DORIS RINEX data processing at CNES/CLS AC

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Method and implementation in the GINS software

1. METHOD

BASIC EQUATIONS

A- CONVERSION BETWEEN PROPER TIME τ OF A CLOCK AND COORDINATE TIME t

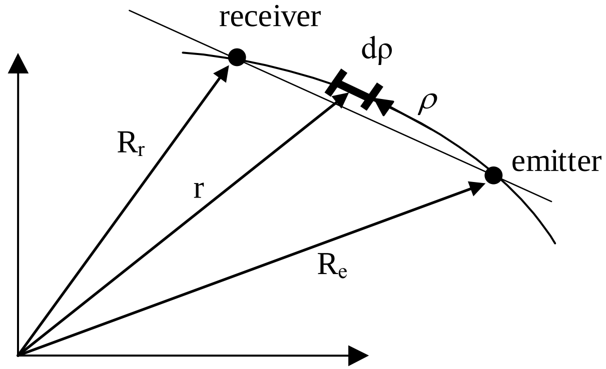
(1)

$$d\tau \approx \left[1 - \frac{U}{c^2} - \frac{V^2}{2c^2}\right] dt$$

Where:
U is the gravitational potential at the location of the clock
V is the velocity of the clock in the coordinate reference frame
c is the velocity of light in the void

Method and implementation in the GINS software

B- TRANSIT TIME OF A PHOTON BETWEEN A POINT OF EMISSION AND A POINT OF RECEPTION



(2)

$$\Delta t_{transit} \approx \frac{\rho}{c} + 2\frac{\mu}{c^3}\ln\left(\frac{R_e + R_r + \rho}{R_e + R_r - \rho}\right)$$

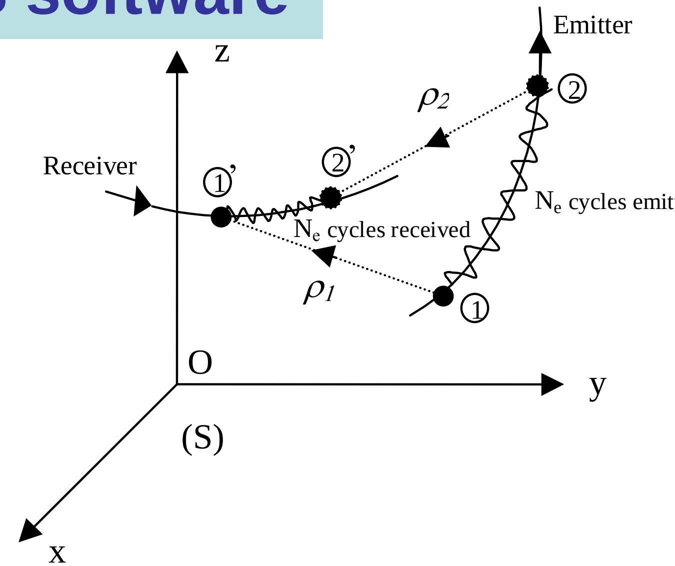
Where:

ρ is the curvilinear trajectory of the photon; close at the first order to the geometrical distance between the emitter and the receiver

μ = ***GM*** , with ***G***: gravitational constant, ***M***: mass of the Earth

$\boldsymbol{R_e}$ and $\boldsymbol{R_r}$ are the geometrical distance of the emitter (resp. receiver) to the center of the reference frame, coincident with the center of mass of the Earth

Method and implementation in the GINS software



Let us define the 4 events:

① Emission of the 1st cycle by the emitter

①' Reception of the 1st cycle by the receiver

② Emission of the N_e–th cycle by the emitter

②' Reception of the N_e-th cycle by the receiver

During the proper time interval $\Delta\tau_r = \tau_{r_{2'}} - \tau_{r_{1'}}$, the receiver has received the N_e cycles sent by the emitter, with $N_e = f_e \Delta\tau_e$, f_e being the proper frequency of the emitter. The receiver is also equipped with an oscillator and during the proper time interval $\Delta\tau_r$, it has generated a number $N_r = f_r \Delta\tau_r$ of cycles, f_r being the proper frequency of the receiver. The Doppler measurement is the count, by the receiver electronics, of the number of cycles of difference between N_e and N_r:

$\boxed{N_{DOP} = N_e - N_r}$ => $\boxed{N_{DOP} = f_e \Delta\tau_e - f_r \Delta\tau_r}$

Method and implementation in the GINS software

In the RINEX files, this Doppler count is the difference between two phase measurements done at different time tags in the proper time of the receiver.

Let us express $\Delta\tau_e$ as a function of $\Delta\tau_r$, using coordinate time as an intermediary:

$$\Delta\tau_e = \tau_{e_2} - \tau_{e_1} \approx \left(1 - \frac{U_e}{c^2} - \frac{V_e^2}{2c^2}\right)(t_2 - t_1)$$

From (1), assuming U_e and V_e are constant over

$$(t_2 - t_1) = (t_2 - t_{2'}) + (t_{2'} - t_{1'}) + (t_{1'} - t_1)$$
$$= -(t_{2'} - t_2) + (t_{2'} - t_{1'}) + (t_{1'} - t_1)$$

$$t_{2'} - t_2 = \frac{\rho_2}{c} + \frac{2GM}{c^3}\ln\left(\frac{R_2 + R_{2'} + \rho_2}{R_2 + R_{2'} - \rho_2}\right)$$

From (2)

$$t_{2'} - t_{1'} = \Delta t_r \approx \left(1 + \frac{U_r}{c^2} + \frac{V_r^2}{2c^2}\right)\Delta\tau_r$$

From (1), assuming U_r and V_r are constant over

$(\tau_2 - \tau_1)$; that is to say, in the case of an upward Doppler, for small orbit eccentricities.

$$t_{1'} - t_1 = \frac{\rho_1}{c} + \frac{2GM}{c^3}\ln\left(\frac{R_1 + R_{1'} + \rho_1}{R_1 + R_{1'} - \rho_1}\right)$$

From (2)

