IMPROVING THE TOPEX/POSEIDON ORBIT USING DORIS TRACKING

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ABSTRACT *- The DORIS radial accuracy Mission objective for TOPEX/POSEIDON (T/P) has been satisfied, with 2-3 cm NASA Precision Orbit Ephemeris (POE) orbits routinely produced. However, with refined measurement modeling it may be possible to take greater advantage of the dense tracking DORIS has to offer to further improve the accuracy of the POE. Tests include using time correlated troposphere estimation, the ITRF97 station coordinates, improved station weighting, and precise timing bias estimates. Subsequent application of the reduced-dynamic approach in GEODYN using current DORIS and SLR tracking may further improve the T/P POE, and will contribute to a better understanding for meeting the 1-cm JASON goal.*

Introduction

DORIS is a globally distributed, all-weather system providing nearly continuous (80 %) precise Doppler tracking of TOPEX/POSEIDON (T/P). Precise Orbit Ephemeris (POE) orbits computed by the Precise Orbit Determination and Production System (PODPS) at GSFC have a radial accuracy of 2-3 cm, and rely on DORIS and Satellite Laser Ranging (SLR) tracking. Orbits computed using only DORIS compare to the POEs to within 2-cm (Fig1). However, we believe the full potential of DORIS tracking for current T/P precise orbit determination (POD) has not been realized. This paper investigates modifications of the current POD strategy (Table 1) to make better use of DORIS data.

POD Strategy

The current POD strategy for processing DORIS weakens the modeled measurement. Preliminary tests evaluate increasing measurement strength, improving the measurement modeling, and taking greater advantage of the nearly continuous coverage (Table 2). The tests were conducted using GEODYN [Rowlands 1999], a least squares orbit determination program which is also used to compute the POEs. Several indices used in this report to gauge orbit accuracy include SLR residuals, orbit differences with the POE and orbit differences with the JPL reduced-dynamic orbit computed using GPS tracking [Bertiger 1994]. For the test case selected, Cycle 046, the JPL reduced-dynamic is considered the most accurate orbit available [Zelensky 1996]. However it must be acknowledged that improvements past levels of 2-cm orbit accuracy may be difficult to measure definitively or sometimes even identify.

Compared to SLR, DORIS residuals are not sensitive to orbit error. For example, the significant improvement in the 2nd generation POE [Marshall 1995], is clearly seen by the improvement in SLR fits starting with cycle 92, but not with the DORIS (Fig 2). On the one hand the DORIS measurement itself (viewed as a range difference) is not so sensitive to orbit error, which will be smooth over the duration of a pass. On the other hand, some of the residual orbit (and other) signal may be absorbed in the unconstrained pass-by-pass adjustment of the DORIS troposphere and measurement biases, and therefore not present in the DORIS residuals.

In a test arc the level of orbit error is increased two-fold, by modifying the POD strategy to reduce the standard number of adjusted parameters: from 3 drag coefficients/day to 1/day, and from 1 cycle-per-revolution (1cpr) empirical acceleration / day to 1/10-day arc. As show in Fig 3, the SLR residuals increase two-fold, whereas the DORIS stay about the same. Analysis of the residuals for information content is conducted by applying a least-squares adjustment of a measurement and timing bias to each pass of GEODYN residuals. Such an adjustment is believed to remove the remaining signal, leaving what is considered to be noise. This residual analysis applied to our test arc shows the level of signal in SLR residuals increases dramatically for the test arc, whereas the level of signal in the DORIS residuals stays about the same (Fig. 3). Notice the level of estimated noise remains the same between the nominal and test arcs, as expected. This test suggests that the residual orbit signal is distributed in the pass-by-pass DORIS measurement and troposphere bias adjustments rather than remaining in the DORIS tracking residuals (Fig 4).

Measurement Bias

In Doppler measurements the difference between the beacon and receiver frequencies is an unknown quantity which must be accounted for (Fig 5). In our solution this quantity is represented by the measurement bias adjusted for every DORIS pass. However, the satellite receiver and ground beacon frequencies are very stable and well calibrated so that their difference may not require re-estimation for each pass of data. In fact looking at the station average of the pass-by-pass biases shows little variation in the bias values for a given station or even between stations (Fig 5).

Adjusting only one DORIS measurement bias over the entire arc only slightly degrades the SLR fit, but dramatically increases the signal content of the DORIS residuals (Fig 6). Now, changes in the level of orbit error are better represented by the DORIS residuals (Table 3).

This example illustrates that a pass-by-pass adjustment of the DORIS biases removes a considerable amount of orbit and possibly other signal from the DORIS residuals. A more sophisticated strategy for constraining DORIS bias adjustment may be found to take advantage of the increase in orbit signal and to improve POD. In fact even adjusting the measurement bias by-station moves the orbit closer to the JPL reduced-dynamic (Table 4).

Troposphere Bias

The strategy of freely adjusting the troposphere bias for each pass of data may also be improved with the application of constraints. The delay due to refraction caused by the troposphere is computed using the Hopfield model. Surface meteorological (SM) temperature, pressure, and humidity measurements provided by each ground station are used to better represent the “dry” and “wet” components of the delay. Although the wet component comprises only about 10% of the total delay, it is highly variable and SM data is not sufficient for adequate modeling [Tralli 1990]. Thus a troposphere bias is adjusted to account for the variation. Typically a station will track the satellite with 3-4 pass per day with at least two successive passes separated by no more than 112.5 minutes (one orbit revolution). As a first cut, an exponentially correlated time constraint (Fig 7) between passes for the same DORIS station is applied to the adjustment of troposphere biases (Fig 8). The assumption made here is that on average for a given station, the weather (humidity) will not dramatically change over short periods of time (90 minutes). Not surprisingly, the DORIS fits slightly increase upon application of these constraints, but the orbit also moves a little closer to that of the JPL reduced-dynamic (Table 4). These preliminary results looks promising and encourage further study. The physical significance of the adjusted troposphere bias values and applied constraints remain to be evaluated. Also other studies have shown that better troposphere bias constraints can be applied [Willis 1998].

DORIS network time bias

The DORIS time tag is estimated using the two master beacons (Toulouse and Kourou) and is thought to be accurate to about 6 microseconds [Berthias 2000]. It is interesting and useful to evaluate an offset of the DORIS time wrt SLR network time, believed to be accurate to 1 microsecond. This offset, or DORIS network time bias is routinely adjusted over a 10-day arc to align the DORIS and SLR time systems for orbit computation (Fig 9). Although a daily estimate is possible (Fig 9) and is used to identify the rare anomalies in DORIS data, its effect on the orbit is minimal (Table 4).

DORIS station position and velocity

DORIS-only solutions using both the nominal CSR95D01 and the ITRF97 DORIS station complements. were evaluated over 17 cycles spanning 940409 – 000301. The average DORIS fits with the ITRF97 are somewhat better (0.538 mm/s) than with the CSR95D01 (0.544 mm/s). SLR data did not contribute to the solutions but was included to evaluate the DORIS-only orbits also shows lower average fits with the DORIS ITRF97 stations (5.37 cm vs 6.04 cm). Graphs of the DORIS-only solutions testing the ITRF97 station complement more clearly indicate that the ITRF97 position and especially velocity values are superior to the CSR95D01 set used by PODPS (Fig 10). On the other hand, but using a much smaller subset of 4 arcs spanning 930409-000307, SLR-only solutions with CSR95L02 show consistently better fits than when using the ITRF97 SLR station complement (on average 3.13 cm vs 3.38 cm). These results are consistent with tests using the LAGEOS satellite. The degradation of the DORIS CSR station position accuracy over time can explain the progressive divergence of the DORIS-only orbit from that of the POE (Fig 1 and Fig 11). It is expected that CSR will shortly release a new DORIS and SLR station solution [Ries 2000]

Enhanced Parameterization

Given the strong, spatially and temporally very dense coverage provided by DORIS, one can consider the application of a reduced-dynamic technique to further reduce residual accelerations and orbit error which remain in a dynamic solution [Barotto 1995]. The POE is the product of a dynamic solution. Such an approach which allows the simultaneous adjustment of the orbit state and other parameters together with exponentially constrained, closely spaced empirical accelerations (Fig 7), has been implemented in GEODYN, and will be referred to as “enhanced parameterization”.

