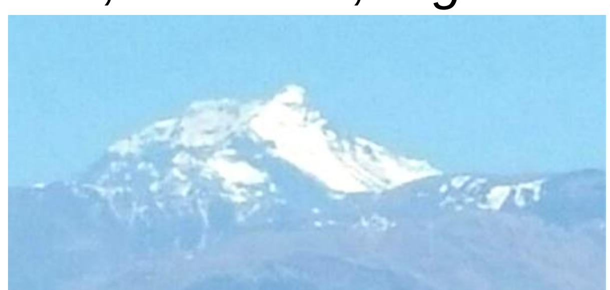
Some applications of ionospheric and geodetic models supported by real-time GNSS measurements

M. Hernández-Pajares(1), A. García-Rigo(1), D. Roma-Dollase(1,2),
C. Fernández-Prades(3), J. Arribas(3), M. Majoral(3), J. Vilà-Valls(3)

(1) UPC-IonSAT, Barcelona, Spain
(2) UB-Dept. Electronics, Barcelona, Spain
(3) CTTC, Barcelona, Spain

Contact e-mail: manuel.hernandez@upc.edu

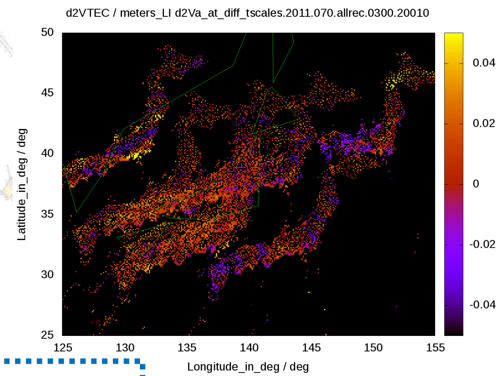
SIRGAS 2017 Simposium, Mendoza, Argentina, Nov.27th, 2017



UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

IonSAT

Layout



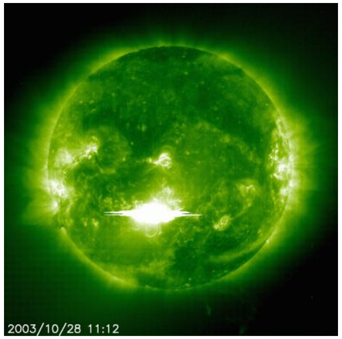
Border color legend:

Fully implemented & mature

Partially implemented & room for improment

Potentially feasible, to be refined & implemented

Solar Flare meas. & detection

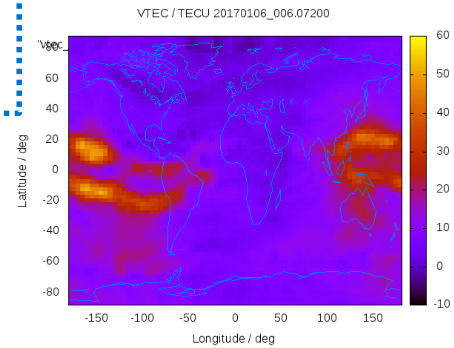


Potential Tsunami early detection

RT-GNSS datastream

Precise Agriculture

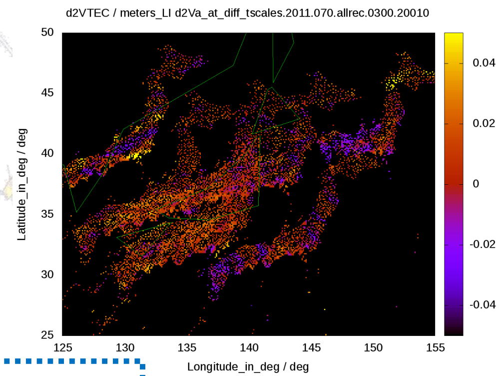
Open Global Ionospheric Maps (IGS)



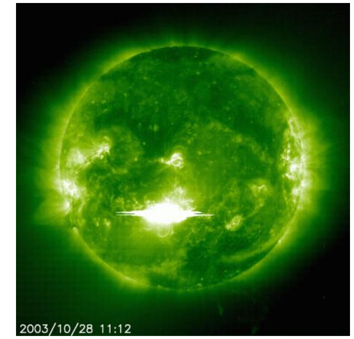
UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

