Atmospheric Characteristics, gravity field and sea topography estimation using GNSS

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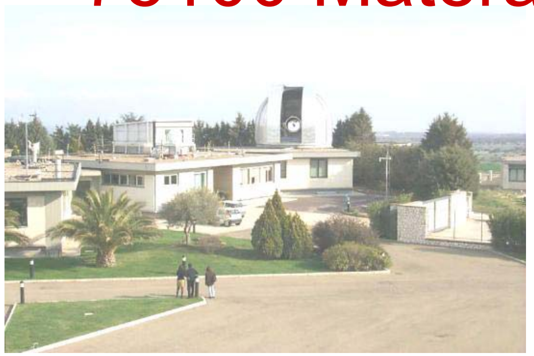


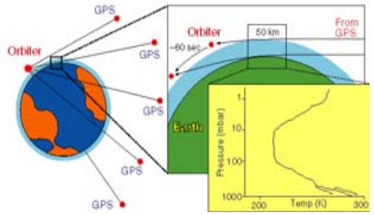
Atmosphere

- Approach to Estimate/Eliminate ZTD
- Validations and Comparisons
  - Internal Validation
  - Validation with other obs.
  - Validation with models
- GNSS for MSL and Sea Topography

From GPS Data to NWP

GPS observables

$$\Phi = \rho + c(dt - dT) + \lambda A - d_{ion} + d_{trop} + \varepsilon$$



data reduction → ZTD

$$d_{trop} \cong ZTD \cdot m(el)$$

$$ZTD \cong 10^{-6} \int N dz$$

4 DVAR

ZTD can be directly assimilated
(or $\Delta\nabla\Phi/\alpha$ for RO)
(HIRLAM)

separation → IWV (or RO Profiles)

$$IWV \cong \Pi(T_m) ZWD = \Pi(T_m)\,(ZTD - ZHD)$$

4 DVAR

assimilation → Meteo Forecasts

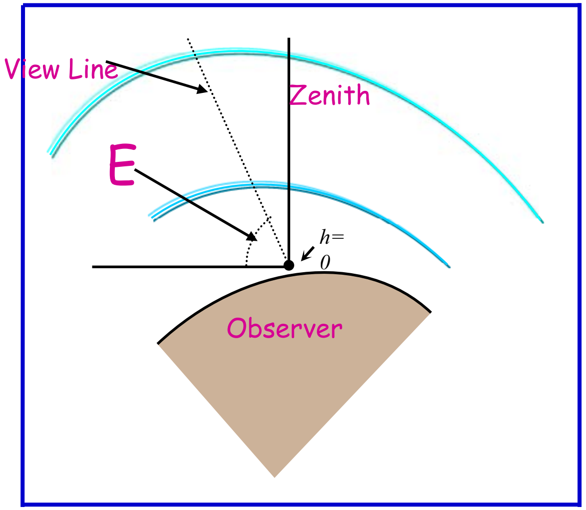
Physical Principles

The Phase Observed by GPS: $\Phi = \rho + c(dt - dT) + \lambda A - d_{ion} + d_{trop} + \varepsilon$

The path of GPS signal from the satellite to the ground receiver is ruled by Fermat Principle:

$$L = \int n \, ds \,, \quad \Delta^{trop} = \int (n-1) \, ds = 10^{-6} \int N^{trop} \, ds$$

$$N^{trop} = k_1 \frac{P_d}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2}$$ Refractivity as from Smith & Weintraub (1953)



P_d=surface pressure (mbar)
e=wet pressure
T=temperature

$$\Delta^{trop} = ZTD \cdot M(E)$$ With:

$$ZTD = 10^{-6} \left[\int k_1 \frac{P_d}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2} dz \right] = ZHD + ZWD$$

M(E)=Mapping Function

Physical Principles:

Mapping Function

$$m(E)=\cfrac{1}{sinE+\cfrac{a}{sinE+\cfrac{b}{sinE+\cfrac{c}{sinE+\dots}}}}$$

Marini Murray

$$\Delta^{trop}=ZHD\cdot M_d(E)+ZWD\cdot M_w(E)$$

$$a_d=[1.2320+0.0139\cos\varphi-0.0209h+0.00215(T-283)]\cdot 10^{-3};$$
$$b_d=[3.1612-0.1600\cos\varphi-0.0331h+0.00206(T-283)]\cdot 10^{-3};$$
$$c_d=[71.244-4.293\cos\varphi-0.149h-0.0021(T-283)]\cdot 10^{-3}.$$

Niell Mapping Function

$$a_w=[0.583-0.011\cos\varphi-0.052h+0.0014(T-283)]\cdot 10^{-3};$$
$$b_w=[1.402-0.102\cos\varphi-0.101h+0.0020(T-283)]\cdot 10^{-3};$$
$$c_w=[45.85-1.91\cos\varphi-0.29h+0.015(T-283)]\cdot 10^{-3}.$$

$$ZTD=m_h(E)ZHD+m_w(E)ZWD+m_\Delta(E)\cot E[G_N\cos\phi+G_E\sin\phi]$$

Physical Principles
(continue)

The precipitable water IPWV is:

$$IPWV = \Pi(T_m)ZWD \qquad \Pi(T_m) = \frac{10^6}{\rho_w R_v\left(\frac{k_3}{T_m} + \left(k_2 - \frac{M_w}{M_d}k_1\right)\right)}$$

$$T_m = 70.2 + 0.72T_s$$

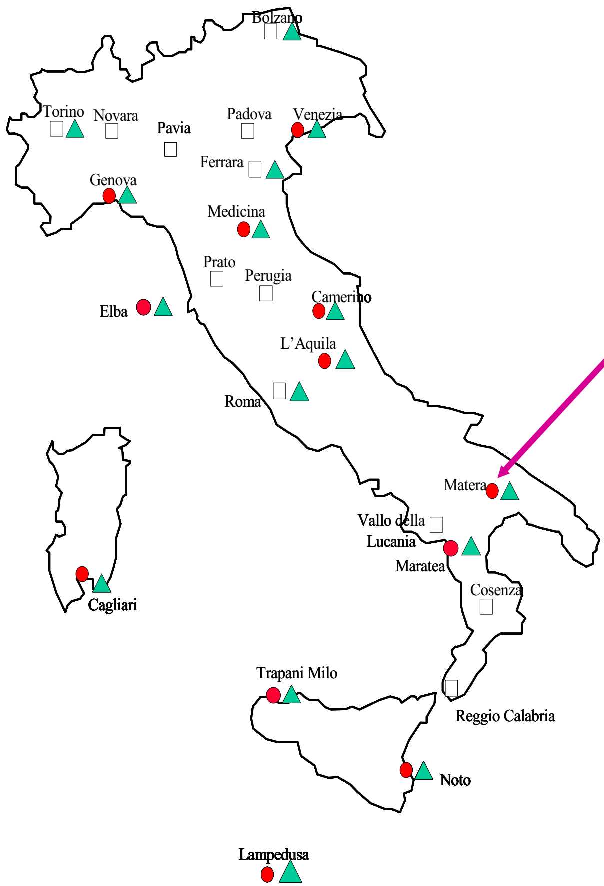
$$ZHD = \left(2.2768 \pm 0.0024 \times 10^{-7}\right)\frac{P_0}{f(\lambda, H)}$$

The total zenith delay is estimated from GPS measurements using a mapping function to account for the satellite elevation. Then the estimate of the hydrostatic zenith delay derived from surface pressure can be subtracted leaving the effect of the wet zenith delay. The factor Π can be calculated given the information available for the temperature profile at the site, Π is empirically determinated. Generally ⚐” 0.15.

ZTD-Near Real Time" for NWP

- Ultra Rapid Orbit (24 h estimated and 24 predicted) - IGS (~30 cm)
- Hourly RINEX data from stations (<15')
- Processing within 1h 45'. "sliding windows strategy"
- ZTD assimilated in NWP models within 3 h

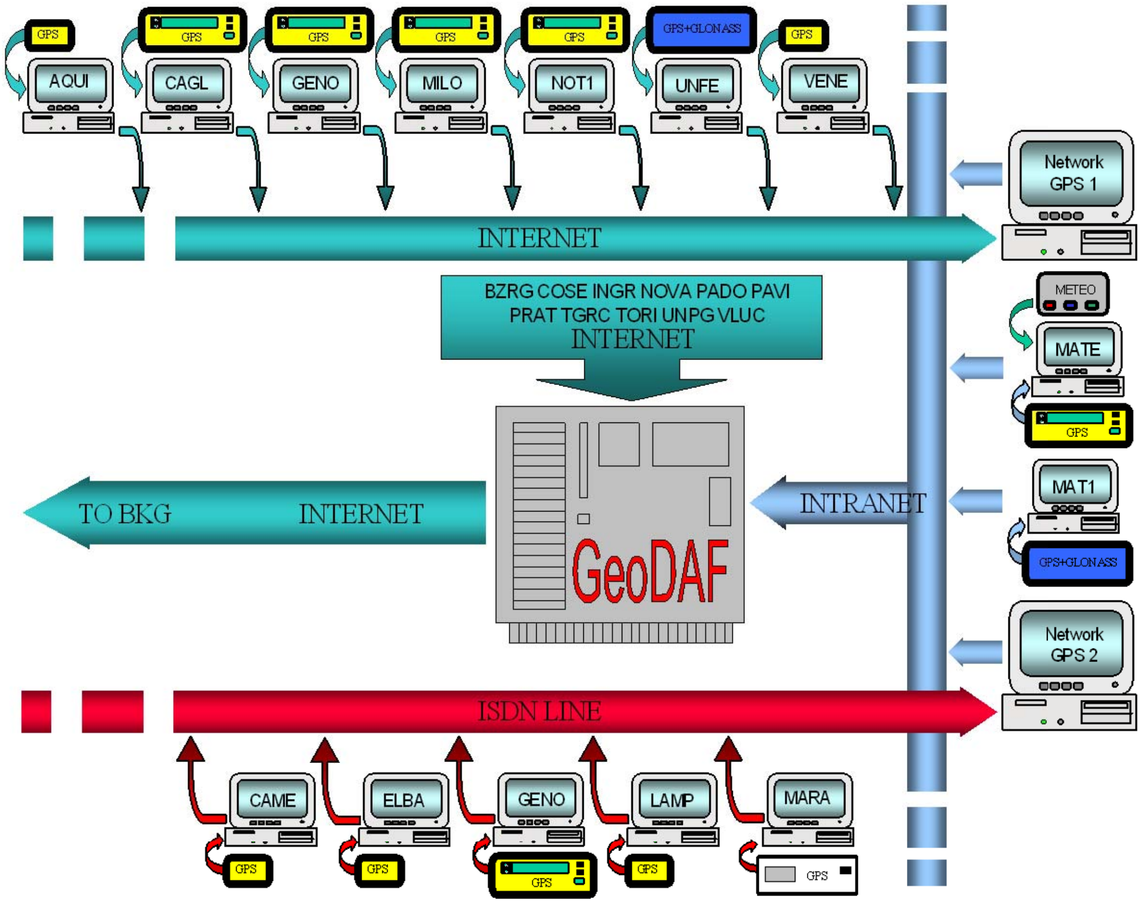
Italian GPS Fiducial Network



Matera ASI-CGS

- 12 ASI SITES
- 12 OTHER INSTITUTION SITES
- 16 HOURLY SITES

Operational & Archiving Activities



GeoDAF

ftp://geodaf.mt.asi.it

http://geodaf.mt.asi.it

hourly data on line for 1 week

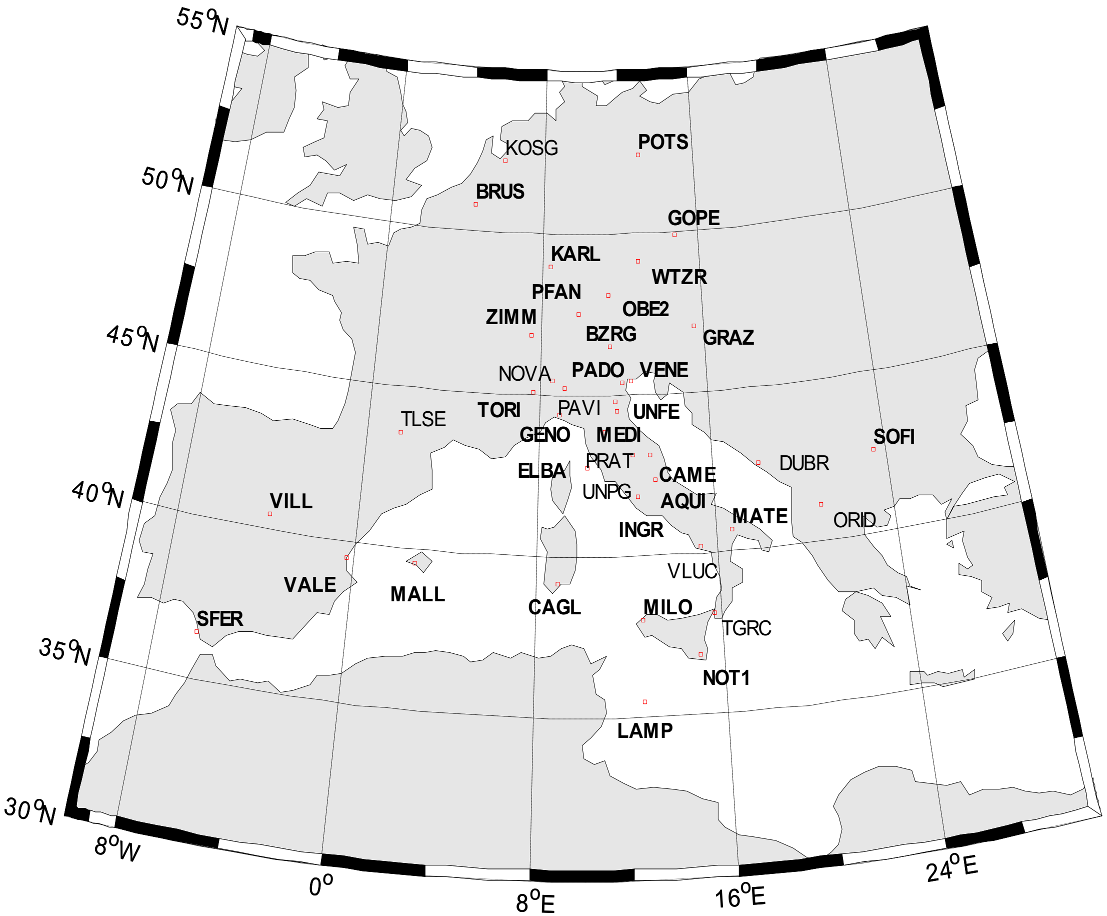
/GEOD/GPSD/NRTDATA/yyyy/doy

Nominal latency 3-12min

MATE high rata data available on line

/GEOD/GPSD/SHRDATA/yyyy/doy

ASI Analyzed GPS Ground Network



40 stations in Post-Processing Mode

30 stations in Near-Real Time Mode

Near-Real Time GPS Data Processing for Zenith Total Delay Estimation

Software	GIPSY-OASIS II, based on Square Root Information Filter
Strategy	Network Solution
Data Sampling Rate	5min
Cut-off angle	10deg
Sites	30 European Stations, Italy primary region
Data handling	24h sliding window
GPS satellite orbits	Fixed to IGU orbits
'Bad' satellite detection	Sp3 accuracy code Automatic detection & removal based on post fit phase observation residuals
'Bad' station detection	Automatic detection & removal based on post fit phase observation residuals
Station coordinates	Heavily constrained to 1 month of post-processed solution aligned to IGS-00
Earth Rotation Parameters	IGU
Ocean Loading	Applied (values provided by H.G.Scherneck)
Mapping function	Niell
ZWD constraint	20mm/sqrt(h)
Estimated Parameters	Satellite & station clocks w.r.t. a reference one Phase ambiguities (float) ZWD with time resolution of 5 minutes

Near-Real Time Processing Schedule

The NRT processing starts every hour at hh:18

1. GPS hourly files are retrieved from GeoDAF, IFAG & CDDIS;
2. at 03:20 & 15:20 UTC IGU products are fetched from IGSCB;
3. RINEX hourly files are merged into a single file with the previous 23 hours & pre-processed;
4. Parameter estimation & ZTD delivered to U.K. Met Office in COST716 V1.0 format.

The total computing time is about 40min for 50 stations on a workstation HP VISUALIZE C3600.

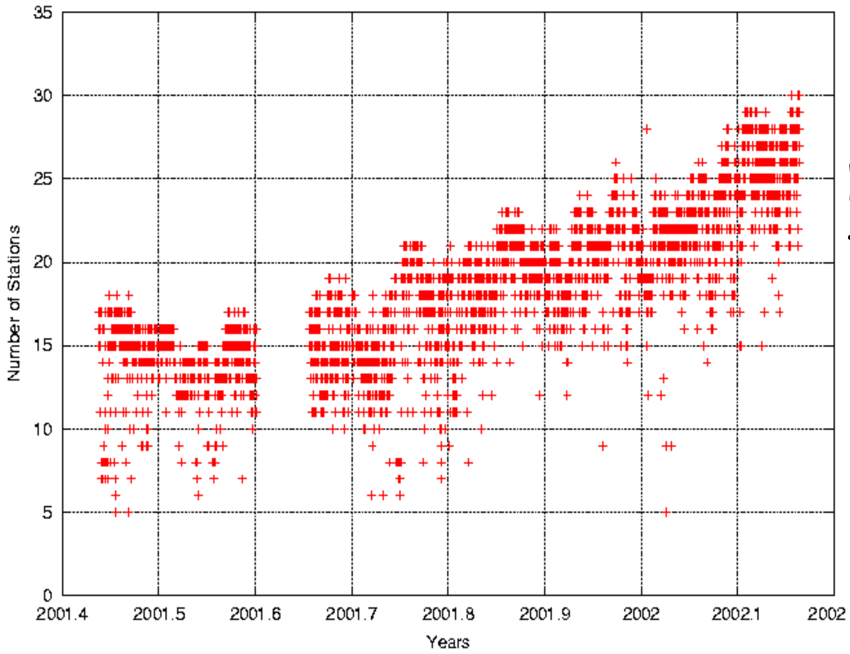
Step 1 to 3 take about 10min, step 4 takes about 30min.

The processing lasts more than the nominal CPU time if a 'bad' satellite or a 'bad' station is detected and removed based on post fit phase observation residuals, in this case step 4 has to be re-run causing an overlap of more batches.

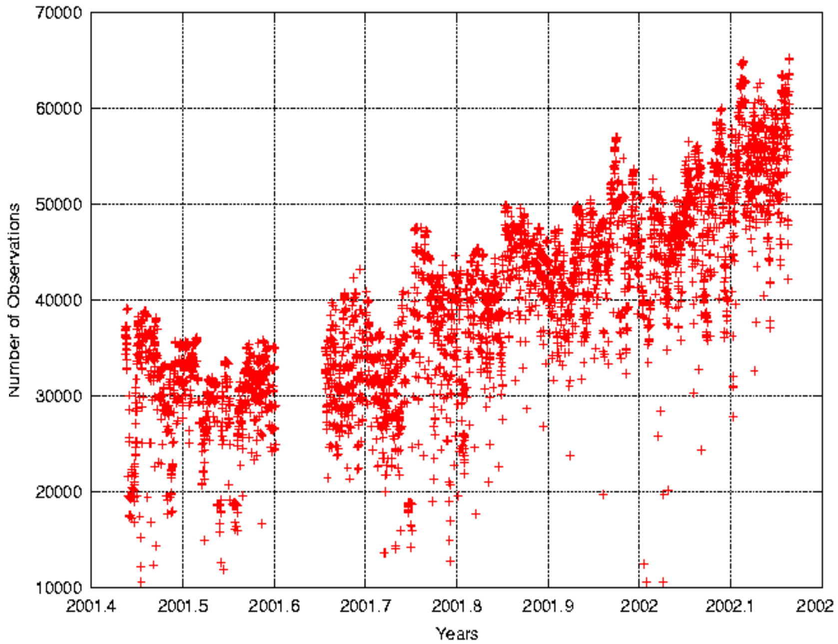
Processing Statistics

June 2001-February 2002

Number of analyzed stations versus time.



Number of observations versus time.



Timeliness and Accuracy requirements for Operational Weather Forecast

Timeliness

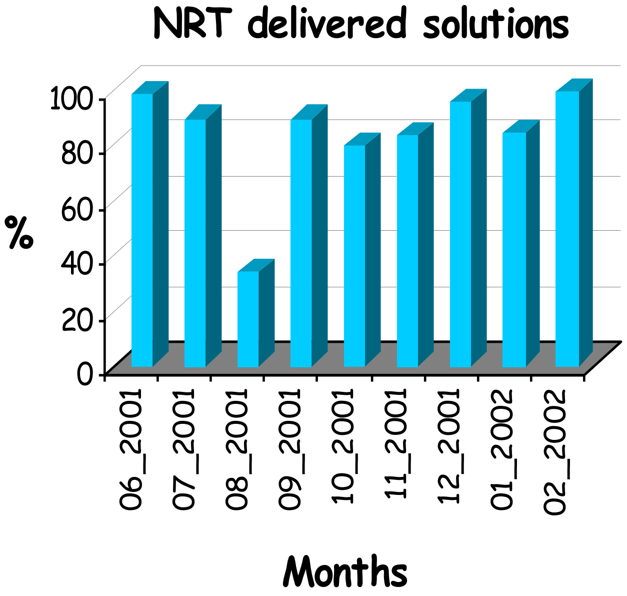
- 75% of observations must arrive within 1h45'
- Use of predicted GPS orbits
  - "Bad" orbits happen
- Fast and reliable data flow (GPS and ZTD)

Accuracy

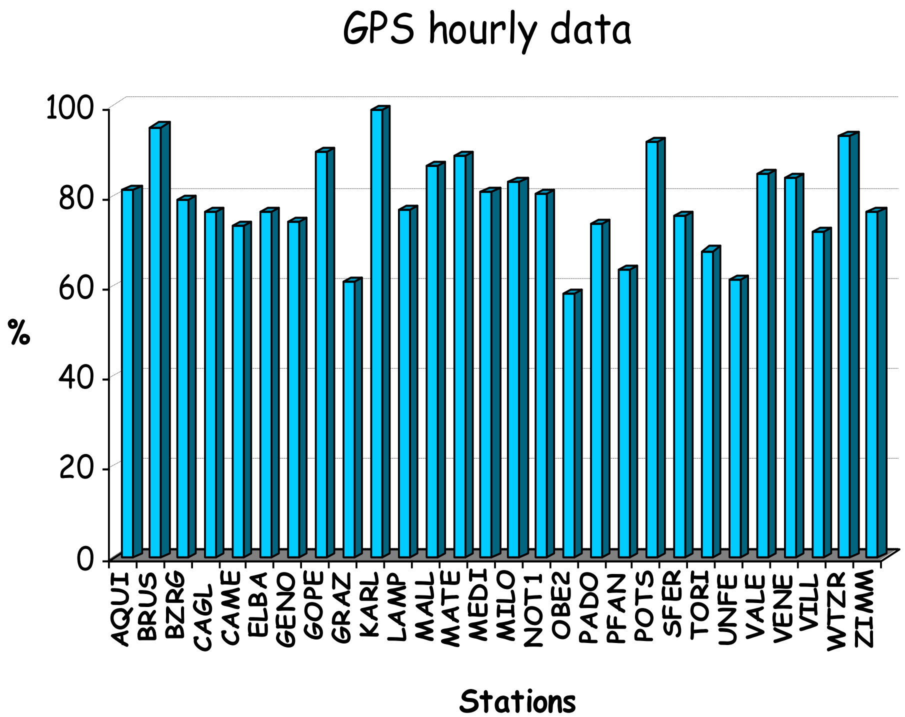
- Use of predicted orbits with minimum degradation of ZTD products w.r.t Post-Processed (NRT STD 3-10mm)
- ZTD retrieved from end of processing window

Near Real Time System Performances

June 2001-February 2002



An average of 80% of NRT solutions are delivered each month.

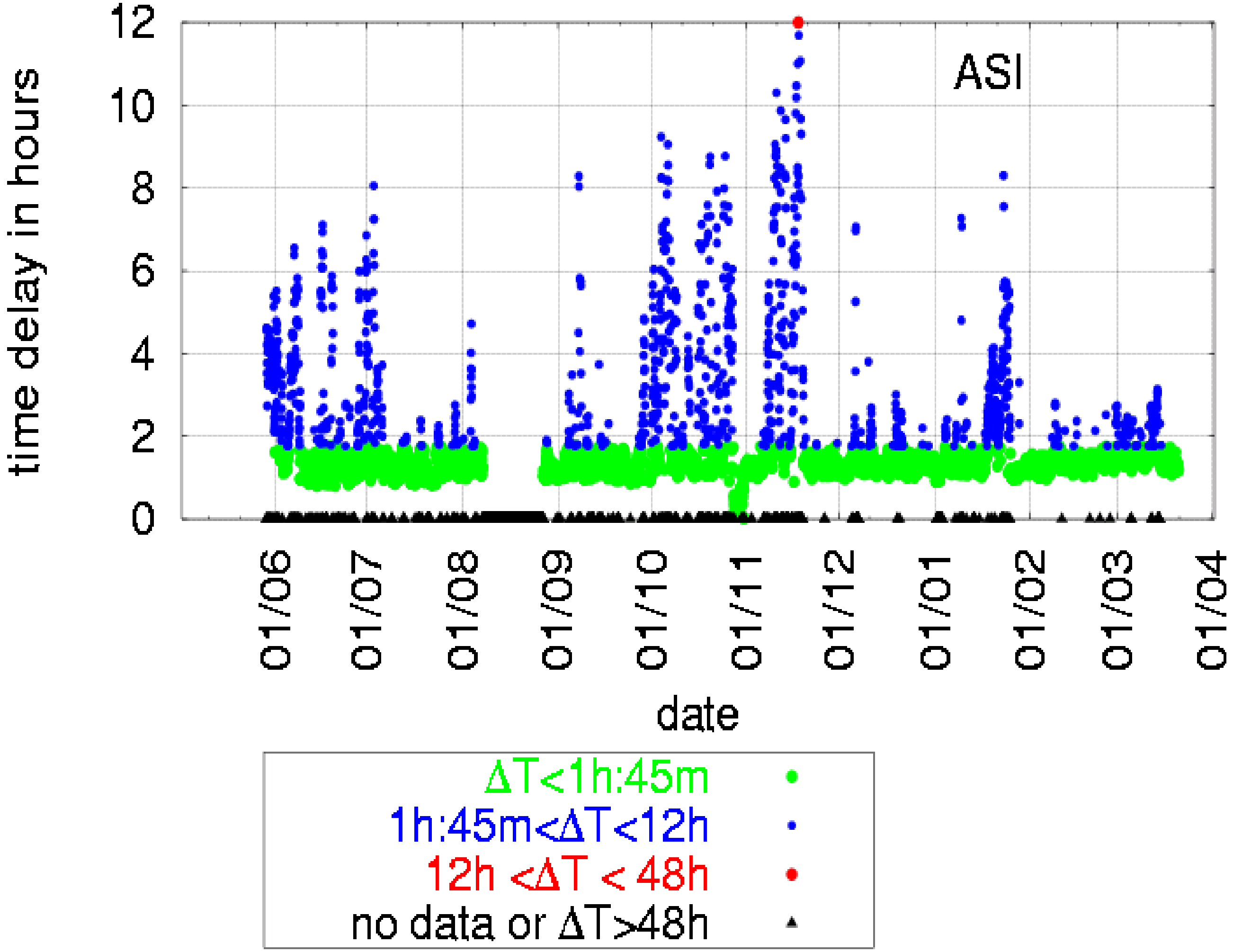


An average of 80% of hourly files are available to be processed in NRT mode. 20% of data arrive too late or are lost.

Near Real Time System Performances

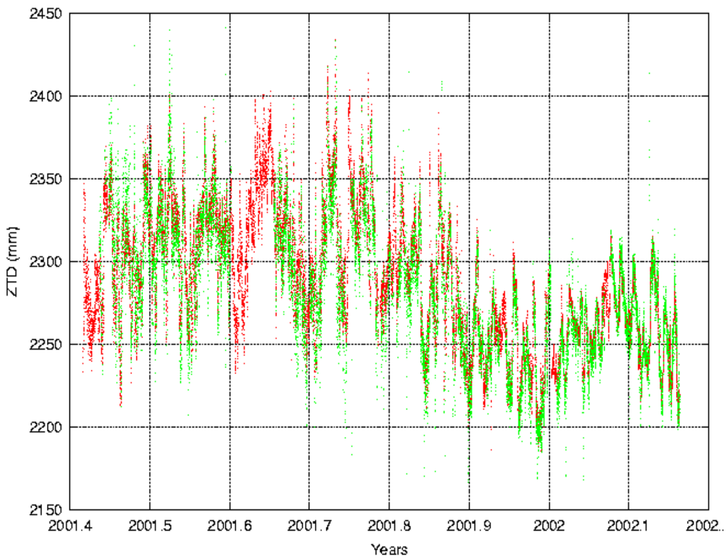
June 2001-February 2002

http://www.knmi.nl/samenw/cost716/stat/latencyASI.html



The green solutions reach the met office within 1h45', the blue ones occur when a bad satellite and/or station is detected and removed.

Post-Processed versus NRT ZTD



ZTD time series for Matera.

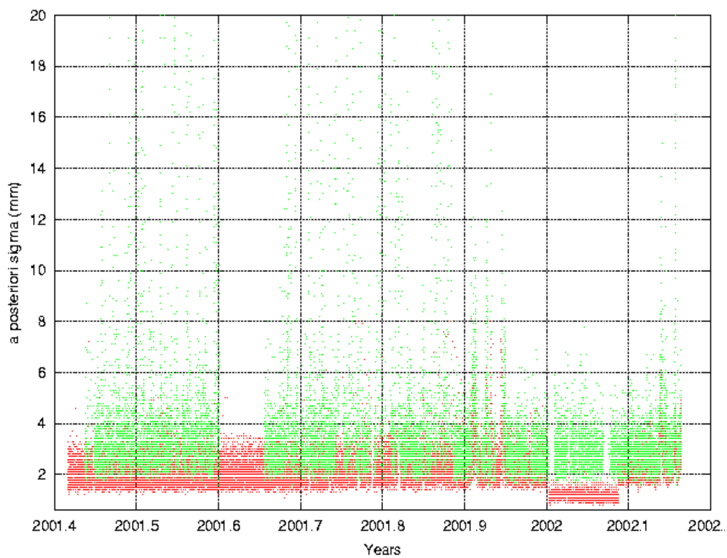
Red= Post-Processed

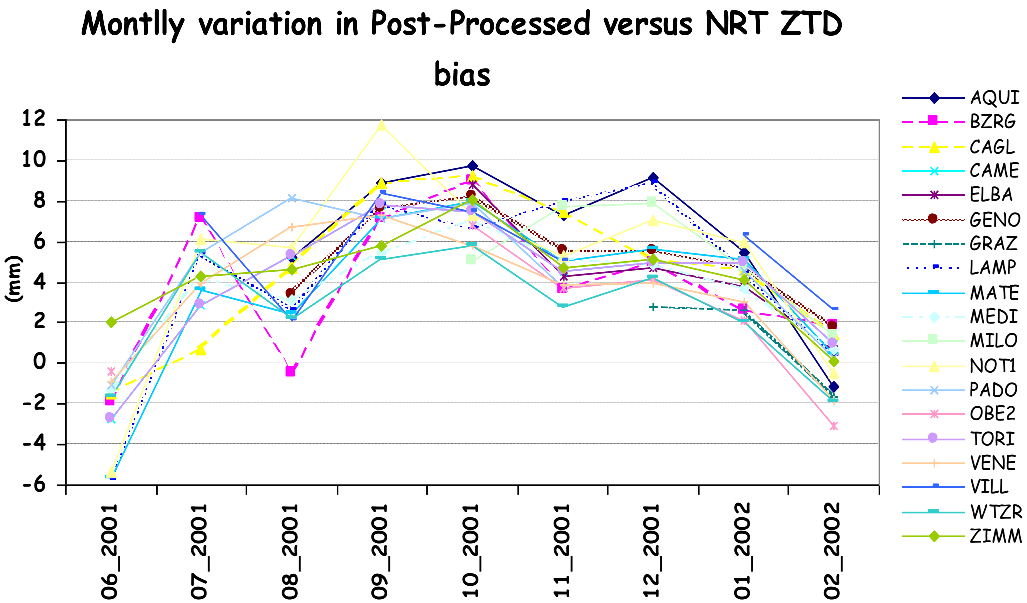
Green=Near-Real Time

A posteriori σ_{ZTD} for Matera.

