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Laser ranging application to time transfer using geodetic satellite and to other Japanese space programs

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ABSTRACT

Communications Research Laboratory (CRL) has been developing a laser time transfer system using a satellite laser ranging (SLR) system. We propose Japanese geodetic satellite 'AJISAI' , launched in 1986 as a target satellite. The surface is covered not only with corner cube reflectors but also with mirrors. The mirrors are originally designed for observation of flushing solar light reflected by the separate mirrors while the satellite is spinning. In the experiment, synchronized laser pulses are transferred via specified mirror from one station to another during the satellite is up on the horizon to both stations. The system is based on the epoch timing ranging system with 40 ps ranging precision, connected together with UTC(CRL). Simulation study indicates that two stations at thousands of km distance from each other can be linked with signal strength of more than 10 photons and the distributed images of laser beam from AJISAI mirrors give many chances to two stations to link each other during a single AJISAI pass.

In other topics on the application to Japanese space programs, Retro-reflector In Space for Advanced Earth Observation Satellite (ADEOS) and RendDezVous docking mission of Experimental Technology Satellite-VII (ETS-VII) are briefly presented.

1. Laser Time Transfer via Geodetic Satellite AJISAI

1.1 Introduction

Users of time and frequency standards have been able to take a variety of time comparison techniques even if they pursue the highest accuracy. The precision of GPS common view observation, for example, have got to several few nano seconds and 1 ns or higher precision have been attained by radio techniques such as two way time transfer via satellite (Ref.1). The requirement of such an extremely high precision may exist in deep space navigation, space geodesy, relativity physics and astronomy which always demand extreme precision and accuracy in their measurements. In addition to the radio techniques, time transfer using optical pulses has recently been suggested as one of potential for giving precision of sub-nano or picosecond time transfer to overcome the maximum bandwidth of radio waves (Ref.2).

Satellite laser ranging (SLR) have progressed as one of space geodetic techniques in the field of global geodesy and geophysics. Some SLR stations measure the range to as precise as 30 ps or higher (Refs. 3,4). Since the SLR system is essentially a highly precise epoch recorder transmitting and receiving of optical pulses, a combination of two or more SLR systems has potential as a highly precise time comparison and transfer system.

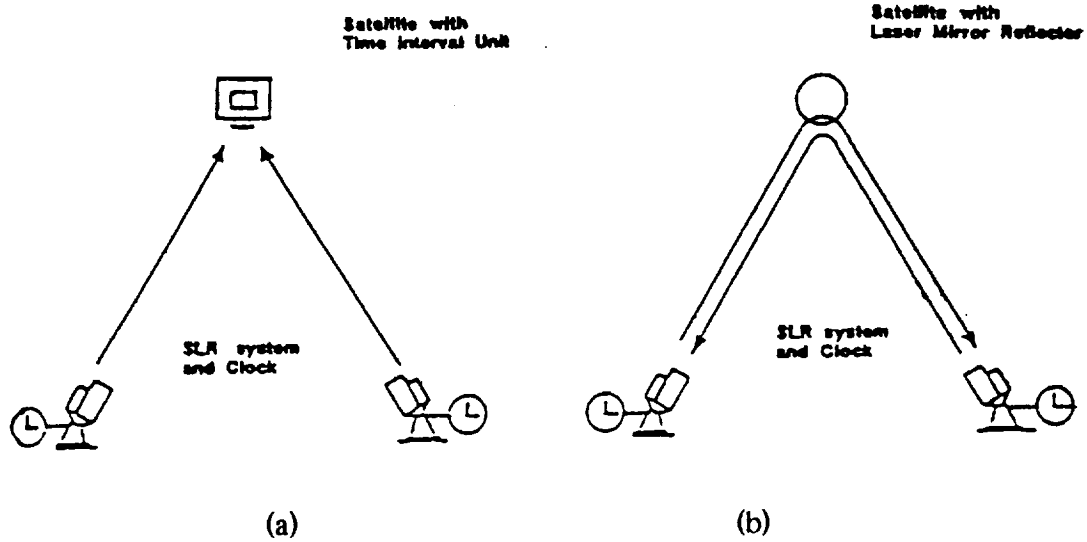

Fig.1 Configuration of Laser time transfer
(a) One way uplink (LASSO) (b) Two way

