Initial Orbit Determination Results for Jason-1: Towards a 1-cm Orbit*

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BIOGRAPHIES

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ABSTRACT

The U.S/France Jason-1 oceanographic mission is carrying state-of-the-art radiometric tracking systems (GPS and Doris) to support precise orbit determination (POD) requirements. The performance of the systems is strongly reflected in the early POD results. Results of both internal and external (e.g., satellite laser ranging) comparisons support that the 2.5 cm radial RMS requirement is being readily met, and provide reasons for optimism that 1 cm can be achieved. We discuss the POD strategy underlying these orbits, as well as the challenging issues that bear on the understanding and characterization of an orbit solution at the 1-cm level. We also describe a system for producing science quality orbits in near real time in order to support emerging applications in operational oceanography.

INTRODUCTION

The Jason-1 spacecraft was launched from Vandenberg Air Force Base on December 7, 2001, and has been successfully placed in a circular, 1335-km orbit around the Earth. A joint U.S./France oceanographic mission, Jason-1 represents the first in a series of altimetric missions designed to carry on the legacy of precise sea-level observation begun in 1992 by the TOPEX/Poseidon (T/P) mission.

Still returning useful scientific data over 10 years after its August 1992, launch, the T/P satellite has far exceeded expectations in terms of both mission duration and measurement-system performance. Sea-surface height measurements (single pass) are accurate to about 4 cm in a root-mean-squared (RMS) sense (vs. a pre-launch requirement of 13 cm). Underlying this achievement is the computation of orbits accurate to 2.5 cm (RMS) in the height component. In order to guarantee a seamless transition between the Jason-1 and T/P sea-level records, Jason-1 carries this 2.5-cm requirement for Precise Orbit Determination (POD). Acting on input from the science team, the project is also carrying an aggressive goal of 1 cm (RMS) for the radial accuracy of the orbits.

Like its predecessor, the Jason-1 spacecraft supports three advanced satellite tracking systems: 1) the Global Positioning System (GPS); 2) the CNES Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) system and 3) satellite laser ranging (SLR). The GPS and DORIS systems are considerably more advanced than their counterparts launched on T/P a decade ago. Preliminary tests of orbits computed using Jason-1 tracking data in a "reduced dynamic" strategy suggest the RMS radial accuracies are already better than 2 cm, and that the 1 cm goal is within reach. The principal focus of this paper is the GPS system, but combined GPS and Doris solutions will also be presented. These complementary data types offer the strongest evidence that 1 cm radial accuracy is achievable.

In addition to the current Jason-1 POD results, we will discuss a prototype GPS-based system for delivering precise orbits in near real time. Emerging operational applications of Jason-1 and T/P altimetry, such as short-term climate forecasting and real-time ocean current monitoring, place important demands on the latency of accurate orbit height estimates for the purposes of forming sea-level observations. The BlackJack data on Jason-1 can serve as the basis for providing sea-level measurements accurate to a few cm within hours or real time.

JASON-1 TRACKING SYSTEMS

The BlackJack GPS receiver design was conceived at the Jet Propulsion Laboratory (JPL) to meet demanding positioning and scientific requirements of NASA remote-sensing missions as the space agency embarks on the new millennium. The receiver uses advanced-codeless tracking techniques to enable the formation of precise pseudorange and carrier-phase observations on the two principle GPS frequencies (L1 and L2) regardless of the encryption status of the GPS constellation. The first BlackJack flew on the Shuttle Radar Topography Mission (SRTM) in February 2000. Data from the receiver were successfully used to generate the precise orbital position estimates underlying the widely publicized terrestrial topographic maps from the mission [*Bertiger et al.*, 2000].

Subsequent experimental versions of the receiver are successfully operating on CHAMP (German scientific mission launched in July, 2000) and SAC-C (Argentine satellite launched in November, 2000). Using the BlackJack data, *Kuang et al.* [2001] achieved accuracies of better than 10 cm (3D) for the CHAMP orbit. The receivers on both of these missions have also supported the collection of atmospheric sounding data using the GPS occultation technique [*Hajj et al.*, 2002].

