TOPEX-class Orbits for the ERS Satellites

Remko Scharroo, Gertjan Mets, Pieter Visser,
and Boudewijn Ambrosius

American Geophysical Union, 1996 Spring Meeting
Baltimore, Maryland, 20–24 May 1996

Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands Fax: +31 15 278 5322 http://dutlru8.lr.tudelft.nl/

Outline

Delft Institute for Earth-Oriented Space Research

Precise Orbit Determination

- Simultaneous orbit determination for ERS–1 and ERS–2 during Tandem Mission
- Joint Gravity Model JGM-3
- Satellite Laser Ranging and altimeter crossovers (OPR)
- 3 May – 28 Aug 1995 (ERS–1 Cycles 145–148, ERS–2 Cycles 1–4)

Results

- SLR and crossover residuals and estimated parameters
- Collinear track analysis

Gravity Field Tailoring

- Delft Gravity Model DGM-E01, an adjustment of JGM-3
- Results

Conclusions

Dynamical models and measurements

Delft Institute for Earth-Oriented Space Research

SLR observations	Quick-look SLR 20-s normal points. Weight: 8 cm plus system-dependent noise level (varying from 1 to 20 cm).
Single xovers	ERS–1 and ERS–2 single satellite crossover residuals. Weight for each measurement component: 8 cm plus sea surface variability.
Dual xovers	Crossover residuals between ERS–1 and ERS–2. Weight for each measurement component: 8 cm plus sea surface variability.
Satellite model	Satellite-specific macro-models, consisting of 8 fixed and 2 rotating panels.
Gravity model	JGM-3
Atmospheric model	DTM 87.
Solar radiation	Albedo, umbra, penumbra, and occultation by Moon modelled. C_R = 1.0 (fixed).
Station coordinates	DUT(LSC)95L02 11-year LAGEOS solution including 3-D motions.
Estimated parameters	State vector, 12-hourly C_D, near-daily empirical forces (1-cpr along-track and cross-track accelerations), selected station coordinates and biases, altimeter bias difference, altimeter time tag bias.
Orbit reference	GRS80: a_e = 6378137.0 m, $1/f$ = 298.257.
Arc length	5.5 dyas with a 2-day overlap with the previous and consecutive arcs.

SLR Measurements

Observations. Global quick-look SLR data, 20-s normal points.

Data weighting. RSS combination of the assumed overall model accuracy (8 cm) and noise level of the system.

Troposphere. Marini-Murray model.

Geometric correction. LRR optical centre offset (4.3 cm) and LRR centre-of-mass offset.

Editing. Cutoff elevation = 10 deg. Spurious data removed.

Altimeter measurements

Observations. Single and dual satellite crossovers, created from ERS OPR altimeter data spanning the orbital arc.

Data weighting. Weight sigma of each measurement is an RSS combination of the assumed radial model accuracy (8 cm) and the local sea level variability multiplied by $\sqrt{2}$.

Data corrections. The altimeter ranges are corrected for atmospheric path delays and solid earth tides [OPR]; Grenoble FES95.2 ocean tides and tidal loading [Le Provost et al.]; 5.5% sea state bias [Gaspar et al.]; 100% inverse barometric correction; time tag bias [estimated].

Dynamic model

Gravity model. Joint Gravity Model JGM-3, complete to degree and order 70, including secular C_{21} and S_{21} and dynamic polar motion. GM = 398600.4415 km^3/s^2.

Speed of light. c = 299792.458 km/s.

Solid Earth tides. Frequency-dependent Wahr model (1981); permanent tide excluded according to IERS Standard (1989).

Ocean tides. JGM-2 ocean tide model.

Third body attraction. Sun and planets according to JPL DE200 ephemeris.

Atmospheric drag. French Density Model (DTM 87) with daily $F_{10.7}$ values and 3-hourly K_p values from NOAA.

Radiation. Solar radiation pressure at 1 AU = 4.5783 $\times$ 10^6 N/m^2. Umbra, penumbra, occultation by Moon, and Earth albedo modelled. Solar radiation coefficient C_R=1.0.

Satellite cross-sections. Satellite-specific macro-models (8 fixed and 2 rotating panels).

Pole tide. Dynamical effect of pole tide applied.

Relativistic effects. included.

Orbit manœuvres. Estimated. A priori information according to ESOC predictions.

Reference frame

Station coordinates. LSC(DUT)95L02 11-year LAGEOS solution (epoch 1 Jan 1988), advanced to epoch by 3-dimensional motions incorporated in the coordinate solution.

Reference ellipsoid. GRS80: $a_e = 6378.1370$ km and $1/f = 298.257$.

Earth rotation. Values from IERS EOP 90 C 04 solution.

CIS. Mean equator and equinox of J2000.0.

Precession. IAU 1976 (Lieske model).

Nutation. IAU 1980 (Wahr model).

Tidal uplift. Love model, including frequency dependent and permanent tides.

Pole tide. Geometrical effect of pole tide accounted for.

Ocean loading. not applied.

Numerical integration

Software. NASA/GSFC/STX GEODYN orbit determination package, adjusted by DEOS to properly incorporate dual-satellite crossover height differences and PRARE tracking.

Step size. 60 seconds.

DEOS
Delft Institute for Earth-Oriented Space Research

Estimated parameters per orbital arc

State vector. Position and velocity at epoch.

Drag. Half-daily drag coefficients (C_D: 11 parameters).

Empirical forces. Near-daily 1-cpr along-track and cross-track *empirical* accelerations (6 times 4 parameters).

Orbit manœuvres. Accelerations in three directions.

Station coordinates. Of some (mobile) stations.

Measurement offsets. Range and timing bias for some stations. Altimeter time tag bias per satellite and relative range bias.

Output ephemeris

Data arcs. Arc length of 5.5 days with an epoch spacing of 3.5 days.

ODR. The position of the satellite's *nominal* centre-of-mass is given in the Conventional Terrestrial Reference System (CTRS) as latitude, longitude, and height above the GRS80 reference ellipsoid, centred around the mean IERS pole origin. UTC time-tags.

Step size. 60 seconds.