There are two configurations considered for ground-based-laser time transfer system using a satellite (See Fig.1). The first is called the one-way up-link configuration. Both SLR stations transmit a laser pulse to the time interval unit (TIU) on the satellite and the TIU measures the interval between their arrival times. Such an optical time comparison has been performed in Europe in the LASSO experiment (Refs. 5,6). In the LASSO experiment of European phase, laser echoes were successfully received at Grasse, France and at other European laser ranging sites. The second is the two-way configuration. Each station transmits a laser pulse to the other station via a satellite with mirror reflectors. The satellite also has corner cube reflectors for conventional SLR, and they are used to determine the distance from each station to the satellite to give support to the time transfer solution. In this paper, we examines the two-way configuration using the Japanese SLR satellite AJISAI, including time transfer concept, calibration methods, signal strength and spatial distribution of the reflected beam. The system performance is based on the CRL SLR system (Refs. 7,8), including additions to be made for two-way time transfer.

1.2 Target satellite AJISAI

Table 1 : Major specifications of AJISAI

Launch Date:	August, 1986	
Configuration:	Polyhedron inscribed in sphere of diameter 2.15 m	
Weight:	685kg	
Corner cubes:	1436 pieces,	Effective area :91.2 cm^2
Number of mirrors	:318 pieces,	Curvature of mirrors :8.4-9 m
Reflective efficiency:	0.85,	Brightness : 1.5-3.5 star mag.
Duration of a flash :	. 5 msec,	Rate of flashing : 2 Hz
Spin rate:	40 rpm	
Launch orbit:	Altitude 1500 km,	
	Inclination 50 deg,	Eccentricity 0.001

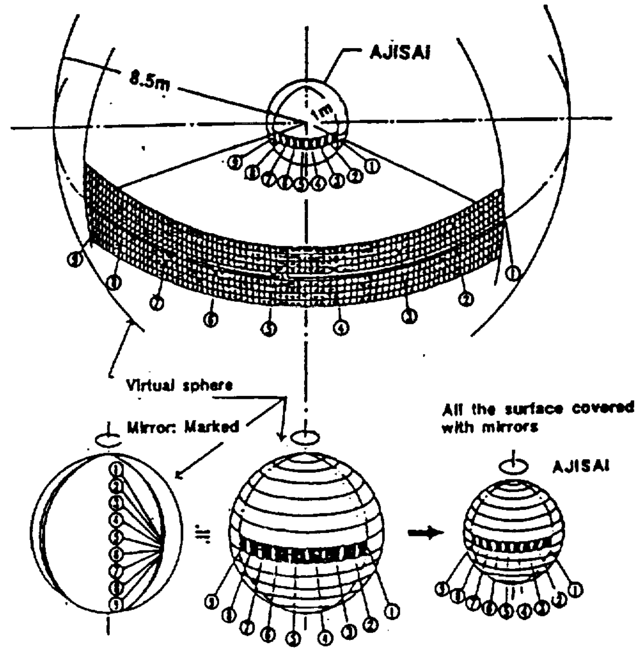

Fig.2 Arrangement of mirrors on AJISAI
Parts of an 8.5m radius virtual sphere (mirror) is placed on the surface of the 1-m radius AJISAI maintaining their latitude angles.

AJISAI is the Japanese geodetic satellite launched in 1986 by the National Space Development Agency (NASDA). The major specifications of AJISAI are listed in Table 1. The satellite is a hollow sphere 2.15 m in diameter and weighs 685 kg. The surface is covered with mirrors as well as corner cube reflectors. The orbit is a circular with an inclination of 50 degrees and an altitude of 1500 km (Ref.9). The mirrors were originally designed for observing flashing solar light reflected by separate mirrors while the satellite is spinning at about 40 rpm. Each mirror is a piece of a surface with a radius of curvature of 8.5 m. Three elements from the same latitude of the 8.5-m sphere at longitudes of 0, 120 and 240 degrees are put on the surface of a 1-m radius satellite retaining the phase angle of the original sphere (See Fig.2). The latitudes from which every set of three is taken are uniformly selected from the original surface so that a distant observer can observe the light reflected from the front surface flashing three times per rotation.

