A-3.2.3 Accuracy anayssis of laser long path absorption measurement using a retroreflector in space (Final report)

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1.Introduction

Accuracy of measurement of the atmospheric trace gases by using the laser long path absorption between the ground and a satellite is affected by many factors, which are included the stability of the laser, the detector noise, the atmospheric turbulence and tracing accuracy. A big hollow cube as called RIS (Retro-reflector In Space) was installed as one of missions of the ADEOS satellite in 1996 by Environment Agency of Japan. The RIS was used to measure the atmospheric trace gases affected to the global environment by means of the long path absorption method between the ADEOS and the ground station.

2. Research Objective

Objectives of the project is to make accuracy analysis of the laser long path absorption measurements of the atmospheric trace species using a retroreflector in space and to develop a way of more precise prediction of the ADEOS satellite by using data obtained by the satellite laser ranging (SLR) network.

3. Research Method

Precise orbital prediction of the satellite and a telescope with a precise mount are necessary to track it accurately. The 1.5m CRL telescope was improved for the RIS experiment to deduce the encoder periodic error, which is the most big factor to track satellite. A way was developed to predict the orbit of the ADEOS by using data obtained by the satellite laser ranging (SLR) network..

Satellite Laser Ranging (SLR) is applied to the orbit determination of the ADEOS satellite which is a earth observing satellite not a geodetic one. It would be able to derive a satellite orbit within an accuracy of a few meters by long-arc precise orbit determination..

Possible error sources of the measurements of the RIS experiment have been considered.. One of the important error sources is due to light signal fluctuation. Two laser pulse pair correlation can deduce light signal flucutuation since DIAL technique is used in the long path absorption measurements. The uncorrelated variations were analyzed by using data of the RIS experiment.

(1) 1.5m telescope system of the Communications Research Laboratory

The 1.5m telescope will be used for the experiments of RIS installed ADEOS and is one of the instruments of the Space Optical Communication Ground Center, which is one of the facilities of the Communications Research Laboratory, Ministry of the Post and Telecommunications. The telescope have been constructed for the research of the optical communication in space. However, it is multi-purpose telescope since it also can be used the satellite laser ranging, astronomy, lidar and so on[1]. Fig1. shows a schematic figure of the telescope system. The telescope mount is a type of Azimuth and Elevation and is installed top of a concrete pier. The coude path of the main telescope is located at center of the pier. There are 4 optical tables with a coude optical port attached to the pier, which a big experimental system can be installed. All experimental instruments of RIS including the visible laser for the active tracing will be installed on the one of the optical tables.

A 20cm guide telescope is installed top of the main telescope tube and is used for initial acquisition of the satellite, since the guide telescope could have wide field of view.