Method and implementation in the GINS software

Finally we get **(3)**:

$$N_{DOP} = f_e\left(1-\frac{U_e}{c^2}-\frac{V_e^2}{2c^2}\right)\left[\left(1+\frac{U_r}{c^2}+\frac{V_r^2}{2c^2}\right)\Delta\tau_r-\frac{\rho_2-\rho_1}{c}+2\frac{GM}{c^3}\left[\ln\left(\frac{R_1+R_{1'}+\rho_1}{R_1+R_{1'}-\rho_1}\right)-\ln\left(\frac{R_2+R_{2'}+\rho_2}{R_2+R_{2'}-\rho_2}\right)\right]\right]$$

Assuming $\frac{V}{c}<<1$ and $\frac{U}{2c^2}<<1$, and converting to velocity, we get the equations used in GINS:

(4)

$$v_{measured} = \frac{c}{f_{e_N}}\left(f_{e_N}-f_{r_T}-\frac{N_{DOP}}{\Delta\tau_r}\right)+\Delta V_{IONO}+\Delta V_{TROPO}+\Delta V_{REL}$$

$$v_{theo} = \left(1-\frac{U_e}{c^2}-\frac{V_e^2}{2c^2}\right)\frac{\rho_2-\rho_1}{\Delta\tau_r}-\frac{c\left(\frac{N_{DOP}}{\Delta\tau_r}+f_{rT}\right)}{f_{e_N}}\frac{\Delta f_e}{f_{e_N}}$$

Method and implementation in the GINS software

- $v_{measured}$ is the measured relative velocity between the emitter and the receiver between the events 1') and 2'), based on the Doppler count N_{DOP}, corrected for the ionospheric, tropospheric and relativistic effects;

- v_{theo} is the theoretical (or computed) velocity between the emitter and the receiver between the events 1') and 2'), corrected for a solved-for frequency bias per pass $\frac{\Delta f_e}{f_{e_N}}$ of the emitter;

- $f_{r_T} = f_{r_N} + \Delta f_r$ is an estimate of the true proper frequency of the receiver based either on a polynomial regression over the frequency offsets estimated during the passes over the master beacons (which have a quasi-nil proper frequency offset), or from the receiver frequency estimates found in the RINEX files. Beware: in that case the frequency estimation is not smooth enough, and a linear (or polynomial) interpolation has to be done between the first and last value of the RINEX file.

- U_r and U_e are the gravitational potential of resp. the receiver and the emitter

Method and implementation in the GINS software

- $\Delta V_{REL} = \Delta V_{REL_H} + \Delta V_{REL_T}$ is the relativistic correction which is composed of two parts, the clock correction ΔV_{REL_H} and the transit correction ΔV_{REL_T} :
  - $\Delta V_{REL_H} = \frac{1}{c}\left[U_r - U_e + \frac{V_r^2 - V_e^2}{2}\right]$
  - $\Delta V_{REL_T} = \frac{2\mu}{\Delta\tau_r\, c^2}\left[\ln\left(\frac{R_1 + R_{1'} + \rho_1}{R_1 + R_{1'} - \rho_1}\right) - \ln\left(\frac{R_2 + R_{2'} + \rho_2}{R_2 + R_{2'} - \rho_2}\right)\right]$

Method and implementation in the GINS software

2. Implementation in GINS software

a) **Time scales**

b) **Correction of aberration**

c) **Ionospheric correction**: In the RINEX files, the ionospheric correction has to be done by the users. A first-order iono-free measurement is built by combining the 400 MHz and 2 GHz measurements in the following way:

$$D_{iono-free} = \frac{\gamma D_{2GHz} - D_{400MHz}}{\gamma - 1}$$

Where D_{2GHz} and D_{400MHz} are the pseudo distance measurements on 2 GHz and 400 MHz, and γ is the square of the frequency ratio: $\gamma = \left(\frac{f_{2GHz}}{f_{400MHz}}\right)^2$.

Converting to iono-free phase measurement on the 2 GHz channel using:

$$D_{iono-free} = \lambda_{2GHz} * L_{iono-free-2GHz},\ D_{2GHz} = \lambda_{2GHz} * L_{2GHz} \text{ and } D_{400MHz} = \lambda_{400MHz} * L_{400MHz}$$

Method and implementation in the GINS software

$$L_{iono-free-2GHz} = \frac{\gamma L_{2GHz} - \sqrt{\gamma} L_{400MHz}}{\gamma - 1} = L_{2GHz} + \frac{L_{2GHz} - \sqrt{\gamma} L_{400MHz}}{\gamma - 1}$$

Where:

- L_{2GHz} is the phase measurement on 2 GHz
- L_{400MHz} is the phase measurement on 400 MHz

When using these measurements, the 2 GHz phase centers can no longer be used as the end points of the measurement, the iono-free phase centers have to be used. The coordinates of the iono-free phase centers are given by the following formula:

$$\vec{r}_{2GHz,iono-free} = \frac{\vec{r}_{400MHz,2GHz}}{\gamma - 1}$$

Where:

- $\vec{r}_{2GHz,iono-free}$ is the vector from the 2 GHz phase center to the iono-free phase center
- $\vec{r}_{400MHz,2GHz}$ is the vector from the 400 MHz to the 2 GHz phase center

Method and implementation in the GINS software

The iono-free phase centers are located a few mm away from the 2 GHz phase centers, in the direction opposite to the 400 MHz phase centers.

Unit = mm	Ref. point – 400 MHz	Ref. point – 2 GHz	400 MHz – 2 GHz	2 GHz – iono-free	Ref. point – iono-free
STAREC satellite antenna (Jason-2)	155	319	164	**6**	325
STAREC satellite antenna (Cryosat-2)	158	312	154	**6**	318
STAREC satellite antenna (HY-2A)	154	316	162	**6**	322
STAREC satellite antenna (SARAL)	156	314	158	**6**	320
STAREC **ground** antenna	0	487	487	**19**	506

DORIS RINEX data processing results

Processing context

•We analyzed DORIS data with 3.5-day arcs and a cut-off angle of 12°

- 4 years of DORIS data for Jason-2 and Cryosat-2 (from January 2011 to December 2014)
- ~3 years for HY-2A (from October 2011 to December 2014)

•We used the following DORIS data

- DORIS2.2 Doppler measurement
- DORIS RINEX 3.0 phase measurement converted to DOPPLER

DORIS RINEX data processing results

•Orbit results

- DORIS and SLR RMS of fit of the orbit determination
- Comparison of the orbit obtained from the DORIS2.2 data to the orbit from RINEX data