1.3 Two way time transfer

The equation for two-way time transfer via laser pulse is in principle the same as those being developed in radio frequency band (Ref. 1). The time difference d_{12} (: positive when clock 1 is ahead of clock 2) between the clocks of stations 1 and 2 is given by:

$$d_{12}= (t_{21}-t_{12}+t_1-t_2)/2 + (R_{12}-R_{21})/2c \quad (1),$$

where : $(i,j = 1, 2)$,

t_i : Epoch of pulse departure at station i measured by station clock i,

t_{ij} : (i .NE.j) Epoch of station i 's pulse reflected by a satellite mirror arriving at station j measured by station clock j,

R_{ij} : (i .NE.j) One-way distance of a laser pulse to travel from station i to station j via the satellite, and

c: speed of light.

The last term $(R_{12}-R_{21})/2c$ is expected to be nearly zero because of the good symmetry of travelling paths, but not negligible due to the effect on motions of both satellite and stations. It is related to the difference between the satellite position at the times the two laser pulses arrive. It approaches zero if the two pulses arrive at nearly the same time on the satellite. This is done by controlling the firing timing at both stations. Timing control within the precision of 1-ms is necessary to obtain a station to station link by a mirror of AJISAI with 20cm x 20cm size spinning at 40 rpm. If the laser fire timing is controllable to 1μs, $(R_{12}-R_{21})/2c$ is down to a few ps on the assumption that both the predicted position of the satellite and the clock synchronization are known with the accuracy of less than 1 μs (300 m in distance) before the experiment. The μs firing control can be performed by a fully active mode-locked laser operation. In this observation mode, we can apply the geometric method rather than dynamical one to the orbit solution using SLR range data (Ref.10).

1.4 Laser ranging system

We use an active-passive mode-locked Nd:YAG laser to generate 532 nm wavelength optical pulses 100 ps wide. The passive mode-locking is performed by saturable dye. The energy is 100 mJ per pulse and the nominal repetition rate is 10 pulses per second. The repetition rate can be controlled from 7 to 14 pps by real-time software. If the passive mode-locking by a saturable dye is replaced with an active component, the synchronization of firing timing can be controlled on nanosecond level (Ref.11) .

The receiving telescope aperture has diameter of 1.5 m. A micro-channel plate photo multiplier (MCP-PMT) is used for detector. It has a 300-ps rise time, 8% quantum efficiency and the transit time jitter of less than 30 ps with a constant fraction discriminator. The MCP detector can be also gated temporarily by the prediction of photons arrival in 20-ns time steps.

The timing system consists of a high performance disciplined quartz oscillator, a GPS receiver, and a time interval unit (TIU). Either a GPS timing receiver or cesium clock of UTC (CRL) can keep the reference to UTC. Timing epoch is measured for up to 4 stop events with a resolution of 40-ps.

1.5. Calibration system

In the actual experiment, we must consider that the reference signal of the atomic clock is transmitted to the SLR system via cables and electronics. Furthermore, the laser transmitting and receiving point is not at the telescope reference point.

The cables and electronics delay between the atomic clock and the TIU is monitored by an independent measurement system. Figure 3 is a block diagram of the monitoring system used in the experiment. The combined 5-MHz+1-pps signal from the cesium clock room is transmitted via a 500-m optical fiber. Output signal (50 MHz) of the quartz oscillator is phase-locked by the 5-MHz and used as the reference frequency in TIU. The 1 pps signal is used for the epoch reference of UTC. The 5-MHz and 1-pps signals are combined again at SLR site and are sent back to the clock room. Then delay and phase difference with respect to the original signals are continuously monitored at the clock room. It has been installed to get the characteristics of the long-term stability of the system.

