Ionospheric activity & Wide Area RTK: Fundamentals, performance and potential applications

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https://scholar.google.es/citations?user=Tm-DcsMAAAAJ&hl=en

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Ionospheric activity & WARTK: Fundamentals, performance and potential applications

Outline

1. Introduction to Wide Area RTK.
2. Why are precise ionospheric corrections needed in precise navigation.
3. Ionospheric effects on GNSS signals.
4. Ionospheric perturbations.
5. Summary of MSTIDs parameters.
6. Real-time MSTID model (DMTID).
7. Experiment on MSTID modelling and results.
8. WARTK Applications.
9. Conclusions.

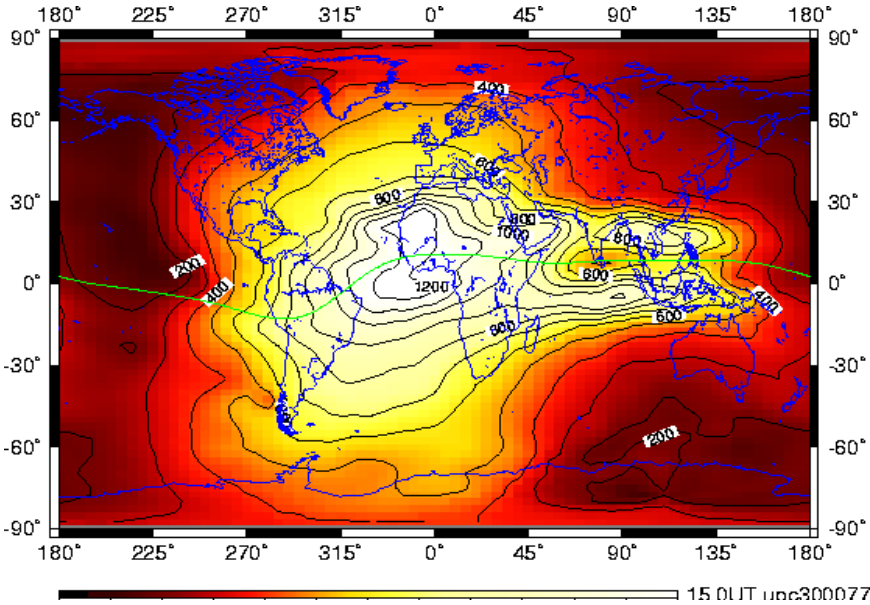
1. Introduction to Wide Area RTK

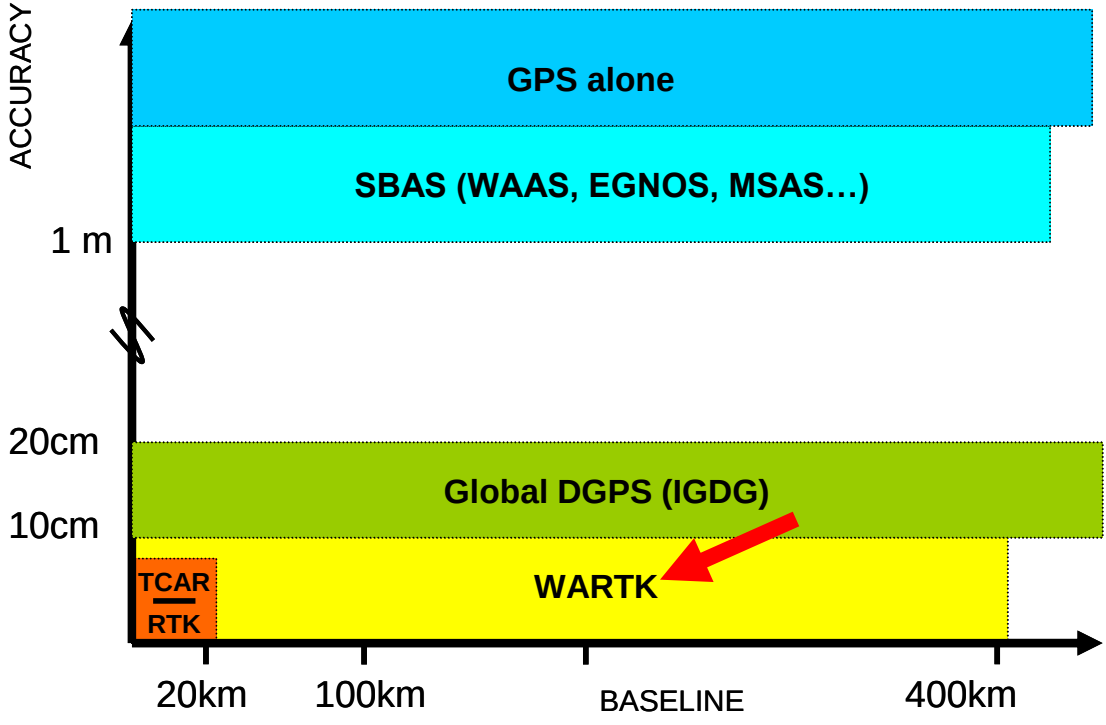
WARTK: subdecimeter-error navigation at hundreds km away

- **The differential ionospheric refraction typically limits the real-time ambiguity fixing (and the corresponding navigation with sub-decimeter errors) to baselines of few tens of km in different approaches in both two and three-frequency systems (such as RTK and TCAR).**
- **Wide Area RTK (WARTK) overcome this problem by incorporating an accurate real-time ionospheric model: (1) in two-frequency systems (GPS: WARTK), and (2) in three-frequency systems (Galileo and Modernized GPS: WARTK-3, which allows the extension of the Local Area Galileo services to continental scales).**
- **Both approaches (WARTK and WARTK-3) were presented in different meetings and papers, and demonstrated in many experiments including a real-time iono. prototype.**

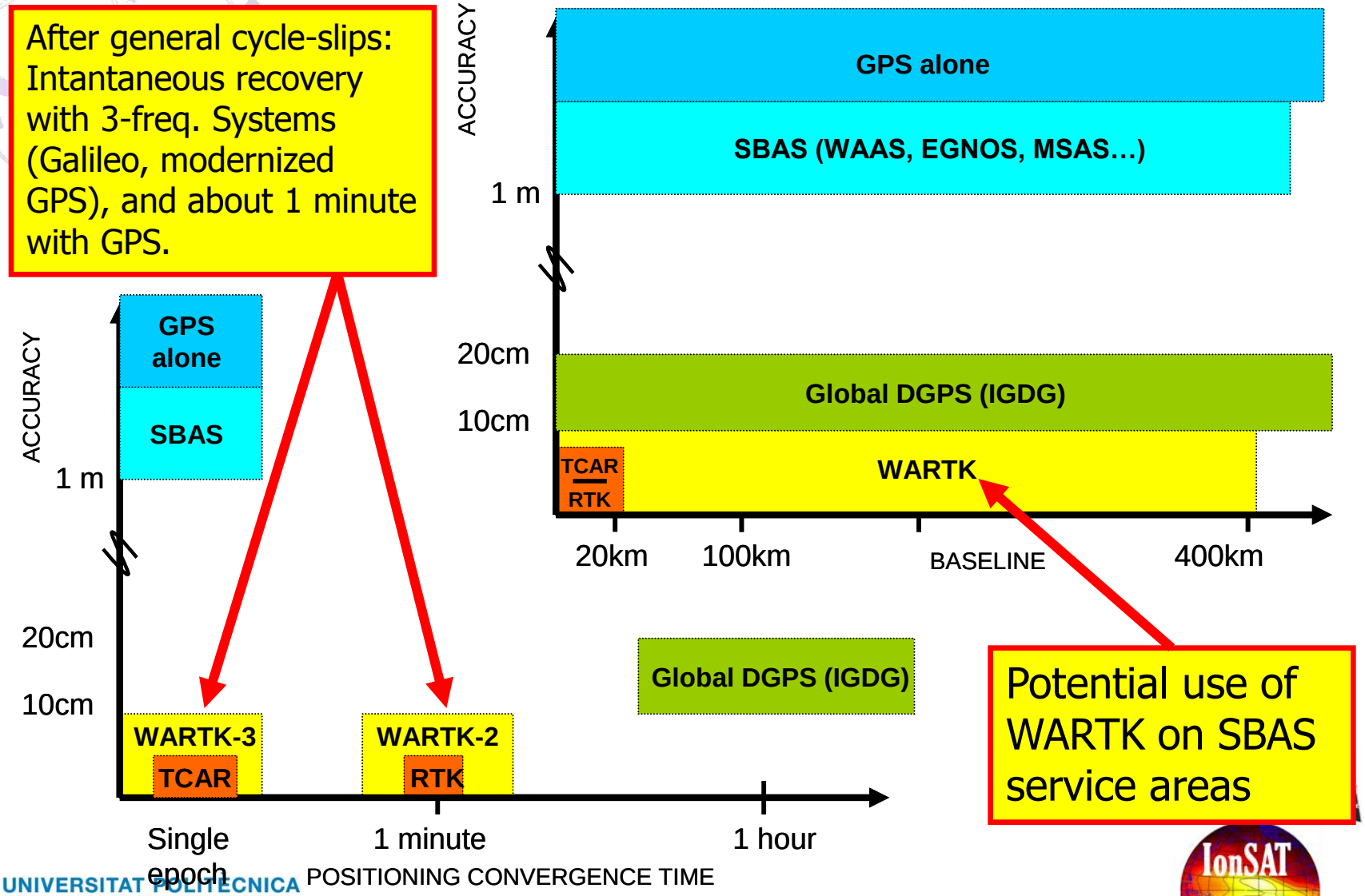
UPC Global Ionospheric Map: 077 2000, 15UT

Units: tenths of TECU



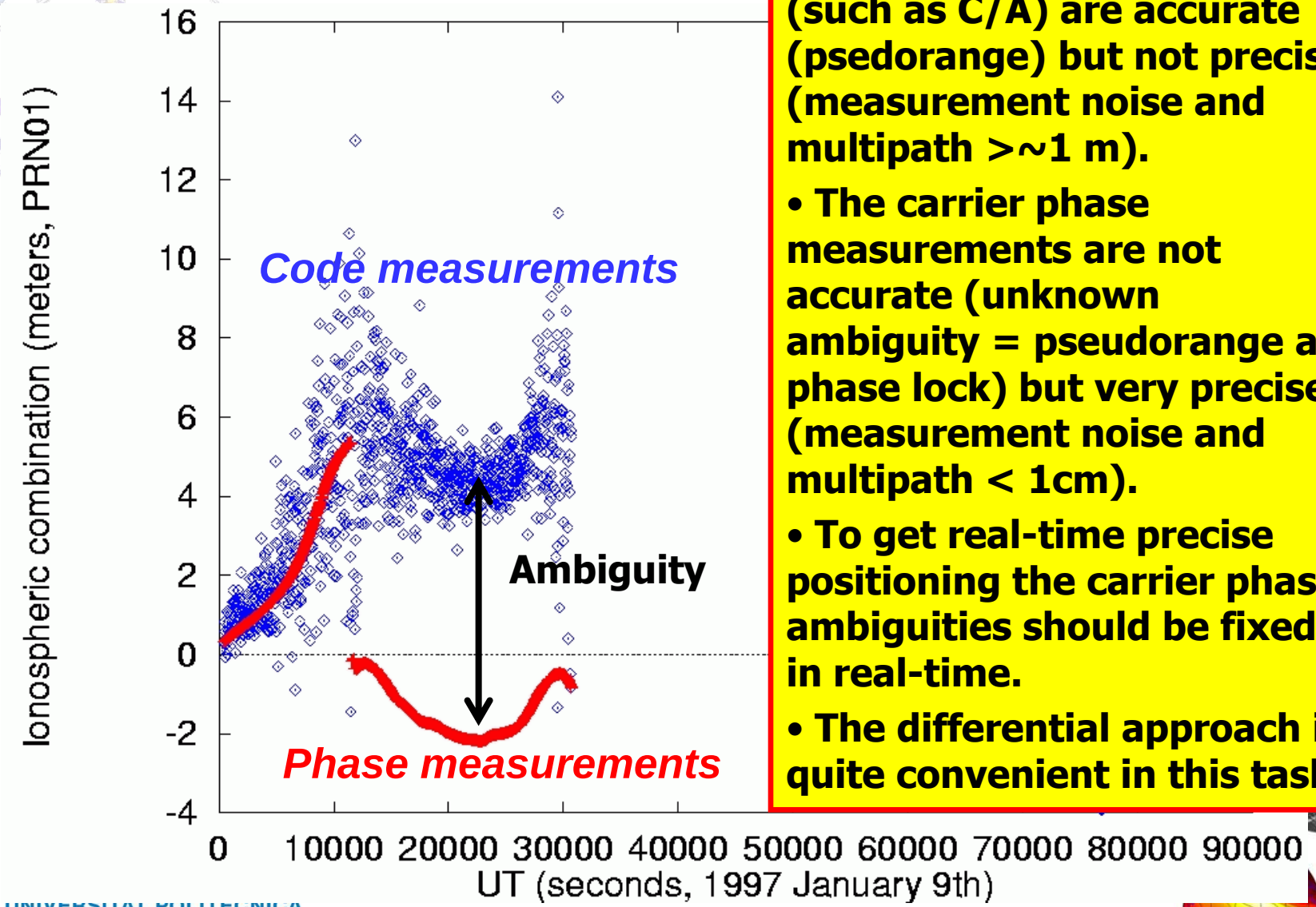


WARTK: subdecimeter-error navigation at hundreds km away, and in single-epoch with 3-frequency systems



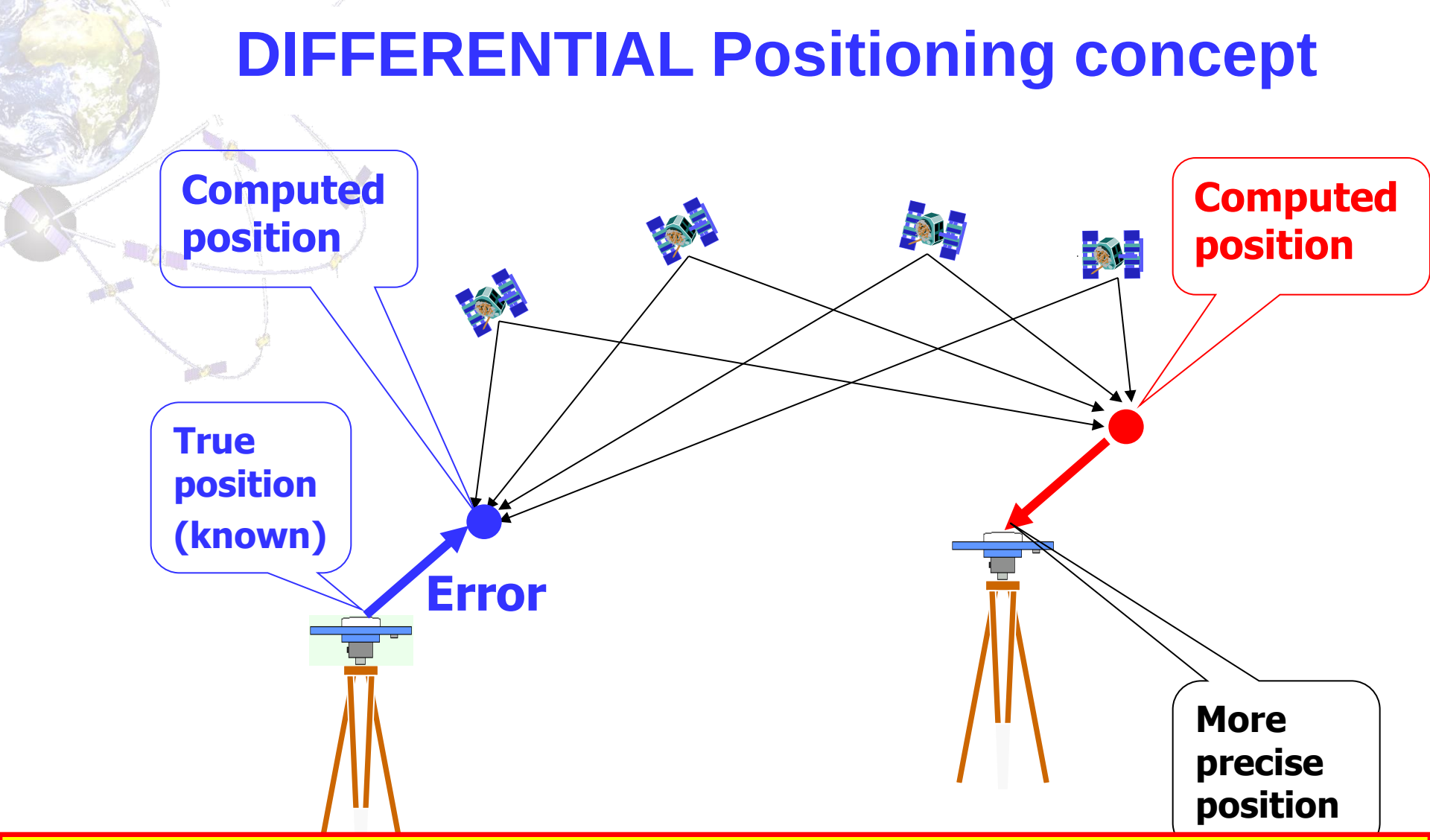
2. Why are precise ionospheric corrections needed in accurate navigation

Carrier phase ambiguity fixing: key for precise navigation



- **The code measurements (such as C/A) are accurate (psedorange) but not precise (measurement noise and multipath >~1 m).**
- **The carrier phase measurements are not accurate (unknown ambiguity = pseudorange at phase lock) but very precise (measurement noise and multipath < 1cm).**
- **To get real-time precise positioning the carrier phase ambiguities should be fixed in real-time.**
- **The differential approach is quite convenient in this task.**

DIFFERENTIAL Positioning concept



- In baselines shorter than few tens of km, similar errors are expected in differential approach, cancelling-out (exactly for satellite clocks, approximately for GPS orbital errors and for ionospheric error). –
- The extension to longer baselines is a problem specially due to the ionospheric error (quite difficult to predict it accurately).

