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Precise orbit determination for Jason-1 satellite using on-board GPS data with cm-level accuracy

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The joint US/French Jason-1 satellite altimeter mission, launched from the Vandenberg Air Force Base on December 7, 2001, continues the time series of centimeter-level ocean topography observations as the follow-on to the highly successful T/P radar altimeter satellite. Orbit error especially the radial orbit error is a major component in the overall budget of all altimeter satellite missions, in order to continue the T/P standard of observations. Jason-1 has a radial orbit error budget requirement of 2.5 cm. In this work, two cycles (December 19, 2002 to January 7, 2003) of the Jason-1 on-board GPS data were processed using the zero-difference (ZD) dynamic precise orbit determination (POD) technique. The resulting Jason-1 orbit accuracy was assessed by comparison with the precise orbit ephemeris (POE) produced by JPL, orbit overlaps and SLR residuals. These evaluations indicate that the RMS radial accuracy is in the range of 1—2 cm.

Jason-1, GPS, precise orbit determination (POD), zero-difference (ZD)

After the Topex/Poseidon (T/P) mission, the Jason-1 radar altimeter satellite, a follow-on cooperative effort between US National Aeronautics and Space Administration (NASA) and French Center National d'Etudes Spatiales (CNES), was launched from the Vandenberg Air Force Base on December 7, 2001. It will take over the T/P spacecraft which has performed successfully for 9 years since 1992 to continue measuring the sea surface topography at least at the same performance level of T/P. This provides an extended continuous time series of high-accuracy measurements of ocean topography from which scientists can determine the general circulation of ocean and understand its role in the Earth's climate[1]. Therefore, the Jason-1 satellite follows the same ground track as T/P, orbiting at an altitude of 1336 km above the Earth with a 66.03° inclination.

Satellite altimetry program was first put forward by Williams in 1969. As for the satellite altimeter, the usefulness of the sea surface height measurement depends on the accuracy of the radial component of the satellite altimeter position[2,3]. Previous missions, such as SEASAT (1978), GEOSAT (1985—1989), ERS-1 (1991—1994), just used the technique of satellite altimetry to make precise and accurate observations of sea level. The principal limitation of past missions to study ocean circulation was the error in determining the geometric radial position of the altimeter. The best Seasat orbits, for example, had a radial accuracy of about 40 cm RMS. This is not enough for monitoring the global sea level change[1,4−6]. Fortunately, the joint US/French T/P satellite altimeter mission made significant advances in orbit design, precise orbit determination measurement and solution methodology. A high orbit altitude was selected to minimize atmospheric drag and gravity forces acting on the satellite, and to make orbit determination easier and more accurate. T/P carried Topex microwave

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radiometer (TMR) yet, which measures water vapour content in the atmosphere so that we can determine how it impacts radar signal propagation. In addition, T/P carried receivers for DORIS (Doppler orbitography and radiopositioning integrated by satellite), SLR (satellite laser ranging) and GPS (global positioning system) in support of the precise orbit determination (POD). This made significant improvement in orbit accuracy and sea surface height measurement[2,3]. T/P was the first extensive use of the GPS with a spaceborne receiver for LEO POD. A pre-launch requirement of its radial orbit accuracy is 13 cm, but about 4 cm in root-mean-square (RMS) sense had been achieved[7,8]. The highly successful GPS flight experiment on the T/P mission prepared the ground for the on-board GPS receiver widely placed on the future LEO missions to support their orbit accuracy requirements.

Being the follow-on to T/P, Jason-1 has a radial orbit error budget requirement of 2.5 cm[1,9]. Only so can guarantee a seamless transition between the Jason-1 and T/P sea-level records, and meet the various kinds of scientific needs on high accuracy orbit. Like its predecessor, the Jason-1 spacecraft supports the following three satellite tracking systems: DORIS, SLR and GPS. The GPS and DORIS systems are considerably more advanced than their counterparts launched on T/P a decade ago[7], so the orbit accuracy of Jason-1 should be theoretically better than that of T/P. Jason-1 precise scientific orbits computed by Jet Propulsion Laboratory (JPL) using on-board GPS data based on the reduced-dynamic strategy suggest that the RMS radial accuracies have already achieved 2 cm[9–11]. In this work, we also compute the Jason-1 orbits using on-board GPS data in a zero-difference (ZD) dynamic strategy. The orbit accuracy is assessed using a number of tests, which include the comparison with the precise orbit ephemeris (POE) produced by JPL, orbit overlaps and independent SLR validation. All those will be discussed in the subsequent sections in detail.