JPL's industry partner, *Spectrum Astro Inc.*, built the receivers for Jason-1, as well as the NASA ICESat mission (planned December, 2002 launch) and Australian Fedsat microsatellite (planned November, 2002 launch).

Advanced versions of the BlackJack capable of supporting POD and atmospheric sounding functions, as well inter-satellite ranging and star camera data, are flying on the twin GRACE satellites (March 2002 launch). Early results from the GRACE BlackJack receivers can be found in these proceedings [*Dunn et al.*, 2002; *Bertiger et al.*, 2002].

The Doris receiver on Jason-1 supports the collection of precise Doppler measurements on two radio frequencies (2036.25 MHz and 401.25 MHz). At the foundation of this French system is a global network of transmitting beacons, presently comprised of 60 stations. The Jason-1 Doris receiver features better in-flight noise characteristics (< 0.4 mm/s on range-rate) than its counterpart on T/P (0.5 mm/s). More important, the receiver is capable of observing two terrestrial Doris beacons simultaneously, improving the geometric observability in orbit. The Jason-1 Doris system also features a real-time orbit determination capability called *Diode* (Détermination Immédiate d'Orbite par Doris Embarqué).

The Jason-1 spacecraft also carries a laser retro-reflector array (LRA) that serves as a target for ground-based satellite laser ranging (SLR) systems. The definitive Jason-1 orbits to be provided with the geophysical data will combine GPS and DORIS, as well as SLR. In this study, SLR observations are withheld from the orbit solutions and used instead for estimating the radial orbit accuracy of orbits determined solely from the radiometric data.

BLACKJACK TRACKING PERFORMANCE

In its current configuration, the BlackJack on Jason-1 is capable of tracking up to 12 GPS satellites simultaneously on two frequencies. While 12 GPS can be in view from the Jason-1 orbit at the same time, the average number of satellites that can be tracked with sufficiently high signal-to-noise (SNR) ratio is less (Figure 1).

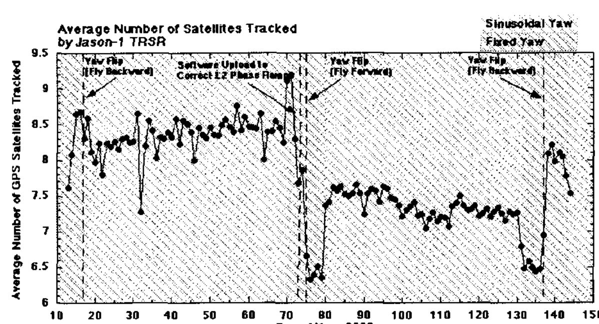

Fig 1. Number of GPS satellites tracked (daily average) as function of time for Jason-1 BlackJack receiver.

Clearly evident in the figure (daily averages) is a dependence on the yaw regime of the Jason-1 satellite. This can be understood in the context of the antenna orientation. The Blackjack antennas are located on the top front of the s/c payload section, and the respective boresites are canted 30° from zenith toward the front of the s/c to reduce multipath (Figure 2).

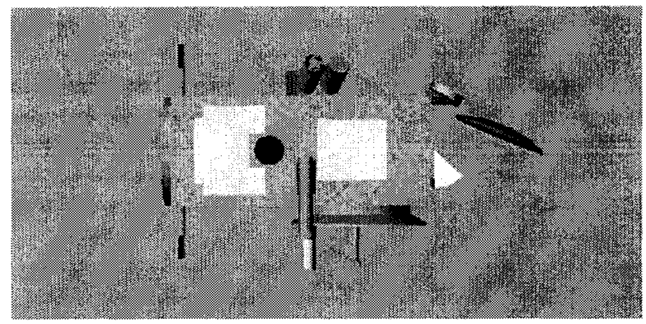

Fig 2. Side view of Jason-1 spacecraft bus showing GPS antenna (upper right) canted away from spacecraft (courtesy Marek Ziebart).

When Jason-1 is flying backwards, lock can be maintained on setting GPS satellites after they have descended well below the local horizon. In contrast, the initial lock on rising satellites is not made until the GPS s/c have ascended above the elevation (8°) used be the receiver's tracking scheduler to ensure that the SNRs are sufficient to support tracking.