Role of differential iono. corrections in precise navigation

In words

- **At short distances (<10-20 km) the differential (double-differenced) measurement of iono. (geometry-free) combination of carrier phases gives a very good estimation for a (non-integer) combination of L1 and L2 integer ambiguities. But the differential ionospheric error impedes this for larger distances.**
- **And a second linearly independent combination of L1 and L2 integer ambiguities (widelane) can be simultaneously estimated, from filtered pseudoranges and/or from a good knowledge of the user position.**
- **From both ionospheric and widelane ambiguities the L1 ambiguity (for example) can be estimated and fixed (assuming right widelane fixing) if the error in the ionospheric ambiguity is lower than 2.7 cm (i.e. 0.25 TECU and ~4 cm in L1).**

In equations

$$\nabla \Delta B_I = \nabla \Delta L_I - \nabla \Delta STEC_{ext}$$

$$\nabla \Delta N_w = \begin{cases} \frac{1}{\lambda_w} \nabla \Delta (L_w - P_w) \\ or \\ \frac{1}{\lambda_w} \nabla \Delta \left(B_c + \frac{\lambda_w}{\lambda_1 + \lambda_2} \cdot B_I \right) \end{cases}$$

$$\nabla \Delta N_1 = \frac{-1}{\lambda_2 - \lambda_1} \nabla \Delta B_I + \frac{\lambda_2}{\lambda_2 - \lambda_1} \nabla \Delta N_w$$

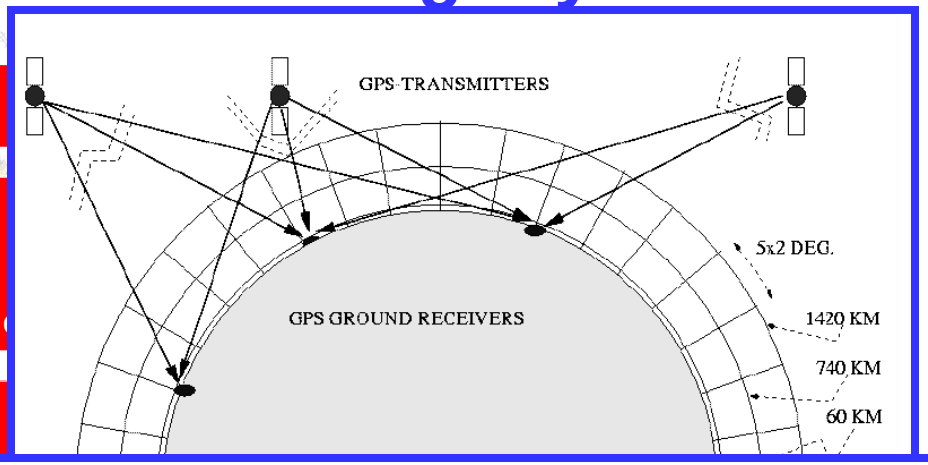
$$\frac{1}{\lambda_2 - \lambda_1} \varepsilon [\nabla \Delta B_I] < 0.5 \, cycles \quad \Rightarrow$$

$$\Rightarrow \varepsilon [\nabla \Delta B_I] \approx \varepsilon [\nabla \Delta STEC_{ext}] < \frac{\lambda_2 - \lambda_1}{2} = 2.7 \, cm$$

- **And this is the challenge solved by Wide Area RTK : to provide typically such centimeter-error level accuracy for rover/reference-site baselines up to several hundreds of kilometers.**
- **This is done by modelling the differential geodetic and ionospheric models, including: (1) a more accurate tomographic description of the electron content, and (2) a simple ionospheric perturbation model for mitigating the Medium Scale Travelling Ionospheric Disturbances.**

The Differential Ionospheric refraction also affect Three Carrier Ambiguity Resolution (TCAR)

1.
lan
ps



WARTK Iono.
(from ref.sites)

$$L_I = STEC + B_I = \int_{REC}^{SAT} N_e \, dl + B_I = \sum_i \sum_j \sum_k (N_e)_{i,j,k} \Delta s_{i,j,k} + B_I$$

3. The L1 phase ambiguity is derived from the difference between L1 and the unambiguous wide lane obtained previously

$$error \quad (\nabla \Delta I) < 0.26 \; TECU$$

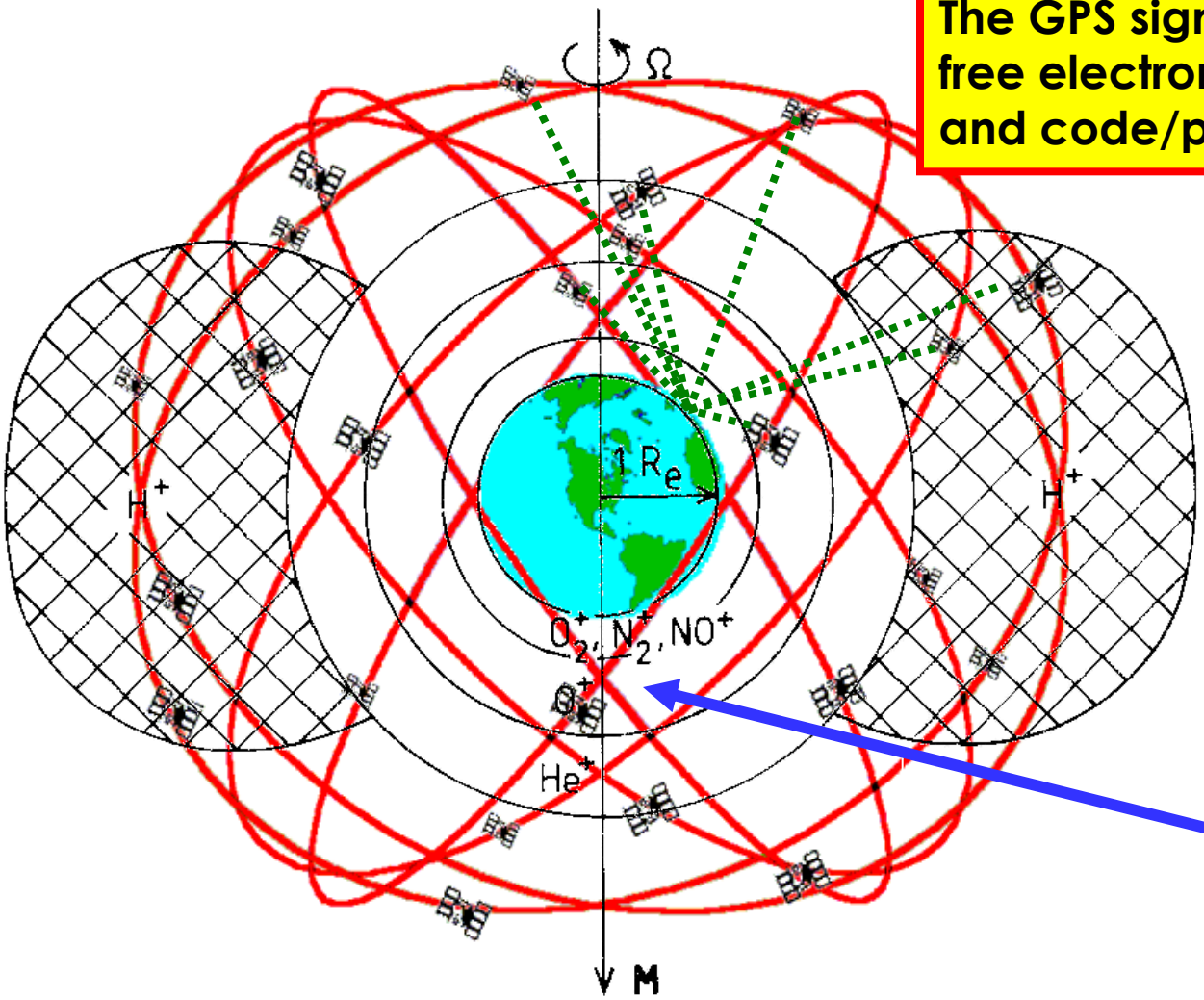
-1.95 cycles N1/TECU

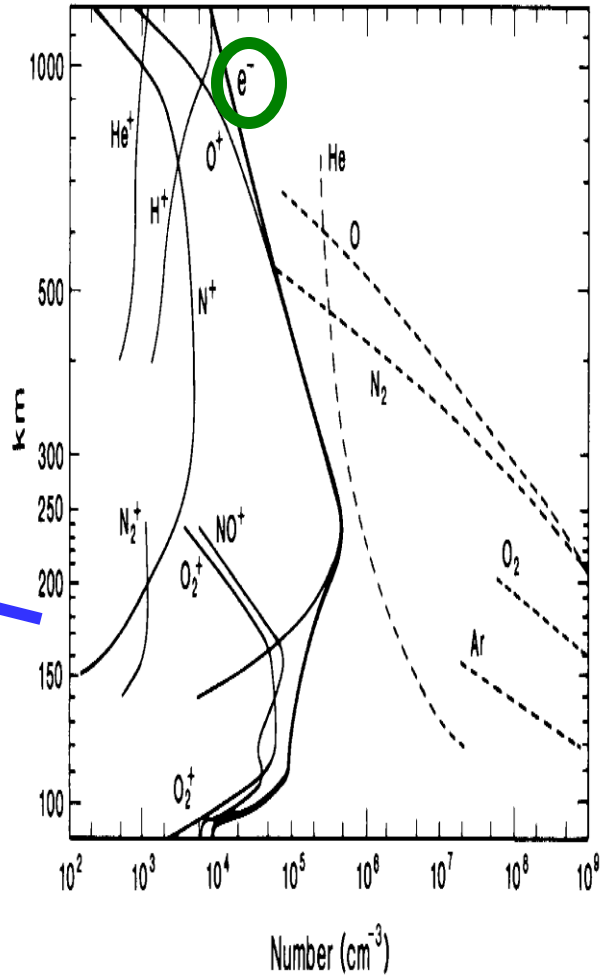
$$\nabla \Delta \hat{N}_1 = \frac{1}{\lambda_1} \nabla \Delta (L_1 - L_w + \lambda_w N_w) = \nabla \Delta N_1 - \frac{1}{\lambda_1} \nabla \Delta (\varepsilon_w + m_w - m_1) + \frac{1}{\lambda_1} (\alpha_1 - \alpha_w) \nabla \Delta I$$

3. Ionospheric effects on GNSS signals

GPS and the Ionosphere

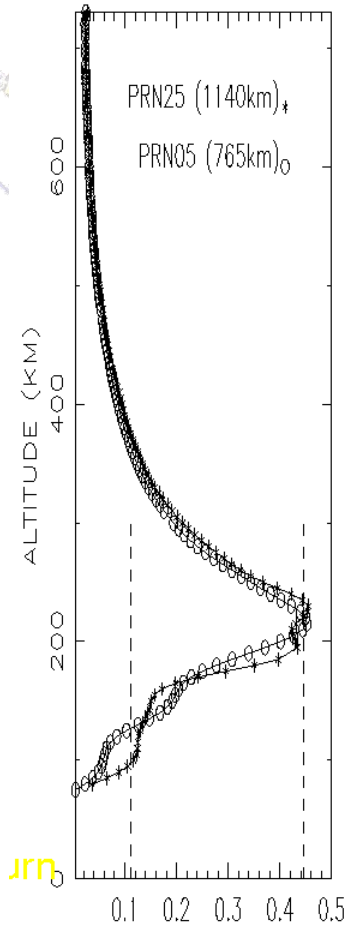
The GPS signals are affected by the free electrons: carrier phase advance and code/pseudorange delays.

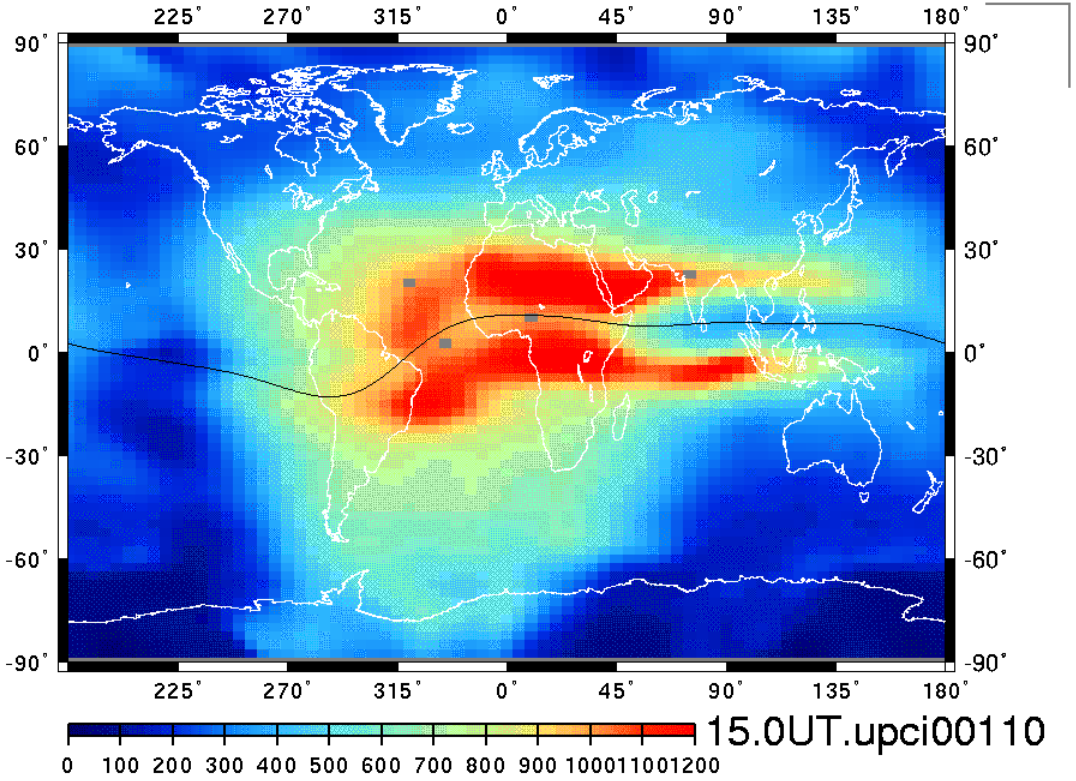




The UV (and X) Solar radiation ionizes the region above 50-100 km: Ionosphere (to 1000 km) and Protonosphere/Plasmasphere (above 1000 km).