1 Jason-1 GPS-based ZD dynamic orbit determination

For the highly successful GPS experiment on T/P, more and more LEO satellites have been equipped with GPS receivers. Here, the low-cost, portable, all-weather, high-accuracy, continuous, global coverage and three-dimensional nature of GPS measurements make on-board GPS become one of the key POD approaches for LEO satellites. Currently, there are a variety of orbit determination methods for LEOs using on-board GPS data: (1) Kinematic approach, which is independent of satellite dynamics due to the advantage that GPS system allows continuous and multi-dimensional tracking of LEOs, can receive several GPS signals simultaneously, and only requires the geometric information contained in the GPS observations (at least, four GPS satellites) to determine the LEO satellite position directly. (2) Dynamic approach, namely the traditional POD approach, which is the most general method of POD, relies on physically accurate force models and adjusts a relatively small number of force model parameters as part of the orbit solution process. In such a way, the resulting orbit represents all observations best in a least squares sense, and the orbit is completely determined by the dynamic model implemented in the equations of spacecraft motion; (3) Reduce-dynamic approach, which balances the contributions from the force models and the geometric information, by estimating the pseudo-stochastic pulses (in general, a first order Gauss-Markov noise process) acting on spacecraft to compensate for the dynamic force model errors to improve the orbit accuracy[5]. Based on the previous studies[12], the following study was also performed using the SHORDE-III procedure, which was developed by Shanghai Astronomical Observatory for the use of precise orbit determination for LEO satellites with on-board GPS receivers. At present, SHORDE-III can support zero-difference dynamic orbit determination as well as single-difference dynamic orbit determination using on-board GPS data by fixing GPS ephemeris and clock bias. If the spacecraft carries an accelerometer yet, then the orbit determination can be realized using on-board GPS data combined with accelerometer data as well[13].

The Jason-1 orbit's repeat cycle is just under 10 days. In this work; we processed complete 20 days from December 19, 2002 to January 7, 2003 (cycle35 and cycle 36) Jason-1 real on-board GPS data using the ZD dynamic orbit determination technique. Table 1 summaries the data types used in orbit determination and validation. Details of the force models and estimated parameters are given in Table 2. Orbit solutions that do use GPS data are generally made in shorter arcs, typically 30 h[9]. This paper also selects the 30 h GPS-based data which spans 30 h centered on noon as the data for orbit determination.

Table 1 Overview of data types used in orbit determination and validation

Data type	Description
On-board GPS data	real Jasson-1 data with 10 s data interval, from AVISO
GPS orbits and clock	GFZ final GPS orbit products, 30 s data interval
SLR data	normal point at 15 s data interval, from CDDIS
Earth orientation parameters	bulletin B (IAU1980), from IERS
GPS antenna phase center offset	satellite body fixed (SBF *X*, *Y*, *Z*); (1.158, 0.598, 0.6828) (m)
LRR center of mass	(SBF *X*, *Y*, *Z*); (2.389, –0.218, –0.504) (m)

Table 2 Overview of force models and estimated parameters

Force/model	Description	Remarks
Gravity field model	GGM02c	150×150
Atmospheric drag	DTM94	1 drag coefficient estimated
Solar radiation pressure	box-wing	Rim 1992
Solid earth tides	IERS96 convention	McCarthy 1996
Ocean tides	CSR4.0	Eanes 1994
General relativity perturbation	IERS2003 convention	McCarthy and Petit 2002
Empirical rtn perturbations	refer to ref. [12]	coefficients in T and N direction
N-body perturbation	sun and moon	JPL DE/LE 200
Estimated parameters		
Initial state vector	3-D position and velocity	estimated per section of arc
Drag coefficient	bias per arc	estimated 6-hourly
Empirical force	bias per arc	estimated 15-hourly
Jason-1clock bias	bias epoch-wise	60 s sample interval

