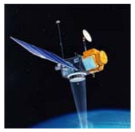

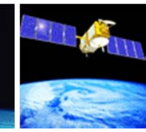

# Status of Precise Orbit Determination for Jason-2 using GPS, SLR, & DORIS data at NASA/GSFC

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## 1. ABSTRACT

The JASON-2 satellite, launched in June 2008, is the latest follow-on to the successful TOPEX/Poseidon (T/P) and JASON-1 altimetry missions. JASON-2 is equipped with a TRSR BlackJack GPS dual-frequency receiver, a laser retroreflector array, and a DGXX (7-channel) DORIS receiver for precise orbit determination (POD).

The most recent time series of orbits computed at NASA GSFC, based on SLR/DORIS data have been completed using both ITRF2005 (std0905) and ITRF2008 (std1007). These orbits have been shown to agree radially at 1 cm RMS for dynamic vs SLR/DORIS reduced-dynamic orbits and in comparison with orbits produced by other analysis centers (Lemoine et al., 2010; Zelensky et al., 2010; Cerri et al., 2010). We have recently upgraded the GEODYN software to implement model improvements for GPS processing. We describe the implementation of IGS standards to the Jason2 GEODYN GPS processing, and other dynamical and measurement model improvements.

Our GPS-only JASON-2 orbit accuracy is assessed using a number of tests including analysis of independent SLR and altimeter crossover residuals, orbit overlap differences, and direct comparison to orbits generated at GSFC using SLR and DORIS tracking, and to orbits generated externally at other centers. Tests based on SLR and the altimeter crossover residuals provide the best performance indicator for independent validation of the NASA/GSFC GPS-only reduced dynamic orbits (gps_red_std0905). For the ITRF2005 and ITRF2008 implementation of our GPS-only obits we are using the IGS05 and IGS08 standards. Reduced dynamic versus dynamic orbit differences are used to characterize the remaining force model error and TRF instability. We evaluate the GPS vs SLR & DORIS orbits produced using the GEODYN software and assess in particular their consistency radially and the stability of the altimeter satellite reference frame in the Z direction for both ITRF2005 and ITRF2008 as a proxy to assess the consistency of the reference frame for altimeter

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## 2. POD Challenge

The long-term stability and precision of the satellite orbit is a critical component of the Jason-2 (OSTM) mission, providing the reference frame for ocean mapping using altimeter data. A very demanding 1-cm radial orbit accuracy and an implied sub-mm/year orbit stability goal objective has been set by the Jason-2 OSTM community. Achieving and maintaining such levels of orbit accuracy requires: 1) the best possible POD modeling and parameterization, 2) the implementation of the most recent terrestrial reference frames (TRFs) 3) the careful monitoring of the health of the tracking systems used for POD, 4) product validation and inter comparisons with external analysis centers. Previously the GPS/SLR/DORIS dynamic orbits have been determined to an accuracy close to 1-cm (*Zelensky et al. 2010, Lemoine et al. 2010, Cerri et al. 2010, Bertiger et al. 2010*). *Luthcke et al. (2003)* have also demonstrated 1cm GPS orbit accuracy for Jason-1.

## 3. GPS strategy

- 32 IGS05 and IGS08 stations
- Tracking data : DD LC iono-free tracking data
- GPS PCOs and PCVs : igs05.atx and igs08_1604_woGLO_final
- IGS05 and IGS08 (w station corrections) TRF
- 1/hr scale(wet+dry) troposphere (GMF/GPT-hopfield) s1
- Float ambiguities
- J2 JPL GPS antenna PCV map
- J2 revised LC GPS antenna PCO values
- Solutions S1 : troposphere is adjusted /1 hr using 2 paths (1 station + 2 GPS s/c) during the POD
- Solutions S2 : troposphere is adjusted /1 hr using 4 paths (2 stations + 2 GPS s/c) in a ground network solution

## 4. Jason-2 GPS antenna Phase Center Offset (PCO) and Phase Center Variations (PCV) modeling

In our Jason-2 GEODYN GPS processing we use double differences (DD) iono-free carrier phases where a set of IGS receiver and transmitter PCOs and PCVs are incorporated (IGS05). We determine the in-flight Jason-2 GPS antenna PCOs and PCVs by the use of the direct approach (*Luthcke 2003, Jäggi 2009*). In this approach iono-free PCOs and PCVs are directly set up as estimation parameters when processing the DD GPS iono-free observations. The Jason-2 PCOs and PCVs are estimated in two separate runs. In a first run we keep the PCV values to an initial map (JPL) fixed and solve only for the Jason-2 PCOs in SOLVE. The antenna offset arc parameters are defined as common parameters and estimated either allowing the arc orbit parameters to enter the solution (back-substitution) or suppressing the arc orbit parameters from the solution. When the arc parameters are allowed to freely adjust together with the antenna offsets (back-substitution), the offset estimates in X and Y per 10-day cycle are unreliable (Fig. 1c). For comparison we also include the DORIS PCO determination (Fig. 1a and Fig. 1b)

