Precise Orbit Determination for Jason-1: GPS and the 1-cm Solution

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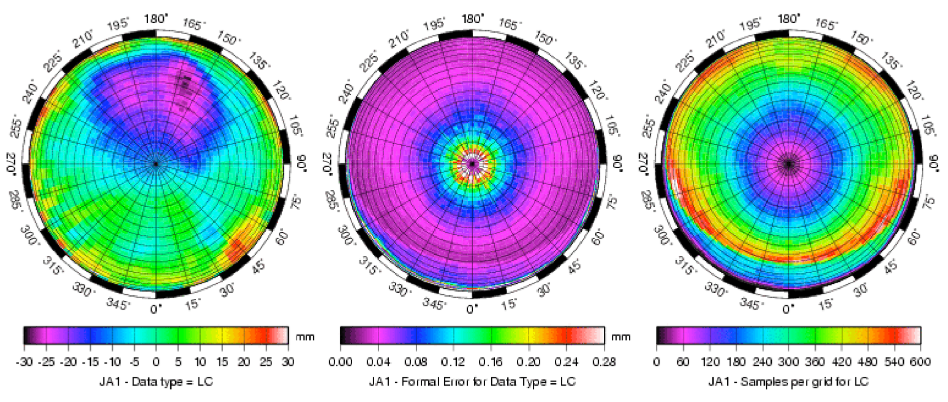
Abstract

The Jason-1 satellite is carrying a state-of-the-art GPS receiver to support precise orbit determination (POD) requirements. Developed at the Jet Propulsion Laboratory and manufactured by *Spectrum Astro Inc*., the BlackJack receiver (TRSR) tracks up to 12 GPS spacecraft simultaneously on two frequencies. The BlackJack is significantly more capable than its predecessor, the GPS Demonstration Receiver (GPSDR), on the TOPEX/POSEIDON (T/P) mission (1992-present). The Jason-1 receiver uses advanced-codeless tracking techniques to enable the formation of precise pseudorange and carrier-phase observations regardless of the encryption status of the GPS constellation. Also important is the enhanced observability afforded by the increase in satellite tracking capacity (12 for the BlackJack on Jason-1 vs. 6 for the GPSDR on T/P). The performance of the Jason-1 BlackJack receiver was strongly reflected in early POD results from the Jason-1 mission, enabling radial accuracies of 1–2 cm soon after the satellites 2001 launch.

We have made further advances in the GPS-based POD for Jason-1. Our recent efforts have been focused in three areas:1) Development of phase-center variation maps for both the receiver (Jason-1) and transmit (GPS s/c) antennas. These maps are based on evaluation of in-flight data, and have proven highly effective at accommodating multipath and other systematic measurements system errors. 2) Evaluation of new geopotential fields from the Gravity Recovery and Climate Experiment (GRACE). 3) Evaluation of a new high-resolution solar/thermal force model based on pixel array techniques (see separate Ziebart et al. poster). The outcome of these investigations has enabled us to better exploit the unique contributions of the BlackJack GPS tracking data in the POD process. Results of both internal and external (e.g. laser ranging) comparisons indicate that the 1-cm goal for Jason-1 radial orbit accuracy (RMS) has been reached using GPS data alone.

