3. Solutions

Further scrutinization finds that the calculation divergence may as well be accounted for by direct use of a default value of parameter ε in our software for the study of satellite precision orbit determination and dynamical geodesy (Huan, 1985). ε is computer-dependent (Lafontaine and Hughes,1983), which can be empirically expressed as follows:

$$\varepsilon = f(\varepsilon_0)$$

where, as a variable, ε_0 is the significant figures available on the computer operating system Micro VAX3800 at Shanghai Astronomical Observatory.

In the default case, ε is chosen to be 10^{-14}. As demonstrated by the calculation, the results are divergent. Tracing into the resultant file given by our software, we find that the RMS for the observational data is nomalous. As a rule of thumb, we commence to doubt whether there is something wrong with some initial evaluations of constant parameters, especially ε.

when ε is set to be 10^{-13}, as shown by calculation, results remain divergent. If let ε be 10^{-12}, then calculation comes to be convergent. Certainly some other ε-dependent parameters have been adjusted during the cases of adopting different values of parameter ε. For the sake of conciseness and no redundancy, we have to omit those detailed references to the choices of ε-dependent parameters here.

4. Comparisons and Conclusion

In order to make a comparison, DTM model is employed to make data reduction from satellite Ajisai. Using both DTM and J77 Models, we have analyzed the data from Ajisai covering the period between Septemper 1st., 1995 and Septemper 20th., 1995. Multistage-multiarc method is taken into consideration (He, Zhu, and Feng, et al., 1989); the sub-subarc,subarc and the whole arc last respectively 5^d ,10^d, and 20^d. The data statistics are shown in figure 1; the adopted force models,reference system and measurement models are listed in table 1. The quantitative and qualitative results are respectively presented in table 2 and figure2.

From the comparison, we can see that after parameter-adjustment, RMS in the case of J77 agrees very well with that in the case of DTM. Therefore J77 is safe to apply in the atmospheric drag realm, especially in the case of the satellite Ajisai.

Table 1.

Force Models	Reference System	Measurement Models
GEM-T3 Earth gravity model	J2000.0 mean equator and mean equinox	Marini-Murray's atmosphere refractivity model
Lunisolar gravity model	IAU76 Precession model	Offset correction for centre of mass
Wahr solid tide model	IAU80 Nutation model	Displacement for stations by solid tide
Schwiderski Ocean tide model (2-6)	DE200/LE200	Displacement for station by ocean load
Solar radiation pressure and that of earth		

Table 2.

Atmospheric Models / Arcs	J77 Model (m)	DTM Model (m)
Sub-sub arc1 *RMS*	0.274377	0.275961
Sub-sub arc2 *RMS*	0.320080	0.318562
Sub arc1 *RMS*	0.292065	0.292395
Sub-sub arc3 *RMS*	0.224982	0.226459
Sub-sub arc4 *RMS*	0.185197	0.187381
Sub arc2 *RMS*	0.201999	0.203859
Total arc *RMS*	0.244969	0.246013
Required CPU Time	$16^h10^m24^s$	$14^h47^m16^s$

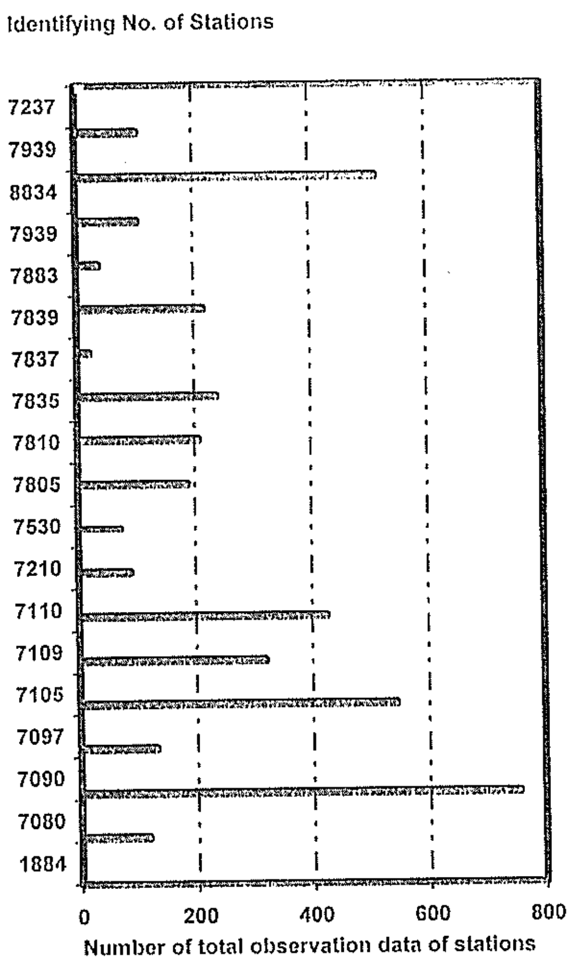

Figure 1.

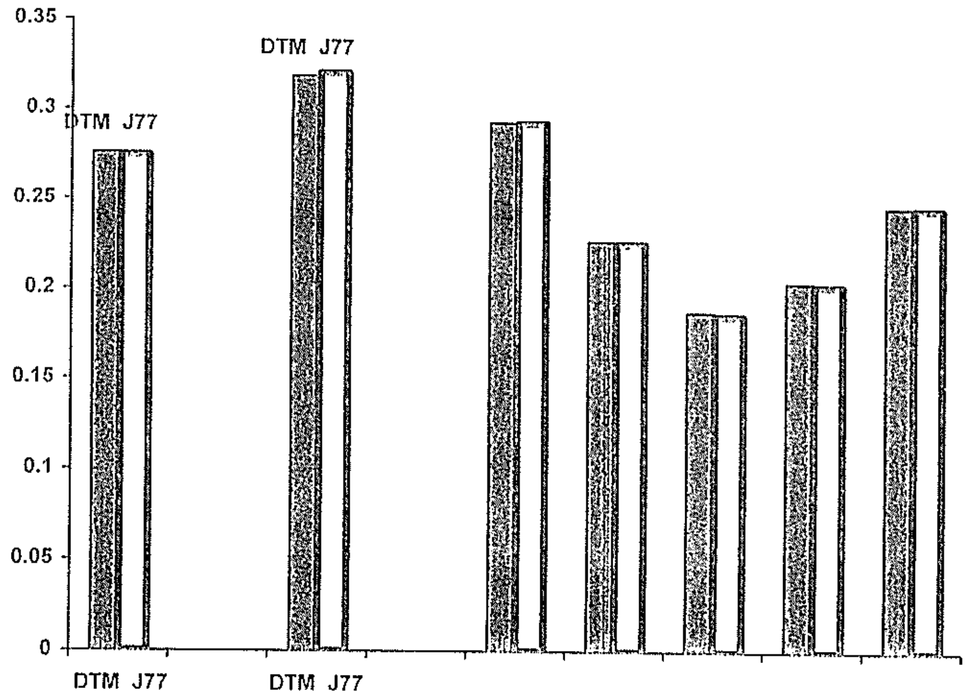

Figure 2.

References:

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Late Coming Papers

Keystone SLR System

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1. Introduction

The Keystone Project (KSP) was initiated in 1993 by Communications Research Laboratory to establish four state-of-art geodetic fiducial sites around metropolitan Tokyo, monitoring site displacement very precisely by means of space geodetic techniques, Very Long Baseline Interferometer (VLBI) and Satellite Laser Ranging (SLR) systems. It aims to have any signs of major earthquakes with millimeter accuracy on baseline and heights of the stations, namely, Kashima, Koganei, Miura and Tateyama. Fig.1 shows a schematic geography of KSP stations and a picture of SLR observatory building at each site.

While VLBI observation started in 1994, the construction of SLR station started in 1995. It has incorporated a wide range of new technologies, including telescope, dome, laser, timing system, calibration system as well as automation and remote control system.

This paper describes concept of Keystone SLR system and some of new technologies utilized in KSP.

2. Design Concept

KSP SLR is designed to operate as not only four sets of SLR, but as a single instrument of all four or more SLR networking with each other. The major concept of KSP is categorized as follows:

- Accurate: Modern SLR has pursued ranging accuracy to 1 cm, mainly parameterized single shot precision. However, uncorrected range bias and its instability is much difficult to control in minimum, as they are reported in global orbit analysis often varying over a few cm. The concept lead into design in the system is (1) to provide picoseconds epoch timer and frequency source to ensure ultimate accuracy available, (2) to provide a redundant means to calibrate a system delay to check each other, by multiple reference targets and independent calibrators. We operate ranging in single color, leaving atmospheric correction on a conventional model, except Kashima station which will have a multiple wavelength ranging capability to asses atmospheric model error.
- High Yield and Automation: Since the Keystone demands the regular monitoring of site displacement with high temporal resolutions and the increasing number of missions/satellite for SLR in various fields, system has capability to continues observation with maximum efficiency and tolerance as long as weather permits. The station itself is designed as autonomous manner. Possibility of down time due to environment such as temperature and precipitation must be

minimized. Networking the multiple stations and control overall system from a center is important features in order to make a flexible expansion of the network.

- Eye-safe: The SLR, especially in urban area demands the operation in accordance of any kind of safety regulation. The typical laser used in SLR has mode-locked high power laser, with a class 3B or more, potentials of dangerous exposure in the beam out of the telescope. Keystone SLR adopted a infra-red aircraft detection laser, as a second laser superimposed in the ranging laser to prevent laser beam from contact to aircraft and local personnel.

3. Subsystem for Keystone SLR

3.1 Telescope and Dome

Figure 2 illustrates the Keystone SLR system including dome building and trailer box housing laser and electronics.

The KSP telescope and dome are designed for dedicated SLR with the mm accuracy and installed in a KSP observation tower. The telescope has a 75 cm primary mirror on Alt-AZ mount. A 15cm secondary mirror is on a spider structure sustained by on a dimension-temperature compensating tube (a schematic diagram in Fig.3). A drive speed specified 12deg/s for both axes. A Coude configuration optics lead a beam down through optical table where transmitting laser is located. Figure 4 is an example of interferometer response for the primary surface with 0.037 wavelength rms. Both the tracking camera on the secondary 20cm diameter telescope on the main and on the Coude path end enable us to automatic acquisition of the target.

The KSP dome is fully sealed and optical interface is a ranging window made of high quality glass. In the observation tower, temperature and Humidity of the room is controlled by air-conditioner to +/- 2 degrees C and 50 %, respectively. Because of no possibility of weather intrusion, it reduces mechanical corrosion in dome, and to be fail-safe under power fail conditions and stabilize temperature, lower humidity and dust proof which are crucial to telescope optics performance in an automatic operation in a long run.

3.2 Laser optics and Electronics

All the optics and electronics except for telescope and dome needed in SLR is set in a temperature controlled trailer box dimensioned by 7.5m x 2.4m x 2.2m. It aims that each trailer box can be exchanged by spare box when repair is needed and multiple boxes can be collocated at an observation tower with common telescope for test and calibration at the same time.