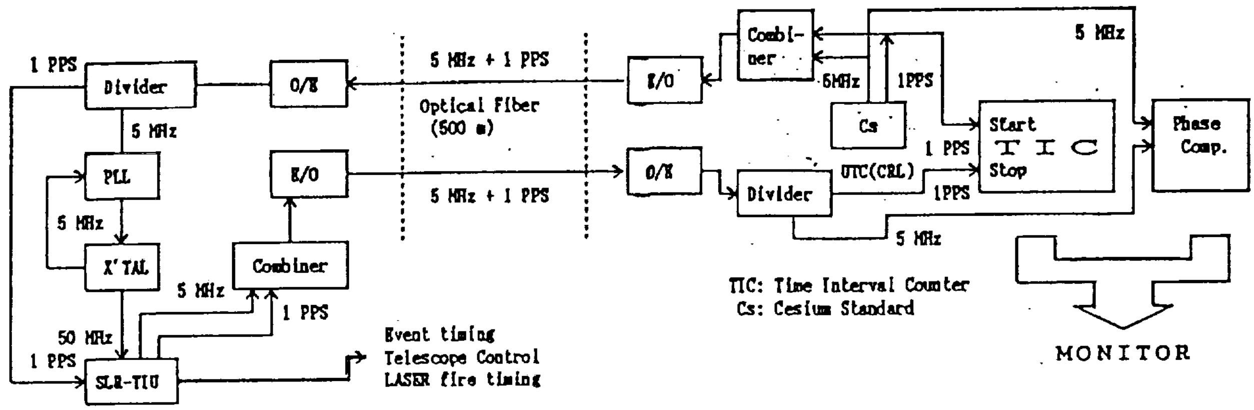

Fig.3 Reference signal monitoring system

The epoch latch point at each laser pulse start and stop must be treated as if these events occurred at the telescope reference point (intersection of two rotation axes). The calibration target is put on the telescope moving axis, as it takes partial reflection of transmitting beam and its physical distance from reference point must be measured precisely.

The time difference between clocks including calibration term (d'_{12}) is given by:

$$d'_{12} = (t_{21}-t_{12}+t_1-t_2)/2 + (R_{12}-R_{21})/2c + \{ (t_{1,a}-t_{1,b})-(t_{2,a}-t_{2,b})+(t_{2,x}+t_{2,y})-(t_{1,x}+t_{1,y}) \}/2 \qquad (2),$$

where : (i=1,2), in addition to the parameter defined in Eq.1,

$t_{i,a}$: Optical path delay from firing (laser input) point to telescope reference point at station i,

$t_{i,b}$: Optical path delay from telescope reference point to receiver point at station i,

$t_{i,x}$: Electronic delay from firing point to start-epoch latch gate at station i, and

$t_{i,y}$: Electronic delay from receiver point to stop-epoch latch gate at station i.

In order to calibrate the time difference between clock 1 and 2, each value of parameter in { } in the Eq.2 must be evaluated. The optical delay can be measured by a distance meter or by scales, and it will be stable in time unless optical design is changed. To cancel out the electronic delay, the common portable receiver can be collocated at two stations. This measurement would still have errors coming from the dependence on signal strength and temperature.

1.6 Link budget

In the laser time transfer experiment, the number of photons (N_p) detected at the remote ground station are calculated according to the following equation:

$$N_p=(E\lambda/hc)\cdot(r_1 r_2 r_3 r_4^2)\cdot(16A_s A_t/\pi^2 R_1^2 R_2^2 q_t^2 q_s^2) \qquad (3)$$

where E : Energy in a pulse, λ : Laser wavelength,
h : Planck's constant, c : Velocity of light,
r_1 : Transmission beam efficiency, r_2 : Receiving beam efficiency,

r_3 : Target reflector reflectivity,
r_4 : Atmospheric transmission efficiency (one-way),
A_s : Total reflector surface area, A_r : Received aperture surface area,
R_1 : Station 1 to satellite distance, R_2 : Station 2 to satellite distance,
q_t : Transmission beam divergence, and
q_s : Reflectors beam divergence for incident light return

Figure 4 shows the expected number of photons for AJISAI mirror reflection and the satellite elevation from stations, assuming the parameters have the values listed in Table 2. We also assume the position of AJISAI is roughly in the middle of the two station's common sky. From stations 2500 km apart, AJISAI is observed at above 40 degrees and more than 10 photons are expected.