•Positioning results: Solution compared to ITRF2008 computed by CATREF

Helmert parameters: Scale and Geocenter / WRMS by component (North East Up)

- Single satellite solutions: Jason-2, Cryosat-2 and HY-2A
- Multi-satellite solution Jason-2 + Cryosat-2 + HY-2A

DORIS RINEX data processing results

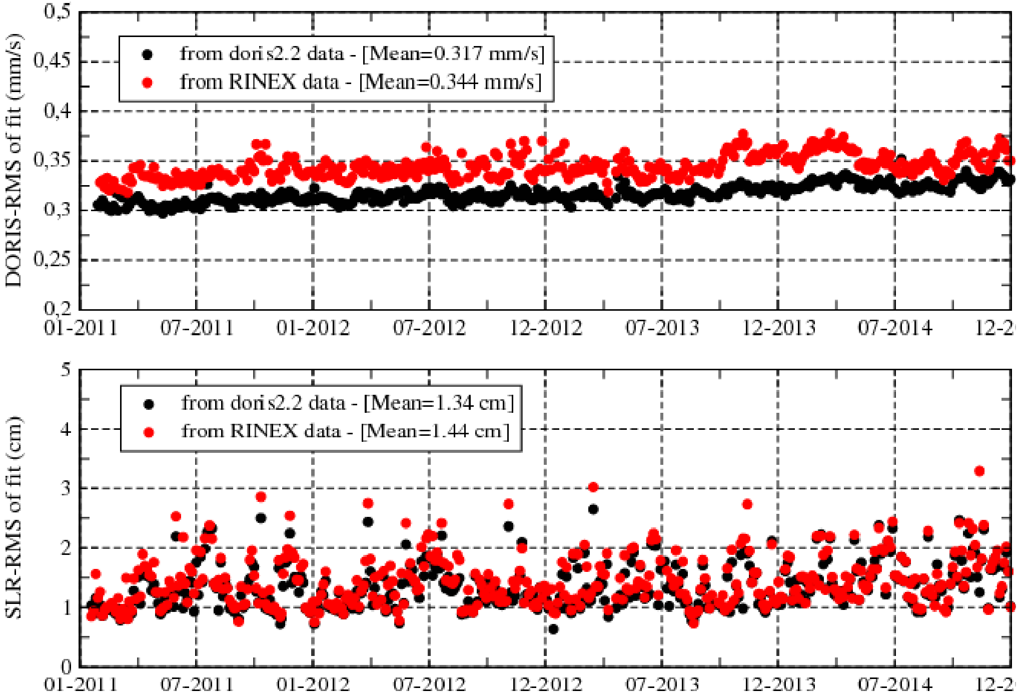
Jason-2 orbit results

- DORIS and SLR RMS of fit of the orbit determination

- Orbit differences, Average and RMS by component RTN

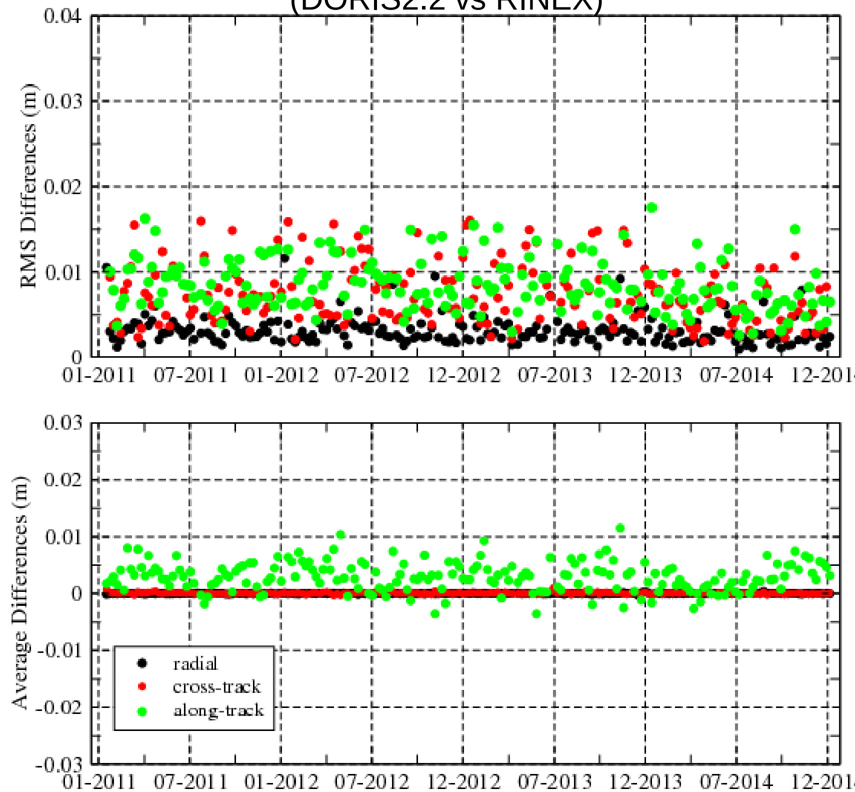
DORIS and SLR RMS of fit

in black from DORIS2.2 data and **in red from DORIS RINEX data**



Orbit differences

(DORIS2.2 vs RINEX)



- **DORIS RMS of fit higher in the case of DORIS RINEX data** (0.344 mm/s vs 0.317 mm/s)
- **SLR RMS of fit slightly higher in the case of DORIS RINEX data** (1.44 cm vs 1.34 cm)
- **Along track Bias of 0.3 cm between the two orbits**