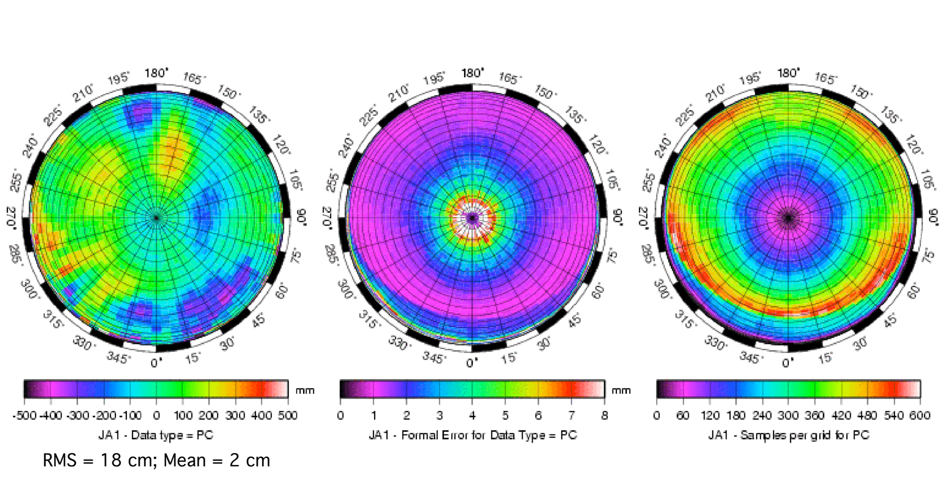
Antenna Phase Center Variations

The mismatch between model and observations in the POD process is manifest in the postfit residuals. To examine multipath effects and in-flight phase center variations, over one year's worth of residuals for both ionosphere-free carrier phase (LC) and pseudorange (PC) were gridded in local antenna coordinates (azimuth and elevation with respect to antenna boresite). We observed that the maps were nearly invariant over time, regardless of the spacecraft's attitude. The carrier phase map (below) depicts a significant systematic variation from the low elevations (at the edges) to the zenith direction (30º from the antenna boresite). This can be largely approximated by a simple translation of the phase center in the zenith direction.



RMS = 1.2 cm; Mean = –0.1 cm

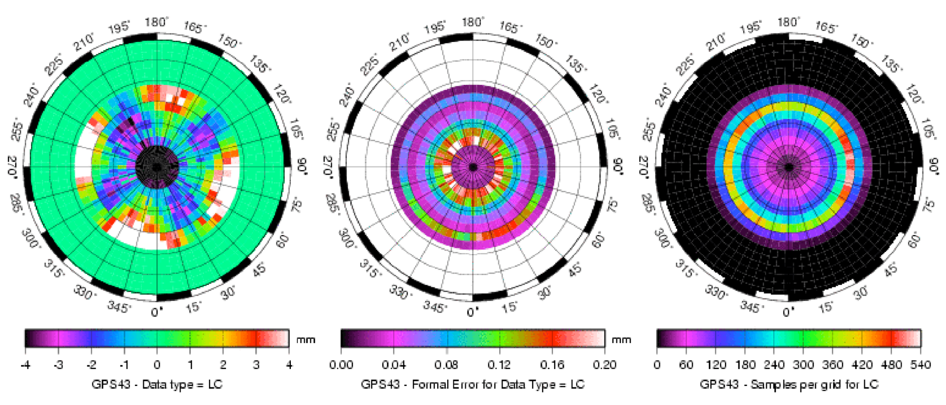
The pseudorange map depicts several regions of apparent multipath errors from neighboring spacecraft surfaces:

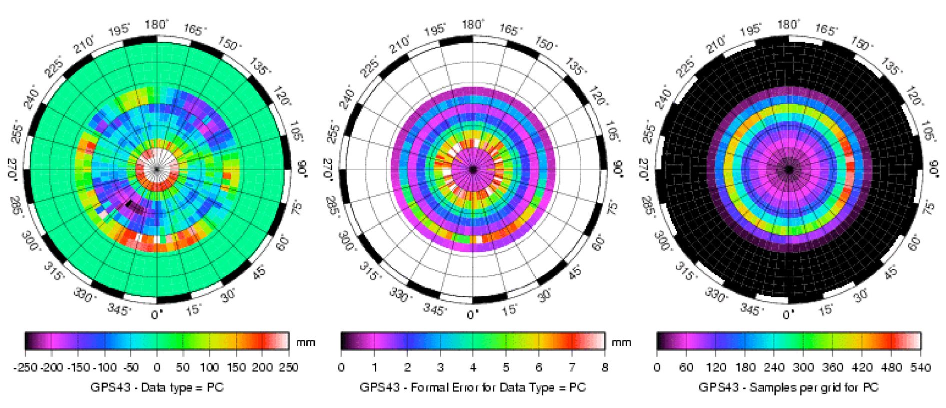


RMS = 18 cm; Mean = 2 cm

The maps explain significant fraction of the energy in the postfit residuals, prompting us to incorporate them in the POD process. Aside from improving the POD results across different attitude regimes, the maps obviate the need to model the 4-cm phase center offset previously noted in the zenith direction. It should be noted that similar maps have been used to improve geodetic time series from GPS ground stations [*Hurst and Bar-Sever*, 1998].