IonSAT

Layout



Solar Flare meas. & detection



Border color legend:

Fully implemented & mature

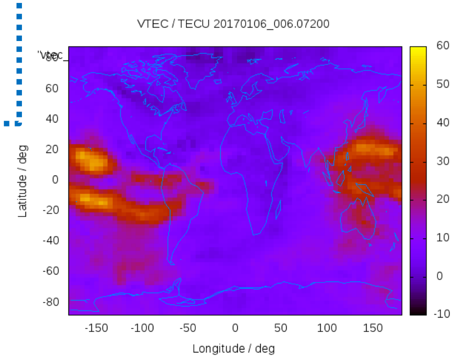
Partially implemented & room for improment

Potentially feasible, to be refined & implemented

Potential Tsunami early detection

RT-GNSS datastream

Precise Agriculture



Open Global Ionospheric Maps (IGS)

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

IonSAT

“Engine” inspiring & allowing new applications:

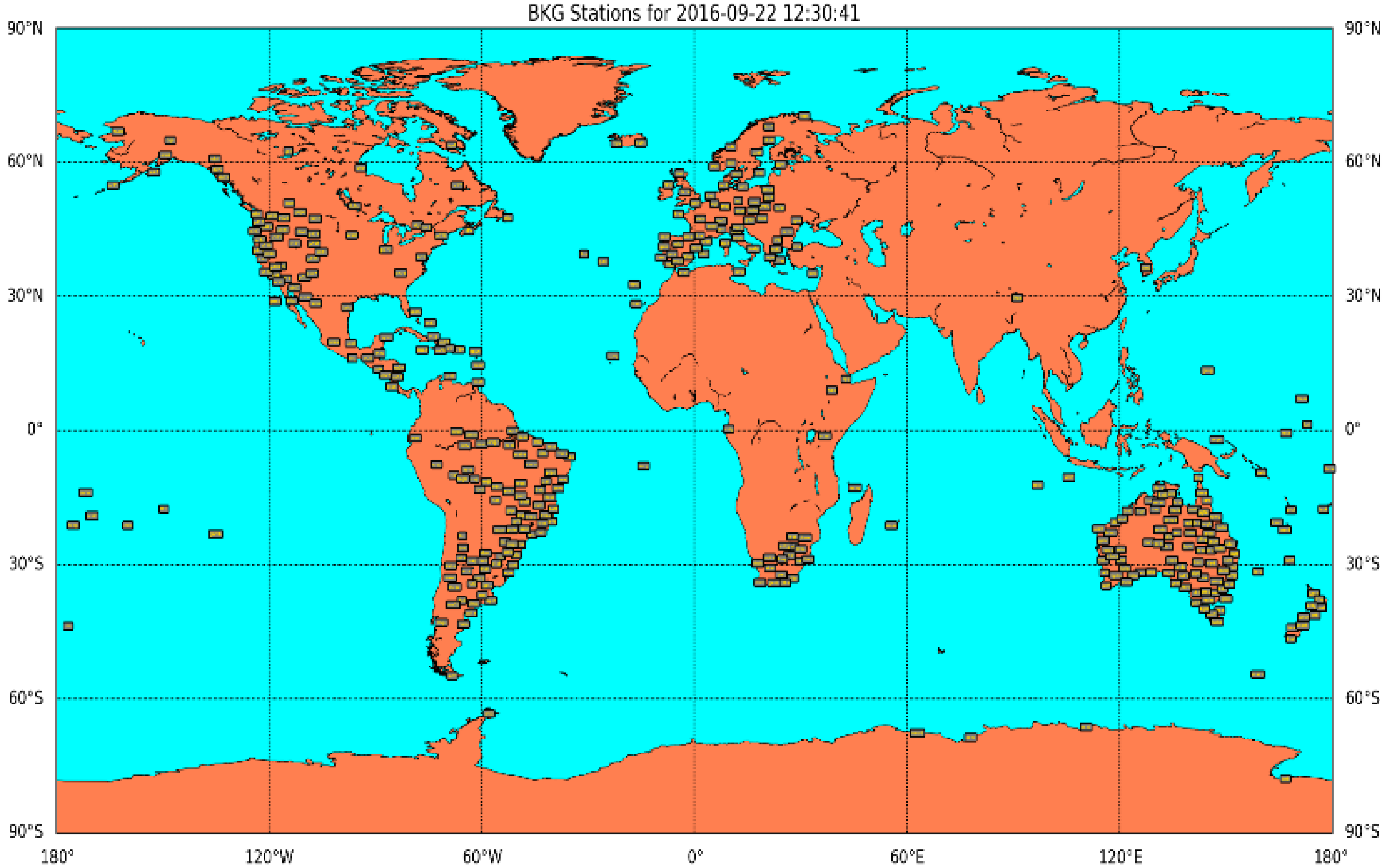
RT-GNSS datastreams & BNC

- From our experience the available RT-GNSS datastreams and the BNC functioning **can be considered mature and implemented in RT in a stable way.**
