RESULTS OF THE PRECISE ORBIT DETERMINATION EXPERIMENT WITH ADEOS-II

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ABSTRACT

At the last symposium, we reported that the accuracy within a few meters was achieved using linear combination data of carrier phase data and pseudorange data of ADEOS-II (Advanced Earth Observation Satellite II) [1].

Our subsequent analysis revealed that there was an offset of about 4m between the orbit determined by linear combination of carrier phase and pseudorange and the orbit determined by SLR data. We investigated a lot of possible causes and finally found that there was 1ms difference in the internal processing of the GPS receiver (GPSR) between the time tag of pseudorange and of carrier phase. This time difference of 1ms is just equivalent to 7.5m, when it is converted into the position of the satellite, which is 3.7m in our analysis. The problem here is which time tag has a deviation. Since there was no discrepancy, in the result of orbital determination according to the SLR and carrier phase, we determined that the deviation was generated in pseudorange and corrected pseudorange. As a result of correcting, it succeeded in improving the orbit determination accuracy for ADEOS-II within 39.6cm (RMS: Root Mean Square).

1. INTRODUCTION

1.1 Outline of GUTS

JAXA developed and completed a precise orbit determination (OD) system, which uses GPS data and SLR (Satellite Laser Ranging) data, called "GUTS" (Global and high accUracy Trajectory determination System) in March 2004. At present, for the full-scale operation of the system and for the achievement of the high-precise orbit determination technique, we are carrying out experiments in order to evaluate the system performance of GUTS.

The outline of orbit determination technique using the GPS data is as follows:

ADEOS-II's onboard GPSR and a GPS ground station receive signals from the same GPS satellites. In this process, the GPS station data is gathered from not only JAXA station but also data of GPS station in all over the world in the Internet. Based on this GPS data, it is possible to carry out a high accurate orbit determination by using high-precise observation model compliant with the IERS Standard [2, 3] together with the satellite motion model.

For SLR, JAXA SLR station has been just completed in the end in March, 2004. With receiving cooperation of ILRS (International Laser Ranging Service), we carry out the orbit determination with high accuracy by using data of the JAXA/SLR station and data of the overseas SLR station.

The final goal of GUTS is to achieve the same level of orbit determination accuracy as the IGS analysis center, for the GPS satellites and other user satellites. The present goal of GUTS is to achieve an orbit position accuracy of less than 1m (Peak to Peak) and 50 cm (RMS) for user satellites, such as ALOS (Advanced Land Observing Satellite, scheduled for launch in 2005).

Details of GUTS, such as system constitution, method of processing data, and various models employed in the system, were reported by Maeda, et al [1].

1.2 The outline of the ADEOS-II orbit determination experiment

ADEOS-II was developed in order to investigate worldwide climatic variations such as global warming. It was launched in December, 2002. Its operation was terminated by the failure of the power supply in October, 2003. Though the operation period of ADEOS-II was short, sufficient data were obtained to analyze the high-precise orbit determination experiment.

In terms of the orbit determination, the GPSR mounted on ADEOS-II was the type which receives only a single L1 band. Therefore, there is a limit of orbit determination accuracy because the noise of pseudorange goes into the ionosphere correction. Thus, we set a target accuracy of within 10m for the orbit determination experiment. ADEOS-II also had RRA (Retro Reflector Array) for the SLR observation. Because of a short operation period and of laser interference problem with the observation equipment, the SLR data is not sufficient. However, we could use the SLR data effectively for the verification of orbit accuracy calculated from the GPS data.

2. REVIEW OF THE PREVIOUS ORBIT DETERMINATION EXPERIMENT

2.1 Case Definition and Notation

Table 1 is the list of the cases quoted in this paper.

Table 1. Case List

	Data correction	kind of data	weight of data	observation bias
case1	none	L1P	1m	Estimate
case2	PR	L1P	1m	Estimate
case3	none	L1 C1	1m 10m	Estimated None
case4	PR	L1 C1	1m 10m	Estimated None

In the above, L1P=(L1+C1)/2, where L1 and C1 are the carrier phase data and pseudorange data, respectively. In carrier phase and pseudorange, the effects of ionospheric delay are of the same magnitude, but of the opposite sign. In order to remove the effect of the ionospheric delay, we use linearly combined data (case1, 2). We also examined the case in which we consider different weight of data correspond to the measuring precision (case3, 4).