Using similar techniques, we are developing maps for the transmit antennas of the GPS spacecraft. In a preliminary exercise, we used data from the Jason-1 and GRACE (A & B) satellites, already corrected for the phase center variations of the receiver antennas. Examples of the recovered transmitter antenna maps for a particular GPS spacecraft (GPS43) are given below. Launched in 1997, GPS43 (PRN13) is the first of the so-called "Block IIR" spacecraft.



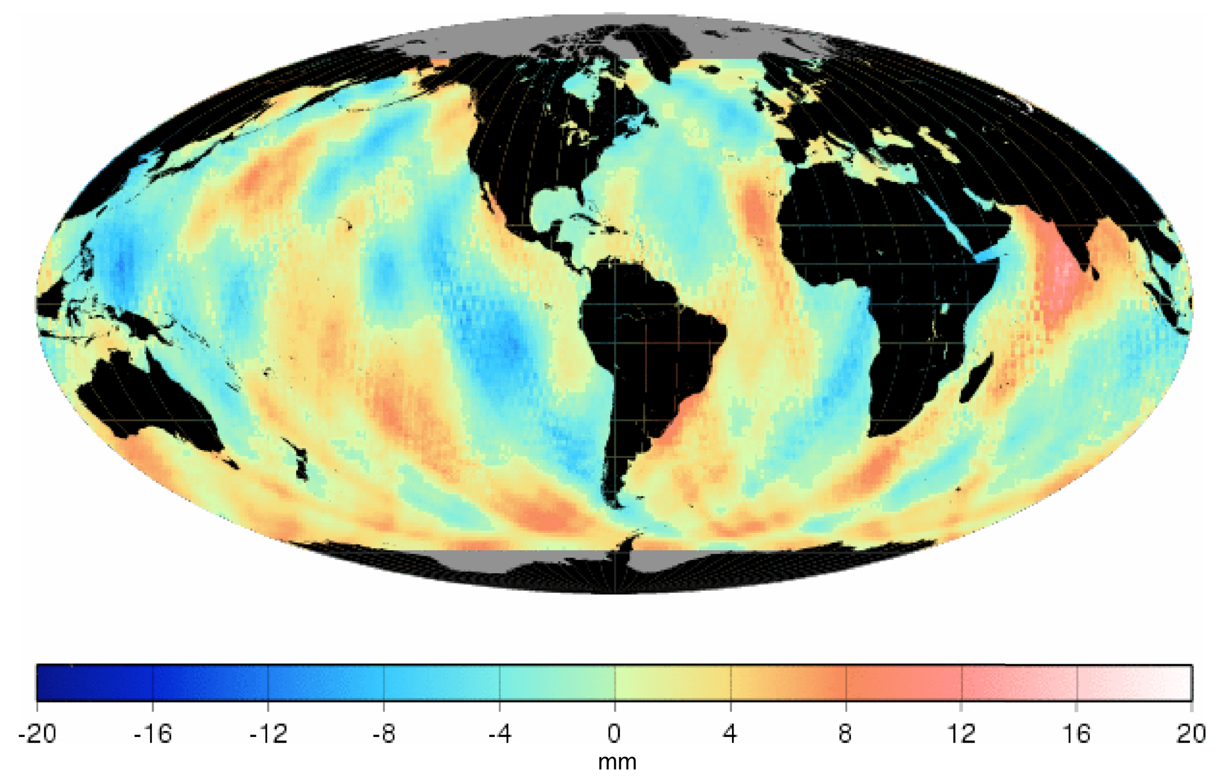


We have adopted the preliminary GPS s/c antenna maps in our current Jason-1 POD strategy, and plan to further refine the estimates and characterize the effects on the Jason-1 orbit. We note that the development GPS s/c antenna maps should also benefit analyses of data from terrestrial GPS stations for a variety of geodetic and meteorological applications.