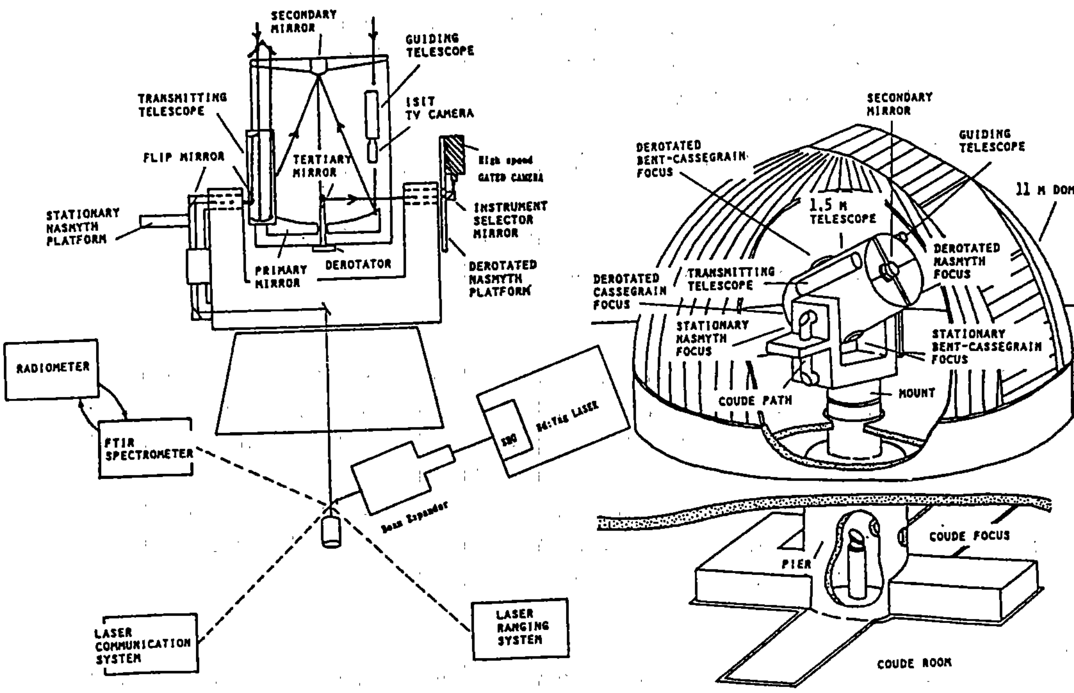

Fig.1 Schematic figure of the telescope system

(2) Development of the precise orbital prediction by using data of the satellite laser ranging (SLR) network.

Satellite Laser Ranging (SLR) is applied to the orbit determination of the remote sensing satellite by demonstrating an improvement of tracking accuracy for ADEOS which was launched into space in August, 1996. RIS (Retro-reflector In Space) is on the ADEOS originally designed to measure absorption spectrum by the atmospheric trace species such as Ozone, Methane, and CO_2 in a reflected beam. Since precise pointing to the satellite by the narrow laser beam and prediction of orbit and tracking stability is critical, we develop a prototype of advanced orbit determination system by SLR technique in cooperation with international Laser tracking network.

ADEOS is in solar synchronous orbit of altitude 800km and RIS onboard has a shape of single hollow cube with effective aperture size of 50 cm. Thinking to a wide range spectrum of the reflectivity of the RIS, two beams, one infrared of 0.1 mrad divergence for laser long path absorption measurement and another visible of wider divergence of 0.4 mrad for tracking purposes are transmitted simultaneously from ground station. 20Hz Q-switched Nd:YAG laser with 200mJ energy per 3ns pulse width is used for tracking beam.CRL 1.5m diameter optical telescope is used for a ground station capable of active optical guiding which recognizes a target as the brightest spot in the field of view illuminated by laser beam. Table 1 lists the specification of telescope for active satellite tracking.

Table 1 Specification of Telescope for Active Satellite Tracking

Main Telescope	Diameter	1.5m
	Mount and Focus	AZ-EL, Coude Focus
	Field of view	30 arcseconds
	Maximum drive speed	5 degrees/sec
	Transmission efficiency	30%
	Transmission/Receive beam	CommonT/R beam
	Trans. beam Divergence(YAG)	0.4mrad
	Trans. beam Divergence(CO2)	0.1mrad
	Coude Camera	CCD with gated image intensifier
Guiding System	Focus	Schmit Cassegrain
	Diameter, Focal Length	20cm, 200cm
	Guide Camera	CCD with gated image intensifier
	Spectrum filter	532nmBandpass filter
	Field of View	0.5 Degree