2 Orbit accuracy assessment

Achieving cm-level orbit accuracy presented not only the challenge of determining the best orbit strategy and producing these orbits, but also the challenge of demonstrating the accuracy of these orbits[9]. Because we do not have a measure of absolute orbit accuracy, we must use several different performance tests to help us gauge and understand the orbit error contained in the POD solutions. Currently, there are several commonly used measures to assess orbit accuracy: tracking data post-fit residual, orbit overlaps, independent orbit comparison, orbit connection points and crossover analysis. The independent orbit comparison can be the comparison between two independent tracking systems, and also can be the comparison between the orbits produced by two different groups. In the following section, we will use a number of tests, which include comparison with POE, orbit overlaps and independent SLR validation to assess the Jason-1 orbits computed using GPS-based data in the ZD dynamic orbit determination technique in detail.

2.1 Comparison with POE

The POE was produced by JPL using Jason-1 GPS-based data in the reduced-dynamic orbit determination technique. The RMS radial orbit accuracy of POE is in the range of 1−2 cm[9–11]. Figure 1 shows the three-dimensional (3-D) orbit difference RMS between SHORDE-III solutions and POE for cycle 35 and cycle 36. The horizontal line in this figure indicates the days of year, and the vertical line indicates the 3-D orbit difference RMS per orbital arc in centimeter. Figure 1 clearly shows that the complete 20 orbital arc 3-D orbit difference RMS is consistently below 7 cm, with an average of about 5.17 cm. The orbit difference RMS at radial (R), along-track (T), and cross-track (N) directions and the 3-D orbit difference RMS are given in Table 3 in detail. We could not display all the 20 days residuals between SHORDE-III solution and POE one-to-one here. Only a sample of the orbit difference on December 24, 2002 at R, T and N directions is shown in Figure 2. In this figure, the horizontal line indicates time in hours, and the vertical line indicates the residuals in the R, T and N directions in centimeter. The RMS difference is 1.62 cm in radial, 4.07 cm along-track and 1.71 cm cross track. From Figure 1, Table 3 and Figure 2, we can see that if we consider POE as the reference orbits, Jason-1 orbits computed using models, strategy and procedure described here may achieve cm-level accuracy, and there would be no obvious systematic bias between these two independent solutions.

As a satellite altimeter measures the distance above the ocean surface, the radial orbit error was thus the dominant component of the overall budget. Figure 3(a) detailedly shows the radial RMS between Jason-1 orbit solutions and POE per arc for cycle 35 and cycle 36 (the horizontal line indicates the days of year, and the vertical line indicates the radial RMS per orbital arc in millimeter) and the complete 20 days radial residuals (Figure 3(b), the horizontal line indicates the days of year and the vertical line indicates the residual in the radial direction in centimeter). The complete 20 days daily radial RMS accuracies are consistently better than 2 cm, and the overall RMS of the 20 days radial residual is about 1.71 cm. These results demonstrate that 2-cm radial orbit accuracy for Jason-1 satellites has probably been achieved, which can meet the Jason-1 radial orbit error requirement of 2.5 cm.

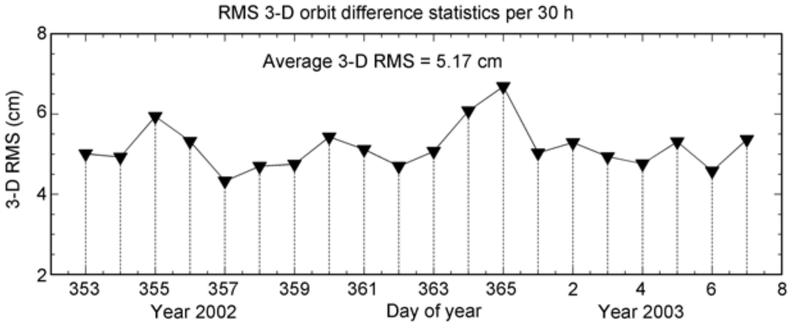

Figure 1 3-D orbit difference RMS between Jason-1 orbit solutions and POE.