The strong observability afforded by the high satellite tracking capacity is one factor in explaining the achievement of radial RMS orbit accuracies superior to T/P. While the Jason-1 Blackjack averages 7–9 GPS spacecraft (s/c) simultaneously, the GPS Demonstration Receiver (GPSDR) on T/P is hardware-limited to tracking a maximum of six s/c.

A yaw-regime dependence is also observed in the statistics for mean track length, (Figure 3) with continuous tracking arcs averaging 30–40 minutes. The uninterrupted advance and retreat of the precise GPS carrier phase over these long, continuous tracking arcs are fundamental to ultra-precise GPS-based POD techniques.

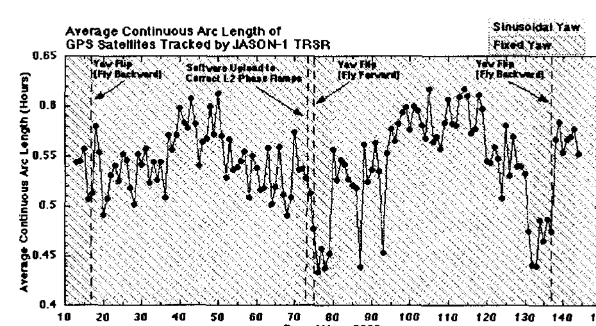

Fig 3. Length of track (daily average) as function of time for Jason-1 BlackJack receiver.

One of the BlackJack receiver design philosophies was to use commercial-grade components instead of potentially expensive radiation hardened parts. As a consequence, system resets were designed into the autonomous receiver operations as a means of clearing "soft bit" errors induced by cosmic rays and the occasional "latch up" condition. In orbit, the Jason-1 BlackJack typically experiences 3–8 resets per days, resulting each time in loss of lock and a data gap with typical duration of 6–12 minutes. A global map of the location of BlackJack data gap onsets (Figure 4) indicates that a majority of the gaps are occurring over the South Atlantic Anomaly, strongly suggesting that they are radiation induced.

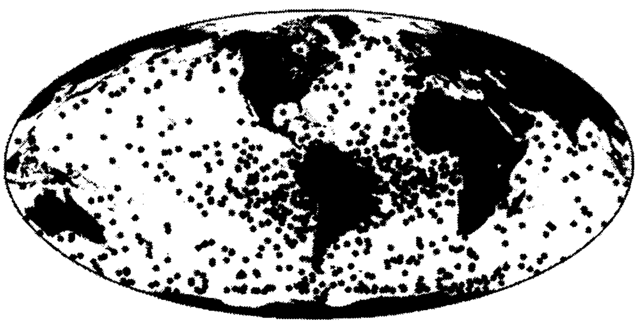

Fig 4. Location of suspected BlackJack receiver resets from January 10, 2002, to September 5, 2002.

Resets stemming from errors in the embedded receiver software are also experienced. A software improvement effort has been undertaken to reduce the number of software-induced resets for on-orbit BlackJack receiver operations. As a result, reset rates for other BlackJack receivers in space are now as low as 3–5 per month (e.g., for GRACE-A). We expect a significant drop in the Jason-1 reset rate when a new version of the software is uploaded to the spacecraft. On the other hand, we do not expect to match the low reset rates experienced by receivers in lower Earth orbits (e.g., CHAMP, GRACE) where the radiation environment is more benign.

GPS-BASED PRECISE ORBIT DETERMINATION

We have processed over seven months of the Jason-1 Blackjack data using the Gipsy/Oasis II software and a reduced-dynamic (RD) precise orbit determination (POD) technique. The daily orbit solutions span 30 hrs centered on noon, implying that consecutive orbit solutions overlap by 6 hours. Details of the solution strategy are given in Table (1). In many respects, the strategy is modeled after POD procedures developed for T/P over the last decade. For additional discussion, the reader is referred to e.g., Bertiger *et al.* [1994], Tapley *et al.* [1994], and Haines *et al.* [1999]. There are, however, some differences between the T/P and Jason-1 POD strategies. Most notable among them is the treatment of the GPS antenna phase center position.