Ionospheric delay at a glance





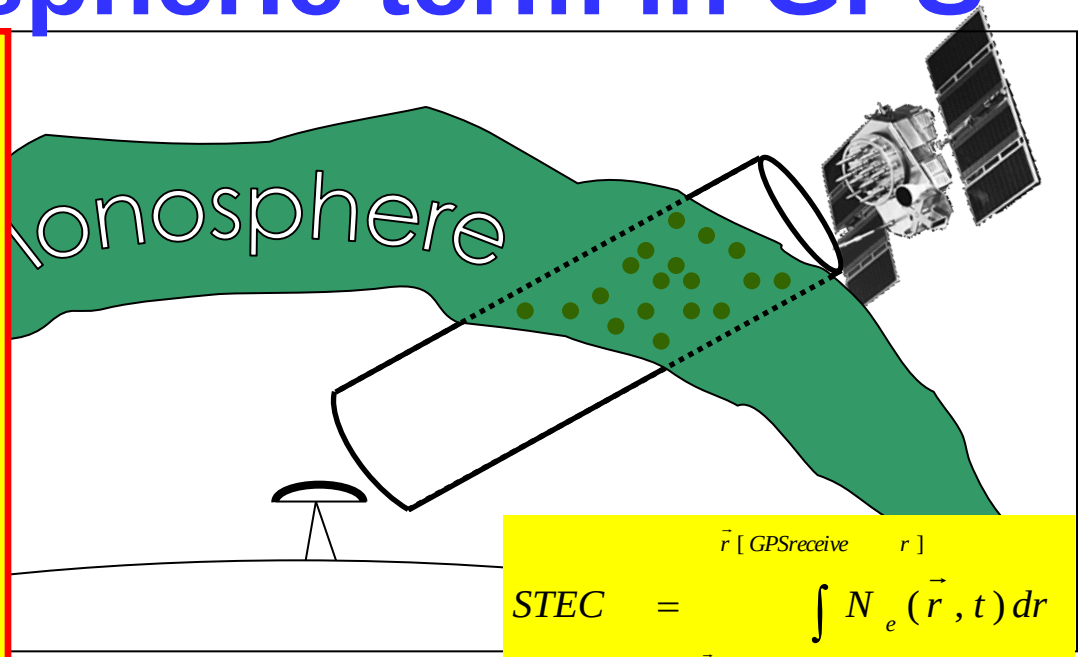
$$\delta R_{IONOSPHERE}[m] \simeq 0.4 \frac{STEC[TECU]}{f^2[GHz^2]}$$

$$1\,TECU = 10^{16} el./m^2 \simeq 15\,cm \simeq 0.5\,ns \text{ in } L_1$$

Typical noon VTEC ionospheric values ranges at mid latitude from 20 to 80 TECU, depending on the Solar cycle and season (3 to 12m in L1, 0.1 to 2 m in C band) (*) 1 TECU=16 cm at L1

The Ionospheric term in GPS

GPS signal is very sensitive to free electron distribution, which respond to the EM field, oscilating and generating a secondary EM wave which overimposes and change the velocity of the GPS signals (main iono. efect on GPS code and phase).



$$STEC = \int_{\vec{r}\,[GPStransmitter]}^{\vec{r}\,[GPSreceiver]} N_e(\vec{r}, t)\, dr$$

The Slant Total Electron Content (STEC) is defined as the surface electron density along the GPS ray path

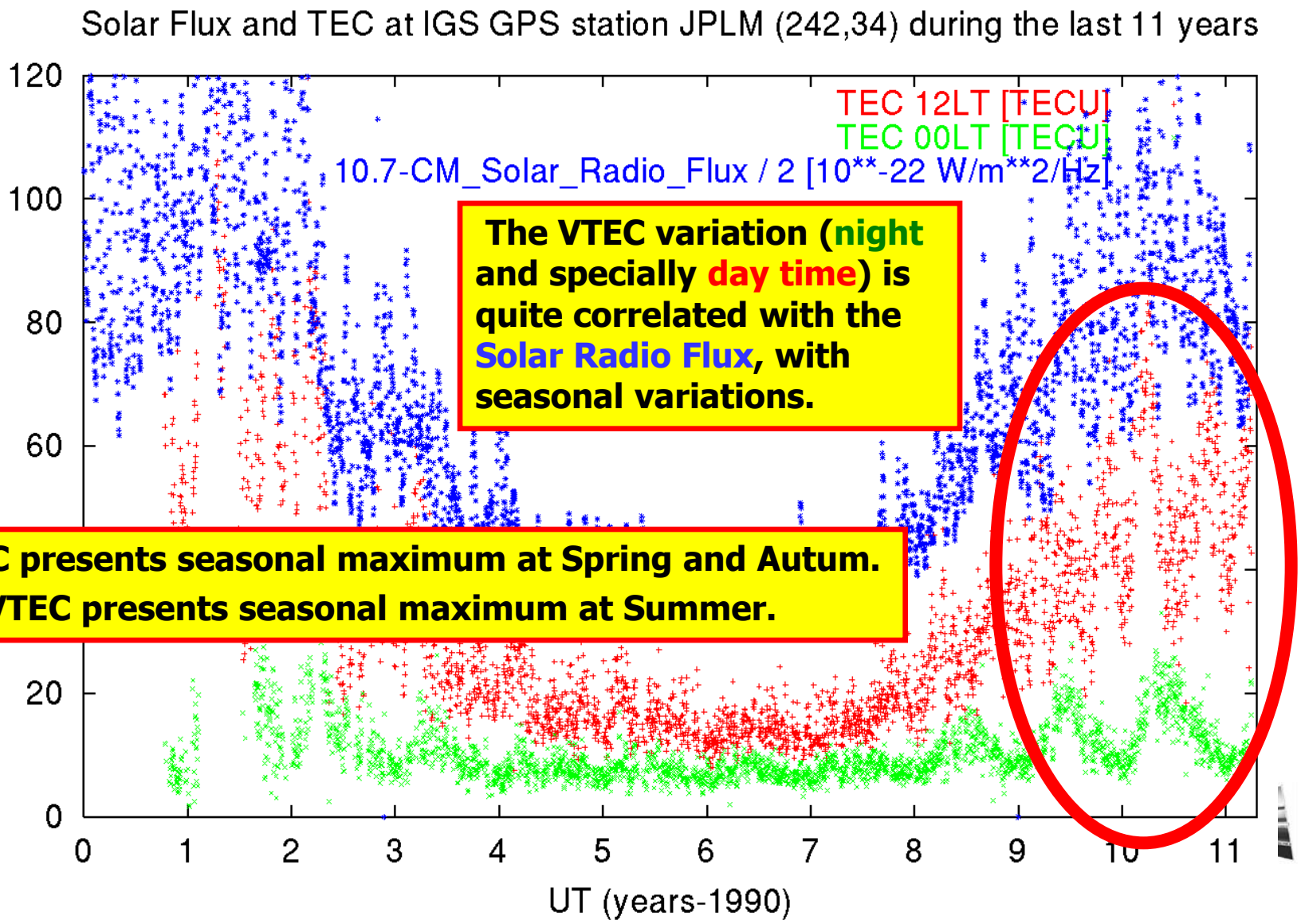
The first order iono. term in GPS signal (99.9% of total) is proportional to Slant Total Electron Content (STEC) and to the inverse of the squared frequency (from Appleton equation, neglecting magnetic field and collisions).

$$\delta I_P \equiv \delta I_{PSEUDORANGE} = 40.3 \frac{STEC}{f^2}$$

$$\delta I_L \equiv \delta I_{CARRIER-PHASE} = -\delta I_P$$

MKS units

VTEC: Modulated by the Solar Cycle

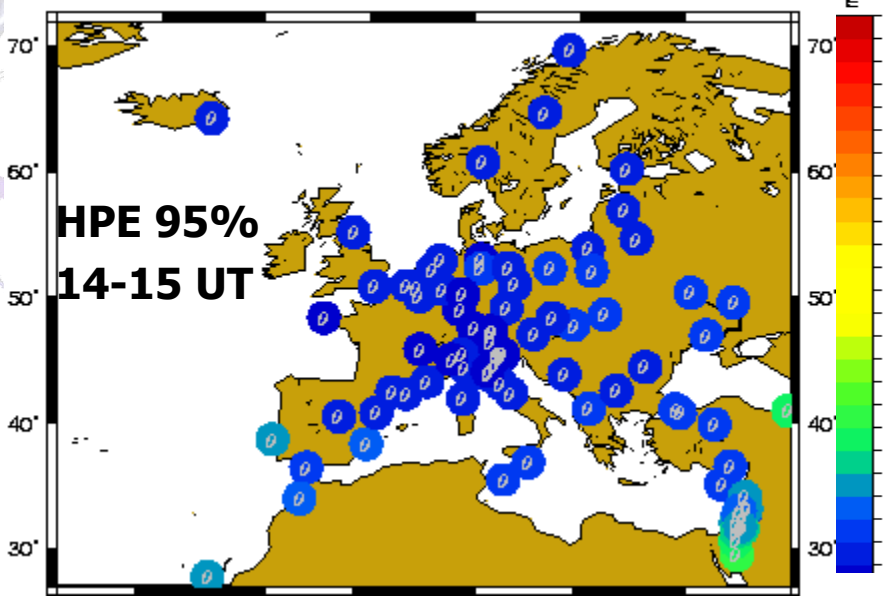


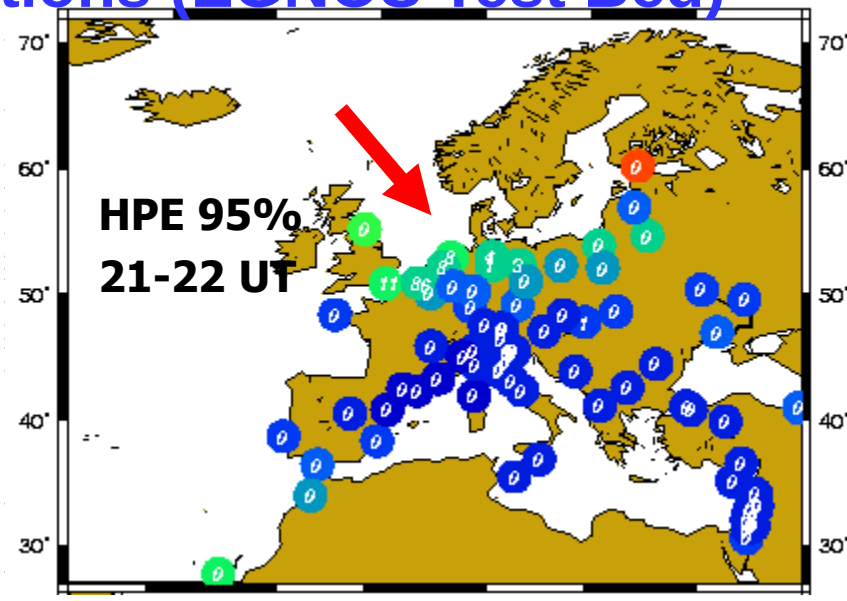
The VTEC variation (night and specially day time) is quite correlated with the Solar Radio Flux, with seasonal variations.

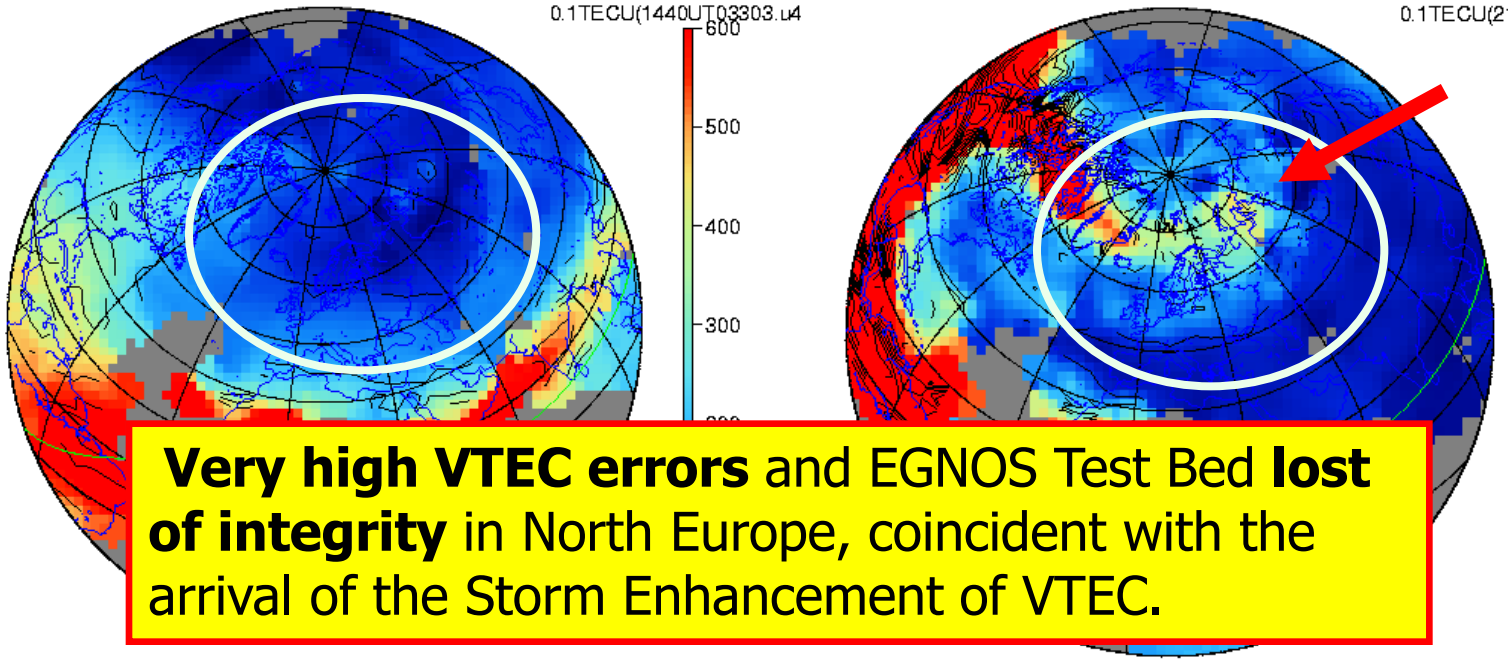
Noon VTEC presents seasonal maximum at Spring and Autum.
Midnight VTEC presents seasonal maximum at Summer.

Effects on single-frequency navigation based on broadcasted iono corrections (EGNOS Test Bed)

Ionospheric Storm during October 30th,2003

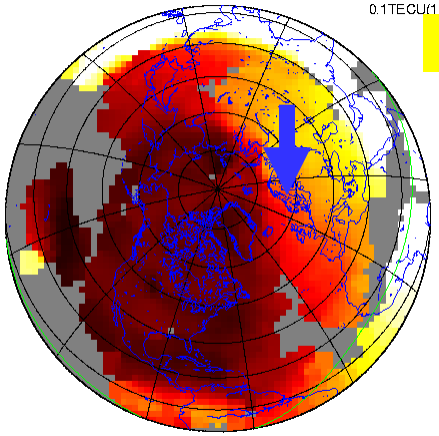




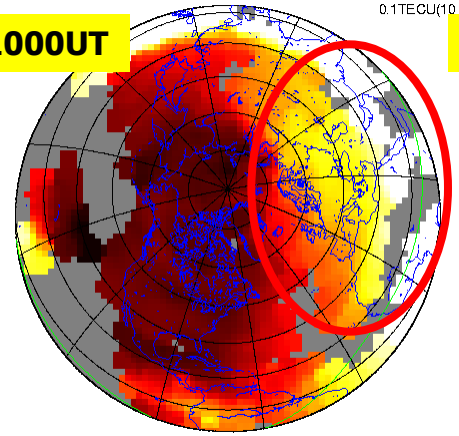


Very high VTEC errors and EGNOS Test Bed **lost of integrity** in North Europe, coincident with the arrival of the Storm Enhancement of VTEC.