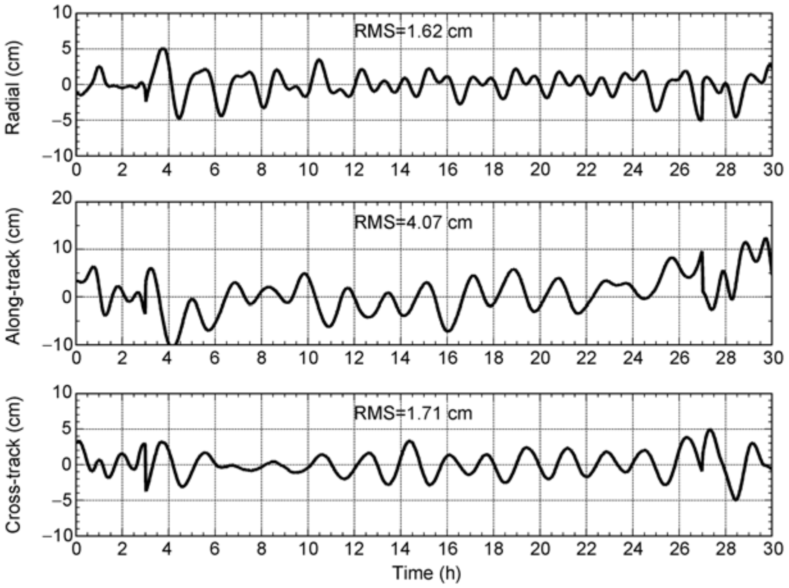

Figure 2 The comparisons between Jason-1 orbit solutions and POE in the R, T and N directions on December 24, 2002.

Table 3 Orbit difference RMS in the R, T, N directions and 3-D position difference RMS

Date	σ_R (cm)	σ_T (cm)	σ_N (cm)	$\sigma_{3\text{-}D}$ (cm)
2002-12-19 (353/2002)	1.50	4.51	1.59	5.01
2002-12-20 (354/2002)	1.45	4.41	1.66	4.93
2002-12-21 (355/2002)	1.63	5.36	1.99	5.94
2002-12-22 (356/2002)	1.80	4.18	2.75	5.32
2002-12-23 (357/2002)	1.17	3.65	2.01	4.33
2002-12-24 (358/2002)	1.62	4.07	1.71	4.70
2002-12-25 (359/2002)	1.34	4.30	1.50	4.75
2002-12-26 (360/2002)	1.95	4.85	1.49	5.43
2002-12-27 (361/2002)	1.91	4.47	1.61	5.12
2002-12-28 (362/2002)	1.44	3.76	2.43	4.70
2002-12-29 (363/2002)	1.98	4.39	1.60	5.07
2002-12-30 (364/2002)	1.30	4.91	3.34	6.08
2002-12-31 (365/2002)	1.99	6.11	1.87	6.69
2003-01-01 (001/2003)	1.95	4.25	1.85	5.03
2003-01-02 (002/2003)	1.91	4.39	2.25	5.29
2003-01-03 (003/2003)	1.93	4.13	1.91	4.94
2003-01-04 (004/2003)	1.86	4.00	1.79	4.76
2003-01-05 (005/2003)	1.71	4.59	2.04	5.31
2003-01-06 (006/2003)	1.65	3.99	1.50	4.58
2003-01-07 (007/2003)	1.69	4.80	1.72	5.37

2.2 Orbit overlap analysis

As mentioned above, GPS orbit solutions were computed in 30-h arcs, beginning 3 h before midnight of one day and ending 3 h after midnight of the next day. Between two consecutive days there is a 6-h overlap period, as shown in Figure 4. Although part of the data used is common in yielding the two orbit solutions in this overlap period, they are believed to be quite uncorrelated due to the independent determination of GPS-based orbits and dynamics. Therefore, the orbit agreement in the overlap is a good indication of the orbit quality[14].

A sample of the orbit difference during the 6-h overlap between December 23 and December 24, 2002 is shown in Figure 5(a). In this figure, the horizontal line indicates the overlap time in hours and the vertical line indicates the residuals of orbit overlaps in the R, T and N directions in centimeter. The RMS difference is 0.76 cm in radial, 2.53 cm along-track and 1.87 cm cross