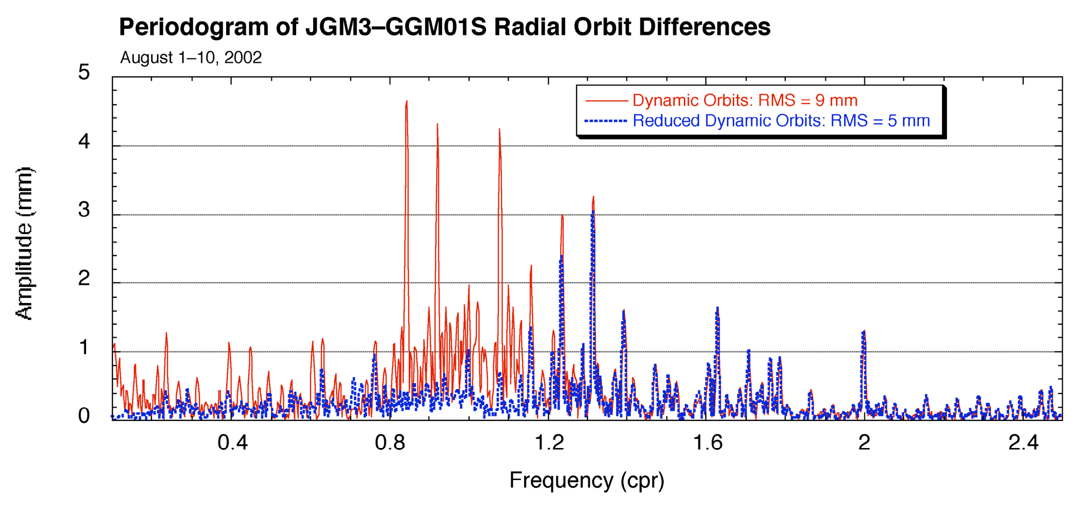
GRACE Gravity

The first static geopotential field models from the GRACE mission were publicly released in July 2003. Developed from GRACE data alone, GGM01S clearly outperforms JGM–3 in Jason-1 POD tests (e.g., high-elevation SLR and altimeter crossover residuals). Inasmuch as GGM01S is based on only three months of data—and JGM-3 was tuned with TOPEX/POSEIDON data—this is an important testament to the unprecedented performance of the GRACE mission. Shown below is a map of the reduced-dynamic (RD) orbit differences (JGM–3 minus GGM01S). We interpret the patterns as expressions of geographically correlated errors (GCEs) in our prior JGM-3–based RD solutions.

JGM-3 — GGM01S RD Orbit Differences for Repeat Cycles 1–62 (Global RMS = 4 mm)



To understand how these GCEs can be expressed in RD solutions, it is instructive to consider the nature of our Jason-1 RD filter. Designed to be forgiving of gaps in the BlackJack tracking data (e.g., from receiver resets and other outages), the filter targets orbit errors at frequencies lower than ~1.3 cycles-per-revolution (cpr). It is tuned to capture errors at the satellite resonance period (1 cpr), and modulations thereof, as well as lower frequencies. This characteristic of our filter is best depicted in a plot of the RD orbit differences in frequency space (below). For comparison, the frequency content of the radial orbit differences (JGM-3 minus GGM01S) from the corresponding dynamic solutions is also provided.

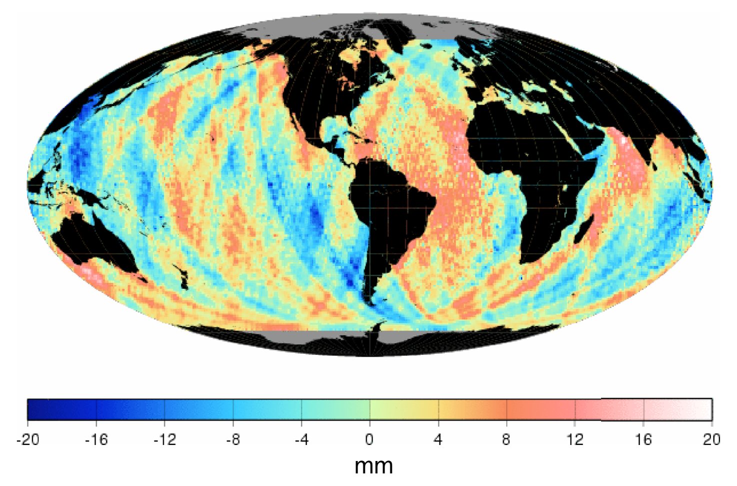


The efficacy of the RD filter in removing errors in a band framing the satellite resonance frequency (1 cpr) is clear. On the other hand, smaller amplitude errors at higher frequencies are not captured. The new GRACE gravity model allows us to mitigate these errors without relaxing the RD filter.