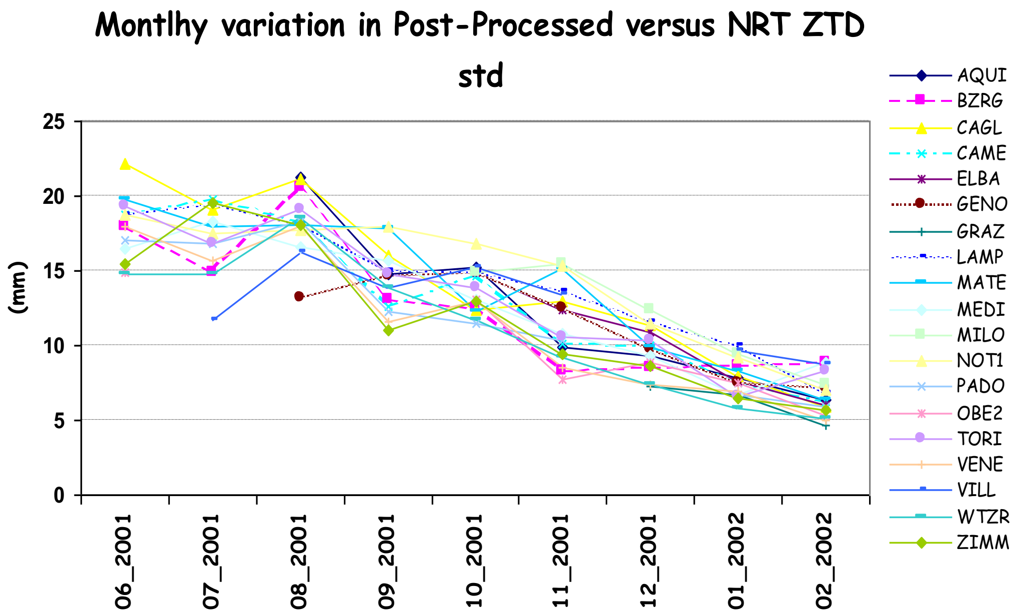
≈1,3 mm for Post-Processed

≈1.5, 10mm for NRT





Bias: -6mm to 10mm



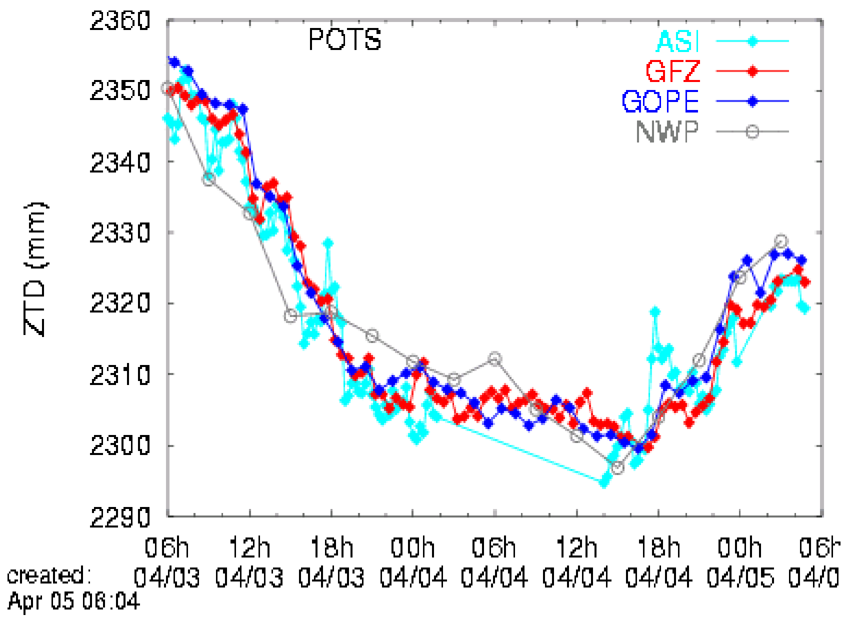
STD: 20mm to 5mm

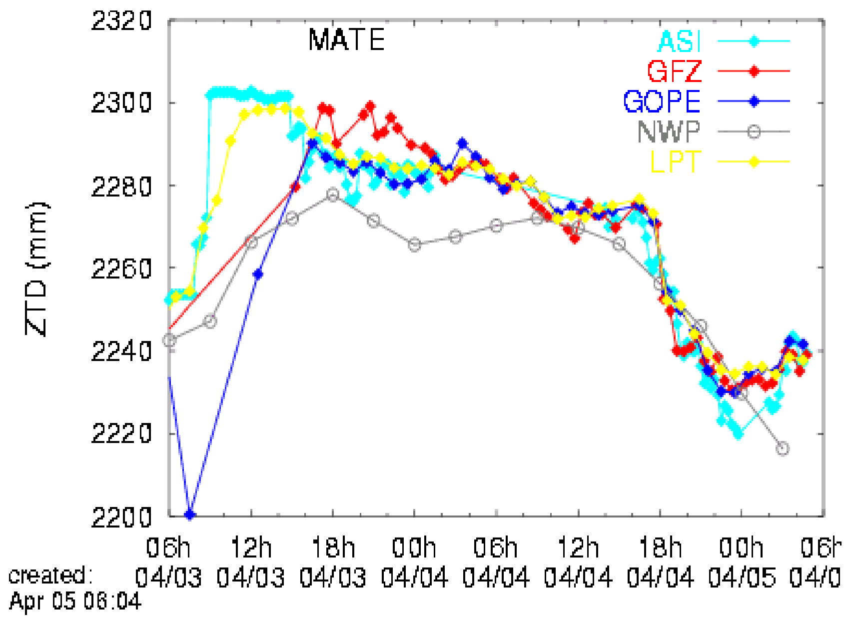
[1 kg/m^2 PWV = 6mm ZTD]

COST-716 NRT ZTD and IWV

http://www.knmi.nl/samenw/cost716/ztd_iwv.html

About 130 sites in Europe continuously monitored in NRT mode, processing distributed among 6 AC.





Comparisons with independent NRT ZTD estimates

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BRUS

ASI-GFZ

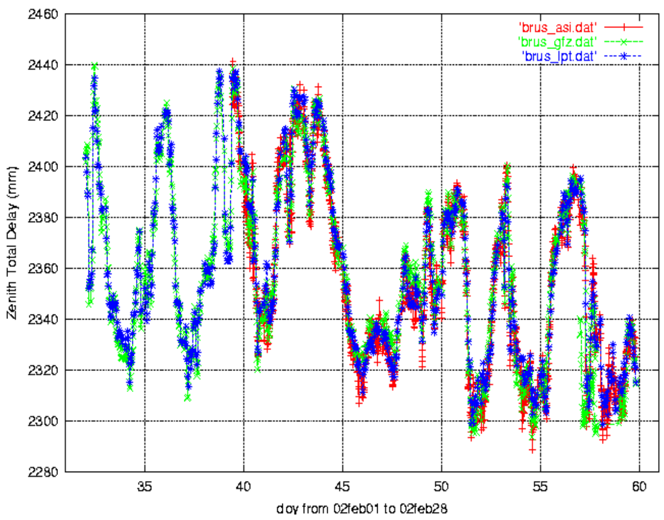
Bias=-1.36mm

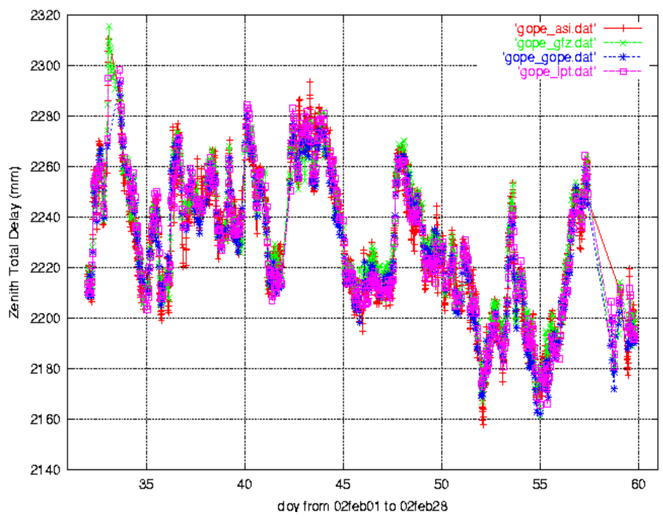
Std=7.12m m

ASI-LPT

Bias=-2.31mm

Std=6.02m m





GOPE

ASI-GFZ

Bias=-1.92mm

Std=5.88mm

ASI-LPT

Bias=-0.20mm

Std=6.19mm

ASI-GOPE

Bias=0.80mm

Std=6.13mm

CAGL

ASI-GOPE

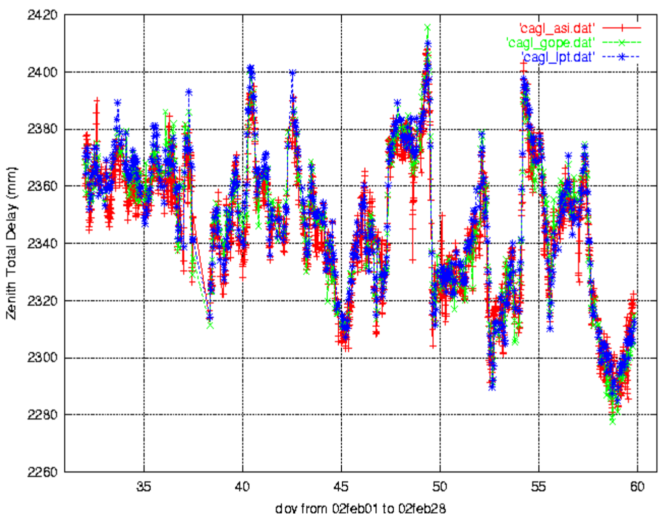
Bias=-2.38mm

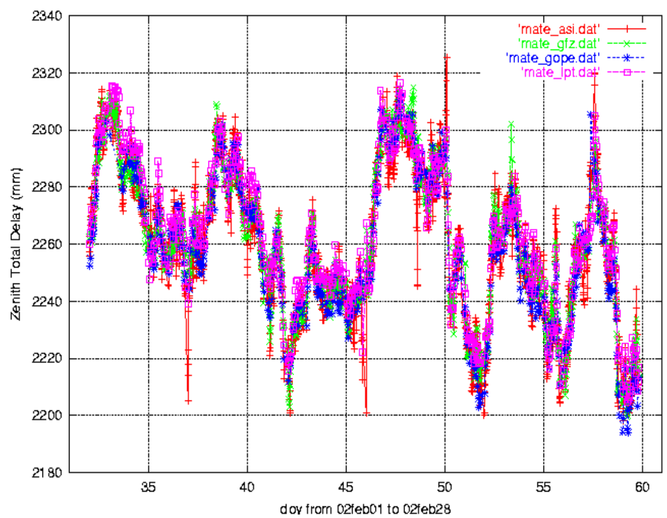
Std=7.04mm

ASI-LPT

Bias=-3.09mm

Std=6.33mm





MATE

ASI-GFZ

Bias=-0.71mm

Std=6.71mm

ASI-LPT

Bias=-3.23mm

Std=7.18mm

ASI-GOPE

Bias=1.46mm

Std=7.70mm

Comparisons with independent NRT ZTD estimates

PFAN

ASI-GFZ

Bias=-2.89mm

Std=5.41mm

ASI-LPT

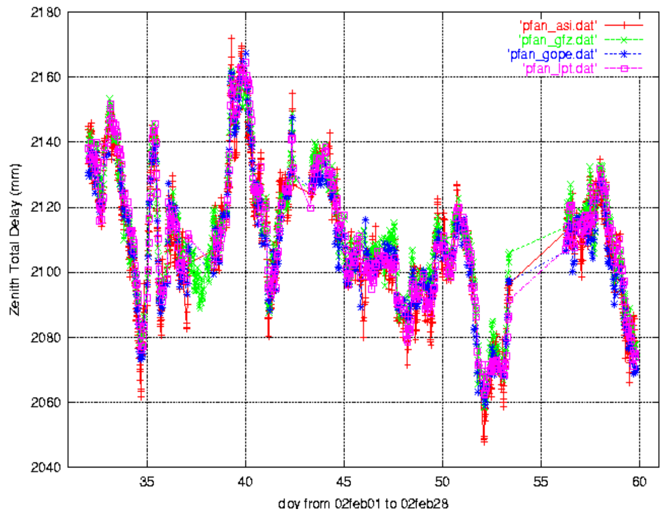
Bias=-1.52mm

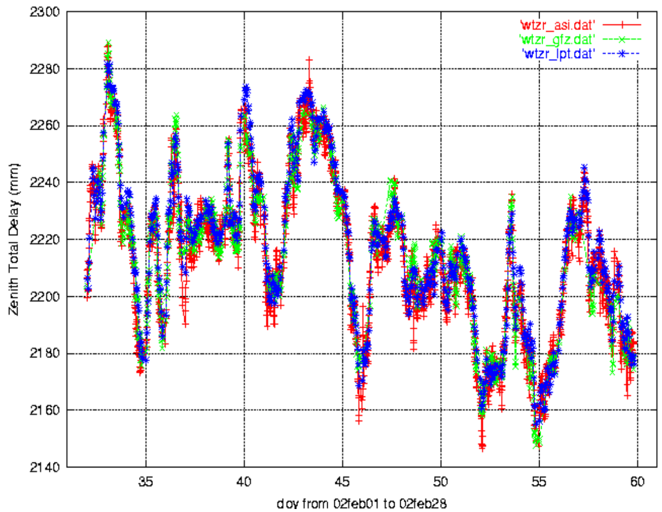
Std=5.92mm

ASI-GOPE

Bias=0.39mm

Std=6.23mm





WTZR

ASI-GFZ

Bias=-0.92mm

Std=6.12mm

ASI-LPT

Bias=-2.75mm

Std=5.52mm

POTS

ASI-GFZ

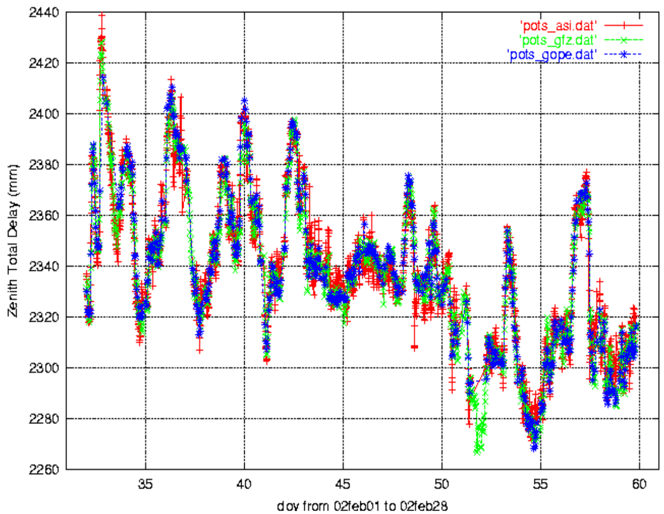
Bias=0.91mm

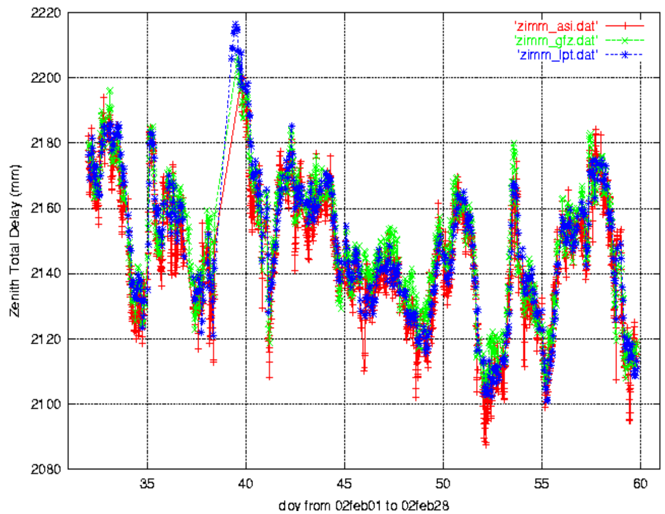
Std=6.14mm

ASI-GOPE

Bias=0.36mm

Std=6.00mm





ZIMM

ASI-GFZ

Bias=-4.54mm

Std=5.98mm

ASI-LPT

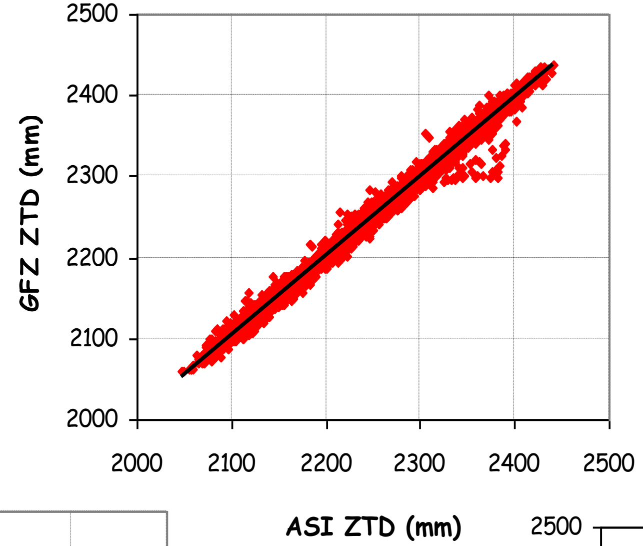
Bias=-2.61mm

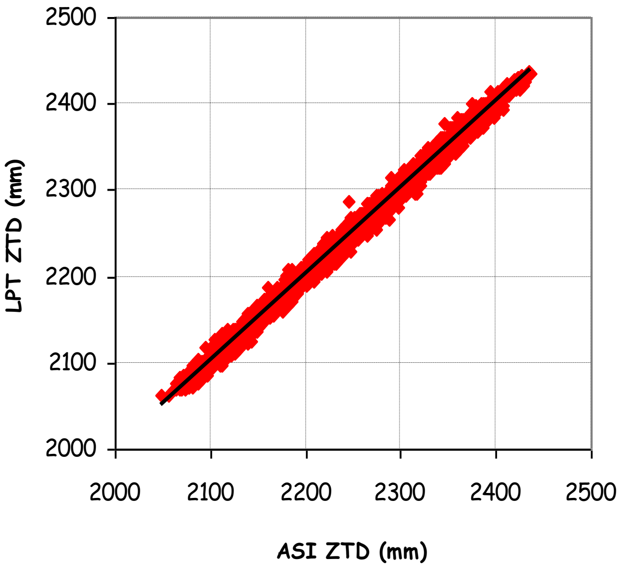
Std=5.95mm

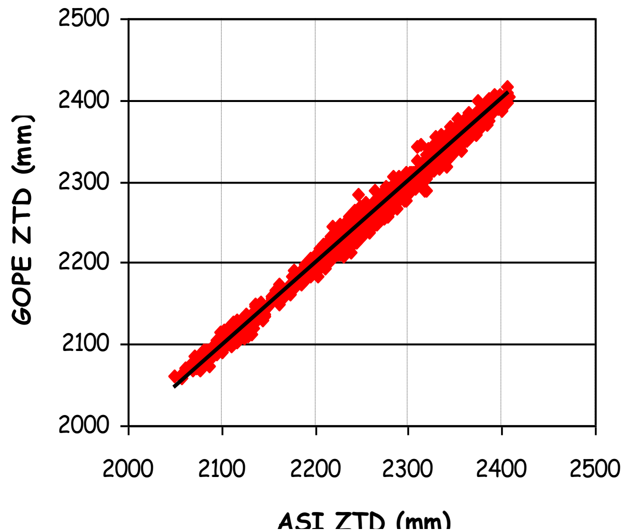
Comparisons with independent NRT ZTD estimates

February 2002

Correlation Coefficient ≈ 1







Analisi degli Errori Doluzioni NRT

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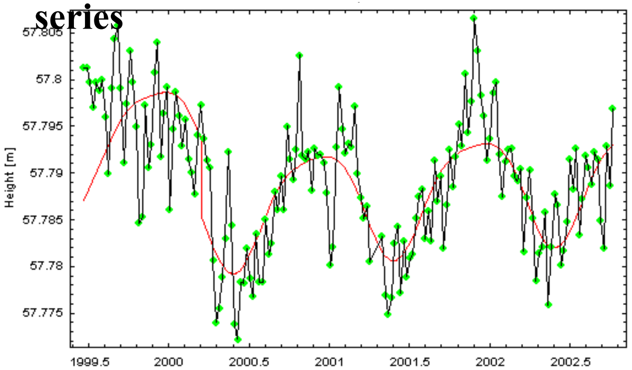
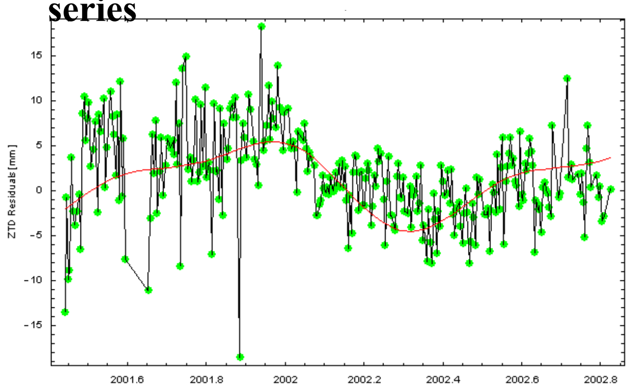
Lampedusa EUREF Height time series



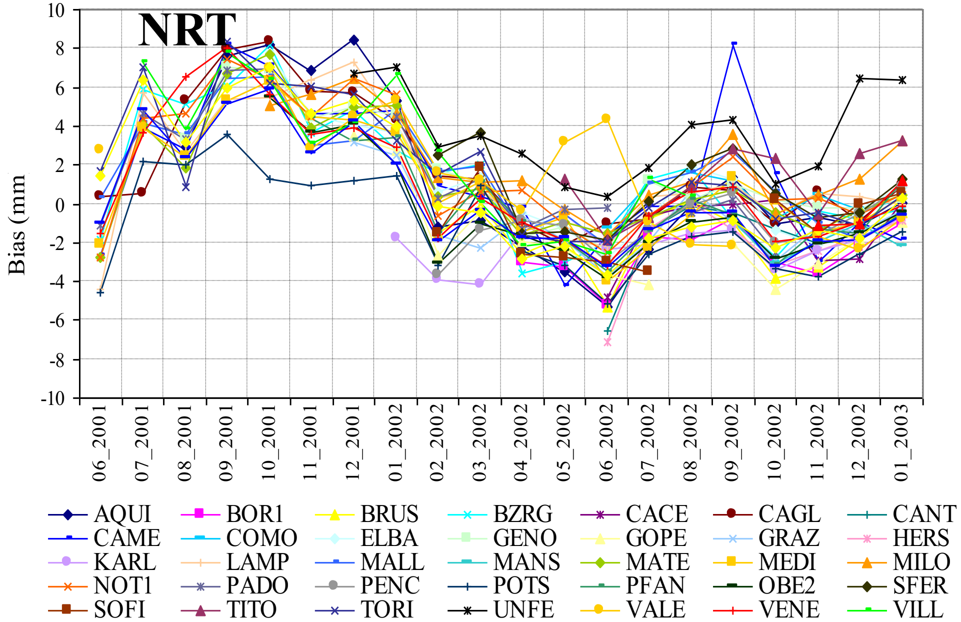
Lampedusa ZTD residuals time series



Annual signals

EUREF h time series		PP h time series		ZTD residuals time series	
A (mm)	$\phi+\pi$(rad)	A (mm)	$\phi+\pi$(rad)	A (mm)	ϕ (rad)
5.71	3.44	4.77	3.28	4.11	2.44

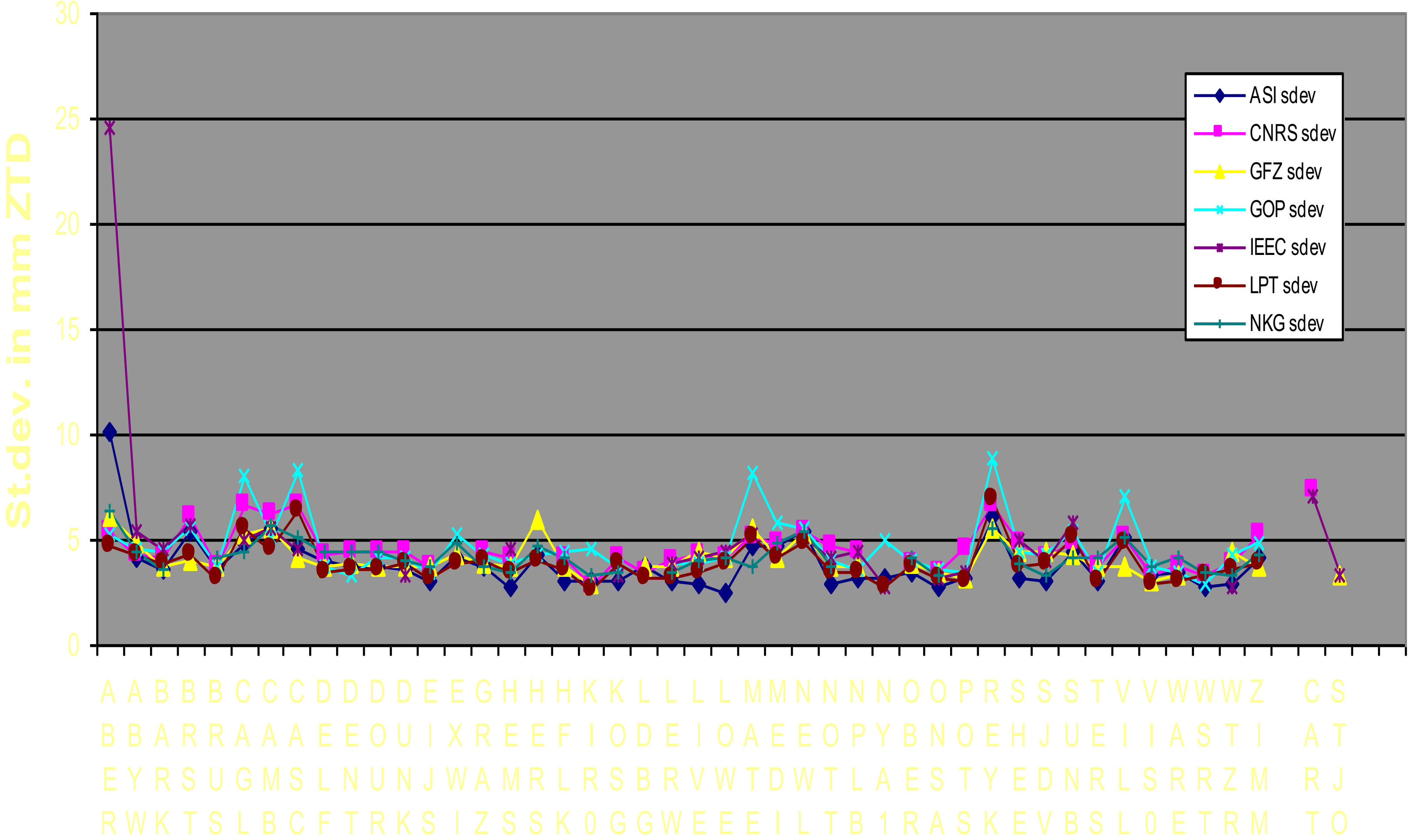
Monthly variations BIAS PP vs NRT



- Seasonal signals in ZTD and height time series.
- Methodology for dealing with updated of TRF.
- Check that differences between processing centres estimates for the reference IGS stations (are or) are not due to orbit, coordinate or reference frame errors.
- Check the quality of GPS ZTD/IWV data by examining the repeatability of site coordinates.

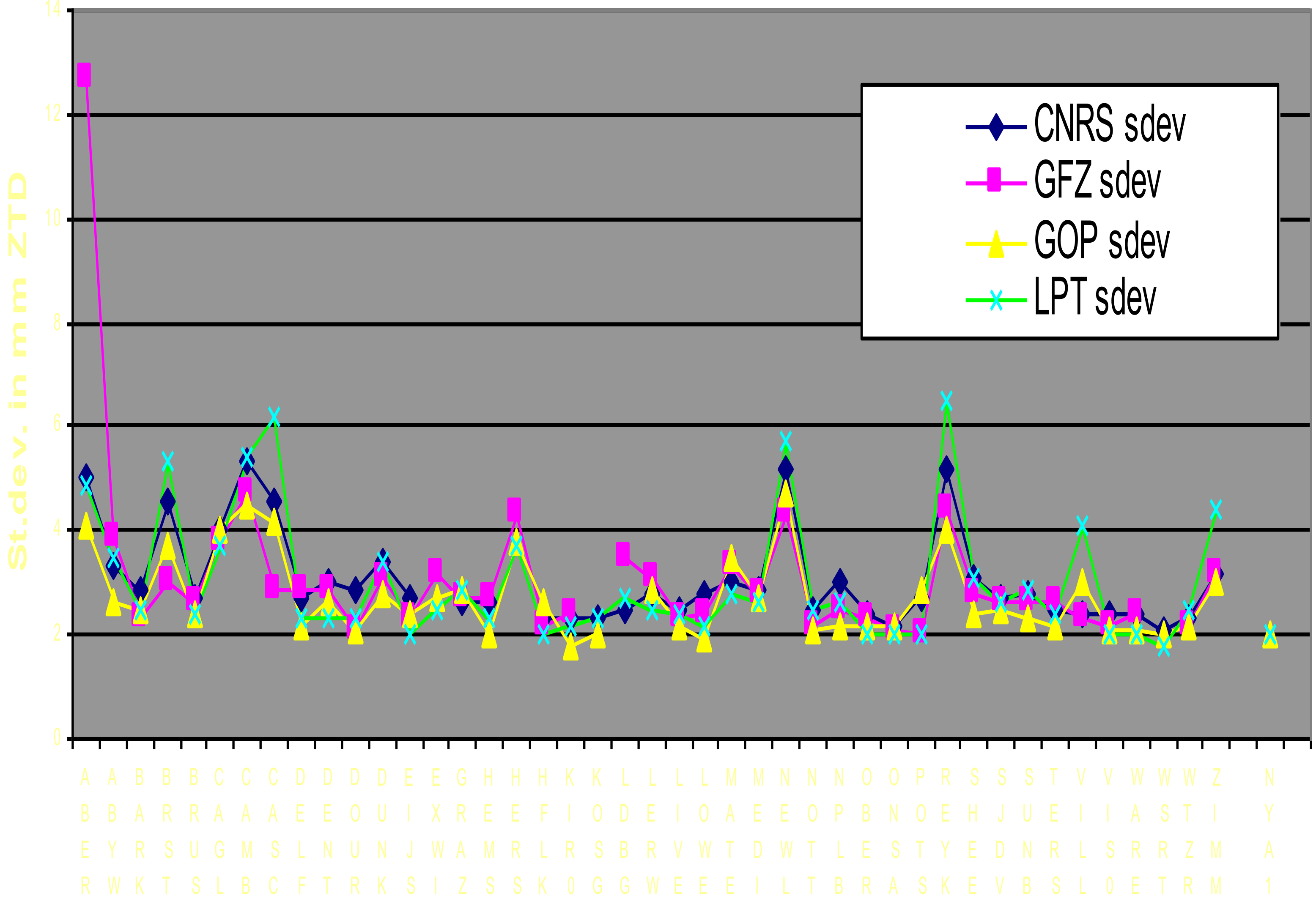
Validazione Interna

NRT Solutions



Validazione Interna

Post processed solutions



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GPS, WVR, RAOB PWV

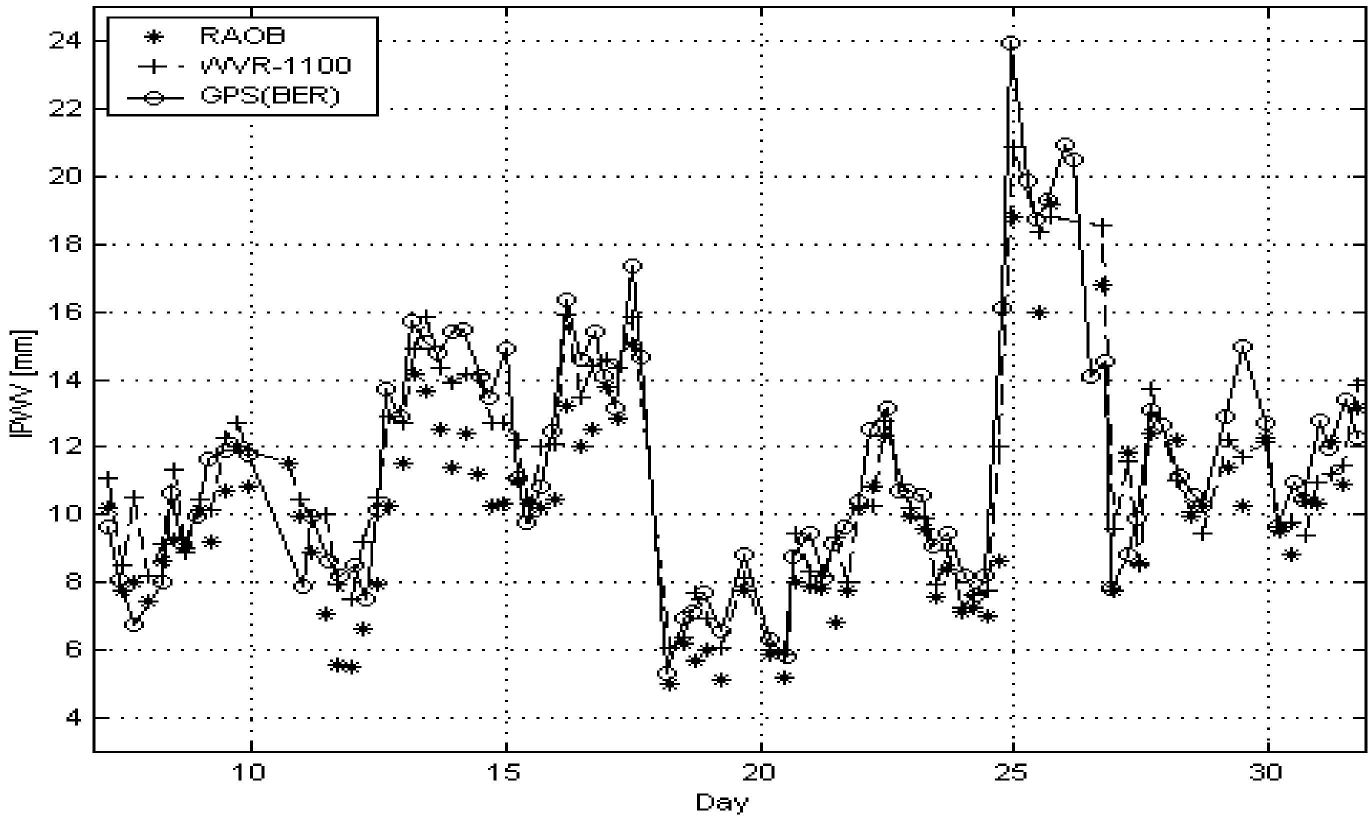
CAGLIARI

In the first half of 1999, a WVR was collocated at Cagliari Observatory with a permanent GPS receivers.

GPS (Bernese and MicroCosm), WVR and RAOB PWV have been compared for March 1999.

	mean (mm)	rms (mm)	sample #
GPS (BER) - RAOB	1.12	1.72	89
GPS (MCR) - RAOB	0.88	2.09	86
WVR - RAOB	1.03	1.23	85
GPS (BER) - WVR	0.22	1.34	82
GPS (MCR) - WVR	- 0.02	1.57	79
GPS (BER) - GPS(MCR)	0.27	1.34	85

GPS, WVR, RAOB PWV
CAGLIARI



GPS PWV and MM5 PWV

During 1999, CGS group worked with Università de L'Aquila, Phisics Dept. to compare GPS PWV with independent MM5 values as a first step in view of data assimilation.

We compared PWV obtained by GIPSY ZTD with MM5 PWV for the station of L'Aquila, Matera and Cagliari when surface pressure data were available.