DORIS RINEX data processing results

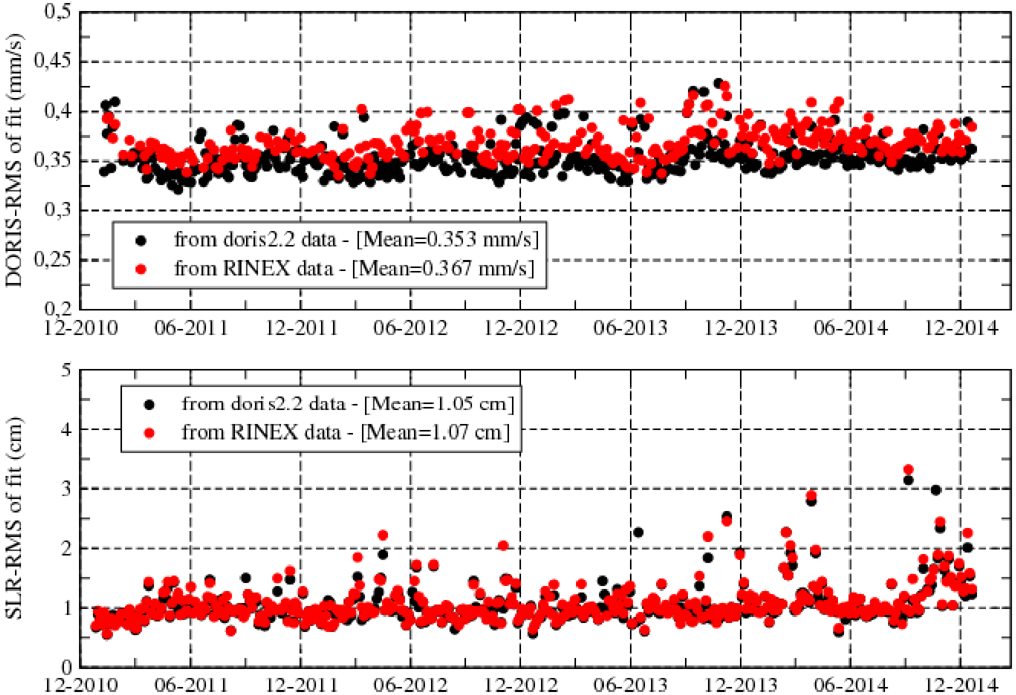
Cryosat-2 orbit results

- DORIS and SLR RMS of fit of the orbit determination

- Orbit differences, Average and RMS by component RTN

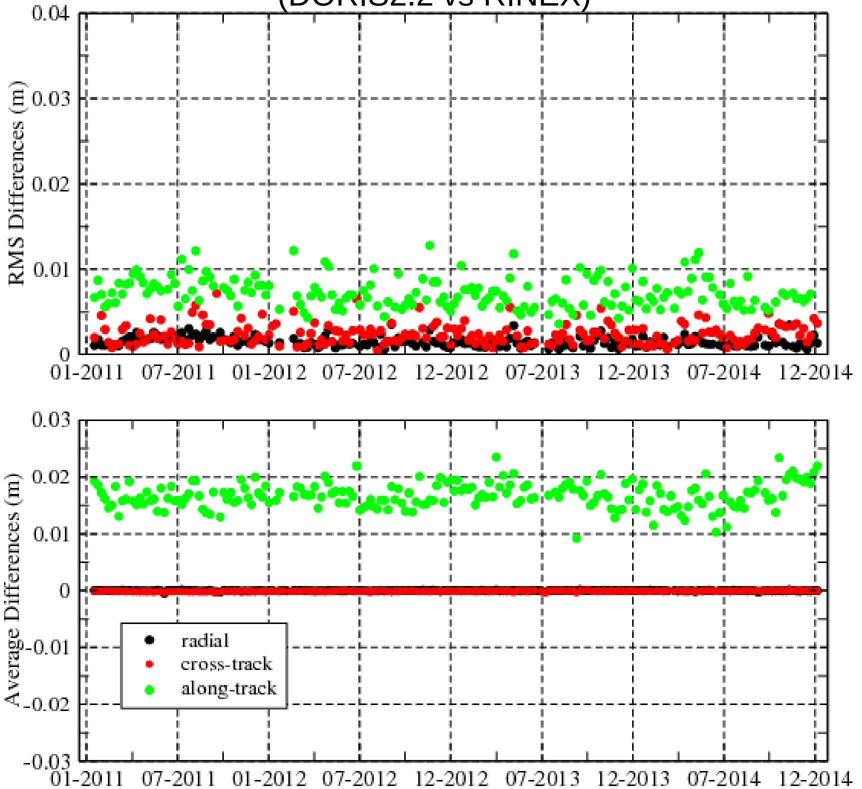
DORIS and SLR RMS of fit

in black from DORIS2.2 data and **in red from DORIS RINEX data**



Orbit differences

(DORIS2.2 vs RINEX)



- **DORIS RMS of fit slightly higher in the case of DORIS RINEX data** (0.367 vs 0.353 mm/s)
- **SLR RMS of fit is at the same level for the two sets of data**
- **Along track Bias of 1.7 cm between the two orbits**

