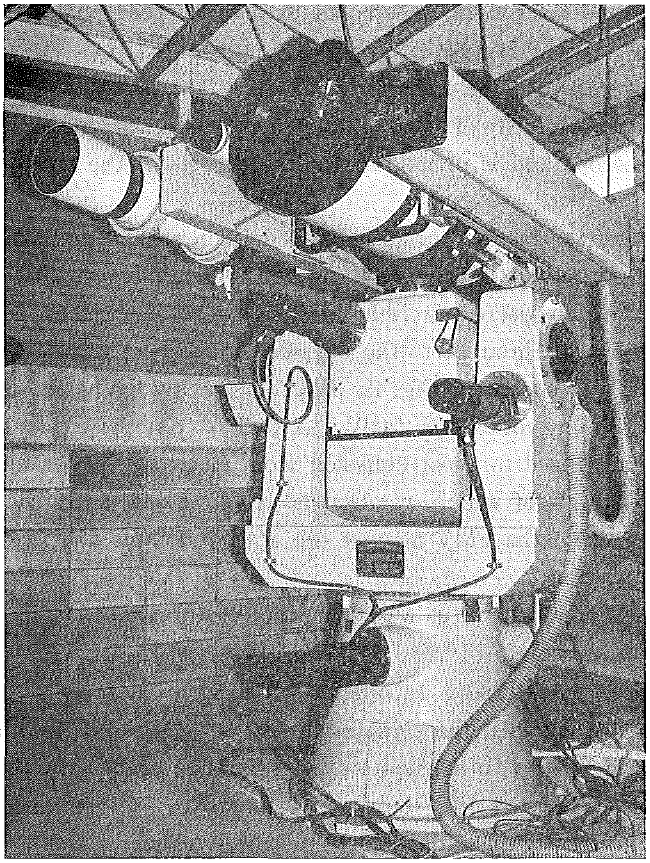


Fig. 3 Telescopes and mounting

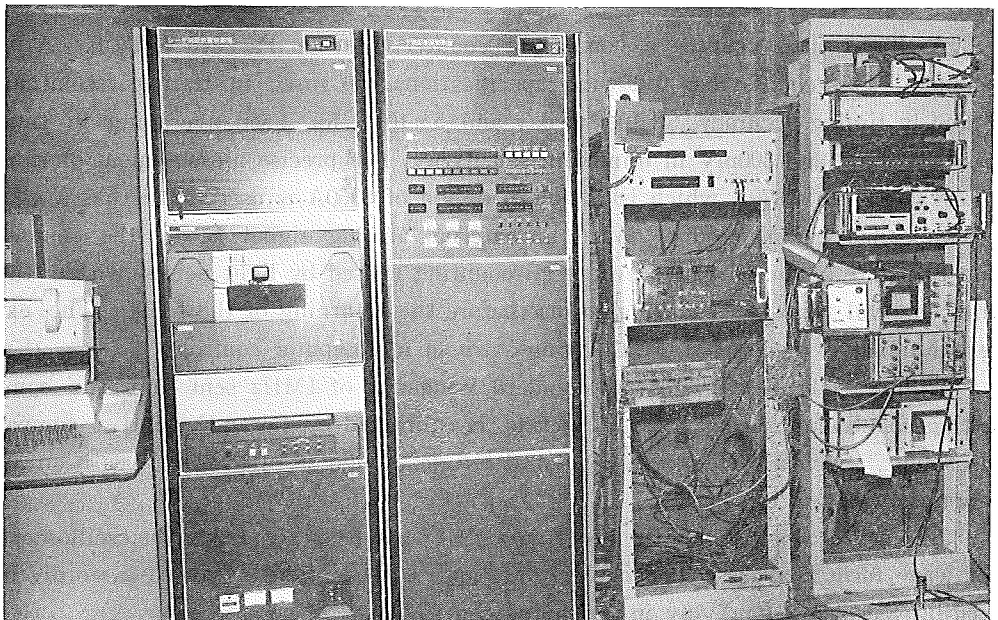


Fig. 4 Measuring equipments and computer system

This system has two controllers. One is the controller for laser transmission and range measurement. Another is for mounting control.

The former controls laser transmission, operation of measuring equipments, photographing of images on the oscilloscope screen, shutter rotation, I/O cycles between CPU and measuring equipments and between CPU and mounting controller. Firing intervals can be set by digital switches from 5 sec to 99 sec. Every I/O cycle between CPU and mounting controller is selected from 0.1 sec to 9.9 sec by this controller. Though the computer treats many data, manual control can be executed without the computer if necessary. At that case time of laser fire and flight time are printed out by two back-up printers, respectively.