	L'Aquila 1 month	Cagliari 4 months	Matera 2 months
MM5 – GPS wmeant±sigma (mm)	1.7±2.3	3.0±5.2	6.2±6.7

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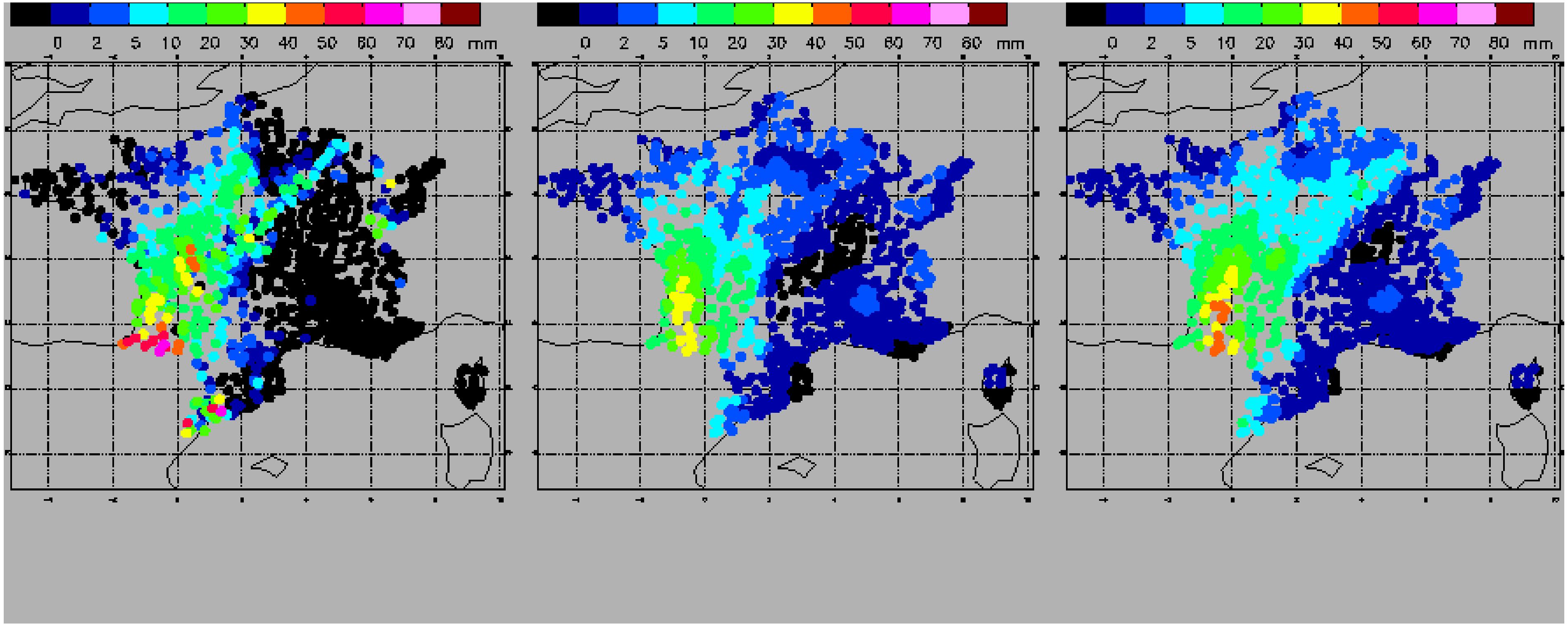

Confronto fatto fra le previsioni meteorologiche con i dati GPS e senza i dati GPS.

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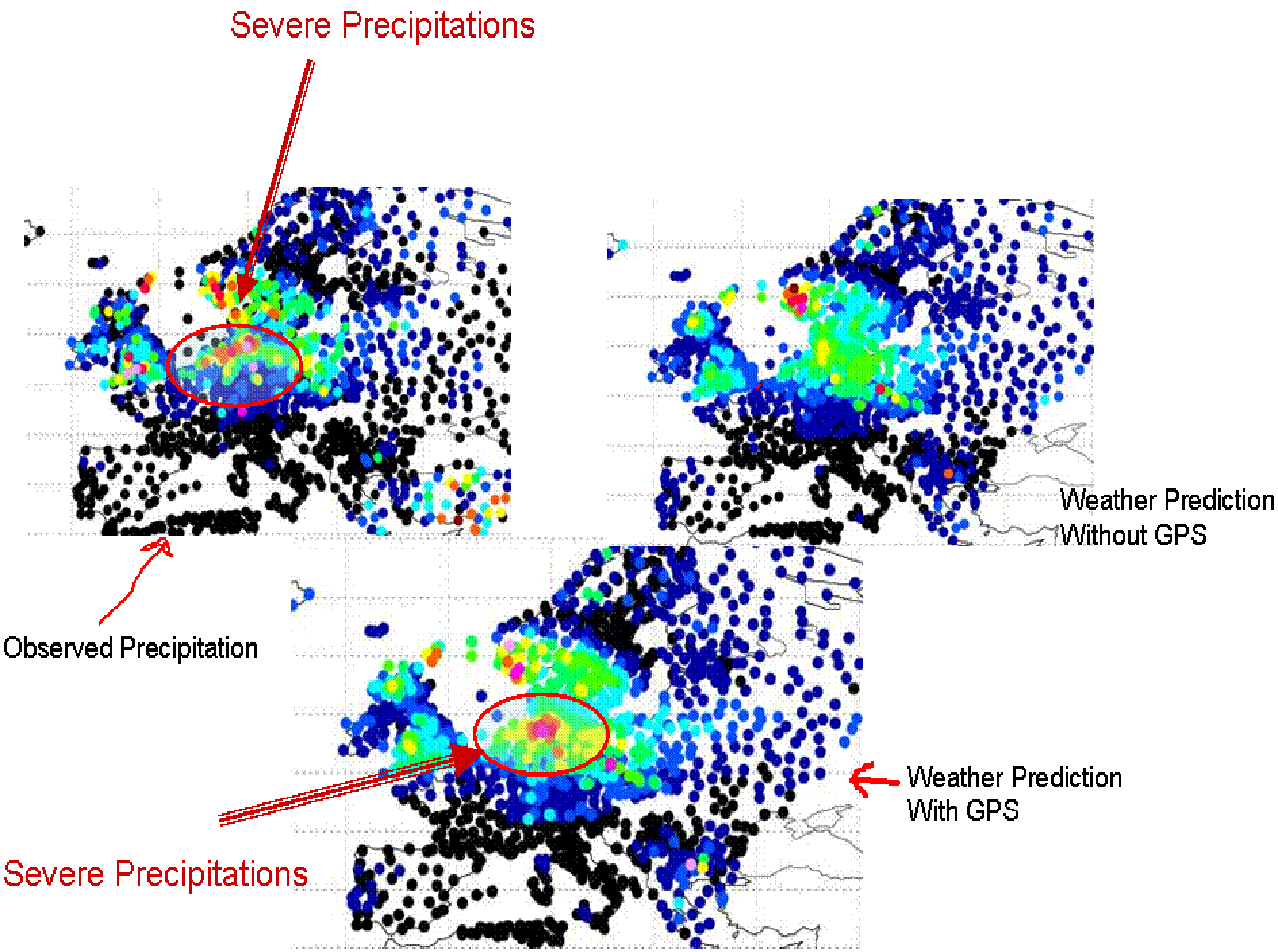
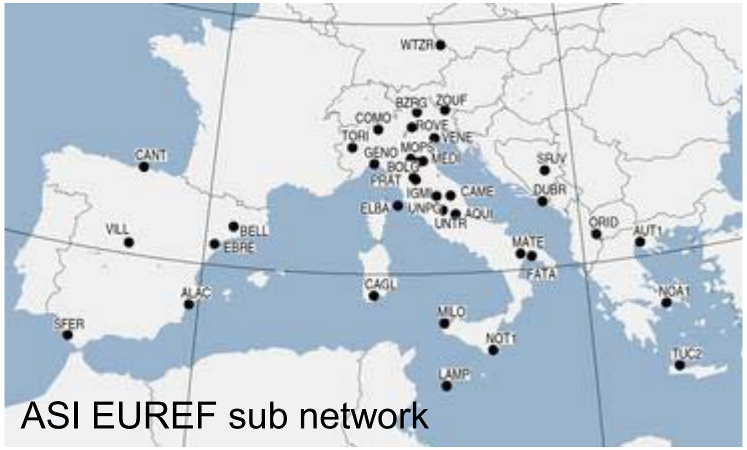
Meteorology



ASI has been involved in GPS data analysis of regional permanent network since September 1996 when its solutions are incorporated in EUREF.



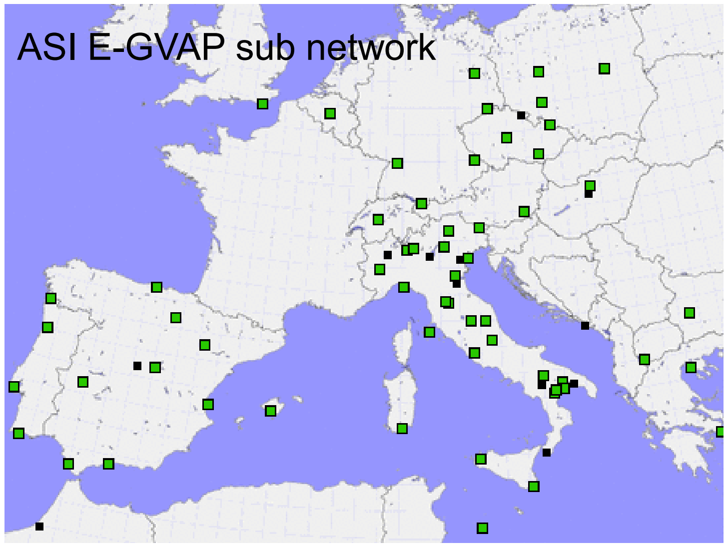
GPS-Meteo Projects

MAGIC

COST 716

TOUGH

EUMETNET
The Network of European Meteorological Services



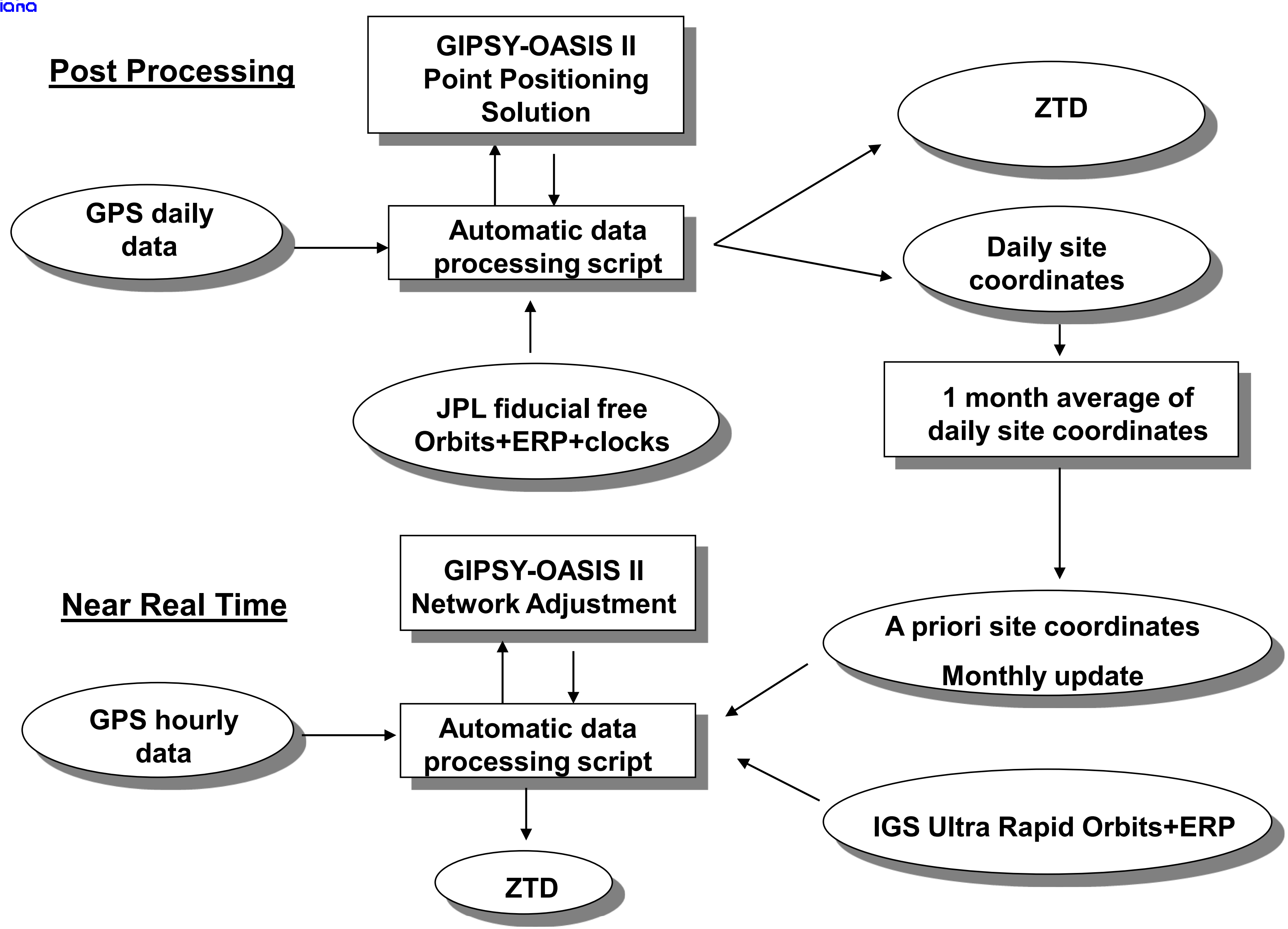
1999 MAGIC *develop and test the capacity for meteo organizations to benefit from GPS as new data source*

2001 COST-716 *NRT demonstration campaign*

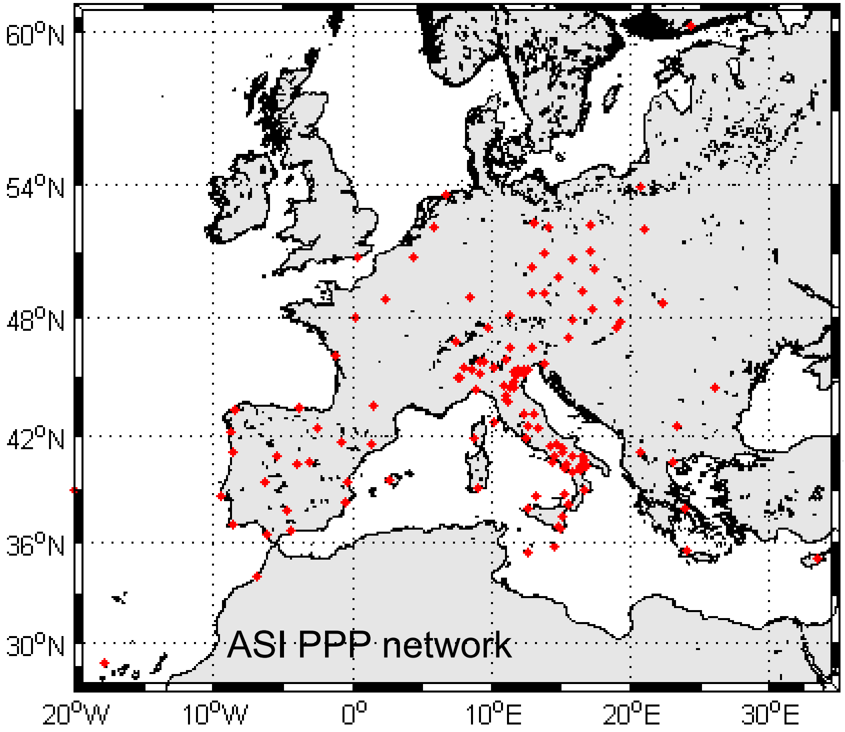
2003 TOUGH *Targeting Optimal Use of GPS Humidity Measurements in Meteorology*

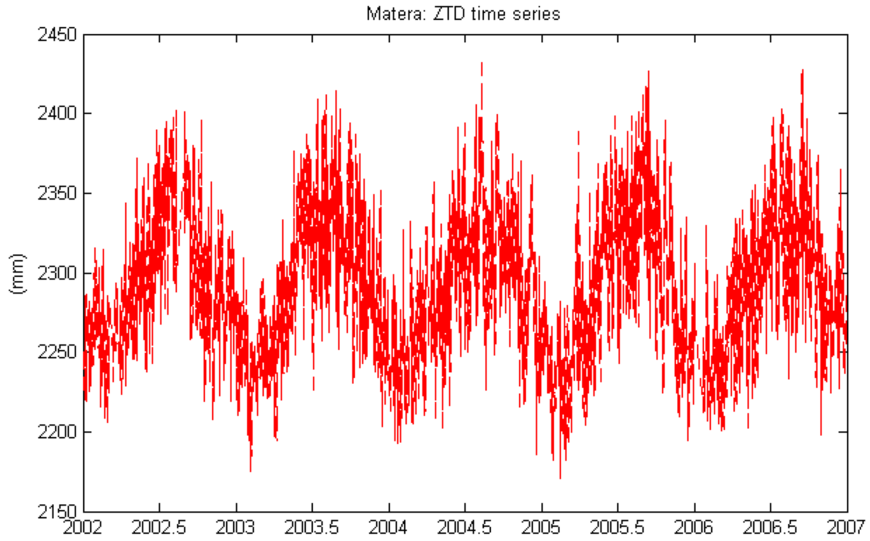
2005 E-GVAP *towards operational use and establishing a GPS delay observing system*

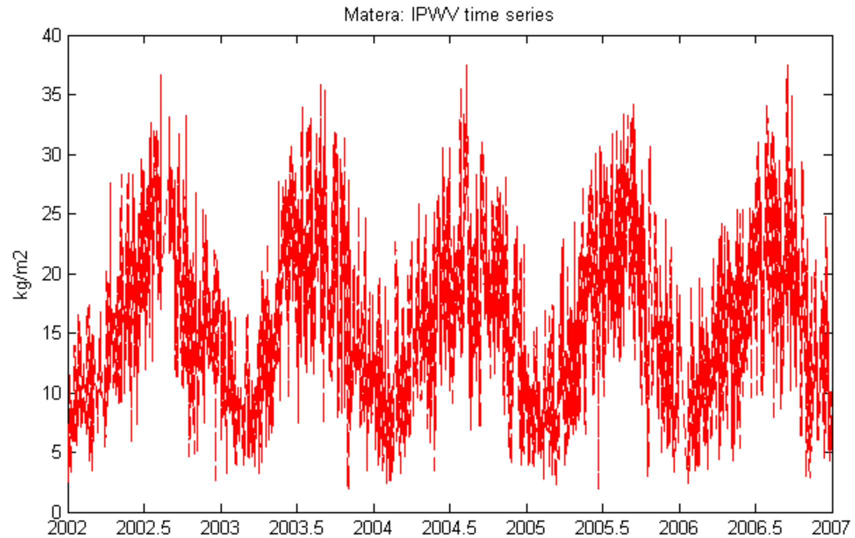
Analysis scheme for ZTD generation: Post Processing and NRT



Post Processing ZTD/IPWV time series

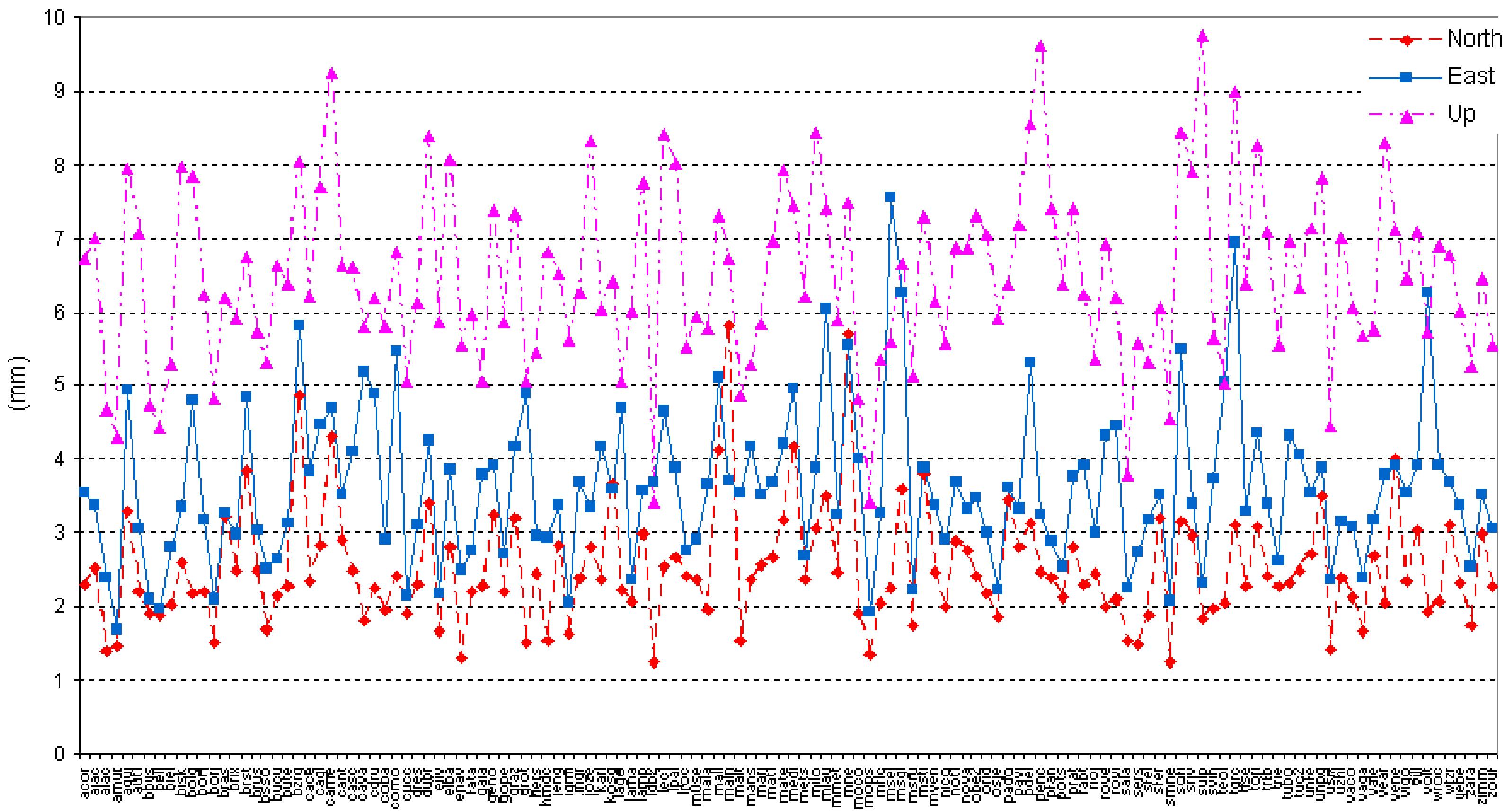






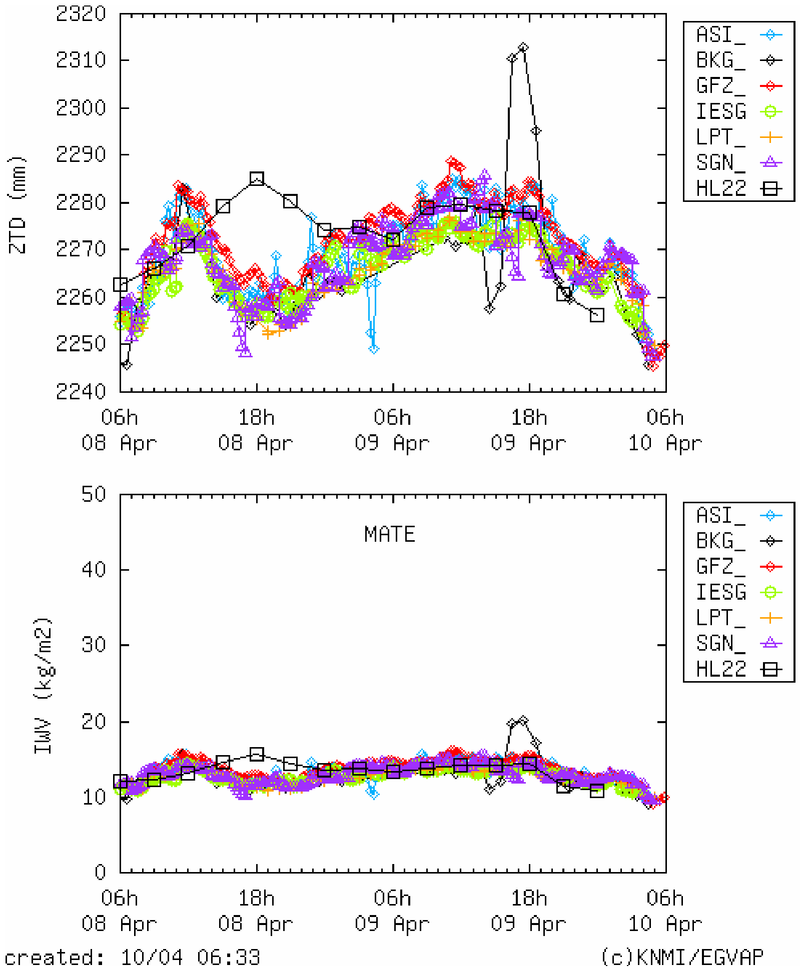
Post Processing: site coordinate repeatability

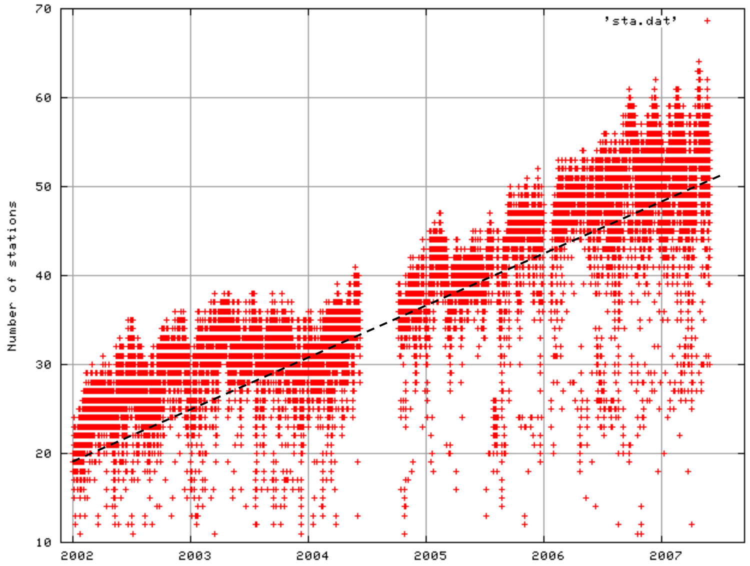
Heights coordinate repeatability as indicator for ZTD quality

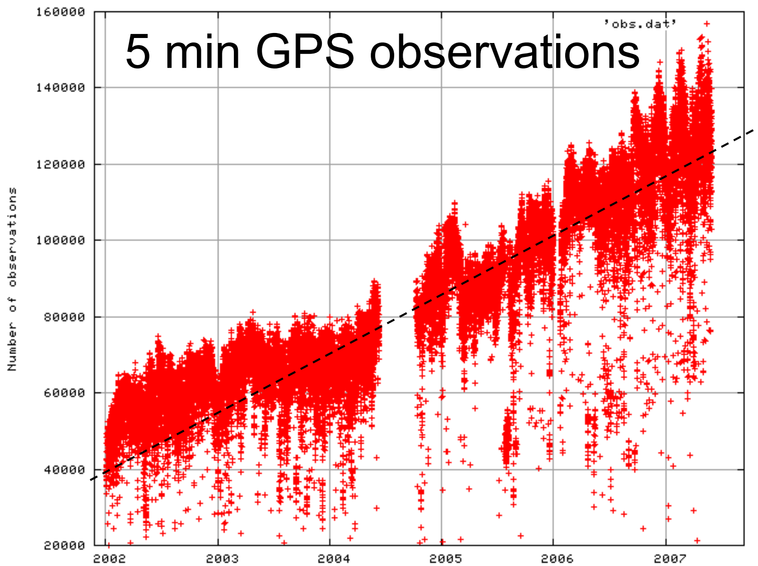


To get 0.45mm IPWV we need 3mm ZTD that is 9mm H

NRT Processing: evolution with time



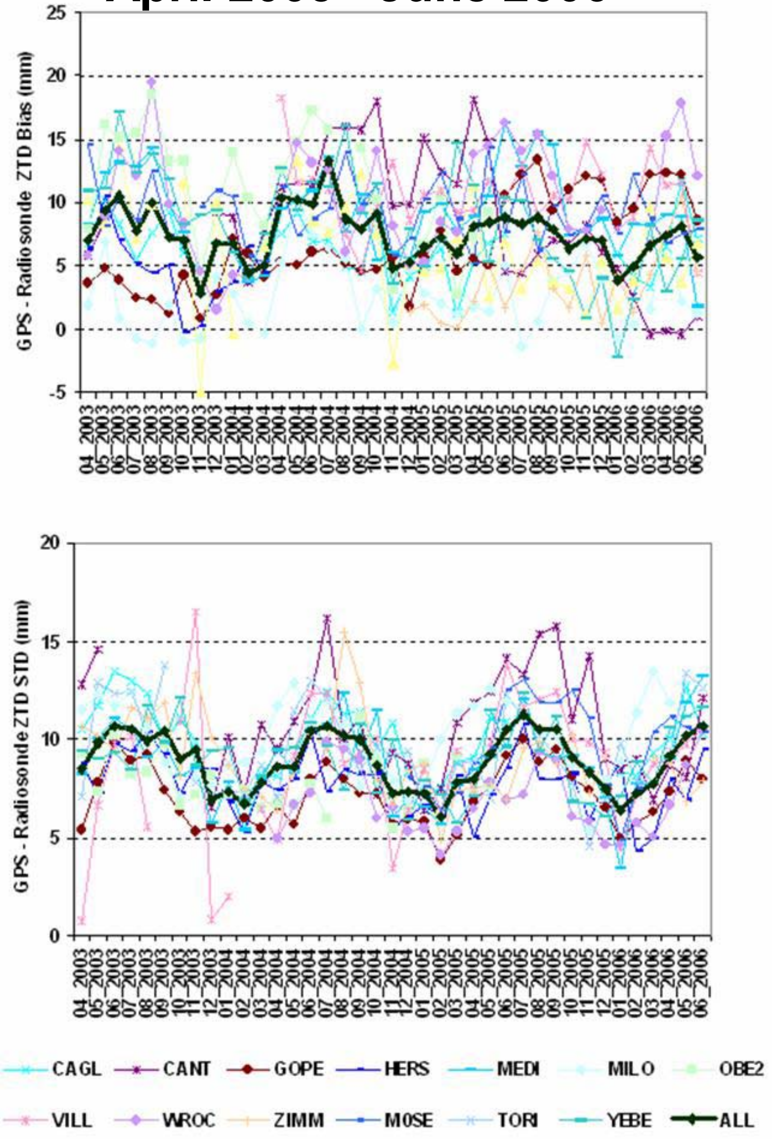




A linear increase in the number of the stations and of the observations

NRT validation: GPS vs Radiosonde

April 2003 - June 2006

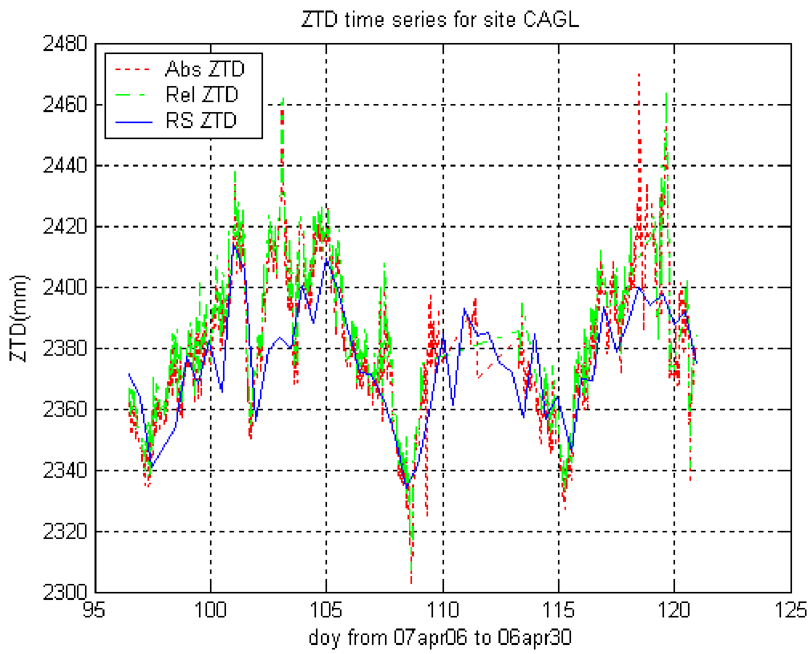


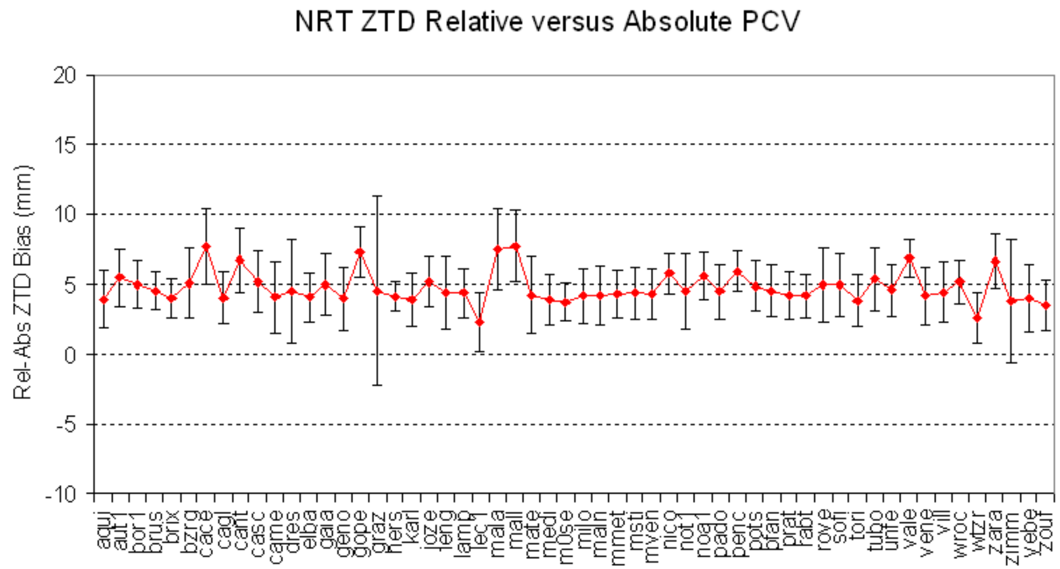
•Bias: radiosonde are dryer than GPS.

•STD: seasonal dependence which seems to fit the atmospheric thermal cycle. It is about 10 mm in summer and 7 mm in winter.