Fig 1a : J2 DORIS antenna X-PCO estimate (std1007)

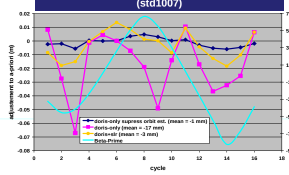



Fig 1b : J2 DORIS antenna Y-PCO estimate (std1007)

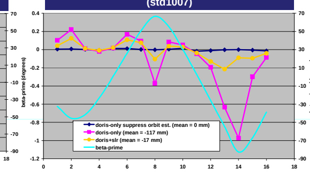



Fig 1c : J2 GPS antenna 3D-PCO estimate (gpsr_std0905)

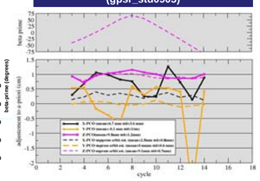



Fig 2a : JPL J2 GPS PCV map

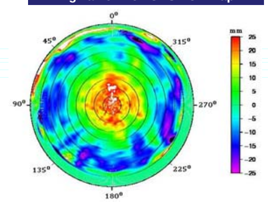
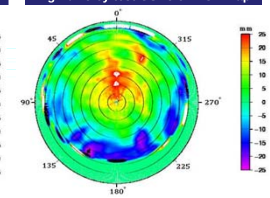



Fig 2b : 3-cy test GSFC J2 PCV map




In a second step, the PCVs are neglected in the modeling of the carrier phase observations. The daily normal equations are then accumulated using SOLVE into a combined system, and are inverted to solve for the PCV corrections. The degraded J2 orbit are introduced as known and PCVs are estimated on a grid of 10° in elevation and 1° in azimuth. The procedure is repeated iteratively till convergence and for a new set of PCOs and PCVs internally consistent. The neglected PCVs are correctly recovered by the direct approach. This approach is not harmed by the estimation of the ambiguity parameters. All DD troposphere parameters are considered known from a separate ground station solution where only precise ground station PCOs and PCVs were used. Up to this step we've only tested our procedure by producing a 3-cy PCV map (Fig. 2b) and compared it to the one from the JPL (Fig 2a).

**Acknowledgements**: to *Oleg Bordyugov* for the PCV plots

## 5. GPS orbit Performance

The dense and highly precise Jason-2 GPS tracking provides significant improvement for POD capability. To better evaluate this a reduced-dynamic (RD) technique is applied to process the GPS data alone. The concept of RD solution is based on the denser geometrically stronger GPS tracking data rather than the force model accuracy (*Luthcke et al. 2003*). In our GEODYN RD implementation once per-rev (OPR) along & cross-track accelerations are estimated every 30 min with sigma=1.e-09 and correlation time of 1hr. As indicated by the independent crossover residuals the RD gpsr_std0905 and jpl_gpsr_rlse10a orbits show the greater accuracy over cycles 3-14 (Table 1). Also the newly IGS08 incorporated RD orbits gsfc_gpsr_igs08_s2 compare at the same level (bottom of Table 1). The lowest crossover residuals come from both the gpsr_std0905_s1 and jpl_gpsr_rlse10a orbits.

**Table 1 : J2 orbit performance summary cycles 3-14**

| test | mean points | | mean RMS residuals | | |
|---|---|---|---|---|---|
| | doris | slr | doris (mm/s) | slr (cm) | xover (cm) |
| dyn slr+doris std0905 | 161242 | 2582 | 0.3687 | 1.070 | 5.550 |
| red slr+doris std0905 | 161242 | 2582 | 0.3680 | 1.052 | 5.502 |
| gpsr_std0905_s1 * | 161242 | 2582 | 0.3689 | 1.430 | 5.453 |
| jpl_gpsr_rlse10a * | 161242 | 2582 | 0.3685 | 1.128 | 5.424 |
| cnes_ldg_gdrc | 161242 | 2582 | 0.3689 | 1.047 | 5.554 |
| | | | | | |
| gpsr_std0905_s1 | 160526 | 2574 | 0.3694 | 1.429 | 5.463 |
| gpsr_std0905_s2 | 160526 | 2574 | 0.3695 | 1.489 | 5.470 |
| gpsr_igs08_s2 | 160526 | 2574 | 0.3699 | 1.567 | 5.493 |

* independent data

In terms of radial orbit error budget (systematic and random contributors to the 1-cm radial error) the gsfc_gpsr_std0905 orbits also compare the best (Table 2 and Fig. 3) to the jpl_gpsr_rlse10a in the satellite frame. All orbits compare within 1cm radially. The best inter-technic agreement in the orbit frame comes from GPS-only orbits.