For these preliminary tests, 1cpr along and cross-track accelerations spaced every 30 minutes and constrained with $5x10^{-10}$ m/s^2 steady-state sigma and 15 minute correlation time (Fig 7) were simultaneously adjusted with the orbit state and other parameters over a 10 day arc. The choice of the preliminary constraints is empirically based, and depends on the strength of tracking and degree of measurement error.

It appears that such an approach works best for a combination of SLR and DORIS data which includes the constrained troposphere adjustment (Table 4). Orbit overlap differences between arc ends over cycles 43-48 indicate that the “enhanced parameter” orbits are more consistent than the dynamic POEs (Fig 12).

As SLR global tracking is lopsided, with only a few stations in the Southern Hemisphere, care must be given to selecting relative weights between SLR and DORIS in the enhanced parameter solution. The geographical bias in the SLR tracking may induce a 1/rev-orbit error which the SLR fits would not detect.

Indeed the correlation between the SLR tracking density and the dynamic – "enhanced parameterization" orbit difference increases with increased weight given to the SLR data (Table 5). It appears a larger weight should be given to DORIS in the enhanced parameterization solution than what is assigned in the nominal dynamic solution (Table 6).

Summary

This study has shown that the ITRF97 DORIS station and especially velocities are superior to the CSR95D01 complement currently used by PODPS. A new CSR station solution is anticipated to become shortly available.

The dense DORIS tracking allows a reduced-dynamic approach for POD. Orbit overlap consistency and SLR data fits suggest the preliminary "enhanced parameter" POE offers a small improvement over the "dynamic" POE orbits. However, evaluation of the 2-3 cm orbits also demonstrates the need for improved orbit accuracy tests.

DORIS offers a powerful satellite tracking capability whose full potential for POD has yet to be realized. The DORIS modeled observation is weakened by the current POD strategy of unconstrained adjustment of pass-by-pass measurement and troposphere biases. The application of crude constraints dramatically increases the level of signal in the DORIS residuals, and in the case of the troposphere appears to even improve the orbit. We will continue our investigation of bias constraints which will strengthen the modeled observation and improve POD accuracy.

Acknowledgments. We thank Ron Williamson for his helpful comments, fruitful advise, and the many discussions of T/P orbits and DORIS data.

Table 1. **T/P Precise Orbit Determination (POD) Strategy using GEODYN**

Model Category	**Description**
Geophysical models	
Gravity	JGM3
Ocean/Earth Tides	T/P Ray '94 / Wahr
Atmospheric density	DTM '87
Spacecraft geometry and surface forces	2nd generation tuned macro model
Station Coordinates	CSR95L02 SLR , CSR95D01 DORIS
Earth Orientation Parameters	CSR95L02 from LAGEOS tracking
Secular pole rate	Gross (Space 1993)
Geocenter motion	T/P Ray '94 tide model
Planetary Ephemeris	DE200
Measurement Model	
SLR	CoM provided, computed LRA offset, analytical attitude
Doppler	CoM provided, *a priori* antenna offset, analytical attitude
Tracking Data Weights	
SLR	10 cm
DORIS	2 mm/sec
Estimated Parameters	Orbit state, Atmospheric drag C_D coefficient per 8 hours Along-track 1cpr empirical acceleration per day Cross-track 1cpr empirical acceleration per day DORIS measurement and troposphere bias per pass DORIS network time bias per 10-day arc

Table 2. Tests for Improving the POE

Model	POE	Test
DORIS measurement bias adj.	unconstrained pass-by pass	one measurement bias
DORIS troposphere bias adj.	unconstrained pass-by pass.	constrained every 90 minutes / station
DORIS network time bias adj.	over 10-day arc	over 1 day
DORIS station positions	CSR95D01	ITRF97
Empirical acceleration (1cpr along and cross-track) adjustment	unconstrained, every 24 hours	constrained, every 30 minutes

Table 3. Test (double the orbit error) Vs Nominal solution RMS Residuals

Solution	SLR (cm)	DORIS (mm/s)
Pass-by-pass DORIS bias		
nominal	2.7	.563
test (double the orbit error)	5.3	.571
One DORIS bias		
nominal	3.0	.922
test (double the orbit error)	5.4	.943
Test (double the orbit error) minus Nominal residual difference		
pass-by-pass DORIS bias Δ RMS	4.5	.1
one DORIS bias Δ RMS	4.6	.2

Table 4. Sensitivity to Possible Orbit Improvements (Cycle 46)

Solution	DORIS fit (mm/s)	SLR fit (cm)	Radial orbit difference (cm)	
			POE	JPL reduced-dynamic
Nominal POE (SLR+DORIS)	.563	2.73	---	1.74
Nominal DORIS-only	.562	5.07	1.70	1.91
1) POE: adjust 1 DORIS meas. bias	.922	2.97	0.75	1.74
2) POE: adjust DORIS meas. bias / station	.893	2.99	0.82	1.71
3) POE: constrain DORIS troposphere adj.	.578	2.74	0.11	1.72
4)POE: daily DORIS timing bias adj.	.562	2.71	0.15	1.77
5) POE: constrain empirical accel. adj.	.563	2.48	0.96	1.76
Enhanced parameterization combinations				
a) Nominal POE (5+3)	.577	2.49	0.96	1.72
b) Nominal DORIS-only (5+3)	.575	5.47	1.72	1.89
c) POE adj. 1 DORIS meas. bias (5+3+1)	.937	2.86	1.57	2.16

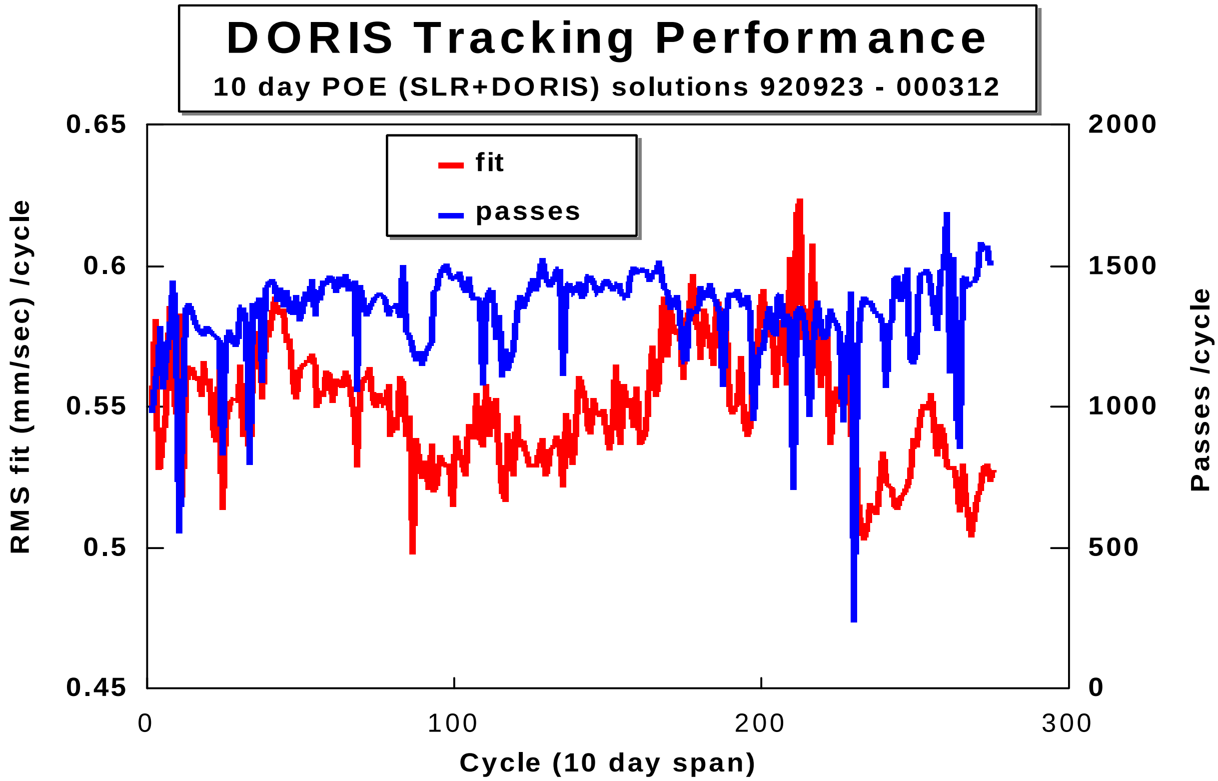
Table 5. Cross Correlation: SLR Data Density –Vs- Orbit Difference (POE – Enhanced Parameter) (Correlation coefficients at lag time = 0)