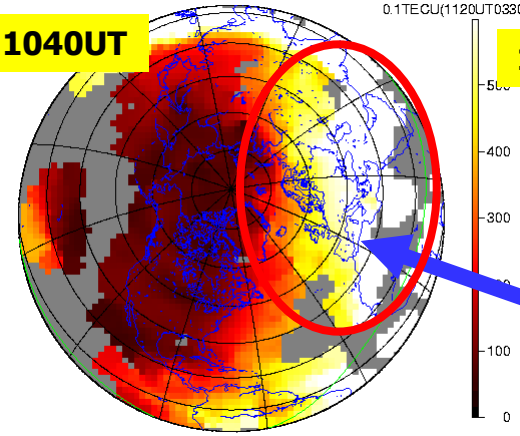
Global and sudden STEC increase in the day hemisphere due to Solar X-flares



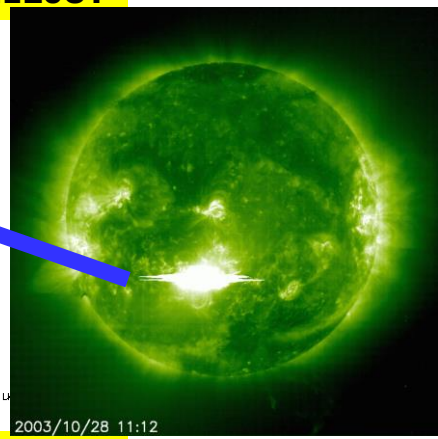
1000UT

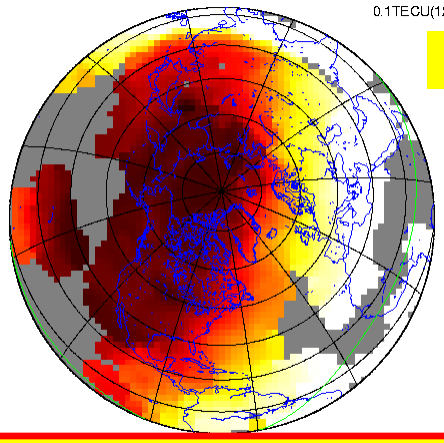


1040UT

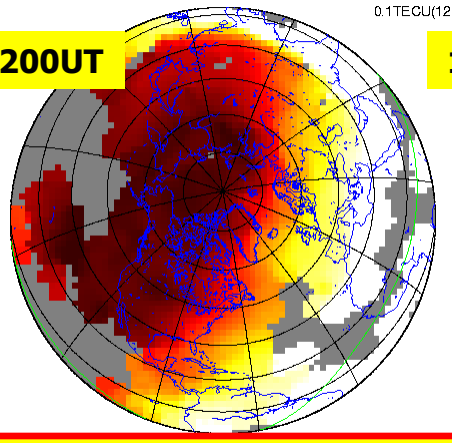


1120UT

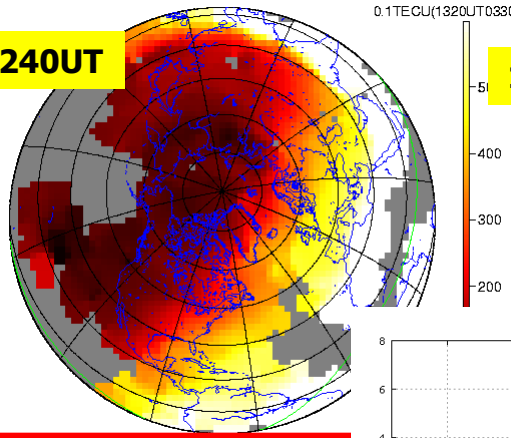




1200UT

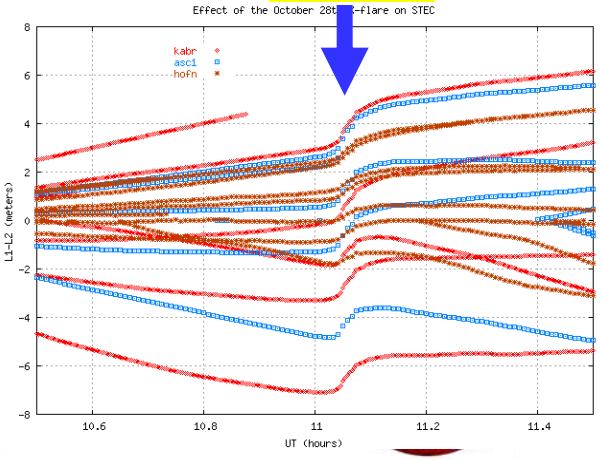


1240UT



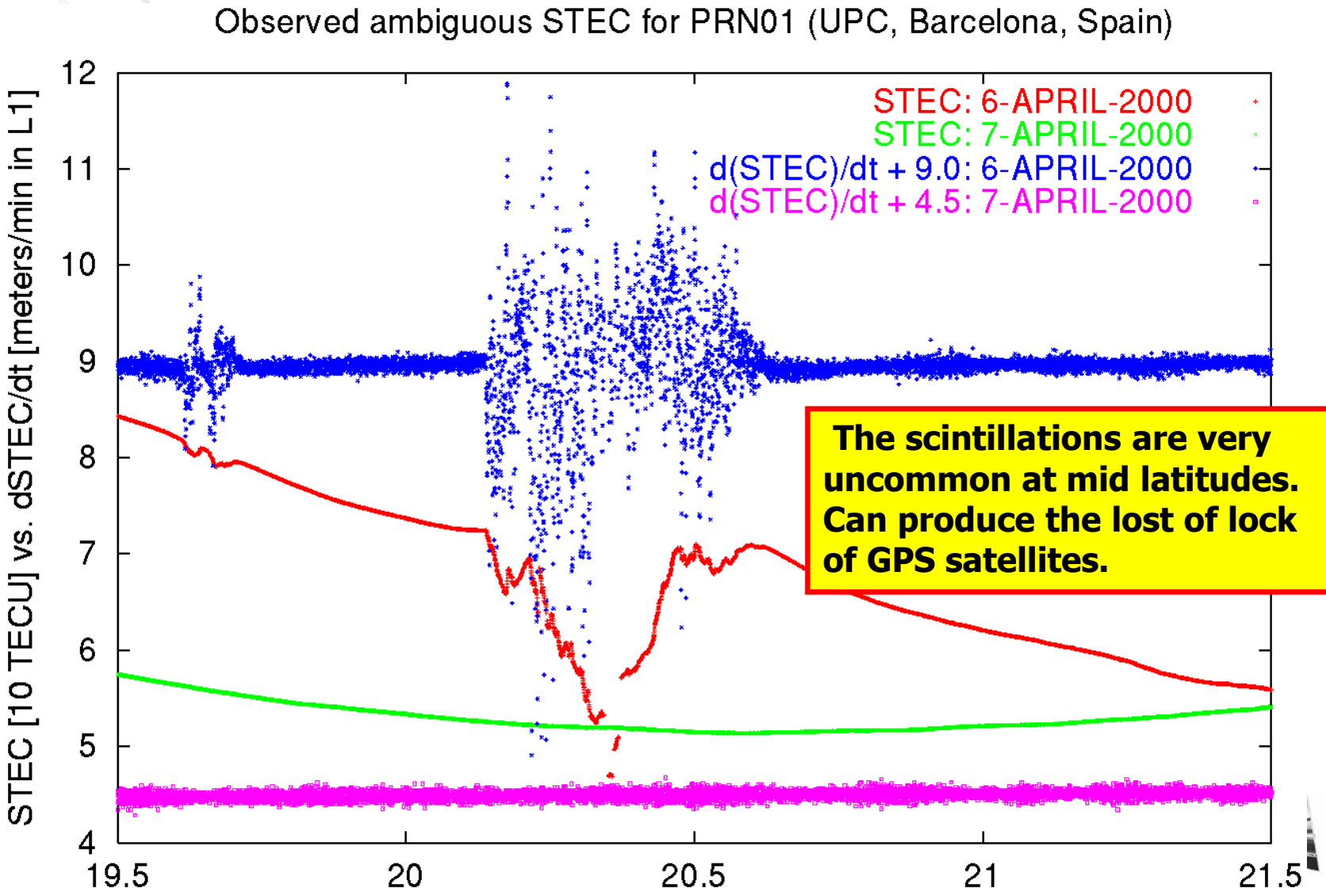
1320UT

1103UT



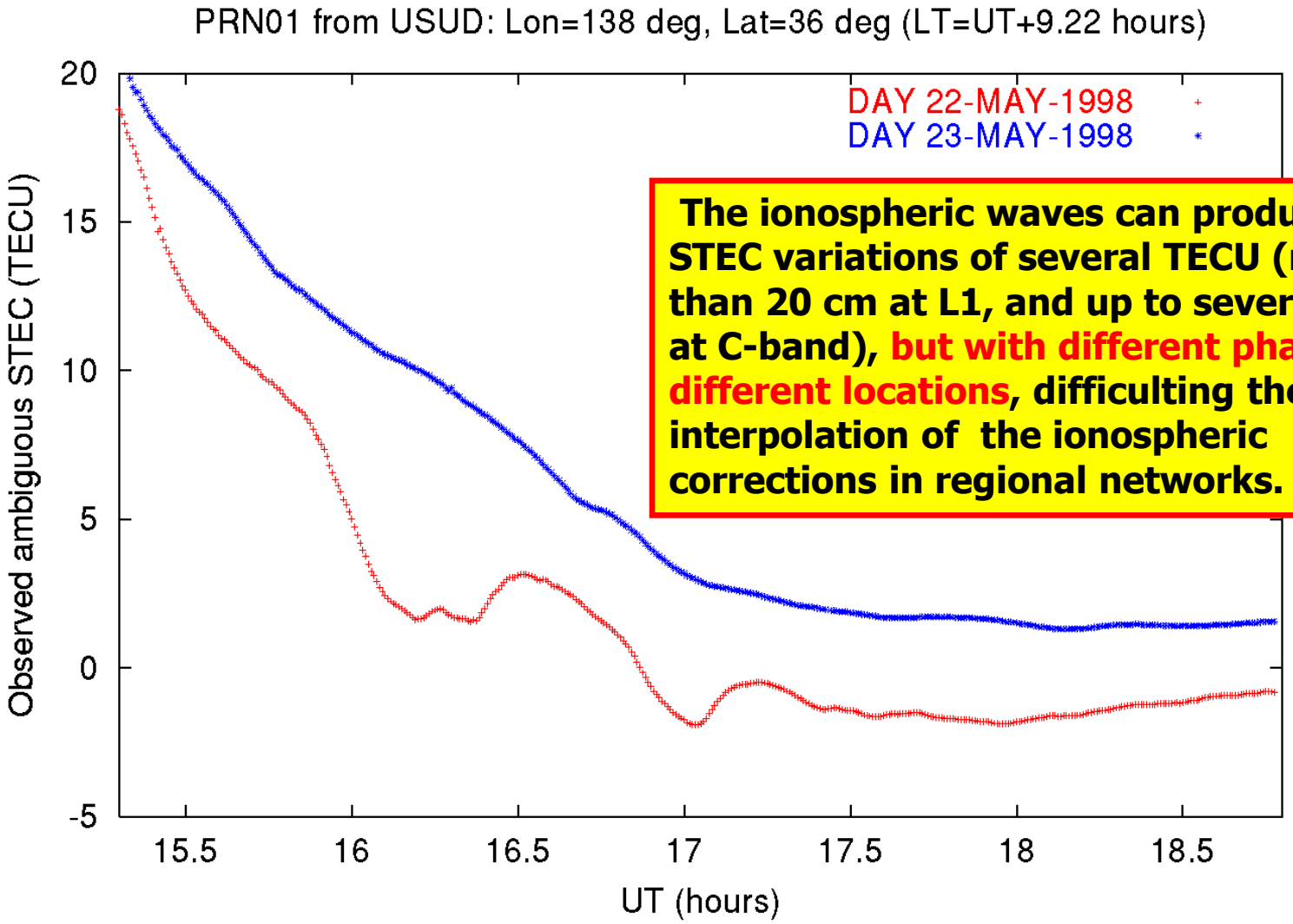
High and sudden STEC variations are experienced in the day hemisphere GPS receivers due to the arrival of the X-rays extra radiation due to Solar X-flares (example: event during 28 Oct. 2003, 11UT approx, preceding the previous mentioned superstorm).

Scintillation: Very rapid VTEC variations



The scintillations are very uncommon at mid latitudes. Can produce the lost of lock of GPS satellites.

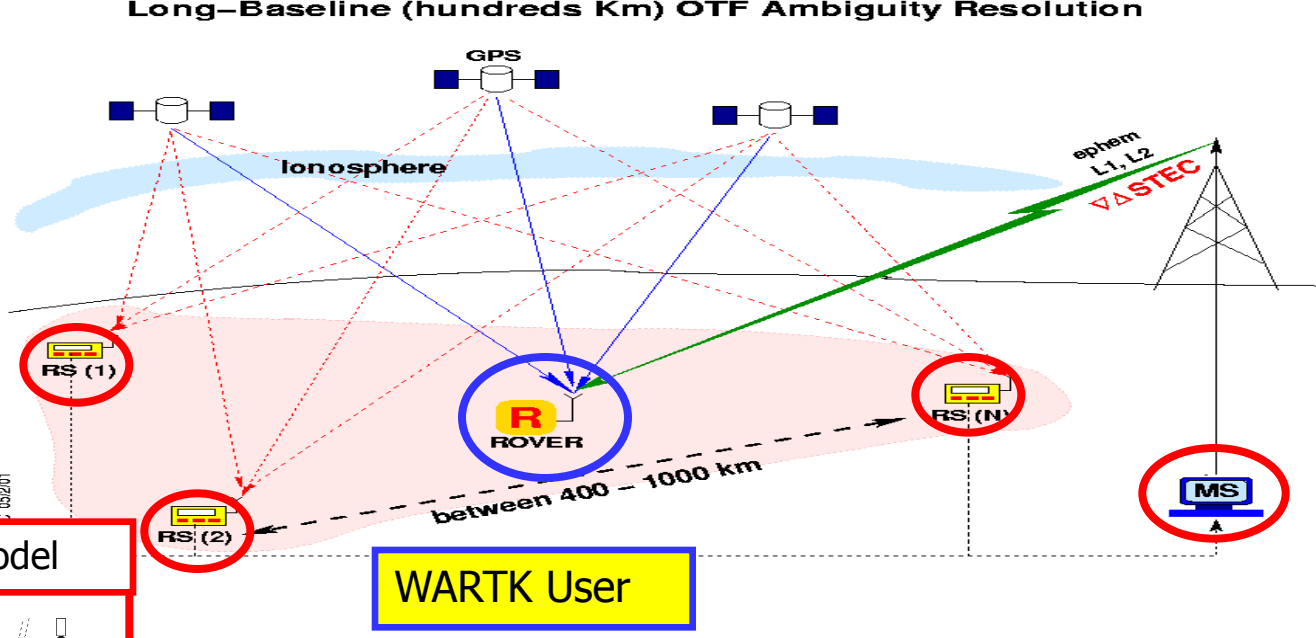
STEC can be affected by Travelling Ionospheric Disturbances



The ionospheric waves can produce STEC variations of several TECU (more than 20 cm at L1, and up to several cm at C-band), but with different phases at different locations, difficulting the interpolation of the ionospheric corrections in regional networks.

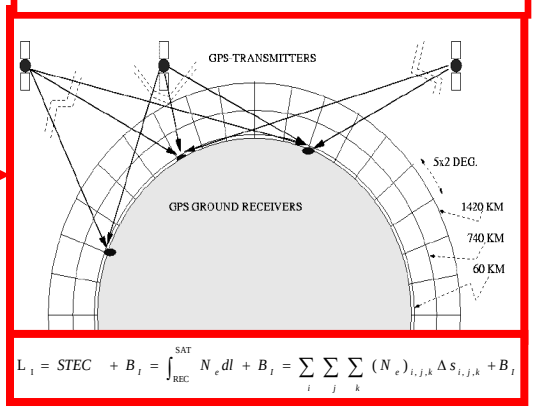
4. Ionospheric perturbations: an issue to consider in local and regional networks. New model within WARTK.

WARTK



WARTK Central Processing Facility

Real-time Iono. model



Real-time geodetic model

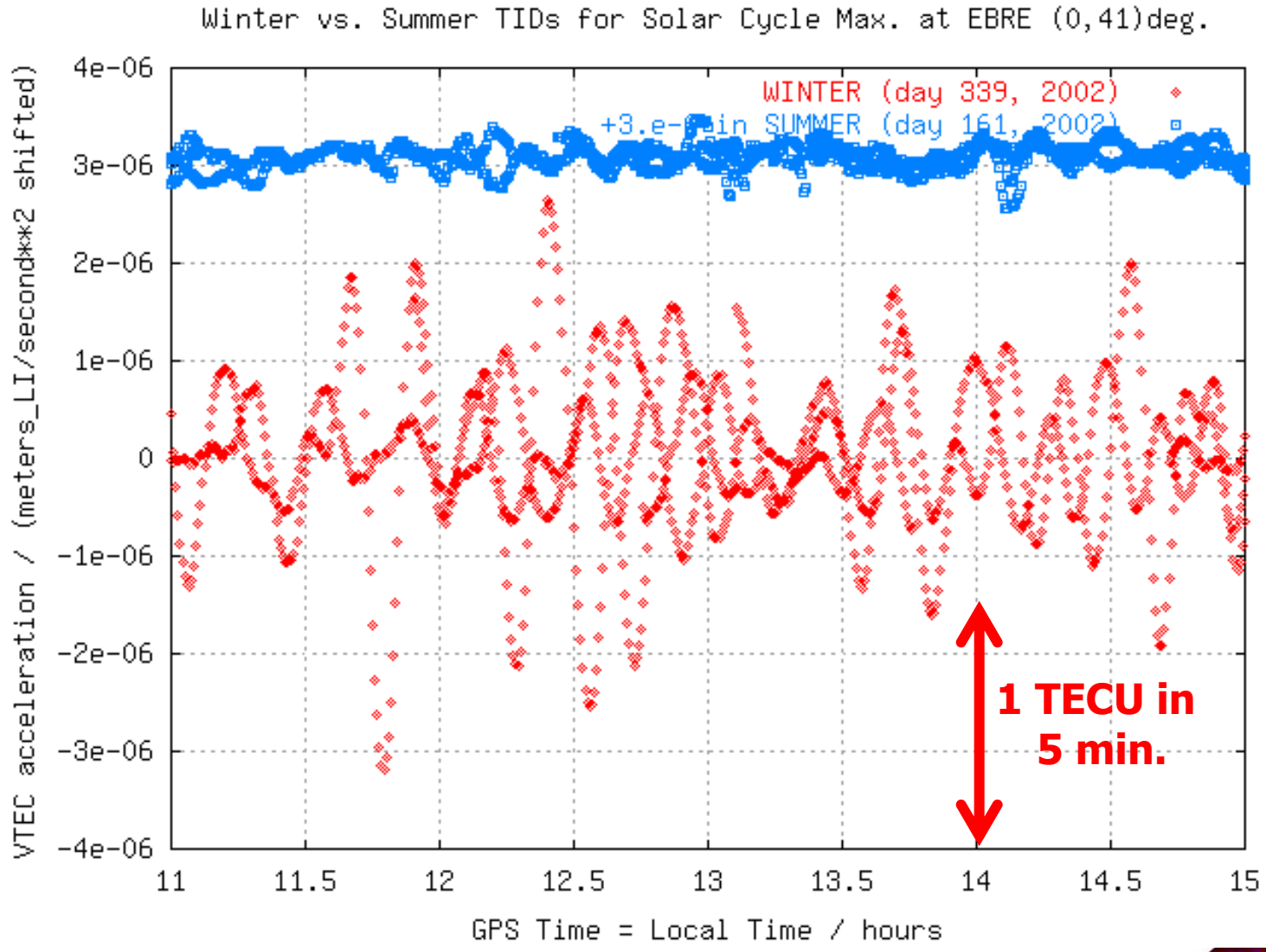
WARTK User

- In Wide Area RTK the usual dependence of differential ionospheric refraction can be predicted with errors of few tenths of TECU (few cm in L1), also in difficult scenarios (low latitude, Solar cycle maximum and distances of many hundreds of kilometres, see Hernández-Pajares et al. 2000,2002).
- This allows centimeter-error-level navigation at distancies up to hundreds of kilometers from the nearest GNSS reference site (at single epoch in Galileo and Modernized GPS).
- But "shorter scale" ionospheric perturbations (such as MSTIDs) –from tenths to few TECUs- can affect to GNSS precise positioning at both WARTK & RTK scales.