DEOS
Delft Institute for Earth-Oriented Space Research

Statistics for 34 orbital arcs (3 May – 28 Aug 1995)

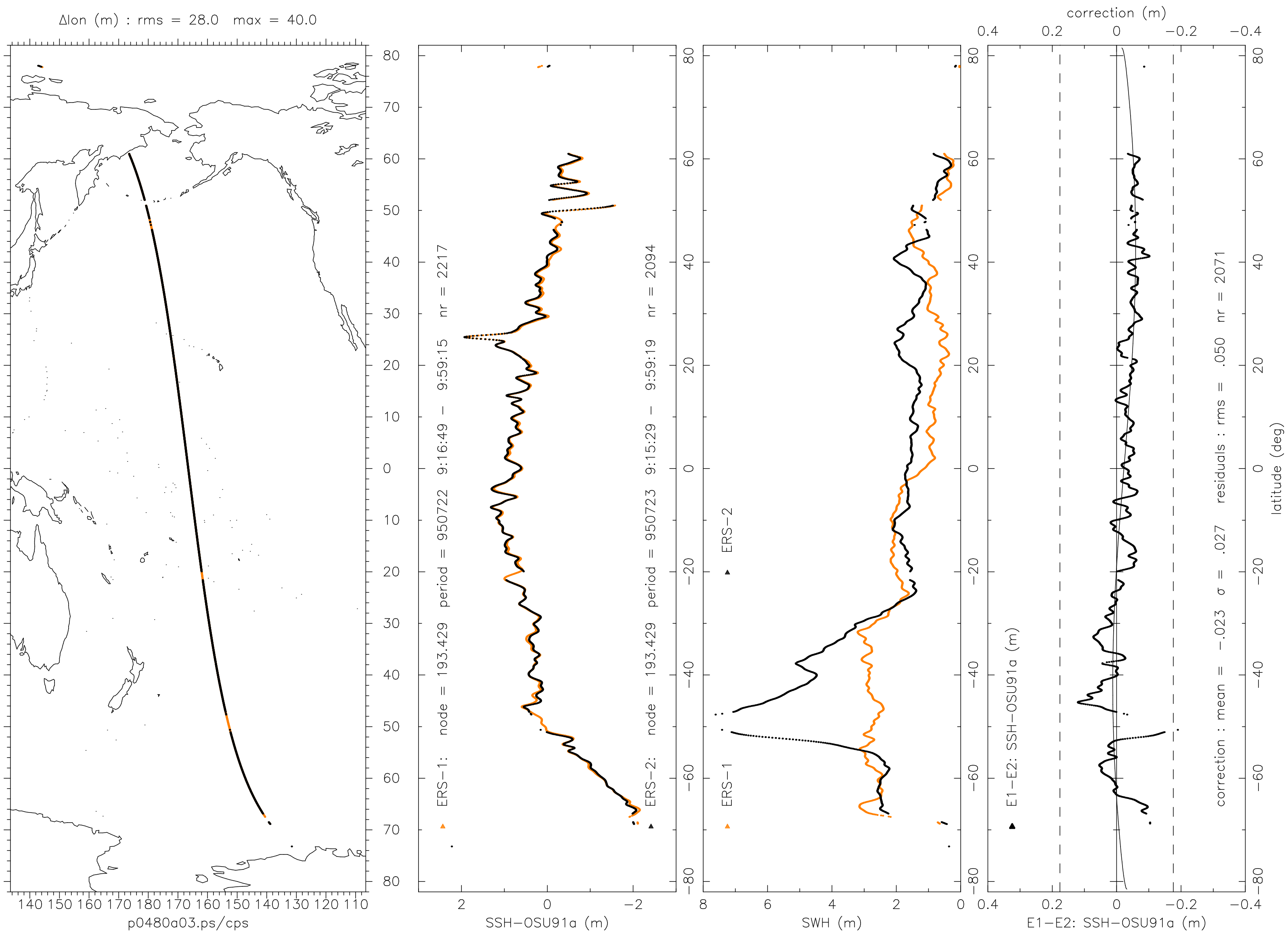
- ERS–1 and ERS–2 orbits are generated simultaneously for each 5.5-day orbital arc.
- SLR and crossover height residuals (ERS–1 and ERS–2).
- Time tag biases Δt (ERS–1 and ERS–2).
- Relative altimeter range bias (ERS–2 minus ERS–1).

Gravity model	ERS–1					ERS–2					range bias (cm) (ERS–2 – ERS–1)
	SLR		crossovers			SLR		crossovers			
	number	RMS (cm)	number	RMS (cm)	Δt (ms)	number	RMS (cm)	number	RMS (cm)	Δt (ms)	
JGM-3	39486	7.5	63805	9.3	–1.4±0.2	36903	7.4	62625	9.4	–1.3±0.2	–1.8±0.5

- Note the considerable time tag bias of the altimeter data (with respect to the SLR time standard).
- Relative altimeter range bias is approximately 2 cm. (Depends strongly on further calibration of SWH).

Collinear tracks

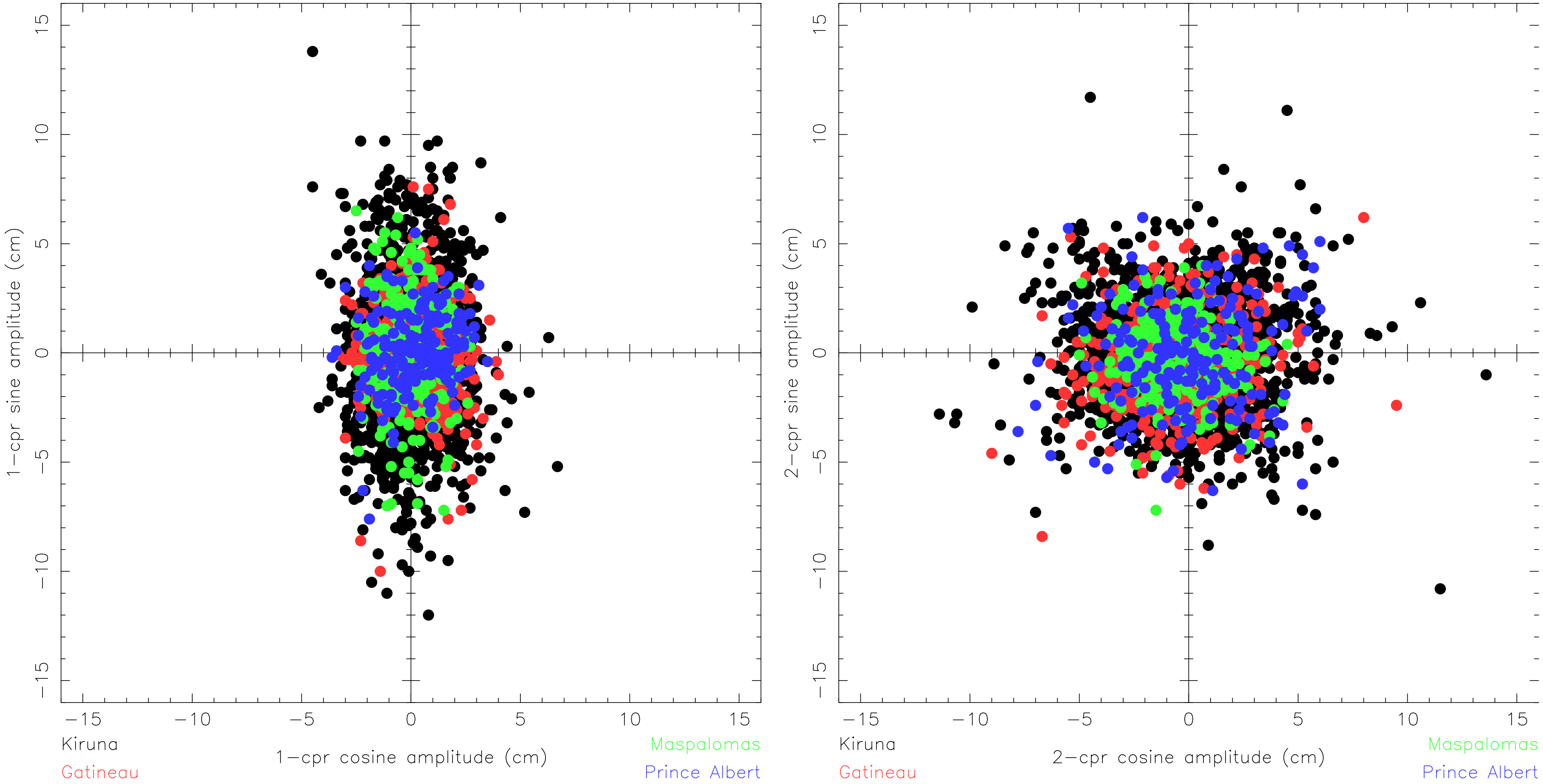
Delft Institute for Earth-Oriented Space Research