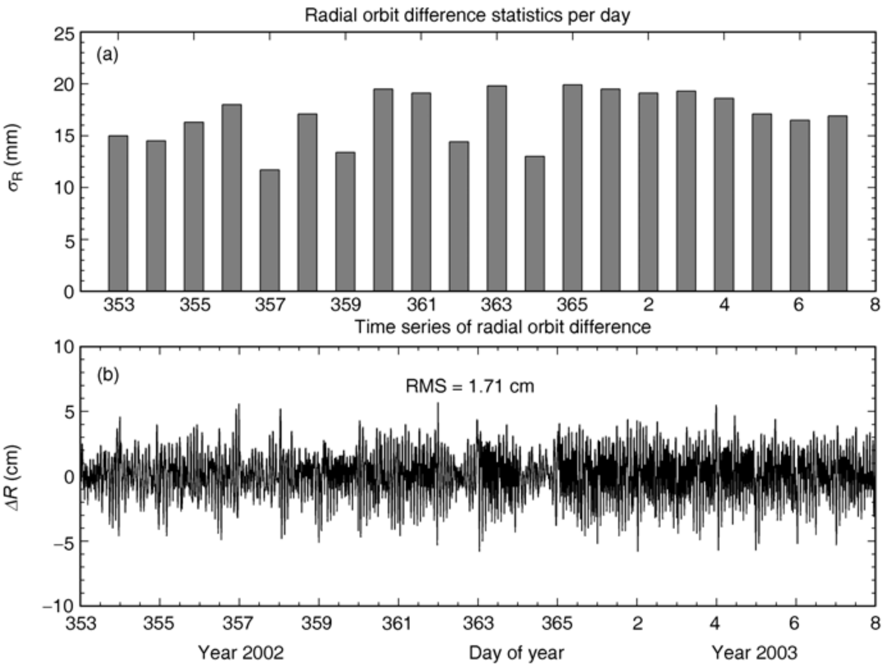

Figure 3 Radial orbit accuracy.

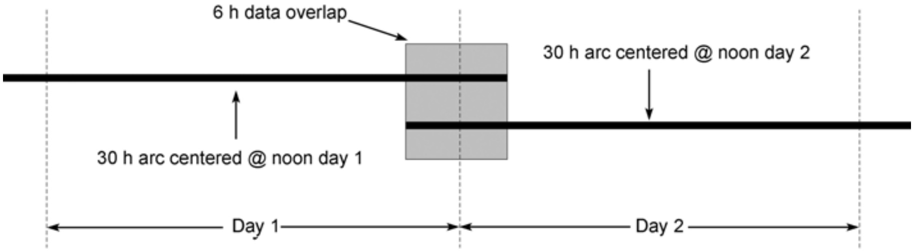

Figure 4 The overlap zone for comparison of POD solutions.

track. There are total 19 sections of the 6-h orbit overlap among the 20 days solutions. All the radial orbit error RMS per overlap arc is shown in Figure 5(b). The horizontal line in this figure indicates the number of overlap arcs and the vertical line indicates the radial RMS and the 3-D orbit RMS in centimeter. From Figure 5, It can be seen that the radial RMS of the orbit overlap varies between 0.7 and 2.1 cm, and the average of radial RMS and 3-D orbit difference RMS is about 1.45 cm and 4.89 cm, respectively. The agreement of orbit overlaps appears to be slightly better than the results compared with POE, so we draw the conclusion that the comparison results with POE are reliable.

2.3 SLR validation

In one of the most powerful tests of radial orbit accuracy, laser-ranging observations of the Jason-1 satellite can be used to independently assess the accuracy of the GPS-based orbits. The orbits determined from on-board GPS data are held fixed, and the SLR data are passed through the solution to determine the level of mismatch between the laser ranges and the orbits. Therefore, if the SLR observation ranges at station A is ρ_{o}^{i} at time t_i, and the theoretical ranges computed from the on-board GPS solution is ρ_{c}^{i}, then the SLR residuals can be written as follows:

$$\Delta^i = \rho_{\mathrm{o}}^{i} - (\rho_{\mathrm{c}}^{i} + \Delta\rho_{\mathrm{stides}} + \Delta\rho_{\mathrm{oloading}} + \Delta\rho_{\mathrm{atm}} + \Delta\rho_{\mathrm{rl}} + \Delta\rho_{\mathrm{com}} + \Delta\rho_{\mathrm{ec}} + \Delta\rho_{\mathrm{st}} + \varepsilon_i),$$

where $\Delta\rho_{\mathrm{stides}}$ is the effect of solid earth tides, $\Delta\rho_{\mathrm{oloading}}$ is the effect of ocean loading, $\Delta\rho_{\mathrm{atm}}$ is the correction of the atmospheric delay, $\Delta\rho_{\mathrm{rl}}$ is the correction of General relativity, $\Delta\rho_{\mathrm{com}}$ is the satellite center of mass offset,