The latter controller with arithmetic circuits controls the mounting. Tracking of satellite is performed in either of three modes; manual, programing and automatic. In any case the mounting is driven by pulse moters and the pointing direction of the telescopes are detected by encoders.

In manual mode, rough tracking are performed according to the set values on a key board. Fine adjustment of the driving speed of the mounting axes is made manually with handswitches by sighting the satellite in the telescope field visually.

In programing mode, the computer provides tracking velocities to the controller for pulse motor driving and reads out the integrated values of output pulses of encoders from the controller. If a deviation between the position of the actual satellite and one of the prediction exists, the observer controls the direction of the telescope visually with hand switches and commands the computer to correct the prediction suitably. Then, tracking accuracy is superior to that of the manual mode.

In automatic mode, the telescope for tracking follows the satellite motion automatically after capture of the satellite image. Main units of this mode are; telescope, image intensifier, TV camera and XY-analyzer. Tracking is executed in the following way. If a satellite image deviates from a set point of the TV camera, the XY-analyzer detects it's amount and generates voltage level corresponding to the displacement. The output level from the analyzer is digitalized in A/D converter and then added to the tracking speeds initially set in the arithmetic logic unit. Thus the satellite image is kept stationary at the same position on the screen.

Two controllers are fully available in case of using computer. NOVA-01 (Nippon Mini-Computer) with core-memory of 24kilowords is adopted as computer with peripherals of a magnetic disk of 24Megawords, a paper tape reader and a tele-typewriter. Measuring equipments and two controllers are linked to CPU through interfaces of six I/O modules and three multiplexer modules. In addition to the on-line system control, CPU calculates and revises the prediction. The CPU also processes the obtained data and stores them into the disk.

(6) Self check and safety system

The system has following check-up functions. The system controller has laser transmitting and receiving simulation circuits which check measuring instruments and I/O cycles of the computer. According to the switched values of delay time of laser transmission and flight time these circuits generate simulation pulses. The computing counter has self-check mode. The I/O data of the computer are checked by a software checking program.

The system contains some sources of danger. They are high output power laser which seriously harms eyes when it goes in and high voltage power supply of big capacity. In order to avoide accidents safety switches are prepared at critical points and they stop the system when someone opens these switches. In addition laser firings are warned by buzzar sounds.

3. Tests of each part of the system

Some performance tests of each part and examinations of their specifications have been made.

(1) Laser

The pattern of the transmitted laser beam was examined by exposuring on photographic printing paper and a circular image of almost uniform intensity has been obtained. Output energy was measured by using caloriemeter. Examples of the result are shown in Fig. 5. Fig. 6 shows relation between output power and pressure of nitrogen gas. The output energy attains to 3.3 Joules in maximum and half height width is 21nsec. They correspond to 160 Mw. When the shutter is equipped those values becomes 0.2 Joules, 6nsec and 34Mw. The wave forms are shown in Fig. 7 and 8, respectively.

(2) PMT

Quantum efficiency has been measured by use of spectrometer. As can be seen in Fig. 9, the efficiency is 4% at tne wave length 6900A. Transit time and rise time, both of which affect the accuracy of distance measurement directly, have been measured with pulse generator, high speed photodiode and TK 7904. Obtained data are shown in Fig. 10.

(3) Miscellaneous

Fair results have been obtained in the various tests about the performance of the control system and relating parts. For instance, many electric circuit tests, delay time measurements of simulation signals, laser and telescope divergence test, adjusting of field center of telescopes and so on. As for the tracking, the automatic mode was examined for stars up to 6th magnitude. Some superior results were reported by a member of GSI.

(4) Ranging tests to a ground target

A ground target was set at 18511 meters apart from the system and ranging tests were performed. In a case, the measured mean distance was 18527.8 ± 0.1m by 34 emissions without the electro-optical shutter and the standard deviation to one pulse was 0.6m. The main part of difference in distance will be explained by the delays of amplifiers (2.0m), PMT (10.2m), attenuators (1.2m) and cables. The remainder is interpreted as relative triggerlevel-difference between transmitted signals and received signals. The further investigation for the difference is con-