Reducing the uncertainty in locating the phase centers on both GPS transmitter and receiver antennas has emerged as an area of active research in the GPS geodetic community. The physical locations of the Jason-1 antenna reference points were precisely measured prior to launch, as were the electronic phase center locations. The effective phase center positions, however, can vary significantly depending on the local environment. In recognition of this, we elected to solve for the 3D position of the mean BlackJack antenna phase center using data collected on orbit.

Depending on the attitude regime of the Jason-1 satellite, the phase-center solutions are well determined. The estimation is made possible because the path followed by the antenna phase center departs from the path taken by the satellite's center of gravity (CG). The latter path is governed by the forces (e.g., gravity) underlying the satellite motion, and can be very well determined in a dynamically constrained POD solution. Departures of the Jason-1 antenna phase center—located about ~1.4 m from the CG—from this path can then be accommodated by solving for the 3D antenna offset in spacecraft coordinates.

Especially valuable in this context are occasional attitude events during which the Jason-1 satellite undergoes a "yaw flip". In this case, the spacecraft makes a 180° turn over the span of a few minutes. As the spacecraft rotates, the outboard GPS antenna traces out a path in inertial space that is wholly inconsistent with any plausible motion of the CG. (Note that this would not be the case if the antenna were located directly over the CG.) In the case of Jason-1, this type of attitude behavior enables recovery of the effective phase center with no prior information on the location of the antenna on the vehicle. The fidelity of the force models for the 1335 km Jason-1 orbit is one key to the success of this approach. Depending on the desired accuracy for the phase center recoveries, however, the same technique could be adopted for other missions.

In the present study, we used ~120 consecutive days of BlackJack data to solve for the antenna phase center. In this time span, the Jason-1 orbital plane has rotated once in inertial space, thus ensuring that all possible attitude regimes are represented. In each of the daily POD solutions, we solved for the 3D phase center position using pseudorange and carrier phase separately. (This is not to suggest the carrier and range electronic phase centers should not in theory coincide. Rather, it is to account for possible systematic errors in the pseudorange, e.g., multipath, that do not influence the carrier.)

Table 1. Precise orbit determination (POD) strategy for Jason-1 orbits computed from BlackJack GPS data.

Data Type	σ (Dynamic passes)	σ (Reduced-dynamic pass)
Ionosphere-Free Carrier Phase (LC, 5-min)	1 cm	1 cm
Ionosphere-Free Pseudorange (PC, 5-min)	40 cm	40 cm

Model/Parameter	Jason-1 Selection
Solar Radiation Pressure	"Box-wing" Model (CNES)
Spacecraft Area	"Box-wing" Model (CNES)
Spacecraft Mass	489.1 kg
Atmospheric Density	
Offset of antenna phase center w/ respect to s/c ctr. of gravity	
Carrier phase (s/c body-fixed X, Y, Z)	(1.4321, –0.2180, –0.5469) (m)
Pseudorange (s/c body-fixed, X, Y, Z)	(1.3457, –0.2180, –0.2532) (m)
Antenna Orientation w/ respect to s/c frame	
Boresite (s/c body-fixed X, Y, Z)	(0.498, –0.044, –0.866) (Unit Vector)
X Dipole (s/c body-fixed, X, Y, Z)	(0.867, 0.025, 0.497) (Unit Vector)
Earth orientation/rotation	International Earth Rotation Service (IERS) Bulletin B
GPS spacecraft ephemerides	JPL IGS Analysis Ctr. (Flinn) estimates ITRF2000
GPS spacecraft clocks	JPL IGS Analysis Ctr. (Flinn) estimates
Luni-solar Perturbations	JPL DE-340 ephemerides
Earth Gravity Field	Joint Gravity Model(JGM)-3 70X70
Ocean and Earth Tides	Ctr. for Space Res. 3.0 (R. Eanes) + TEG2B