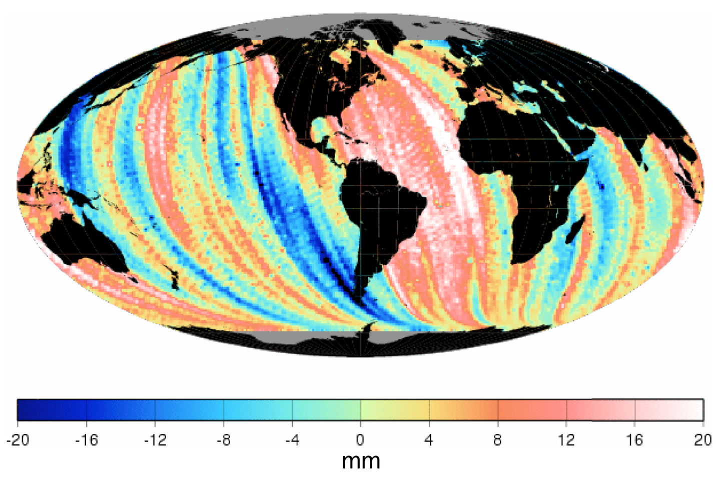
External Orbit Tests

COMPARISONS WITH GDR ORBIT: The precise orbit ephemeris (POE) on the GDR is computed by CNES using SLR+Doris data and the JGM-3 gravity model. We have compared our new GPS-based RD orbits to the CNES POE over the first 62 repeat cycles. The typical RMS radial difference is 15 mm, testifying to the high accuracy of both solutions. However, there remain important geographically correlated errors (GCE) in the differences. The mean GCE (top right panel) is reminiscent of the differences of the JPL RD orbits (JGM-3 vs GGM01s) shown previously, albeit with a larger magnitude and increased trackiness. The map of the ascending and descending GCEs are also given (below). The most conspicuous feature is a large anomaly on descending tracks that spans the Atlantic Ocean. We consider that the GDR orbit is the origin of most of the GCE, although GPS-induced errors cannot be entirely excluded.

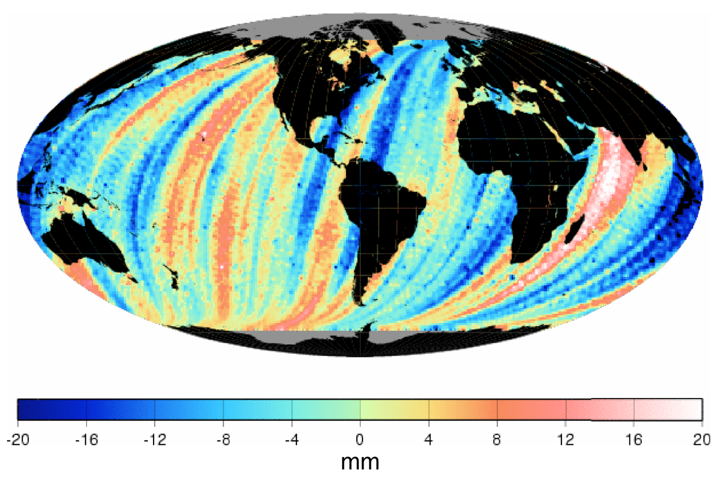
CNES POE — JPL GPS (Mean GCE, RMS = 8 mm)



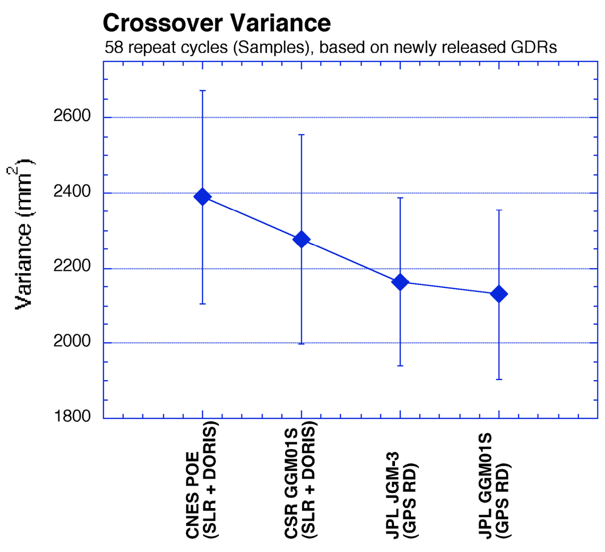
CNES POE — JPL GPS (Descending GCE, RMS = 9 mm)