Some ideas about TIDs

- Travelling ionospheric disturbances (TIDs) are plasma density fluctuations, that propagate through the ionosphere as signatures of neutral atmospheric waves.
- Those which can be typically observed with GPS data are:
  - **Large scale TIDs (LSTIDs)** with a period greater than 1 hour and moving faster than 300m/s.
    - ✓ They seem related to geomagnetic activity and Joule effect at high latitudes.
  - **Medium scale TID (MSTIDs)** with shorter periods (from 10 to 60 min.) and moving slower (50-300 m/s).
    - ✓ The origin of MSTIDs seems related with meteorological phenomena (neutral winds or solar terminator, ST).
    - ✓ They produce atmospheric gravity waves (AGW) manifesting as TIDs at ionospheric heights.
- We will focus on the more frequent MSTIDs: its occurrence and horizontal propagation parameters will be shown in next slides.

Example: MSTIDs (detrended STEC During Noon in winter)

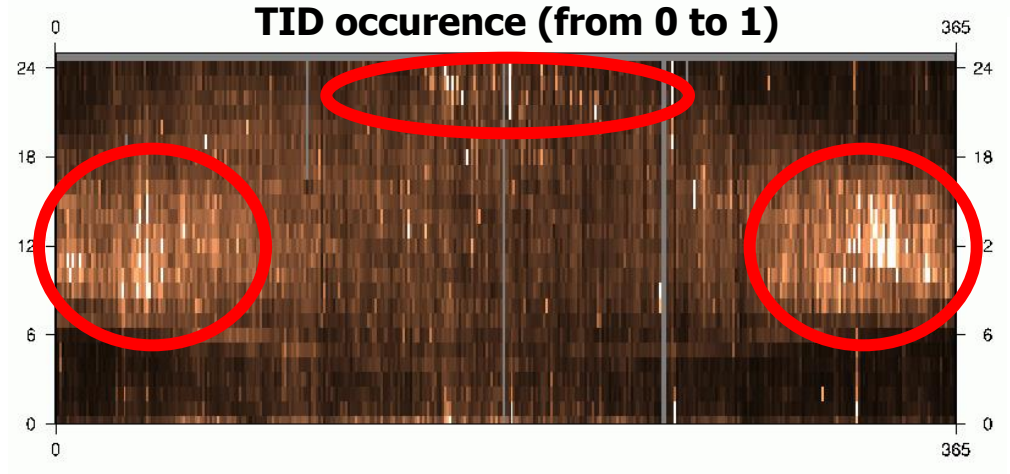


MSTID perturbations ~ few TECUs, significantly greater than the ionospheric error threshold (0.25 TECU) for real-time ambiguity fixing (Zoom at noon time for winter, red, day 339, 2002, and summer, blue[+3e-06], day 161, 2002)

Simple Ionospheric interpolation error vs. MSTIDs occurence (baseline~70km, BELL-MNTC)

Ionospheric interp. Performance (fraction STEC with errors below 0.25 TECu)

Local Time (hours)



Jan.'02 Jul.'02 Dec.'02

Time referred to 2002 (days)

The correlation between poor ionospheric performance and MSTID occurence can be seen: winter-daytime & summer-nighttime.

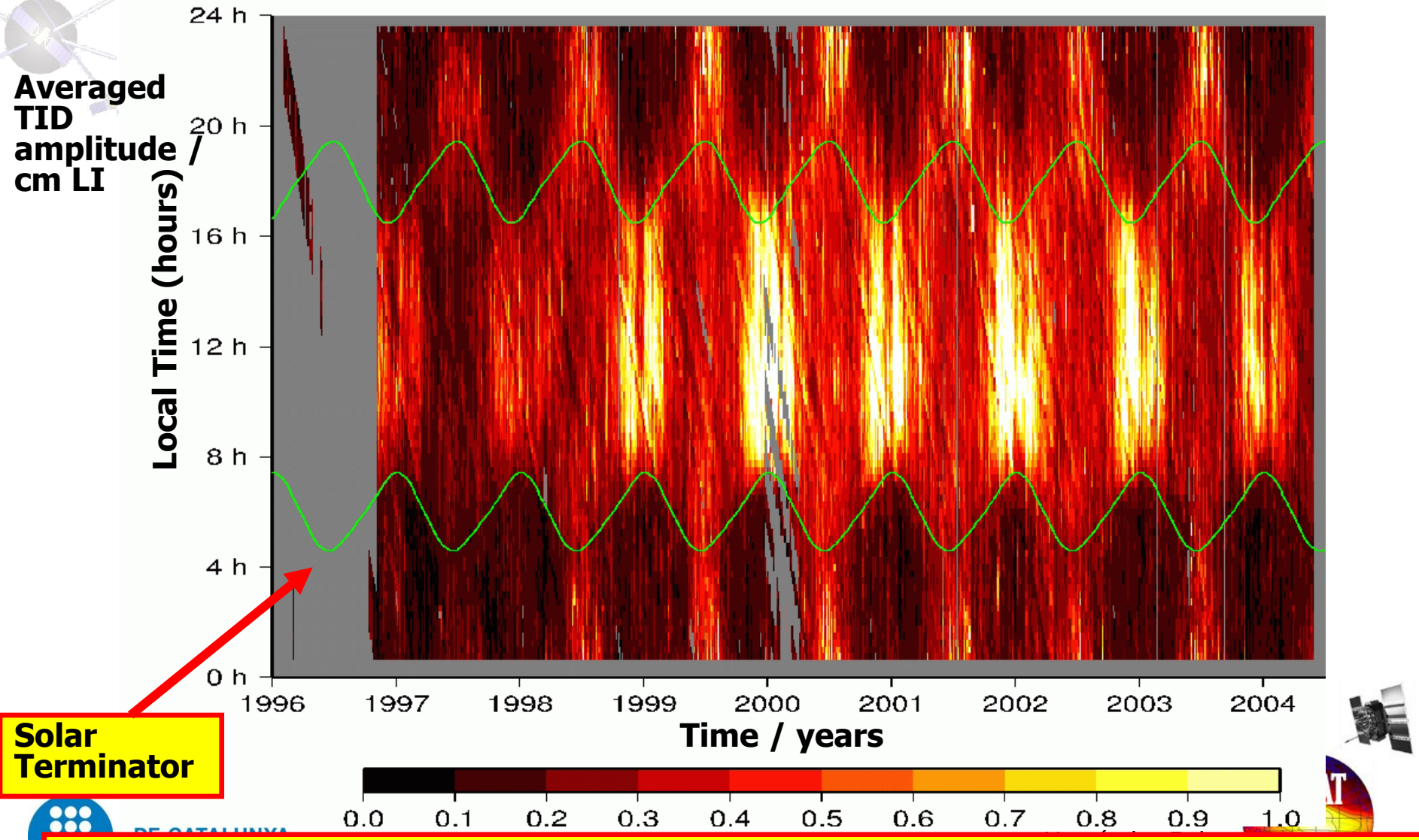
This result bring us to characterize the MSTIDs as a previous step of a real-time model.

5. Summary of MSTIDs parameters
(mostly based on 4 worldwide distributed Local Networks in 2002-2003 –Europe, NorthAmerica, Middle-East, New Zealand-)

(see details in Hernandez-Pajares M., J.M. Juan, J. Sanz, "Medium scale Traveling Ionospheric Disturbances affecting GPS measurements: Spatial and Temporal analysis", JGR-Space Physics, VOL. 111, A07S11, doi:10.1029/2005JA011474, 2006)

MSTIDs intensity during more than half Solar Cycle

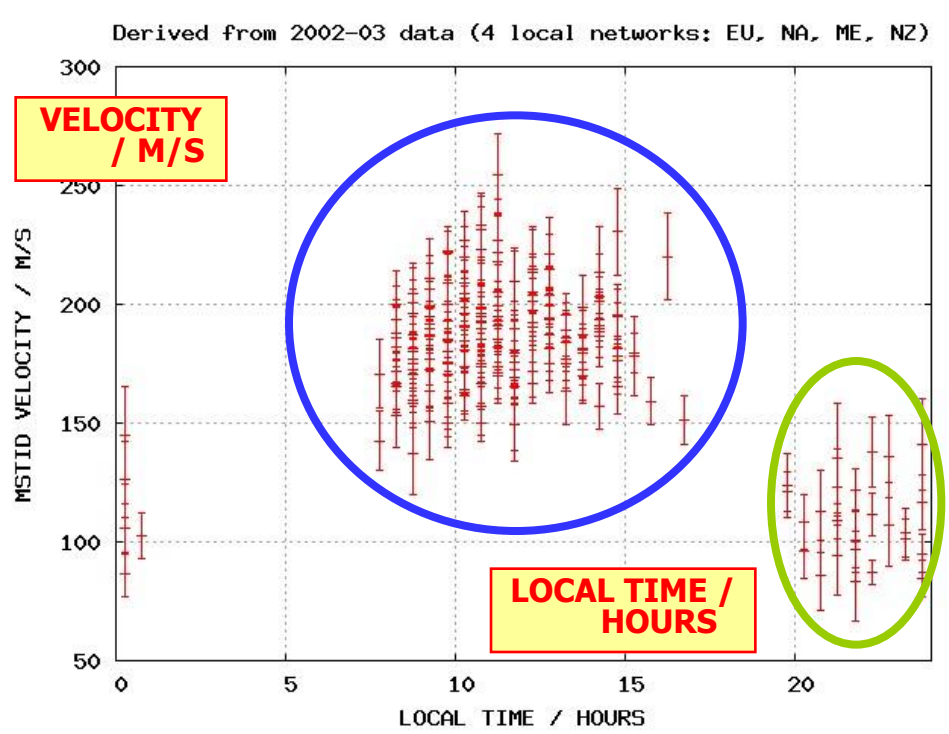
The MSTIDs occurrence since end 1996 at EBRE GPS permanent receiver (NE Spain, 0ºE 40ºN) repeats the seasonal dependence (midday winter, midnight summer), modulated by the Solar Cycle (terminator origin).

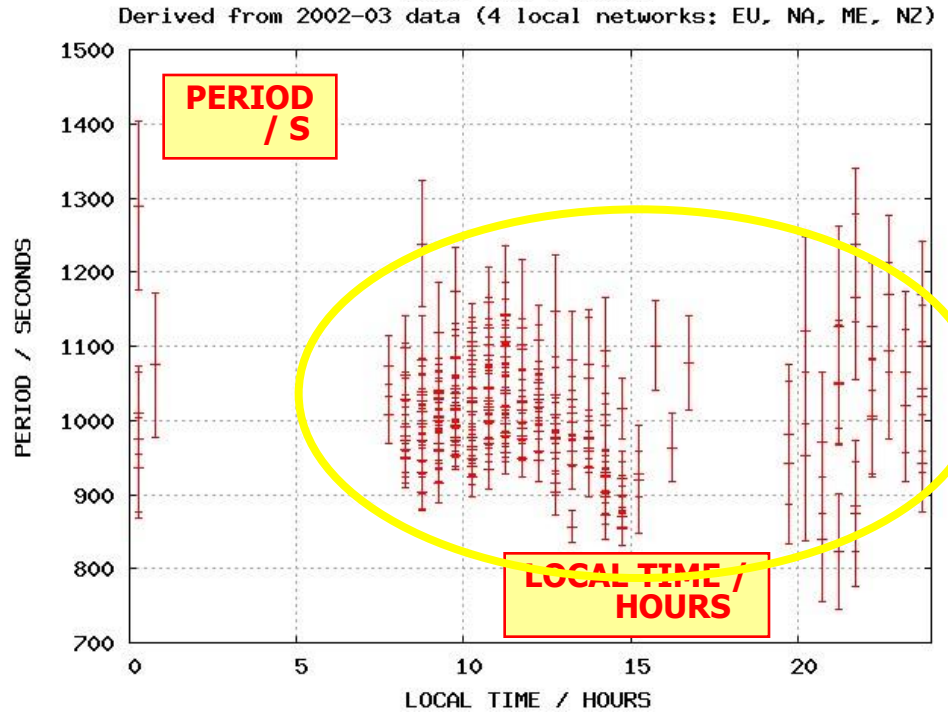


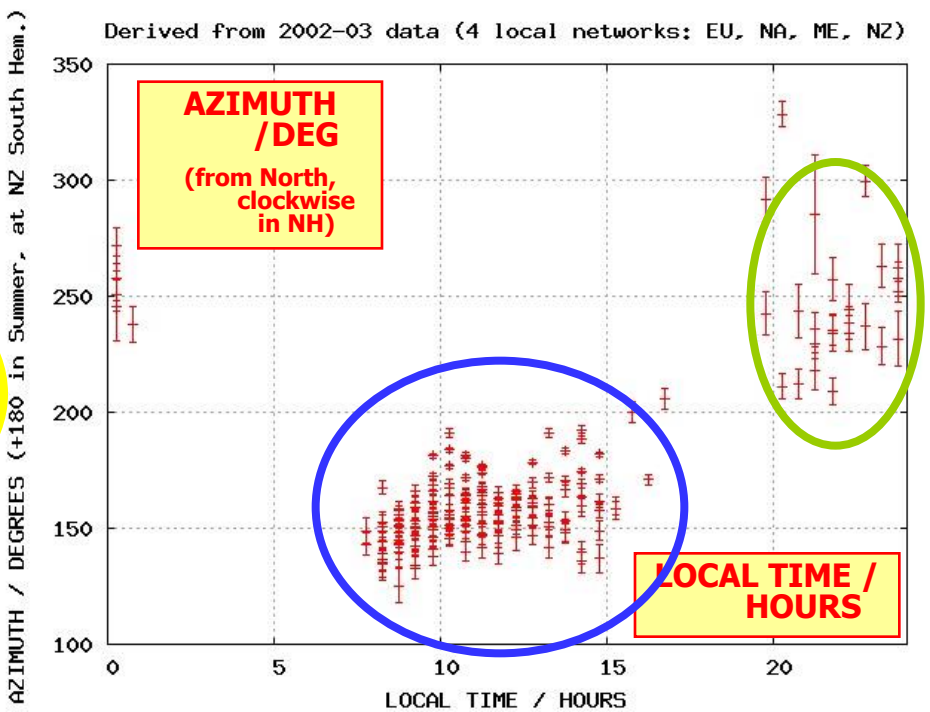
Repeatability: Chances of modelling for RTK/WARTK improvement

MSTIDs propagation parameters

- MSTIDs move Equatorward-East at ~150-250 m/s in local winter/daytime.
- MSTIDs move Westward, ~80-140 m/s in local summer/night time.
- Periods around 1000 sec.