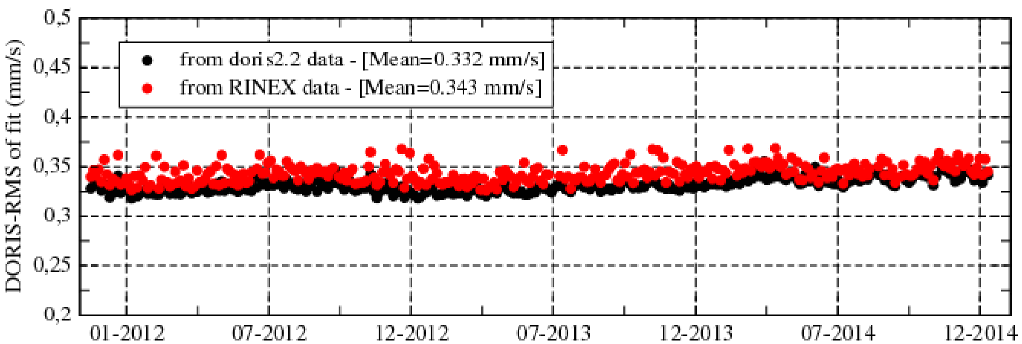
DORIS RINEX data processing results

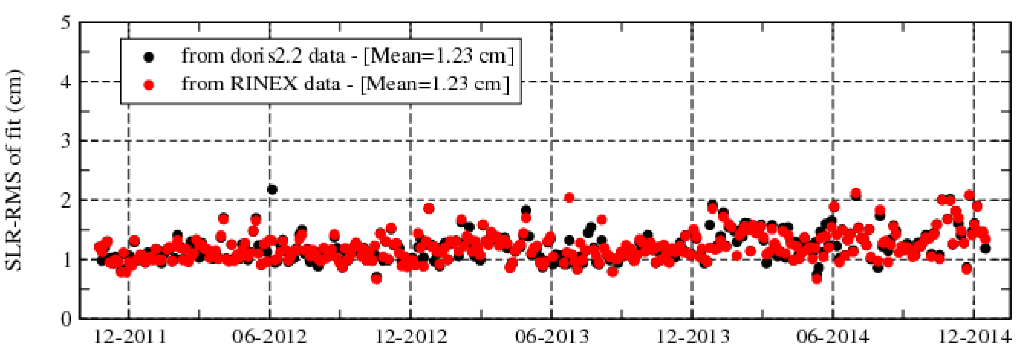
HY-2A orbit results

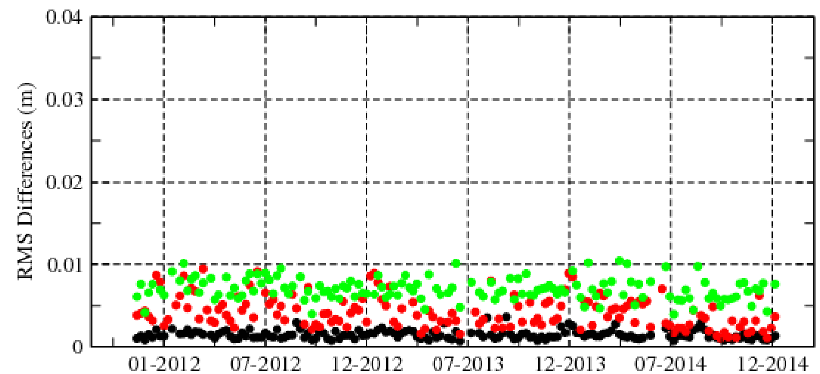
- DORIS and SLR RMS of fit of the orbit determination
- Orbit differences, Average and RMS by component RTN

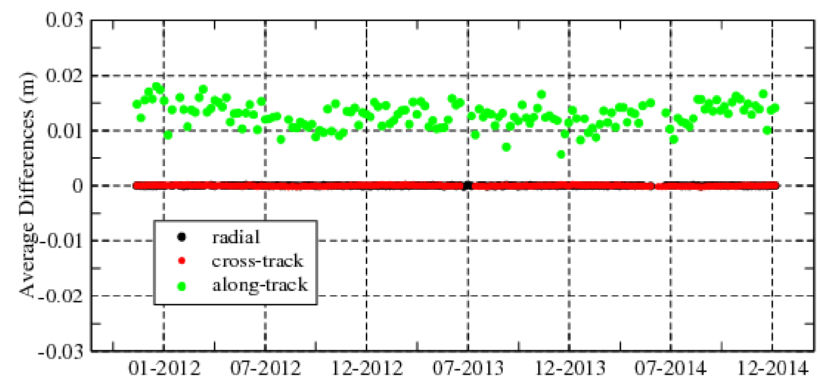
Orbit differences
(DORIS2.2 vs RINEX)

DORIS and SLR RMS of fit
in black from DORIS2.2 data and **in red from DORIS RINEX data**









- **DORIS RMS of fit slightly higher in the case of of DORIS RINEX data** (0.343 vs 0.332 mm/s)
- **SLR RMS of fit is at the same level for the two sets of data**
- **Along track Bias of 1.3 cm between the two orbits**