Collinear height profiles of ERS–1 (grey) and ERS–2 (black). Ascending pass 480, 22–23 July 1995. From top to bottom: location, sea surface height wrt OSU91a, SWH, and height difference including 5-parameter fit.

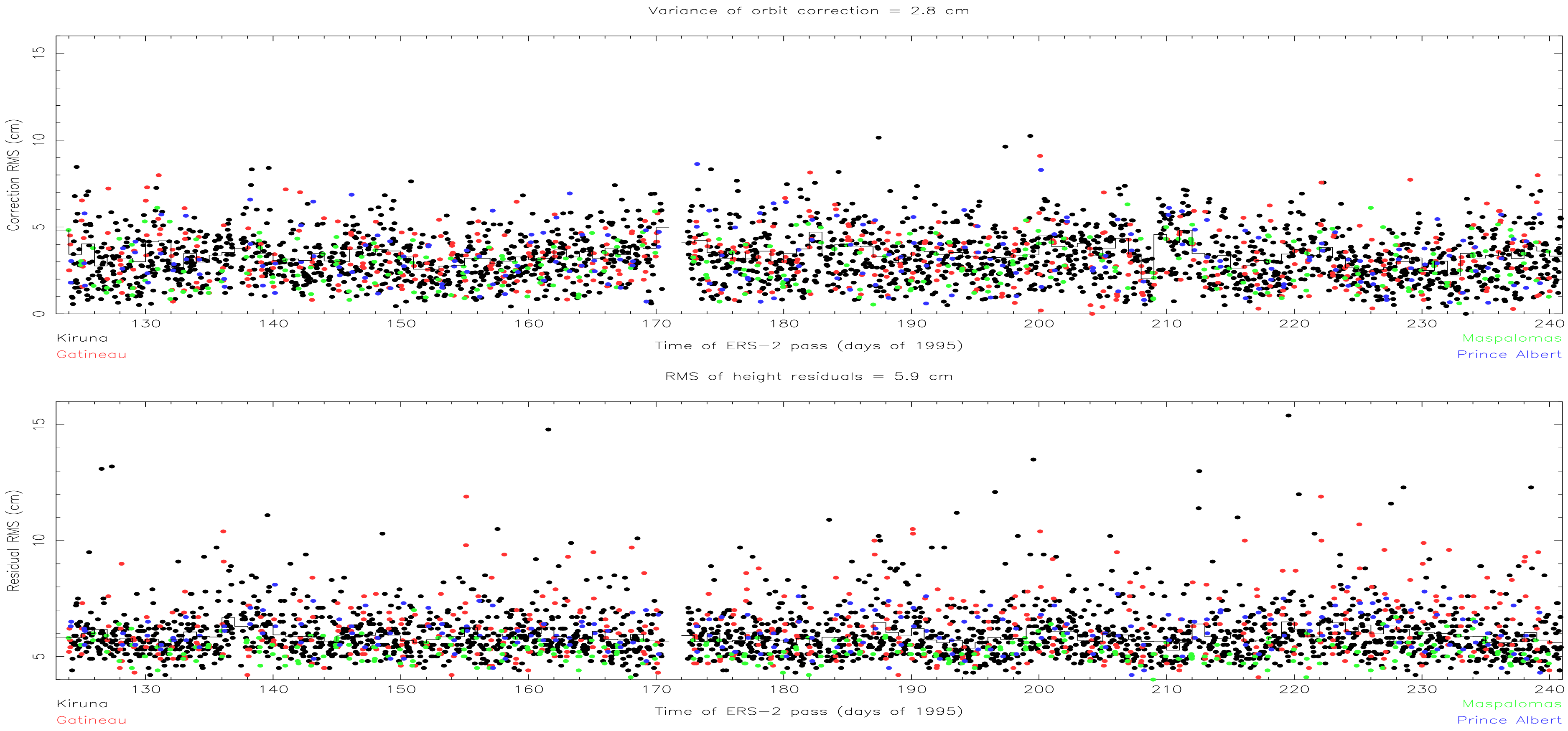
Collinear tracks (ERS–1 minus ERS–2, 1-day lag)

DEOS
Delft Institute for Earth-Oriented Space Research



Estimates of 1-cpr (left) and 2-cpr (right) terms in the fitting of collinear ERS–1 profiles to ERS–2 profiles. 1-day lag. JGM-3 orbits. The larger S_1 term indicates errors in atmospheric density modelling over the Poles.