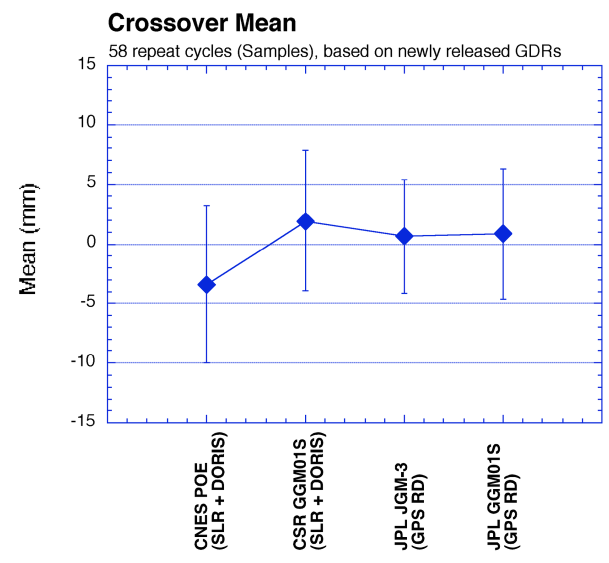


CNES POE — JPL GPS (Ascending GCE, RMS = 8 mm)



CROSSOVERS: We have evaluated four different Jason-1 orbit solutions using a common set of sea-surface height (SSH) crossover residuals for the first 58 repeat cycles. The SSH crossover residuals are formed from the newly released GDRs, and have been "superedited" to remove observations collected during extreme wind/wave conditions. Only crossovers formed within 3 days are considered, in order to mitigate the effects of changing ocean currents. Shown below are the crossover variance and mean statistics for the four contributing solutions. The variance and mean is computed within each repeat cycle, and then the overall statistic is generated by treating each repeat cycle as one of 58 samples:

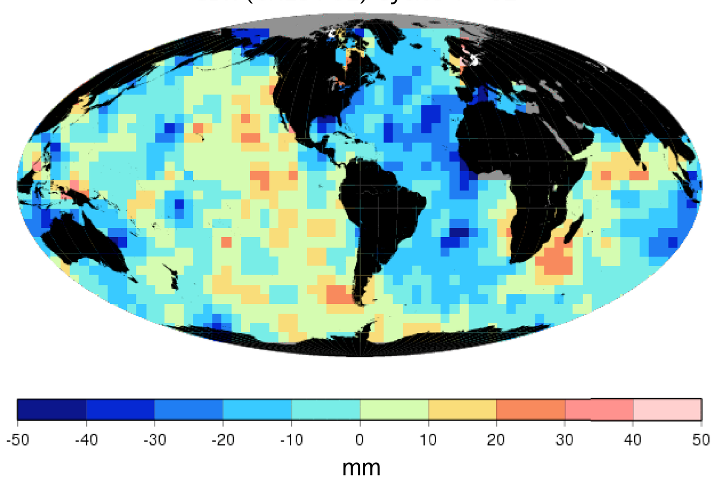




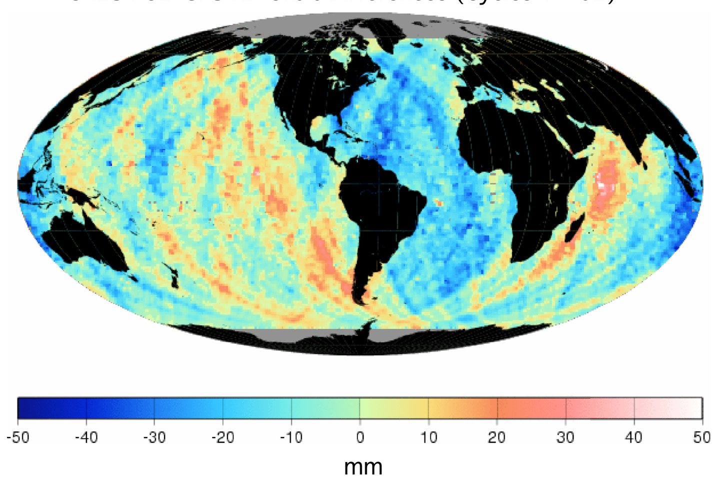
On average, the GPS-based RD solutions reduce the GDR crossover variance by 225 mm^2 (for the JGM-3 based solution) and 260 mm^2 (for the GGM01S-based solution). Also noteworthy is the 110 mm^2 improvement realized through use of new the CSR SLR+DORIS dynamic solutions. While smaller than the variance reduction experienced with the GPS RD solutions, this statistic hints at the potential benefit of switching to GGM01S (from JGM-3) in a traditional dynamic solution.