Enhanced Parameter data sigma weight		Radial	Cross-Track	Along-Track
SLR (cm)	DORIS (mm/s)			
10	2	-.45	-.32	-.50
10	1	-.40	-.31	-.44
10	.5	-.22	-.26	-.29
10	.2	-.03	-.29	-.10

Table 6. Test Solution Orbit Difference wrt JPL GPS Reduced Dynamic (cm)

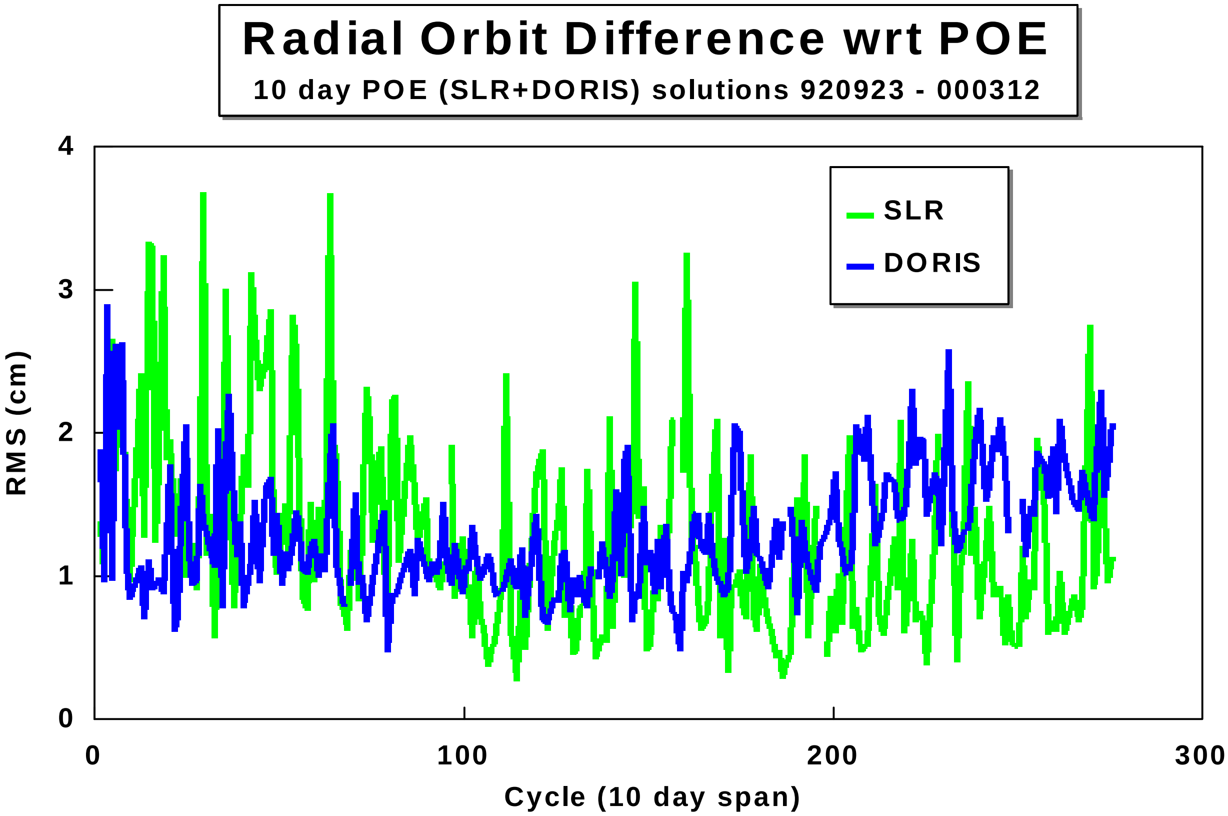
Test Solution (Cycle 046)		Radial	Cross-Track	Along-Track
Nominal POE		1.74	4.56	5.09
Nominal DORIS-only		1.91	7.52	5.53
Enhanced Parameter data sigma weight				
SLR (cm)	DORIS (mm/s)			
10	2	1.72	3.96	4.63
10	1	1.65	3.44	4.11
10	.5	1.91	3.28	5.91
---	DORIS-only	1.89	4.11	6.02

Figure 1.



DORIS Tracking Performance

10 day POE (SLR+DORIS) solutions 920923 - 000312



Radial Orbit Difference wrt POE

10 day POE (SLR+DORIS) solutions 920923 - 000312

Figure 2.