## 6. Orbit and satellite/TRF frame (radial/cross/along + 7p Helmert)

**Table 2 : Jason-2 GPS orbit differences Summary cycles 3-14**

| Orbit differences | RMS (cm) | | | | Mean ECF (cm) | | |
|---|---|---|---|---|---|---|---|
| | radial | cross track | along track | 3D total | X | Y | Z |
| gpsr_std0905_s1-std0905 | 1.12 | 1.81 | 3.37 | 4.00 | 0.02 | 0.28 | 0.48 |
| gpsr_std0905_s1-red_std0905 | 0.92 | 1.71 | 2.75 | 3.38 | -0.06 | 0.29 | 0.43 |
| gpsr_std0905_s1-red_std1007 | 0.87 | 1.69 | 2.71 | 3.32 | 0.08 | -0.18 | -0.19 |
| gpsr_std0905_s1-jpl_gpsr_rlse10a | 0.73 | 0.97 | 1.88 | 2.24 | -0.21 | 0.51 | 0.28 |
| gpsr_std0905_s1-cnes_ldg_gdrc | 1.03 | 1.25 | 2.64 | 3.10 | 0.08 | 0.29 | 0.65 |
| gpsr_std0905_s1-gpsr_std0905_s2 | 0.32 | 0.30 | 0.83 | 0.94 | 0.00 | 0.00 | 0.09 |
| gpsr_std0905_s2-gpsr_igs08_s2 | 0.69 | 0.58 | 2.08 | 2.29 | -0.16 | 0.01 | -0.10 |

Fig. 4 : J2 Mean radial orbit differences over water (cnes_gdrc - test)

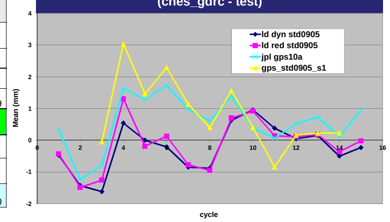



**Table 3 Helmert translation parameter estimates**

| Test cycles 3-14 | Mean (mm) | | | standard deviation (mm) | | |
|---|---|---|---|---|---|---|
| | Tx | Ty | Tz | Tx | Ty | Tz |
| gpsr_std0905_s1 (GPS)- red_std1007_dor (DORIS) | -1.3 | -0.1 | 1.6 | 2.6 | 2.4 | 4.4 |
| gpsr_std0905_s1 (GPS) - red_std0905_dor (DORIS) | -1.3 | 2.7 | 3.9 | 2.5 | 2.4 | 5.4 |
| gpsr_std0905_s2 (GPS) - red_std1007_dor (DORIS) | -1.1 | -0.2 | 1.2 | 2.2 | 2.3 | 5.1 |
| gpsr_std0905_s2 (GPS) - red_std0905_dor (DORIS) | -1 | 2.7 | 3.4 | 2 | 2.3 | 4.7 |
| gpsr_stdIGS08_s2 (GPS) - red_std0905_dor (DORIS) | -2.4 | 2.9 | 2.7 | 2.1 | 2.3 | 3.6 |
| gpsr_stdIGS08_s2 (GPS) - red_std1007_dor (DORIS) | -2.4 | 0 | 0.5 | 2.5 | 2.4 | 3.6 |
| gpsr_std0905_s1 (GPS) - red_std0905 (SLR/DORIS) | -0.5 | 1.5 | 2.8 | 2.2 | 2.3 | 3.7 |
| gpsr_std0905_s1 (GPS) - red_std1007 (SLR/DORIS) | -1.1 | 1.4 | 2.5 | 2.8 | 2.7 | 4.1 |
| gpsr_std0905_s2 (GPS) - red_std0905 (SLR/DORIS) | -0.7 | 2.5 | 4.4 | 2.5 | 2.7 | 4.6 |
| gpsr_std0905_s2 (GPS) - red_std1007 (SLR/DORIS) | -0.9 | 1.3 | 2.1 | 2.6 | 2.8 | 4.9 |
| gpsr_stdIGS08_s2 (GPS) - red_std0905 (SLR/DORIS) | -2.1 | 2.7 | 3.6 | 2.6 | 2.6 | 3.2 |
| gpsr_stdIGS08_s2 (GPS) - red_std1007 (SLR/DORIS) | -2.2 | 1.5 | 1.4 | 2.7 | 2.7 | 3.5 |
| gpsr_stdIGS08_s2 (GPS) -jpl_gpsr_rlse10a (GPS) | -3.5 | 5 | 2.8 | 1.8 | 1.5 | 1.2 |
| gpsr_stdIGS08_s2 (GPS) -gpsr_std0905_s2 (GPS) | 0 | -1.4 | 0.1 | 0.1 | 1.2 | 1.5 |