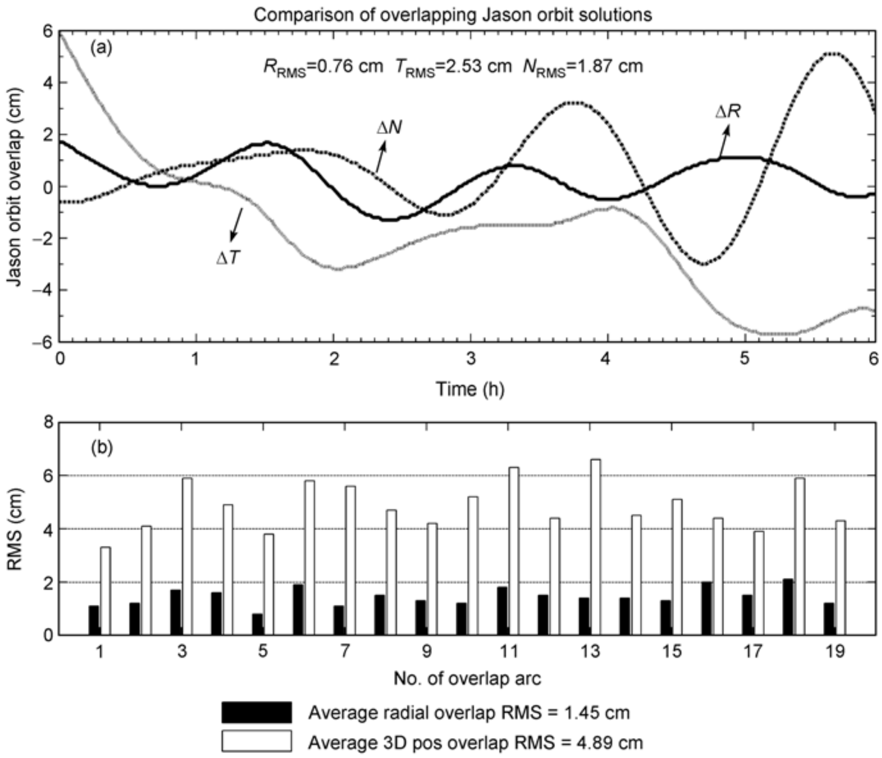

Figure 5 Jason-1 radial orbit overlap performance.

$\Delta\rho_{ec}$ is the correction of station eccentricities, $\Delta\rho_{st}$ is the correction of station movement and ε_i is the observation noise.

If the SLR time event reference was the ground received time, then when computing the real range from SLR observation, we need reduce the time event reference to the satellite received time. If the Jason-1 position at Conventional Terrestrial Reference System (CTS) was $\vec{R}_i$ at t_i, because the SLR observation time is not one-to-one correspondence with the GPS-based solutions, here $\vec{R}_i$ is gotten by chebyshev interpolation polynomials at 8 orders. If the position of station A at CTS is $\vec{R}_A$, then

$$\vec{\rho}^{\,i} = \begin{pmatrix} \rho_x^i \\ \rho_y^i \\ \rho_z^i \end{pmatrix} = (M)(\vec{R}_i - \vec{R}_A),$$

where (M) is the transformation matrix from the terrestrial system to the topocentric coordinates system. Then we can get ρ_c^i, $\rho_c^i = \sqrt{(\rho_x^i)^2 + (\rho_y^i)^2 + (\rho_z^i)^2}$.

The formulation of Marini and Murray (1973) introduced by IERS 2003 convention is commonly used in laser ranging to correct atmosphere delay[15]. This formulation is highly correlated to the elevation angle. The lower the elevation angle, the less accurate the formulation is. In order to minimize the errors caused by the inaccurate model, an elevation cutoff angle of 15° has been applied to the SLR ground stations. Furthermore, in order to better isolate the radial component of the orbit error, for each pass over a laser site, a range bias is determined using laser range observations made above 60°[7,9].