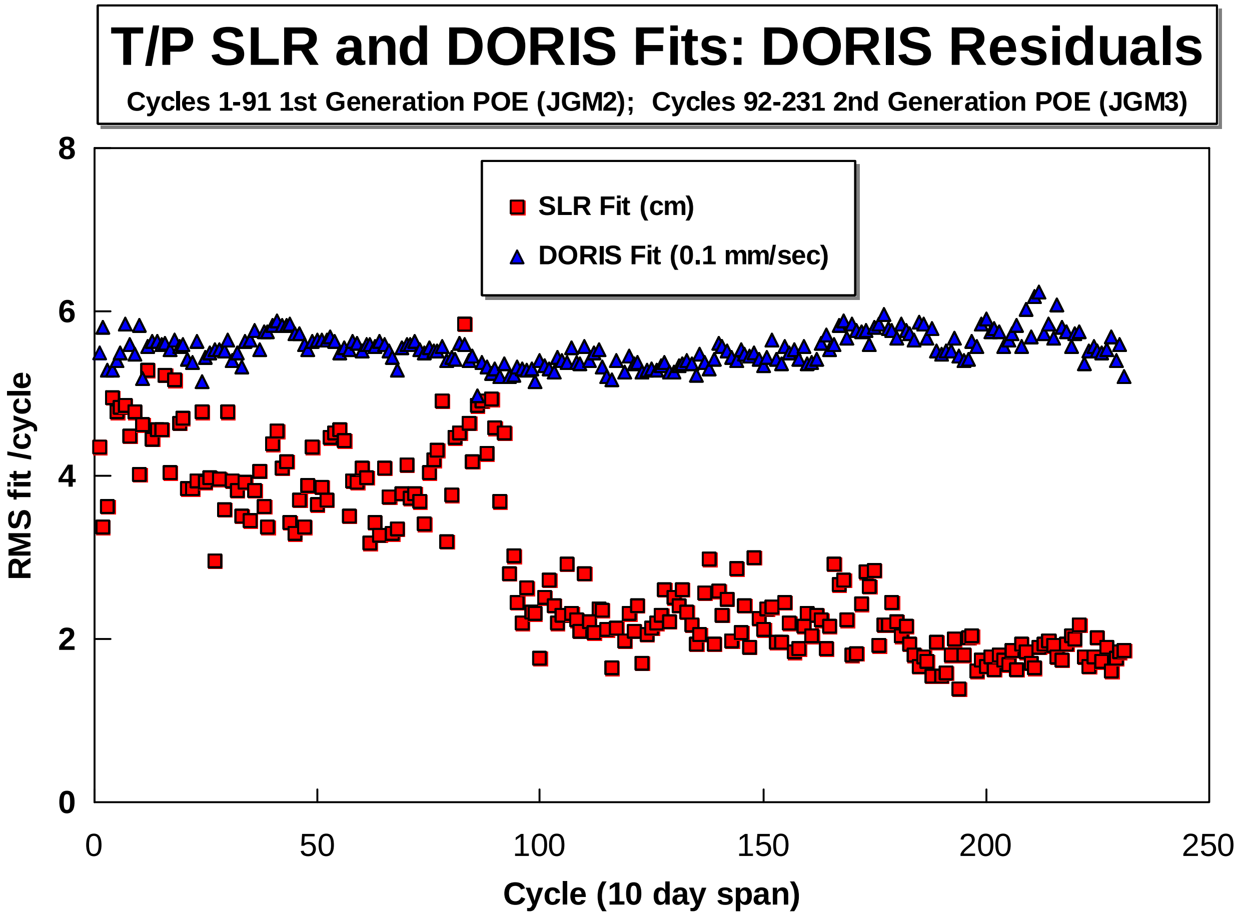
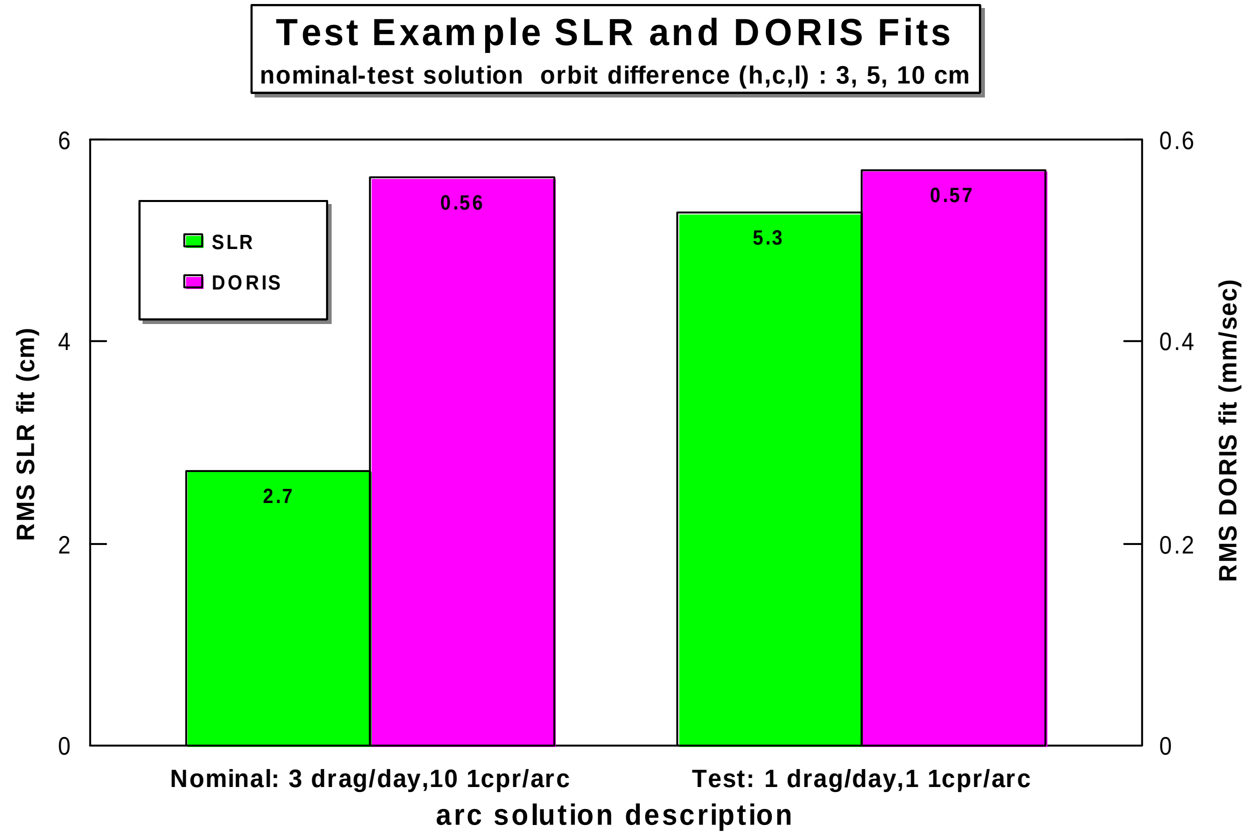
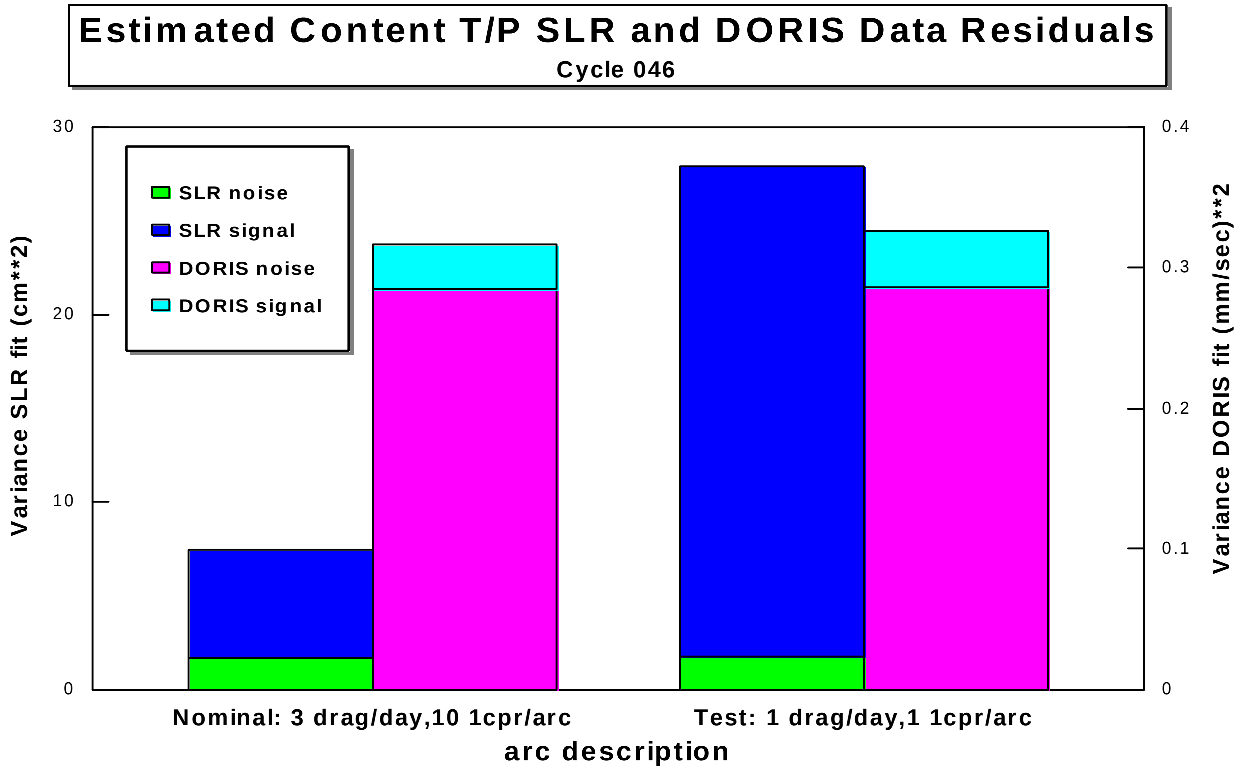

T/P SLR and DORIS Fits: DORIS Residuals
Cycles 1-91 1st Generation POE (JGM2); Cycles 92-231 2nd Generation POE (JGM3)
SLR Fit (cm)
DORIS Fit (0.1 mm/sec)
RMS fit /cycle
0
2
4
6
8
0
50
100
150
200
250
Cycle (10 day span)

Figure 3.


Test Example SLR and DORIS Fits

nominal-test solution orbit difference (h,c,l) : 3, 5, 10 cm


Estimated Content T/P SLR and DORIS Data Residuals

Cycle 046

Figure 4.