- The BNC option of providing an overall sincronized RINEXv3-like measurement stream in form of growing file has been very appreciated for the quick development of new applications.

UNIVERSITAT POLITÈCNICA
DE CATALUNYA
BARCELONATECH

IonSAT

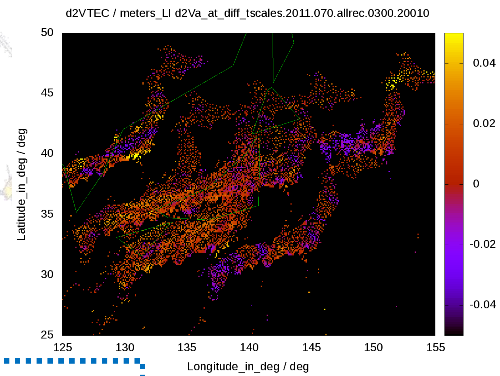
RT-GNSS global network of +200 datastreams used by UPC-IonSAT (RT-IGS & other nets.)



UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

IonSAT

Layout



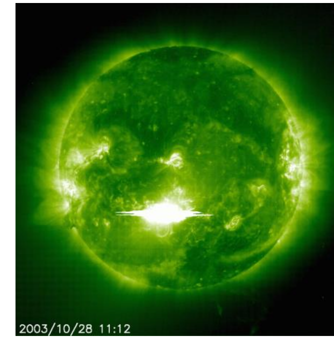
Border color legend:

Fully implemented & mature

Partially implemented & room for improment

Potentially feasible, to be refined & implemented

Solar Flare meas. & detection

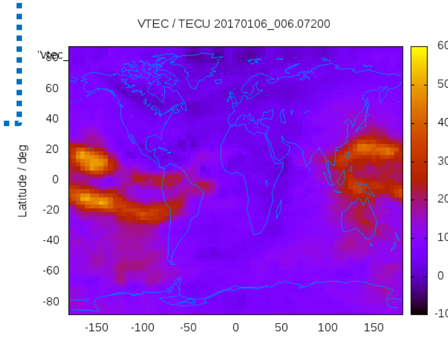


Potential Tsunami early detection

RT-GNSS datastream

Precise Agriculture

Open Global Ionospheric Maps (IGS)



UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

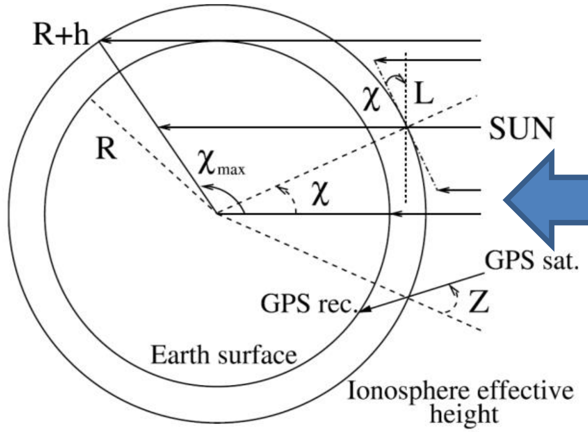
IonSAT

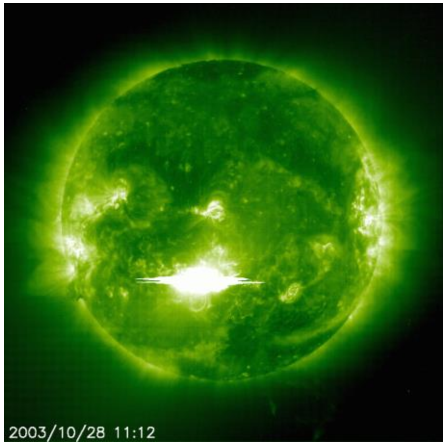
Application #1:

RT-GNSS datastreams becoming a Solar-Flare detection & measurement instrument

- This recent UPC-IonSAT technique is **already mature and implemented in RT in a stable way** (sending solar-flare warning e-mails to interested users).

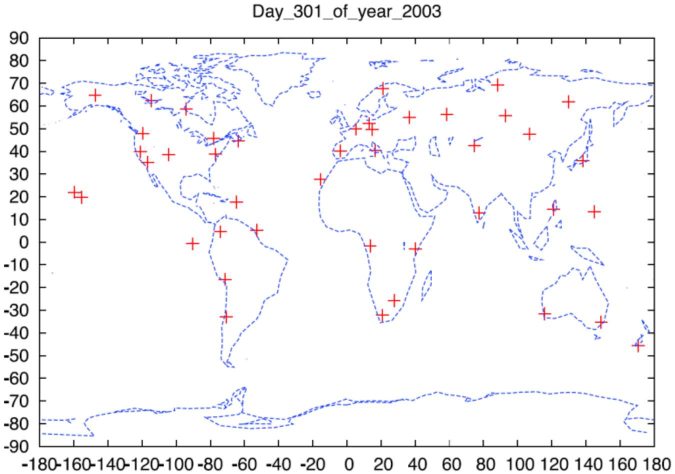
Overionization model: First principles, GPS… and GSFLAI



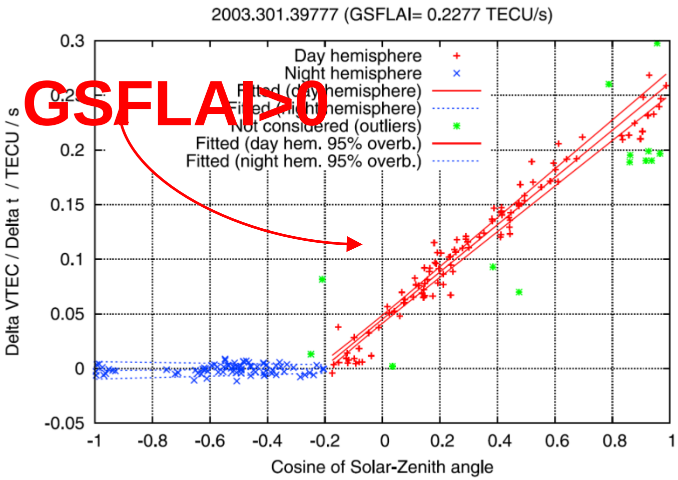


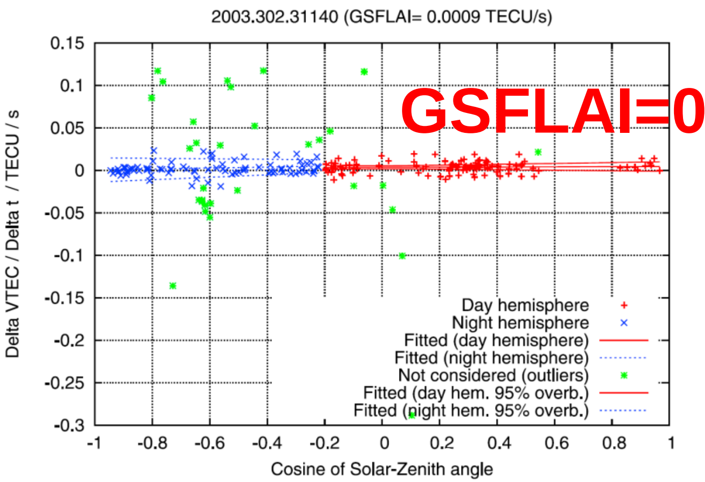
$$\dot{V} = \eta' \cdot C(\chi) \cdot \dot{I}$$

Halloween X-class SF snapshot: **the regresion line slope (GSFLAI)** reacts well.