A diode-pumped laser oscillator followed by regen amplifier and main amplifiers is used for stable operation with high performance of laser pulse and energy and for longer mean time between maintenance break. Figure 5 illustrates the optical layout on the table. Laser has multiple operation mode in pulse energy and repetition rate which enable us to scale a variety of targets from low orbit satellite to geosynchronous satellite in the standard receiving condition.

The second laser which produce a 1.5 micron wavelength which has 10^5 greater MPE(Maximum

Permissible Exposure) than visible light. is used to detect aircraft or any other target before the main laser pulse emission. If the first pulse detect target in the beam, second (SLR) laser will interlocked immediately.

Ranging electronics consists of receivers (a single photon avalanche diode and Micro Channel Plate photo multiplier), an picosecond epoch timing unit, a GPS timing receiver. We can use frequency and timing signal from Hydrogen maser used for VLBI by switch.

Any status and operational parameters to affect the system accuracy and automation performance can be monitored and recorded by computer.

3.3 Network and Software

Koganei has a function of control and monitoring of all the Keystone stations using a dedicated 128 kbps communication network.

The central station delivers the schedule and orbit information. Each station observes satellites automatically and send the observation data and instrument status. An operator at Koganei station can override any command to initiate and stop observation by monitoring weather information, alarm status as well as video information from multiple cameras in the station. Fig.6 shows a block scheme of the control and monitoring of Keystone network. Analysis center is also located at Koganei, where all the orbital prediction and determination and baseline analysis are conducted by commercial GEODYNE-II based CRL analyzer working on three Windows NT based high performance PCs. If any one of the station is successful to acquire a satellite, the orbit correction is transferred to the rest of station through the network.

4. Installation and Schedule

The project commenced in October 1995 with contracts for delivery 4 complete SLR stations and one mobile system. They were designed, manufactured and delivered in March 1996, and are starting integration firstly at Kashima and Koganei. After link establishment at the stations, the accuracy validation phase will be started in early 1977. Nominal operation date of four station will be in the middle of 1997.

Fig.1 Map of Tokyo Metropolitan Area and delivered SLR systems.

Fig.2 Keystone SLR view including dome building and trailer box housing laser and electronics.

Fig.3 Schematic view of Keystone telescope with dimensions.

Fig.4 An example of interferometer response for the 75cm primary surface

Fig.5 The optical layout on the Keystone SLR laser and T/R system

Fig.6 The block scheme of the control and monitoring center of Keystone network.

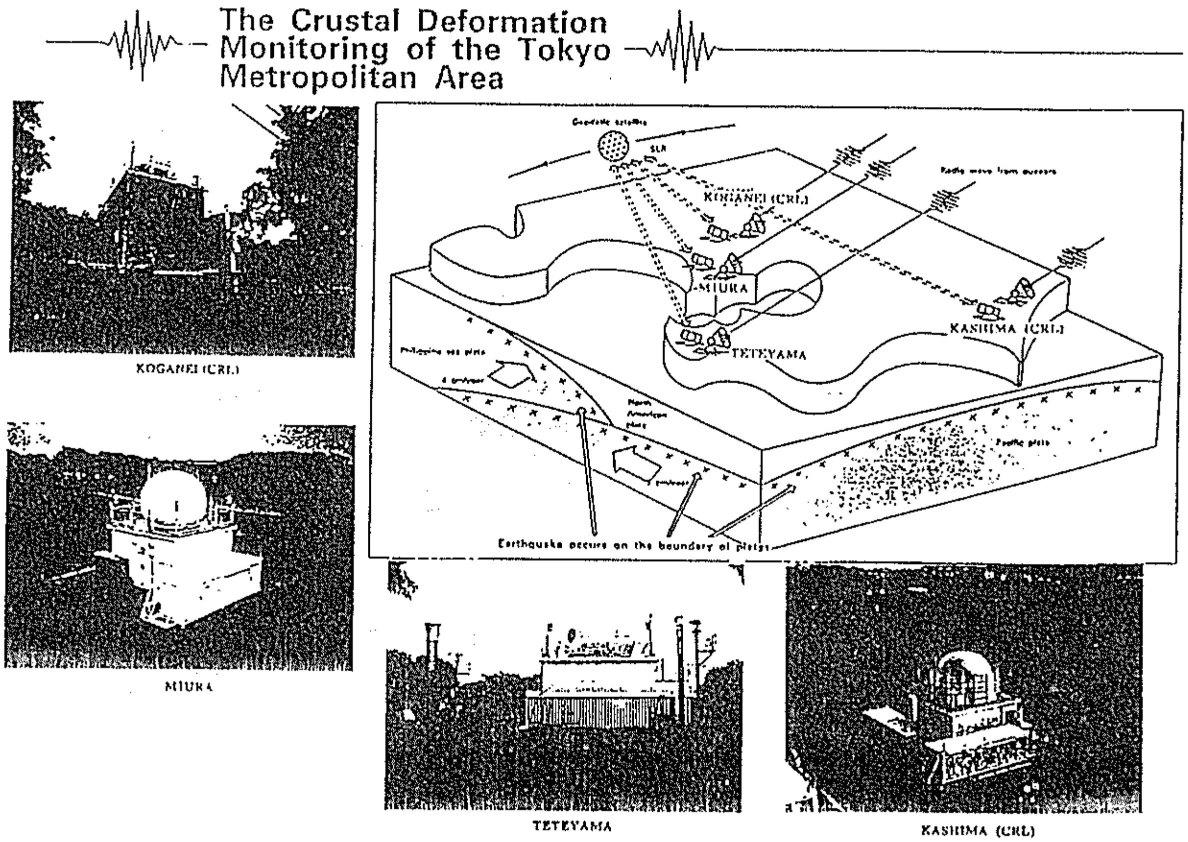

Fig.1
Map of Tokyo Metropolitan Area and delivered SLR systems

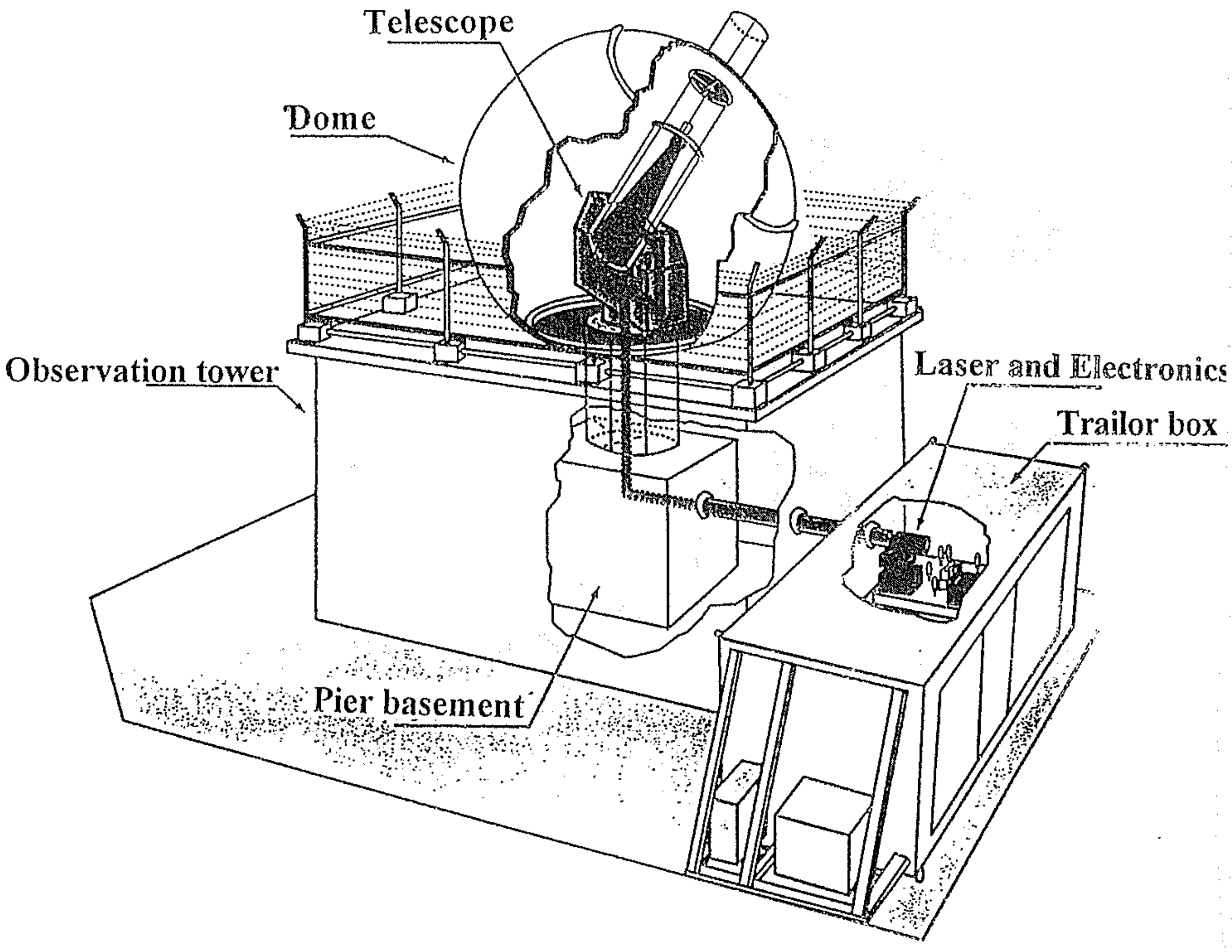

Fig.2
Keystone SLR view including dome building and trailer box housing laser and electronics