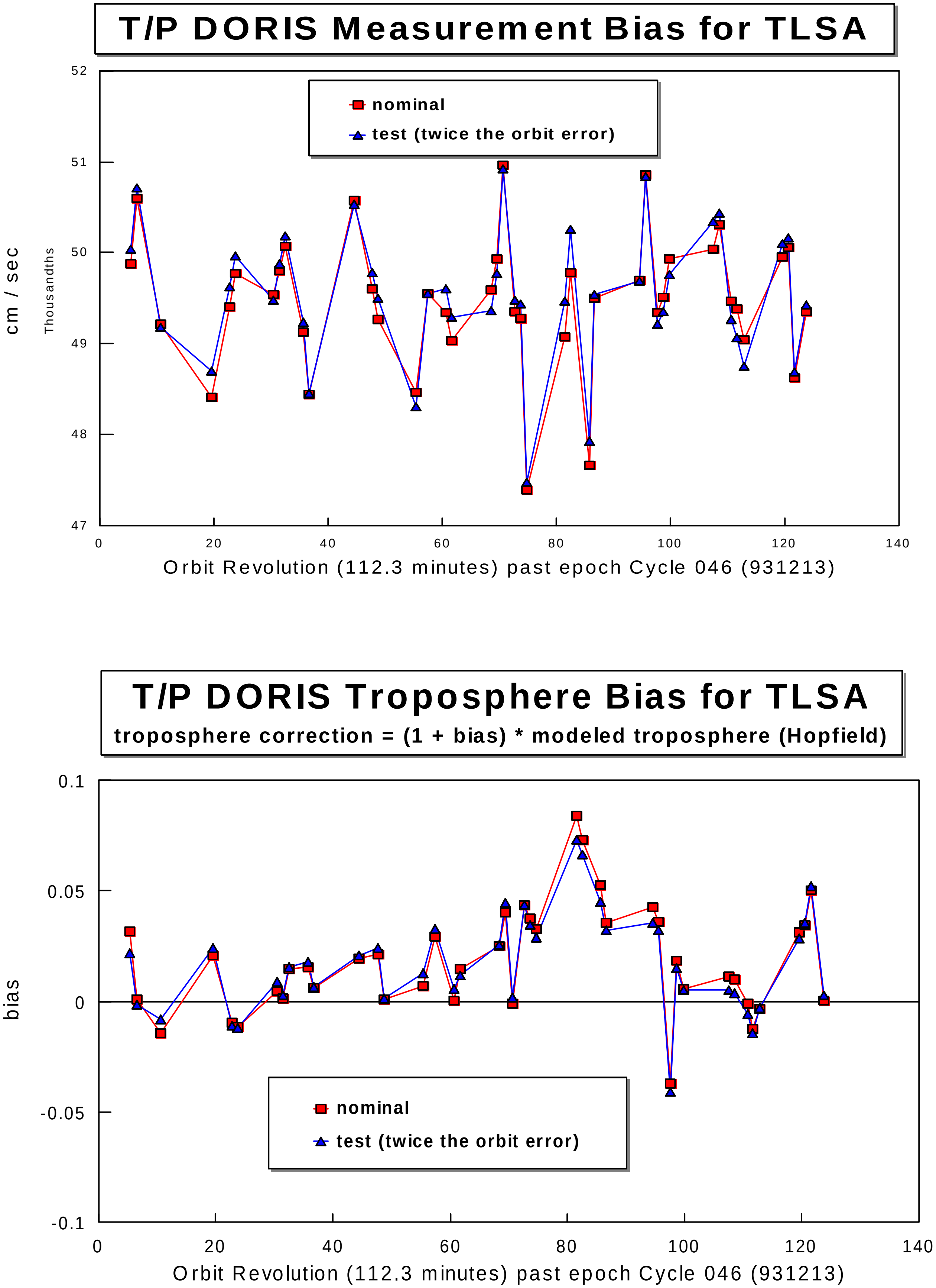

T/P DORIS Measurement Bias for TLSA
nominal
test (twice the orbit error)
cm / sec
Thousandths
52
51
50
49
48
47
0
20
40
60
80
100
120
140
Orbit Revolution (112.3 minutes) past epoch Cycle 046 (931213)
T/P DORIS Troposphere Bias for TLSA
troposphere correction = (1 + bias) * modeled troposphere (Hopfield)
bias
0.1
0.05
0
-0.05
-0.1
nominal
test (twice the orbit error)
0
20
40
60
80
100
120
140
Orbit Revolution (112.3 minutes) past epoch Cycle 046 (931213)

Figure 5.

Basic Doppler Equation

$$N_{jk} = \underbrace{(f_g - f_t)\,\Delta T_{kj}}_{\text{measurement bias}} + (f_g / c)\,\Delta R_{kj}$$