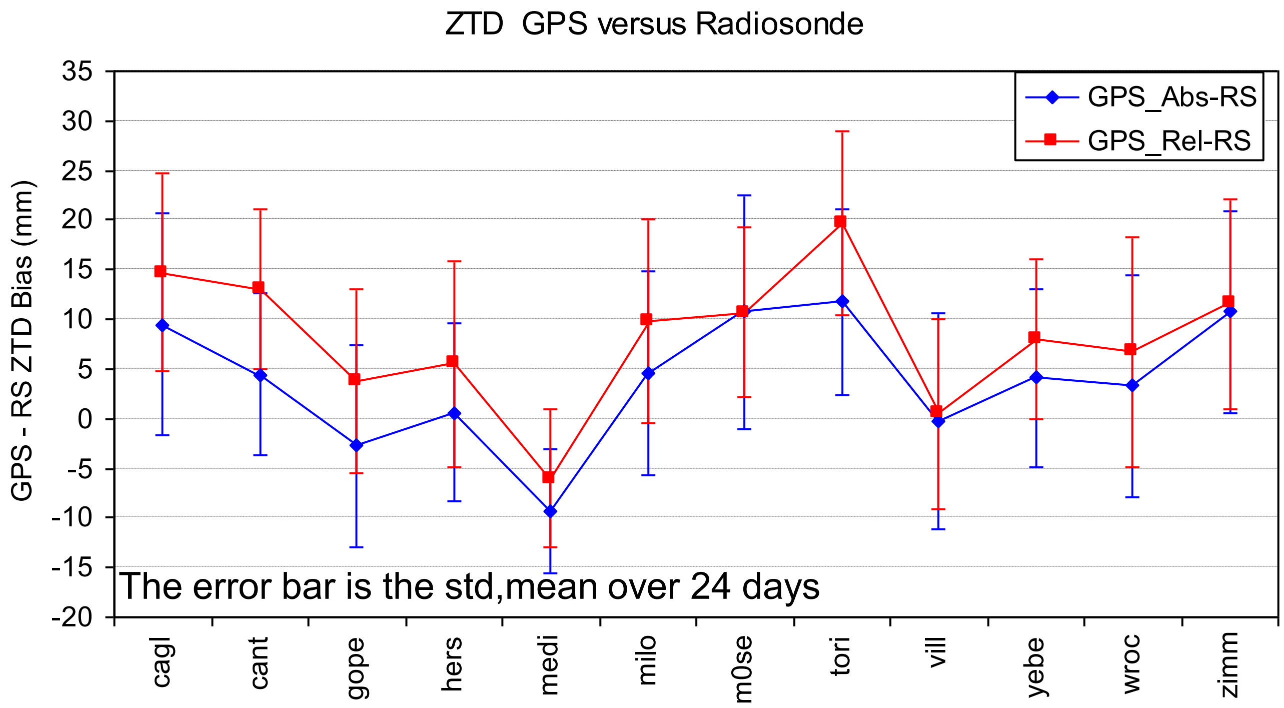
NRT ZTD absolute versus relative PCV (1/2)

- 2 NRT parallel runs one with absolute and the other with relative PCV are set-up.
- For the period 07apr06-07apr30 (gps week 1421-1425) NRT ZTD estimates for 56 stations from both products lines are compared. A mean bias in ‘relative minus absolute ZTD’ of about 5mm is detected.





NRT ZTD absolute versus relative PCV (1/2)



The use of Absolute Phase Center values reduces the 'GPS versus Radiosonde' bias

Assessment of the uncertainties of GPS NRT estimates (1/4)

If we have different data sets x_i and y_i, which are measurements of the same variable in time and space, we can assess the real uncertainties of one of the measurements that is that intrinsically less precise.

If y_i is more precise than x_i, we can define the non-dimensional data set z_i as:

$$z_i = \frac{(x_i - y_i)}{\sqrt{\sigma_{x_i}^2 + \sigma_{y_i}^2}}$$

If x_i and y_i are unbiased and if their internal error is not underestimated, z_i behaves according to a Gaussian distribution with $\mu=0$ and variance $\sigma_z^2=1$. The error on the mean σ_μ should behave according to a normal distribution

$$\sigma_\mu = \frac{\sigma_z}{\sqrt{n-1}}$$

If μ is significantly different from 0 (i.e. more than 3 sigma) it means that the x dataset is biased. The variance behaves according to the χ **2** function with n-1 degrees of freedom.

We must check if the value $\sigma_z^2=Dz=1$ is within the variance interval that is determined by fixing the confidence level to 90%.

Assessment of the uncertainties of GPS NRT estimates (2/4)

We consider $$V = \frac{\tilde{D}(n-1)}{D}$$

where ***D*** is the variance for which we want to know the confidence interval, and $\tilde{D}$ is the estimated variance of the "***z***" dataset.

V behaves according the **χ2** distribution with n-1 degrees of freedom.

The confidence interval of the parameter V is $X_1 \le V \le X_2$ with $\chi^2(X_1) = \frac{1-\beta}{2}$

Thus $$\frac{\tilde{D}(n-1)}{X_2} \le D \le \frac{\tilde{D}(n-1)}{X_1}$$ $$\chi^2(X_2) = \frac{1+\beta}{2}$$

If the nominal value of Dz =1 is outside the range set with the previous equation, then the variance is biased, either underestimated or overestimated.

We apply this method considering the less accurate "x" dataset the NRT ZTD time series coming from the different TOUGH analysis centres, and considering the "y" dataset the EUREF combined tropospheric solution.

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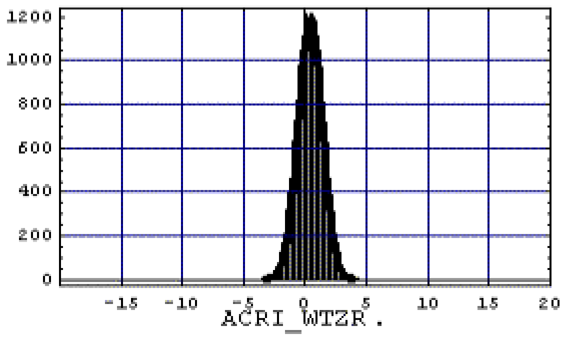
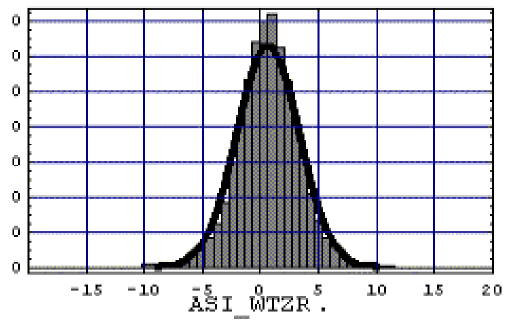
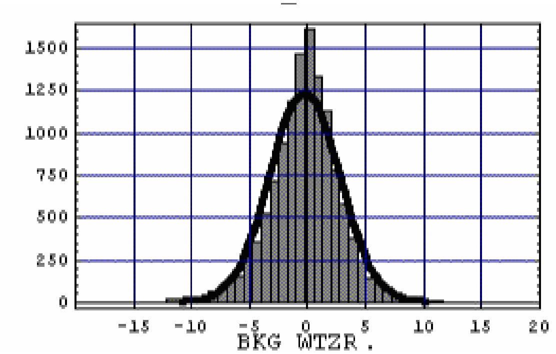
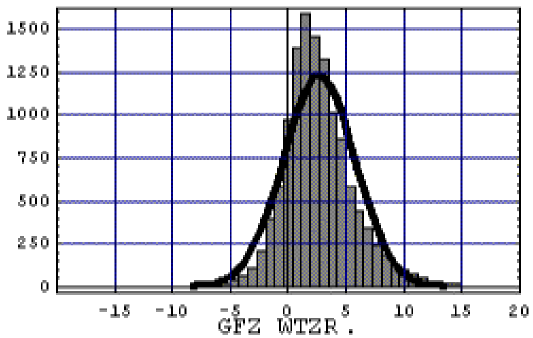
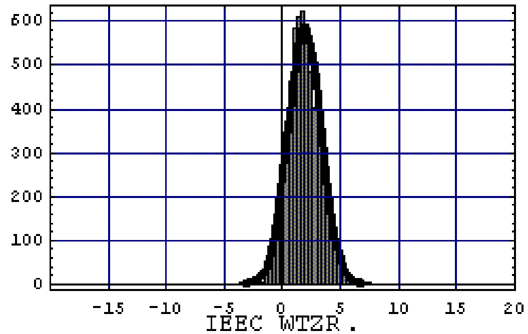
Assessment of the uncertainties of GPS NRT estimates (3/4)

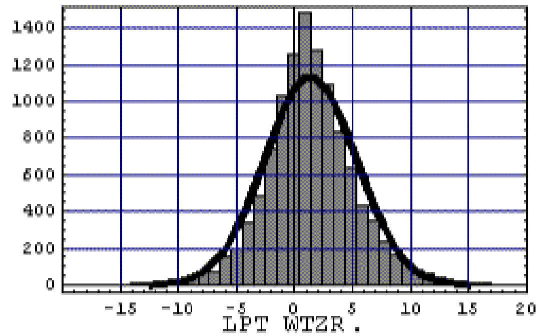


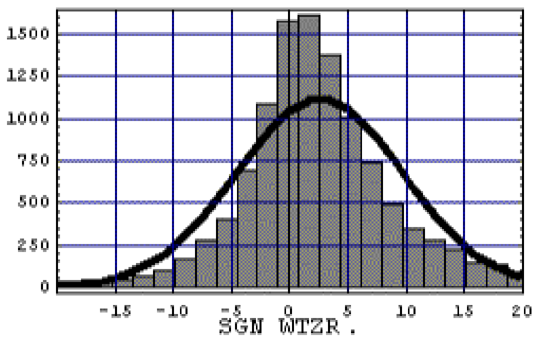






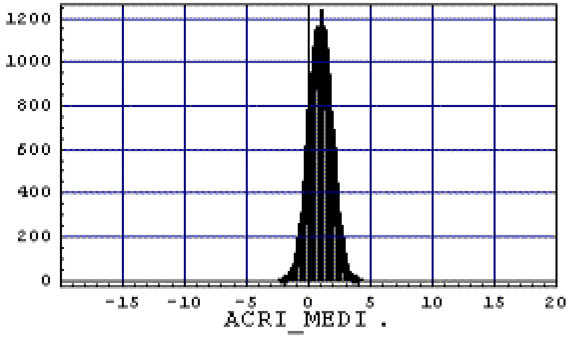


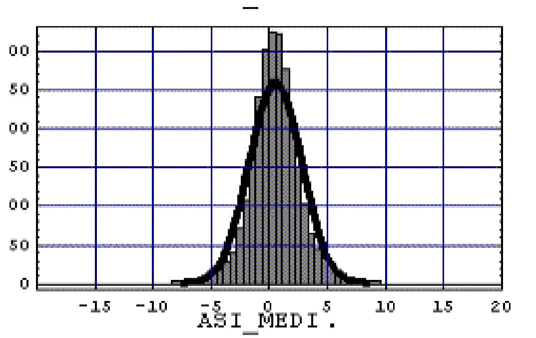


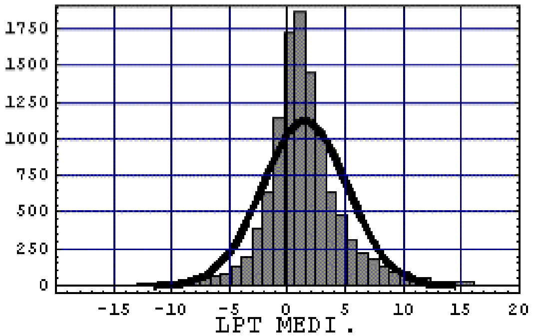


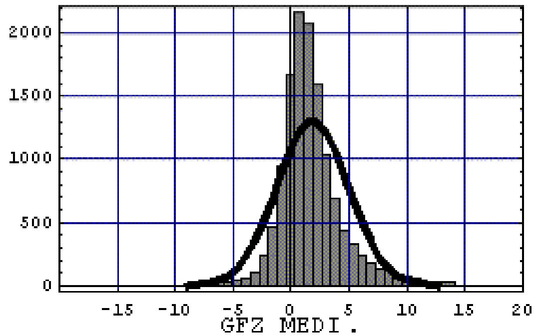
The *y* datasets are the EUREF combined ZTD solutions for WTZR while the x datasets are ACRI, ASI, BKG, GFZ, GOPE, IEEC, LPT, SGN NRT solutions. The black line represents the Gaussian function having the same mean and variance of the x dataset. The non-dimensional values of the combined *z* dataset and the number of the estimates are reported along the x and y-axis respectively.

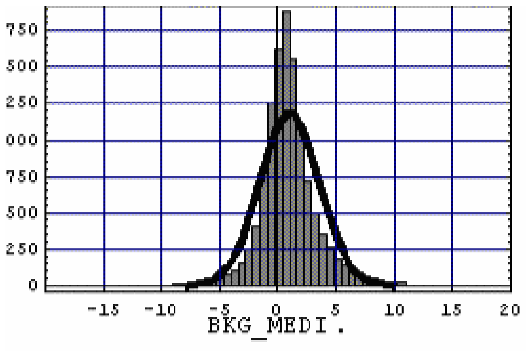
Assessment of the uncertainties of GPS NRT estimates (4/4)











	Scaled Factor	Scale Sigma (mm)
ACRI	0.9	8.3
ASI	2.4	5.6
BKG	2.7	3.2
GFZ	2.8	2.9
GOP	2.8	3.0
IEEC	1.4	7.7
LPT	3.5	3.9
SGN	5.8	3.6

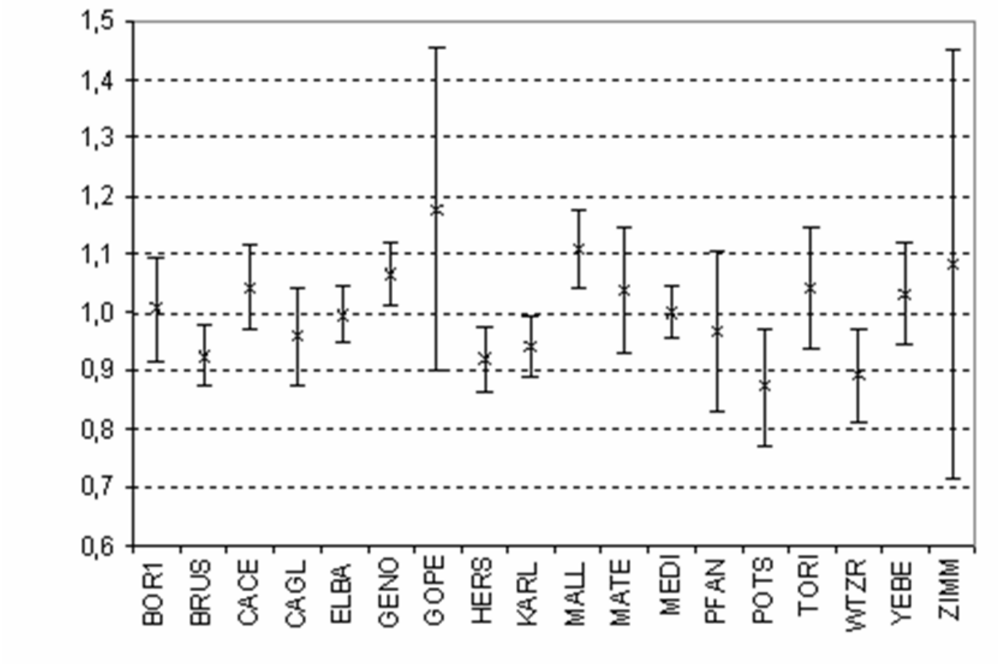
All Bernese and GIPSY solutions (BKG, GOP, LPT, SGN, ASI and IEEC) have underestimated uncertainties and their statistical distribution is not exactly Gaussian; while ACRI solutions using the GAMIT software have over-estimated uncertainties and their statistical distribution is nearly Gaussian. The uncertainties seem to be correlated more to the analysis strategies (troposphere modelling and estimation process) than to the quality of the stations.

Station Quality

A measure of the quality of the *i* station is given by the non-dimensional quantity

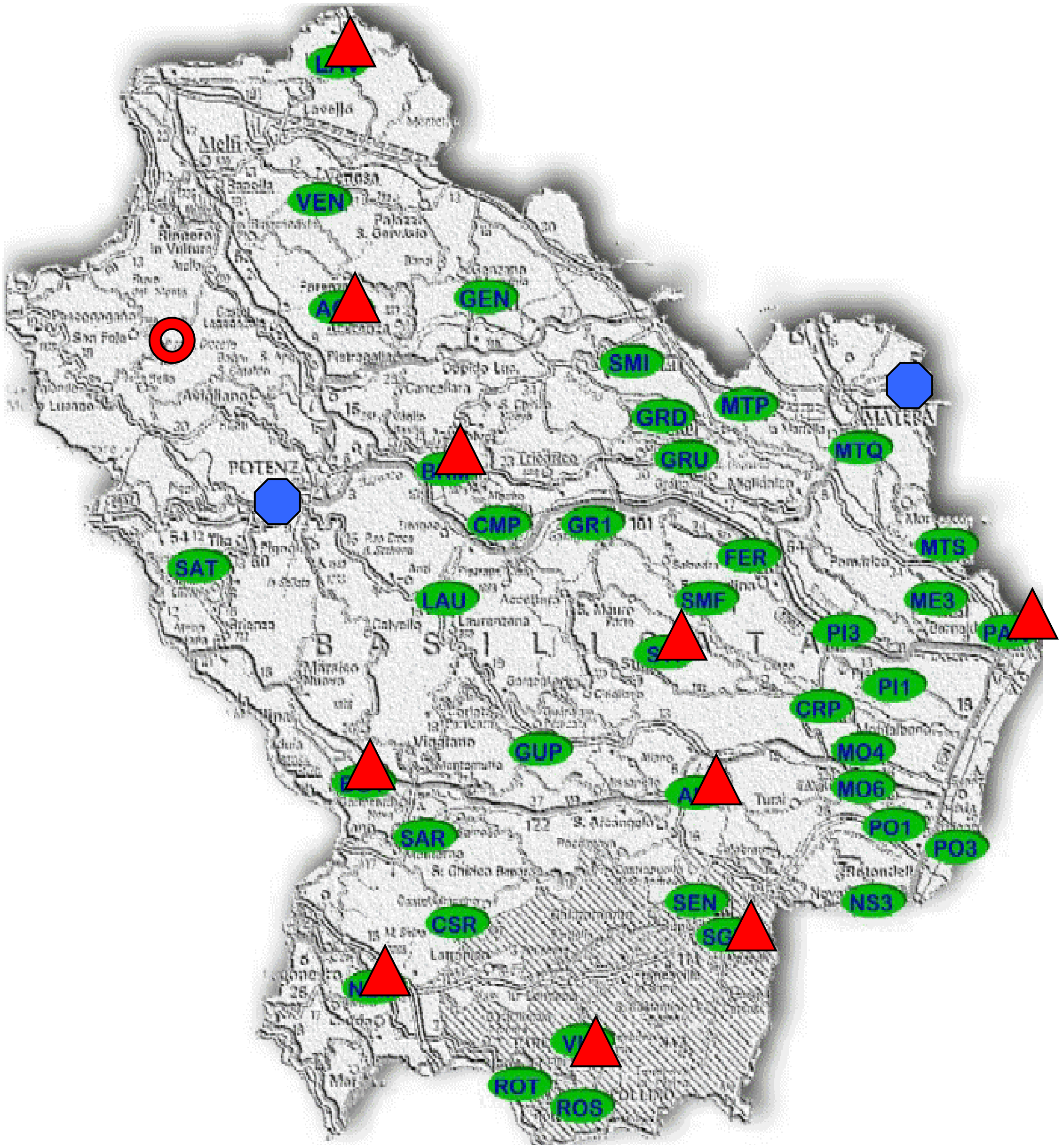
$$\nu_i = \sum_{j=1}^{k} \frac{\sigma_{ij}}{\sigma_j}$$

where σ_{ij} is the mean value of the σ estimated by the j analysis center AC_j for the station *i* ;while σ_j is the mean of the σ estimated for each station by the AC_j. The station *i* is considered 'good' or 'bad' if ν_i,, is significantly lower or greater than 1.



The approach has been very helpful in singling out stations which have problems that require attention.

MAGIC II Project



Siti ALSIA selezionati ▲

Lavello	(LAV)	q.s.m.	300 m
Brindisi di Montagna	(BRM)	q.s.m.	900 m
Marsico Vetere	(BG1)	q.s.m.	1000 m
Aliano	(ALI)	q.s.m.	600 m
Nemoli	(NEM)	q.s.m.	700 m
Viggianello	(VIG)	q.s.m.	550 m
S. Giorgio Lucano	(SGL)	q.s.m.	400 m
Metaponto	(PAN)	q.s.m.	30 m
Stigliano	(STI)	q.s.m.	1000 m
Acerenza	(ACE)	q.s.m.	300 m

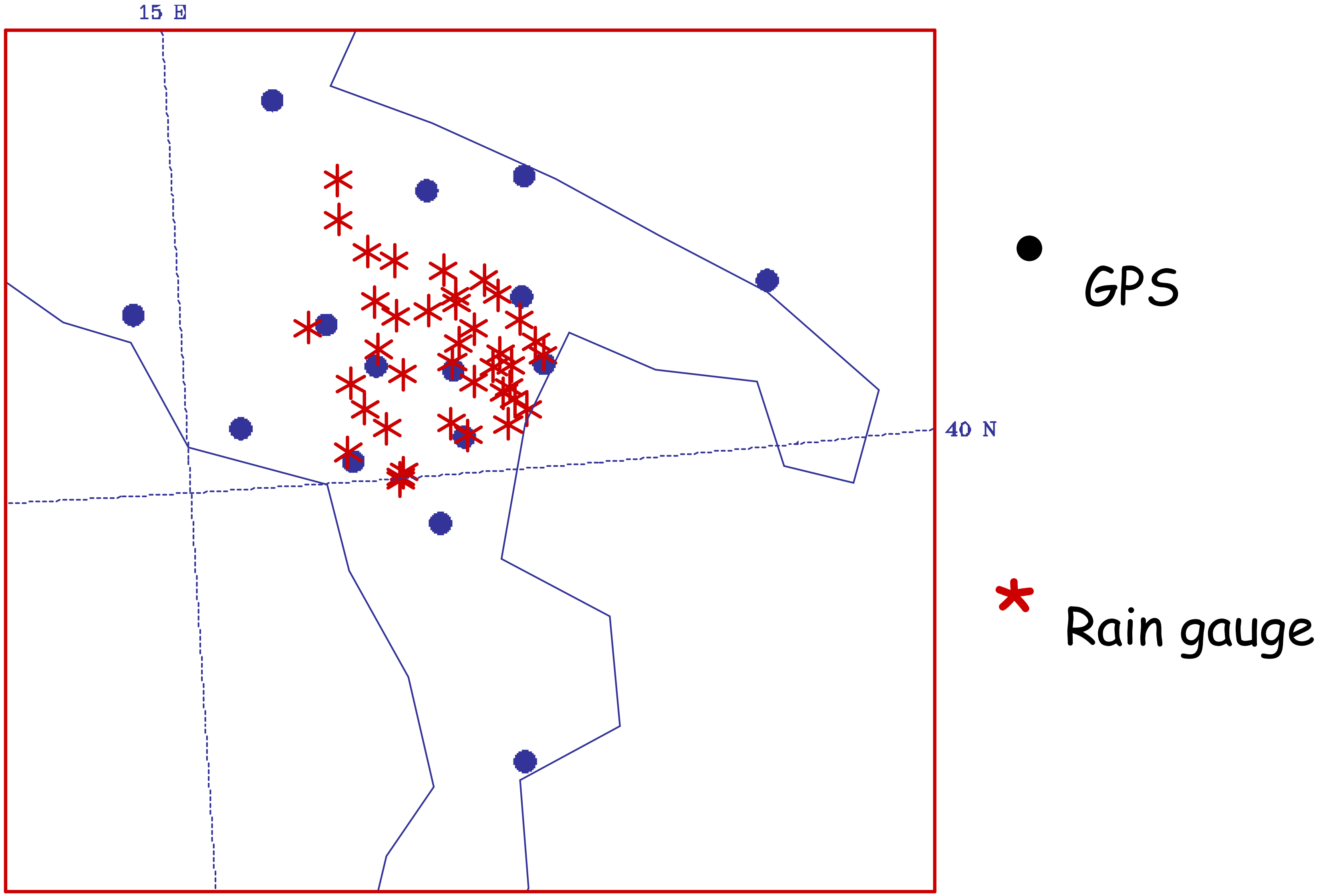
Ulteriori siti disponibili

Matera	(CGS)	q.s.m.	500 m
Tito	(TIT)	q.s.m.	600 m

Siti completamene da installare

Toppo di Castelgrande

Rete di stazioni GPS e Pluviometri



3DVAR

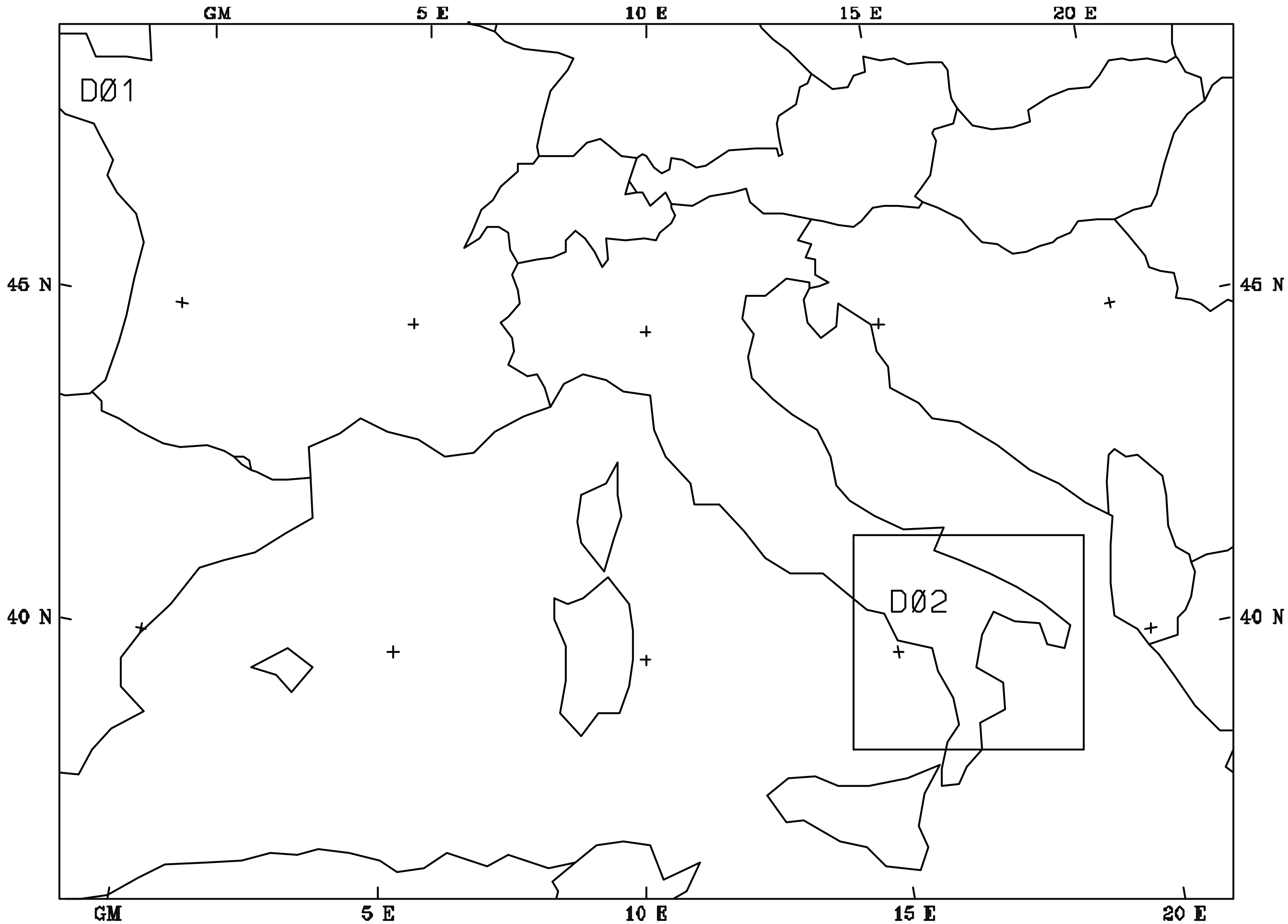
A variational data Assimilation technique not depending in time (3DVAR) has been used to assimilate the GPS ZTD on the NCEP analysis used as First Guess. 3DVAR produces improved initial conditions by minimizing the function

$$J = \frac{1}{2}\left(x^b - x\right)^T B^{-1}\left(x^b - x\right) + \frac{1}{2}\left(y^o - H(x)\right)^T (R)^{-1}\left(y^o - H(x)\right)$$

where x^b is the generic variable of a priori state (first guess), y^o is the observation, and H is the operator that converts the model state variables to the observed variables at the observation location. **B** and **R** are the error covariance matrices for the first guess and for the errors, respectively.

MODEL SETUP

Fig.2



Model Used: **MM5 version 3**

Parameterizations:
- **Kain-Fritsch for cumulus**
- **Reisner for explicit moisture scheme**
- **MRF for PBL**

2 nested domains (27km D1, 9km D2)

29 σ levels

Initial Conditions: **1200UTC of each day**

Forecast: **36 hours**.

2 experiments per day: **CNTR with no assimilation and**
EXP with GPS ZTD assimilation by 3DVAR

RESULTS

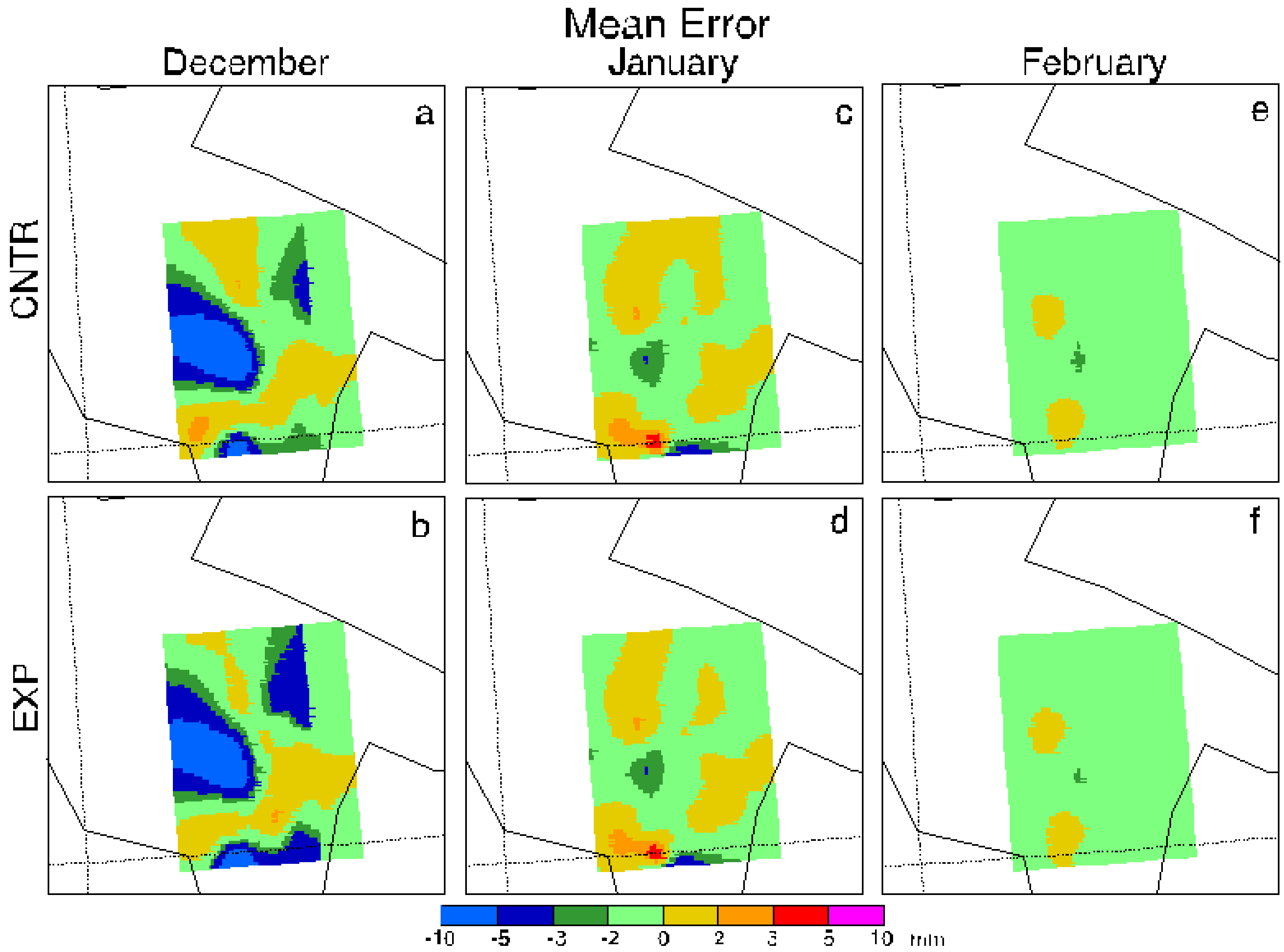
The validation of the results has been evaluated using the Mean error and the RMS defined as

$$M = \frac{\Sigma(Mod - obs)}{N} \qquad RMS = \sqrt{\frac{\Sigma(Mod - obs)^2}{N}}$$

where OBS is the observation and IC is the analysis at the *i-th* station location. The observation used for validation is the precipitation. The distribution of the pluviometers which provided the data are the dark grey asterisks in Figure 1. Average mean errors and RMS have been evaluated for the winter season, from December 2003 to the end of February 2004, and the spring season, from March to the end of May 2004. They are showed in Figures 3, 4, 5, and 6.
The Mean error shows that during December 2003 (Fig.3a,b) CNTR produces an underestimation (orange in Fig.3a) of the precipitation close to the west side of the Apennines (bottom left). This error is reduced and shifted eastward if ZTD from GPS is assimilated into the model (EXP, Fig.3b). Moreover it reduce the underestimation on the top of the domain. On the other hand, EXP overestimate (blue areas) the precipitation on the southern and eastern domain. On January (Fig.3c,d) EXP produces improvements on the top of the domain only, and no remarkable changes are found for February (Fig.3e,f). In March (Fig.4a,b) the assimilation of ZTD from GPS reduces the

overestimation on the bottom of the domain (Fig.4b) respect to CNTR (Fig.4a), and reduces the underestimation area on the bottom left corner, showing a great agreement with the observations. This is probably due to the increasing amount of humidity available during this month (passage from winter to spring) that it is not correctly reproduced by the NCEP analysis, but it can be provided to the model by assimilation of GPS ZTD. April (Fig.4c,d) and May (Fig.4e,f) do not show any remarkable difference between CNTR and EXP. This is probably due to the high precipitation occurred during these months: as explained before, ice and liquid water do not contribute to the ZTD, therefore, when it rains, the water vapour availability in atmosphere is reduced and it mostly exists as a cloud liquid water and raining drops. In Spring 2004 April and May had respectively 28 and 23 rainy days.
In Figure 5 the RMS for December shows a reduction of the maximum (purple, Fig.5a) for EXP (Fig.5b) on the left side of the domain and on the right side (from magenta to red), but an increase of the error (light green) on the top right corner). As for the Mean error, EXP of January (Fig.5d) reduces the error on the top left of the domain, but no remarkable changes are found between CNTR and EXP for February (Fig.5e,f).
March (Fig.6a,b) confirms the large improvement of EXP (Fig.6b) respect to CNTR (Fig.6a) removing the maximum on the bottom left corner of the domain. April (Fig.6c,d) and May (Fig.6e,f) still do not show any improvement of the ZTD assimilation.