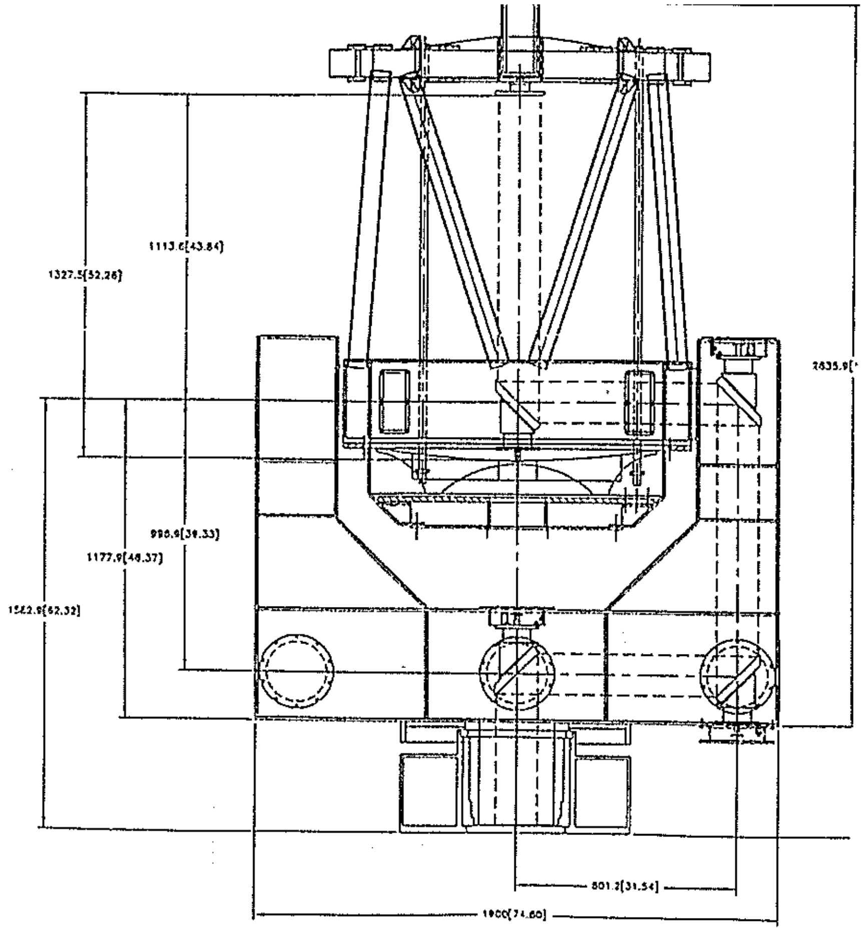

Fig.3
Schematic view of Keystone telescope with dimensions

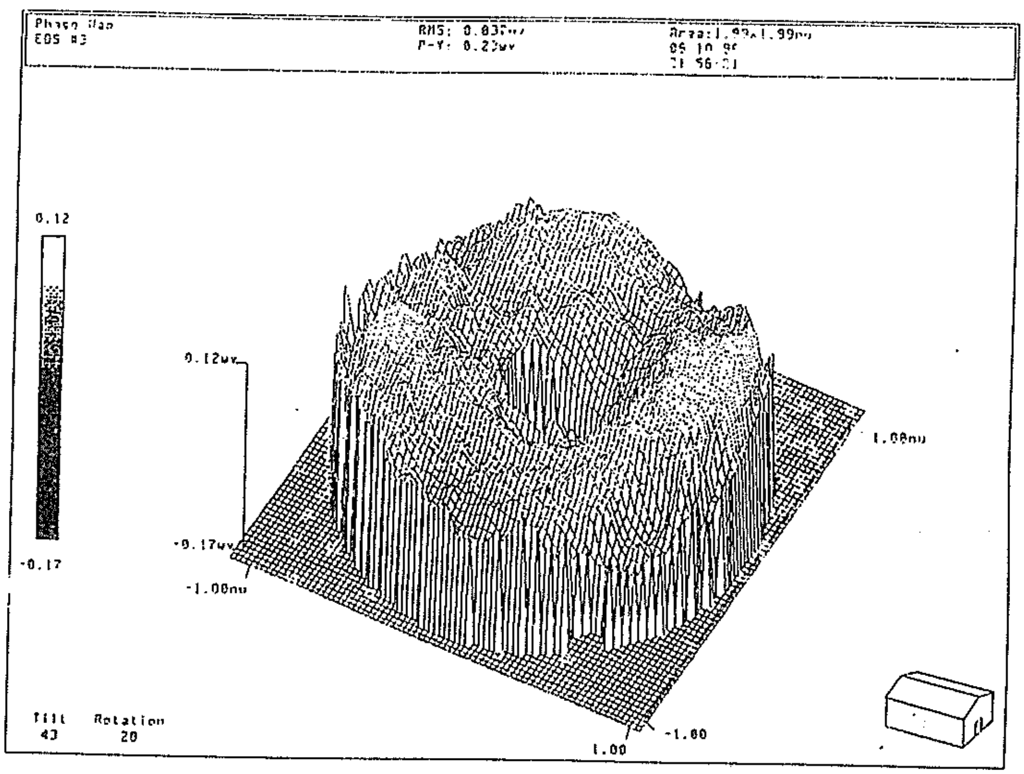

Fig.4
An example of interferometer response for the 75cm primary surface

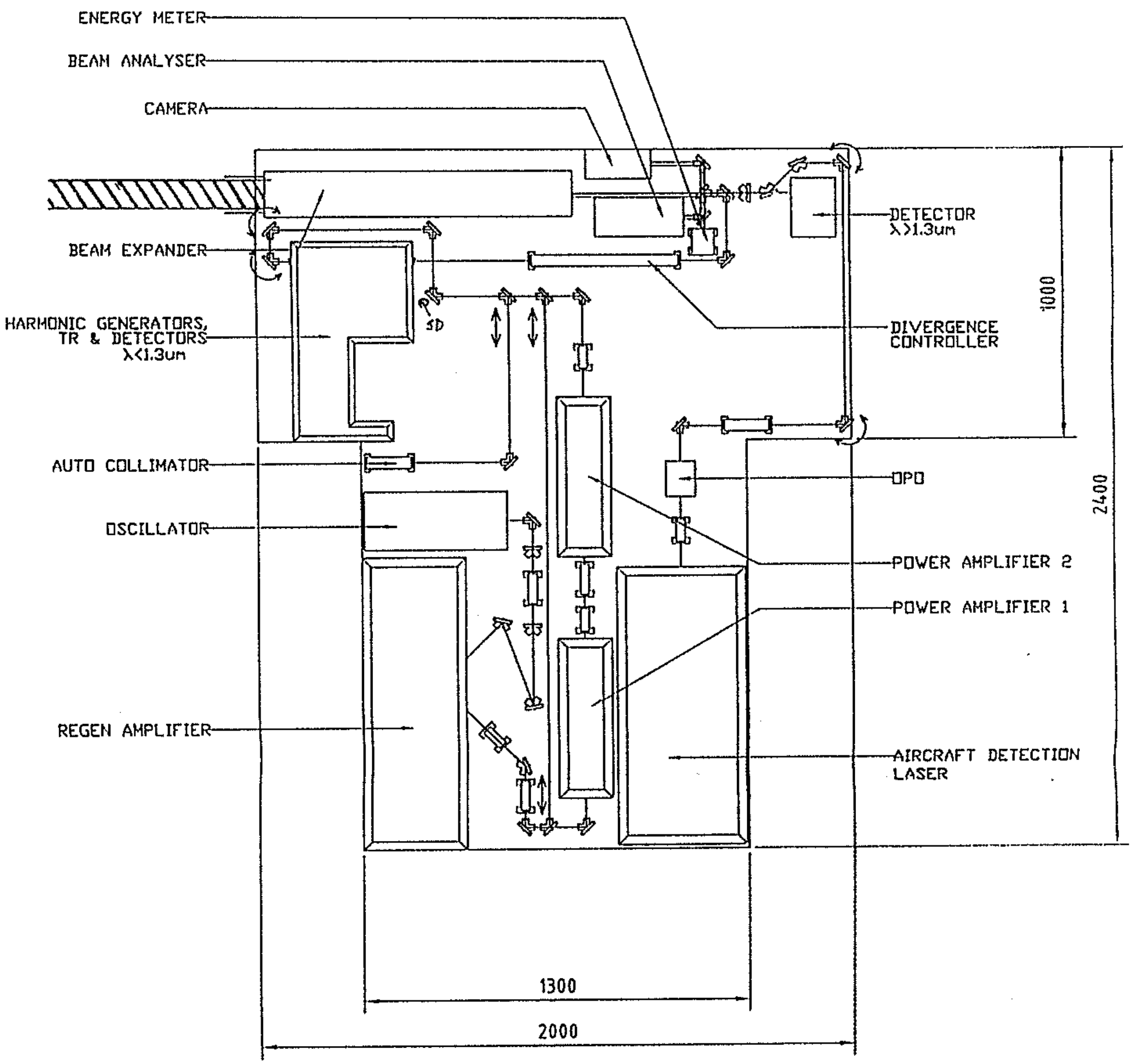

Fig.5
The optical layout on the Keystone SLR laser and T/R system

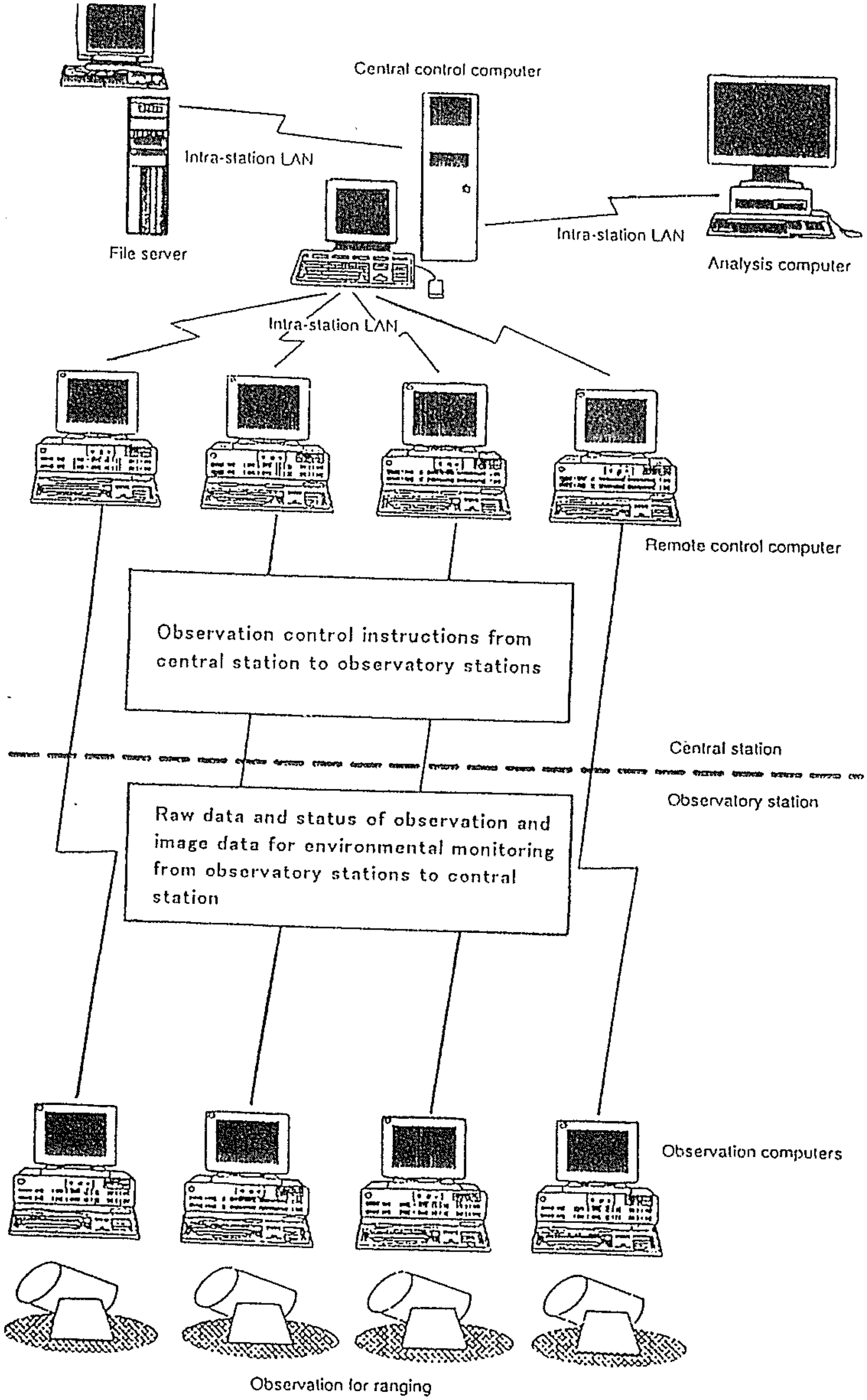

Fig.6
The block scheme of the control and monitoring center of Keystone network

Preliminary Report on ADEOS/RIS Laser Tracking Experiments

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* Poster presented in the session Target design, signature and biases

1. Introduction

Advanced Earth Observing Satellite(ADEOS) was launched in August, 1996. ADEOS is carrying CCR(Corner Cube Reflector) called RIS(Laser Reflector In Space). RIS provided by Environment Agency is a hollow cube-corner retroreflector with an effective diameter of 0.5m [1]. Main mission of the RIS is to measure the absorption spectrum of a small amount ingredient, such as ozone, methane and nitrogen oxide, in the atmosphere.