Estimated Parameters	Parameterization	A priori σ
Jason-1 epoch state		
3-D epoch position (X, Y, Z)	Bias per arc	1 km
3-D epoch velocity (X, Y, Z)	Bias per arc	10 m/s
Jason-1 empirical accel. (dynamic passes):		
Drag Coefficient	Bias per arc	$1x10^3$
1 cpr cross track (cos, sin)	Bias per arc	0.1 m/s^2
1 cpr down track (cos, sin)	Bias per arc	0.1 m/s^2
Jason-1 empirical forces (reduced pass):		
Down track	Colored noise with $\tau = 6$ hr	1 nm/s^2
Cross Track	Colored noise with $\tau = 6$ hr	1 nm/s^2
1 cpr cross track (cos, sin)	Colored noise with $\tau = 6$ hr	2 nm/s^2
1 cpr down track (cos, sin)	Colored noise with $\tau = 6$ hr	2 nm/s^2
Carrier phase biases	Bias over continuous pass	$3x10^5$ km
BlackJack clock offset	White-noise process (reset every 5-min obs.)	1 sec

The estimated antenna phase center from the ionosphere-free carrier (LC) is about 4 cm above the position inferred from pre-launch antenna range measurements. This is consistent with the 5-cm result obtained on T/P when the radial component of the antenna location was estimated [*Bertiger et al.*, 1994]. The consistency between T/P and Jason-1 is intriguing, and may lend insight on the source of the offset. The carrier phase suggests that the antenna phase center is ~2 cm closer to the CG than inferred from pre-launch measurements. The direction of the adjustment is consistent with the expected displacement of the CG due to fuel consumption. However, the magnitude of the adjustment is much larger than expected based on the amount of fuel expended. Other possible explanations are being sought.

The estimated antenna phase center from the ionosphere-free pseudorange (PC) is displaced by ~30 cm from its LC counterpart. This unexpectedly large displacement is principally in the direction opposite the antenna boresite. Multipath is being examined as a possible explanation. Regardless of the source of the on-orbit antenna phase center offsets, adopting the new estimates in the POD process appreciably improves the orbit accuracy as inferred from a variety of metrics. The solved-for values are thus used in the generating the nominal orbit solutions from the Blackjack data.

ACCURACY ASSESSMENT

The mismatch between model and observations in the POD process is manifest in the postfit residuals. This is a basic measure of data quality, and is not considered a strong indicator of orbit accuracy. Plots of the postfit residuals (daily statistics) are provided in Figure 5 for both pseudorange and carrier phase

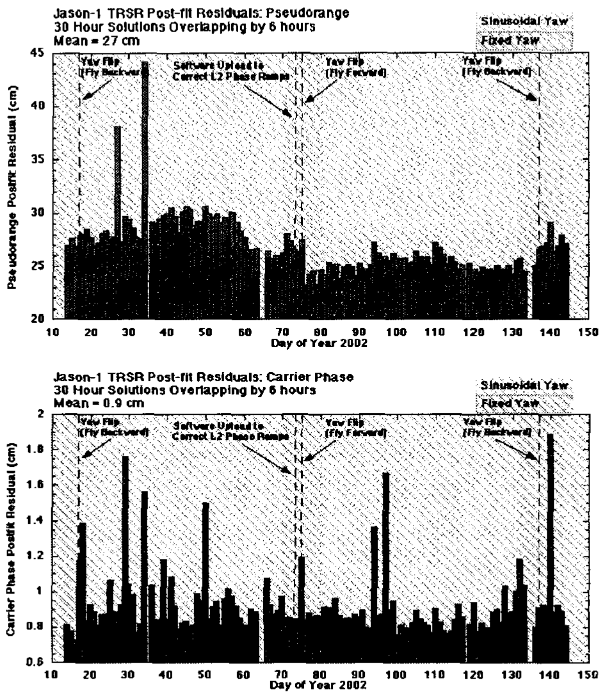

Fig 5. Time history of Jason-1 BlackJack postfit residual RMS for pseudorange (top) and carrier phase (bottom).

The pseudorange data quality for the Jason-1 BlackJack (27 cm) is much better than that experienced with the GPSDR on T/P (70 cm). In contrast, the fits to the carrier phase are somewhat degraded (9 vs. 5 mm). Further investigation is required to determine if this higher scatter is attributable to the observations (e.g. the manner in which the carrier phase is smoothed by the embedded software, absence of phase center calibration tables in the current strategy, multipath), or the POD models.