2.2 Orbit determination by SLR and GPS

We carried out an orbit determination using the data for 4 days from June 11th to 14th 2003. Orbit determination arc length was 30 hours, and 6 hours out of 30 hours were used as an overlap period. We calculated a position difference during overlap period. The analytical result is shown in Table 2 and Fig. 1.

Table 2. Summary of the analytical result (unit cm)

Case1	average of difference			dispersion of difference		
	radial	Cross Track	Along Track	Radial	Cross Track	Along Track
	-3.9	-2.3	-17.3	8.9	21.4	34.5
	Root Mean Square					
	Radial	Cross Track	Along Track	RMS		
	9.7	21.5	38.6	45.2		

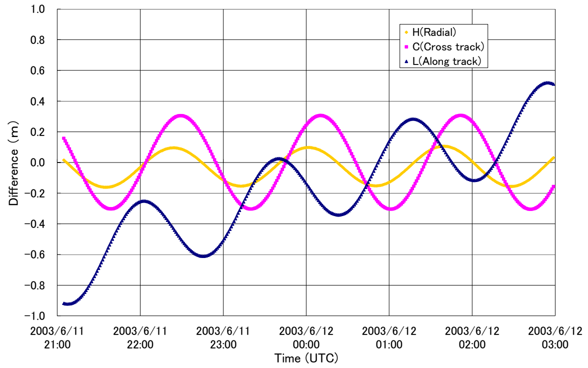

Fig. 1. OD difference by the overlap method for Case 1

Fig. 1 shows each component of the difference of orbital position (the horizontal axis shows the time, and the vertical axis shows the difference). Large error exists for the Along component. The orbit difference is within 1m.

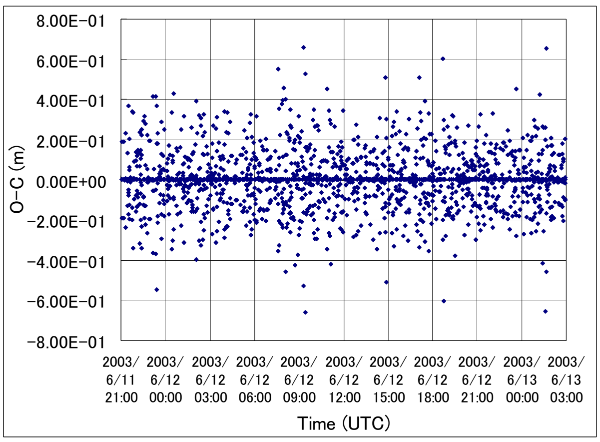

Fig. 2. OD residual by GPSR data for Case 1

In Fig. 2, the horizontal axis shows the time, and the vertical axis shows orbit determination residual. The orbit determination residual is within 1m.

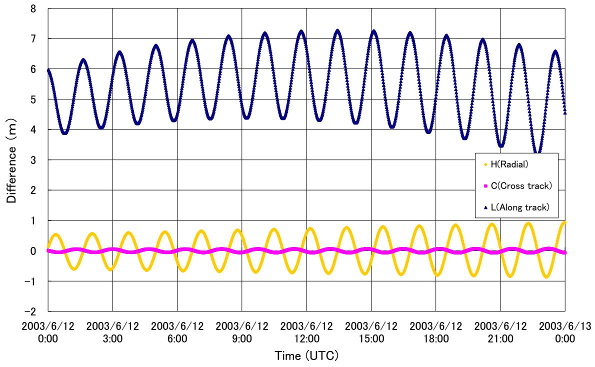

Fig. 3. Difference between OD by GPSR data and OD by SLR data for Case1

Fig. 3 shows the difference between the orbit determined by the GPS data and the orbit determined by SLR data. The accuracy of orbit determination with SLR data is lower, since there are only 5 passes of observational data for 2 days at only one SLR station. However, there is sufficient accuracy in order to compare with the orbit determination by the GPS data. If the orbits determined with GPS data and SLR data is identical, the orbit determination difference should be distributed around 0. However, Fig. 3 shows the bias. Thus we considered the orbit determination accuracy concluded from Fig. 1 as unreliable. As a result from the above analysis, we determined that orbit determination accuracy achieved last year was within a few meters.