Because the RIS is a single-element corner cube with a large aperture, there will be no jitters in the reflection, and the reflection from the RIS will be much brighter than that from other targets for satellite laser ranging. In addition, by its clean spectrum response the RIS is an ideal test target for multiple wavelength satellite laser ranging experiments.

With the requirement from future Japanese earth observation satellites, it is necessary to determine the position of the satellite more accurately than the present and the high accuracy trajectory prediction is necessary for the observation operation of RIS, as well.

NASDA is determining the satellite orbit at present based on range and range rate (R&RR) between the ground stations and the satellite obtained by radio wave link where the precision of the measurement of range by S-band radio wave is about 1 m . However, the delay due to temperature drift in transponders or to ionosphere, uncertainly will easily reach tens of meter, respectively. The orbit determination accuracy by R&RR becomes about 1(km) for Geostationary satellites, about 150(m) for satellites in the Low earth orbit. As for orbit determination by SLR or by GPS, higher accuracy will be expected, as in Figure 1.

2. Data communication system

The Communications Research Laboratory (CRL) has developed a data center for the distribution and archiving of SLR data of ADEOS/RIS, and NASDA carries out generation of orbital information as a research phase. NASA's support in prediction of orbit is requested to confirm the accuracy of the prediction by CRL/NASDA. Figure 2 illustrates the data communication system in ADEOS/RIS network.

The Laser ranging data obtained by international SLR stations is once gathered at the CRL through Internet. with checking the quality of those data, CRL transmits them to the Tracking & Control Center, TACC of NASDA via Earth Observation Center, EOC of NASDA. Data handling is operated automatically. TACC generates three types of orbit information, namely TIRV, Time bias and orbit determination result report. Those kinds of orbit information are transmitted to the SLR stations' networks through the course that is the same as the reception course of SLR data.

3. Pre-launch test with AJISAI and ERS2

Since the launch of ADEOS in August, mission check out has been performed for 3 month, and we have been obtaining RIS SLR data since October 30, 1996.

Before the ADEOS/RIS experiments, we performed pre-experiments using other satellites with laser reflector, AJISAI and ERS2. Figure 3 shows 19 SLR stations used for pre-launch analysis. The SLR stations exist mainly in the middle latitudes such as Asia, Europe, and north and south America.

We also show the models used for these analyses in Fig.4 . Basically, we apply the IERS Standards 1992 .

As shown in Fig. 5, when we perform long-arc orbit, we use 3.5 day data arcs, which have 0.5 days overlap. For AJISAI, we performed 10 cases of orbit determination, and for ERS-2, 8 cases. Figure 6 show the difference in orbit position and velocity during overlapped period. The difference in AJISAI is about 3-9(m), whereas in ERS-2, 10-60(m) . This is supposed to be the influence of the air drag, which is not successfully modeled yet and comes out more strongly to ERS-2 with lower altitude.

On the other hand, in the short-arc orbit determination, for each orbit determination, we use 1 pass data that include data obtained by plural SLR stations as shown in lower in Fig.5. The data arc is approximately 5 - 10 minute each. Fig.7 shows the deference between observed value and calculated value, and standard deviation. Total O-C for short-arc determination is an order of magnitude smaller than that of for long-arc determination. The residuals in the cases using fewer stations are smaller, but its standard deviations of determined positions are larger. This is because there is less geometric restriction.

4. Preliminary ADEOS/RIS experiment

We have received 23 passes data since October 30 before November 6.

We performed orbit determination using long-arc data, in the same manner as AJISAI and ERS-2. During the overlapped period, the differences in orbit position are 5 to 15 m, and the differences in velocity are 2 to 11 mm/sec. Figure 8 shows the comparison of our TIRV with NASA TIRV. Discrepancy is about several hundreds meters and millimeters/seconds in position and velocities, respectively. It is good enough accuracy for tracking purpose, however, further analysis is needed since we have not received the detailed information about NASA TIRV yet. We would like to continue this analysis with cooperation of other analysis center.

5. Future Plan

We are going to continue these SLR experiments for the duration of the ADEOS mission period, and to improve the accuracy of orbit determination and prediction by improving force models and measurement models.

As for force models, we are planning to improve space craft shape model that is related to modeling of air drag, to adopt more precise Geopotential model, such as JGM-3, and so on. As for measurement models, we are planning to apply the precise center of mass correction and so on.

We suppose the results of this experiment system will contribute to make a basis of high accuracy trajectory determination system in the future.

References

[1] ADEOS/RIS Tracking Standards, published by RITAG, July, 1996.

RITAG: ADEOS/RIS Tracking Support Coordination Group, National Institute for Environmental Study, Communications Research Laboratory and National space Development Agency of Japan.

CRL LASER RANGING

Fig.1

S/C Orbit determination Accuracy

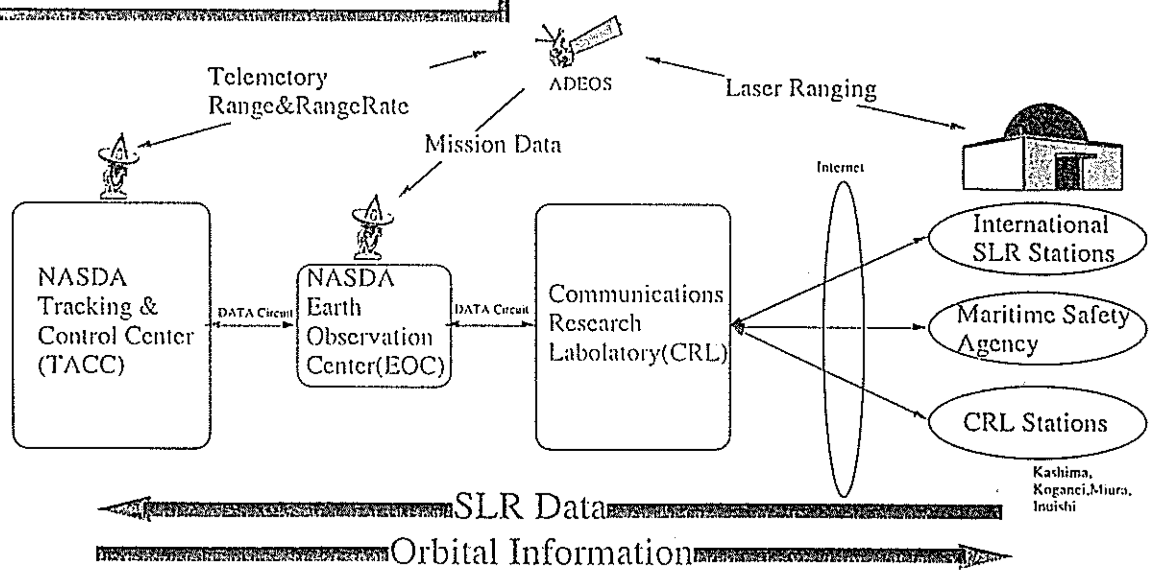
Method	LEO	GEO	Luner Mission
S-band Range & Range Rate	150m	1km	~km
Satellite Laser Ranging	~cm	1m	-
On board GPS	100m	-	-
Differential GPS using code	10 ~1m	-	-
Differential GPS using phase	10~1cm	-	-

NASDA

CRL LASER RANGING

Fig.2

ADEOS/RIS Network



· TIRV
· Orbit determination result report
· time bias function

NASDA

CRL LASER RANGING

Fig.3

Stations

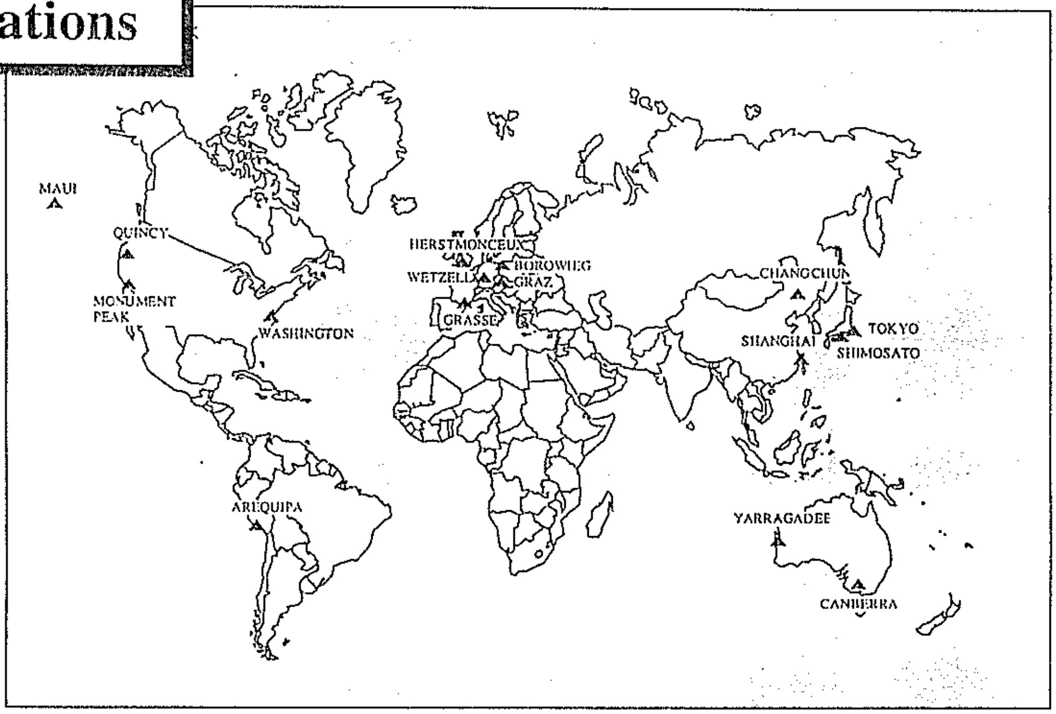


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Fig.4

Software Model

Inertial	Mean equator and equinox of 2000.0
Geopotential Model	GEM-T3 to degree and order 36
Atmospheric density model	Jacchia-Nicolet
Tropospheric refraction	Marini and Murray model