Each of the daily orbit solutions spans 30 hrs, implying that consecutive orbit solutions overlap by 6 hrs. The consistency of the orbit solutions during these overlap periods is an important, albeit potentially optimistic, indicator of orbit accuracy. It is important to note that the precise GPS spacecraft orbit and clock offsets (from JPL IGSAC) serving as a framework for the POD are independently determined for each day. In addition, the duration of the overlaps are small in comparison with the arc length. As depicted in Figure 6, the median RMS radial overlap is less than 1 cm.

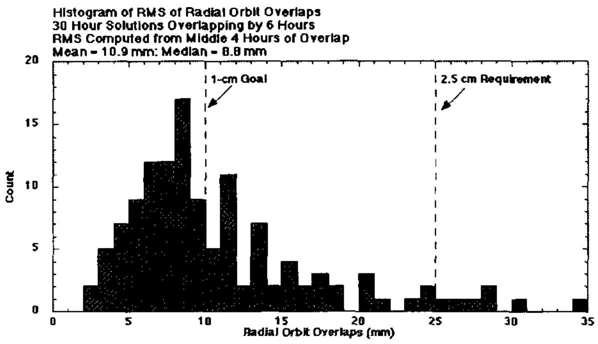

Fig 6. Histogram of RMS Radial Overlap Statistics: Jason-1 GPS-based orbits.

The GPS-determined orbits for Jason-1 have been compared with solutions provided by other agencies using independent tracking data (SLR+ Doris), POD software packages, and POD strategies (dynamical or quasi-dynamical approaches). Shown in Figure 7 is a representative time series of radial RMS differences over three consecutive repeat cycles (30 d). The comparison orbit in this case is from the University of Texas Center for Space Research and is based on SLR + Doris data (J. Ries, personal communication). The independent orbit solutions (JPL/GPS vs UT/SLR+Doris) agree to within ±2 cm 75% of the time, and to within ±1 cm 45% of the time.

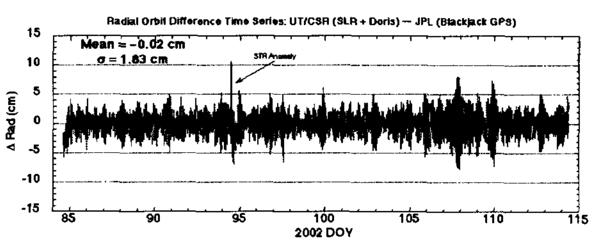

Fig 7. Time series of radial orbit differences for Jason-1: JPL Blackjack vs U. Texas SLR+Doris orbit.

The same orbit differences can also be projected on the global oceans (Figure 8). Noteworthy is the good relative centering of the two orbit solutions. The mean orbit differences in all three Cartesian components (X, Y, Z) of the terrestrial reference frame (TRF) are less than 1 cm. Particularly encouraging is the small offset (0.4 cm) along the Earth's spin axis. A slight offset (~1 cm) along the Earth's equatorial plane contributes to a pattern that is reminiscent of the force model errors exposed by the GPSDR on T/P [*Christensen et al.*, 1994]. The pattern may thus be symptomatic of small, mismodeled s/c accelerations in the dynamic (SLR+Doris) solution. The GPS RD orbit should be less sensitive to force-model errors. Such errors would not be unexpected at this early stage of the mission, and additional tuning of the underlying models (e.g., surface forces, gravity) may alleviate them. Measurement model effects (either from GPS or SLR+Doris) also cannot be excluded as a possible cause.