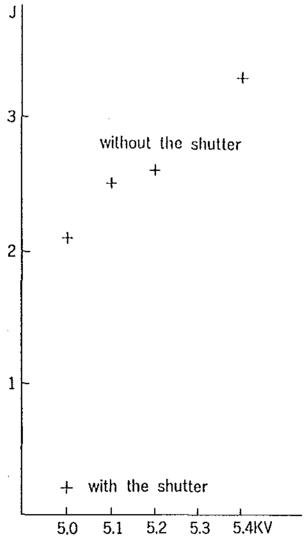


Fig. 5 Output laser energy and supply voltage (cooled at 15℃)

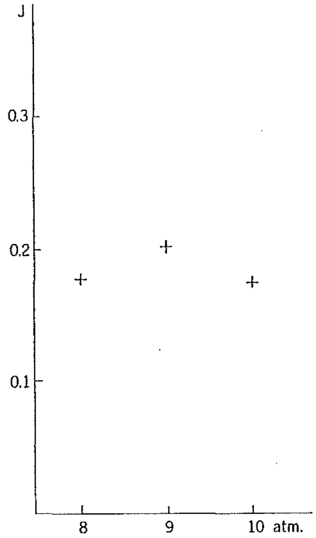
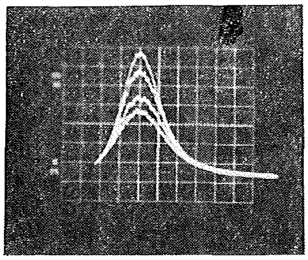
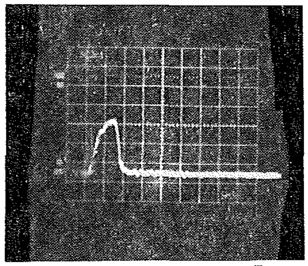


Fig. 6 Output laser energy and supply N_2 gas pressure



10nsec/div

Fig. 7 Laser output wave forms at 4.9, 5.0, 5.1, 5.2KV of supply voltage



5nsec/div

Fig. 8 A laser output wave form with the shutter at 5.0KV of supply voltage and 8atms of N_2 gas pressure

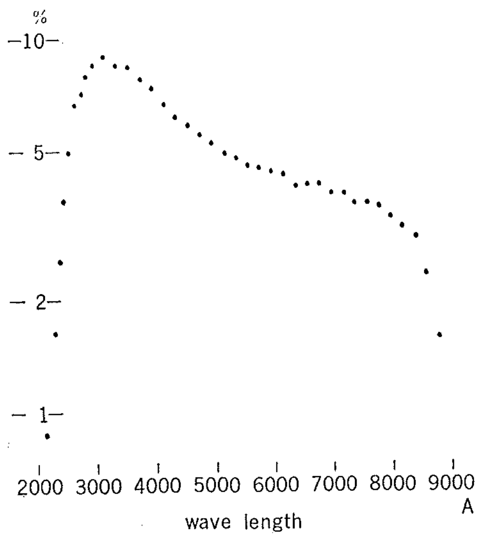


Fig. 9 Observed values of quantum efficiency of RCA31034

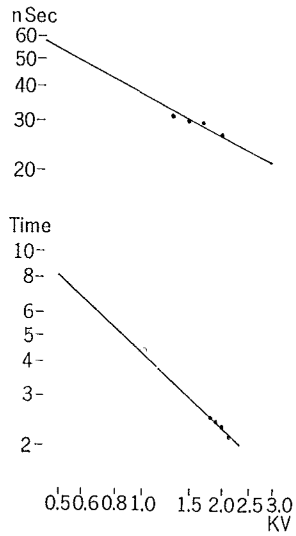


Fig. 10 Transit time and rise time of RCA31034

tinued.

4. Concluding remarks

Although it is difficult to assert that the system has been completed, the fundamental problems are considered to have been solved through the manufacturing works and some tests described above.

(i) The electro-optical shutter effects satisfactorily to sharpen the emitting light, though output power has not been as large as was aimed at first. However, this situation is considerd to be improved by inserting a power amplifier of laser light between the shutter and the transmitting telescope. It is desired that the actual type for field works is equipped with an amplifier.

(ii) Specifications of present system are summarized in Table 1, where values followed by an asterisk (*) are those taken from the original design or from the data catalogs of each equipment or estimated values. According to these data and some assumed values relation between number of receiving photoelectrons and range are estimated using the formula;

$$N=(E/h\nu)G_TA_SG_SA_R(T^2/\rho^4)\alpha\beta\gamma\eta$$

where E: laser energy (3.3 Joules without the shutter and 0.2 Joule with the shutter), $h\nu$: energy per photon (at wave length $\lambda=0.69\times10^{-6}$m), G_T: transmitter gain (full width $\theta=1.0\times10^{-3}$rad), A_S: satellite effective area (0.09m^2), G_S: satellite mirror gain ($\theta=1.0\times10^{-4}$rad), A_R: receiver area (diameter d=0.4m), T: atmospheric transmission factor (0.5), ρ: range to satellite, α: transmitting efficiency (0.5), β: mirror efficiency (0.5), γ: receiver efficiency (0.2) and η: quantum efficiency (0.04).