(Mainly According to IERS Standard)

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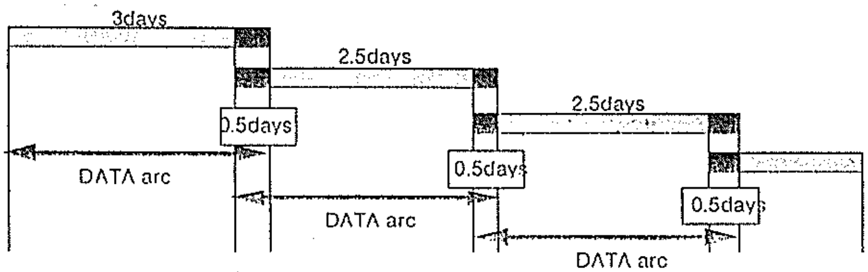
CRL LASER RANGING

Fig.5

Orbit determination using LONG-Arc data



Orbit determination using SHORT-Arc data

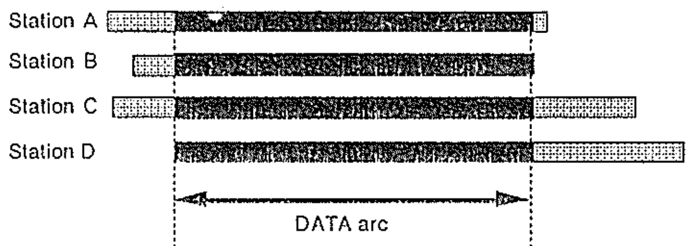


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Fig.6

Orbit determination using LONG-Arc data

AJISAI

Arc No.	Overlap	Stations	Pass	Difference in position(m)			Difference in Velocity(mm/s)		
				X	Y	Z	VX	VY	VZ
1 − 2	96/5/02 0h - 12h	5	6	< 2	< 5	< 3	< 2	< 2	< 3
2 − 3	96/5/05 0h - 12h	2	4	< 1	< 8	< 3	< 6	< 1	< 3
3 − 4	96/5/08 0h - 12h	3	6	< 2	< 3	< 3	< 2	< 2	< 2
4 − 5	96/5/11 0h - 12h	5	7	< 2	< 8	< 3	< 6	< 2	< 3
5 − 6	96/5/14 0h - 12h	4	7	< 2	< 8	< 5	< 6	< 2	< 5
6 − 7	96/5/17 0h - 12h	3	4	< 2	< 9	< 1	< 7	< 2	< 1
7 − 8	96/5/20 0h - 12h	4	5	< 2	< 7	< 2	< 5	< 2	< 2
8 − 9	96/5/23 0h - 12h	7	11	< 2	< 7	< 2	< 5	< 2	< 2
9 − 10	96/5/26 0h - 12h	3	4	< 2	< 7	< 4	< 5	< 2	< 4

ERS-2

Arc No.	Overlap	Stations	Pass	Difference in position(m)			Difference in Velocity(mm/s)		
				X	Y	Z	VX	VY	VZ
1 − 2	96/8/01 0h - 12h	1	1	< 5	< 60	< 5	< 60	< 10	< 10
2 − 3	96/8/04 0h - 12h	5	6	< 5	< 50	< 5	< 50	< 10	< 10
3 − 4	96/8/07 0h - 12h	7	8	< 3	< 10	< 3	< 10	< 3	< 3
4 − 5	96/8/10 0h - 12h	3	3	< 3	< 25	< 3	< 25	< 8	< 3
5 − 6	96/8/13 0h - 12h	2	2	< 5	< 25	< 5	< 25	< 5	< 5
6 − 7	96/8/16 0h - 12h	4	6	< 1	< 15	< 5	< 15	< 1	< 5
7 − 8	96/8/19 0h - 12h	3	3	< 3	< 25	< 3	< 25	< 3	< 3

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CRL LASER RANGING

Fig.7

Orbit determination using SHORT-Arc data

AJISAI

CASE No	Residual in orbit determination (m) 960521-2024 BOROWIEC	960521-2025 GRAZ	960521-2031 WETTZELL	960521-2023 HERSTMONCEUX	Total O-C RMS (m)	Standard Deviation Orbit Position (m)	Orbit Velocity (mm/s)
1	0.1052	0.0039	0.0082	0.0143	0.0610	0.272	0.123
2	0.0307	0.0035		0.0150	0.0210	0.438	0.154
3	0.0525		0.0072	0.0225	0.0370	0.549	0.352
4		0.0040	0.0078	0.0142	0.0090	0.296	0.124
5	0.0912	0.0041	0.0085		0.0600	0.522	0.239
6	0.0146			0.0109	0.0130	1.240	1.130
7		0.0035		0.0145	0.0100	1.320	1.260
8			0.0067	0.0108	0.0090	1.870	1.210
9	0.0299	0.0035			0.0230	0.563	0.477
10	0.0128		0.0064		0.0110	0.636	0.585
11		0.0035	0.0067		0.0050	0.654	0.368
Long-Arc	0.0691	0.1038	0.1588	0.1370			

ERS-2

CASE No	Residual in orbit determination (m) 960521-2024 BOROWIEC	960521-2025 GRAZ	960521-2031 WETTZELL	960521-2023 HERSTMONCEUX	Total O-C RMS (m)	Standard Deviation Orbit Position (m)	Orbit Velocity (mm/s)
1	0.1900	0.0023	0.0215		0.1100	1.860	2.000
2	0.0402	0.0018			0.0270	0.339	0.384
3	0.0429		0.0029		0.0320	0.926	0.738
4		0.0019	0.0035		0.0030	1.500	1.510
Long-Arc	0.3057	0.1729	0.1599				

NASDA

CRL LASER RANGING

Fig.8

ADEOS/RIS Experiments

- Received 23 data ('96.10.30-'96.11.7)

- Orbit determination using Long-Arc data

Overlap	Stations	Pass	Difference in Position (m) X	Y	Z	Difference in Velocity (mm/s) VX	VY	VZ
96-11-02 0h - 12h	1	1	<5	<5	<15	<8	<5	<9

- Comparison with NASA TIRV

Epoch	Difference in Position (m) ΔX	ΔY	ΔZ	ΔR	Difference in Velocity (mm/s) ΔVX	ΔVY	ΔVZ	ΔV
96-11-4 0h	2.180	16.164	-61.211	63.347	63	22	6	68
96-11-7 0h	-135.653	-54.320	-65.509	160.137	59	66	-149	173
96-11-10 0h	-203.195	-158.936	244.547	355.460	-246	-80	-266	371
96-11-13 0h	209.263	39.047	432.479	482.031	-374	-267	200	501
96-11-16 0h	459.677	319.222	-36.910	560.864	100	-56	568	579

NASDA

Synchronous Satellite Laser Ranging for Millimeter Baselines

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H. Kunimori
Communications Research Laboratory, Japan
B. Greene
Electro Optic Systems Pty Limited, Australia

Abstract

We propose a synchronous Satellite Laser Ranging which in principle leaves only the ranging system accuracy as the limiting effect on baseline accuracy. Initial simulations for the Japanese Keystone Project network are provided using by Kalman filter formulated simulator and demonstrated to determine baselines and heights to a few mm per day over 150 km baselines using at least 5 SLR stations operating synchronously and with careful station location.

1 Introduction

SLR has a wide range of applications, including the determination of station coordinates and baselines for geodetic monitoring. SLR baseline now routinely achieve a precision of several centimeters, but a limiting factor is often the uncertainty, or error, in the determination of the orbits of the satellites used. The orbit uncertainty will always be worse than uncertainty of the range measurements to the satellites.

Short arc analysis techniques were designed to reduce the orbit error contamination of the baseline integrity by utilizing the geometry of at least two SLR stations which range quasi-simultaneously to a satellite. However, these techniques, although producing better results than those which ignore geometry, have never completely removed the effect of satellite orbit error from the baseline.

Synchronous ranging uses additional constraints on the measurement geometry to completely remove any effects of orbit error from the baseline, or relative coordinates, solution, if it hits simultaneously the same position. Synchronous ranging in principle this leaves only the ranging system accuracy as the limiting effect on baseline accuracy. Figure 1 shows a concept of synchronous ranging and number of parameters to be solved for in a single arc. Modern systems have a precision and accuracy in absence of atmosphere of better than one millimeter, synchronous ranging can preserve this into a baseline.

Initial simulations for the synchronous ranging applied to the Japanese Keystone Project [1] network are outlined. Keystone SLR system has operating mode which capable to synchronize a laser firing timing at satellite with a precision of 5 ns.

2 Synchronous SLR Simulator

The simulator for synchronous satellite laser ranging (SSLR) system is developed based on Kalman Filter formulation. At each measurement epoch, the position of satellite being observed is assumed to have position errors with standard deviation of 1km. The a priori uncertainty in station position is assumed to 1m. These standard deviations are sufficiently large that they have no impact on the final answers. Measurements are made to this satellite with assumed random noise +/- 1mm for the range measurements. Such measurements are assumed to be made every 30 seconds that a satellite is visible. In the Kalman filter, station positions and the instantaneous satellite position are estimated.

Figure 2 is a map showing the locations of sites used. In addition to the four Keystone sites, three additional simulation sites SI01, SI02 and SI03 as shown in the map. Provided four or more stations make measurement simultaneously, the system of equations can be solved within an arbitrary rotation and translation of the station coordinate frame. The distances between the sites are uniquely determined, but to establish station coordinates we fixed the position of one site, two coordinates of another site and one coordinate of a final site. The first three of the constraints resolve the translation rank deficiency and the latter three constraints remove the rotational rank deficiency. These constraints have not effect on the standard deviation of the baseline length estimates.

In the simulator, we assumed measurements were made to satellites with the same inclination and semi-major axes as Lageos-1, Lageos-2, Starlette, and Ajisai. The longitudes of the nodes of these satellites were set to arbitrary values. The measurement scenario was set such that when more than one satellite was visible, a satellite would be observed for 5 minutes and then another satellite would be observed. All visible satellites are cycled through in this fashion.

All the results should really be scaled by the effective range noise to the satellite. This error budget would include any ranging errors, atmospheric errors, and the definition of the point being measured on the satellite.