where

N_{jk} = integrated Doppler count between time j and k

f_g = stable receiver (satellite) reference frequency

f_t = stable ground beacon transmitted frequency

ΔT_{kj} = difference between times k and j

c = speed of light

ΔR_{kj} = difference between ranges k and j

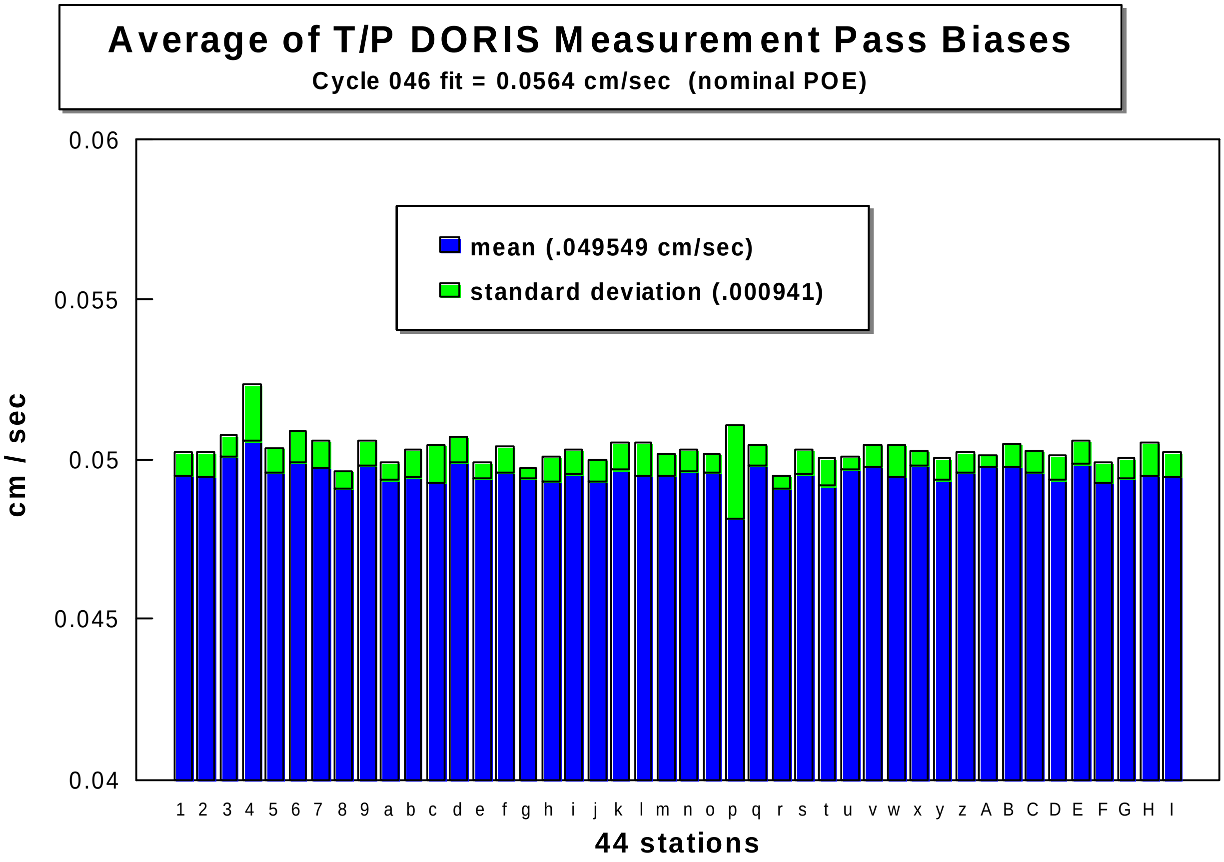
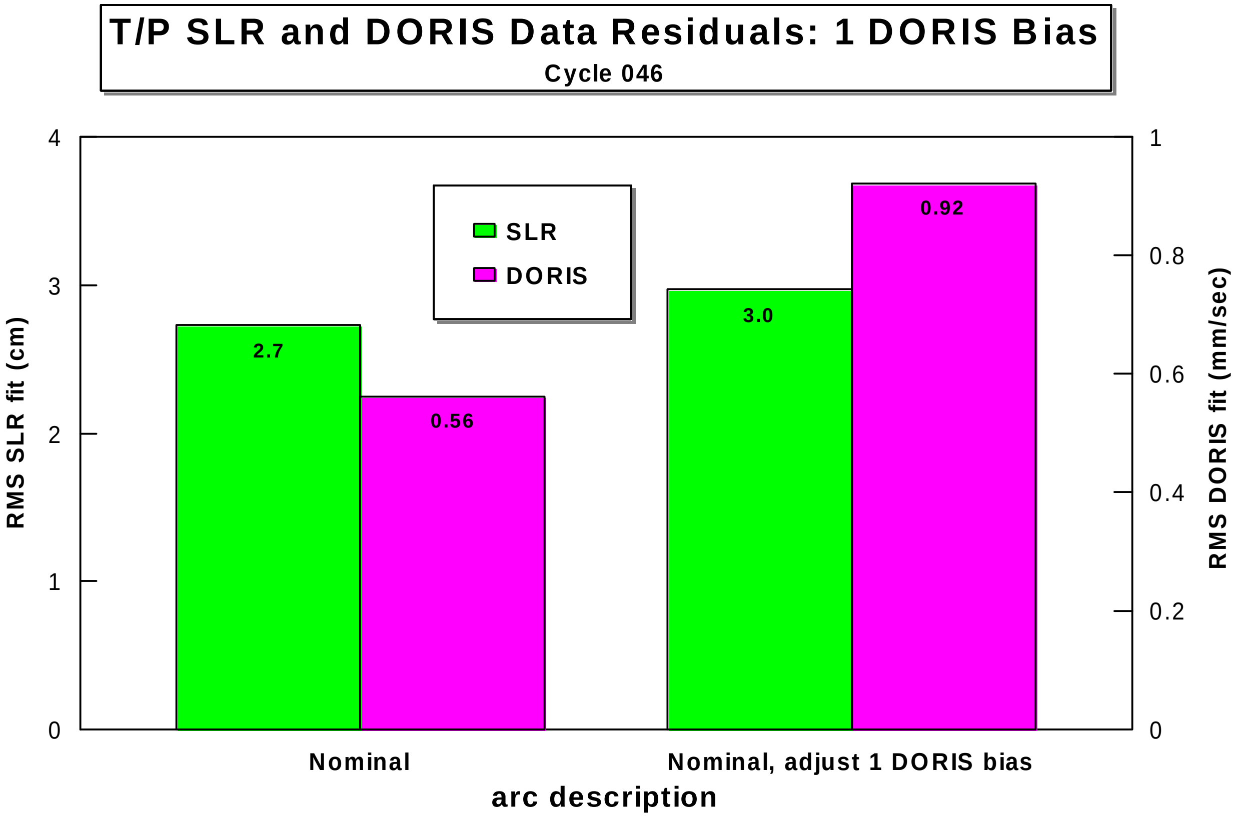


Figure 6.


T/P SLR and DORIS Data Residuals: 1 DORIS Bias
Cycle 046
SLR
DORIS
2.7
0.56
3.0
0.92
RMS SLR fit (cm)
RMS DORIS fit (mm/sec)
0
1
2
3
4
0
0.2
0.4
0.6
0.8
1
Nominal
Nominal, adjust 1 DORIS bias
arc description

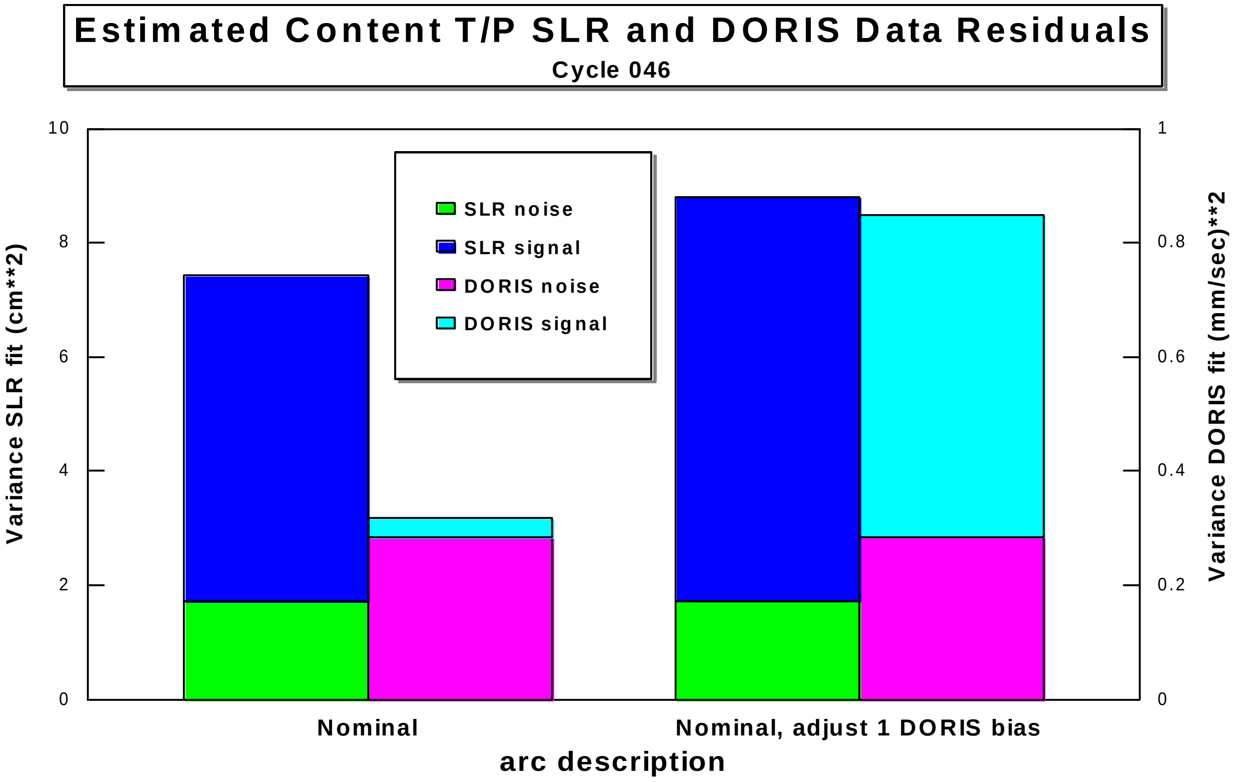

Estimated Content T/P SLR and DORIS Data Residuals
Cycle 046
SLR noise
SLR signal
DORIS noise
DORIS signal
Variance SLR fit (cm**2)
Variance DORIS fit (mm/sec)**2
0
2
4
6
8
10
0
0.2
0.4
0.6
0.8
1
Nominal
Nominal, adjust 1 DORIS bias
arc description

Figure 7.