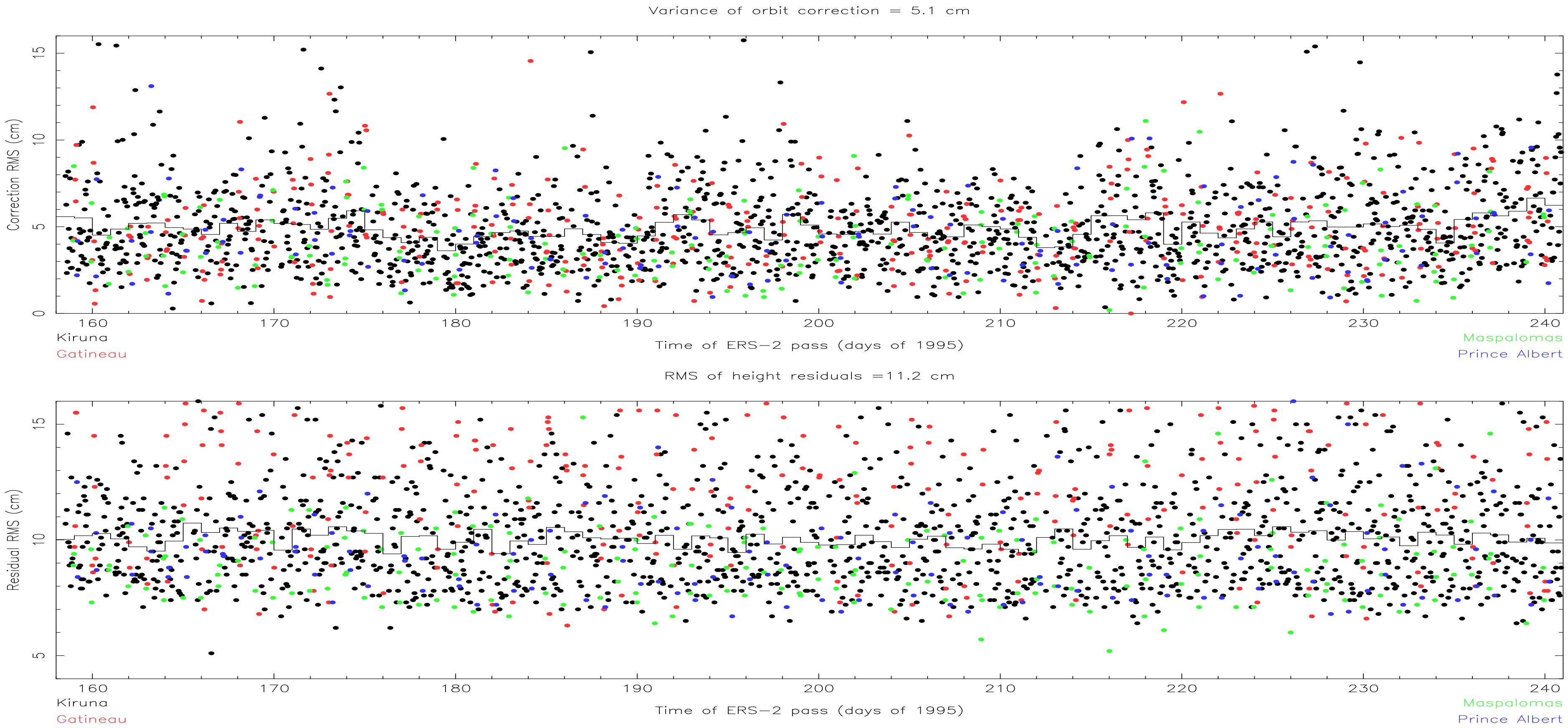
Collinear tracks (ERS–1 minus ERS–2, 1-day lag)



Top: RMS of orbit error correction. 2.8 cm overall RMS is due to non-gravity related orbit errors, partly correlated over the short time-interval.

Bottom: RMS of residual sea height differences. 5.9 cm overall RMS is contribution of rapidly decorrelating altimeter correction errors and noise.

Collinear tracks (ERS–2, 35-day lag)

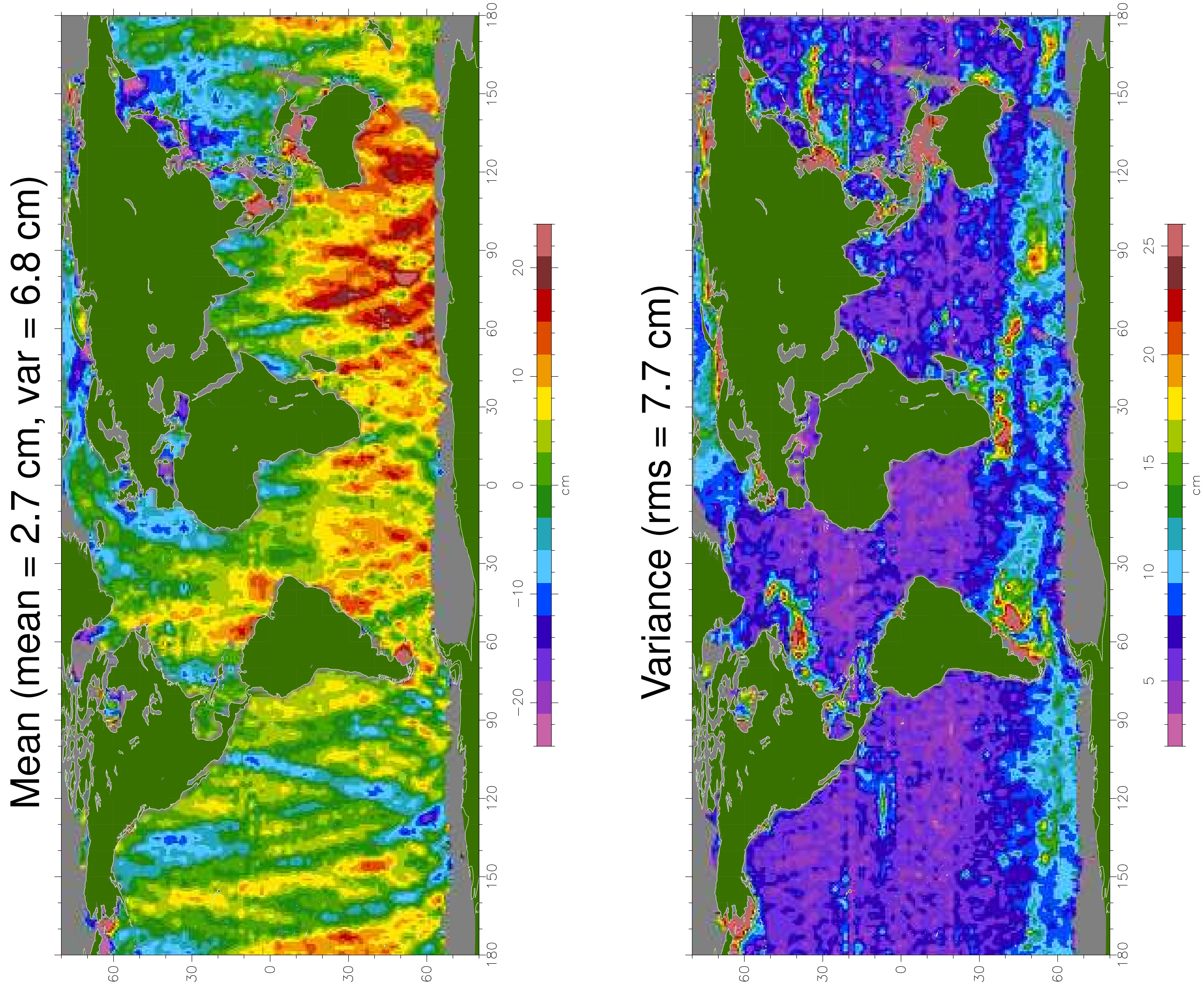


Top: RMS of orbit error correction. 5.1 cm overall RMS is due to non-gravity related orbit errors, fully decorrelated ⇒ 3.6 cm orbit error per pass.