Table 2 : Parameters for estimating the number of photons

Satellite Altitude	: 1500km (AJISAI)
Energy of pulse (E)	: 100 mJ
Wavelength (l)	: 532 nm
Transmission efficiency (r_1)	: 0.6
Receiving efficiency (r_2)	: 0.3
Target reflectivity (r_3)	: 0.9
Atmospheric transmission efficiency (r_4)	: 0.6
Reflector surface area (A_s)	: 0.04 m^2
Received surface area (A_r)	: 0.27 m^2 (60cm aperture)
Transmission beam divergence (q_t)	: 5 arcsec

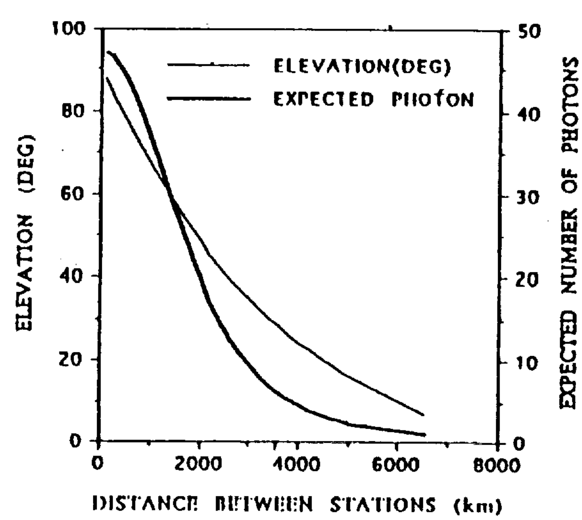

Fig.4 Elevation and Expected number of photon v.s. distance between stations in laser time transfer via AJISAI

1.7 Spatial distribution of laser reflection

We simulate the spatial distribution of laser reflection from AJISAI to study the possibility of an optical link for time synchronization between stations. We calculate first the rotation phase and the incident angle of AJISAI for a given transmitting station and epoch, then project the image onto the ground from all mirrors visible to both stations. The calculation continues according to the given time step.

In Fig.5, each rectangle is the image of the laser reflection on the ground for an instantaneous laser shot and the number by the rectangle shows the reflector number on AJISAI. In Fig.6, three steps of 50 msec (one AJISAI spin) are illustrated successively.

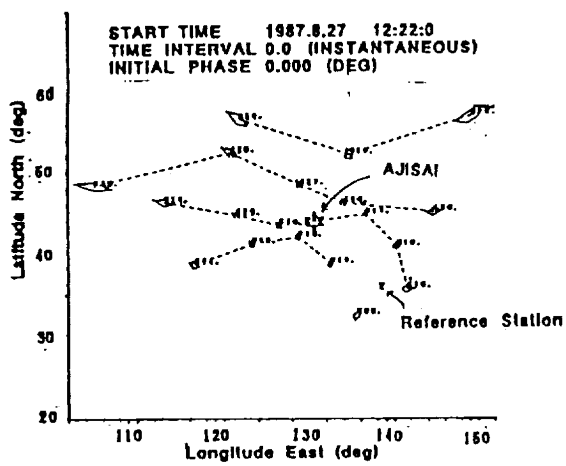

Fig.5 Instantaneous spatial distribution of reflected images on the ground via AJISAI mirror reflector. (The number next to each image indicates the mirror number on AJISAI)

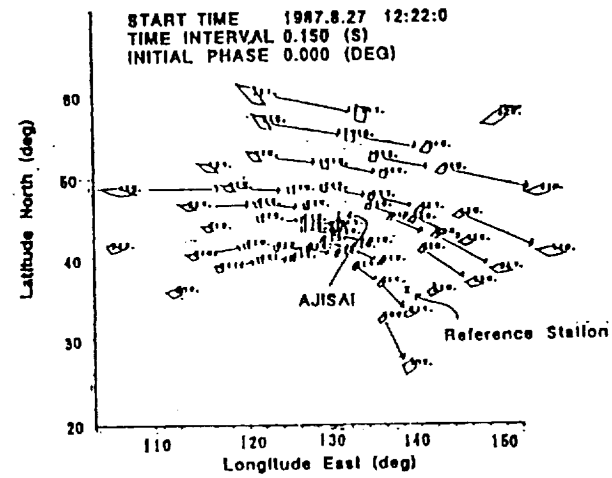

Fig.6 Spatial distribution of reflected images in three 50 msec steps. (The number next to each image indicates the mirror number on AJISAI)

A several percent of East Asia can locate an image, but there is a chance for many stations to get the link every AJISAI pass. If the timing of every shot is as accurate as the prediction, time comparison can be performed on average once every few seconds by simultaneously determining the rotation phase of AJISAI.