In order to remove the ionospheric delay, we carried out the analysis using the data, L1P. In this case, since L1P is a linear combination of carrier phase and pseudorange, it does not specified each error, i.e. carrier phase and pseudorange. Then, we added a weight to carrier phase data and pseudorange data in proportion to the measuring precision (case3). In this case, it is possible to clarify the bias which originates from pseudorange, because observational bias is not estimated (see Table 1).

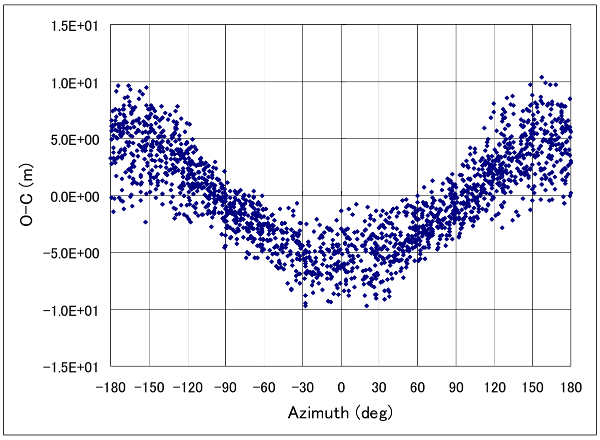

Fig. 4. OD residual of psedorange by GPSR data for Case 3

In Fig. 4, setting the center of mass of the ADEOS-II as the origin, orbit determination residual is plotted as function of azimuth. Degree of Az=0 is the front of moving direction of the satellite. The OD residual distance increases near Az=180. The OD residual distance is shortened near Az=0.

From Figs 3 and 4, it can be seen that the orbital position determined by GPSR of the ADEOS-II is about 4m ahead of the orbit determed using SLR data in along track. This value is far beyond acceptable limits of data error, and it is a strange phenomenon. Therefore, we carried out the investigation of the causes.

3. SPECIFICATION OF THE CAUSE AND CORRESPONDING METHOD

3.1 Specification of the cause

We evaluated many possible causes. Here we omit the details of the analysis. Table 3 shows the summary of the analytical results for major possible causes.

Table 3. Summary of analysis

Possible Cause	Effect (at most)	Note
ionospheric delay	2 m	Evaluated using the SAC-C data
multipath	1 m	Intensity of the reflection is assumed 1/5 times of the that of the direct wave

We describe here an especially meaningful analysis. Fortunately, SAC-C was flying, whose altitude, eccentricity, and orbital plane are almost equal to ADEOS-II, see Table 4.

Table 4. Satellite orbit element

	SAC-C	ADEOS-II
A (km)	7072.55	7182.84
e	0.002	0.001
I (deg)	98.18	98.70

SAC-C has a 2 band GPSR, and its observation data has been opened on the Internet to public. ADEOS-II and SAC-C fly almost the same orbital place at a rate of once per 50 orbits. Therefore, by analyzing the SAC-C data of a suitable pass, we can estimate the effect of ionospheric delay of ADEOS-II. To estimate ionospheric delay of SAC-C, Code-Carrier technique [4, 5] is used. The ionospheric delay quantity is, at most, 2m at the SAC-C orbit (Fig. 5). Because ADEOS-II's orbit is 100km higher than SAC-C, we can assume that the ionospheric delay of ADEOS-II is 2m or less. Thus, we could determine that the offset of 4m was not caused by the ionospheric delay, because the offset is larger than the ionospheric delay.

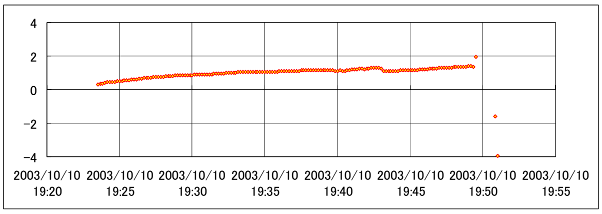

Fig. 5. Ionosphere delay on SAC-C

As a conclusion, though we considered much possibility, we could not find the cause of the offset of ADEOS-II. Then, we also considered the internal processing of GPSR.