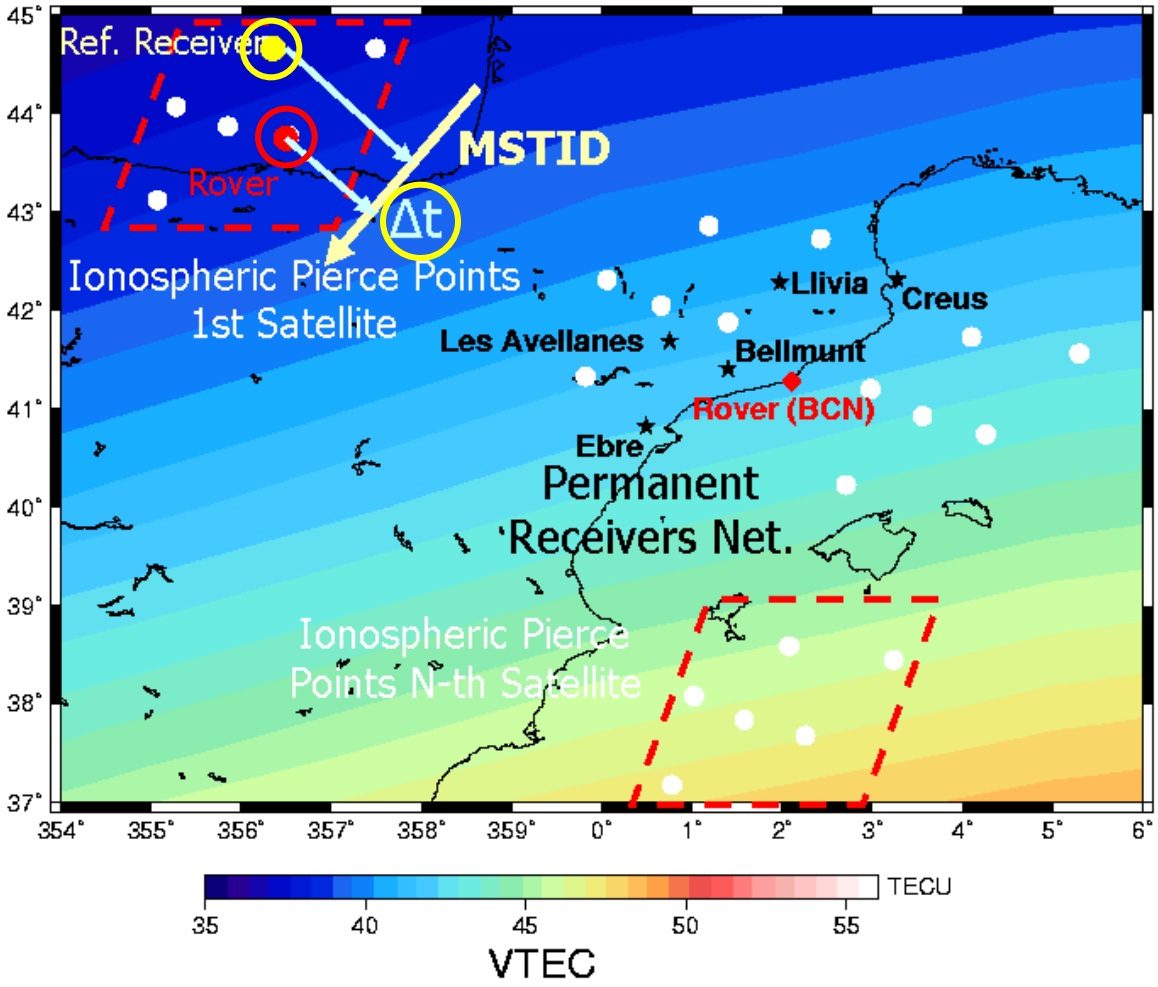


MSTID parameters summary

Local season	In Winter	In Summer	Adopted value in the experiment
Days* of year	**270-366 001-110**	**130-290**	048
Local Time / hours	**0700-1800**	**1800-2400 0000-0400**	0700-1800
Velocity / m/s	**150-250**	**80-140**	200
Azimuth / degrees**	**130-200**	**200-300**	180
Period*** / seconds	900-1100	800-1200	1000

6. Real-time MSTID model (DMTID)

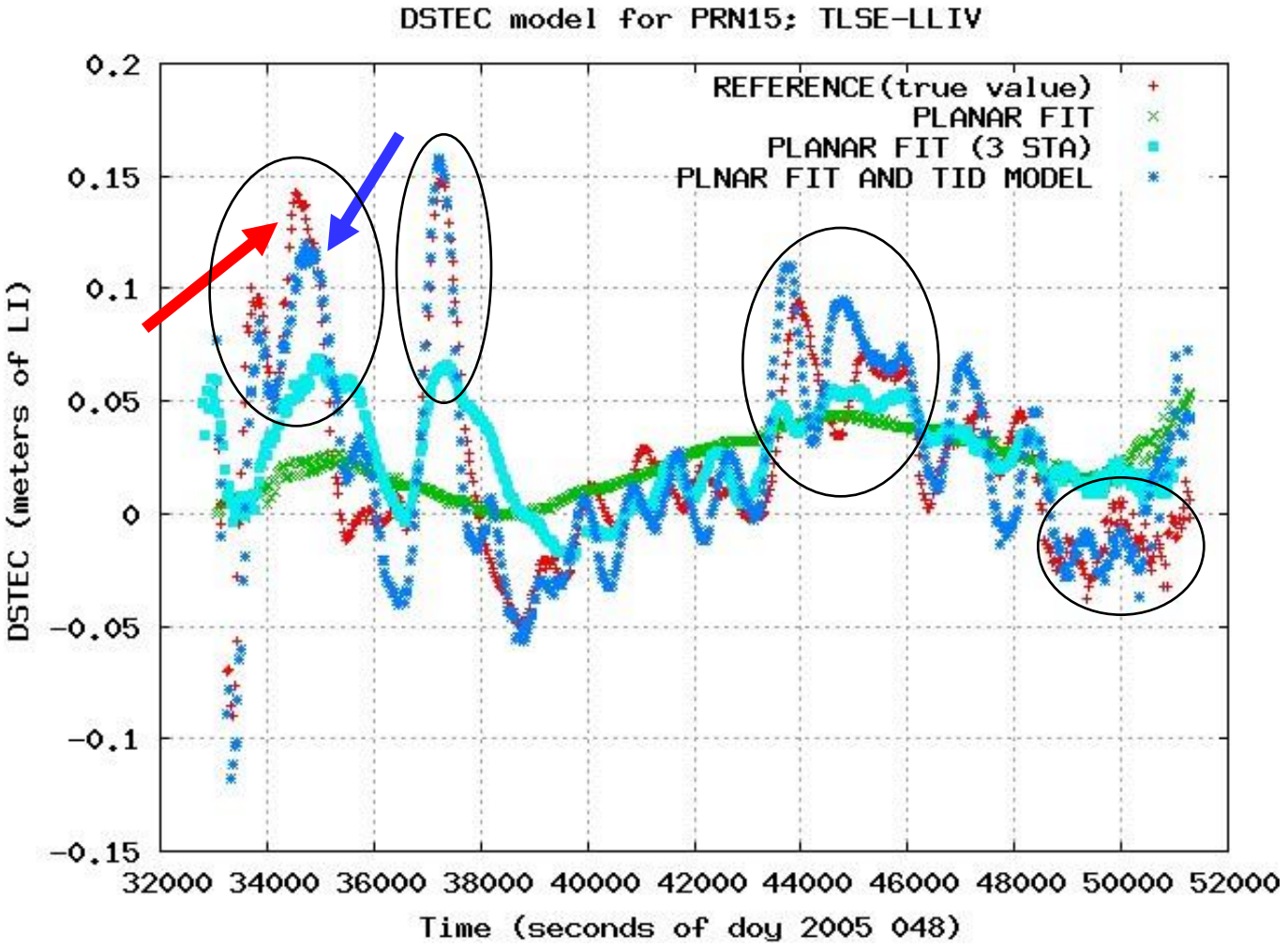
The real-time differential delay model for mitigating MSTIDs (DMTID)



In few words: DMTID consists on correcting the MSTID user state (red pierce point) by the values experienced before by a reference site (yellow pierce point), considering a delay Δt given by a planar wave model, feed with the propagation parameters summarized above.

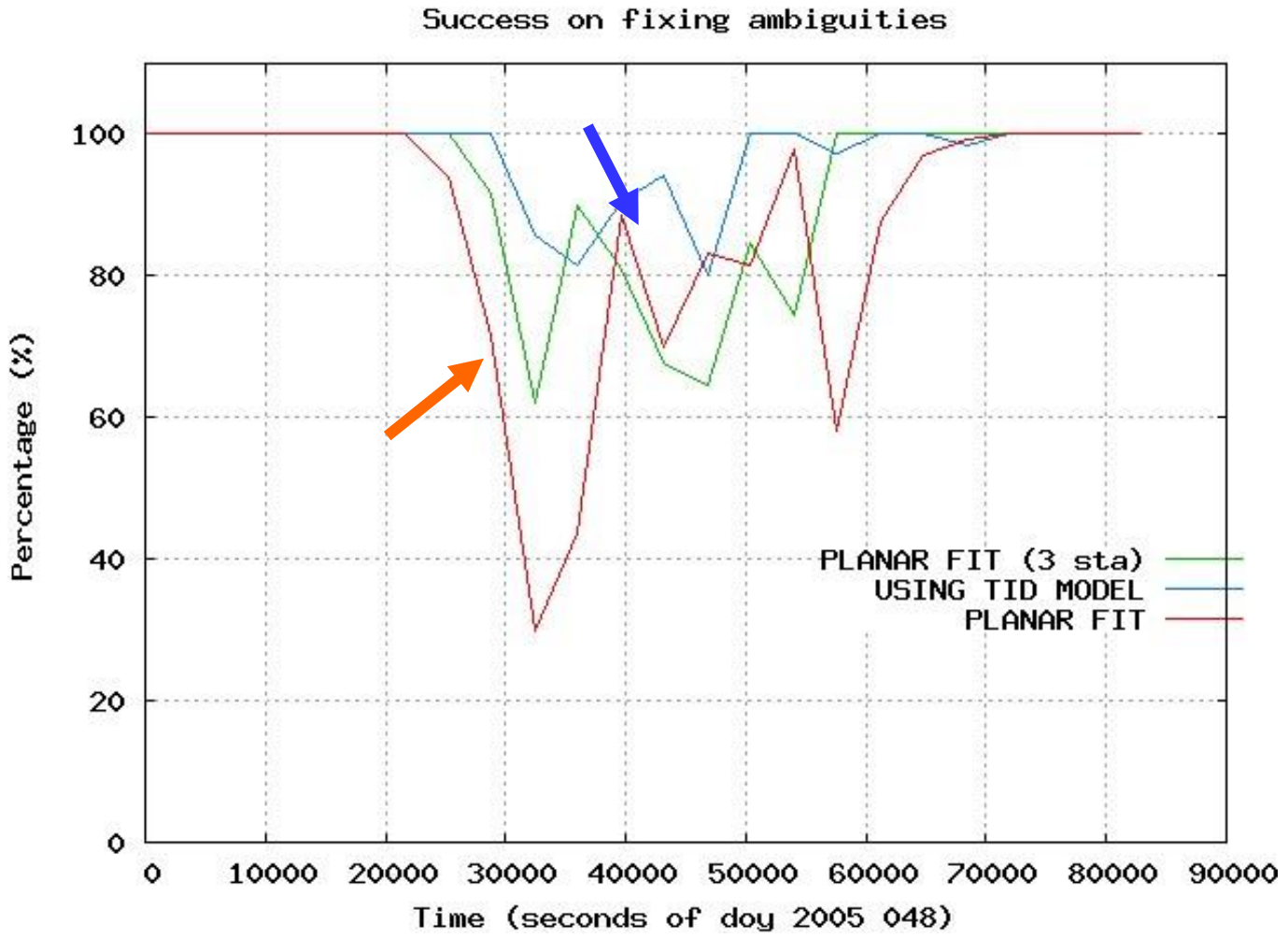
7. Experiment on MSTID modelling and results

Example of DMTID performance



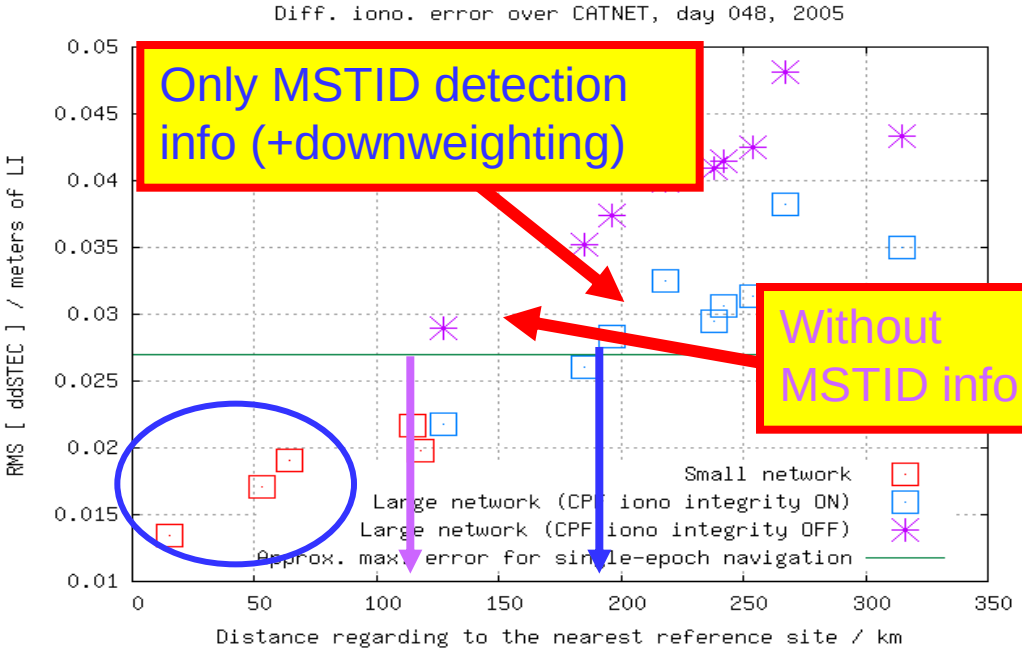
The comparison of linear interpolated single-difference STEC, taking into account the **DMTID predicted delay on the user pierce points –dark blue points-, are more similar to the actual ones –red points-**, than using only linear interpolation procedures without the DMTID delay -in light blue and green- (rover: LLIV, ref.site: TLSE, satellites: PRN 22, 15, 18 &19 respectively, during day 48, 2005 –winter conditions-).

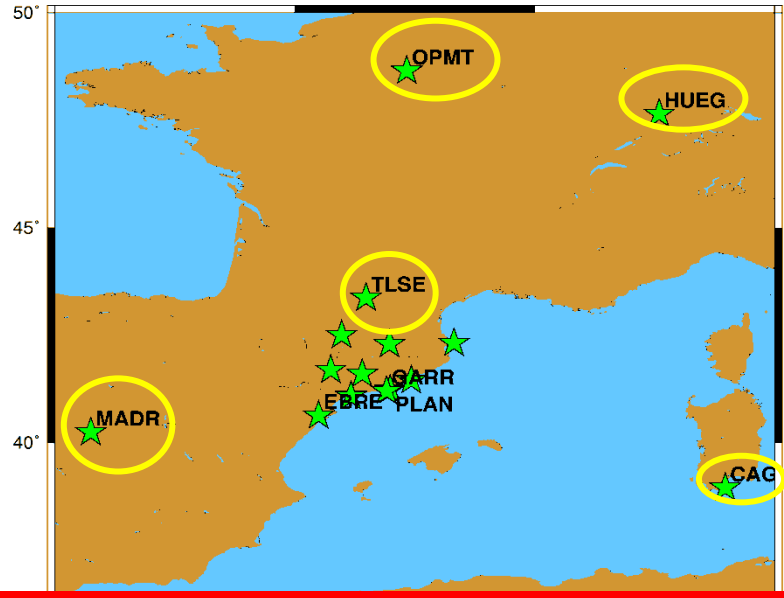
Ambiguity fixing improvement using DMTID