Fig. 3 J2 RMS radial orbit differences (gpsr_std0905_s1 - test)

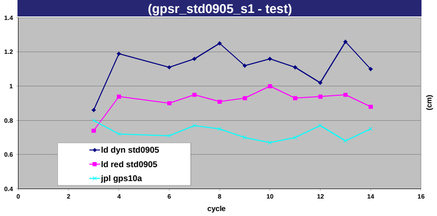
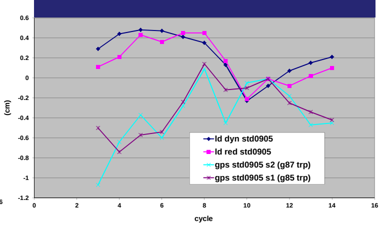
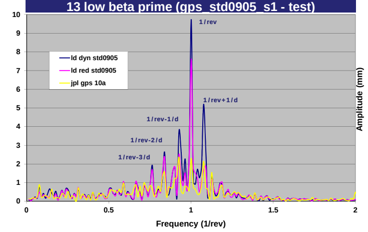



Fig. 5 : J2 mean Z orbit differences (jpl gps10a - test)




## 7. Spectral Analysis

Fig.6 : J2 periodogram radial orbit differences cycle 13 low beta prime (gps_std0905_s1 - test)




## 8. SLR residuals

Fig. 7 : Jason-2 SLR residuals cycles 3-14 binned by elevation angle

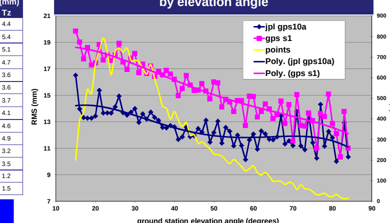
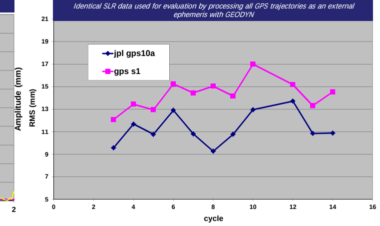



Fig. 8 : Jason-2 independent SLR residuals

*Identical SLR data used for evaluation by processing all GPS trajectories as an external ephemeris with GEODYN*




## 9. Discussion

### Satellite and TRF frame (Table 2, Fig.3, Fig. 4 and Fig.5)

- Table 2 : 5 mm Y-shift difference between jpl_gpsr_rlse10a and our gpsr_std0905 RD orbits implies probably a network effect.
- Table 2 : A NS positive Z-shift of 5 mm is observed between gpsr_std0905 RD orbits and our SLR/DORIS ITRF05 RD orbits. The Z-shift offset between the gpsr_strd0905 and gps_stdIGS08 orbits is -1 mm and is consistent with the effect of transitioning from IGS05 to IGS08 TRF where the TZ is ~ 5mm (see presentation from *Paul Rebischung et al. 2011*). According to *Cerri et al. (2010)* and *Morel and Willis (2005)* the shift induced on Jason GPS-only orbits is about 30% of the TZ displacement applied to the GPS stations. Although *Cerri et al. (2010)* refers to the GPS constellation we believe that this applies also to the GPS stations reference frame since only those are in the IGS08 in our current gps_stdIGS08 orbit set.
- Cy03-14 Z-orbit differences (Fig. 5) do not provide the necessary time-span in order to confirm if any 120-d signal is detected as seen by *Zelensky et al. (2010)* but nonetheless both the JPL and GSFC GPS orbits compare well. The same common behavior is also observed to the radial orbit differences over the ocean water (Fig. 4).

### SLR residuals (Table.1, Fig. 7 and Fig. 8)

- residuals binned by elevation angle (Fig. 7), demonstrate that the gpsr_std0905 orbits have poor RMS at low elevations due to cross & and along track difference, while converging very well radially compared to the jpl_gpsr_rlse10a. The overall agreement is 1.43 cm and 1.12 cm respectively (Table.1 and Fig. 8).

### Spectral analysis (Fig. 6)

- 1m-daily dominated by the TVG model error (*Zelensky et al. 2010, Bertiger et al. 2010*). 1/rev signal largely reflects error probably in the non-conservative force modeling.

## 10. Future work

- Process the rest of the J2 GPS cycles with the current std0905 and produce 2 sets of products a GPS-only and a combined GPS/SLR product.
- Produce an internally consistent Jason-2 GPS PCV map from 12 cy
- Revisit and expand the ground network and re-process all cycles for IGS08
- Implement a hybrid DD ambiguity fixing, incorporate zero-difference tracking data, and optimize the troposphere modeling and estimation strategy