Figure 6 gives an overview of SLR statistics for the 20 days period with 15° elevation cutoff and 60° elevation cutoff. In this figure, the horizontal line indicates the station identifier from NASA Crustal Dynamics Project Pad. The vertical line indicates the RMS of SLR residuals in centimeter. From December 19, 2002 to January 7, 2003, altogether 247 passes of SLR residuals were obtained from 22 stations of the tracking network of the International Laser Ranging Service (ILRS) for Jason-1, where 14 stations got SLR observations above 60°. Figure 6 indicates that the RMS of each station with 15° elevation cutoff is consistently below 7 cm, with the statistic bias (0.07±3.69) cm; the RMS with 60° elevation cutoff is consistently below 2 cm, with the statistic bias (0.49±1.61) cm. These results are in good agreement with the values obtained by the

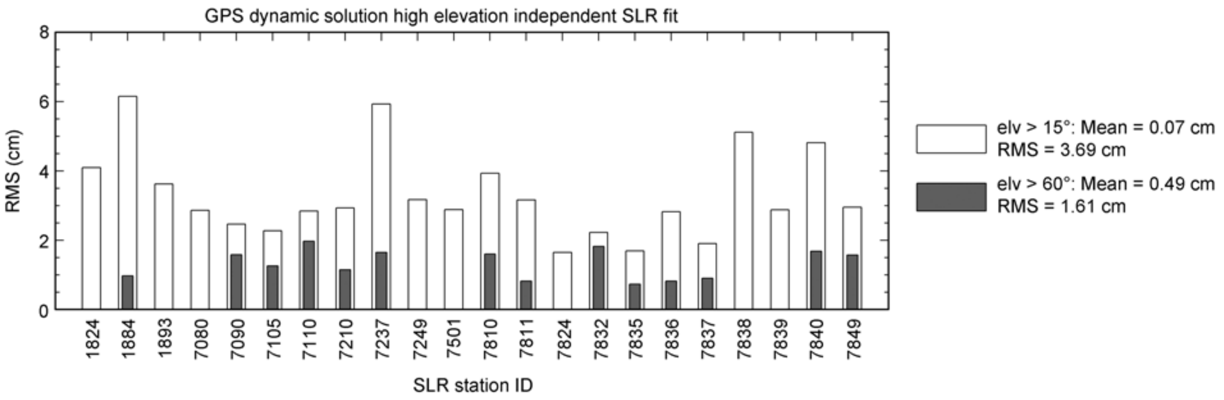

Figure 6 Jason-1 dynamic solution independent SLR fit.

comparison with POE and orbit overlaps. The SLR validation of Jason-1 orbit results let us conclude that there is no significant bias in the SLR observations, the POD procedure SHORDE-III described here is suitable for the Jason-1 precise scientific orbit (PSO) determination, and the PSO requirement of 2.5 cm accuracy for Jason-1 orbits could be met as well.

3 Summary and conclusions

The precise orbit determination for the Jason-1 satellite using 20 days (December 19, 2002 to January 7, 2003) real on-board GPS data in the ZD dynamic POD technique has been successfully carried out in this work. The quality of the orbit solutions has been assessed by comparing orbits with the orbit ephemeris produced by JPL using GPS-based data by the reduced-dynamic technique, orbit overlap and independent SLR validation. Based on the various assessment results, we draw the following conclusions:

(1) There is no obvious systematic bias between POE and orbit solutions computed using models, strategy and SHORDE-III procedure described in this paper. The 3-D orbit difference RMS is about 5.71 cm, and the radial orbit RMS accuracy is about 1.71 cm.

(2) The 3-D RMS of orbit overlaps is about 4.89 cm, and the radial RMS accuracy is about 1.45 cm.

(3) No significant bias has been found for the SLR residuals. The 20 days statistic bias of the SLR residual with 15° elevation cutoff is (0.07±3.69) cm, and the statistic bias of 60° elevation cutoff is (0.49±1.61) cm.

The results from the Jason-1 satellite presented in this paper prove that the models, strategy and procedure described in this paper are viable for use in real-world situations, and provide highly accurate GPS-based solutions. This would give support to scientific missions equipped with GPS receivers, and make its due contribution to the future oceanographic, climate and remote sensing missions of our own country.

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