3.2 Characteristic of GPSR

There was a linear correlation between range rate (RR) and pseudorange, and a time difference of about 1.14ms occurred between pseudorange and carrier phase (Fig. 6). In short, though pseudorange and carrier phase were received in GPSR simultaneously, different time tags were attached to them.

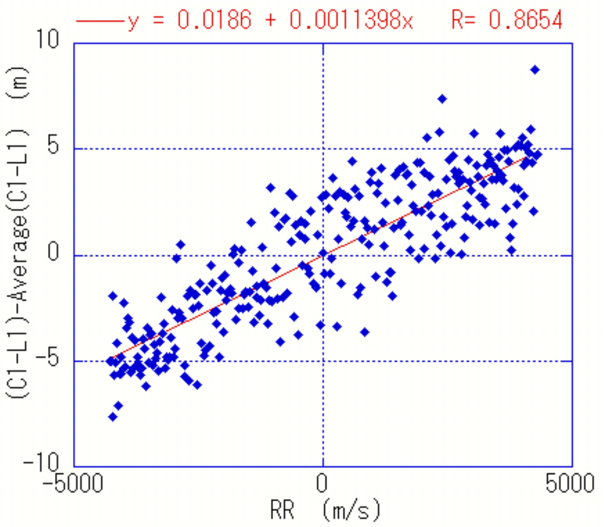

Fig. 6. Position Error and Range Rate.

In Fig. 6, the horizontal axis shows range rate, and the vertical axis shows the difference from the average amount of delay, which is the difference between carrier phase and pseudorange.

Here, we describe the internal structure of GPSR. The structure of GPSR consists of three functional parts: antenna part, tracking part and operation part (Fig. 7). At tracking part, GPS satellites signals are decoded by repeatedly calculating correlation between the receiving wave and code pattern of the GPS satellite, and code demodulation and message demodulation are carried out. The data processing part calculates carrier wave phase, pseudorange based on the data from the tracking part, and attaches a time tag and outputs the data.

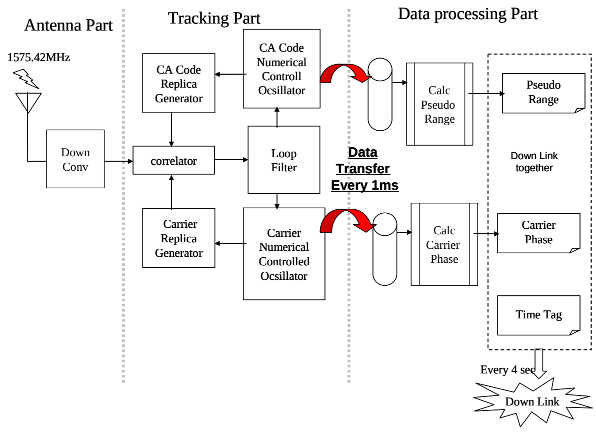

Fig. 7. Processing diagram of GPSR

Inside of the GPSR of ADEOS-II, the system clock of data processing part is 1kHz. The data received from the GPS satellite is transferred from the tracking part to the data processing part every 1ms. In this process, carrier phase and pseudorange were supposed to have the same time tag, but had a time error of 1ms between them, and delivered to the tracking part. The lag of 1.14ms which found in our analysis corresponds to this lag of 1ms.

ADEOS-II moves 7.45m in 1ms, because its speed is 7.45 (km/s). When we estimated the orbit by using L1P data, the offset is calculated to be about 3.7m, which is half of 7.45m. This result can explain why the offset occurred.

3.3 Comparison with SLR

By just analyzing the internal structure and GPSR data of GPSR, we could not determine which time tag of carrier phase or pseudorange was wrong. Thus we compared the GPSR data with the SLR data, and concluded that the time tag of pseudorange deviated by 1ms.

4. RE-ANALYSIS

In order to satisfy the simultaneous observation with carrier phase, we corrected the pseudorange data, i.e., we set back the time tag of the pseudorange data of ADEOS-II by 1ms. Then we re-analyzed the orbit determination experiment of ADEOS-II and obtained the following result.

As shown in Table 1, Case 2 is a reanalysis of Case 1 using a corrected pseudorange data. Also, Case 4 is a modified version of Case 3.