Bottom: RMS of residual sea height differences. 11.2 cm overall RMS is contribution of fully decorrelated altimeter correction errors, and sea surface variability ⇒ 7.9 cm per pass.

Global crossover height differences (JGM-3)

DEOS
Delft Institute for Earth-Oriented Space Research



Mean and variance of ERS crossover height differences (asc-des, JGM-3 orbits)

Tailoring JGM-3 gravity field model (DGM-E01)

DEOS
Delft Institute for Earth-Oriented Space Research

- Mean crossover height difference equals twice the geographically *anti*-correlated radial orbit error.
- Linear perturbation theory (LPT) postulates the global distribution of the geographically correlated and anti-correlated radial orbit error for each gravity field coefficient.
- Select those combination of (l, m) that produce a global RMS radial orbit error of 2 millimetres or more, assuming a 1-sigma error in either coefficient C_{lm} or S_{lm}.
- Estimate corrections for each coefficient in a least squares solution, using the JGM-3 normal matrix as constraint.

$$(A^T W A + N)\mathbf{x} = A^T \mathbf{b}$$

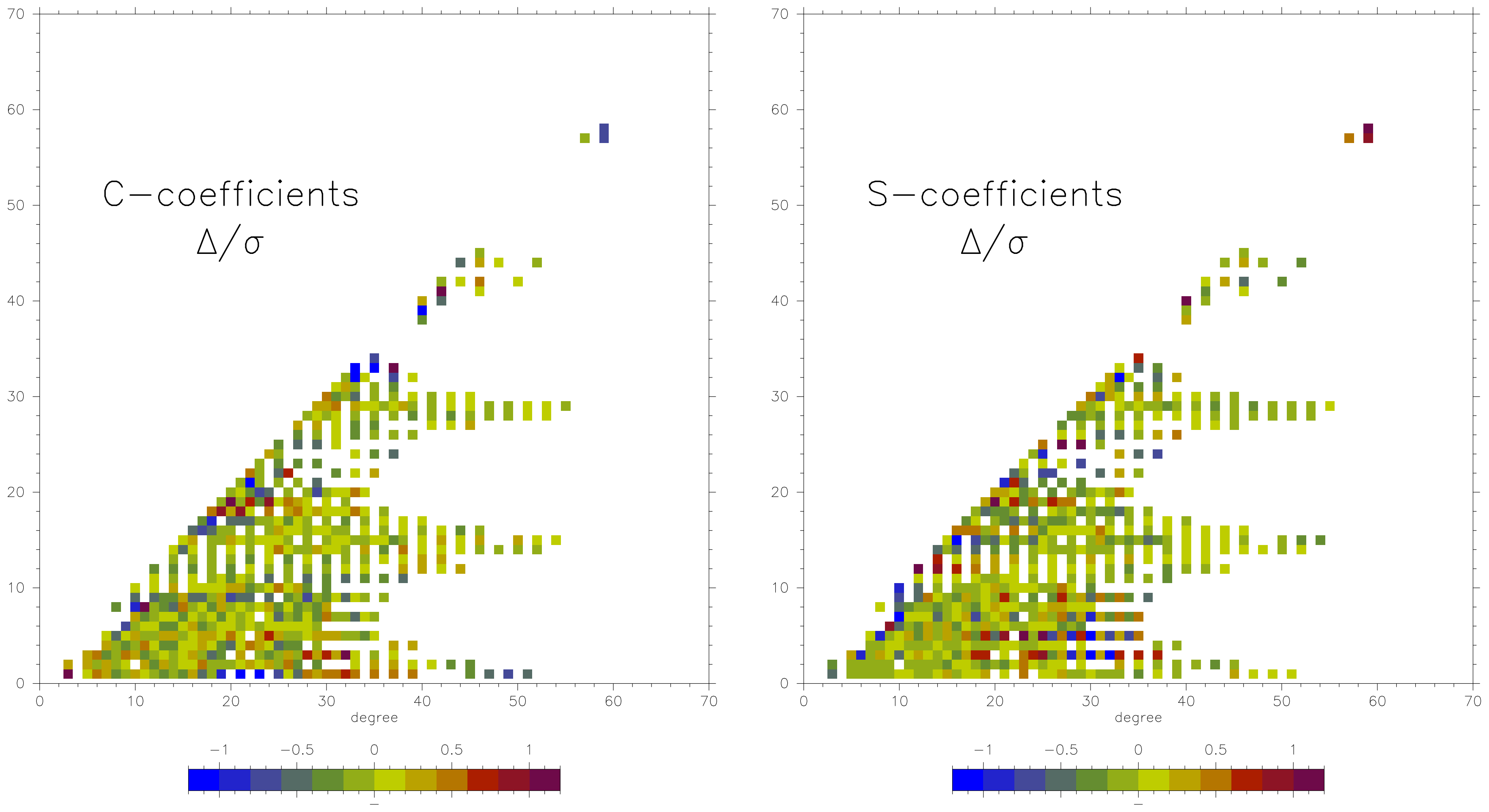
where

$$\begin{aligned} \mathbf{x} &= \text{estimated gravity field coefficient adjustments} \\ \mathbf{b} &= \text{mean crossover height differences} \\ A &= \text{matrix of partials} \\ W &= \text{weight of crossovers = local variability} \\ N &= \text{JGM-3 normal matrix} \end{aligned}$$

$\Rightarrow$ **Delft Gravity model DGM-E01**

- Corrections to JGM-3 (Δ/σ):
  min = –1.41, max = 2.16, mean = 0.02, RMS = 0.35.