Exponential Adjustment Constraint between Parameters of a Time Series

$$W_{jk} = \left(e/\sigma^2\right) e^{-\left(\left|T_j - T_k\right|/\tau\right)}$$

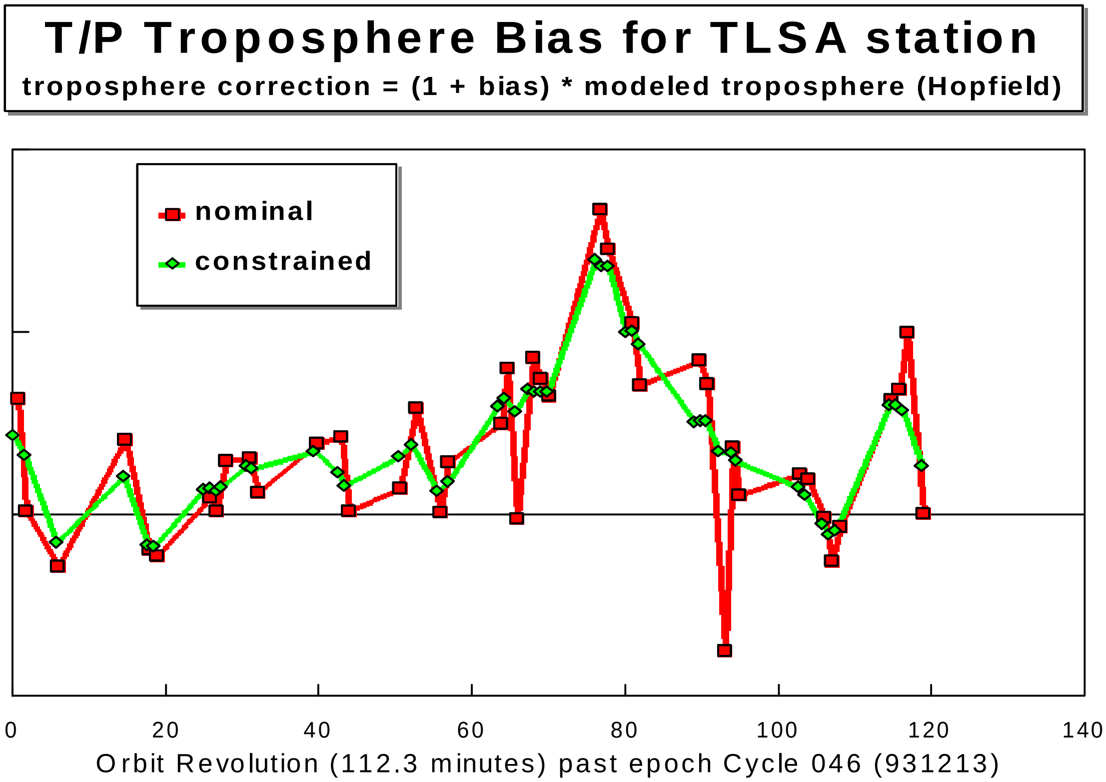
where

W_{jk} = weight for constraint equation between two parameters, one at time T_j and the other at T_k
σ = parameter sigma or process noise (user input)
τ = correlation time (user input)
e = Euler's number

Parameter Constraint Strategy

Parameter	parameter span (min)	σ	τ (min)
troposphere / station	90	1×10^{-2}	90
1cpr acceleration (along and cross track)	30	5×10^{-10} m/s^2	15

Figure 8.


T/P Troposphere Bias for TLSA station

troposphere correction = (1 + bias) * modeled troposphere (Hopfield)

Figure 9.