The re-analytical result is shown in Table 5 and Fig. 8. Comparing Table 5 with Table 2, it is possible to read the effect of the correction for pseudorange. Fig. 8 shows orbit comparison result for corrected data (case 2) by the overlap method. This Fig. 8 should be compared with Fig. 1.

Table 5. Summary of the re-analytical result (unit cm)

	average of difference			dispersion of difference		
	radial	Cross Track	Along Track	Radial	Cross Track	Along Track
Case2	-2.9	-2.6	-15.2	8.2	20.2	29.2
Case3	1.1	-3.5	-22.9	7.1	27.4	16.3

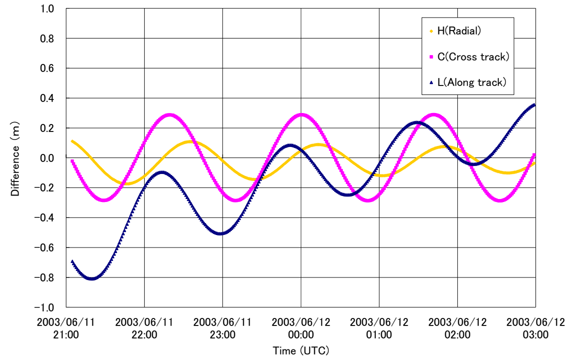

Fig. 8. OD difference by the overlap method for Case2

From Table 5 and Fig. 8, there is self-consistency in the analysis by the overlap method. We obtained an orbit determination accuracy of about 80cm. There is not a large improvement effect in accuracy, when compared with Fig. 1. Because, even if there is an offset in the whole data, the overlap method can not find the offset. Then, we compared the difference between case1 and case2.

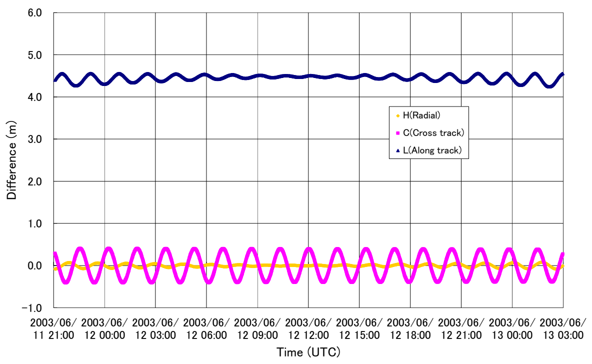

Fig. 9. Difference of Case1 and Case2 by the overlap method

In Fig. 9, the horizontal axis is the time and vertical axis is the difference in the orbit determination. Table 6 shows the summary of defference of each case. From Fig.9 and Table 6, the offset of about 4.5m exists in the along direction. This difference is from the error of 1ms of the time tag inside the GPSR. In the analysis of case2, this offset was removed.

Table 6. Summary of difference of each case (unit cm)

	average of difference			dispersion of difference		
	Radial	Cross Track	Along Track	Radial	Cross Track	Along Track
Case1-Case2	-0.1	-0.5	445.5	3.3	28.0	7.1
Case3-Case2	-0.1	-0.1	23.2	7.6	6.5	35.3

Fig. 10 shows the orbit determination residual.

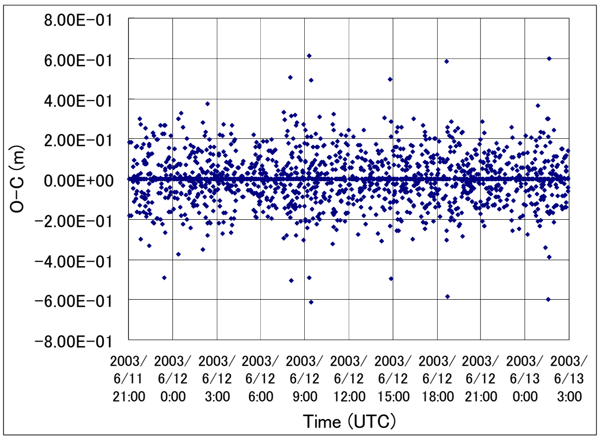

Fig. 10. OD residual by GPSR data for Case 2

Comparing Fig. 10 with Fig. 2, there is not a large change in the observation residual, because the offset of about 4m seen in Fig. 2 is absorbed for the orbit estimation

We plotted the pseudorange residual of the orbital determination by GPS, as in Fig. 4, and obtained the result in Fig. 11.