Fig.3



Trieste 07,04,2010

Fig.4

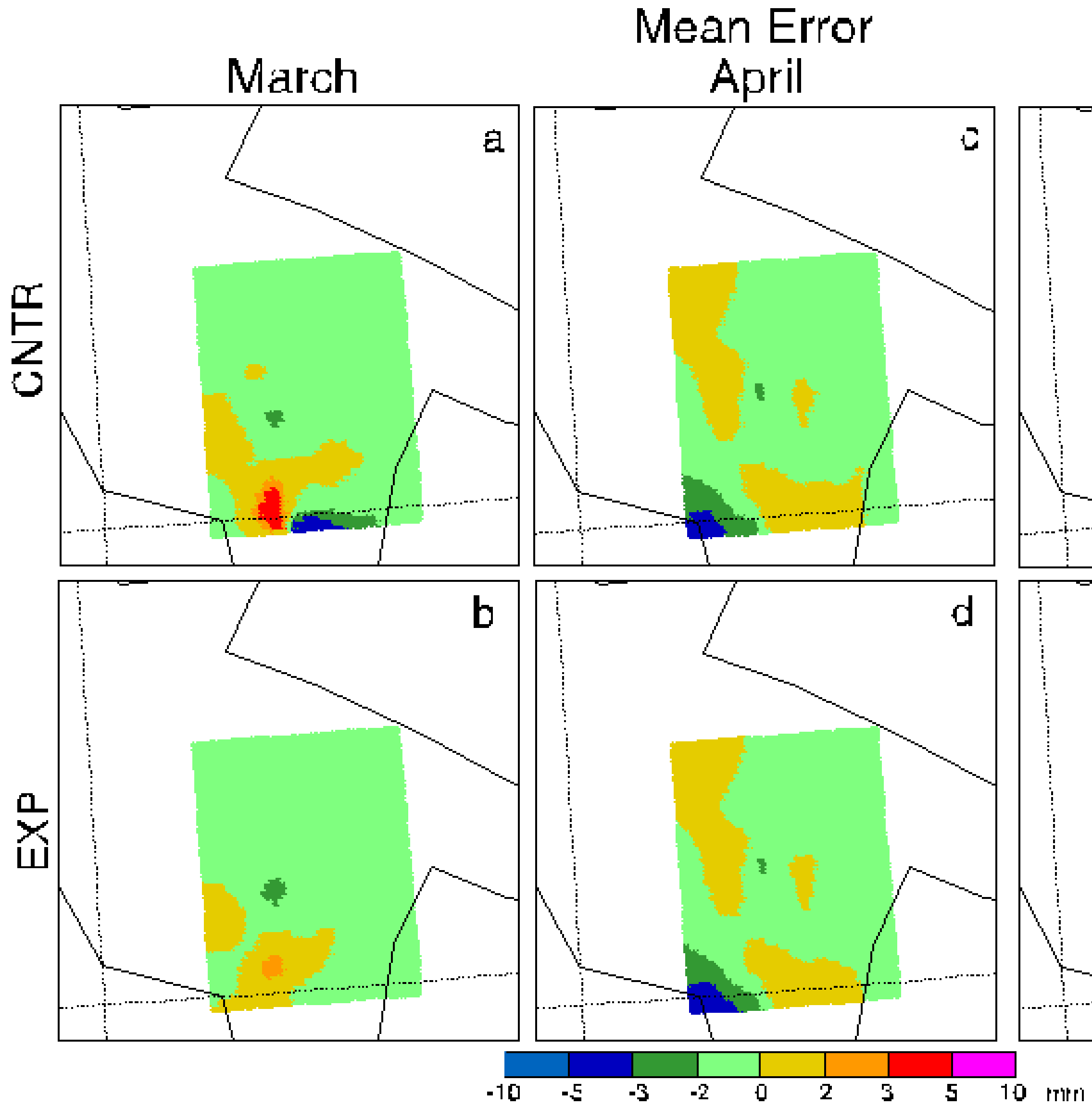


Fig.5

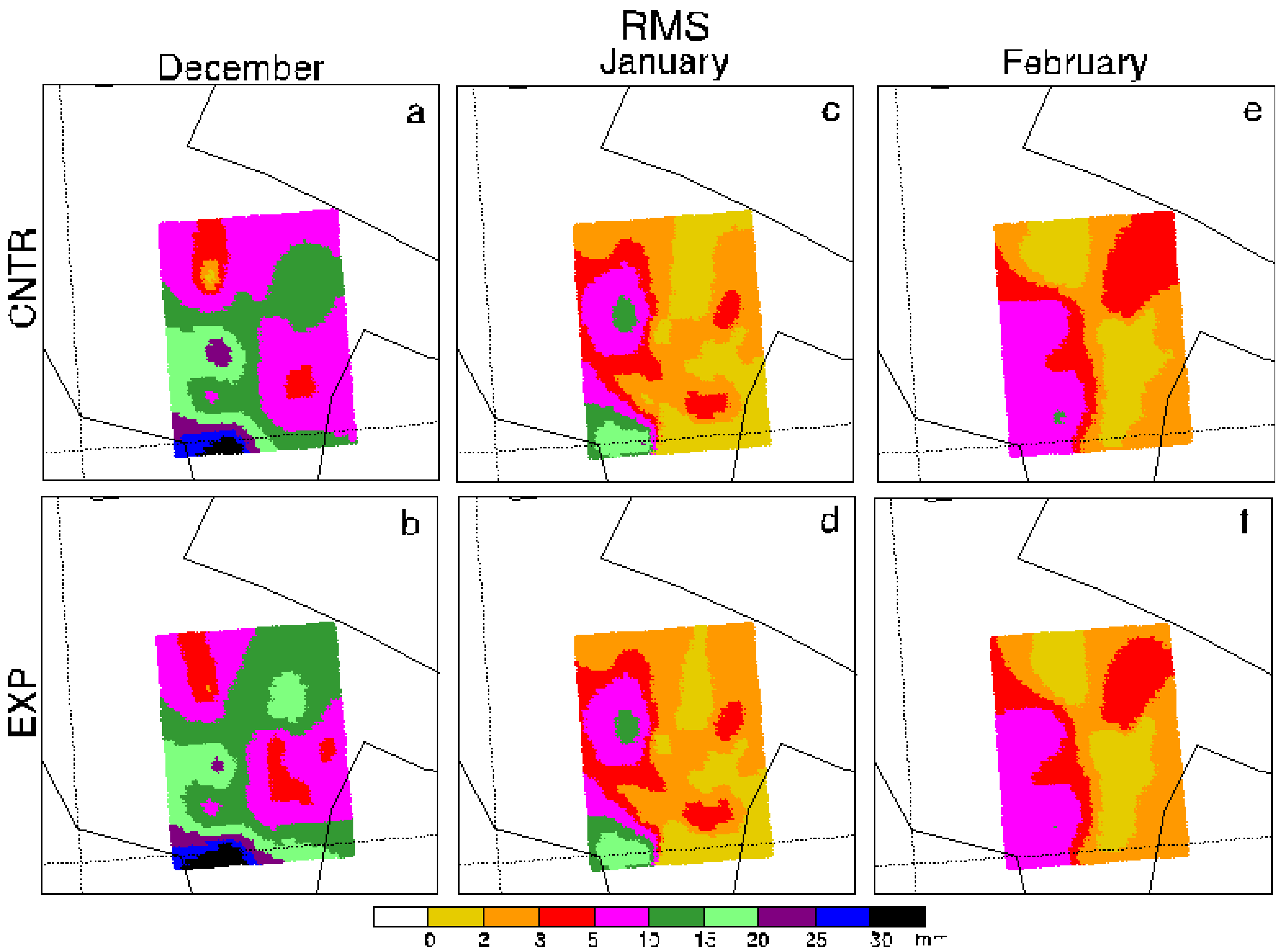
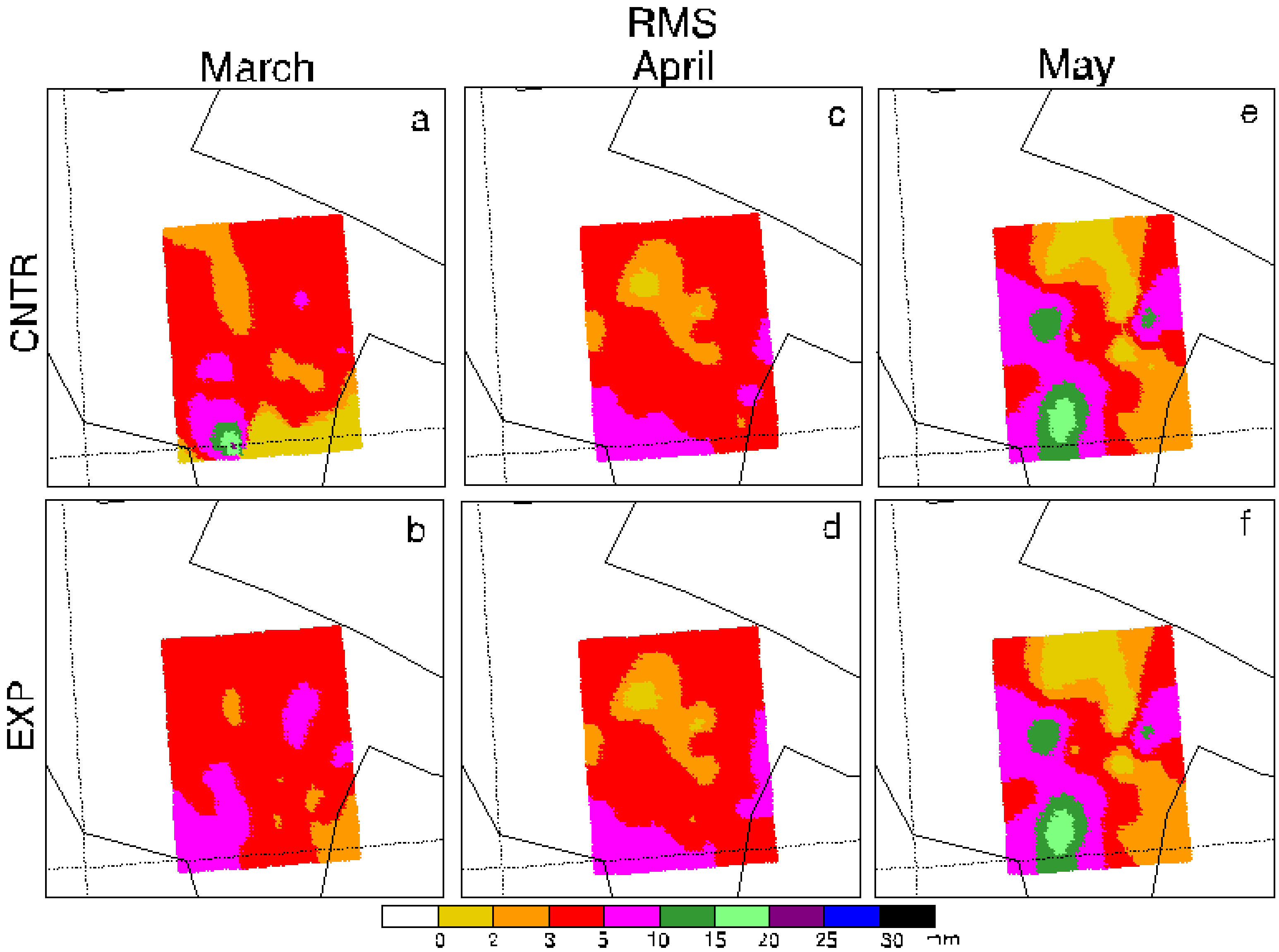

RMS
December
January
February
CNTR
EXP
a
b
c
d
e
f
0
2
3
5
10
15
20
25
30
mm

Fig.6



Back to Mapping Function

- Historic background
- Niell mapping function: How it was computed
- Replace RAOB with RO observation
- MF with RO observation
- Results
- Next upgrades:
  - Global M.F. with RO

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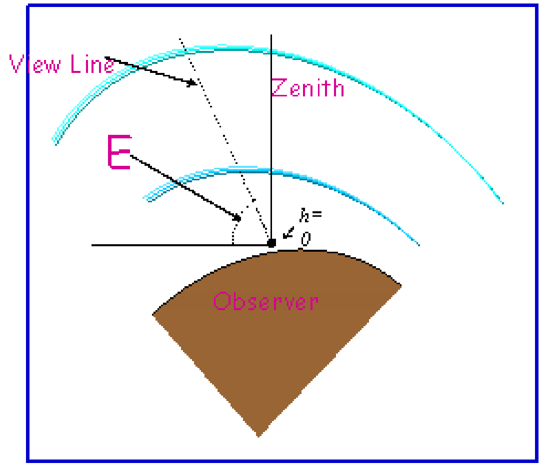
The Phase Observed by GPS: $\Phi = \rho + c\left(dt - dT\right) + \lambda A - \Delta_{ion} + \Delta_{trop} + \varepsilon$

The path of GPS signal from the satellite to the ground receiver is ruled by Fermat Principle:

$$L = \int n\, ds\,, \quad \Delta_{trop} = \int (n-1)\, ds = 10^{-6} \int N^{trop}\, ds$$

$$N^{trop} = k_1 \frac{P_d}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2}$$ Refractivity as from Smith & Weintraub (1953)



P_d=surface pressure (mbar)

e=wet pressure

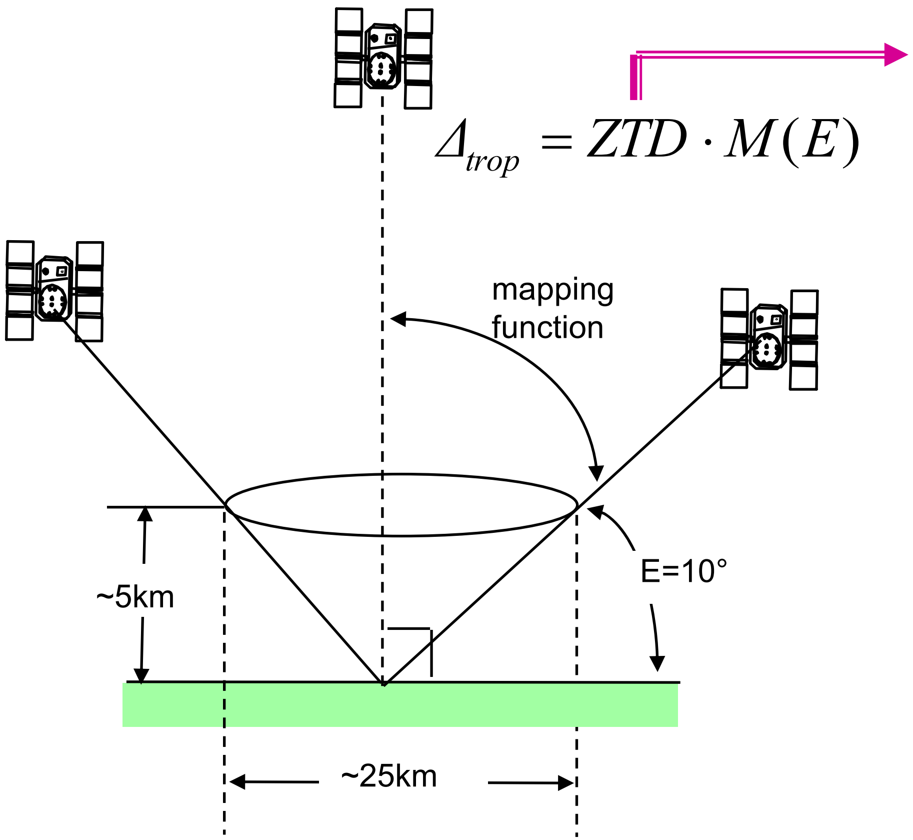
T=temperature

$$\Delta_{trop} = ZTD \cdot M(E)$$ With:

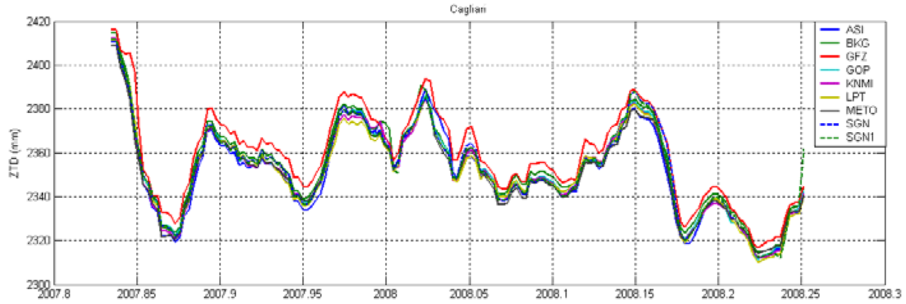
M(E)=Mapping Function $ZTD = 10^{-6}\left[\int k_1 \frac{P_d}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2}\, dz\right] = ZHD + ZWD$

$$\Delta_{trop} = m_h(E) ZHD + m_w(E) ZWD + m_\Delta(E) \cot E \left[G_N \cos\phi + G_E \sin\phi\right]$$

Ground-Based GPS Meteorology



$$\Delta_{trop} = ZTD \cdot M(E)$$



Fundamental Measurement

$$L_S = 10^{-6} \int N(s) ds$$

$$N = k_1 \cdot \left(\frac{P_d}{T}\right) + k_2 \cdot \left(\frac{e}{T}\right) + k_3 \cdot \left(\frac{e}{T^2}\right)$$

A mapping function is applied to determine how the signal delay changes with elevation angle.

The results are averaged over all the satellites to give the ZTD.

HOPFIELD Era (1969)

$$N^{trop} = N_d^{trop} + N_w^{trop}$$

$$N_d^{trop}(h) = N_{d,0}^{trop}\left[\frac{h_d - h}{h_d}\right]^4$$

$$N_w^{trop}(h) = N_{w,0}^{trop}\left[\frac{h_w - h}{h_w}\right]^4$$

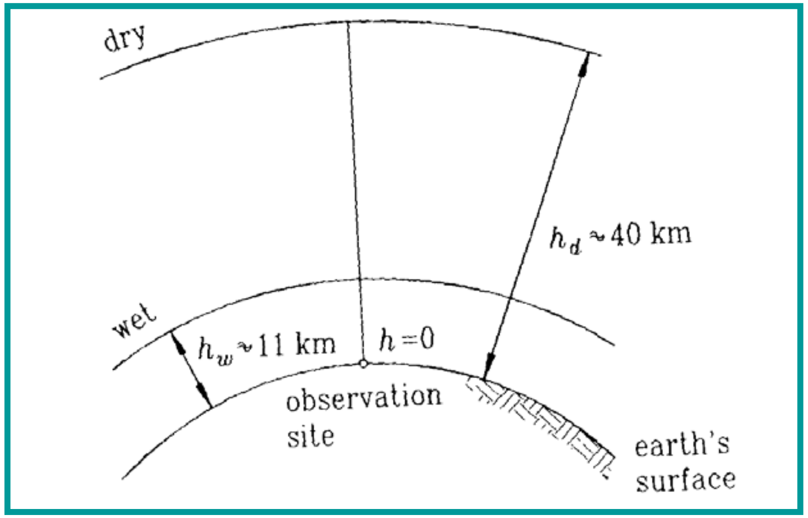
$$N_{d,0}^{trop} = 77.64\,\frac{P_0}{T_0}$$

$$N_{w,0}^{trop} = -12.96\,\frac{e}{T_0} + 3.718\cdot 10^5\,\frac{e}{T_0^2}$$

P_0 e T_0 **are ground measurement.**

$$h_d = 40136 + 148.72(T - 273.16) \quad [m]$$

$$h_w = 11000 \quad m$$



Hopfield MF

$$M_d(E) = \frac{1}{Sin(\sqrt{E^2 + 6.25})}$$

$$M_w(E) = \frac{1}{Sin(\sqrt{E^2 + 2.25})}$$

Saastamoinen Era (1973)

$$\Delta_{trop} = \frac{0.002277}{\cos(z)}\left[p + \left(\frac{1255}{T} + 0.05\right)e - B(h)\cdot\tan^2(z)\right] + \delta R(z,h))$$

z= zenith angle (90-E)
P=Pressure
T=Temperature
e=wet pressure
B=tabled pressure correction
δR(z,h)=tabled delay corrections

Mapping Function Marini-Murray like (1972)

$$m(E) = \cfrac{1}{\sin E + \cfrac{a}{\sin E + \cfrac{b}{\sin E + \cfrac{c}{\sin E + \dots}}}}$$

$$\Delta^{trop} = ZHD \cdot M_d(E) + ZWD \cdot M_w(E)$$

Marini-Murray like Mapping Function (1972)

Herring (1992)

$$a_d = \left[1.2320 + 0.0139\cos\varphi - 0.0209\,h + 0.00215\,(T - 283)\right]\cdot 10^{-3};$$
$$b_d = \left[3.1612 - 0.1600\cos\varphi - 0.0331\,h + 0.00206\,(T - 283)\right]\cdot 10^{-3};$$
$$c_d = \left[71.244 - 4.293\cos\varphi - 0.149\,h - 0.0021\,(T - 283)\right]\cdot 10^{-3}.$$

$$a_w = \left[0.583 - 0.011\cos\varphi - 0.052\,h + 0.0014\,(T - 283)\right]\cdot 10^{-3};$$
$$b_w = \left[1.402 - 0.102\cos\varphi - 0.101\,h + 0.0020\,(T - 283)\right]\cdot 10^{-3};$$
$$c_w = \left[45.85 - 1.91\cos\varphi - 0.29\,h + 0.015\,(T - 283)\right]\cdot 10^{-3}.$$

Parameters involved → Latitude "φ", Height "h", Surface Temperature "T"

Niell (1996)

$$m_{dry}(E)=\frac{1+\frac{a_{dry}}{1+\frac{b_{dry}}{1+c_{dry}}}}{\sin(E)+\frac{a_{dry}}{\sin(E)+\frac{b_{dry}}{\sin(E)+c_{dry}}}}+\left(\frac{1}{\sin(E)}-\frac{1+\frac{a_h}{1+\frac{b_h}{1+c_h}}}{\sin(E)+\frac{a_h}{\sin(E)+\frac{b_h}{\sin(E)+c_h}}}\right)\cdot h$$

$$m_{wet}(E)=\frac{1+\frac{a_{wet}}{1+\frac{b_{wet}}{1+c_{wet}}}}{\sin(E)+\frac{a_{wet}}{\sin(E)+\frac{b_{wet}}{\sin(E)+c_{wet}}}}$$

For the computation of the coefficients ***RAOB*** data were used

$$a(\lambda_i,t)=a_{avg}(\lambda_i)-a_{amp}(\lambda_i)\cos\left(2\pi\frac{t-T_0}{365.25}\right)$$

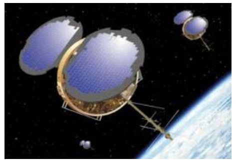
Parameters involved → Latitude "λ", Height "*h*", Doy "*t*"

An equivalent formulation is given for the wet coefficients, but they depend on the latitude only

We used the same formula and procedure applied by Niell but exploiting *Radio Occultation* data !!

RO Data suitable now to build the MF

COSMIC
CHAMP
SAC-C
METOP
GRACE
OCEANSAT_2

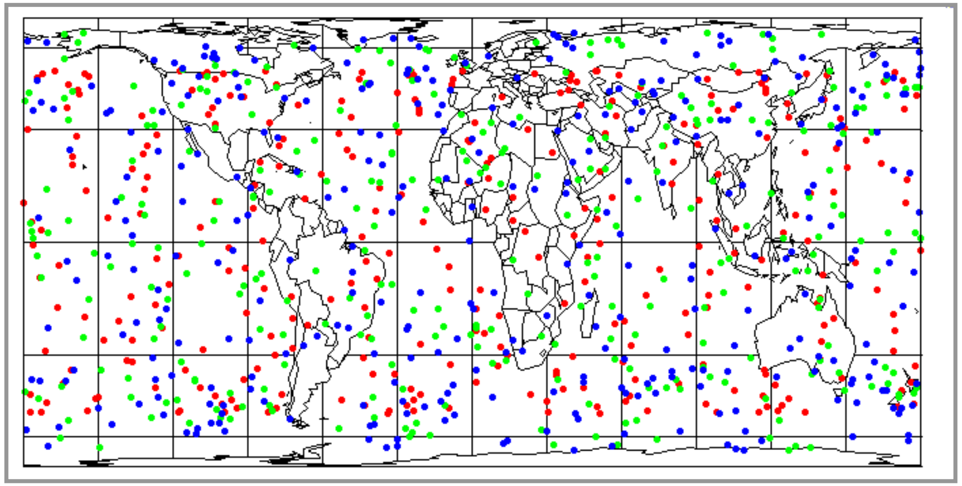


COSMIC : 6 satellites in orbit since 14 April 2006 (~2000 occ/day). Still active

CHAMP : launched on July 2000 (~200 occ/day). Still active

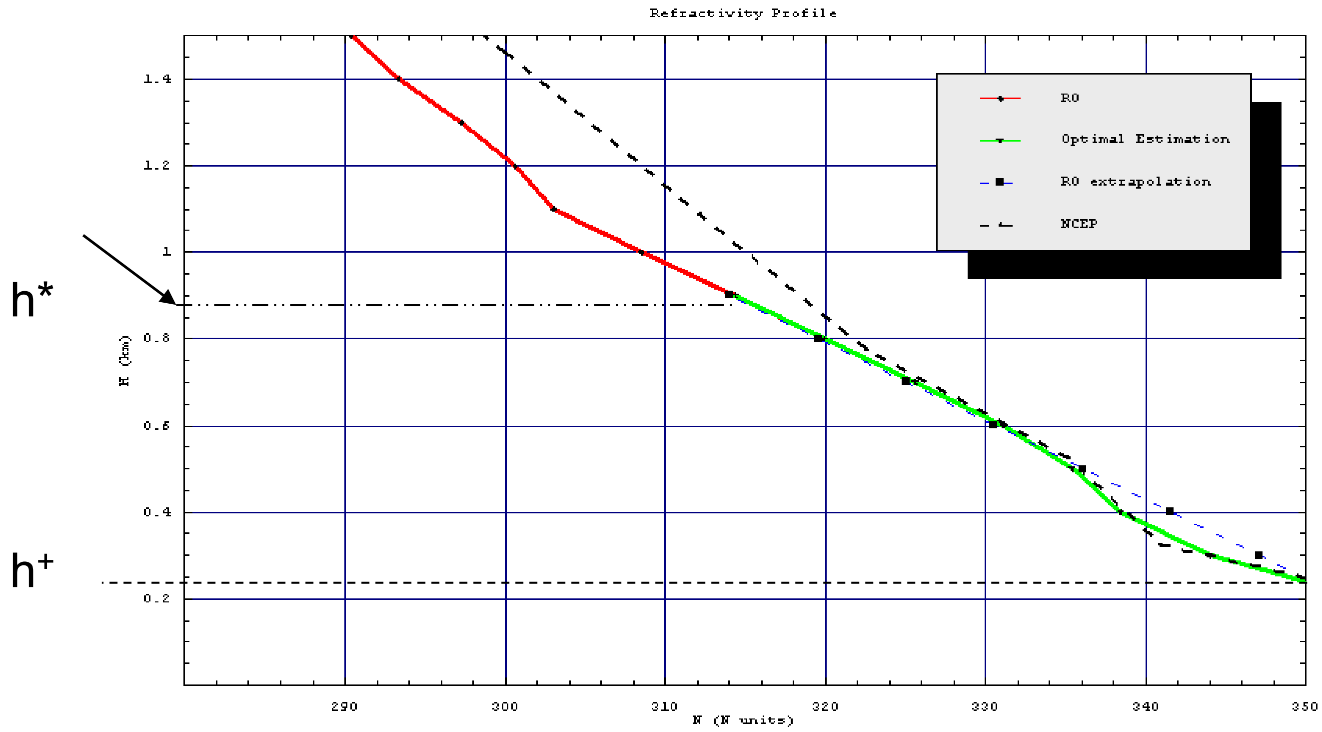
SAC-C : launched on November 2000 (one year only of data)

Large quantities of data available → **1,500,000 *RO events selected !!***



Spread and organized according to the day of the year acquired.
The selected events must provide profiles at a height of h≤1*km* over the ground

RO vs NCEP merging

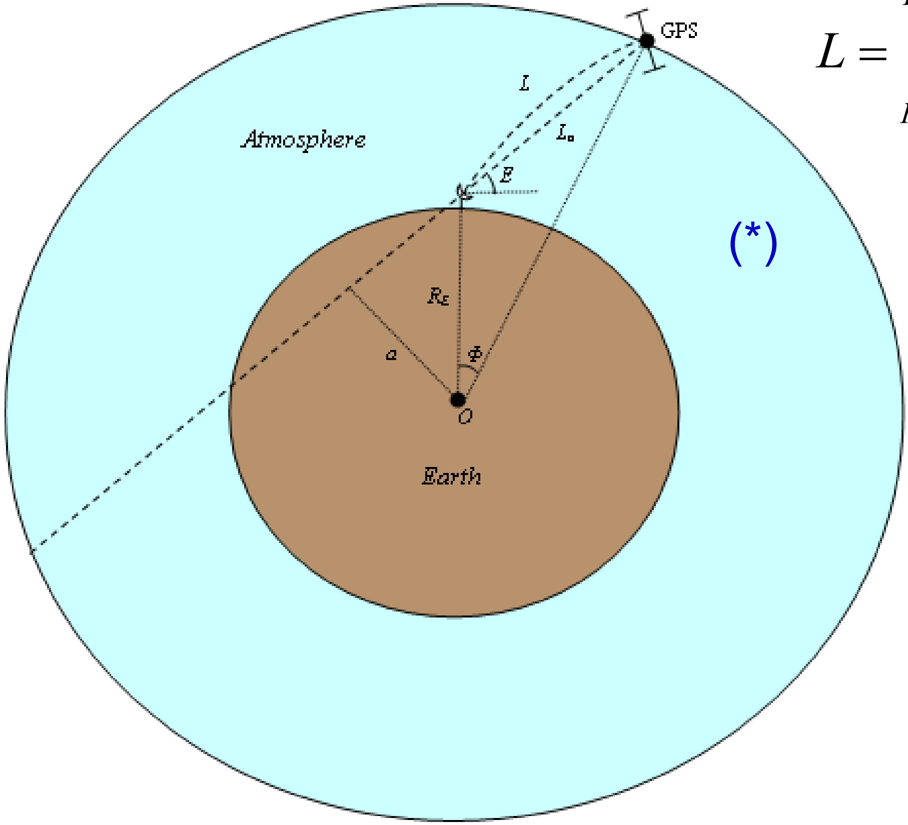


$$N(h) = k(h) \cdot N(h)_{RO} + (1 - k(h)) \cdot N(h)_{NCEP}$$

K(*h**)=1 lowest layer of *RO* data

K(*h*+)=0 lowest layer of *NCEP* data

Estimation of Total Delay (TD)



(*)

The tropospheric delay TD is given by the difference between the optical path of the signal (L) and the geometrical distance satellite-receiver (L0):

$$L = \int_{R_E + h_{topo}}^{R_E + h_{atm}} \frac{n^2(r)\cdot r}{\sqrt{n^2(r)\cdot r^2 - a^2}} dr \qquad a = R_E \cdot \cos(E)$$

$$L_0 = \int_{R_E + h_{topo}}^{R_E + h_{atm}} \frac{dr}{\sin(E)} = \frac{h_{atm} - h_{topo}}{\sin(E)}$$

where:

$$TD = \Delta L = L - L_0$$

- the refractive index ***n(r)*** is provided by RO data or by models (NCEP,ECMWF) ;
- the impact parameter ***a*** is related to the satellite and receiver position.