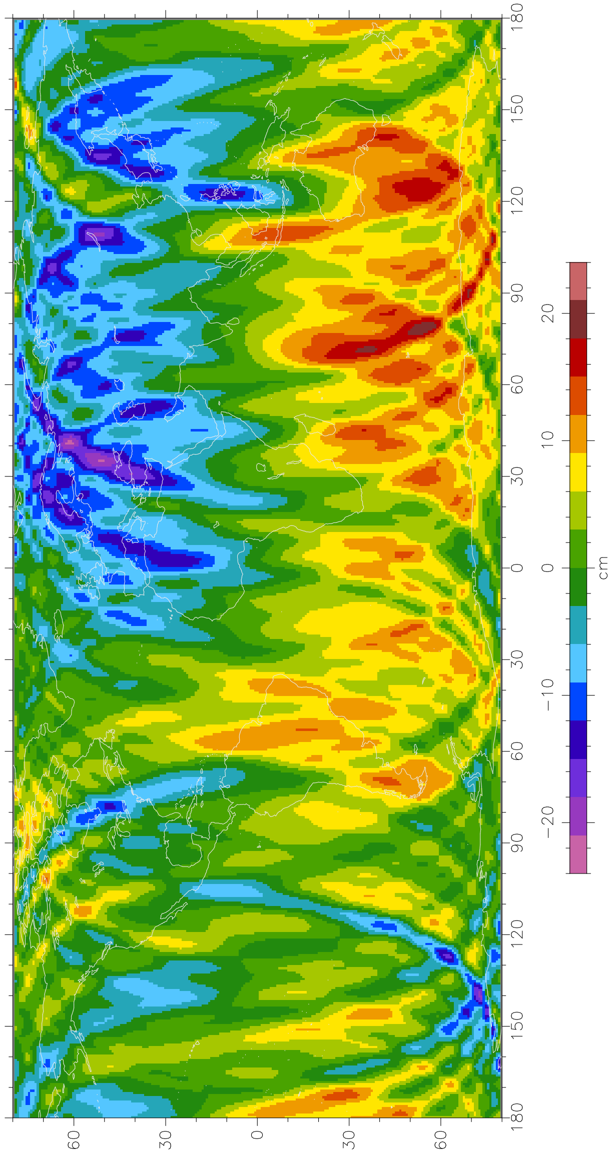
Gravity coefficient adjustments



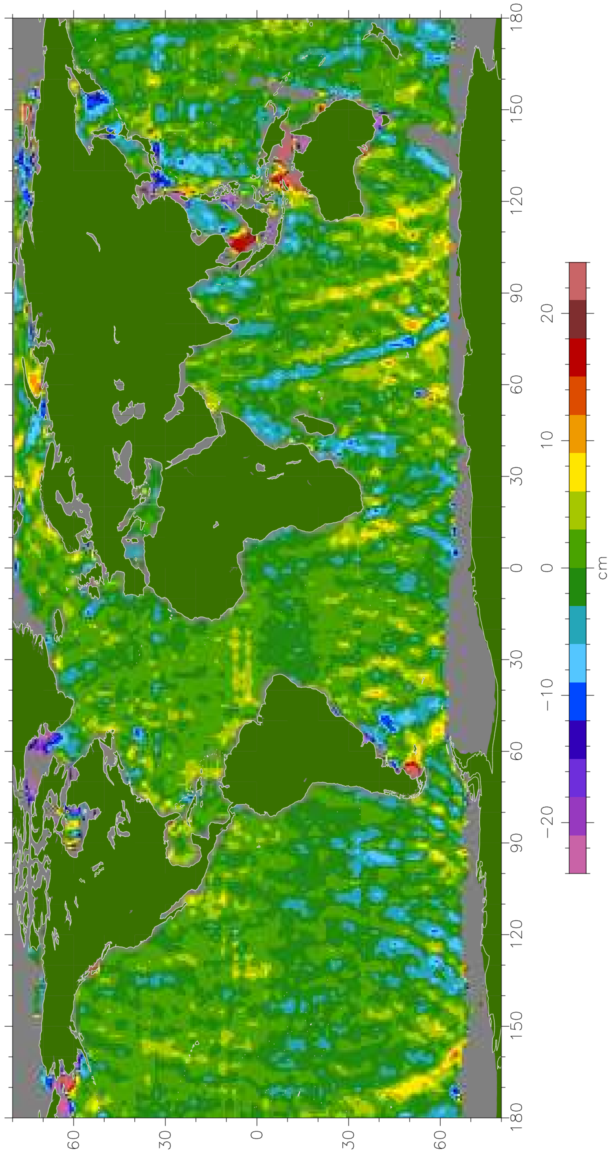
Adjustments to 1100 C- and S-coefficients of JGM-3 divided by their formal standard deviations

Geographically anti-correlated orbit error

2× Resolved error (mean = 1.4 cm, var = 6.2 cm)



Residual (mean = 0.0 cm, var = 3.6 cm)



Geographically anti-correlated orbit error postulated by LPT through adjustment of JGM-3 gravity field

Delft Institute for Earth-Oriented Space Research

Statistics for 34 orbital arcs (3 May – 28 Aug 1995)

- ERS–1 and ERS–2 orbits are generated simultaneously for each 5.5-day orbital arc.
- SLR and crossover height residuals (ERS–1 and ERS–2).
- Time tag biases Δt (ERS–1 and ERS–2).
- Relative altimeter range bias (ERS–2 minus ERS–1).

Gravity model	ERS–1					ERS–2					range bias (cm) (ERS–2 – ERS–1)
	SLR		crossovers			SLR		crossovers			
	number	RMS (cm)	number	RMS (cm)	Δt (ms)	number	RMS (cm)	number	RMS (cm)	Δt (ms)	
JGM-3	39486	7.5	63805	9.3	–1.4±0.2	36903	7.4	62625	9.4	–1.3±0.2	–1.8±0.5
DGM-E01	39486	6.9	63805	8.2	–1.6±0.2	36903	6.6	62625	8.3	–1.5±0.2	–1.8±0.5