Estimated values are following. The range which can be measured with only one photoelectron at 3.3 Joules of laser energy without the shutter is 1.0×10^4km and and the similar range is 5.0×10^3km at 0.2 Joule with the shutter. But with only one photoelectron the received wave form can't be analyzed. If fifty photoelectrons can be obtained the analysis can be fully performed. The ranges with fifty photoelectrons are 3.8×10^3km without the shutter and 1.9×10^3km with one.

(iii) Experiments of the automatic tracking system has given satisfactory results. Although trackings in programing modes have not been tried, they seem to concern only softwares involving proficiency of observers because the tracking mechanisms have been designed to have an accuracy of $\pm0'.5$ and their satisfactory performances have been certificated in the automatic mode.

(iv) This system had been intended to be a portable type but it could not be realized because of some restrictions. On the stage of field works the portability is indispensable Since the present system can be operated without computer as mentioned in section 2-(5), in the case of the next system for practical use it is desired that the system will be operated without computer as the tracking are easily performed owing to the brightness of the satellite. But precise tracking is so important because light divergence affects the intensity of returning light as square of its amount. If the divergence can be a half it makes possible to lessen the aperture of the receiving telescope by a half or output power of transmitting light by a quater. Considering these matters minimization of the system has to be performed within limits of high reliability and high accuracy. Corresponding to the minimization of the laser oscillator, telescopes and mounting, it is required to make those equipments of electric power supply and cooling tower for laser smaller.

Table 1 Specifications of the Laser Ranging System

			with the shutter	
Laser energy	3.3	Joule	0.2	Joule
half-power full width (min.)	21	nsec	6	nsec
power (max.)	160	Mw	34	Mw
light divergence of ruby rod	5	mrad*		
frequency of emission	0.2	Hz		
shutter type	Pockels cell with nitrogen gas			
cooling type	cooled water			
Transmitter objective ϕ	76	mm		
transmitting divergence	1~3	mrad* (variable)		
Receiver objective ϕ	400	mm		
focal length	1200	mm (6600mm effective)		
Range (max., with one photoelectron)	10000	km	5000	km
range (max., with 50 photoelectrons)	3800	km	1900	km
ranging accuracy	1	m*	0.5	m*
Tracking system	3	axes type		
tracking modes	manual, programming and automatic			
drive	3	pulse motors		
direction reading	3	encoders		
auto-tracking	image intensifier, TV camera and XY-analyzer			
tracking accuracy	±1	mrad*		
PMT transit tim (min.)	26	nsec		
rise time (min.)	2.1	nsec		
Oscilloscope resolution	0.5	nsec/div*		
rise time	0.8	nsec*		
Counter resolution	0.1	nsec*		
Amplifier rise time	0.4	nsec*		
CPU memory	24	kwords		
Disk memory	2.4	Mword(real time disk operating system)		

This research is a joint work of the Hydrographic Department and the Geographical Survey Institute. The staffs are

JHD : T. Mori, Y. Ganeko E. Nishimura and M. Sasaki (author)

GSI : T. Hokugo, Y. Miyazaki, Y. Baba and H. Kaneko,

The author is deeply indebted to Dr. A. Tsuchiya and Mr. K. Tomita of the Tokyo Astronomical Observatory for their precious advices and discussions.

References

Kozai, Y., Tsuchiya, A., Tomita, K., Kanda, T., Sato, H., Kobayashi, N. and Torii, Y. 1973, Tokyo Astronomical Bulletin, 223, 2597.

Ono, F. 1966, Report of Hydrographic Researches, No. 1, 63.

Ono, F. 1968, ibid. No. 4, 59.

Tomita, K. and Kanda, T. 1973, Tokyo Astronomical Observatory Report, 16, No. 3, 657.

Yamazaki, A. 1971. Report of Hydrographic Researches, No. 7, 1.

Yamazaki, A., Mori, T. and Ganeko, Y. 1972, *Researches in Hydrography and Oceanography, in commemoration of the centenary of the Hydrographic Department of Japan*, Ed. D. Shoji, Tokyo, p. 251.