Estimation of the MF parameters

$$m(E)=\frac{L-L_0}{ZTD}$$

$$L=\int_{R_E+h}^{R_E+h_{atm}}\frac{n^2(r)\cdot r}{\sqrt{n^2(r)\cdot r^2-a^2}}dr$$

$$L_0=\int_{R_E+h}^{R_E+h_{atm}}\frac{dr}{\sin(E)}=\frac{h_{atm}-h}{\sin(E)}$$

$$ZTD=10^{-6}\int_{R_E+h}^{R_E+h_{atm}}N(r)dr$$

$$Min\left\|M\left(E,\lambda_i,h_j,t_k,\mathbf{P}(\lambda_i,t_k)\right)-\frac{L(E,\lambda_i,h_j,t_k)-L_0(E,\lambda_i,h_j,t_k)}{ZTD(E,\lambda_i,h_j,t_k)}\right\|$$

Where

$$\mathbf{P}(\lambda_i,t_k)=\left(a(\lambda_i,t_k),(b(\lambda_i,t_k),c(\lambda_i,t_k),a_h(\lambda_i,t_k),b_h(\lambda_i,t_k),c_h(\lambda_i,t_k)\right)$$

Estimation of the MF parameters

$$TD = m(E) \cdot ZTD = m_d(E) \cdot ZHD + m_w(E) \cdot ZWD = \Delta L_d + \Delta L_w = \Delta L$$

$$m_{[x]}(E) = \frac{\Delta L_{[x]}}{Z[X]D} \rightarrow Z[X]D = 10^{-6} \int_{R_E+h}^{R_{atm}} N_{[x]}(r)\,dr$$

X stands for
- "w" : wet component
- "d" : dry component

Parameters involved →
- *Latitude*
- *Longitude*
- *Height*
- *Doy*

Estimation of the MF Parameters (2)

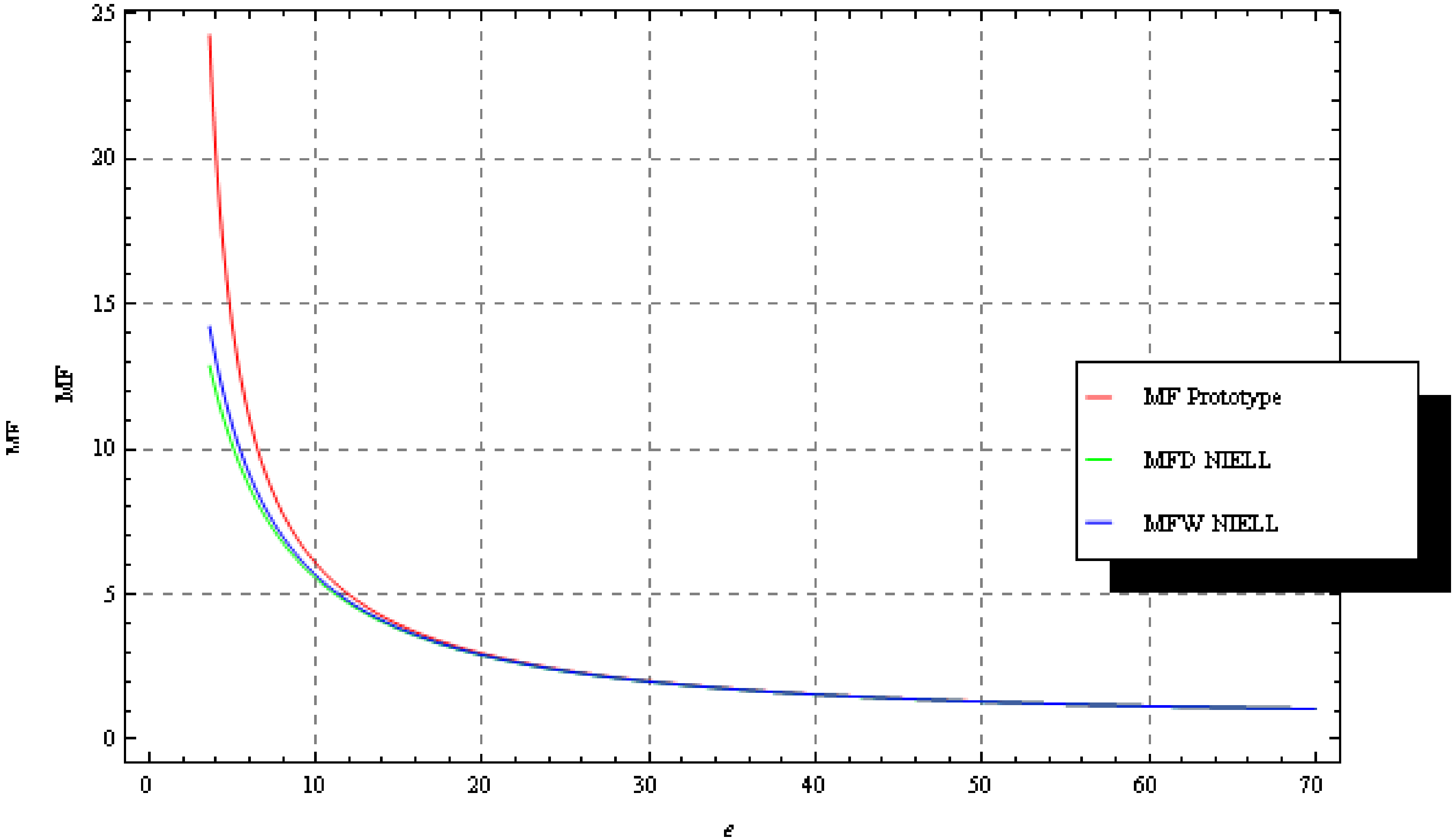
$$Min\left\| m_{[X]}\left(E,\lambda_i,\varphi_i,h_j,t_k,\mathbf{P}(\lambda_i,\varphi_i,t_k)\right)-\frac{\Delta L_{[X]}\left(E,\lambda_i,\varphi_i,h_j,t_k\right)}{Z[X]D\left(E,\lambda_i,\varphi_i,h_j,t_k\right)}\right\|$$

Latitude Gridding **Longitude Gridding**	*15° (12 groups)* *30° (12 groups)*
Number of epochs of the year	*8 (45 days/epoch)*
Layers selected to estimate a_h, b_h c_h	*Up to 2000 meters with steps of 400 meters starting from sea level.* *About 150 different Elevation Angles have been selected for fitting.*

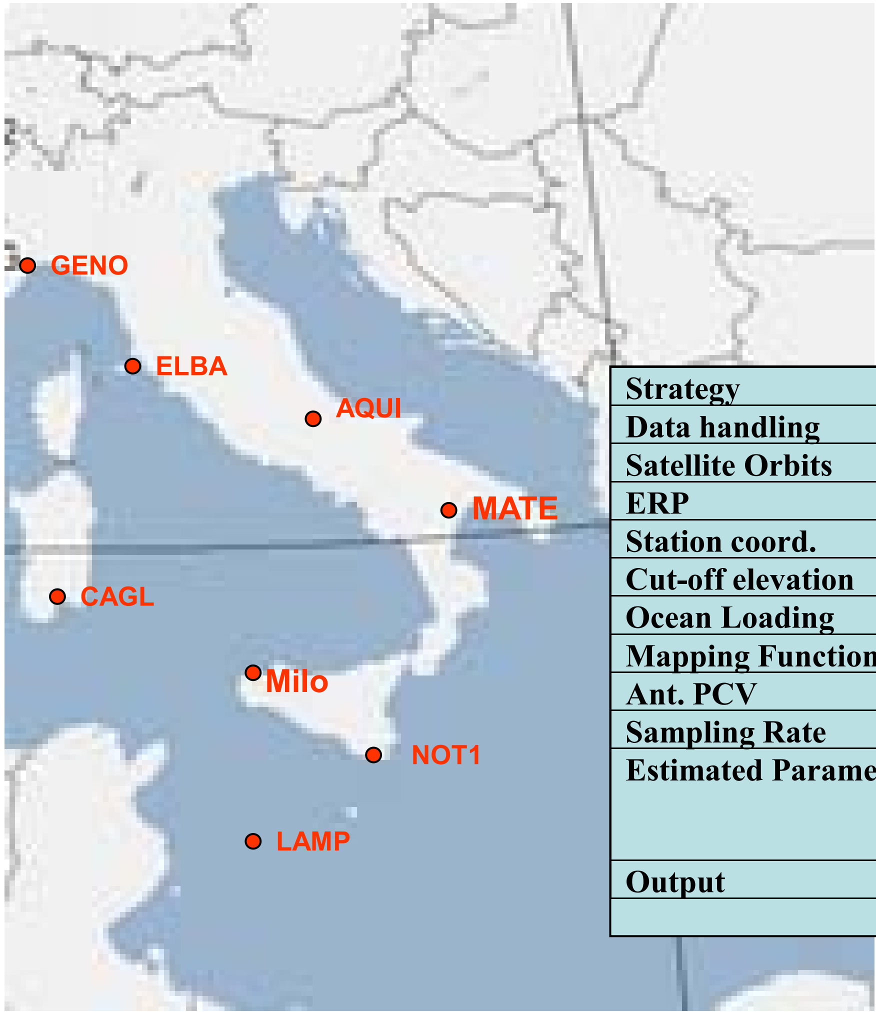
Compute the MF coefficients for each 12x12 x8 cells

For each cell there are *500-600* Radio Occultations!

Niell Mapping Function with RO (INN)



The Network for Testing the INN MF

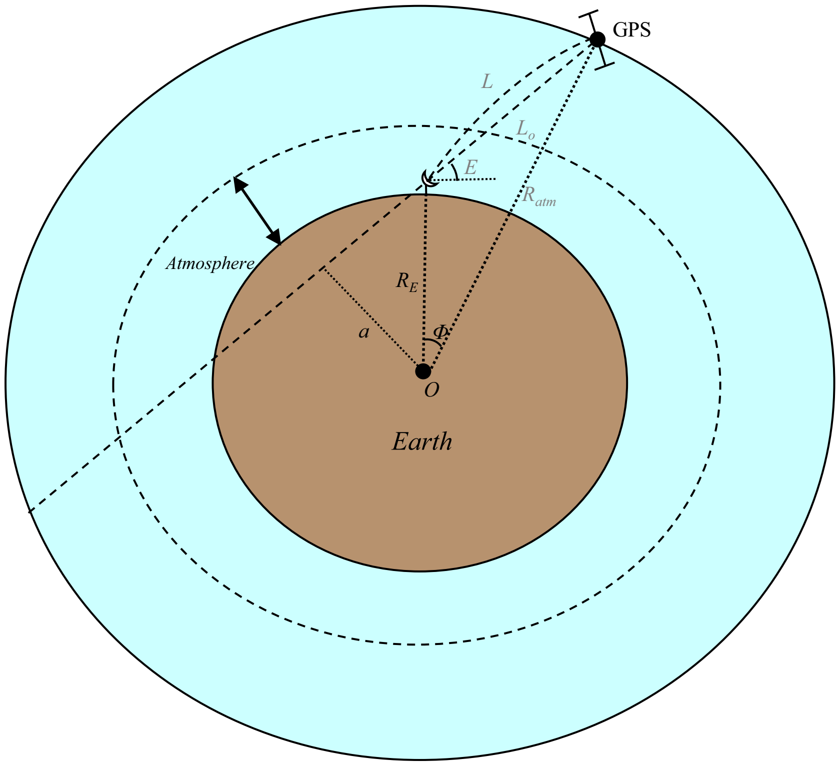


Processing Strategy (BERNESE SW used)

Strategy	Network Adjustment
Data handling	1 week of Data of 8 Perm. GPS Stations
Satellite Orbits	IGS Precise
ERP	IERS-IGS
Station coord.	aligned to IGS00
Cut-off elevation	5°
Ocean Loading	Applied (H.G.Scherneck)
Mapping Function	Neill (1996), MTMF (2008)
Ant. PCV	Absolute
Sampling Rate	30”
Estimated Parameters	Coordinates, Satellite & station clocks w.r.t a reference one, Phase ambiguities (float), ZTD time resolution: every hour
Output	Coordinates, ZTD

Estimation of Total Delay (TD)

The tropospheric delay TD is given by the difference between the optical path of the signal (L) and the geometrical distance satellite-receiver (L_0):



$$TD = \Delta L = L - L_0$$

$$L = \int_{R_E+h}^{R_{atm}} \frac{n^2(r)\cdot r}{\sqrt{n^2(r)\cdot r^2 - a^2}} dr$$

$$L_0 = \int_{R_E+h}^{R_{atm}} \frac{dr}{\sin(E)} = \frac{h}{\sin(E)}$$

being:

- ***n(r)*** the refractive index provided by *RO* data or by models (NCEP/ECMWF)
- ***a*** the impact parameter

Fit the computed coefficients in terms of a harmonic expansion truncated at 8°:

$$a(\varphi,\lambda,t) = \sum_{n=0}^{n=8}\sum_{m=0}^{n} P_{nm}\sin(\varphi)\cdot\left(C(t)_{nm}\cos(\lambda) + S(t)_{nm}\sin(\lambda)\right)$$

$$b(\varphi,\lambda,t) = \ldots\ldots\ldots$$

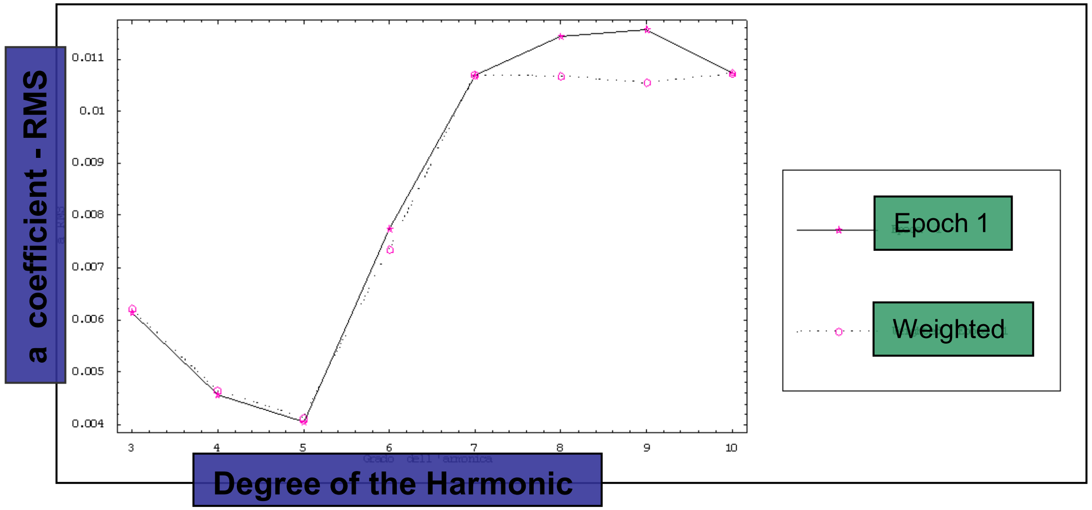
$$c(\varphi,\lambda,t) = \ldots\ldots$$

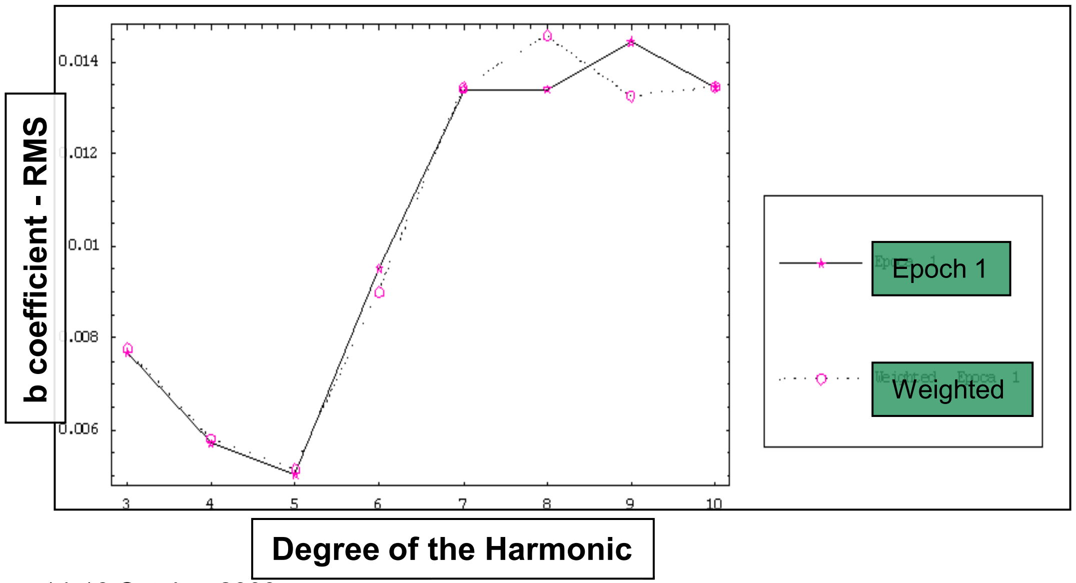
This is the same approach applied by Boehm et al. 2006 using Numerical Weather Models for the construction of a GMF:

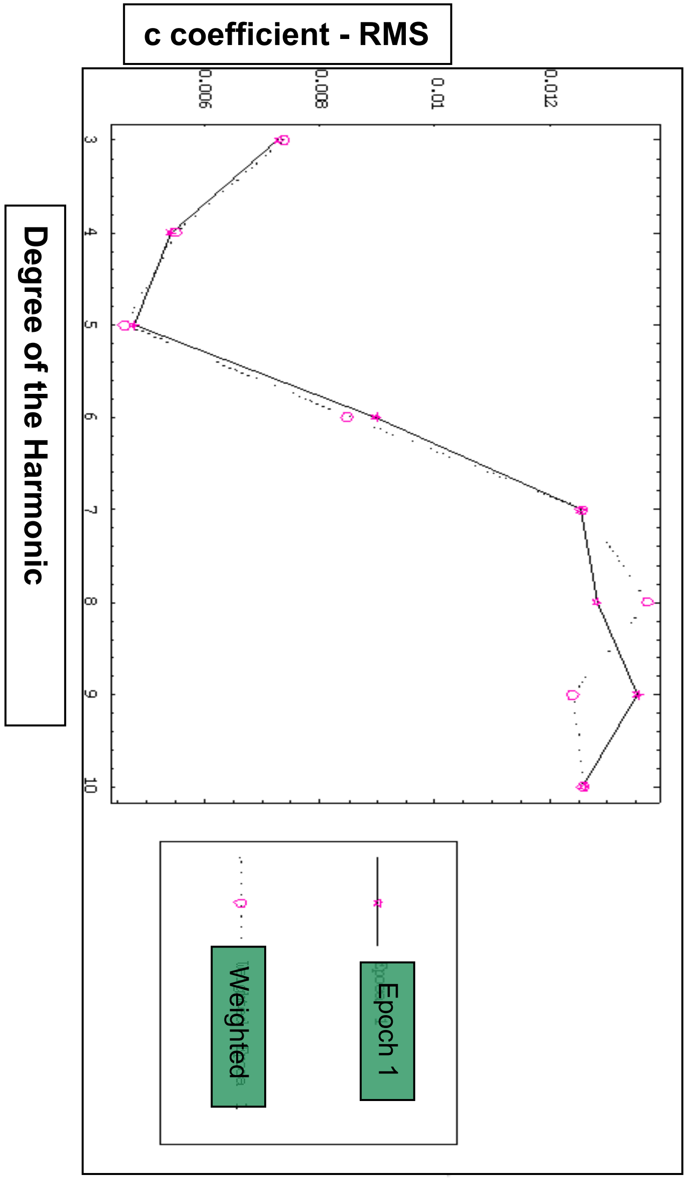
Boehm, J.; Niell, A.; Tregoning, P.; Schuh, H. 2006, "Global Mapping Function (GMF): A new empirical mapping function based on numerical weather model data," Geophysical Research Letters, 33: L07304, doi:10.1029/2005GL025546.

Best Solution: 5th Degree

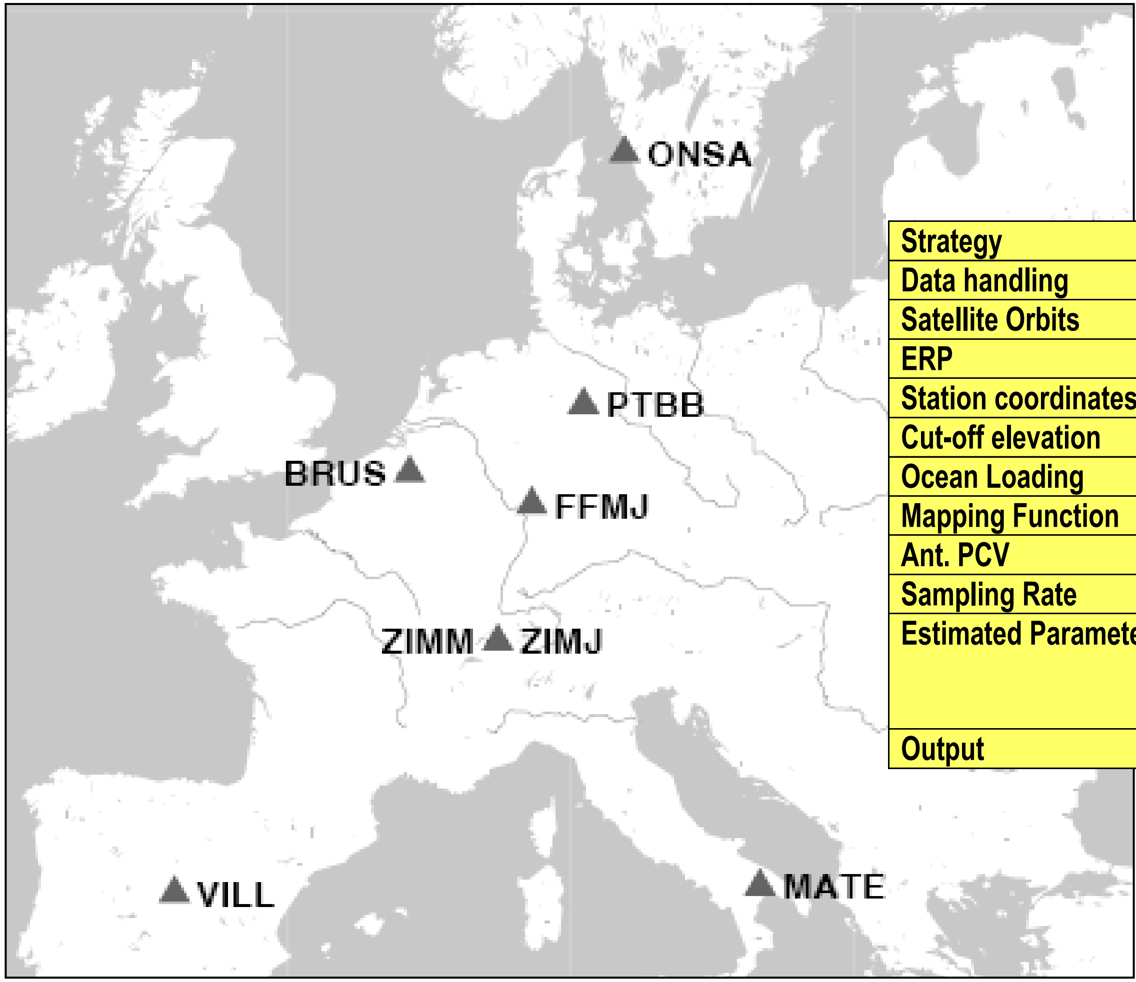
The Optimal Degree of the Harmonics





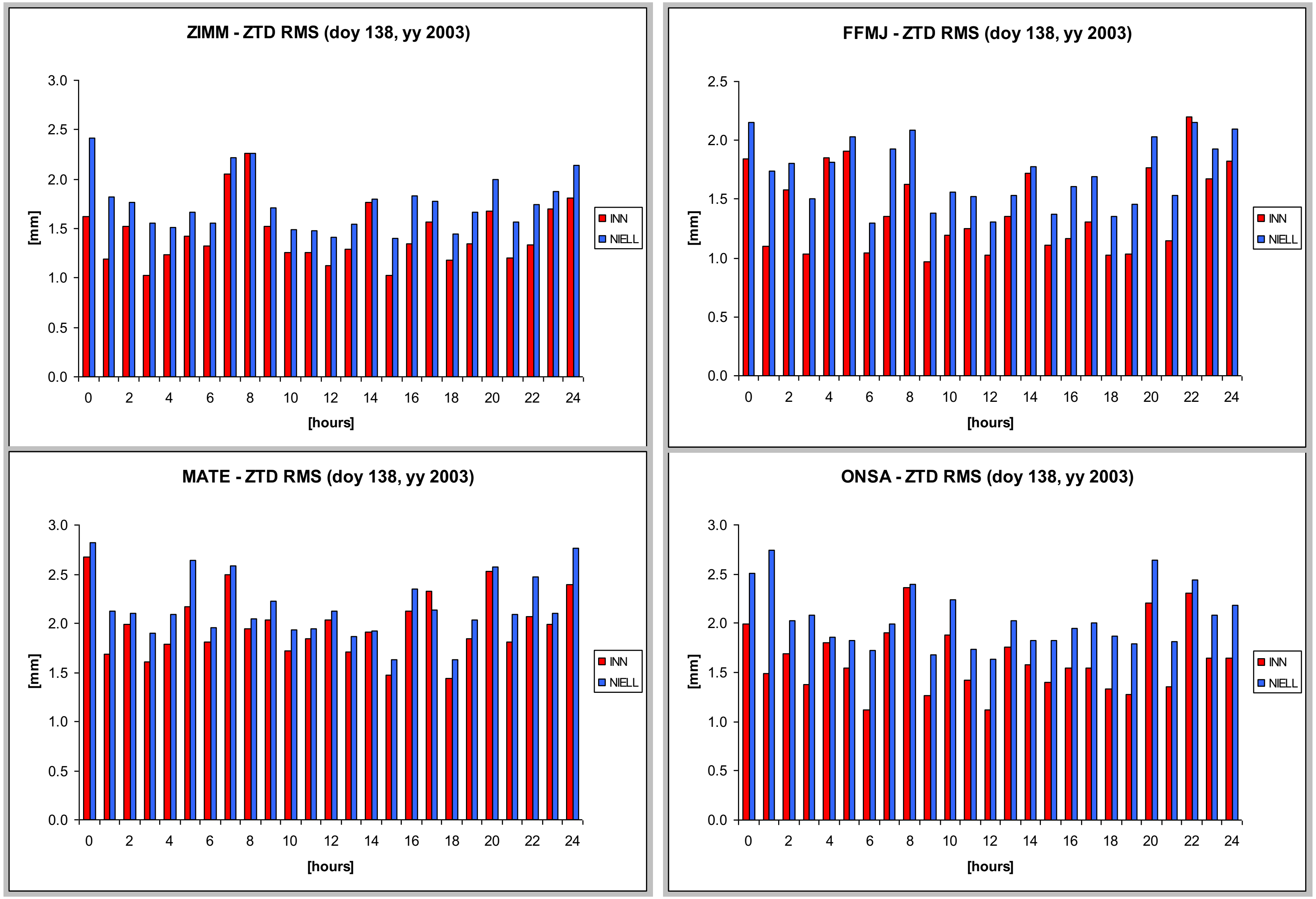


Processing Strategy (BERNESE SW used)



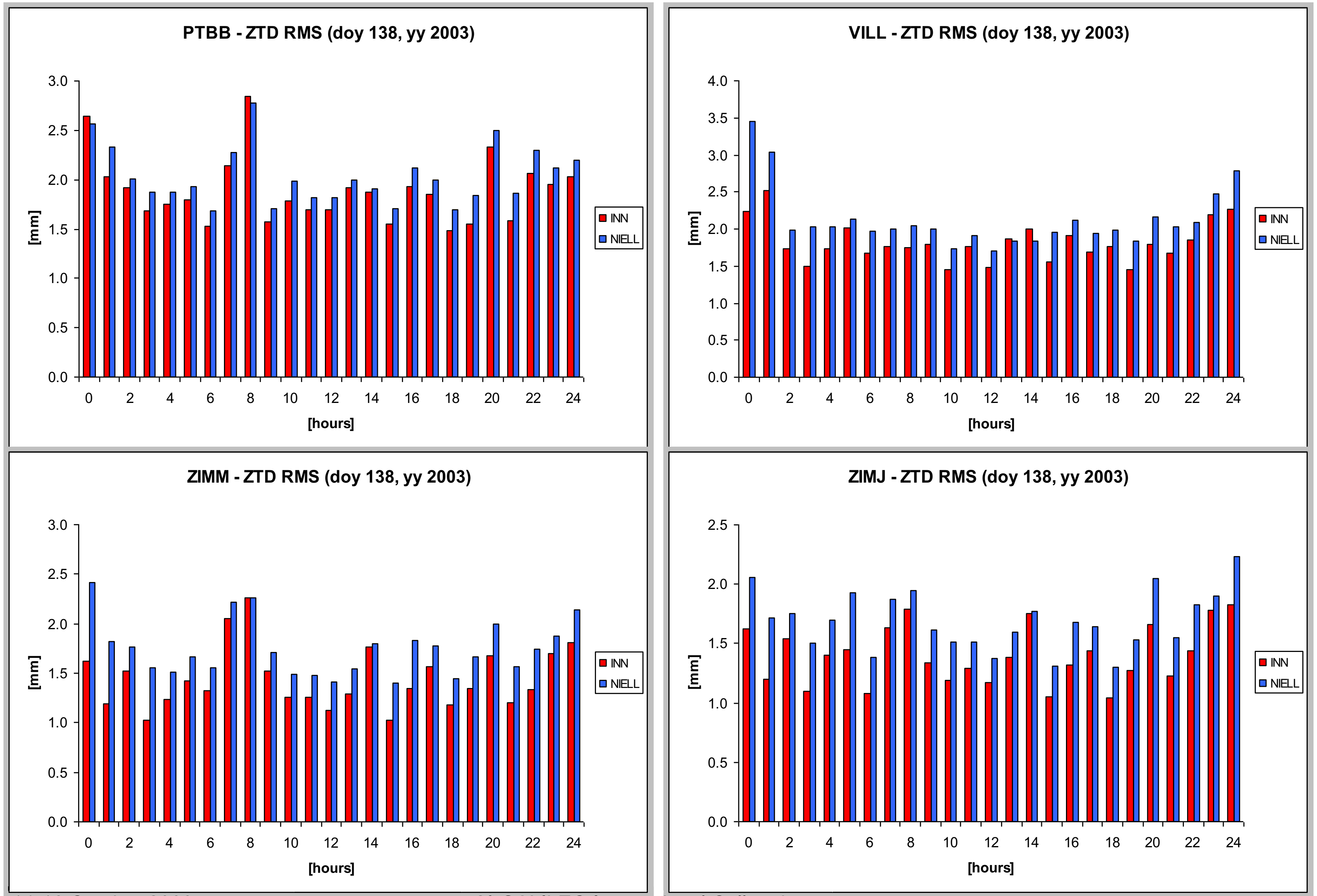
Strategy	*Network Adjustment*
Data handling	*1 week of Data of 8 Perm. GPS Stations*
Satellite Orbits	*IGS Precise*
ERP	*IERS-IGS*
Station coordinates	*Aligned to IGSb00*
Cut-off elevation	*5°*
Ocean Loading	*Applied*
Mapping Function	*Neill (1996), INN (2008)*
Ant. PCV	*Relative*
Sampling Rate	*30"*
Estimated Parameters	*Coordinates, Satellite & station clocks w.r.t a reference one, Phase ambiguities (float), ZTD time resolution: every 2 hours*
Output	*Coordinates, ZTD*

ZTD Results



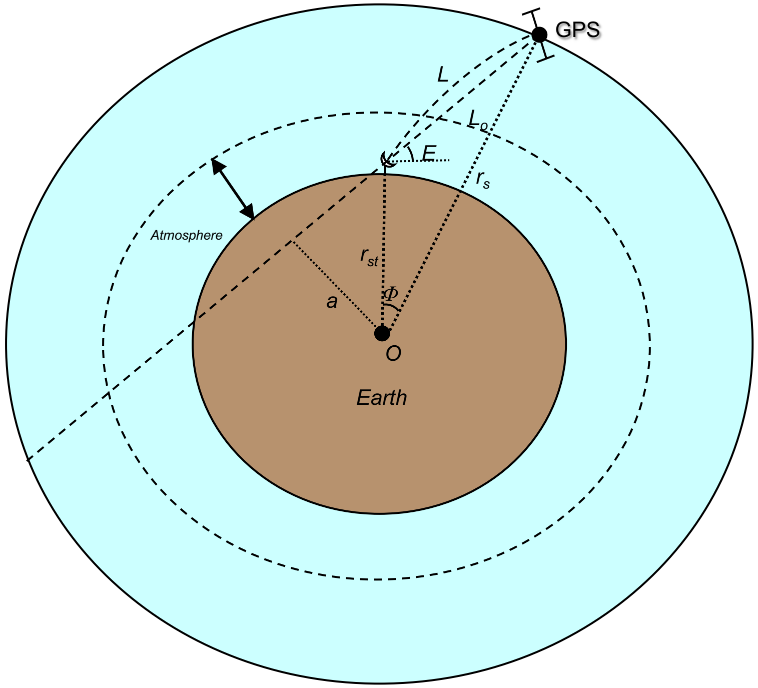
ZIMM - ZTD RMS (doy 138, yy 2003)
FFMJ - ZTD RMS (doy 138, yy 2003)
MATE - ZTD RMS (doy 138, yy 2003)
ONSA - ZTD RMS (doy 138, yy 2003)
[mm]
[hours]
INN
NIELL

ZTD Results_2
Improvements up to ~20%



RAY-TRACING TECHNIQUE

The ray-tracing technique is used to estimate the length ***L*** of the signal path from the GPS satellite to the ground-based receiver



$$L = \int_{r_{st}+h}^{r_s} \frac{n^2(r)\cdot r}{\sqrt{n^2(r)\cdot r^2 - a^2}} dr$$

where:

- $\boldsymbol{r_{st}}$ and $\boldsymbol{r_s}$ are in turn the radius vectors of the station and the satellite
- ***n(r)*** the refractive index provided by RO data or by models (NCEP/ECMWF)
- ***a*** the impact parameter

RAY-TRACING TECHNIQUE

Through the ray-tracing equations it is possible to compute the tropospheric delay TD given by the difference between the optical path of the signal (*L*) and the geometrical distance satellite-receiver (L_0):

$$TD = \Delta L = L - L_0$$

where ⟶ $$L_0 = \left\| \overline{r_s} - \overline{r_{st}} \right\|$$

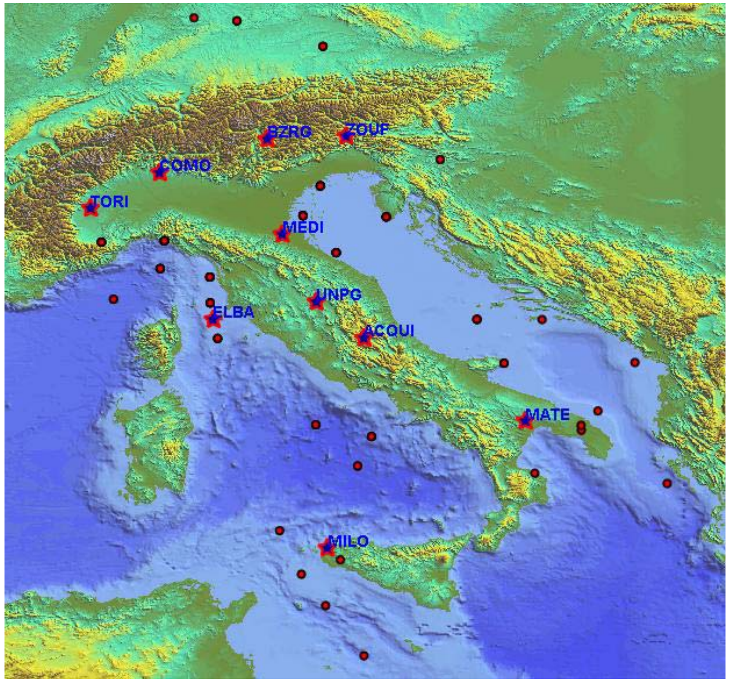
Once computed, the *TD* is removed on both L_1 and L_2 carrier phase measurements.
The correction is applied directly to RINEX files

These "**new**" RINEX files can be used by BERNESE sw in order to estimate station coordinates !!