To provide further insight on potential GCEs, the "super-edited" SSH crossover residuals for the GDRs (based on the CNES POE) can be depicted geographically (left panel, below). The sense of the SSH comparison is "ascending – descending" (A–D). Under the assumption that the new GPS RD orbits are largely free of GCEs, we can simulate the expected pattern of the GCEs introduced in SSH crossovers by the CNES POE. This simulation is undertaken by forming the CNES POE — GPS RD orbit differences in crossover space (A–D). The result is depicted in the right panel (below).

Superedited Jason-1 SSH Crossovers
GDR (CNES POE) Cycles 1—62

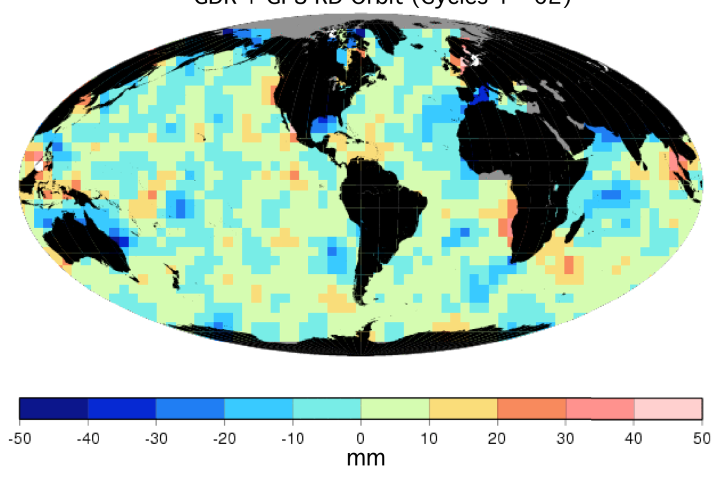


SSH Crossovers Simulated from
CNES POE–GPS RD Orbit Differences (Cycles 1—62)

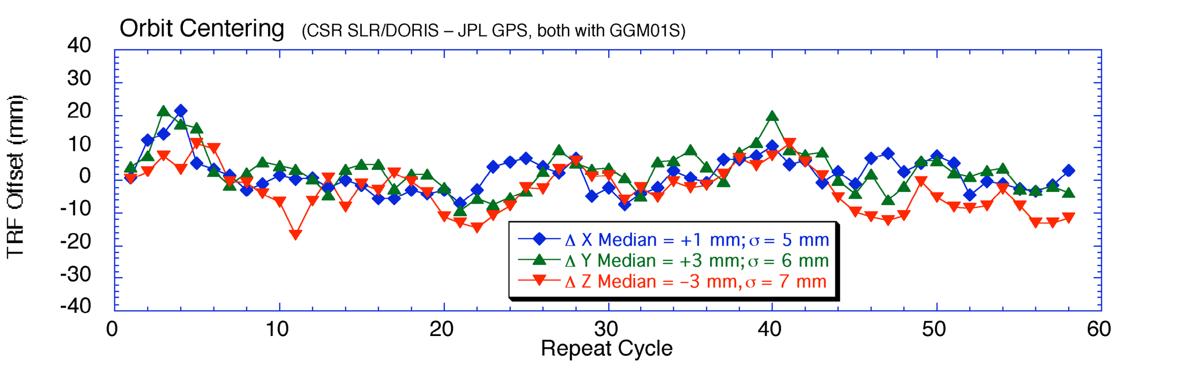


The striking resemblance between the plots (above) testifies to the skill of the new GPS RD orbits in exposing GCEs. It should be noted, however, that the use of the new GRACE gravity model may bear as much responsibility for this skill as the RD strategy itself. We can also map the same superedited GDR crossovers (A-D), substituting the new GPS RD orbit for the CNES POE (right). The GCEs are significantly attenuated, although some residual patterns are still discernable (e.g., off the coasts of southern Africa). As new GRACE gravity models are released, we will examine the results for evidence of further reduction of the GCEs.