DORIS RINEX data processing results

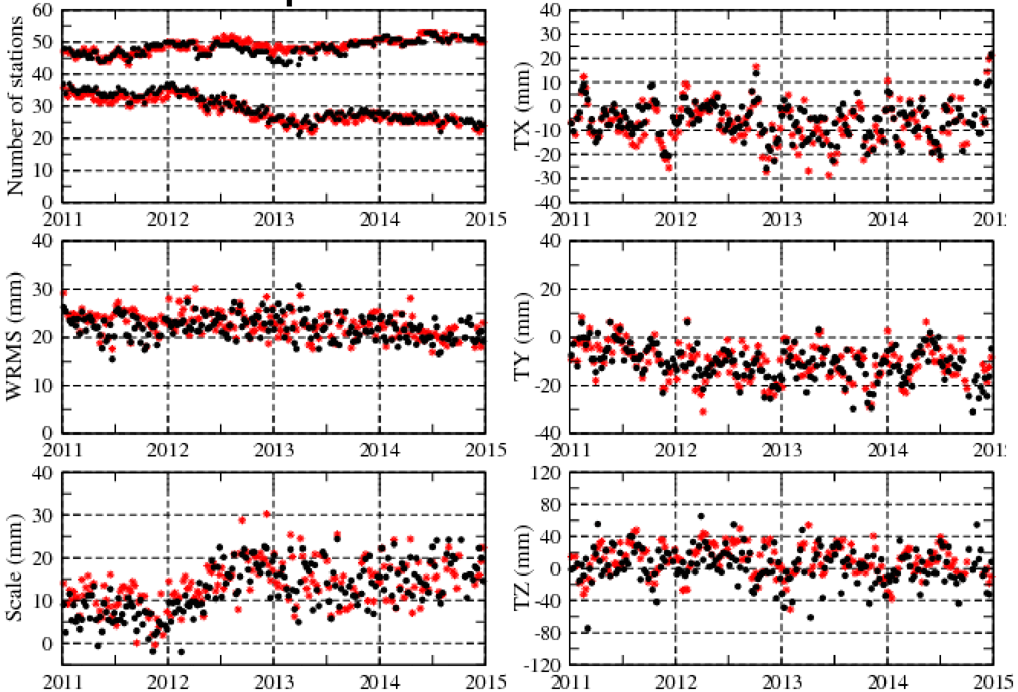
Positioning results

Jason-2 single satellite solution compared to ITRF2008 computed by CATREF

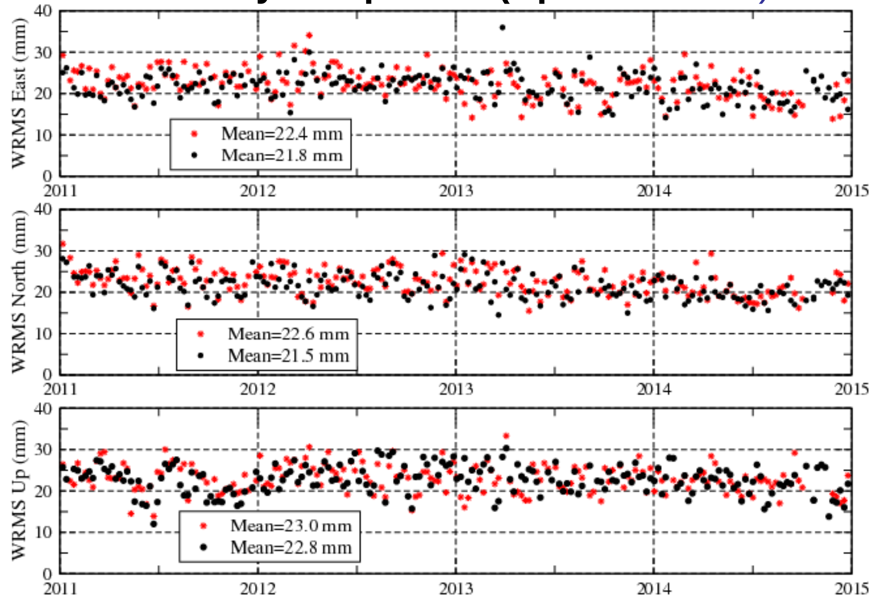
- Helmert parameters: Scale and Geocenter
- WRMS by component (Up North East)

(in black from DORIS2.2 data and **in red from DORIS RINEX data)**

Helmert parameters: Scale and Geocenter



WRMS by component (Up North East)



- Larger scale with DORIS/RINEX (~2.5 cm) vanished thanks to the use of iono-free phase centers instead of the 2 GHz phase centers

-The scale jump in 2012 is also seen when we use DORIS RINEX data

- For Jason-2 the quality with DORIS RINEX data is at the same level than DORIS2.2 data

DORIS RINEX data processing results

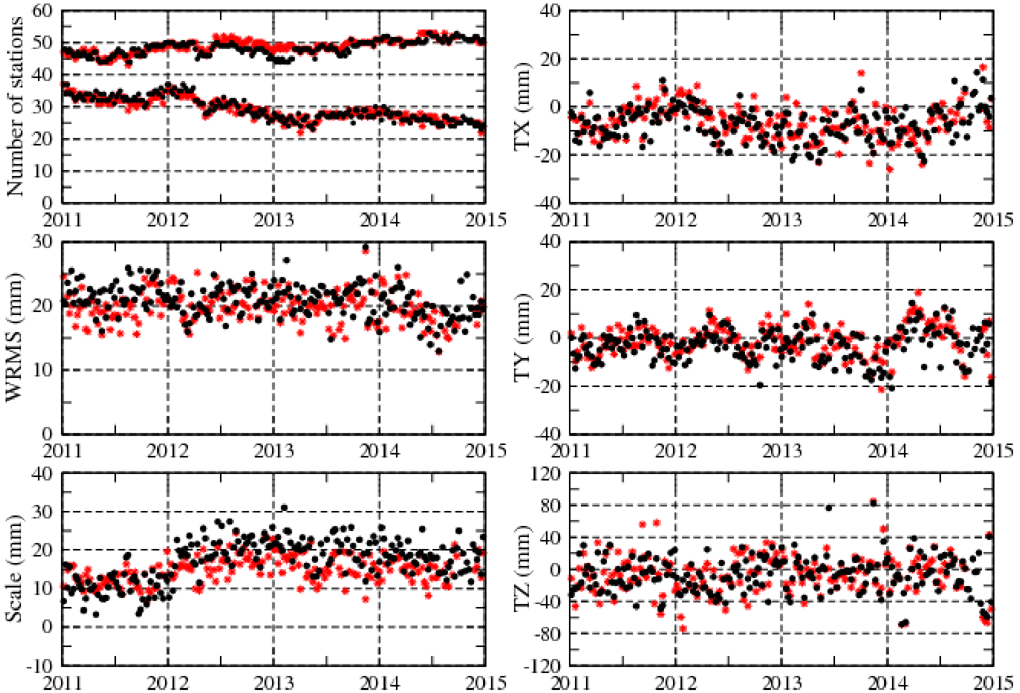
Positioning results

Cryosat-2 single satellite solution compared to ITRF2008 computed by CATREF

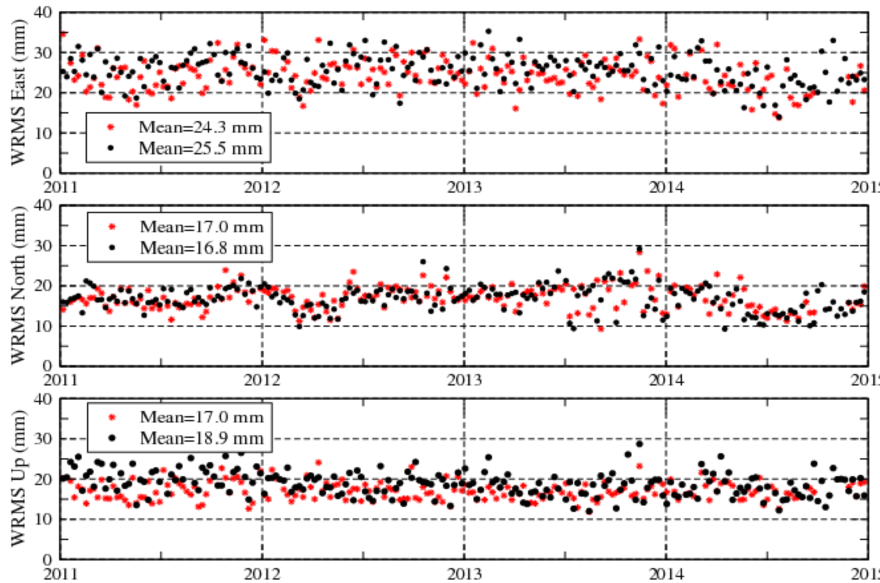
- Helmert parameters: Scale and Geocenter
- WRMS by component (Up North East)

(in black from DORIS2.2 data and **in red from DORIS RINEX data)**

Helmert parameters: Scale and Geocenter



WRMS by component (Up North East)



- Larger scale with DORIS/RINEX (~2.5 cm) vanished thanks to the use of iono-free phase centers instead of the 2 GHz phase centers
- The scale jump in 2012 is also seen when we use DORIS RINEX data but not so strong
- For Cryosat-2 the quality with DORIS RINEX data is at the same level than DORIS2.2 data