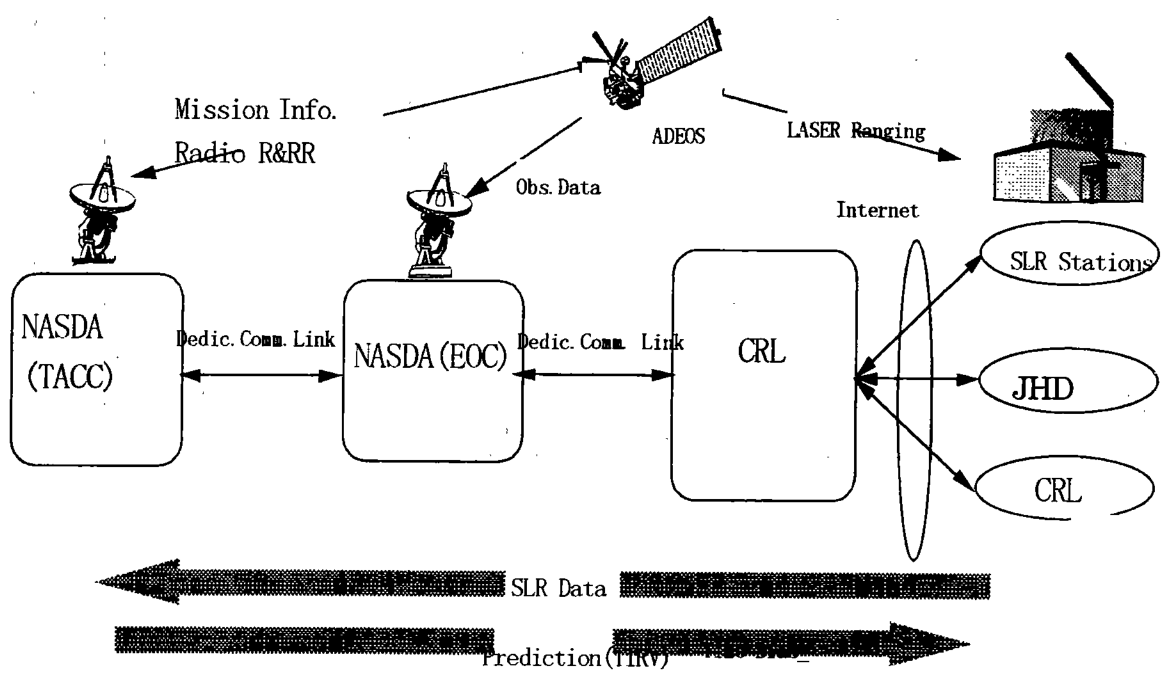

Fig.2 Orbital determination and network system.

Table 2 The statistics of each station acquiring SLR data from ADEOS

No.	STATION ID	STATION NAME	NUMBER OF PASSES	NUMBER OF DATA (NP)	AVERAGE Data in a PASS
1	1864	MAIDANAK	25	192	7.7
2	1868	KOMSOMOLSK	15	61	4.1
3	1870	MENDELEEVO	45	283	6.3
4	1873	SIMEIS	7	37	5.3
5	1893	KATSIVELY	2	9	4.5
6	7080	FORT DAVIS	17	85	5.0
7	7090	YARAGADEE	8	50	6.3
8	7105	WASHINGTON	23	154	6.7
9	7109	QUINCY	4	23	5.8
10	7110	MONUMENT PEAK	47	242	5.1
11	7210	MAUI	13	66	5.1
12	7236	WUHAN	1	4	4.0
13	7237	CHANGCHUN	52	414	8.0
14	7249	BEIJING	38	271	7.1
15	7308	TOKYO	7	68	9.7
16	7403	AREQUIPA	13	53	4.1
17	7404	TLRS-2 (SANTIAGO)	1	6	6.0
18	7548	CAGLIARI	11	55	5.0
19	7805	METSAHOVI	53	393	7.4
20	7810	ZIMMERWALD	1	15	15.0
21	7824	SAN FERNANDO	44	453	10.3
22	7831	HELWAN	1	10	10.0
23	7837	SHANGHAI	5	18	3.6
24	7838	SIMOSATO	48	578	12.0
25	7840	HERSTMONCHEUX	127	580	4.6
26	7843	CANBERRA	84	564	6.7
27	7939	MATERA	30	172	5.7
28	8834	WETTZELL	40	360	9.0
		TOTAL	762	5216	