2. Application to Japanese Space Program

Table 3 lists the satellite name and its launching schedule in Japanese R&D space program. The schedule is released before the H-II rocket engine explosion which will cause at least one year delay shift from original schedule.

2.1 RIS

Retro-reflector In Space (RIS) is one of missions on ADEOS (Advanced Earth Observing Satellite) satellite which is scheduled for launch in 1996. The orbit is a sun synchronous sub-recurrent polar-orbit with an inclination of 98.6 deg. It has a period of 101 minutes and an altitude of approximately 800 km (Ref.12). RIS is a single element cube-corner

Table 3 R&D Satellite Launching Schedule (1992- 2001), released by NASDA in April 1992

Fiscal year	Satellite name
1992	JERS-1,FMPT
1993	ETS-VI, SFU
1994	IML-2,SFU
1995	ADEOS
1996	COMETS
1997	TRMM, ETS-VII
1998	JEM-1,2, ADEOS-II
1999	JEM-n
2001	HOPE

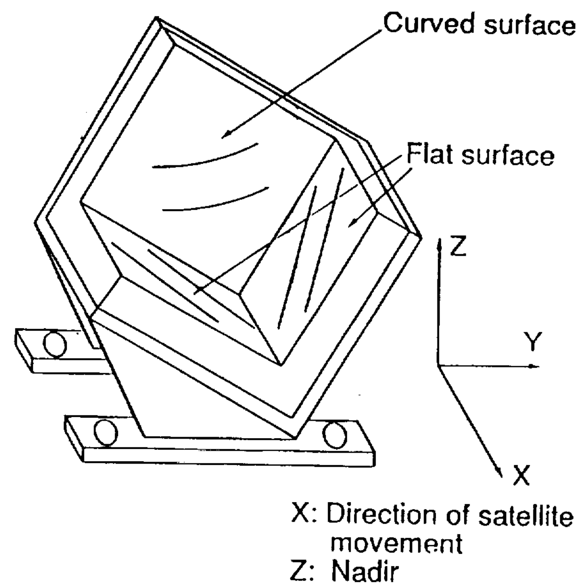

Fig.7 Structure of RIS
(Effective diameter : 50cm)

retro-reflector with a diameter of 0.5 m designed for earth-satellite-earth laser long-path absorption experiments. RIS is proposed by the National Institute for Environmental Studies collaborated with CRL.

In the experiment, laser beam transmitted from a ground station is reflected by RIS and received at the ground station. The absorption of the intervening atmosphere is measured in the round-trip optical path. Figure 7 shows the structure of RIS. We use a slightly curved mirror surface for one of three mirrors forming the retro-reflector, which diverges the reflected beam to overcome the velocity aberration caused by the satellite movement.

We have proposed a simple spectroscopic method which utilizes the Doppler shift of the reflected beam resulting from the satellite movement for measuring the high resolution transmission spectrum of the atmosphere. The wider laser beam is used for illuminating satellite and for autonomous tracking the satellite by guiding camera.

2.2 ETS-VII

NASDA will schedule to launch the Experimental Technology Satellite (ETS-VII) in 1998 whose objectives are development of space robotics and rendezvous control. It consists of two satellites, the chaser and the target, each has GPS receiver for orbit control of chaser. Tentative altitude is 550km and communication to the ground will utilize the data relay satellite.

We have proposed that each satellite should be loaded with corner cube reflector set, one of which is two-color sensitive and be monitored the rendezvous process from the ground. We will track the satellites with switching or simultaneously mode depending on two satellites being within one beam or not.

3. CONCLUSION

We have studied the feasibility of the sub-nanosecond precision laser time synchronization system with a target satellite of AJISAI based on CRL laser ranging system, whose timing system is connected with UTC(CRL).

Simulation study indicates that two stations at thousands of km distance from each other can be linked by laser beam with signal strength of more than 10 photons. The images of laser beam from AJISAI mirrors is uniformly distributed on the ground and two stations have many chances to link each other during a single AJISAI pass. It requires the μsec control of laser fire timing, however, it bring on the precise information of the orbit as well by using the self-returned satellite range data.

The system has been operating in geodetic mode since CRL started the SLR observations to the major geodetic satellites from 1990. While global position of the SLR station has been determined with the precision of several centimeters, we are re-designing our system so that current system has also for time synchronization mode operation as well as adapting for Japanese space program in future.

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