DORIS RINEX data processing results

Positioning results

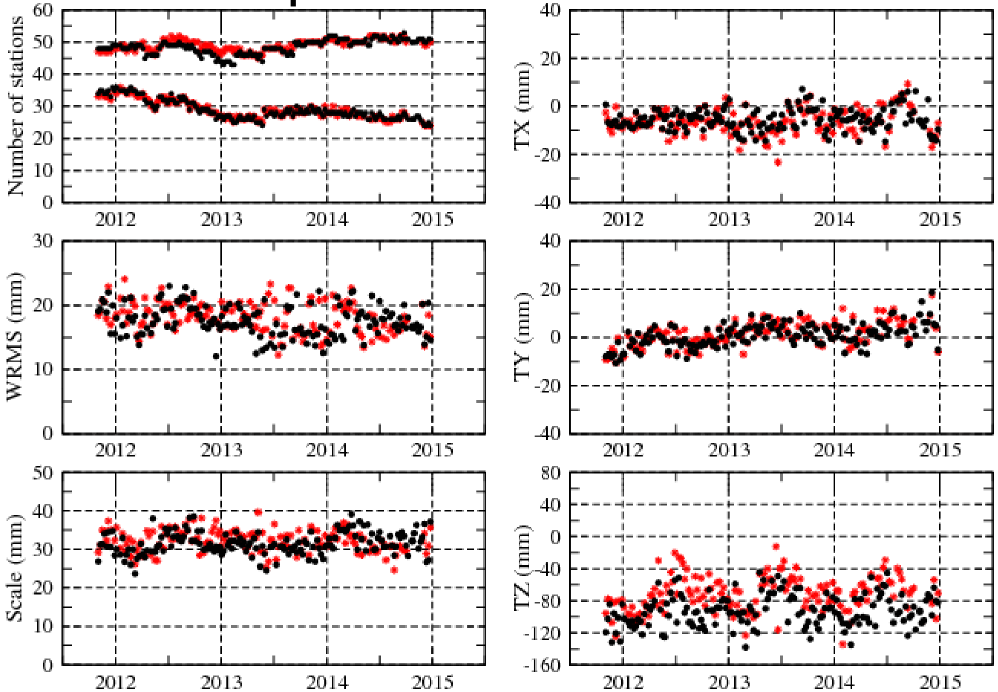
HY-2A single satellite solution compared to ITRF2008 computed by CATREF

•Helmert parameters: Scale and Geocenter

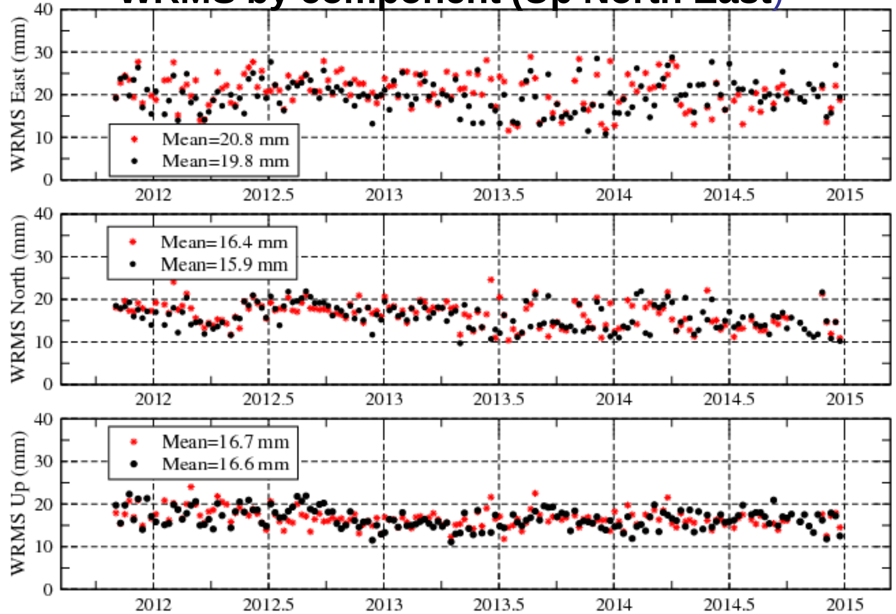
• WRMS by component (Up North East)

(in black from DORIS2.2 data and **in red from DORIS RINEX data)**

Helmert parameters: Scale and Geocenter



WRMS by component (Up North East)



- Larger scale with DORIS/RINEX (~2.5 cm) vanished thanks to the use of iono-free phase centers instead of the 2 GHz phase centers

- The HY-2A scale is higher than the others satellites and there is no scale jump

- For HY-2A the quality with DORIS RINEX data is at the same level than DORIS2.2 data