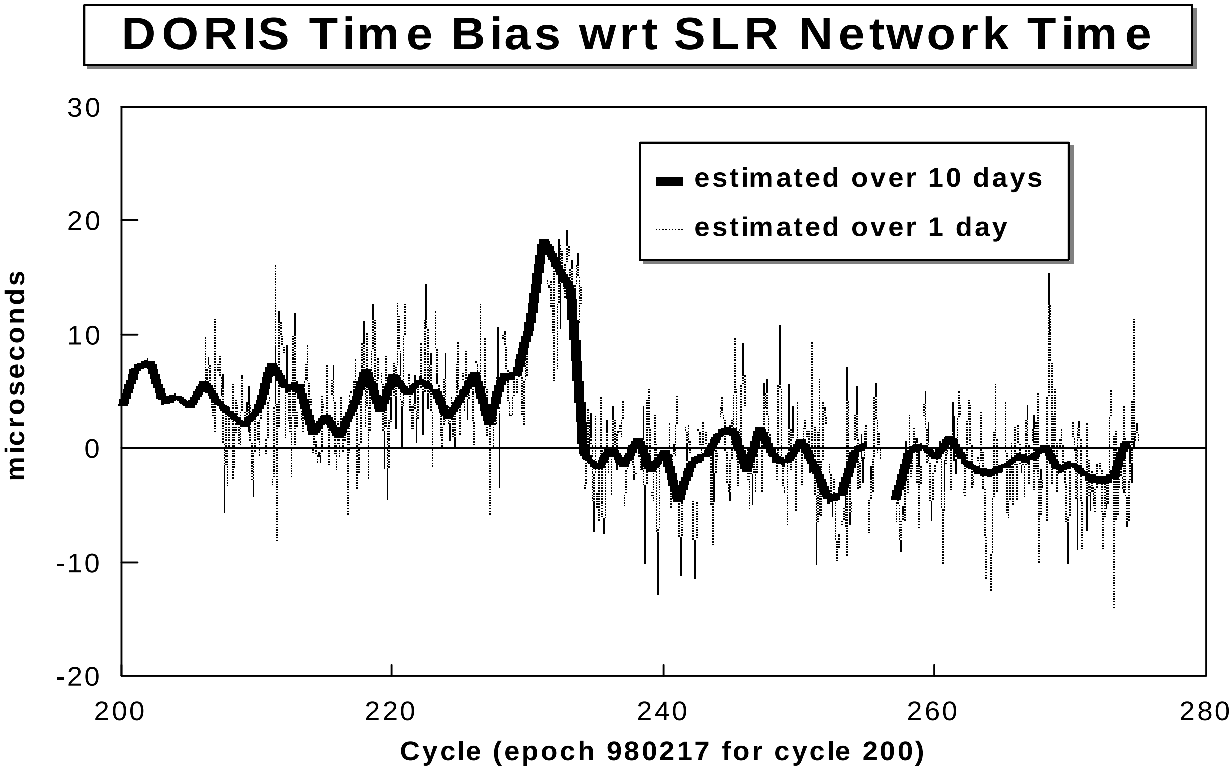

DORIS Time Bias wrt SLR Network Time

Figure 10. ITRF97 Vs CSR95D01 DORIS Station Positions

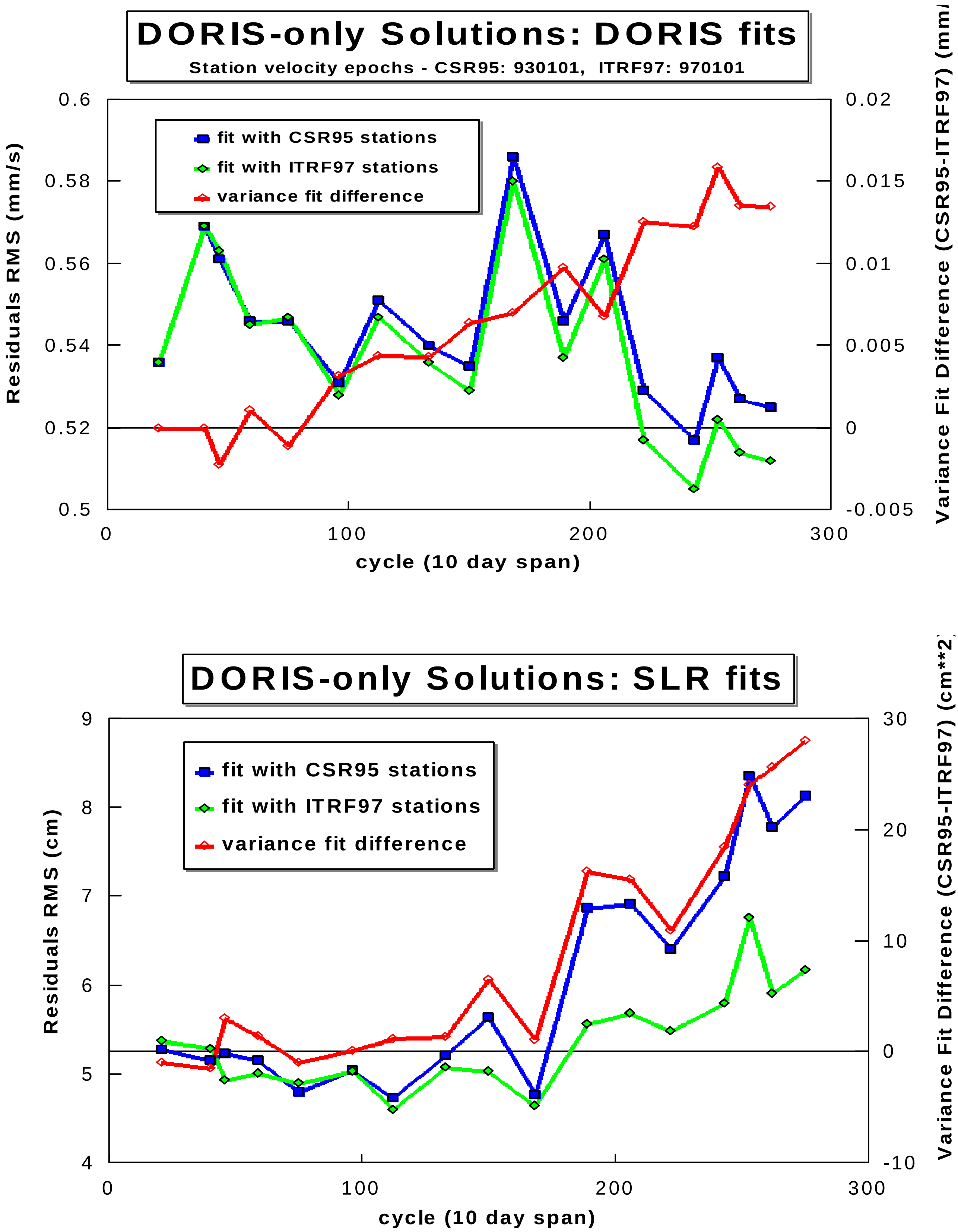


Figure 11.

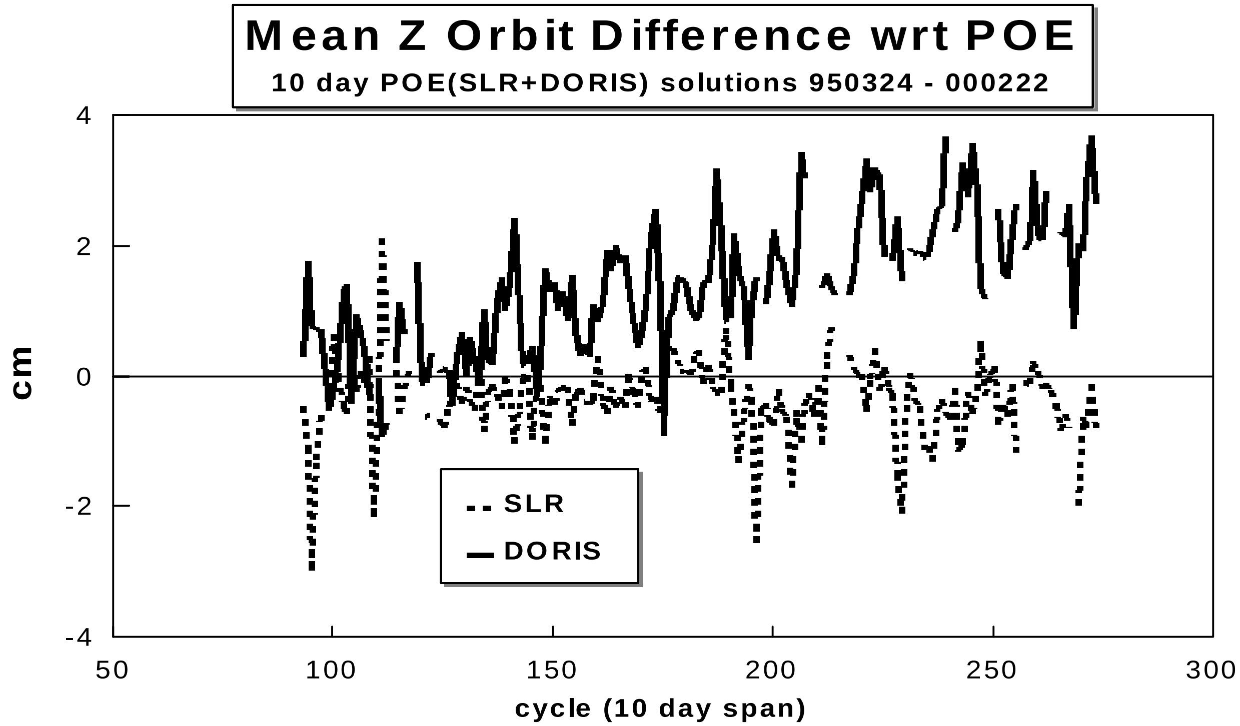
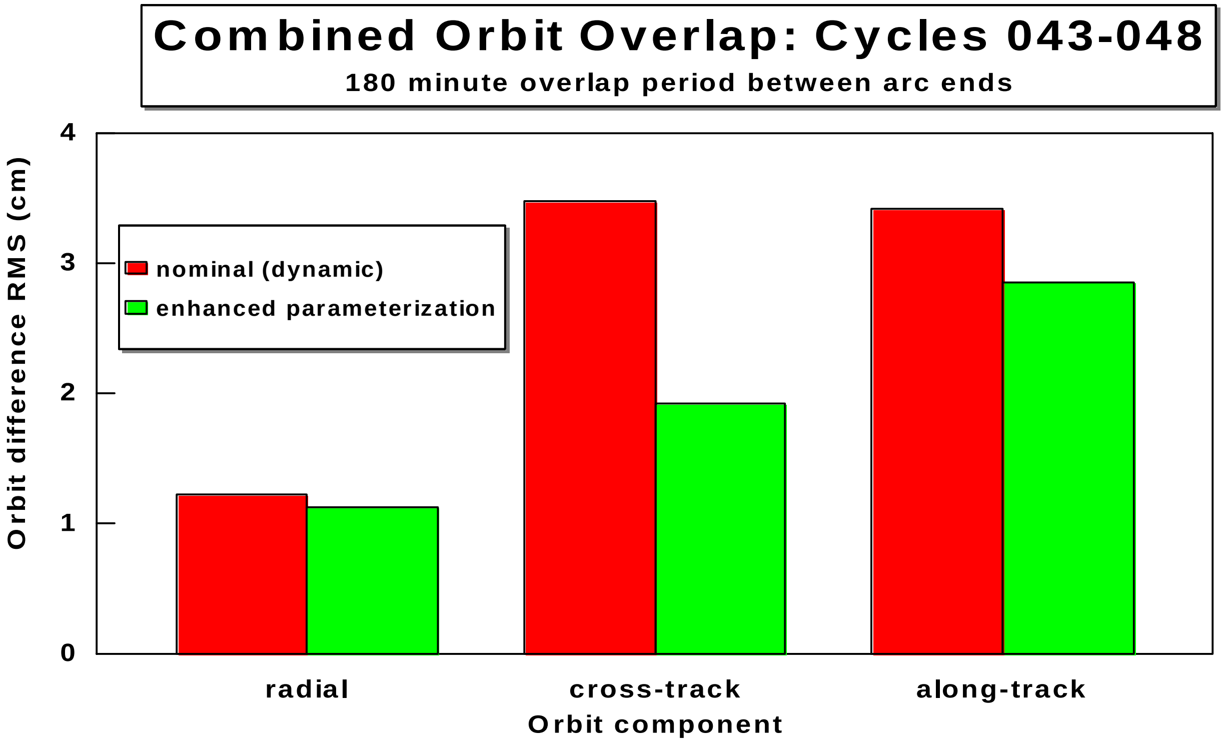


Figure 12.



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