RAY-TRACING TECHNIQUE

The following steps have been performed:

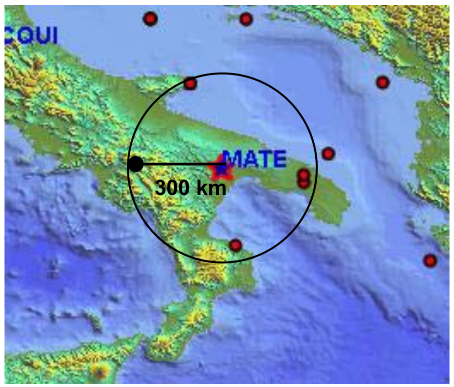
1. definition of the GNSS network (only ASI sites selected, part of EUREF network):



In the year 2008 we chose the week with the largest number of RO events falling in the selected area

RAY-TRACING TECHNIQUE

2. download of the station coordinates *xyz* (in ITRF05 reference system) from the EUREF website;
3. download of their WGS84 coordinates *λφh* from the IGS website and their conversion in EGM96 system;
4. download of RINEX files (observation and navigation) of each station of the selected network;
5. selection of RO refractivity profiles, belonging to COSMIC database, within 300*km* of distance from each station;



RAY-TRACING TECHNIQUE

6. use of "WHERESAT" routine of the GPS Toolkit open source software for the extraction of information from navigation files, such as: satellite coordinates x_k y_k z_k and elevation angles E_k;
7. use of "RINEXDUMP" routine of the GPS Toolkit open source software for the extraction of information from observation files, such as: C_1, L_1 and L_2 for each satellite;

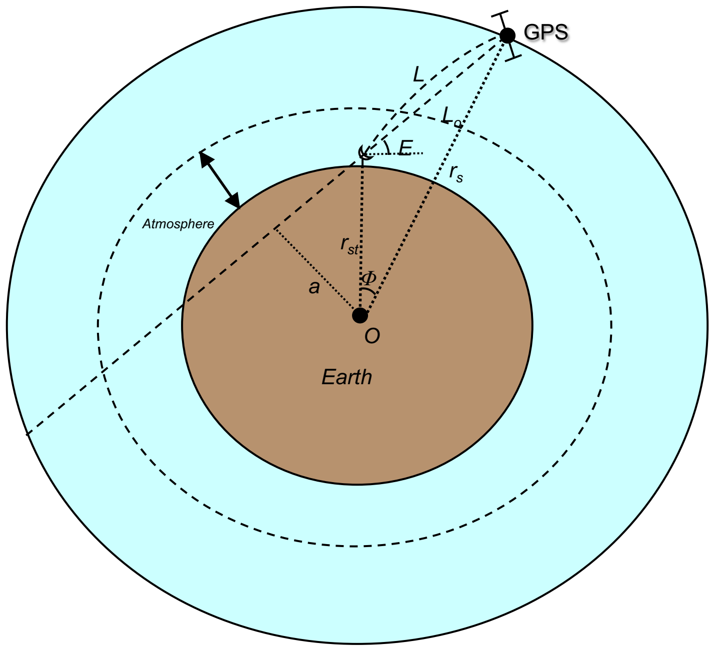
⬇

The ***GPS Toolkit*** is an open source software designed to manipulate and extract information from RINEX navigation and observation files

http://www.gpstk.org/bin/view/Documentation/WebHome

RAY-TRACING TECHNIQUE

8. the impact parameter a_k can be extracted, for the *k-th* satellite, from the ray tracing equation of the position angle:



$$\Phi_k = a_k \int_{r_{st}+h}^{r_{sk}} \frac{1}{r\sqrt{n^2(r)\cdot r^2 - a_k^{\,2}}} dr$$

But the position angle is also given by:

||

$$\Phi_k = \arccos\left(\frac{\bar{r}_{st}}{\left\|\bar{r}_{st}\right\|} \cdot \frac{\bar{r}_{sk}}{\left\|\bar{r}_{sk}\right\|} \right)$$

9. computation of $TD_k = \Delta L_k = L_k - L_{0k}$ (of the order of few meters) for each satellite;

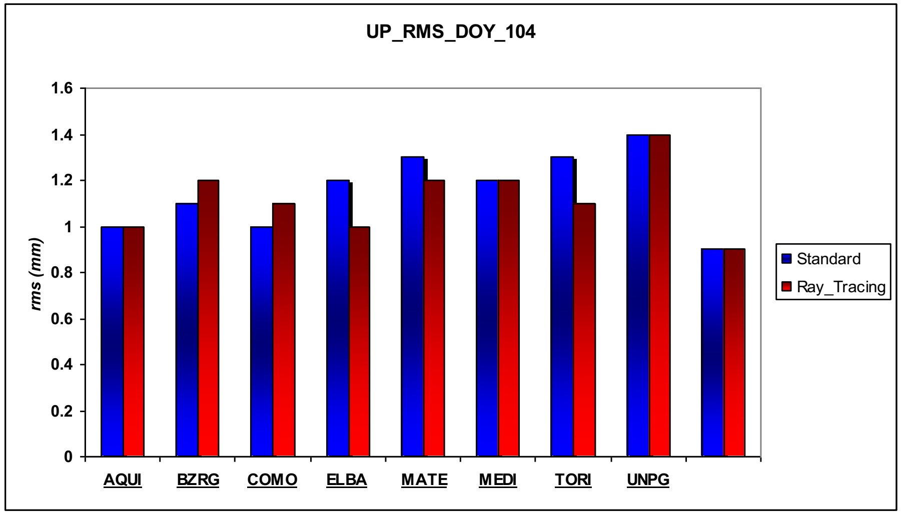
10. subtraction of ΔL_k value in the RINEX observation file from pseudorange C_1 and phase L_1 and L_2 (expressed in meters for C_1, in number of cycles for L_1 and L_2) ;

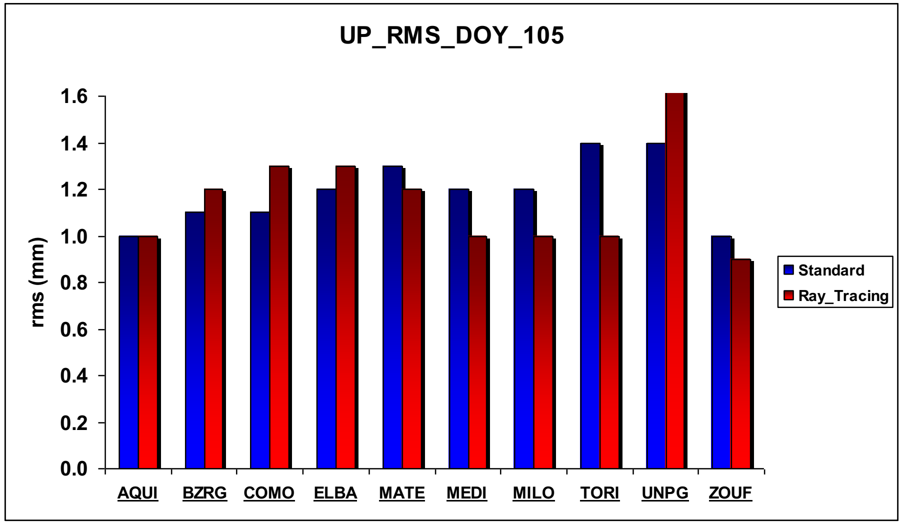
RAY-TRACING TECHNIQUE

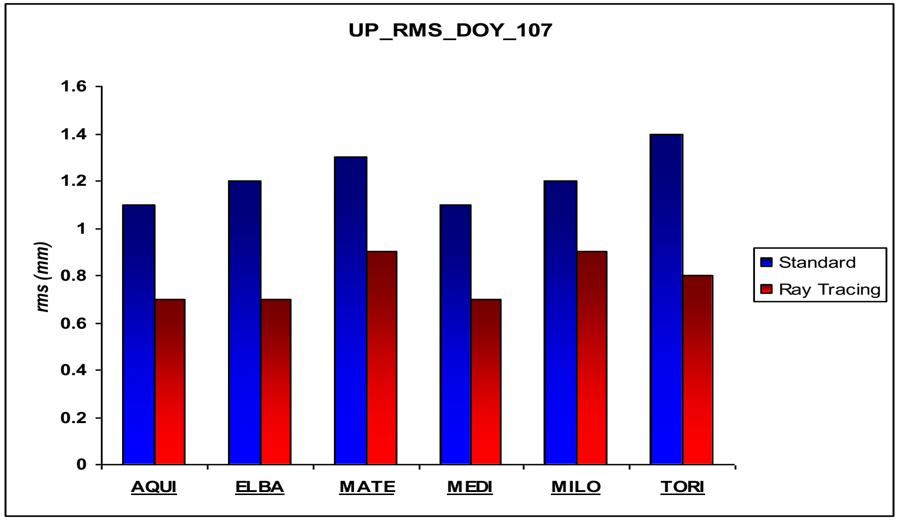
11. the modified RINEX "troposphere free" files are processed by BERNESE sw in order to estimate only the coordinates of the stations (by applying network adjustment approach) **switching off** any tropospheric delay model;
12. comparison of the estimated coordinates with those computed by BERNESE in conventional mode, i.e. using unclean RINEX and estimating the TD applying the Niell MF;

RAY-TRACING TECHNIQUE

Comparison of Up Coordinates Uncertainties







GNSS and GF estimation
Space missions GRACE-GOCE

GNSS for MSL and Sea Topography

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GNSS principles

Maintainance of the Terrestrial Reference Frame ITRFxx

Seismicity and Landslides

Mean Sea level

Ionosphere

Neutral Atmosphere (Meteorology & Climate)

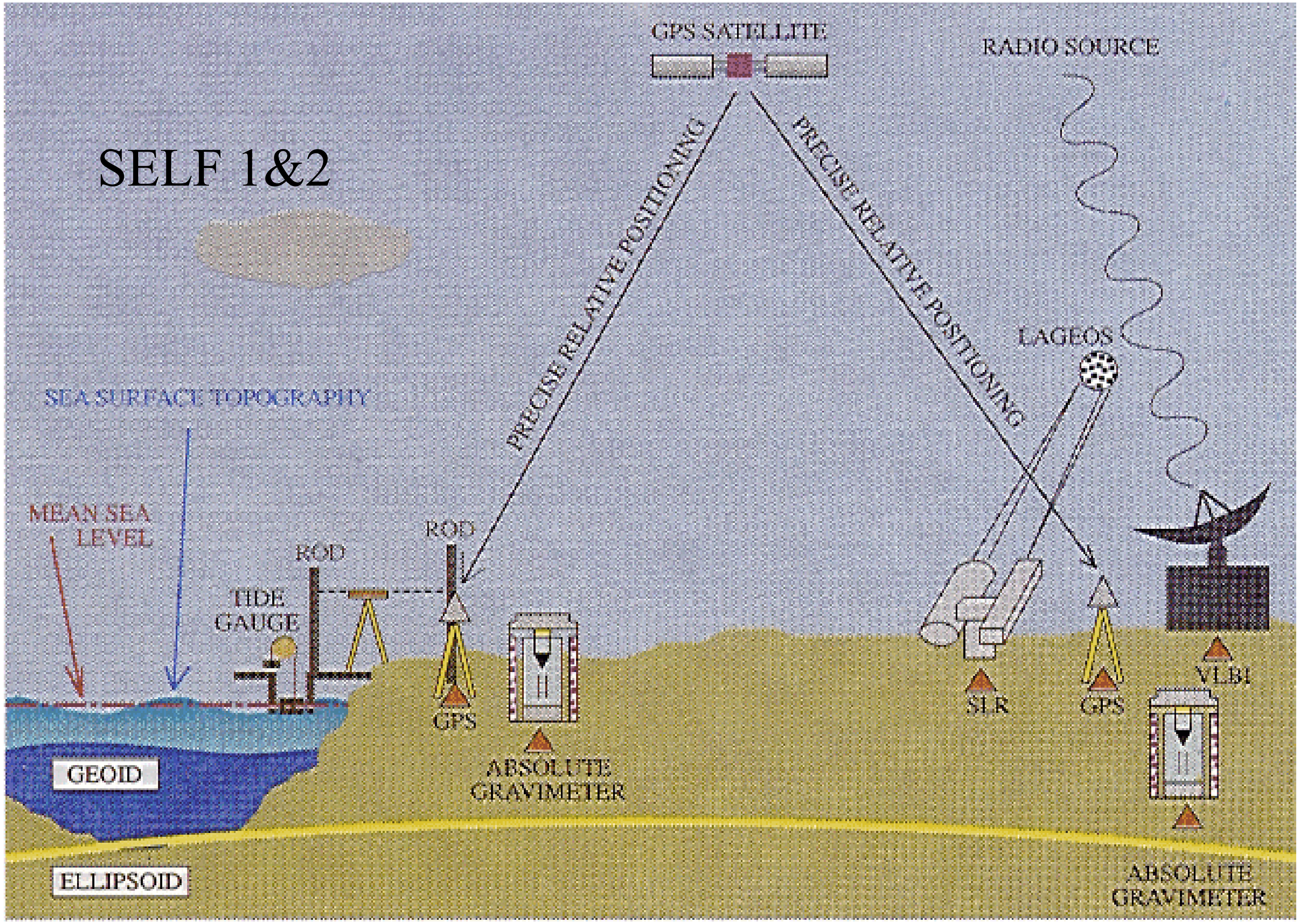
Space Applications
- Radio Occultation
- Gradiometry

Why do we study MSL?

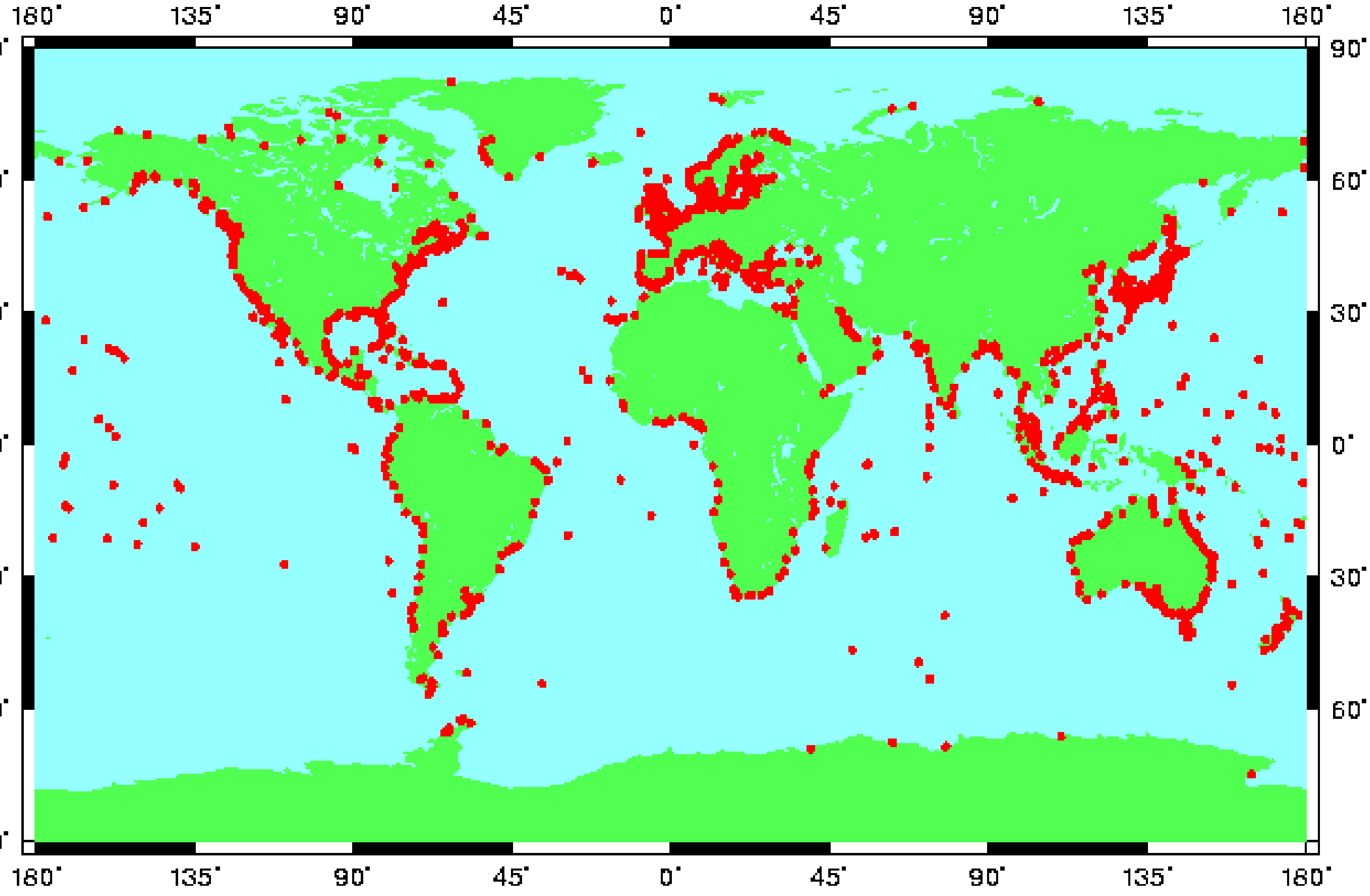
- Climate
- Geodesy: Vertical Datum
- Shore and Sea Instabilities (Subsidence, Erosion, water loading etc.)
- Topography, Cartography etc.

We do need a simphony of different techniques

- Tide-gauges:
  - Relative MSL against the ground
- GPS local network co-located with tide-gauges
- Bathymetry
- Global GPS network to link the local one to ITRF
- Ocean circulation and waves-motion monitoring with SAR, Radar Altimeter, GPS buoys etc.


SELF 1&2
GPS SATELLITE
RADIO SOURCE
PRECISE RELATIVE POSITIONING
PRECISE RELATIVE POSITIONING
LAGEOS
SEA SURFACE TOPOGRAPHY
MEAN SEA LEVEL
ROD
ROD
TIDE GAUGE
GPS
ABSOLUTE GRAVIMETER
SLR
GPS
VLBI
GEOID
ELLIPSOID
ABSOLUTE GRAVIMETER

Distribution of PSMSL Stations

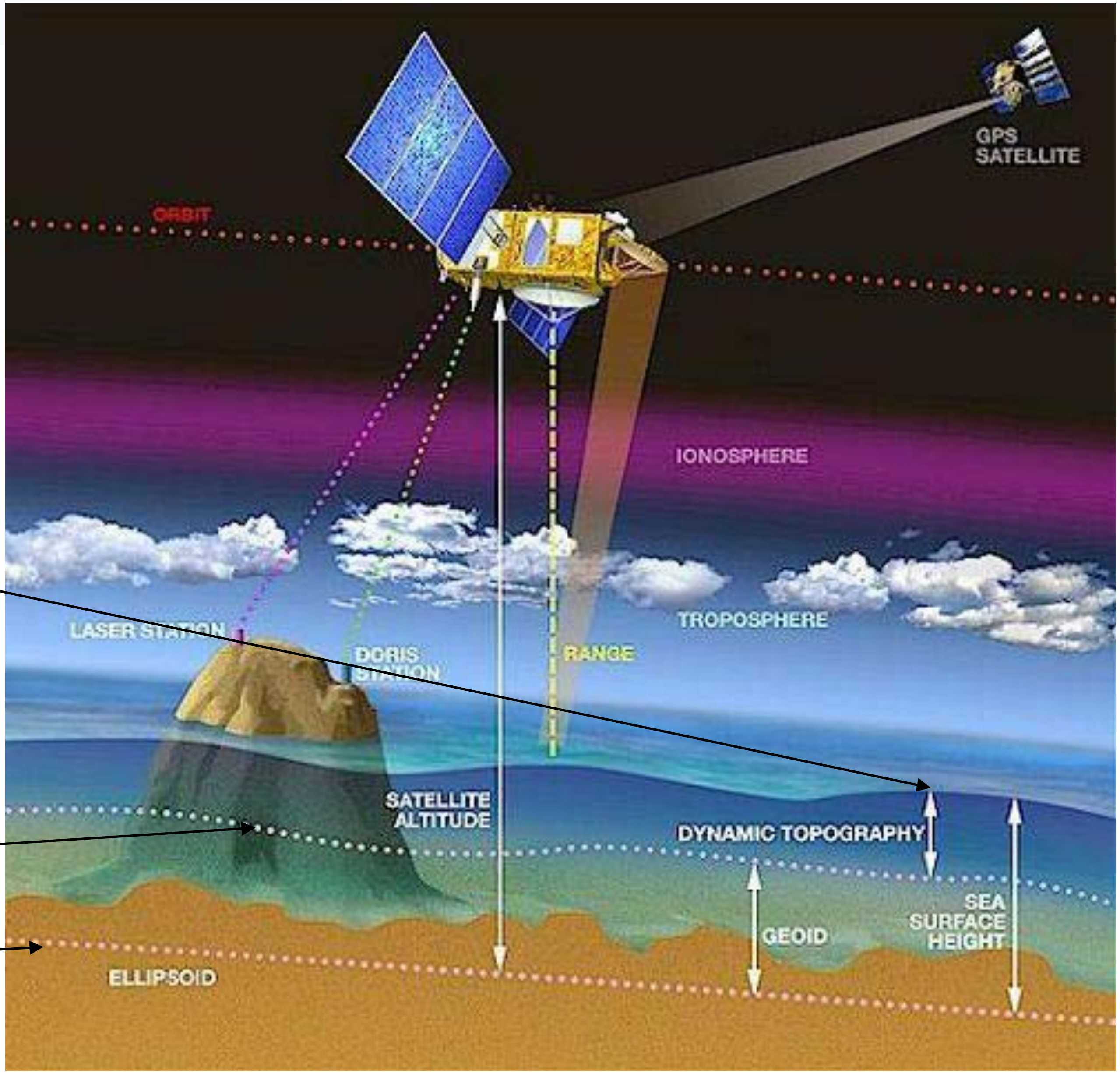


How altimetry works:

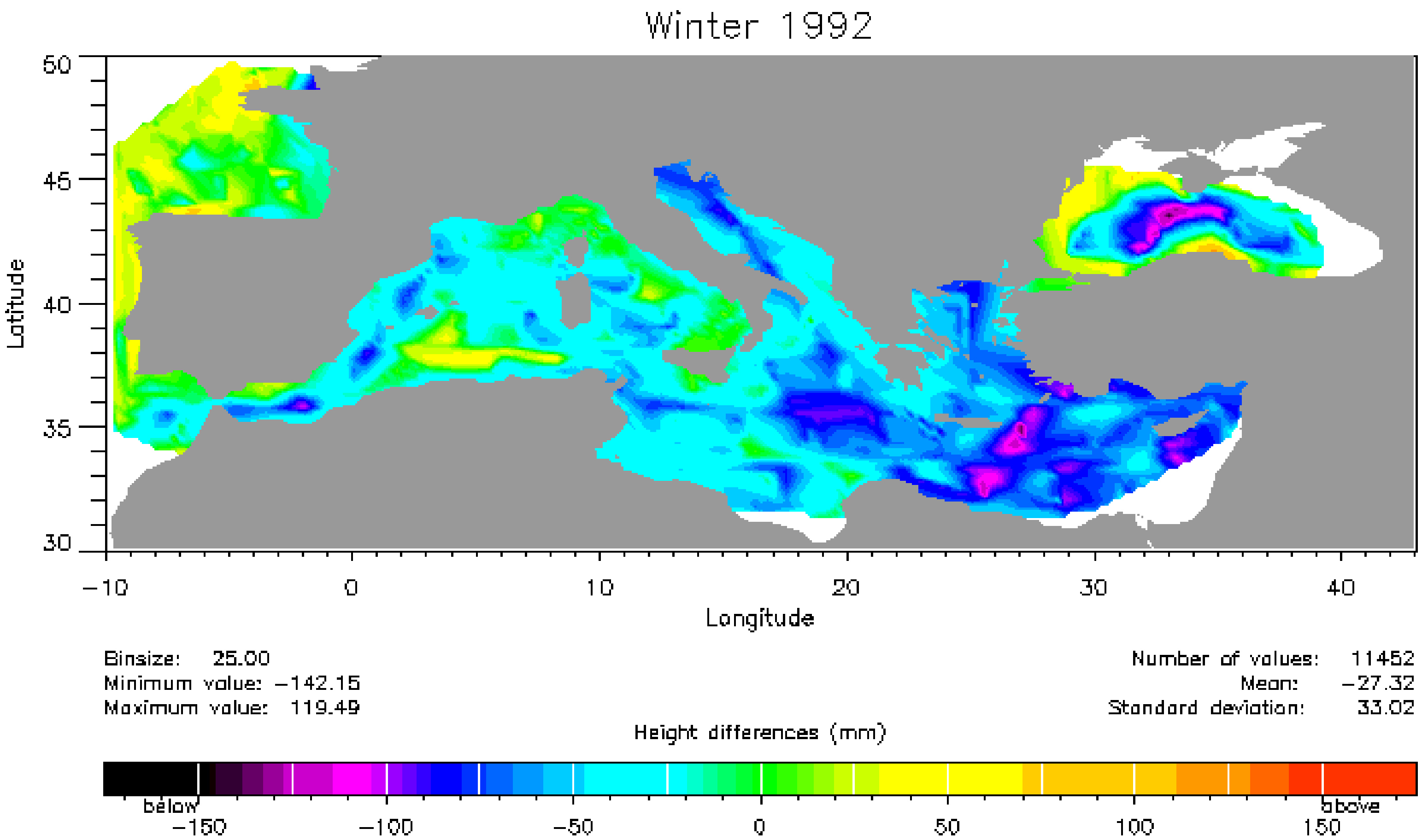
TOPEX-JASON

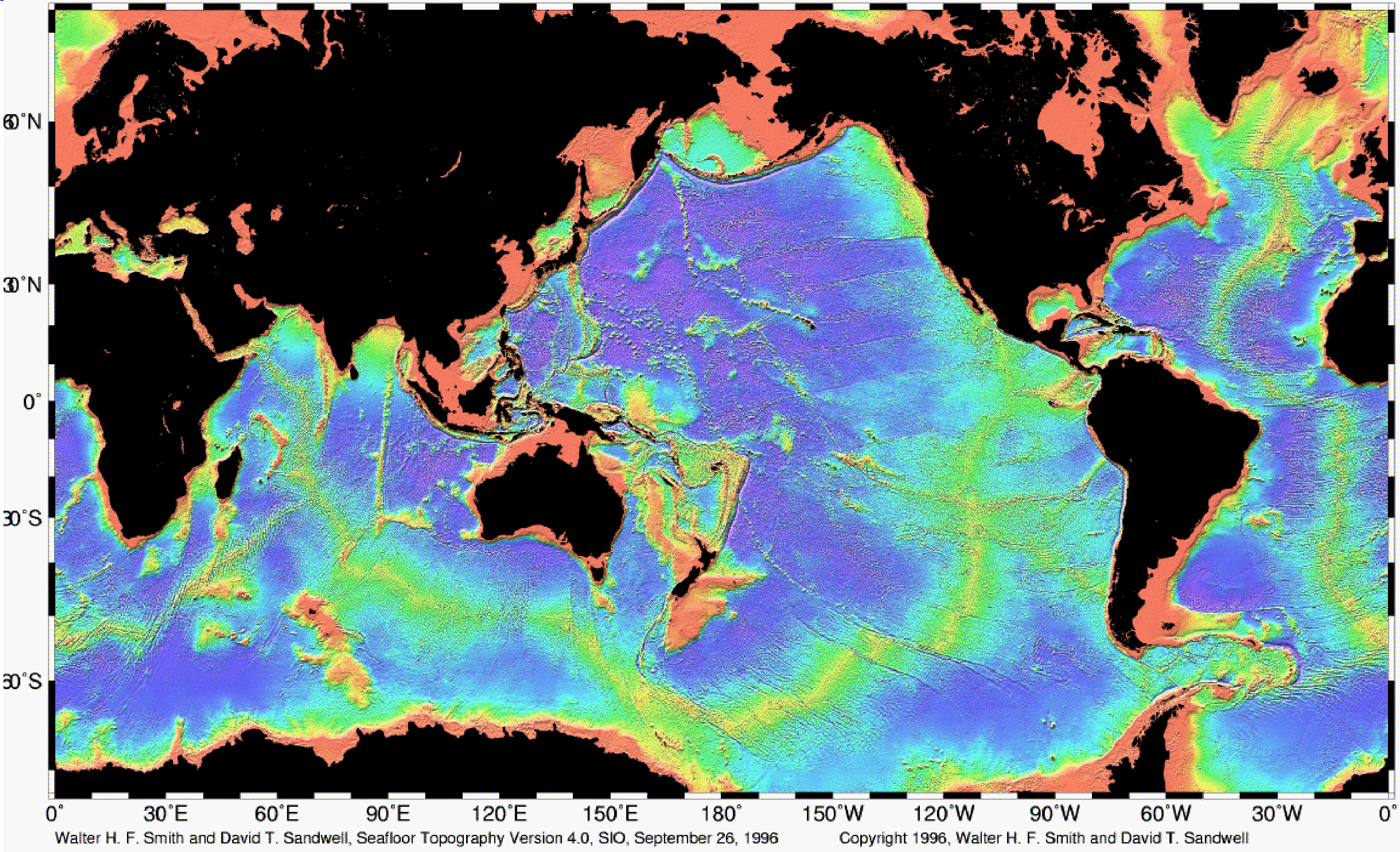
GOCE

GPS

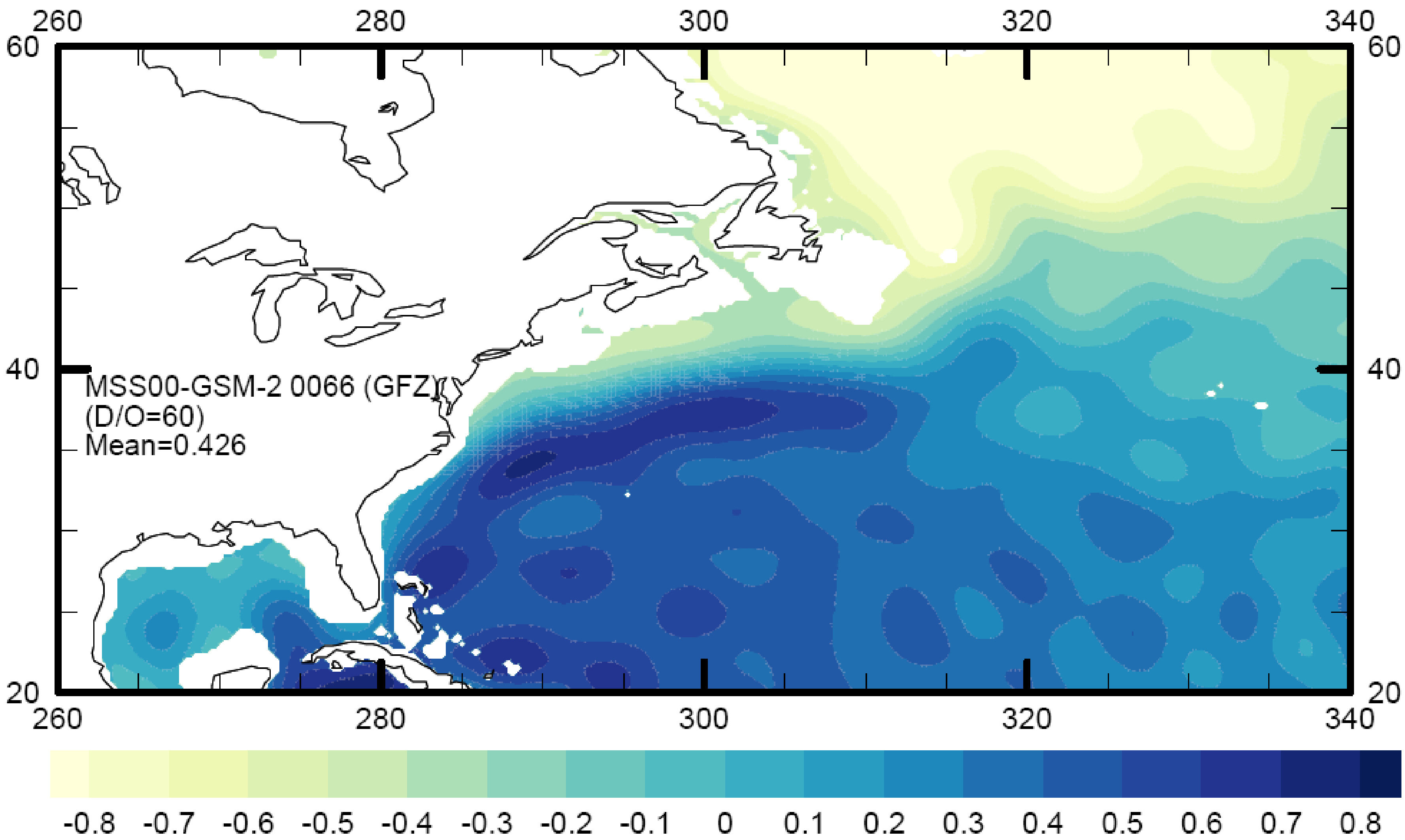


Altimetry principle


Winter 1992
Latitude
Longitude
50
45
40
35
30
−10
0
10
20
30
40
Binsize: 25.00
Minimum value: −142.15
Maximum value: 119.49
Number of values: 11452
Mean: −27.32
Standard deviation: 33.02
Height differences (mm)
below
above
−150
−100
−50
0
50
100
150

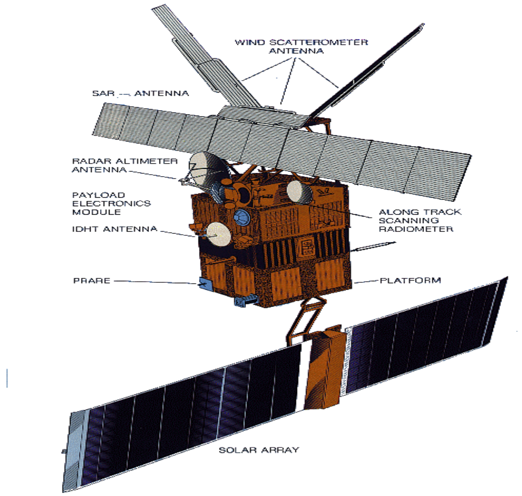


60˚N
30˚N
0˚
30˚S
60˚S
0˚ 30˚E 60˚E 90˚E 120˚E 150˚E 180˚ 150˚W 120˚W 90˚W 60˚W 30˚W 0˚
Walter H. F. Smith and David T. Sandwell, Seafloor Topography Version 4.0, SIO, September 26, 1996
Copyright 1996, Walter H. F. Smith and David T. Sandwell

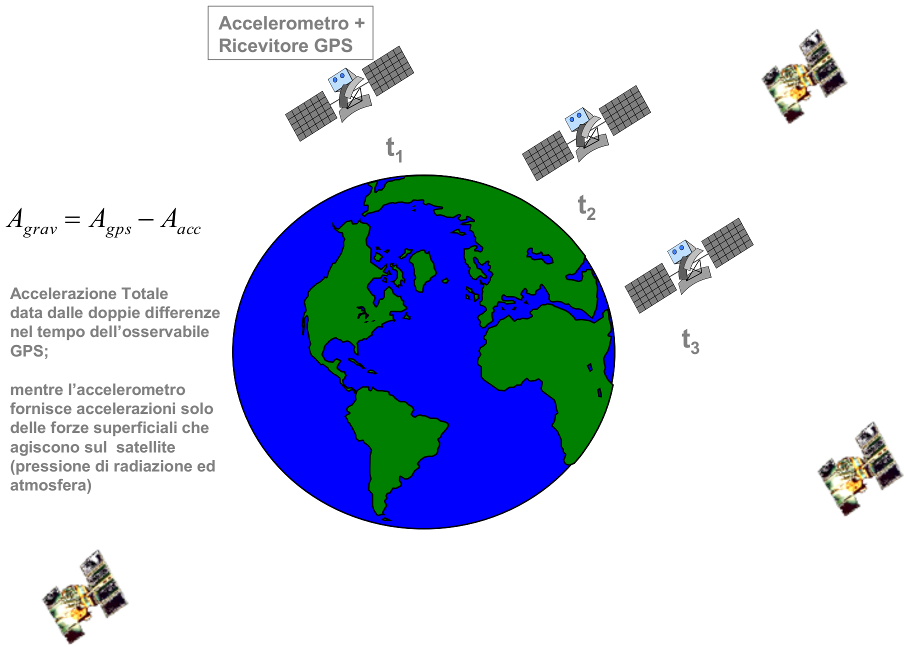


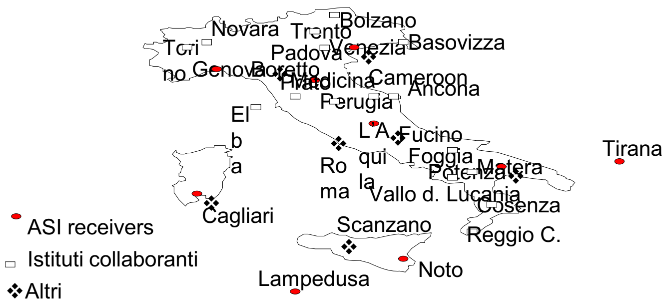
260
280
300
320
340
60
40
20
MSS00-GSM-2 0066 (GFZ)
(D/O=60)
Mean=0.426
-0.8 -0.7 -0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8