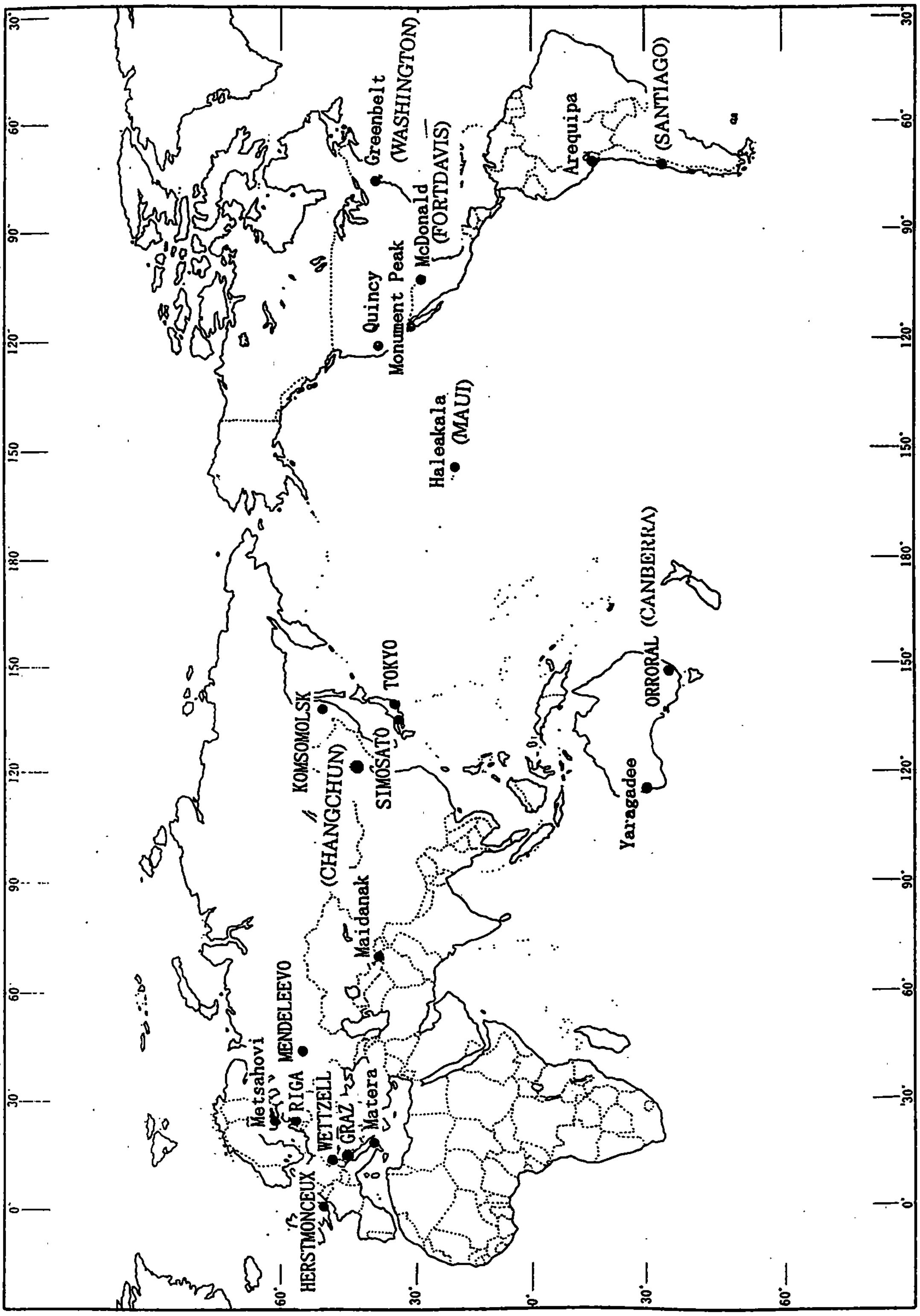

Fig.3 The registerted stations in the RIS experiment.

Fundamental orbit maintenance system is provided by NASDA network via conventional radio range and range rate method. Fig.2 illustrates the orbit determination and network system including global SLR network. CRL in Koganei, Tokyo interfaces the SLR stations in the world through internet. Orbit analyzer is based on one of major orbit trajectory software operated and located at the Tracking and Control Center of NASDA in Tsukuba. CRL and NASDA are linked by dedicated communication line. The prediction file, TIRV and Time bias and SLR data are transmitted/received through the line. TIRV containing estimated orbital elements derived at a certain epoch, and predicted orbital elements derived at every 0 UTC and Time bias defined as a difference expressed in terms of time between latest estimated orbital element and latest estimated orbital element and a latest observation.

Global SLR network has 30 stations in the world participated in the ADEOS/RIS tracking campaign. The registered stations are shown in Fig.3 and data statistics taken in the mission period is listed by station in Table 2.