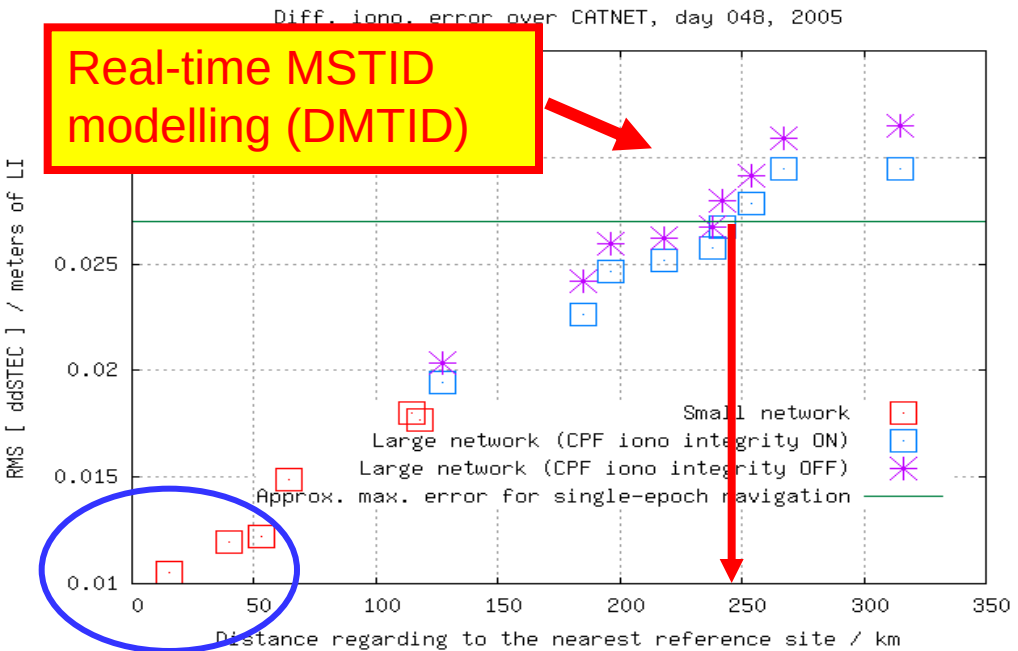


The DMTID positive impact on ambiguity fixing rate is also clear (blue line), which is translated in the corresponding sub-decimeter error-level user navigation, compared to simply applying a more or less local ionospheric interpolation, in green and red lines: The L1 ambiguity success rate is maintained equal or greater than 80%. (receiver LLIV treated as rover in a 127 km baseline, day 048, 2005)

Precise navigation Service area improvement





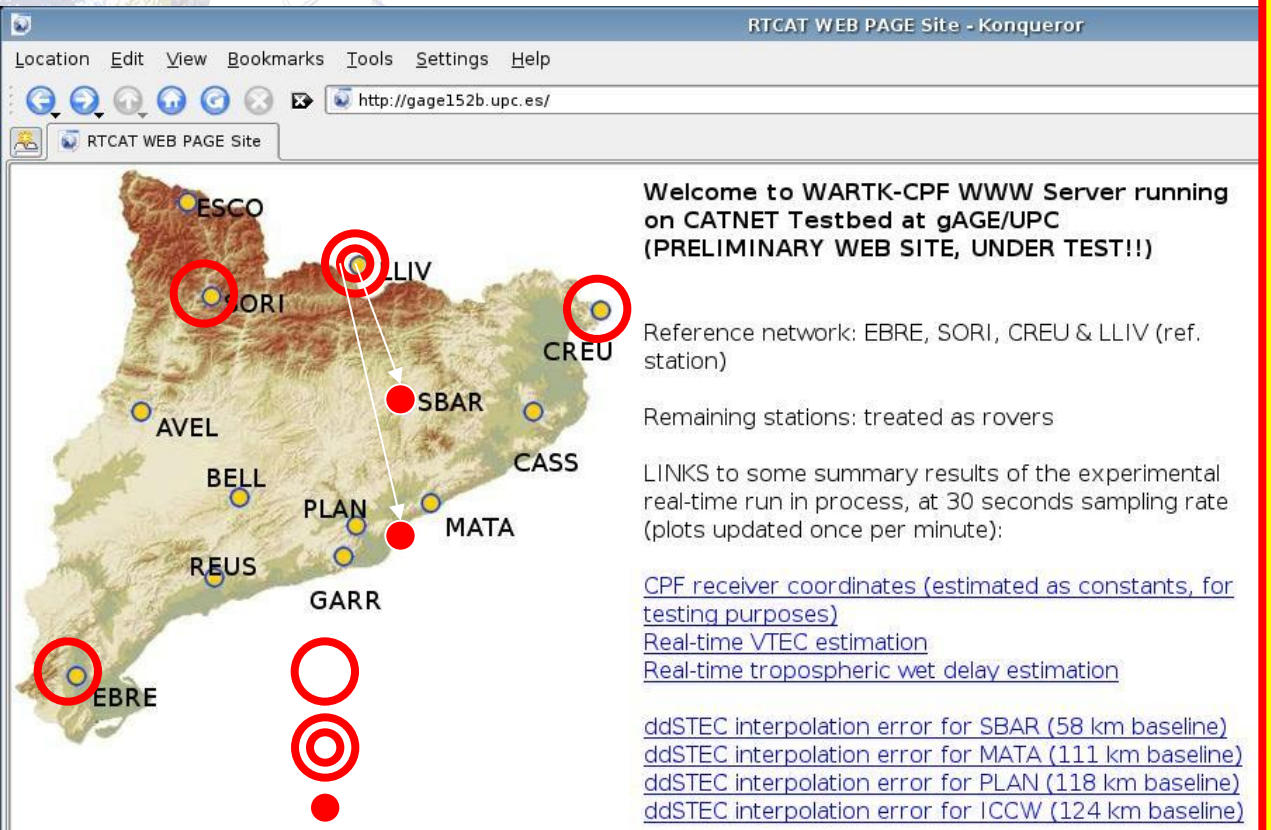


- It can be seen the daily performance vs. the baseline length by using:
(1) Without any MSTID info ("classical" approach, ~115 km max.),
(2) Only the MSTID detection info (downweighting, ~185 km max.)
(3) the DMTID real-time MSTID model (~250 km max.).
- The DMTID **service area is doubled**
- **Also improvement at RTK scales.**

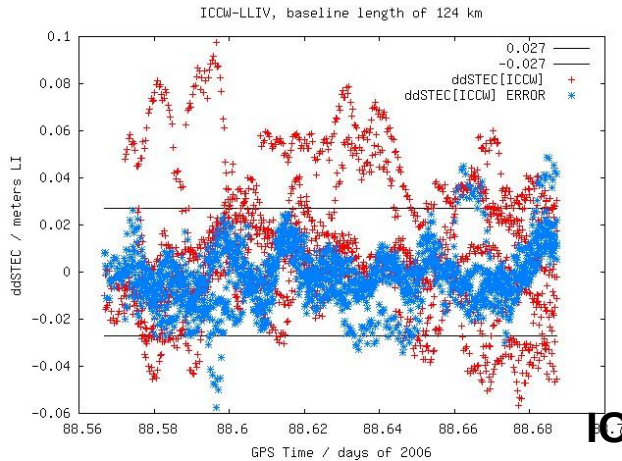
WARTK*: previous experiments & results

Experiment	Shortest baseline/km Rover/Fixed	Ionospheric Activity	Fixed Rec. Ambiguity success %	Roving Rec. Ambiguity success (%	Kind of rover	Region	Dates	Reported in
BellKin99	116 / 286	Mid.Solar Cycle & Quite	97	80-100	4x4 Car	Catalonia, NE Spain	23-03-99	Colombo et al. 99 (ION)
NWPacific1	400/900	Mid Solar Cycle & Active high lat. (Kp=6)	90-100	80	IGS Site	NWCanada-USA	03-05-98	Hernández et al. 00a, Colombo et al. 00 (GRL, PLANS)
NWPacific2	162/900	Mid-Low Solar Cycle & Irreg.	95-100	80-90	IGS Site	NWCanada-USA	28-04 to 01-05-98	Hernández et al. 00b (ION)
SolarMax1	130/500	Solar Maximum	85-95	80	IGS Site	Central Europe	19 to 22-04-00	Hernández et al. 01 (GRL)
SolarMax2	130/500	Solar Max. & Supestorm	50-95	80	IGS Site	Central Europe	12 to 15-07-00	Hernández et al. 00b (ION)
Baltic99	144/285	Travelling Iono. Disturb. (TIDs)	97	83	IGS Site	North Europe	25-08-99	Hernández et al. 01b (ION)
Equator01	1000-3000/.	Solar Max. & Equator & Very Active (Kp to 9)	90	---	IGS Sites	Central Asia to Oceania	06-03 to 02-04-01	Hernández et al. 02 (JGR)
TCARdata (simulated)	130/300	Solar Max.	100	92 (single-epoch)	Sim. car	Central Europe	17-03-00 (noon)	Hernández et al. 03a-b (IEEE TGARS, Navigation)
UNBAR01	70-115/100	Solar Max. & Strong TIDs	100	~80 (with integrity)	Car	Barcelona, NE Spain	11-06-01	Hernández et al. 04 (ION)
WARTK3 Lab.Test 1-2	178-238 /250-600	Solar Max.	100	100	1:Car 2:Air.	Iberian Peninsula	31-03-90 (ionos.)	Hernández et al. 04 (ION)
WARTK3 Lab. Test 3	416/250-600	Solar Max.	100	99	Fixed Site	Iberian Peninsula	31-03-90 (ionos.)	Hernández et al. 04 (ION)

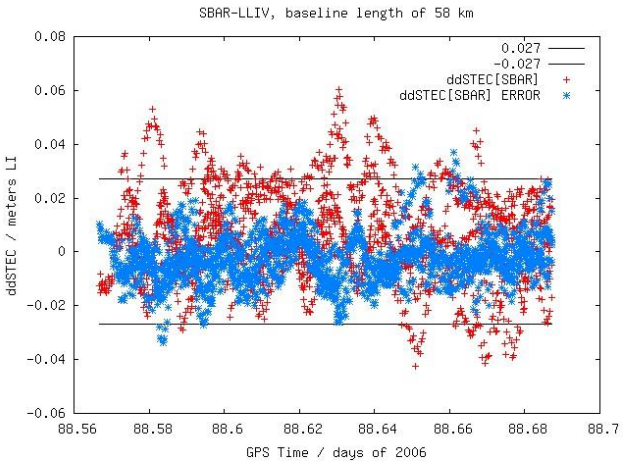
Pre-prototype of WARTK CPF based on CATNET



- **Real-time experiment running continuously during +6 months (WARTK-EGAL GJU-funded project).**
- **From the available 13 CATNET datastreams, several external receivers were used as CPF WARTK reference sites.The remaining sites were treated as roving users.**
- **Previous results confirmed in real-time.**



ICCW (124km)



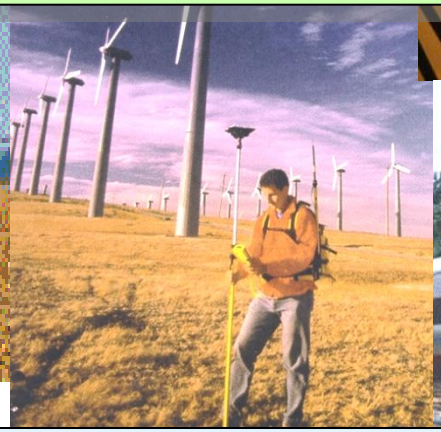
SBAR (58km)

8. WARTK Applications

GALILEO: WARTK3 [gAGE-ESA patent,2002]

allows INSTANTANEOUS (single epoch) ambiguity fixing at a hundreds of Km far from the ref. station

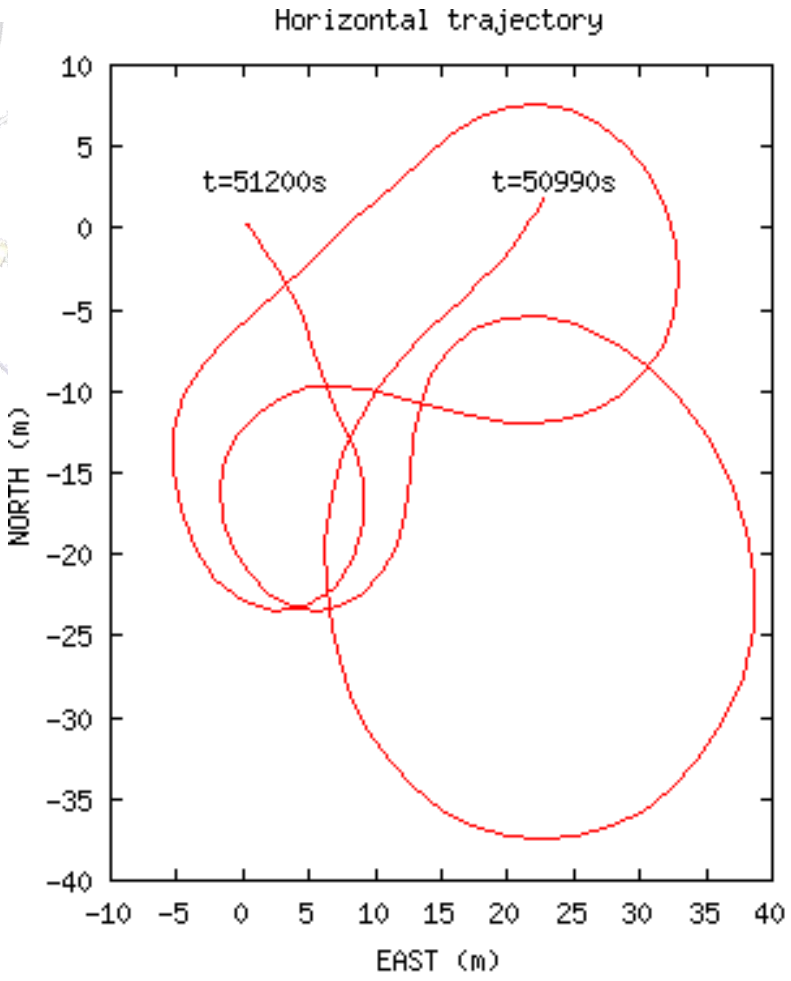
EGNOS-like permanent stations networks have the potential for supporting centimeter Navigation over Europe.

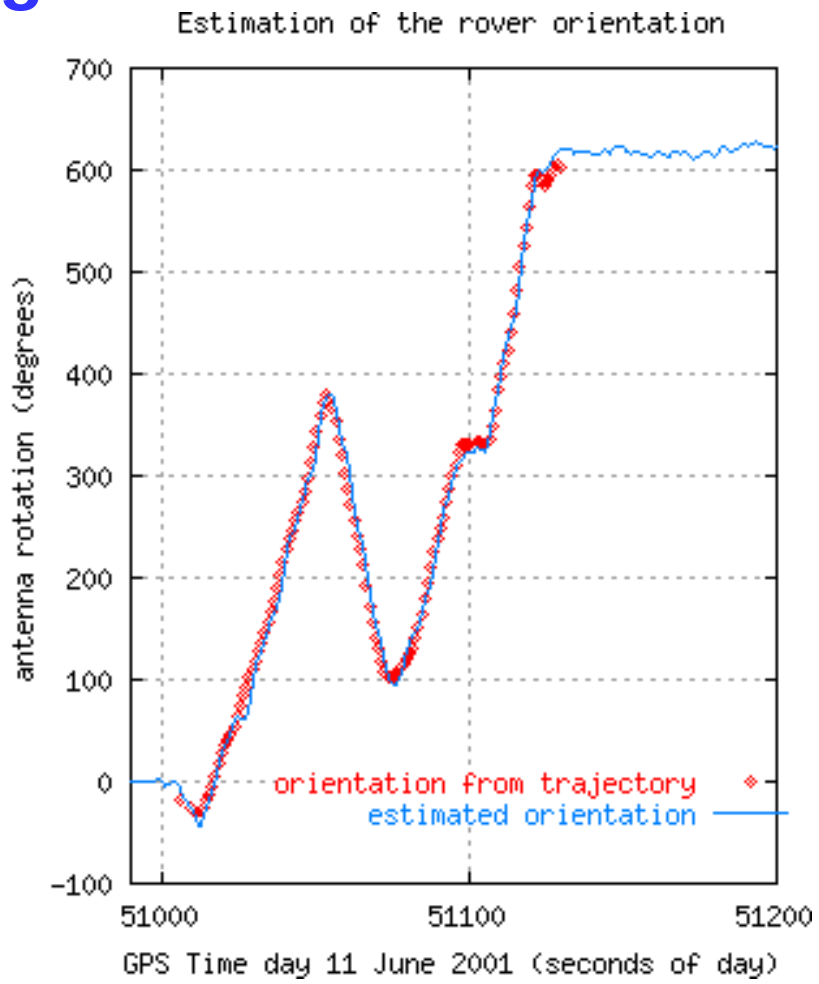


WARTK-EGAL, FES-WARTK: Funded Galileo Join Undertaking and ESA projects, being gAGE/UPC leader of both International Consortia.