3. Results

Figure 3 shows a set of baseline sigma derived from simulator at the end of 24 hours using all seven sites. Baseline length less than 200 km represent combinations of Keystone sites and all have formal errors less than 1mm. However, if we dropped the all external sites SI01, SI02 and SI03, making a network of four sites, the baselines sigma results are around a few tens of milimeters or more, as the geometry of network is so poor. Figure 4 shows an example how the coordinates of site Miura is badly conversing in 24 hours. We tested to put each of external station included in solution and see how the baseline sigmas are improving, and found that if you put one station SI01, at the westward of Tokyo, the baseline sigmas are a converging the best to a few milimeters for Keystone stations.

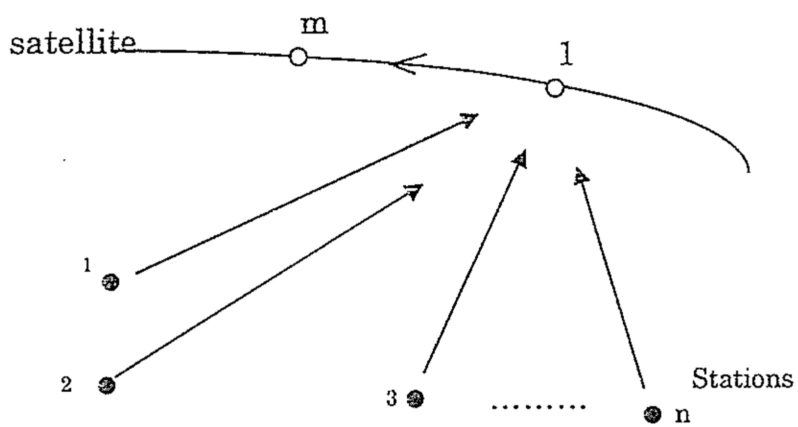
We note it is sacrificing a bit of accuracy of baseline for those of combination to the outlier station. The baseline sigma of all combination and coordinates conversion in Miura of this particular case are shown in Figure 5 and Figure 6, respectively.

4. Conclusions

We simulated the synchronous SLR on Keystone network. Using at least 5 SLR stations including Keystone stations operating synchronously and with careful station location, it is possible to determine baselines and heights to a few mm per day within 150 km baseline length. If more outlying stations are used we determine baselines and heights to 1 mm per day. The network can be extended to longer baselines by adding "outlier" stations which are not resolved to the same precision, indicating that in Keystone SLR network, synchronous SLR will have potentials to determine baselines and heights to 1-3 mm on a daily basis, if a mobile system is deployed as an "outlier".

References

[1] H.Kunimori and et al , Keystone SLR system, Tenth International workshop on Laser Ranging Instrumentation, Shanghai, 1996, in this issue.



n Stations	m Observations
UNKNOWNS	3m + 3n
OBSERVATIONS	mn
Therefore	n > 3 ie n = 4

Minimum number of stations for simple linear equations solve for the unknowns

Fig.1 Concept of Synchronous SLR

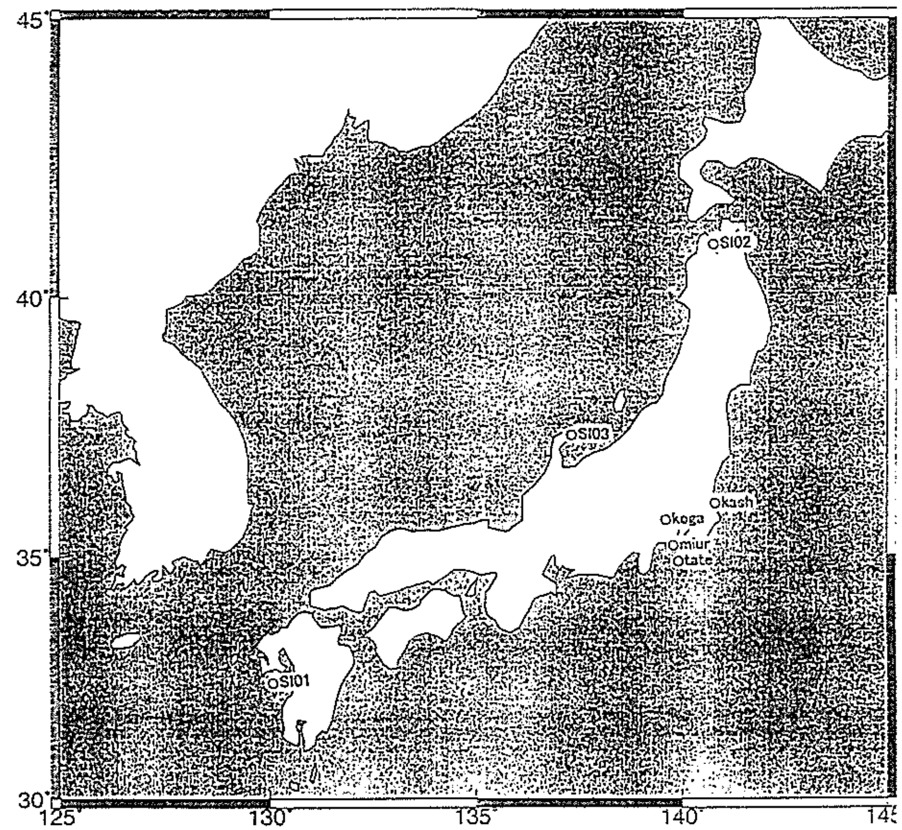


Figure 2 Locations of simulation sites including Keystone network (Koganei, Kashima, Miura and Tateyama)

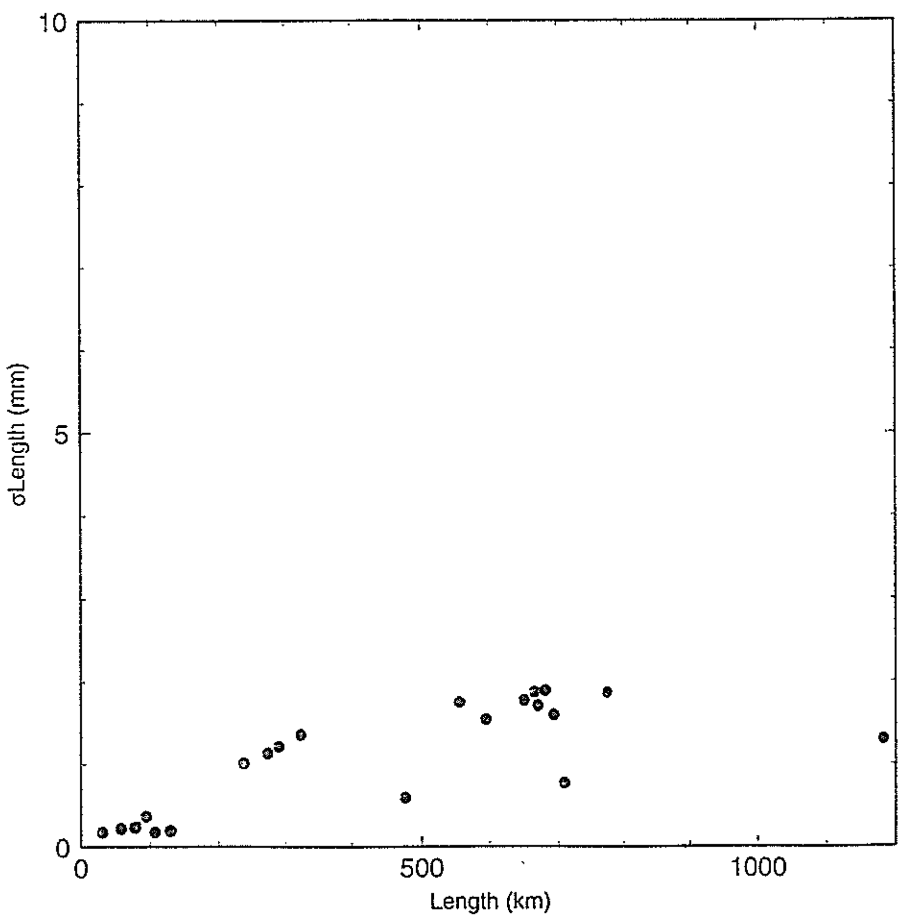


Figure 3 The baseline sigma derived from simulator at the end of 24 hours using all seven sites

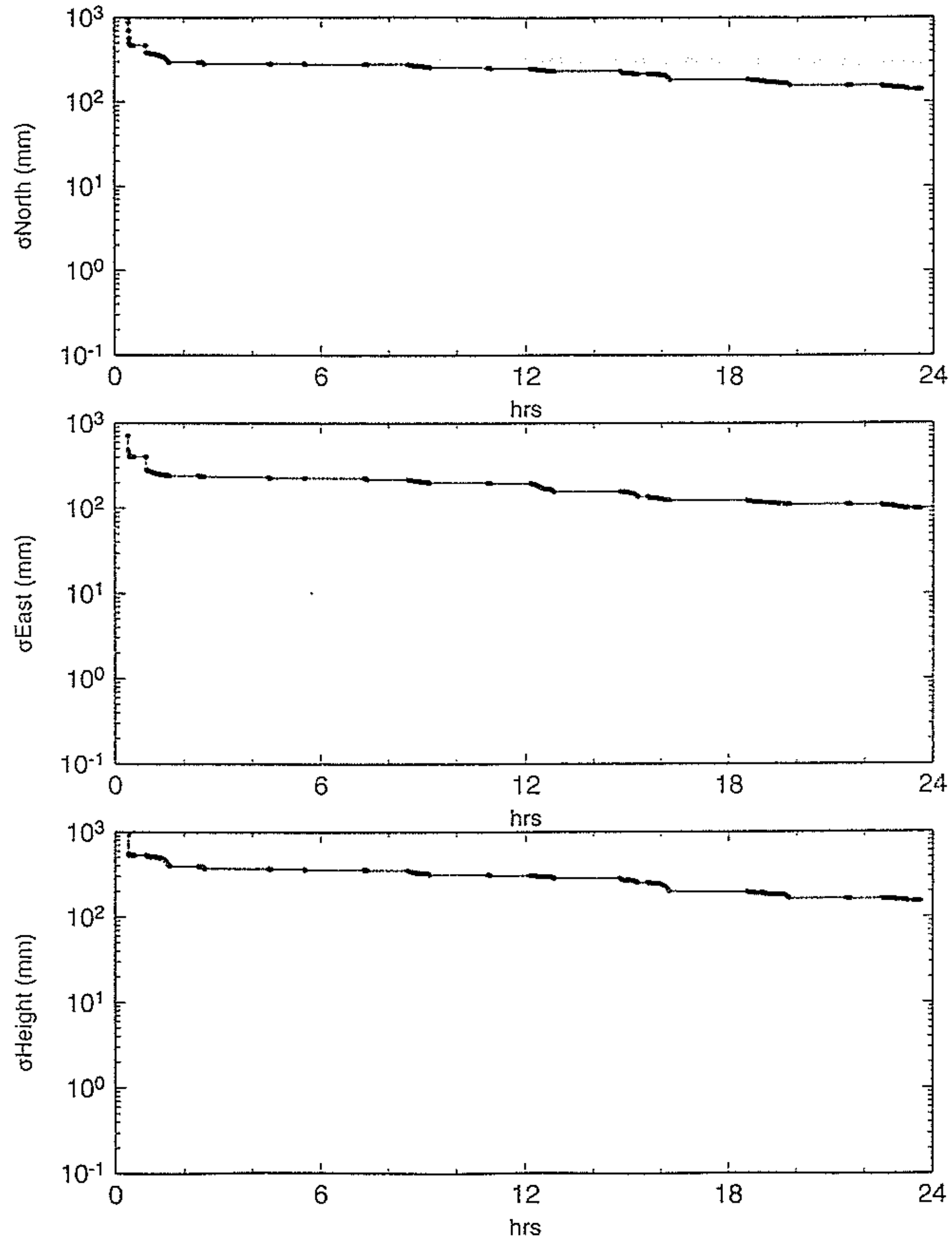


Figure 4 The coordinates (North, East and Height) of Miura conversion within 24 hours by 4 sites simulation