We determined ADEOS/RIS orbit using 3.5 days data arc with 0.5 days of overlap between data arcs in a routine operation. The force and measurement models mostly according to the IERS standards 1992 are summarized in Table 3. Estimated parameters include an orbital element, solar radiation pressure coefficient, and air drag coefficient. Table 4 shows SLR data arc and estimated parameters associated O-C RMS derived our analysis. Precision of the position with one to two meters is attained. Table 5 shows the difference of each element at the same epoch between successive arcs in along, across and radial component to see the repeatability of the orbit estimation. From a few meters in the best case to some 20 meters in the worst case, are evaluated depending on the number of observation. We have tested orbit prediction accuracy comparing to a reference orbit. The prediction of the orbital element after three days and after one week from the epoch differs by 10 meters and by 50 meters from those of the reference orbit, respectively. However, we could not obtain any SLR data from the ADEOS/RIS during high solar activity period. Therefore, this result refers only to those during low solar activity period.

Table 3 Force and measurement models considered for orbit determination

	Item	Contents
Force Model	Geopotential Model	GEM-T 3
	Tidal Effect	Solid Earth Tide (Ref.1)
	Luni-solar Gravity	DE200
	Solar Radiation	Hoard
	Air Drag	Jachier-Nicolet
Observation Model	Tropospheric correction	Marini and Murray(Ref.2)
	Center of Mass correction	3 axis- attitude
Coordinates	Inertial Frame	J2000.0
	Station position	ITRF94
	Earth Rotation Parameter	IERS Bulletin-A
Estimated parameters	State Vector (6 elements)	
	$\Gamma 1$, $\rho 1$	Solar Radiation Coefficient Air Drag Coefficient

Ref:McCarthy, Dennis.D., "IERS Standards (1992)", IERS Technical Note 13, 1992
Ref. Marini J.W., and Murray C.W., "Correction of Laser Range Tracking Data for Atmospheric Refraction at Elevations Avobe 10 Degrees", NASA GSFC X-591-73-351, 1973

Table 4 Data span for trajectory determination, O-C RMS and estimated parameters

Arc No.	Start (UTC)	End (UTC)	pass	site	data	O-C RMS(m)	$\rho 1$	$\Gamma 1$
1	1997/10/30 0:00	1997/11/2 12:00	9	6	55	1.65	0.33	0.73
2	1997/11/2 0:00	1997/11/5 12:00	9	6	55	1.85	0.31	0.35
3	1997/11/5 0:00	1997/11/8 12:00	9	6	50	1.21	0.48	0.56
4	1997/11/8 0:00	1997/11/11 12:00	8	5	52	0.76	0.38	0.67
5	1997/11/11 0:00	1997/11/14 12:00	9	5	52	2.15	0.75	0.15
6	1997/11/14 0:00	1997/11/17 12:00	6	2	47	0.98	0.59	0.56

Table 5 Accuracy of trajectory determination

Arc No.	overlap span (UTC)				POSITION (m)			VELOCITY (mm/s)		
	start	end	pass	site	radial	along	cross	radial	along	cross
1-2	97/11/02 0H	- 97/11/02 12H	1	1	< 8	< 70	< 10	< 8	< 10	< 60
2-3	97/11/05 0H	- 97/11/05 12H	2	2	< 7	< 20	< 4	< 8	< 5	< 20
3-4	97/11/08 0H	- 97/11/08 12H	2	2	< 8	< 25	< 8	< 8	< 8	< 20
4-5	97/11/11 0H	- 97/11/11 12H	0	0	< 10	< 75	< 8	< 10	< 8	< 75
5-6	97/11/14 0H	- 97/11/14 12H	1	1	< 10	< 30	< 7	< 10	< 7	< 30

Throughout the experiment, we have derived a satellite orbit by laser ranging to ADEOS/RIS within an accuracy of a few meters by long-arc precise orbit determination. In orbit prediction, we demonstrate repeatability of predicted satellite position of 10 meters by three days, and 50 meters by one week after epoch, respectively, which are both far better than the original expectation of the specification attained by radio Range and Range rate observation. Through this experiment, we have also developed a prototype of advanced orbit determination system, including active tracking system, algorithm and data collection/delivery system for the future Earth Observing satellite missions in Japan

(3) Accuracy analysis of the laser long path differential absroption measurement between the ground and satellite.