GPS for : POD and Gravity field recovery



Precise Orbit Determination





Trieste 07,04,2010

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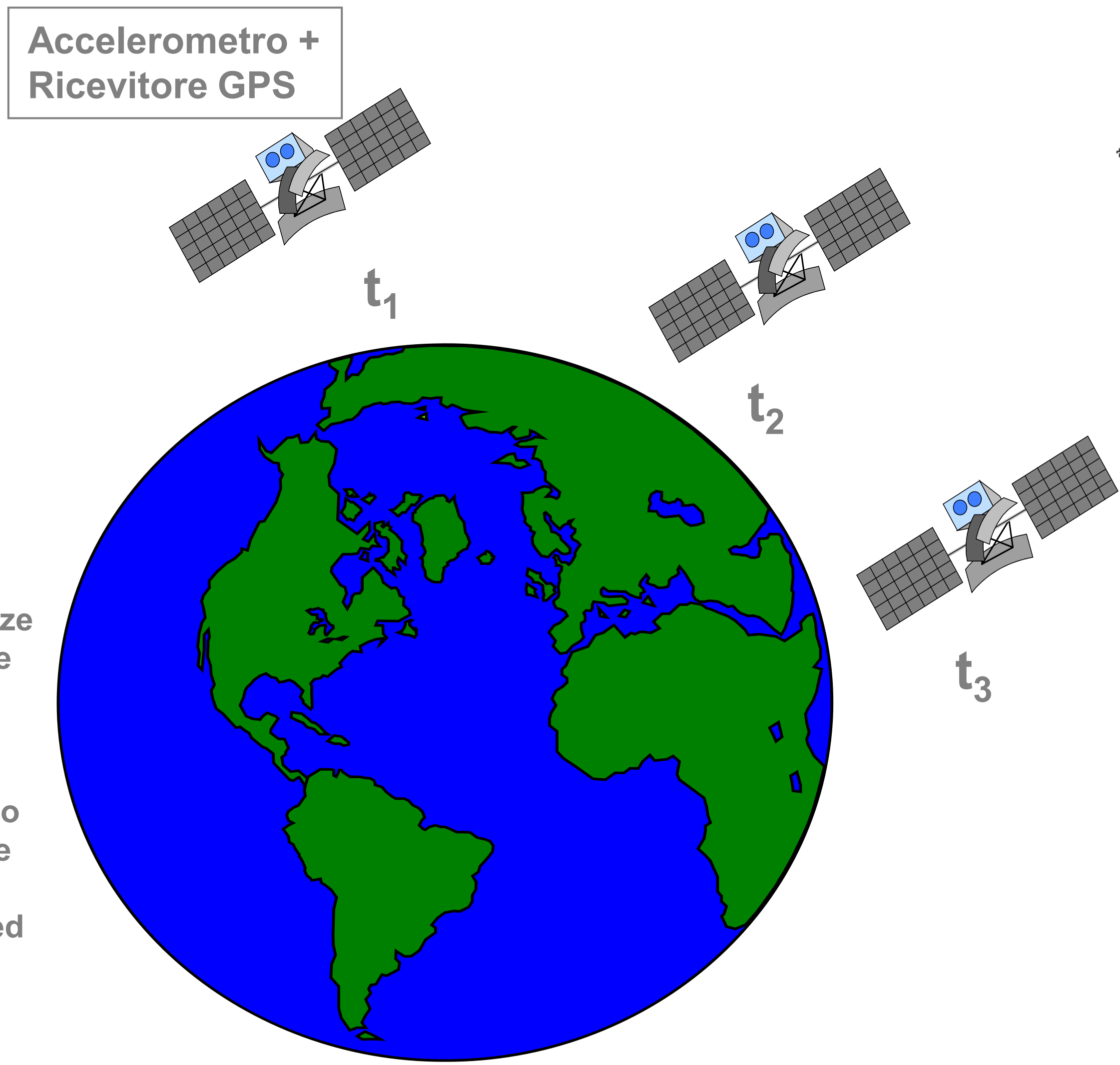
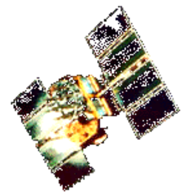
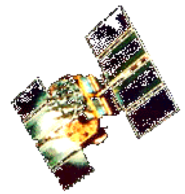


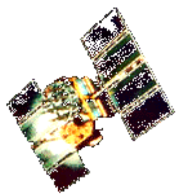


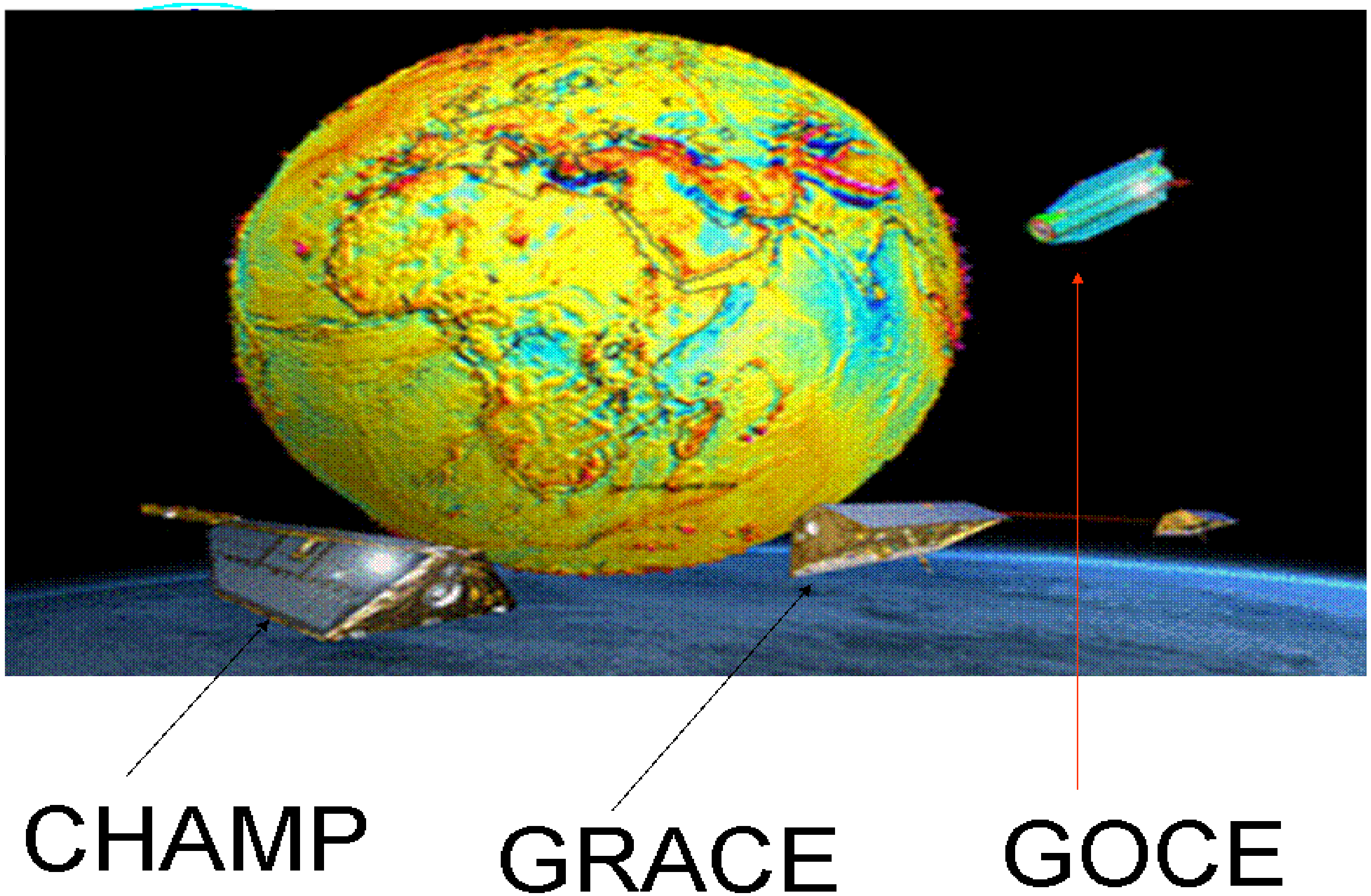
$$A_{grav} = A_{gps} - A_{acc}$$

Accelerazione Totale
data dalle doppie differenze
nel tempo dell'osservabile
GPS;

mentre l'accelerometro
fornisce accelerazioni solo
delle forze superficiali che
agiscono sul satellite
(pressione di radiazione ed
atmosfera)







GGM02 (from GRACE)

~20 times better than EGM96

<1 cmm geoid height to spherical harmonic degree 70

Tapley, B., J. Ries, S. Bettadpur, D. Chambers, M. Cheng, F. Condi, B. Gunter, Z. Kang, P.Nagel, R. Pastor, T. Pekker, S.Poole, F. Wang, "GGM02 - An improved Earth gravity field model from GRACE", Journal of Geodesy (2005), DOI 10.1007/s00190-005-0480-z

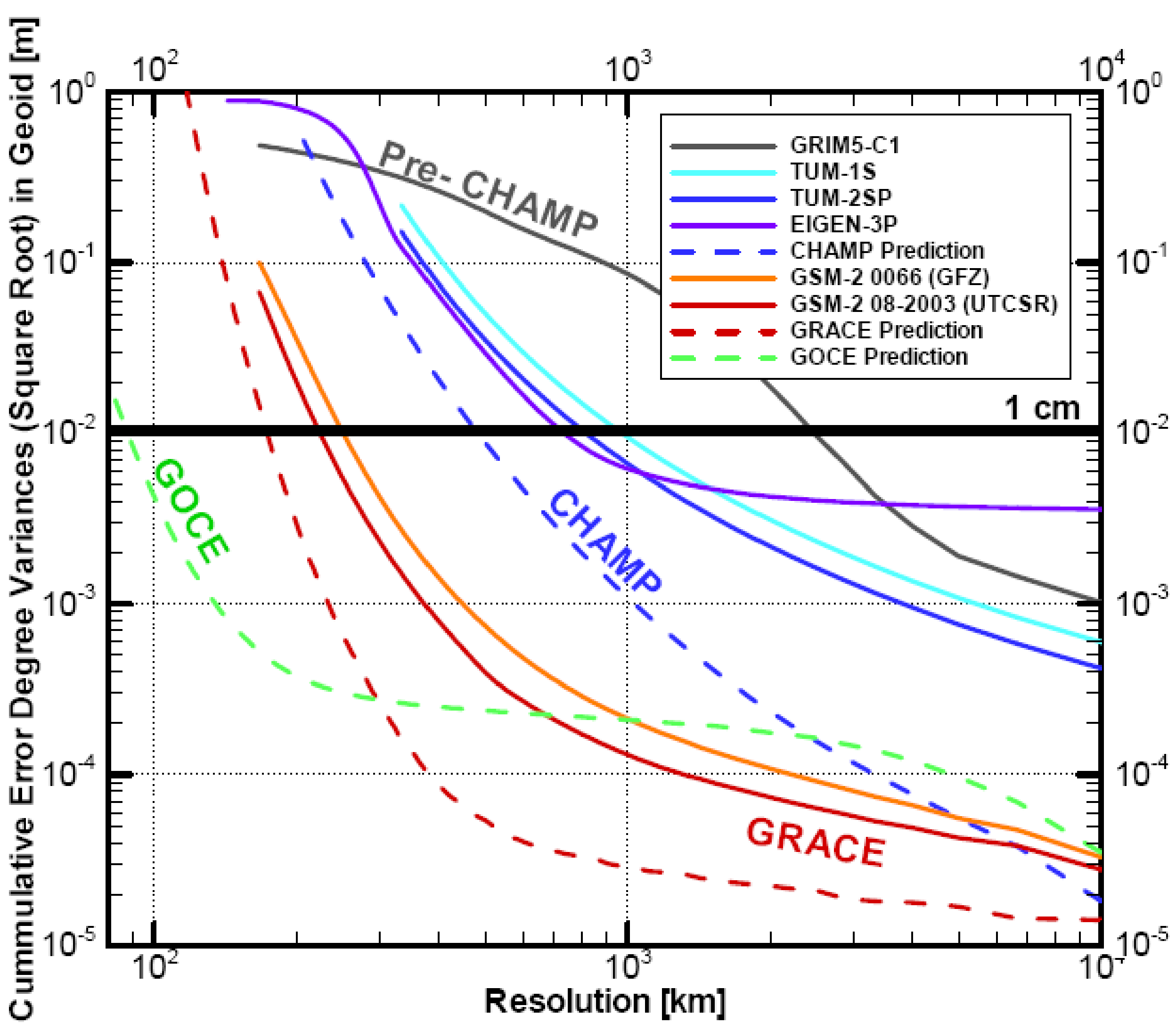


Figure 4: Cummulative Error Degree Variances (Square Root) in terms of Geoid Heights

GOCE

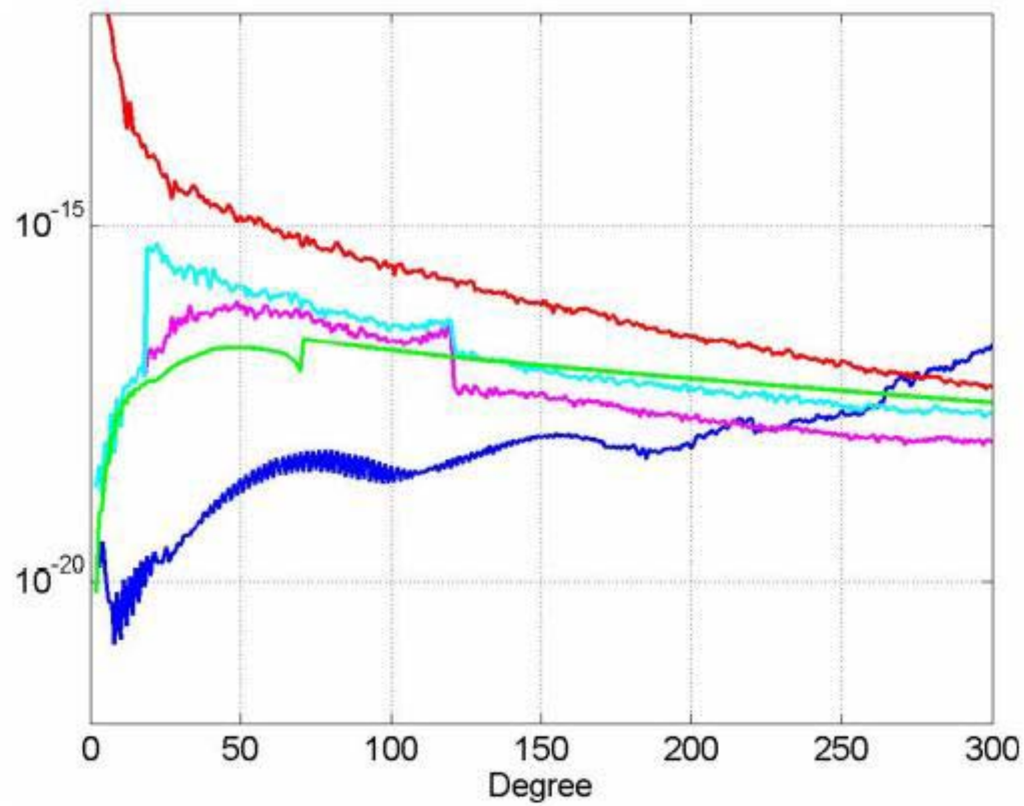
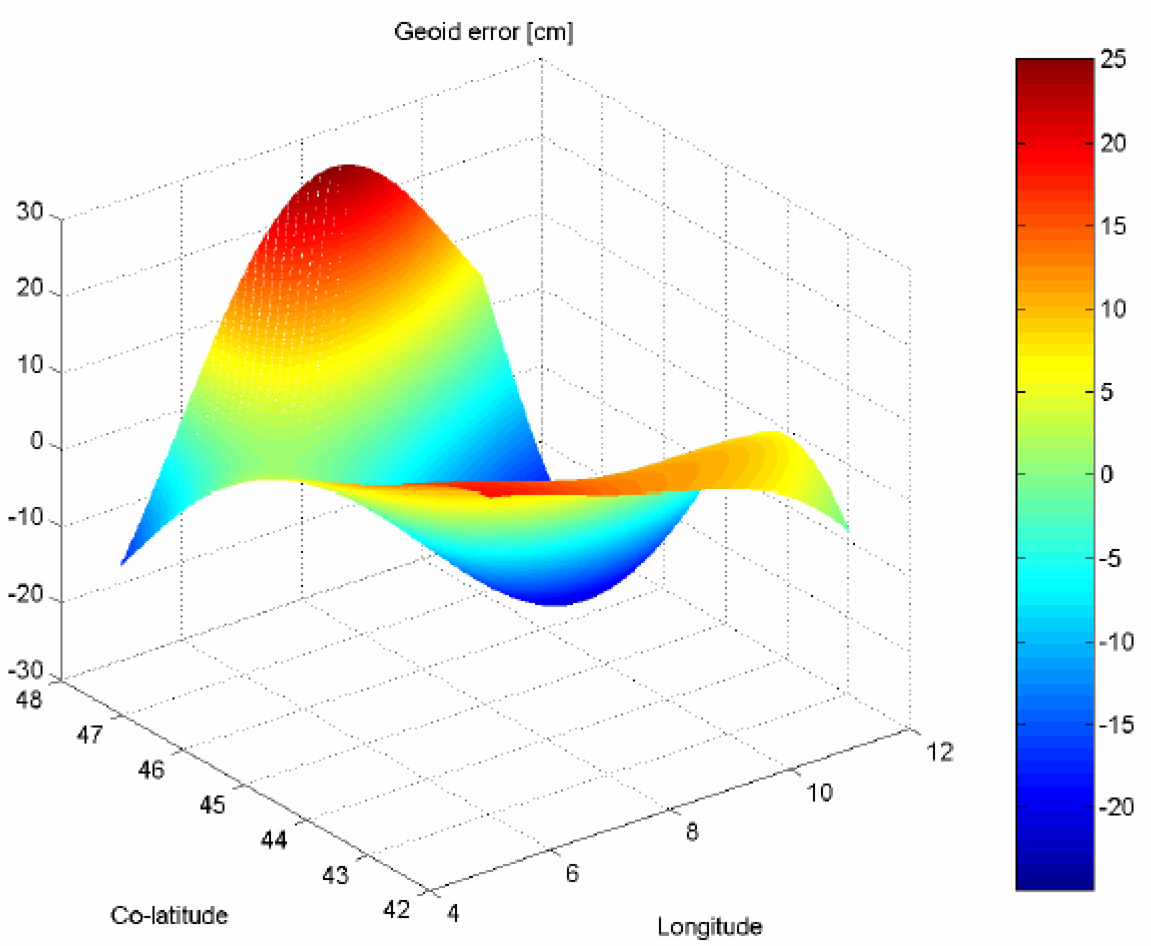


Figure 3: Error degree variances: blue = GOCE simulation error, green = EGM96 nominal error red = EGM96 signal, purple=differences between
EGM96 and EIGEN_cg03c, cyan=differences between
GPM98 and EIGEN_cg03c
This



Geoid Error in North-West part of Italy (Piemonte) using GOCE data

GALILEO

- 30 satellites, The Orbits have a period of 14.35 hours
- 3 MEO orbits, h= 23616 km and I=56°

inclinazione rispetto al piano equatoriale di 56 gradi

- The lifetime of the satellites will be 12 ys at least, Power 1.6 kw, mass di 680 kg and dimensions: 2.7m-1.2m-1.1m

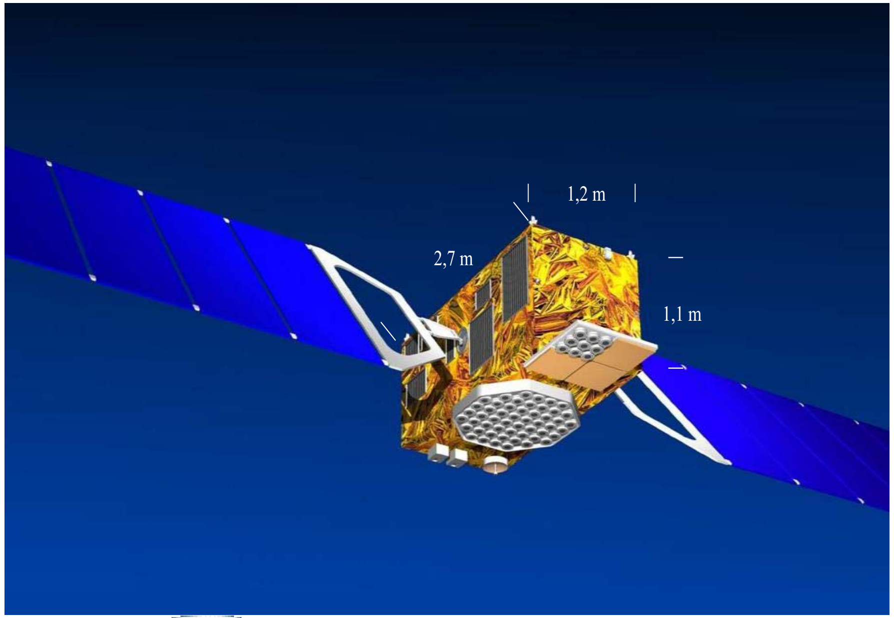
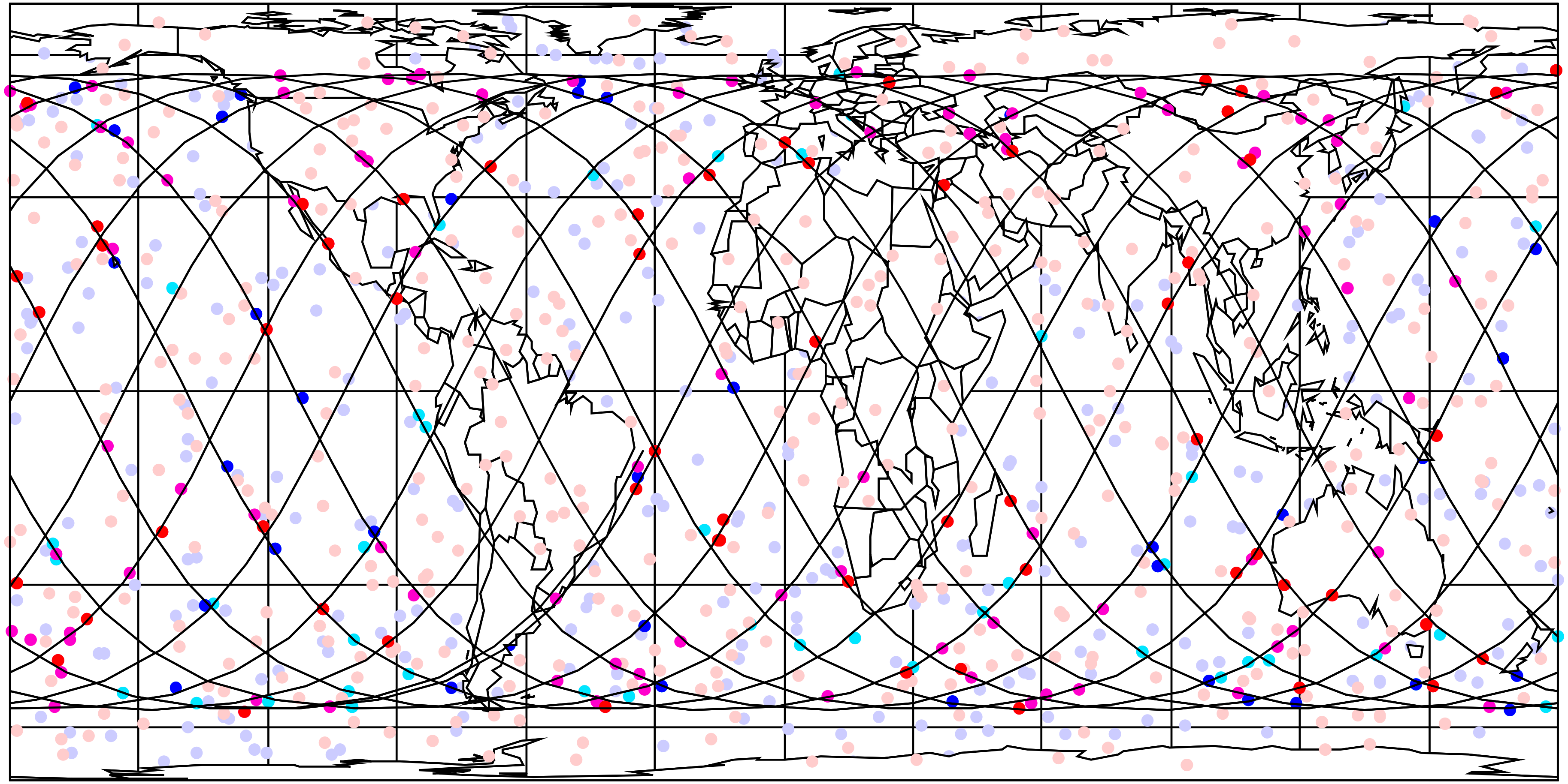


Table of Radio Occultion Events without and with GALILEO

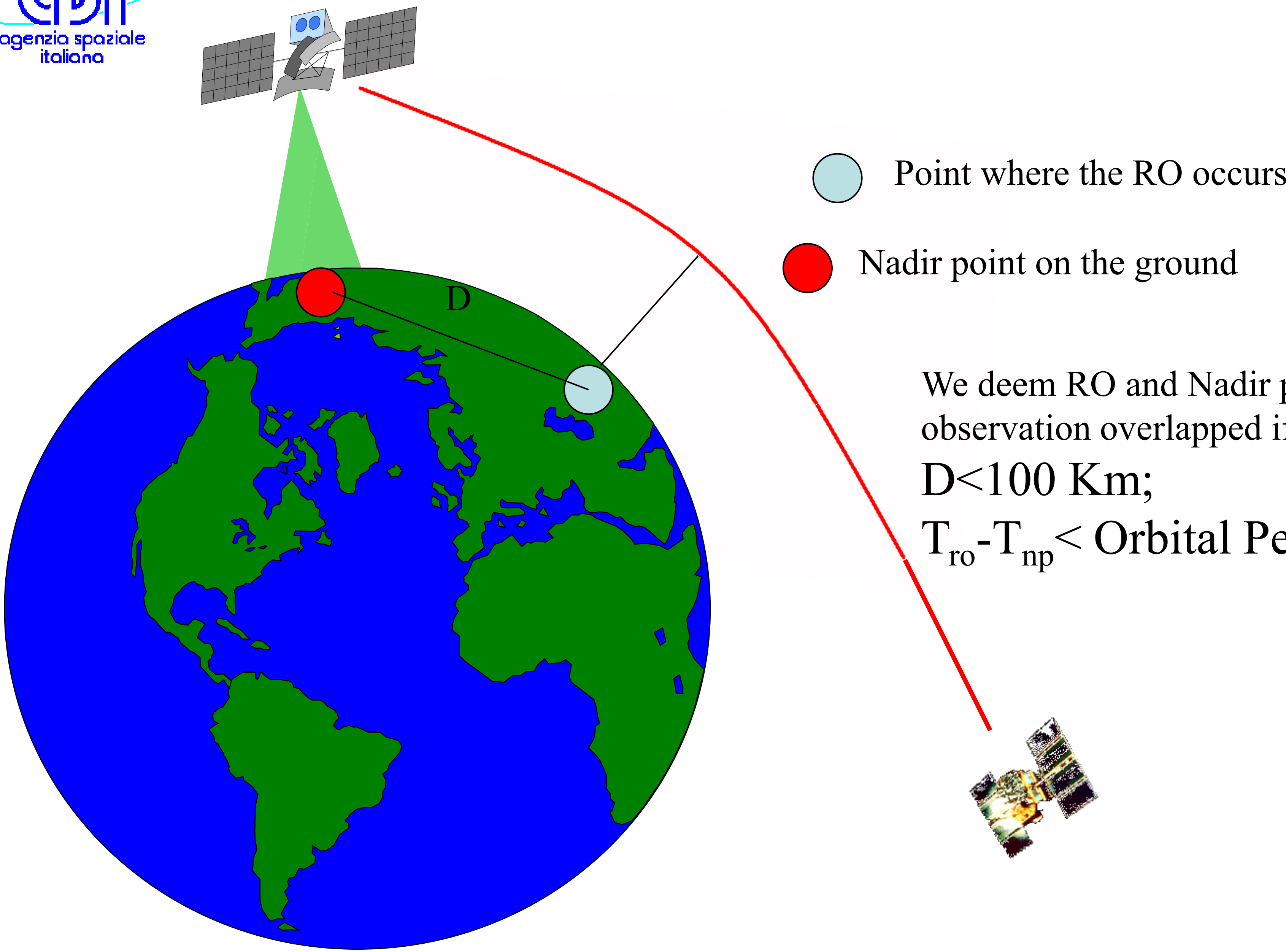
Height: 800 km	Tot. Nr Occultation/Day			Nr. Occ./Day far <100 km from PFS Measurement			Nr. Occ./Day <100 km and Δt < Torb		
Inclination (°)	GPS	GAL	GPS + GAL	GPS	GAL	GPS + GAL	GPS	GAL	GPS + GAL
5°	373	435	808	225	264	489	43	36	79
25°	418	479	897	163	165	328	41	35	76
55°	424	484	908	110	131	241	35	51	86
75°	440	498	938	110	112	222	33	34	67
98°.6	478	553	1031	125	152	277	27	44	71
125°	494	556	1050	126	163	289	44	59	103



CLimatology

- Global
- All Weather
- Relevant (refractivity, tropopause etc.)
- ***Self Calibrating (could be used for "in flight" calibration of other sensors but…)***

agenzia spaziale italiana



We deem RO and Nadir pointing observation overlapped if:

$D<100$ Km;

$T_{ro}-T_{np}<$ Orbital Period

GPS+GALILEO Radio Occultation Table

Height: 800 km	Tot. Nr Occultation/Day			Nr. Occ./Day far <100 km from PFS Measurement			Nr. Occ./Day <100 km and Δt < Torb		
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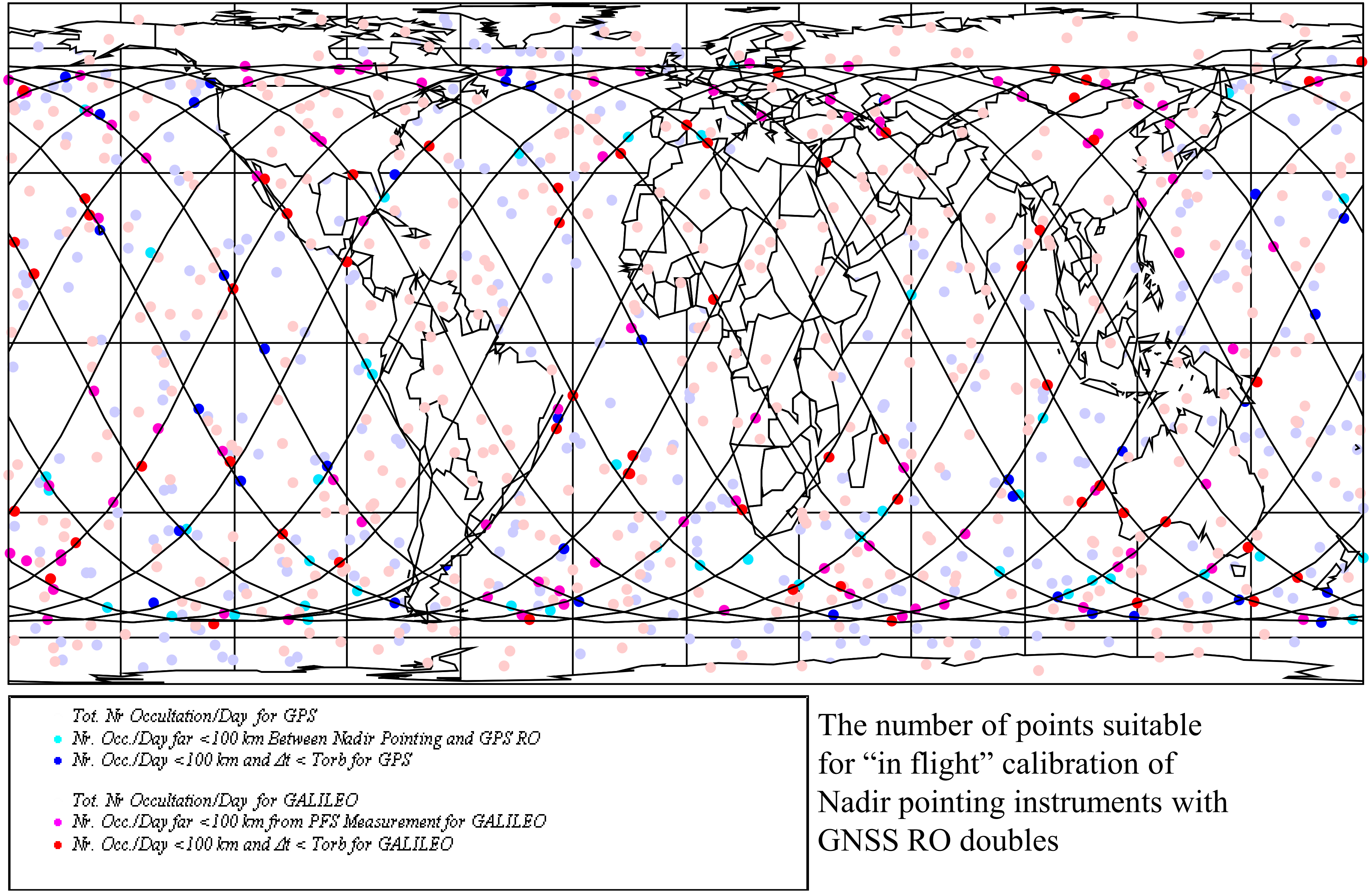

The number of points suitable for “in flight” calibration of Nadir pointing instruments with GNSS RO doubles

CLIMATE

- Refractivity can be estimated with RO with a relative accuracy of 10^{-3}. Suitable for Climate investigations
- Refractivity as a fingerprint to investigate the Climate
- Fingerprint could be formed by combining projections for about 20 different levels below 25 Km, for some 30 different locations over the globe, and for four seasons
- (Goody et al. (1998).

Tables of the number of Radio Occultation with and without GALILEO

Height: 800 km	Tot. Nr Occultation/Day			Nr. Occ./Day far <100 km from PFS Measurement			Nr. Occ./Day <100 km and Δt < Torb		
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