Applications of GNSS navigation at centimeter level over Europe: extending the present applications of RTK (**civil engineering**, **precise farming**, **transport**…), as far as new applications, such as **real-time GPS meteorology**, single GNSS receivers as **orientation sensors** capabilities, **real-time mapping**, **Tsunami detection**, **accurate navigation on deep waters**,… *Let's see a couple of examples!*

Application 1: Real-time single antenna orientation



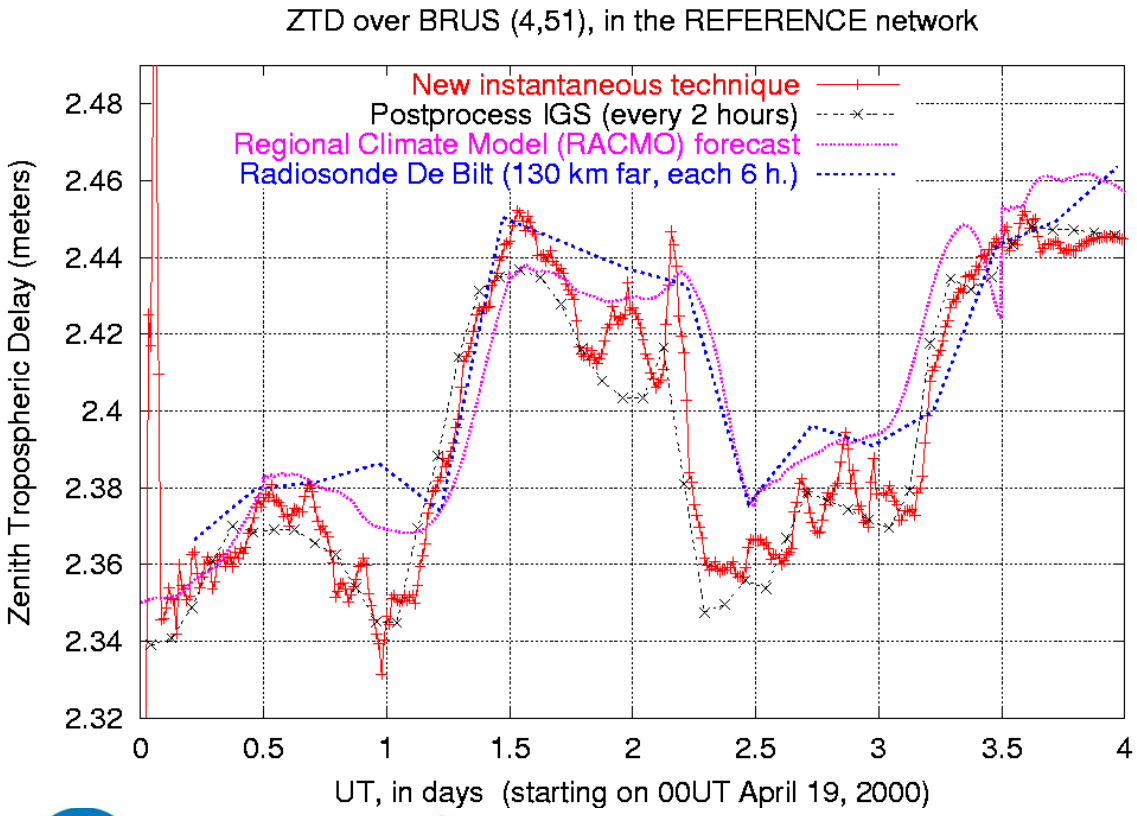


WARTK makes feasible as well the simultaneous user orientation change estimate with a single antenna thanks to the accurate ionospheric modelling.

You can see a real experiment in which the WARTK single antenna rotation estimation is compatible at few-degrees level with the values deduced from both the car trajectory (right hand plot), and a second antenna on the car roof (ION-GNSS 2004).

WARTK is able to support instantaneous GPS meteorology

REAL-TIME Water Vapor Determination



The WARTK reference stations can act as accurate meteorological sensors, providing the water vapour content instantaneously, thanks to the continuous ambiguity fixing.

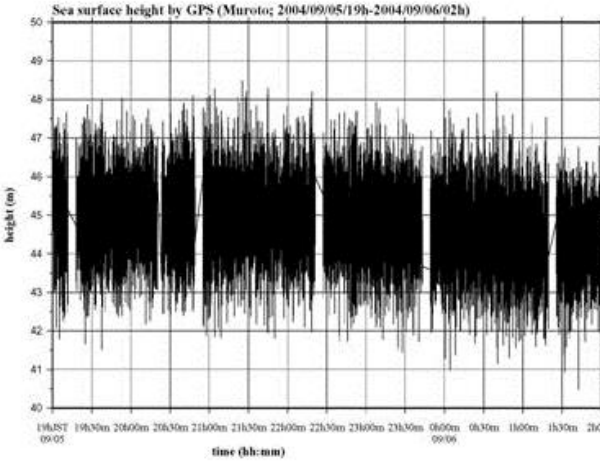
This capability of ingesting such measurements in the weather forecast models can reduce its uncertainties.

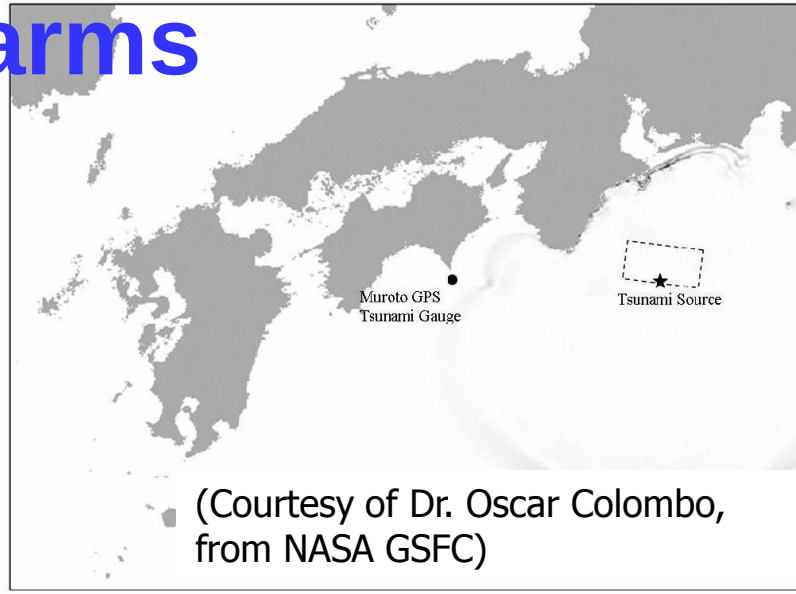
We have shown as well that a dual use of a GPS receiver inside the WARTK Service Area is feasible: both Navigation at cm-level and Meteorological sensor.

WARTK could help on providing useful Tsunami alarms

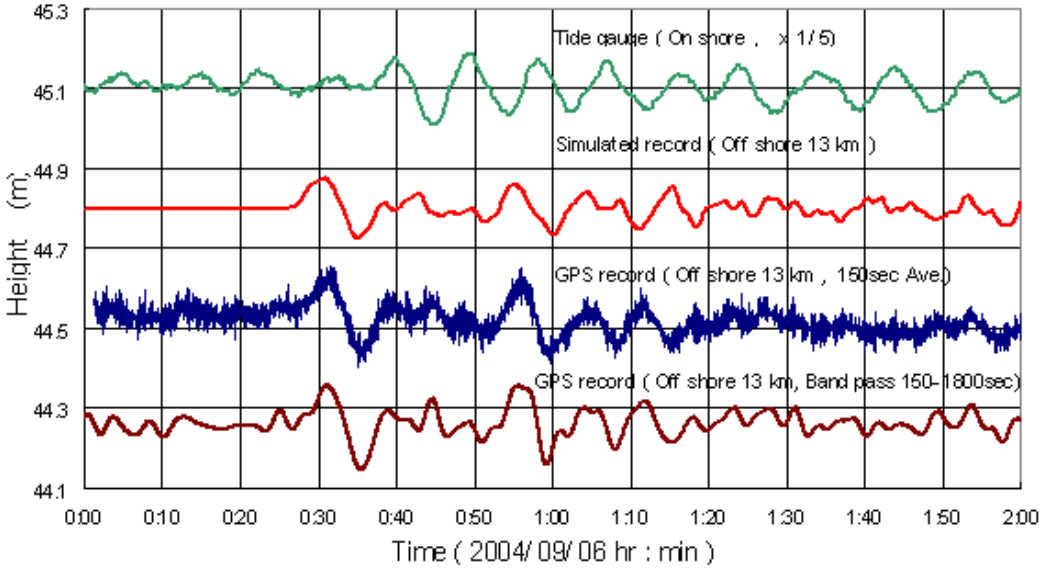
During 6 Sept. 2004 in Japan, it was possible to detect with a GPS buoy, and 10 minutes in advance, the 20 cm tsunamis' amplitude, 15 km north from the coastline.

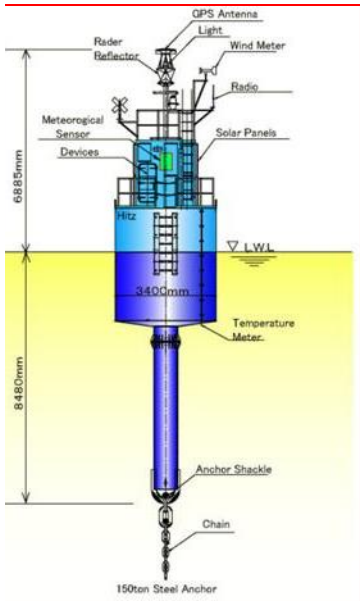
WARTK can help on fixing carrier ambiguities at more than 100 km from the coastline, making more feasible alarms in advance for the population.





(Courtesy of Dr. Oscar Colombo, from NASA GSFC)

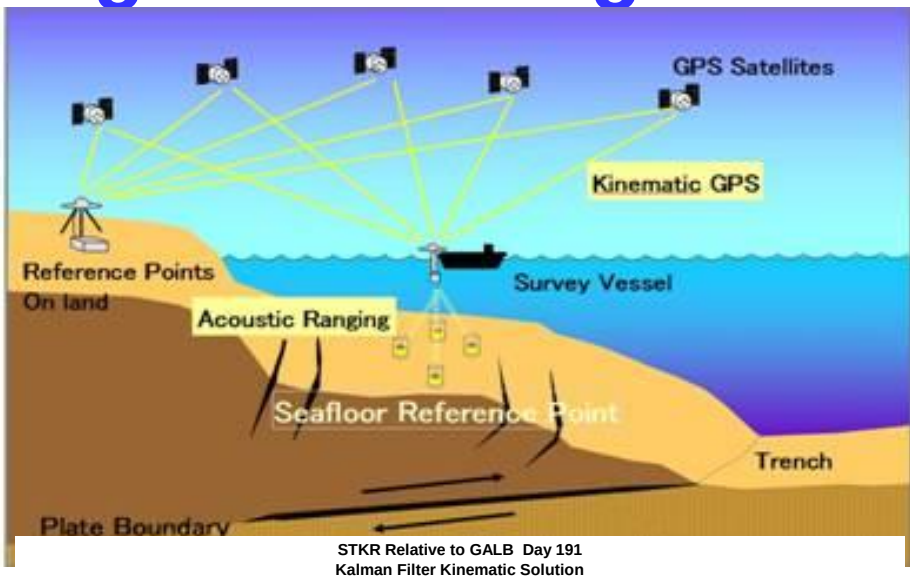


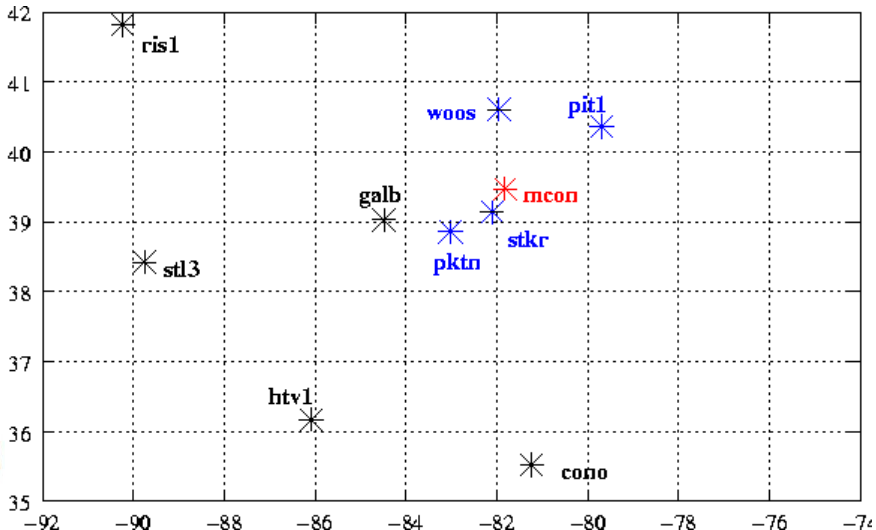


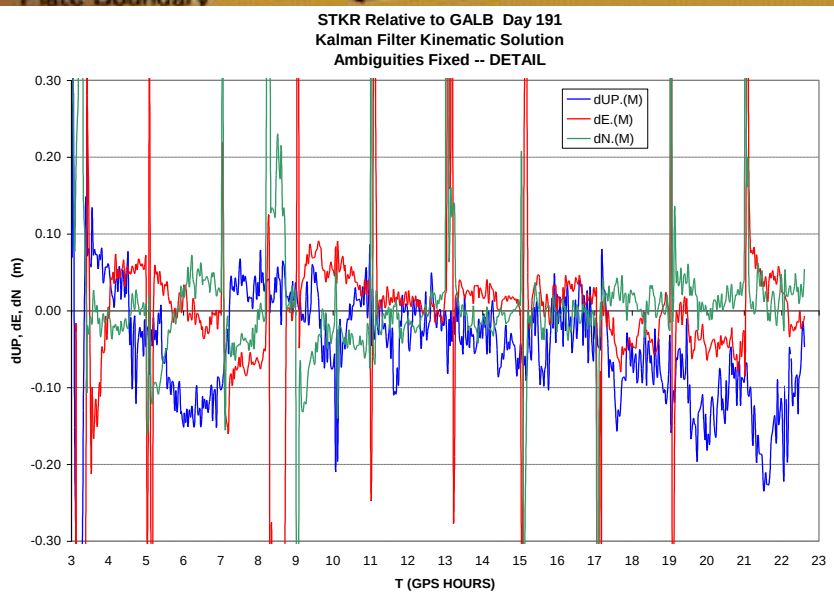
WARTK buoys could help on deep waters precise navigation & pilotage & mooring

The extension of the network of reference receivers with dual-frequency GNSS buoys would allow accurate WARTK navigation (typical errors< 10 cm) on deep waters.

See snapshot of study presented at the ION-GNSS 2005 by Colombo, Hernandez, Juan and Sanz. 2005, in which such accurate buoy-supported navigation can be achieved within a few minutes after each restart.







WARTK
Aid to blind or visually impaired

Practical solutions for the everyday life of blind or visually impaired people. There are already some technologies with GPS and EGNOS/the assistance of GIS software. WARTK would improve these solutions by offering **cm accuracy** (GPS ~15 m , EGNOS ~ 2m) with a certain integrity level.

Precision farming & animal tracking

Management of crops

Satellite guiding (manual and automatic)

Supplies, fertilizers, weeding...

Farmers are interested in activity-indicators derived from individual cow-tracks, especially related to disease or fertility.

Automated Parking Fee Collection

Fully automate the fee collection when parking a car within a specified area. Often these areas are next to the road itself. In order to determine whether the car is located within the parking area or on the road with enough **accuracy**: **WARTK**

Lane keeping

An alarm might be used to warn a driver who is diverting slowly from a lane.

Satellite-based car insurances

Norwich Union 1st UK insurer to introduce "Pay as you drive" car insurance, based on GPS.

9. Conclusions

General conclusions

- The Wide Area Real Time Kinematics with 2 and 3 GNSS frequencies has been briefly presented. It has been tested with real GPS data and simulated GALILEO signals in worst case scenarios, with rovers navigating at hundreds of km away from the nearest reference site.

- The last version (WARTK3.2) includes as well the simultaneous user orientation change estimation capability with a single antenna.

- The results (see more details in papers) confirm previous studies: WARTK makes feasible a new navigation service with errors of few centimeters from continental networks of GNSS stations separated hundreds of km.

- This accurate real-time positioning can be typically achieved instantaneously with 3-frequency systems (such as Galileo), and after the best part of 1-2 minutes with 2-frequency systems such as GPS.

- Several potential applications of WARTK have been mentioned (civil engineering, real-time mapping, transport, sensor orientation…) and some of them summarized, such as the instantaneous GPS meteorology and its capability of helping on Tsunamis' detection, and support accurate navigation in deep seas.

Detailed Conclusions

- We can conclude in detail that the use of a simple "climatological" or blind MSTID model (DMTID) can significantly mitigate the errors introduced in the STEC prediction for a roving user in Local, Regional or Wide Area GNSS networks, **doubling the service area** in WARTK (from ~185 to ~250 km in difficult day of experiment) and improving the results at RTK scales as well.
- To achieve such results, a previous study characterizing MSTIDs was performed, as far as an experiment with actual GPS data in West Europe.
- Further additional improvements could be achieved by using a dedicated poleward/eastward local network providing support to GNSS networks (such as EGNOS, WAAS or future Galileo and GPS III reference sites), providing actual MSTID propagation estimates instead of "climatological" ones.

THANK YOU for your attention!

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

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THANK YOU!