Two laser pulses are tranmitted to the RIS for the measurement of the laser long path differential absoption within a short time interval, in which the atmosphere is freezed. The time interval ia usally less than 1 msec. One of the wavelength of the two laser pulse is for on -line absorption wavelength and another is for off-line one. Trace gas concentraion is obtained by the following term

$$\ln\left(\frac{x}{y}\right) \qquad (1)$$

in the laser long path differential absroption measurement, where x, y are receiving power normalized by the trenmitting power. Characteristics of the RIS experiment are shown in referrence 2[2],[3]. Error of the eq. (1) is shown as follows. A s(x) shows the standard deviation of the parameter x normalized by the mean x.

$$s(x/y)^2 = s(x)^2 + s(y)^2 - 2\rho\, s(x)\, s(y) \qquad (2)$$

ρ is a correlation coefficient which is a function of the the time interval of the two laser puslses.When the time interval is less than 1 msec, the atmospheric turburence is freezed and the value of ρ is a constant[4]. For the RIS experiment the time interval of the two laser pulsed was 200 μsec. When the atmospheric turburence is freezed, s(x/y) becomes a contant uncorrelated error s(u) determined by the experimental system. The s(u) is shown as

$$s(s/y) = s(u)\sqrt{2} \quad (3)$$

and $$s(u) = s(x)\sqrt{(1-\rho)}. \quad (4)$$

Table 6 and 7 show the error obtained by the RIS experiments and other experiment respectively.

Table 6 errors of the RIS ezperiments

DATE	s(x)	s(y)	ρ	s(u)	s(x/y)
96, Dec.23	0.98	0.96	0.90	0.30	0.40
97, Jan.11	0.77	0.62	0.78	0.33	0.51
97, Mar.05	0.80	0.77	0.97	0.14	0.25
97, Mar.24	0.45	0.49	0.41	0.36	0.57
97, Apr.10	0.61	0.64	0.84	0.25	0.47

Remarks:

96, Dec.23 : Two wavelengthes for ozone measurement and without pinholes for laser mode selection.
97, Jan.11 : Two wavelengthes are same and without pinholes.
97, Mar.05 :Two wavelengthes are same and with pinholes.
97, Mar.24: Two wavelengthes for ozone measurement and with pinholes for laser mode selection.
97, Apr.10:Two wavelengthes for ozone measurement and with pinholes for laser mode selection.

Table 7 error result obtaine by the other CO_2 long path absorption experiment.

Ref.	S(x)	ρ	s(u)	s(x/y)	(targer, platform)
(4)	0.22	0.46	0.16	0.23	(extended diffuse)
	0.79	0.87		0.28	(retro-reflector)
	0.62	0.92		0.18	(small mirror)
(5)			0.046	0.064	(ground test,diffuse)
			0.90	0.13	(ground test, diffuse)
			0.91	0.13	(airbone , ocean)
			0.21	0.30	(airbone , land)

The errors of the RIS experiments were cmparativly bigger than the one shown in table. The reson is considered that the small difference of the beam directions of the two transmitteing laser pulses emphasizes due to the satellite tracking error. As shown in data of Mar. 05,1997, the error is very close to the value of table . When the coinsidence of the beam diraction of the two laser pulses and the tracking are more presise, the laser long path diffrential absorption measurement between the ground and satellite is usefutl to measure the atmospheric trace gases.

4. Results

The way of more precise prediction of the ADEOS satellite by using data obtained by the satellite laser ranging (SLR) network was developed and the RIS tracking experiments have been conducted. In orbit prediction, we demonstrate repeatability of predicted satellite position of 10 meters by three days, and 50 meters by one week after epoch, respectively, which are both far better than the original expectation of the specification attained by radio Range and Range rate observation. trough this experiment. We have also developed a prototype of advanced orbit determination system, including advanced tracking system, algorithm and data collection/delivery system.

The uncorelated variations of the light returned from the RIS experiments were calculated. According to papers described experiments of the pulse pair correlation, uncorelated variations of the light returned from RIS were reasonable. It was showed that the laser long path absorption of the RIS installed the ADEOS satellite is very useful for the measurement of the atmospheric trace gases.

5. Discussion

The RIS was used to measure the atmospheric trace gases affected to the global environment by means of the long path absorption method between the ADEOS and the ground station. According to the error analysis, it is shown that he laser long path diffrential absorption measurement between the ground and satellite is usefutl to measure the atmospheric trace gases.

The precie orbital prediction of the earth observing satellite, like as ADEOS, by using the data obtained by the satellite laser ranging (SLR) network is very useful to more precise satellite traciking.

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