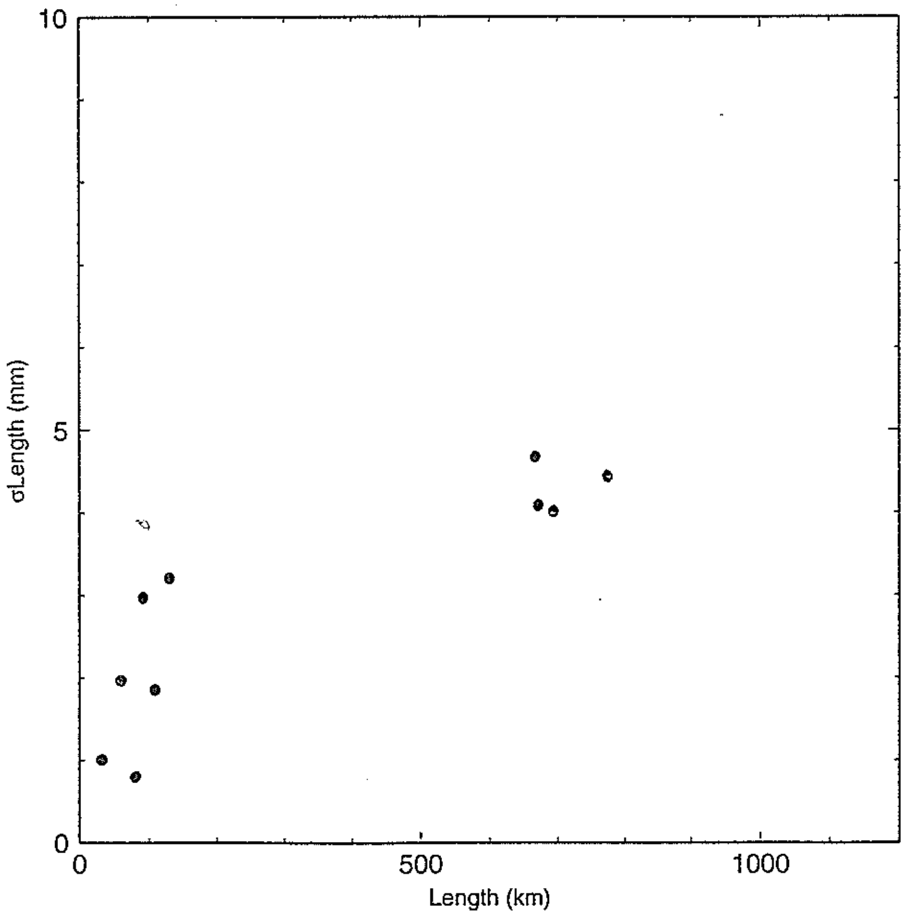


Figure 5 The baseline sigma derived from simulator at the end of 24 hours using Keystone sites plus SI01 site.

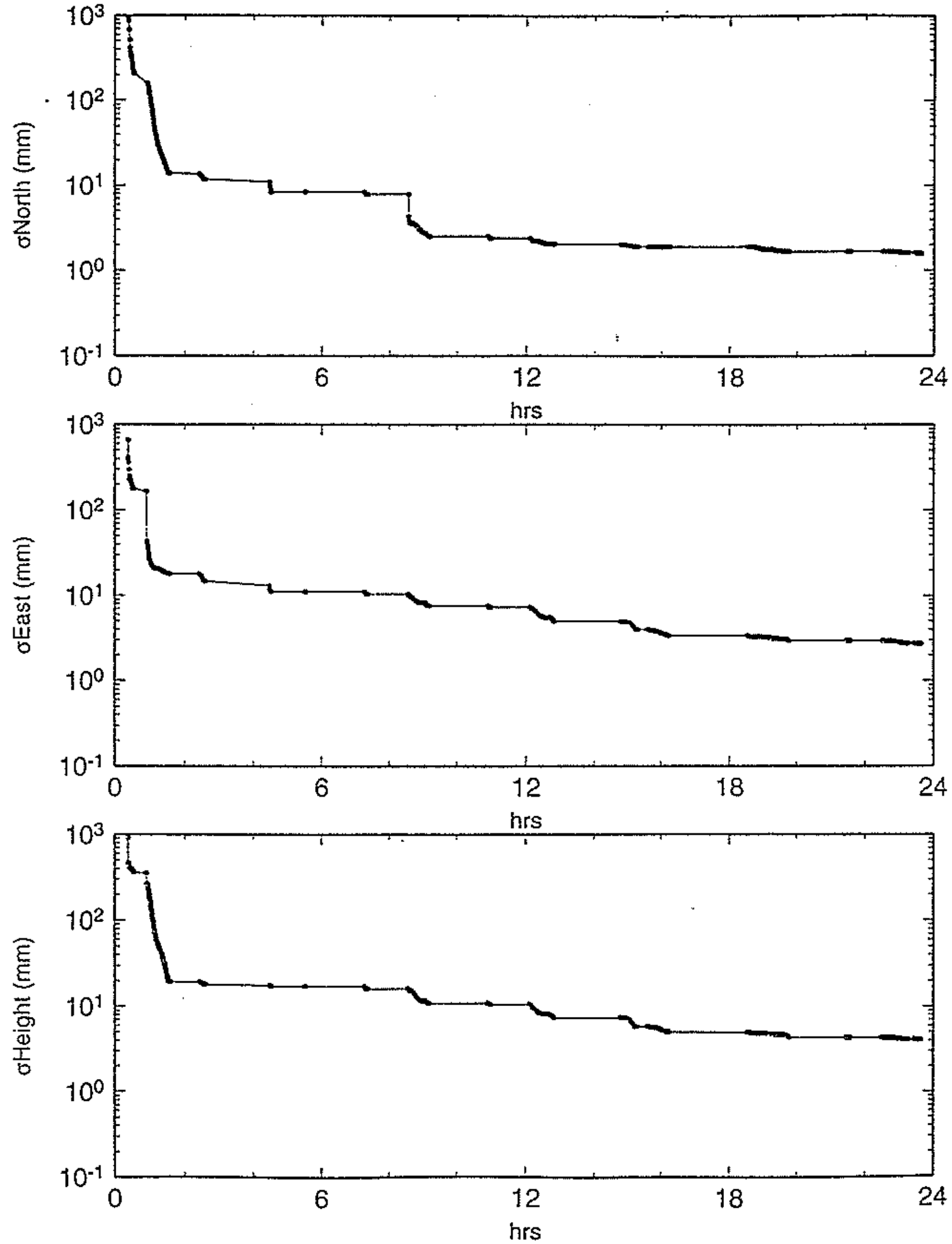


Figure 6 The coordinates (North, East and Height) of Miura conversion within 24 hours by 5 sites (Keystone plus SI01 site) simulation

Session Summaries

and

Resolutions

Science Achievements and Applications

Chairperson: Richard Eanes

Science Achievements

- Temporal variations of the gravity field, geocenter, earth orientation
- Lunar science: relativity, lunar "geophysics", orbital evolution
- Station positioning: horizontal motions, monthly vertical with 10 mm accuracy
- mean gravity field: excellent and improving
- Non-gravitational force modeling

Applications

- Solar system ranging with transponders
- Airborne wide angle ranging for vertical
- Environmental monitoring with LIDAR
- CW Laser ranging
- New target opportunities

Laser Ranging Performance Evaluation

Chairperson: Michael Pearlman

The Session on Laser Ranging Performance Evaluation was organized to give us the opportunity to examine a broad range of issues regarding network performance, including:

How do our customers evaluate our data products? Are we satisfying their needs?
How do the Operations and Analysis Centers evaluate our performance?
Do the Analysis Centers all get the same results?
How do the stations evaluate their own performance?
How can we improve our network effectiveness? How do we know what we have?
What should we expect from the global SLR network and the individual stations within the network?

The session was divided into six sections:

1. Applications, Data Usage, and Requirements (Mike Pearlman),
2. Performance Evaluation by the Data Q/C Operations Centers (Van Husson),
3. Performance Evaluation by the Analysis Centers (Peter Dunn),
4. Performance Evaluation at the Field Stations
5. Baselining Station Performance (Tom Varghese), and
6. Performance Expectation (Mike Pearlman).

The papers that follow in this section address these topics. We have asked the authors to consolidate material where possible.

New Fixed Station

Chairperson: Hiroo Kunimori

NEW STATION since Canberra 1994 Nov.

STARTING OPERATION

• USAF Starfire NRL	(US)

NEW FEATURES and UPGRADE since Canberra

• Changchun (Mount Encoder)	(China)
• Katsively	(Ukraine)
• Borowiec	(Poland)
• Metsahovi	(Finland)

NEW STATION WILL COME OUT and BE STARTING OBSERVATION BEFORE 11-TH WORKSHOP

• Zimmerwald	1997-	(Switzerland)
• Matera MLRO	1997-	(Italy)
• Keystone SLR	1997-	(Japan)

New Mobile Systems

Chairperson: Ulrich Schreiber

6 new stations

- most of them are operational
- very different design

3 dB gain

over the last workshop

Lunar Laser Ranging

Chairperson: Peter Shelus

The lunar laser ranging community has enjoyed a remarkable amount of success during the past several years, both in its ability to increase the quantity and quality of its observations as well as in the amount of science analysis that has been performed. A paper, specifically dealing with LLR-derived science, can be found elsewhere in these Workshop proceedings. A second paper, assessing the adequacy of the quality and quantity of LLR data for the science that needs to be done, can also be found elsewhere in these proceedings. Papers specific to the LLR technique can be found here.

For the past decade or so we have been moving steadily into an era in which there has been a dramatic decrease in the amount of resources being made available to the laser ranging community. At the same time the number of targets that require laser ranging observations has been growing just as dramatically. This is not only true for LLR/SLR, it is also true for the microwave space geodetic techniques, for VLBI, and for GPS. It is clear that we must strive to make the most efficient use of whatever resources exist.