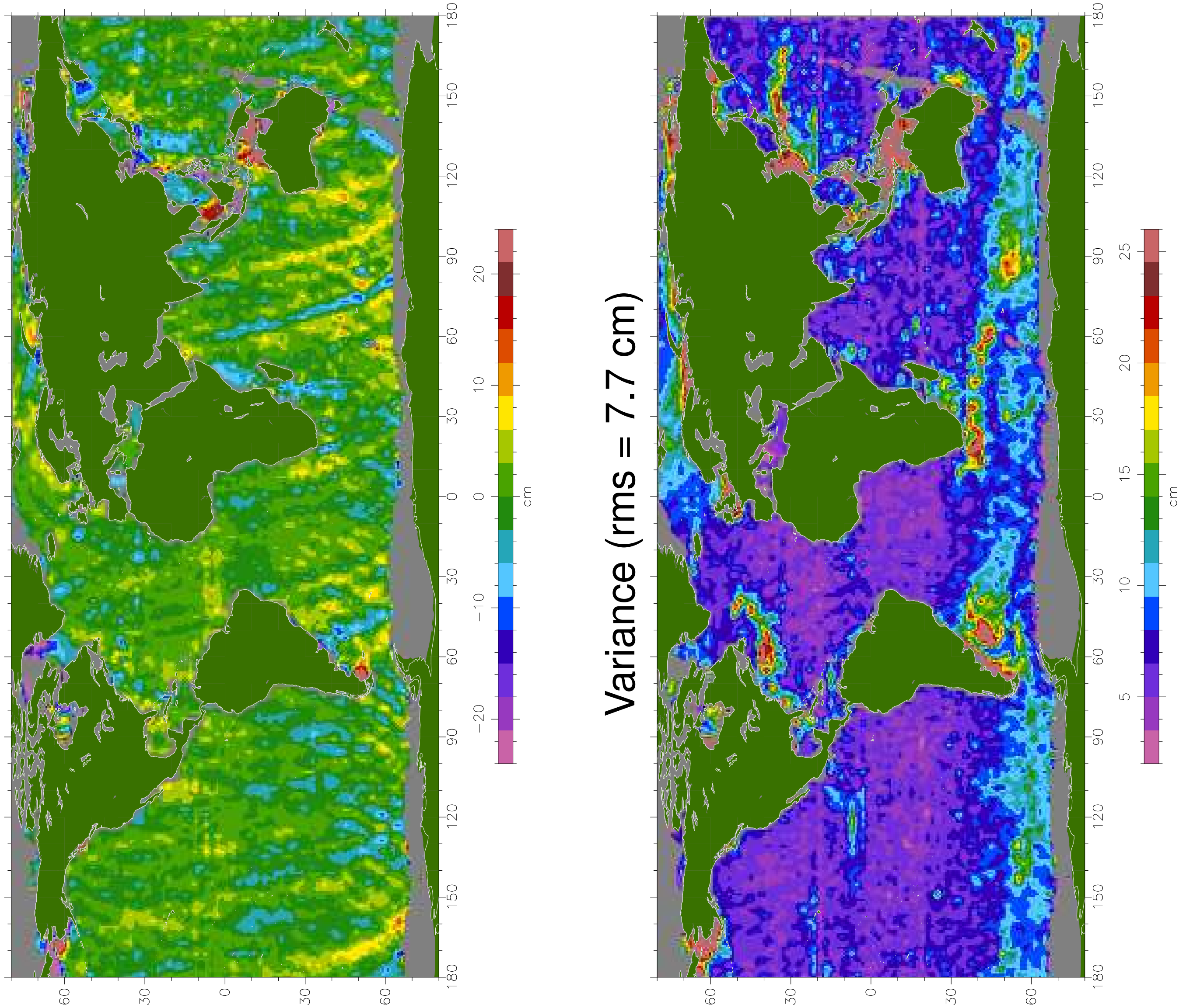
- Note the decrease *both* in corssover RMS *and* SLR residual RMS due to the tailoring of the gravity field.
- Yet, SLR data have *not* been used in the tailoring process.

Global crossover height differences (DGM-E01)

DEOS
Delft Institute for Earth-Oriented Space Research

Mean (mean = 0.1 cm, var = 3.4 cm)

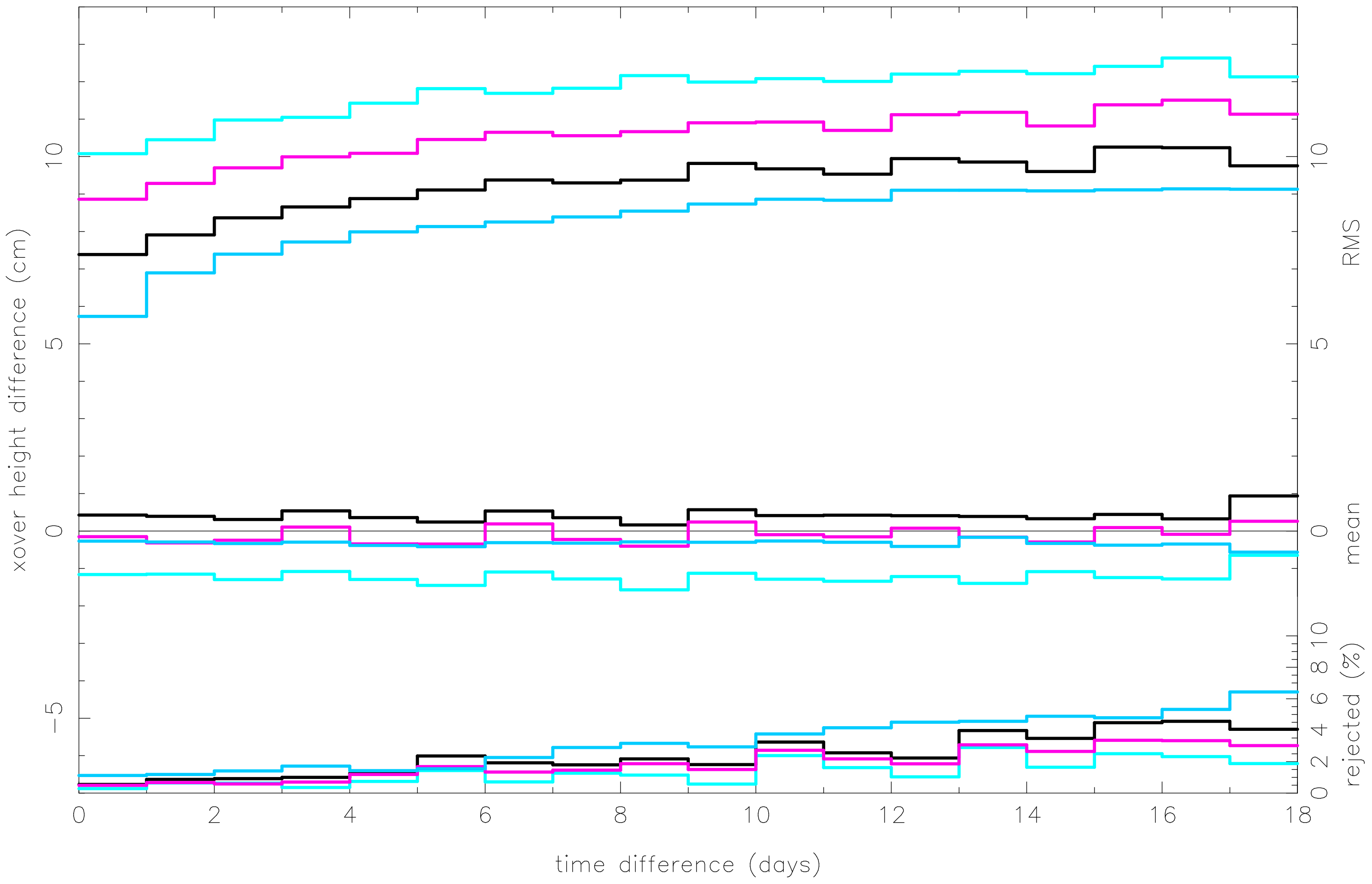
Variance (rms = 7.7 cm)



Mean and variance of ERS crossover height differences
(asc-des, DGM-E01 orbits)