DORIS RINEX data processing results

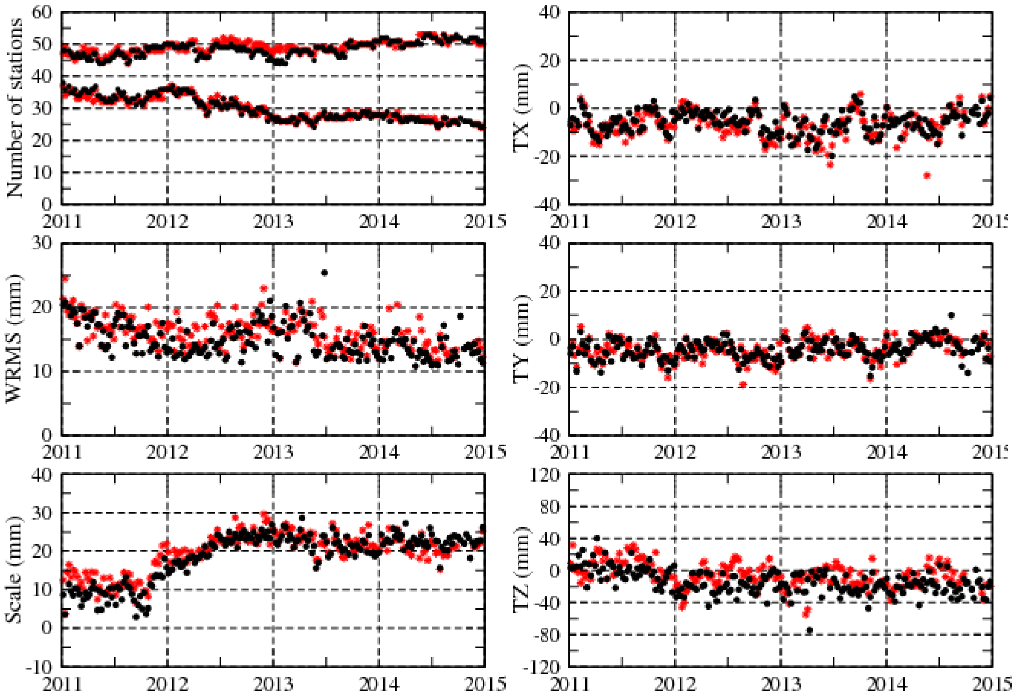
Positioning results

Multi-satellite (Jason2,Cryosat-2,HY-2A) **solution compared to ITRF2008 computed by CATREF**

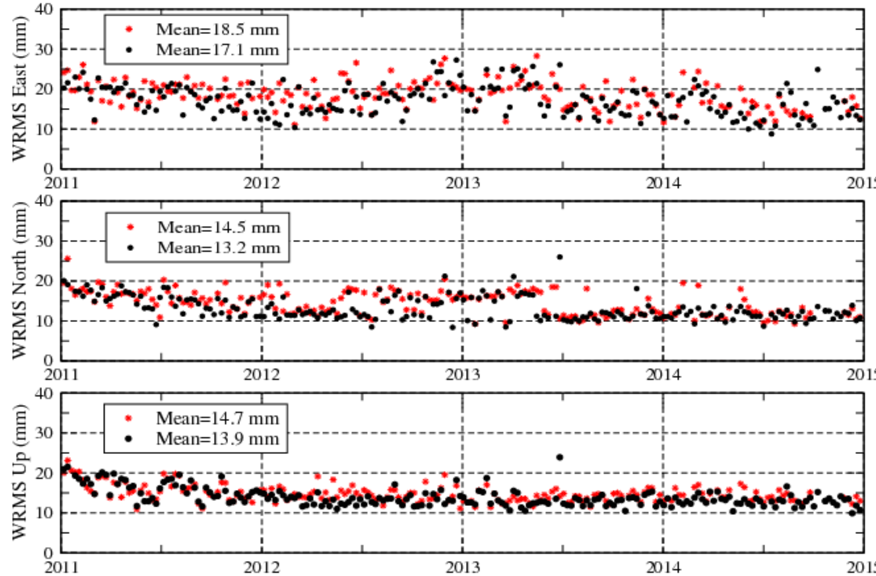
- Helmert parameters: Scale and Geocenter
- WRMS by component (Up North East)

(in black from DORIS2.2 data and **in red from DORIS RINEX data)**

Helmert parameters: Scale and Geocenter



WRMS by component (Up North East)



- Larger scale with DORIS/RINEX (~2.5 cm) vanished thanks to the use of iono-free phase centers instead of the 2 GHz phase centers

-The scale jump in 2012 is also seen when we use DORIS RINEX data

- For multi-satellite solution the scale jump is clearly increased by HY-2A

- For multi-satellite solution the quality with DORIS RINEX data is at the same level than DORIS2.2 data

DORIS RINEX data processing

Conclusions

•The larger scale with DORIS/RINEX (~2.5 cm) vanished thanks to the use of iono-free phase centers instead of the 2 GHz phase centers

• There is a good agreement between the RINEX DORIS data and DORIS2.2
The quality of processing is at the same level when using DORIS RINEX data
But
The DORIS RMS of fit is slightly higher in the case of DORIS RINEX data in particular for Jason-2
There is an Along track Bias between the two orbits (stronger for Crysosat-2 (~1.7 cm))

• The scale jump in 2012 is also seen when we use DORIS RINEX data and clearly increased by HY-2A

Perspectives

• Tests with the upcoming version of the DORIS RINEX including an improved time tagging from SSALTO ‘s component PANDOR

• Investigating the small differences of the results

Backup

Synthesis

Satellite	DORIS RMS / data used (mm/s) DORSI2.2	RINEX	SLR RMS / data used (cm) DORSI2.2	RINEX	Along-track Orbit differences Average (in cm)
Jason-2	0.317 /54850	0.344 /54130	1.34 /1743	1.44 /1737	0.3
Cryosat-2	0.353 /26990	0.367 /27620	1.05 /512	1.07 /507	1.7
HY-2A	0.332 /35930	0.343 /34840	1.23 /120	1.23 /120	1.3

GRG Solutions	Single Jason-2		Single Cryosat-2		Single HY-2A		Multi-satellite	
	DORIS2.2	RINEX	DORIS2.2	RINEX	DORIS2.2	RINEX	DORIS2.2	RINEX
TX (mm)	-6.0 ± 7.5	-7.1 ± 8.6	-7.1 ± 7.1	-6.5 ± 7.1	-5.5 ± 4.6	-6.3 ± 5.3	-5.7 ± 4.6	-6.9 ± 5.5
TY (mm)	-10.8 ± 7.2	-10.2 ± 7.3	-2.9 ± 6.6	-1.1 ± 6.5	0.9 ± 4.7	1.3 ± 4.9	-4.2 ± 4.1	-4.1 ± 4.3
TZ (mm)	3.3 ±21.4	10.1 ± 19.2	-6.9 ±22.4	-6.9 ± 24.2	-92.3 ±19.9	-71.6 ± 21.9	-13.8 ±21.1	-5.3 ± 15.3
Scale (mm)	12.8 ± 5.8	13.8 ± 5.2	17.2 ± 5.5	14.9 ± 3.4	31.6 ± 2.9	32.2 ± 2.8	18.7 ± 6.1	19.5 ± 5.1
WRMS (mm)	22.1	22.7	20.8	19.8	17.7	18.2	14.9	16.1
WRMS North	21.5	22.6	16.8	17.0	15.9	16.4	13.2	14.5
WRMS East	21.8	22.4	25.5	24.3	19.8	20.8	17.1	18.5
WRMS Up	22.8	23.0	18.9	17.0	16.6	16.7	13.9	14.7