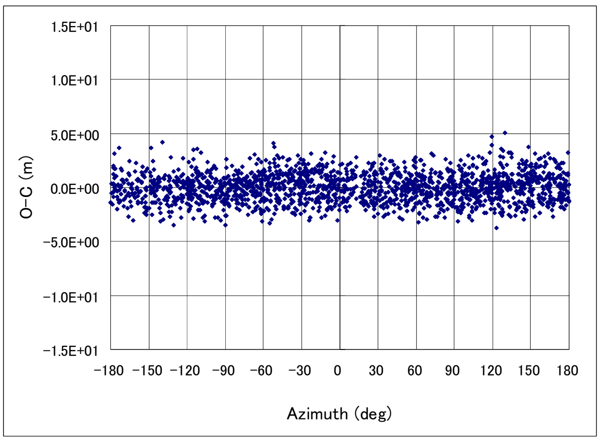

Fig. 11. OD residual of peudorange by GPSR data for Case 4

The offset of orbit determination residual in the satellite running direction is completely removed.

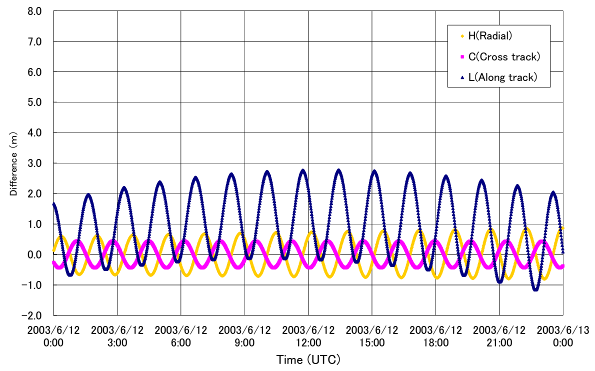

Fig. 12. Difference between OD by GPSR data and OD by SLR data for Case2

Comparing Fig. 12 with Fig. 3, it is possible to read the effect of the correction for pseudorange. Fig. 12 shows that there is not much discrepancy between orbit determination by the GPS and orbit determination by SLR. However, there is still a large error in the along direction. This can be interpreted as an increase of the error by the orbit propagation, since there are not much observation data of SLR.

From the above, we obtained the final accuracy of the ADEOS-II high-precise orbit determination, as shown in Table 7.

Table 7. Summary of final OD accuracy (unit cm)

Case 2	Root Mean Square			
	radial	Cross track	Along track	RMS
	8.7	20.3	32.9	39.6

The orbit determination accuracy was improved from a few meters (last year) to 39.6cm (case2).

5. CONCLUSION

We confirmed that it is possible to achieve the accuracy of about 39.6cm (RMS), using the data of GPSR with only L1 band. The accuracy was improved further than the case which Maeda et al. [1] reported last year.

By comparing carrier phase with pseudorange, it becomes possible to find problems and solutions. In short, it is the significant to carry out the SLR observation and GPS observation simultaneously.

We utilize this experience in the next analysis for ALOS. We have already confirmed that the error of time tag discovered this time does not exist on the GPSR mounted in ALOS.

References

1. Maeda M., et al. NASDA Precise Orbit Determination Experiment of ADEOS-II, 17th International Symposium on Space Flight Dynamics Proceedings Vol2, pp.174-186, Moscow, Russia, 2003

2. Dennis D. M. and Gerard P, IERS Technical Note32, IERS Conventions (1996)

3. Dennis D. M., IERS Technical Note21, IERS Conventions (2003)

4. Hofmann-Wellenhof, B., H. Lichtenegger, and J. Collins, Global Positioning System Theory and Practice, Fourth, revice edition, 1997.

5. Braasch M S, Multipath Effects. In Chapter 14 of Global Positioning System: Theory and Applications, Vol.1, edited by B.Parkinson, J.Spilker Jr., P.Axelred and P.Enge, American Institute of Aeronautics and Astronautics, Washington, D.C. 1996