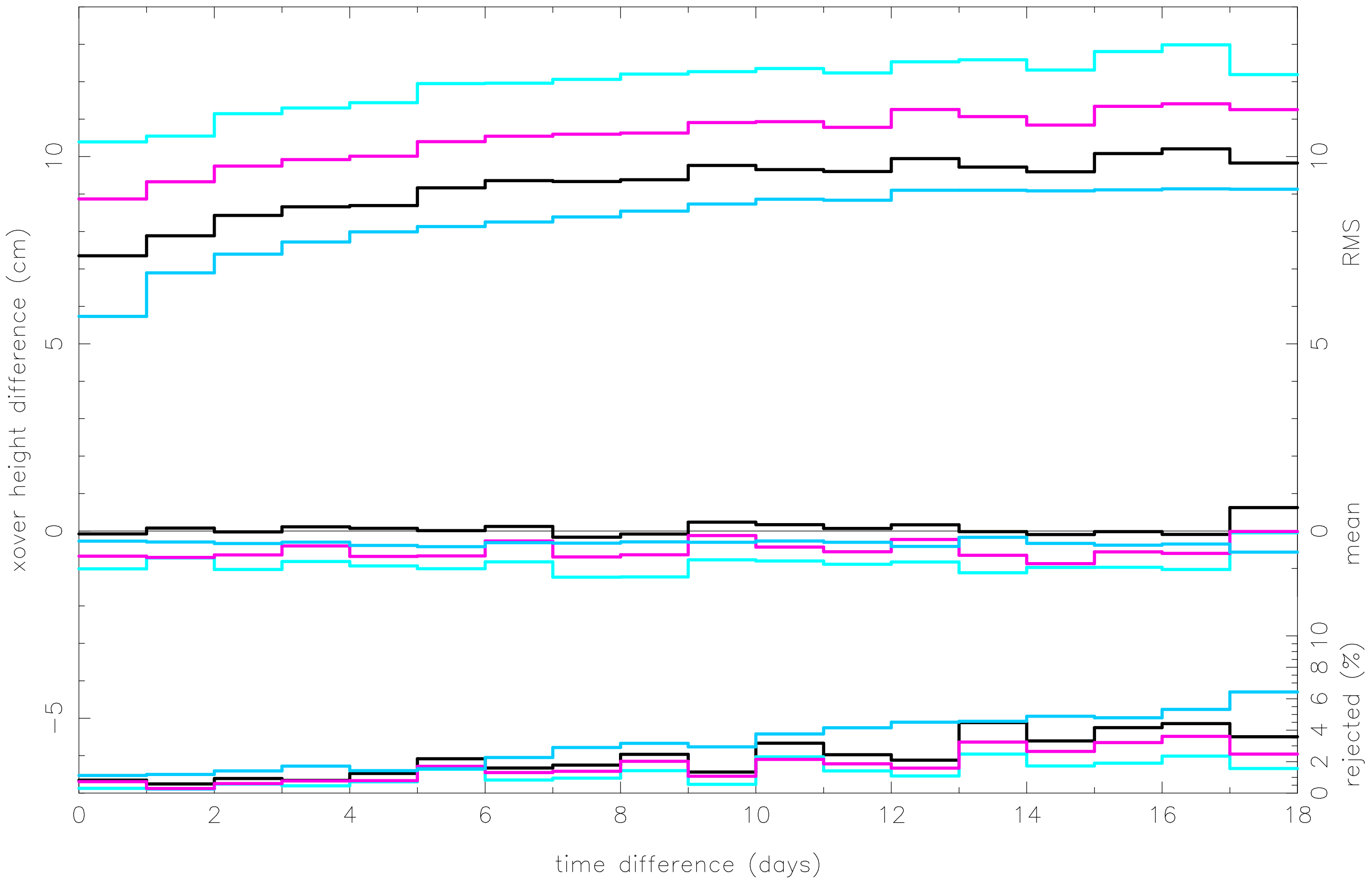
Crossover height differences (ERS–1)

DEOS
Delft Institute for Earth-Oriented Space Research



RMS and mean of crossover height differences (asc-des) as a function of time interval between tracks. Lines are for ERS–1 (GFZ, DUT JGM-3 and DUT DGM-E01 orbits) and TOPEX.

Crossover height differences (ERS–2)



RMS and mean of crossover height differences (asc-des) as a function of time interval between tracks. Lines are for ERS–2 (GFZ, DUT JGM-3 and DUT DGM-E01 orbits) and TOPEX.

Crossover budget (cm)

Source	GFZ	JGM-3	DGM-E01	TOPEX
Meso-scale features				
Dry tropospheric correction	1			
Wet tropospheric correction	1–2			
Ionospheric correction	1			
Ocean tides (Grenoble FES95.2)	3			
Solid earth tides	<1			
Inverse barometer effect	1–2			
Sea state bias	1			
Instrument errors	1			
(Meso-scale) sea surface variability	1–4			
Total	4–6			
Radial orbit				
Geographically anti-correlated	4	3.5	1.5	0.5
Geographically correlated	4	3.5	1.5–3	0.5
Not geographically correlated	4–5	2–3.5	2–3.5	1–3
Total	7–8	6–7	3–5	1–3
Total				
Total crossover RMS	10–13	9–11	7–10	5–9

Conclusions

Delft JGM-3 orbits for ERS

- Large geographically *anti*-correlated orbit error is due to imperfection in the JGM-3 gravity field; approximately 3.5 cm.
- Geographically fully correlated orbit error is not observable in crossovers but probably of similar magnitude; approximately 3.5 cm.
- Non-geographically correlated orbit error is already quite small due to tuning of the macro-model and estimation of 1- and 2-cpr empirical accelerations; approximately 3.5 cm.
- **Total radial orbit error: 6–7 cm.**

JGM-3 orbits available by FTP and through WWW

- ERS–1 orbits and interpolation software freely available.
- Phase C (Multi-disciplinary phase)
- Phase D (Second ice-phase)
- Phase E/F (Geodetic mission)
- Address: http://dutlru8.lr.tudelft.nl/ers1/precorbs/

Conclusions

Delft Institute for Earth-Oriented Space Research

Tailored gravity field model DGM-E01

- Obtained through adjustment of 1100 gravity field coefficients of JGM-3.
- Geographically *anti*-correlated orbit error significantly reduced to approximately 1.5 cm.
- Geographically fully correlated orbit error yet unknown.
  To be investigated through crossing with TOPEX.
  Current estimate, approximately 1.5–3.0 cm.
- Non-geographically correlated orbit error is not affected by tailoring process: approximately 3.5 cm.
- **Total radial orbit error: 4–5 cm.**

To do

- Also incorporate TOPEX/ERS crossovers in tailoring the gravity field, minimising the fully correlated orbit error.
- Demonstrate suitability of gravity model for other satellites: TOPEX/POSEIDON, LAGEOS, SPOT.
- Investigate impact on estimated parameters (empirical forces).

ERS–1 in *Hibernation*

ERS–1 is performing better than expected ...

- ERS–1 has demonstrated its capabilities.
- As an altimetric system it has shown even to conform to the TOPEX/POSEIDON pre-launch specs.
- The satellite, especially the altimeter, is still nearly in 100% health.

.. but, due to lack of political interest ...

- ERS–1 will go into hibernation as of 3 June.
- No more altimeter data, no more SAR interferometry.
- To be revived on demand (if possible).

... what a shame !