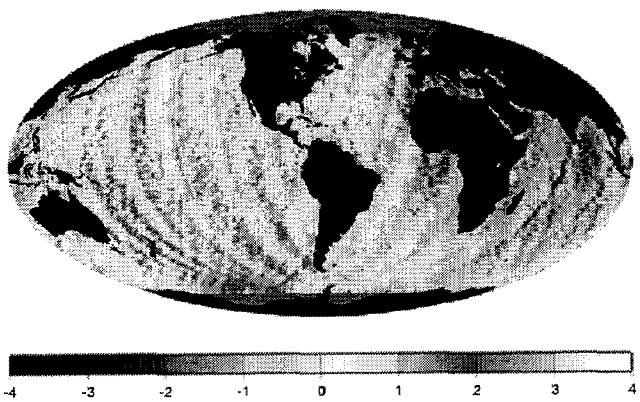

Fig 8. Map of radial orbit differences for Jason-1: JPL Blackjack vs U. Texas SLR+Doris orbit.

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. In this test, the satellite laser ranging data are not allowed to influence the orbit solution. The orbits determined from the Blackjack data are held fixed, and the SLR data are carried along to determine the level of mismatch between the laser ranges and the orbit. The analysis is restricted to high-elevation passes (greater than 60° as observed from the laser observatory), 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°. The global RMS of the range biases is considered a strong indicator of the radial orbit error. In this case, data from seven high-quality NASA and French SLR observatories were considered. Table 2 provides the statistics of fit for each of the stations, based on the first 20 repeat cycles (200 days) of precise orbit solutions.

The RMS of the SLR range biases is 1.4 cm. At this level of fit, small station and satellite-specific SLR measurement biases, as well as unmodeled crustal deformations (e.g., from atmospheric loading), can influence the results. The overall result is consistent with a radial orbit error of less than 1.5 cm in an RMS sense. Strictly speaking, this applies to the portions of the orbit where the Jason-1 satellite was in view at high elevation from one of the above SLR sites. Sites in the continental U.S., Hawaii, Europe, Australia and South Africa were included in large part to provide a suitable global distribution for measuring the orbit accuracy. We expect additional tuning of the strategy, and potential improvements to the Blackjack data (via receiver s/w upload) to improve upon this. Early results also suggest that combining DORIS and GPS data also offer some orbit improvement over GPS alone. This is evidenced in sea-surface height repeatability studies, wherein the orbit solutions based on DORIS and GPS yield slightly better agreement at ground-track crossover locations.

NEAR REAL TIME ORBITS

To support potential emerging applications in operational oceanography, we have developed a prototype system to produce science-quality orbit estimates for Jason-1 in near real time (1–5 hr latency). At the foundation of the system is JPL's Internet-based Global Differential GPS (IGDG) system [*Muellerschoen et al.*, 2000], which supports the routine generation of precise orbit and clock offset information for the GPS s/c in real time. To produce the estimates, the IGDG relies on a global NASA ground network returning data to JPL in real time over the open internet.

The Jason-1 near real-time (NRT) processors are triggered by the arrival of each telemetry download from the BlackJack (approximately every 2 hrs). Jason-1 orbit solutions are then generated using a tracking data arc defined by a sliding window spanning the previous 24 hours. The resulting orbit solutions are then available within one hour of the time of the last data point in the telemetry download. Extensive comparisons with the precise Jason-1 orbits described above, as well as with SLR data, have indicated the radial accuracy to be ~3.5 cm RMS for NRT orbits with 1-3 hour latency, and ~2.5 cm for NRT orbits with 3-5 hour latency. The availability of such science-quality orbits in near real time will enable the derivation of NRT ocean surface height science products with benefits to tactical oceanography, and natural hazard monitoring.

Station	Mean (cm)	Standard Deviation (cm)	RMS (cm)	Min (cm)	Max (cm)	# Arcs
McDonald	+0.3	1.3	1.3	-2.0	+2.5	23
Monument	+0.3	1.3	1.3	-2.0	+4.5	44
Greenbelt	+0.3	1.4	1.4	-2.6	+3.8	59
Haleakala	+0.4	1.4	1.4	-2.8	+2.0	13
Yarragadee	-0.2	1.4	1.4	-3.0	+3.2	57
Grasse	-0.3	1.6	1.6	-4.2	+3.9	48
Hartebeesthoek	+0.2	1.7	1.7	-3.0	+3.4	26
ALL	+0.1	1.4	1.4	-4.2	+4.5	270

ACKNOWLEDGEMENTS

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