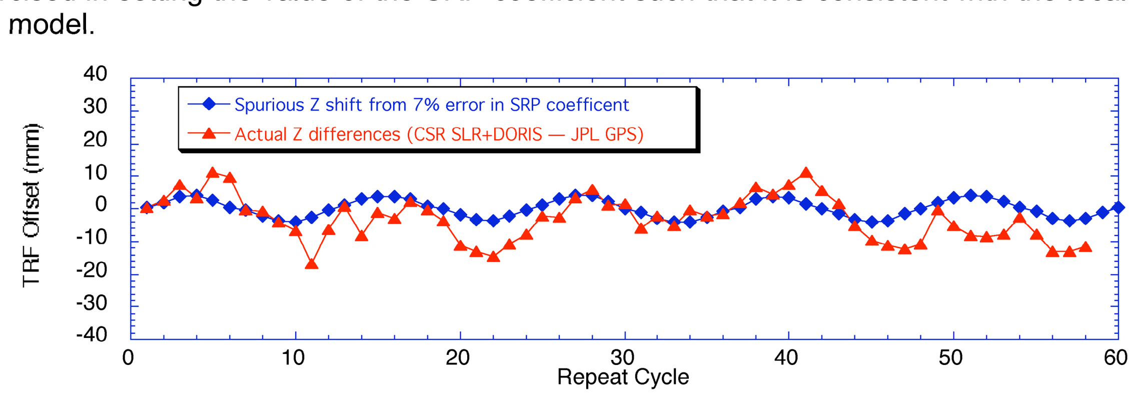
SSH Crossovers Simulated from
GDR + GPS RD Orbit (Cycles 1—62)



ORBIT CENTERING: Any miscentering of the orbit will manifest as a spurious, hemispherical pattern in SSH measurements. This type of GCE is common to ascending and descending tracks, and thus unobservable in crossovers. Comparisons between different orbit solutions, however, can expose problems in the relative centering. For this exercise, we have chosen to compare our GPS solutions with the CSR SLR+DORIS solutions. Shown below are cycle averages of the orbit differences in all 3 Cartesian coordinates of the terrestrial reference frame (TRF).



Both the mean and variable component of the centering differences are at the sub 1-cm level. While this is considered excellent agreement, the time series do exhibit systematic behavior, hinting that further improvement is possible. Some of the periodic behavior appears linked to β', the angle between the orbit plane and sun vector. This prompted us to investigate the solar radiation pressure (SRP) as one possible cause. The SRP coefficient (*Cs)* is not estimated routinely in contemporary POD strategies, owing to correlations with some of the empirical parameters. Our analysis, however, indicates that the GIPSY-based solutions (both GPS and DORIS) prefer a fixed value of 0.93 over the nominal value of 1.00. Shown in the following Figure is a plot of the centering error incurred along the spin (Z) axis if we use the nominal (1.00) rather than the preferred (0.93) value in our RD strategy. Superimposed on this curve are the actual Z differences of our best solution (using *Cs* = 0.93) w.r.t. the CSR orbit (from above plot). The correlation suggests that some of the behavior is due to varying treatments of the surface forces in competing orbit solutions. Our sensitivity study suggests that significant surface forces may remain–even after an RD or "parameterized dynamic" filter pass has been made–and can influence the centering of the orbit. Caution must be exercised in setting the value of the SRP coefficient such that it is consistent with the local implementation of the macro model.



We have performed preliminary tests with the new Jason-1 surface force model from University College London (Ziebart et al., see poster in this session). With the UCL model, the GIPSY-based Jason-1 solutions prefer a *Cs* close to the nominal value of 1.00. More important, the UCL model leads to slightly improved orbit overlap comparisons, particularly during fixed yaw periods. This model will be implemented in the next iteration of our RD solutions.

HIGH ELEVATION SLR RANGE BIASES: In one of the most powerful tests of radial orbit accuracy, the agreement between high-elevation SLR observations and the estimated orbit can be measured. The exercise represents an important closure test that reveals not only the GPS radial orbit error, but also potential unmodeled effects in the laser observations (e.g., LRA corrections, loading of SLR stations). The overall result is consistent with a radial orbit error at 1-cm the level (RMS). We expect that additional tuning of the strategy, and potential improvements to the BlackJack data (via receiver s/w upload) may improve upon this even further.