For LLR, the appropriate scientific community has defined several specific data requirements and observing strategies to support a number of actual experiments. Some of these experiments include the generation of Earth orientation parameters as well as support for interplanetary spacecraft navigation, Solar System ephemeris generation, lunar interior studies, relativity, and gravitational physics. The observing requirements for these LLR-based experiments include sequential multi-reflector series of observations during short intervals of time, more extensive observational coverage at the full Moon and new Moon phases, and the generation of routine sub-cm LLR data.

As can be seen in the reports of this LLR session, the routinely operating, LLR-capable stations are the MLRS at the University of Texas's McDonald Observatory near Fort Davis, Texas in the USA and OCA at the Observatoire de le Cote d'Azur near Grasse, France. Both of these stations are obtaining reasonable amounts of LLR data, while they use the appropriate observational strategies that are defined by the analysts. Both stations are pushing hard to obtain sub-cm data and better lunar phase coverage. However, weather, equipment and funding drop-outs can be devastating to a two-station network.

Therefore, there is a demonstrated need for additional laser ranging stations in the world-wide network that are LLR-capable. As we look at the situation around the world we have glimmers of hope for LLR from the MLRO station in Italy, the Wettzell station in Germany, the Orroral station in Australia, the SALRO station in Saudi Arabia, and a possible LLR-capable station in Kunming, China. Are there others?

In summary, we would like to have more laser ranging stations be LLR-capable because, in a situation with severely limited resources, the building and maintaining of a lunar-only network is impossible. It should be noted that a modest 0.75-m aperture system with epoch timing and a reasonable laser (i.e., 10 Hz repetition rate, 100 millijoule/pulse, 200 psec pulse-length) should be sufficient. The sharing of modest observational requirements across a greater number of LLR-capable stations would place very little observing pressure on any one station. The Moon should be viewed as just another laser ranging target for the laser ranging community.

Target Design, Signature and Biases

Chairperson: Andrew Sinclair

BIASES

J.Luck: effect of signal strength on calibration:

-action taken at Orroral.

S.Schillak: contributions to error budget of SLR:

- signal strength effects on data distribution.

SIGNATURE

T.Otsubo: theoretical determination of satellite signature effect for Ajisai

- good agreement with observed.

e.g. RGO Theory: 29 mm (CoM corrn for Mean)

Observed: 22 mm (Mean-Peak)

TARGET DESIGN

R.Neubert: design of Champ retro -low signature

- 2 colour

B.Greene: new design of satellite - low signature

Shargorodsky et al: mathematical model of WPLTN-1 (Fizeau)

2-spot reflection pattern retros.

Kasser et al: polarisation effects of retros.

- Themes are:
  - reducing signature
  - understanding signature
  - improving reflection efficiency

OTHERS:

Tips,

Laser beam propagation in LLR

Detectors and Spectral Filters

Chairperson: Georg Kirchner

MCP / Microchannel Plates

- Improvements on operational MCP's have been reported from Changchun, Hawai, Star Fire Optical Range, concerning:

    - Sensitivity: To get Single Photons from GPS-36 / GPS-36
    - Accuracy.

CFD / Constant Fraction Discriminators

- Improvements have been made also in

    - Sensitivity: To get Single Photons from GPS-36 / GPS-36
    - Accuracy.

- Time Walk Compensation is achieved now by Hardware and Software.

SPAD / Single Photon Avalanche Detector / Silicon:

- Main improvements on Time Walk Compensation:

    - Some ways have been shown how to compensate/eliminate Time Walk;
    - Circuits for TW Compensation are already operational;
    - Circuits are adapted now for different stations;

- SPAD gating techniques are well established now.

SPAD / Germanium:

- Developments driven by Eye-Safe Requirements;
- Already used now for ranging up to ETALONs;
- Single-Photon Sensitivity for $\lambda = 0.35 \ldots 1.54$ has been demonstrated already;
- Is the only detector for SP sensitivity for this wavelength range.

Laser Technology Development

Chairperson: Karel Hamal

STATUS

LASER	WAVE	ENERGY	REP.	FWHM	RANGE	SITE
	nm	mJ	Hz	psec		
TiSAPPHIRE	846	50	10	50	sat.	Bern
(two color)	423	50	10	50	ground	TIGO
YAG/SHG	532	50	100	15-30	sat.	Keystone
YAG/THG	355	10	100	15-30		Japan
YAG/OPG	1547	5	100	15-30		
YAG/SHG	532	.1 - .5	1000	15-30	ground	
YAG/SHG	532	.2	2000	140		NASA
(uLASER)						SLR2000
RAMAN	1540	5	10	80	sat.	Tokyo
eyesafe	532	35	10	160	sat.	CRL
YAG/SHG	532	30	5	50-100	sat.	Shanghai
(semitrain)						

Eyesafe Systems

Chairperson: Ivan Prochazka

- The review of the eyesafe operations of the SLR has been given: operating on the energy levels below the maximum permitted explosure limit ('micro Joule mode'), operating within an eyesafe wavelength window near 1540 nm or surveying the laser propagation direction using an independent radar operating in microwave or eyesafe wavelength region prior to the ranging laser emission.

- The description of the SLR2000 system operating in a micro Joule mode: project status, correlation processing approach and performance simulation has been presented.

- The first routine ranging of a SLR system operating in an eyesafe window 1540 nm in Tokyo, Japan has been described.

Timing Devices and Calibration

Chairperson: John Luck

Six papers were presented. The session finished within two picoseconds of its allotted time.

The main thrust of the Timing Systems section was the drive to break through the 2 picosecond barrier in resolution, stability and accuracy. Important factors reported include:

- tight control, compensation and calibration of temperature fluctuations within the verniers and their surroundings
- selection and tolerancing of components
- achieving very fast rise-time through high bandwidth components
- averaging multiple verniers or counters
- calibration by variable optical path lengths.

Cautions were sounded about anomalies over very short ranges, and instabilities over long ranges, in counters of the SR620 and HP5370 types, and the need for long warmup times. The developmental models include their own computers, and imminent in one model. Absolute biases still exist, although the ranging method cancels them.

The System Calibration section contained a report from Graz on a very short range target achieved by feeding the transmitted pulse back to the receiver as it leaves the telescope. The path lengths can be measured with 0.1 mm accuracy, and meteorological effects including rain are insignificant. Careful attention to attenuating the received signal and detector triggering methods are needed; and skewness in the detected signal has been eliminated. It has not yet been demonstrated that range bias has been eliminated.

A Portable Calibration Standard was described, which calibrates all parts of a ranging system after the discriminators and provides diagnostic information on other sub-systems. It is an almost complete ranging system itself apart from telescope, laser and detector, and includes predictions software, high precision meteorological sensors, and GPS-disciplined oscillator/time reference. It operated by plugging into spare discriminator channels at the host station during ranging and has less than 1 mm range bias and 10 mm single shot resolution. It does not claim to replace co-location completely, but is a compact adjunct.

Multiwavelength Ranging/Streak Cameras

Chairperson: Jean Gaignebet

Even if Multiwavelength ranging is by essence a multiphoton process, this session is at the crossing of two concepts.

Single photon counting (SPC) with SPAD and electronic timers.

Differential flight time accuracy is obtained by averaging a great number of records on each color (very seldom simultaneously) and as SPC means a low ratio of returns (1/100 now) a tremendous amount of shots is needed.
The only field where is may be adequate is for very long passes (LLR).

Multiphoton Record (MPR)

Direct measurement of differential flight times with a streak camera and a great number of photoelectrons (some 10^2). Shot by shot atmospheric index correction around 5 mm (exactness of the range) is possible.

Reduction of the number of photon via :

New SC concepts
Pulse processing (Stretching and compression).

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Many stations, even single wavelength ones, are far from operating on a true SPC mode and are developing smart "Bricolage" to correct for the multiphoton events.

IT MAY BE TIME TO TAKE ADVANTAGE OF THE POTENTIAL INFORMATION OF EACH PHOTON AND LEARN HOW TO EXTRACT IT.

System Automation and Operational Software

Chairperson: Jan Mcgarry

- **PREDICTIONS**
  - GPS: IGS daily orbit (good ~1m) - 4/day IRVs Available from RGO
  - GFZ-1 Drag must be applied to IRV for accuracy

    Need: 2-3 passed/day (N.Am, S.Hem, Asia)

- **OPERATIONAL SOFTWARE**
  - Multi-processor
  - Internet for communication
  - Windows displays - emphasis on user friendly
  - Remote control, automation are goals

- **AUTOMATION**
  - Goals: reduce cost + increase data yield
  - Processing power onsite now capable
  - Single operator goal at many existing stations
  - Full automation + remote control at new systems
  - Keystone: entire network automated
  - CCD's can effectively be used to aid tracking
  - Data corrections done automatically onsite (R/T)

- **DATA QUALITY**
  - Q/C can effectively be done automatically onsite without orbit (CAL RMS, CAL SHIFT, SAT RMS)
  - More (good) SLR tracks of GPS needed (so SLR can Q/C GPS, not vice-versa)

Data Analysis and Models

Chairperson: Vincenza Luceri

The issues presented in this session can be grouped in these major areas:

- efforts towards the estimation of regional baselines, on one hand, by collecting and analysing data of a dense and local network, on the other, by developing new methods to increase the baseline precision

- attention to the problems of tropospheric correction, station biases and residual distribution and their effects on the analysis results

- implementation of algorithms to save computer and time resources and solve technical problems during the orbit determination process

RESOLUTIONS

1. Recognising the increasing prominence of data processing and analysis, and of quality control of their products, in the deliberations of the Workshop, the participants of the Tenth Workshop RECOMMEND that the word "INSTRUMENTATION" in the Workshop title be deleted. The next Workshop title will be 11th INTERNATIONAL WORKSHOP ON LASER RANGING.

2. Recognising the synergy between the Workshops and the SLR/LLR Subcommission of CSTG, the desire by CSTG to encourage such Workshops and meetings among all its Subcommissions, the desirability of having the Workshops recognised as official activities of internationally accredited organisations such as IAG and COSPAR, and potential economies of organisational effort, the participants of the Tenth Workshop RECOMMEND that the International Workshops on Laser Ranging invite the CSTG SLR/LLR Subcommission to recognise the Workshops as an official activity.

3. This Workshop commends Russia on its new mission ZEYA, and encourages it to continue the development and launch of innovative satellite designs, and RECOMMENDS that the CSTG sub-committee seriously consider the tracking of ZEYA.

4. The participants of the Tenth International Workshop on Laser Ranging Instrumentation express our sincere appreciation and warmest thanks to Shanghai Observatory of the Chinese Academy of Sciences for organising and hosting this wonderful workshop, and particularly recognise the hard work of the Local Organising Committee cheerfully led by Yang Fumin.