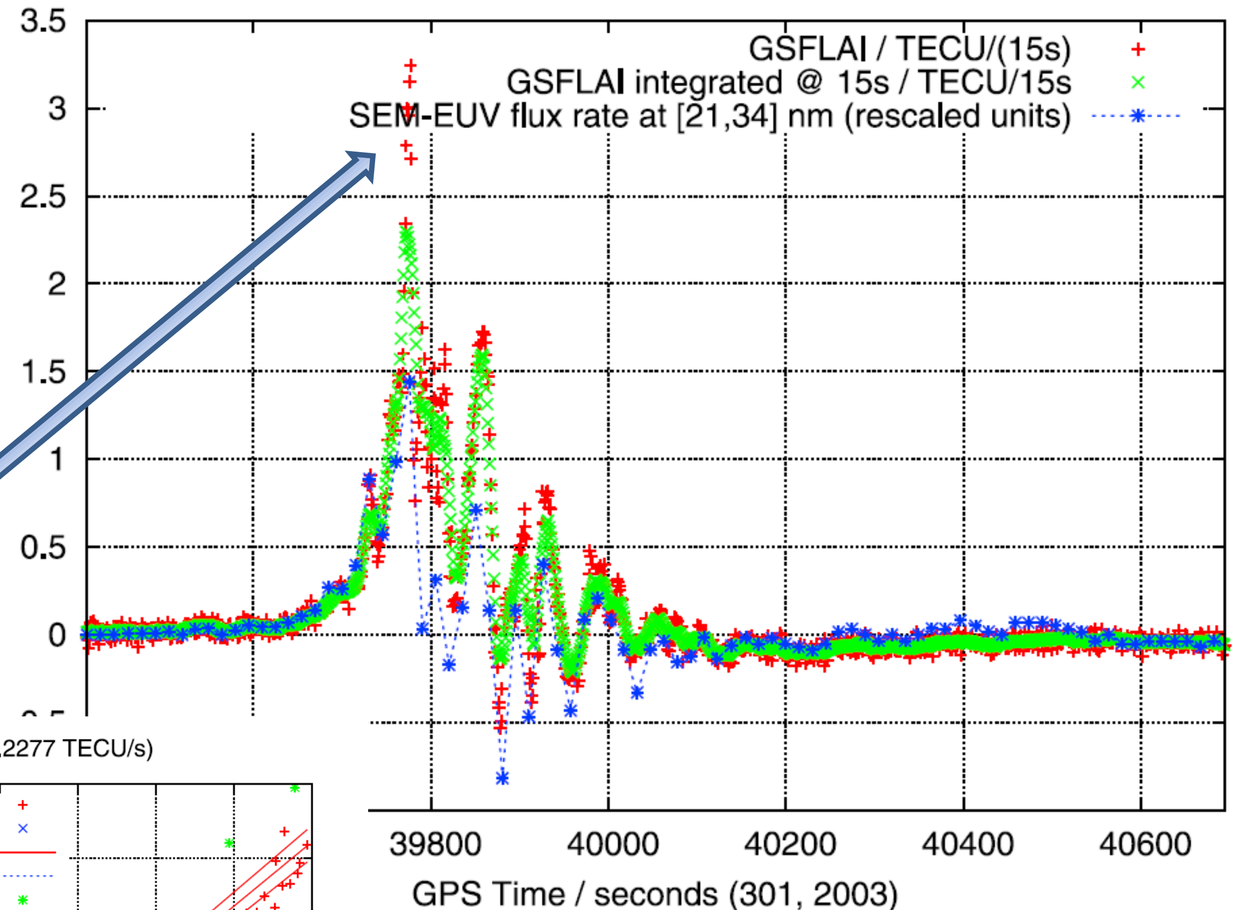


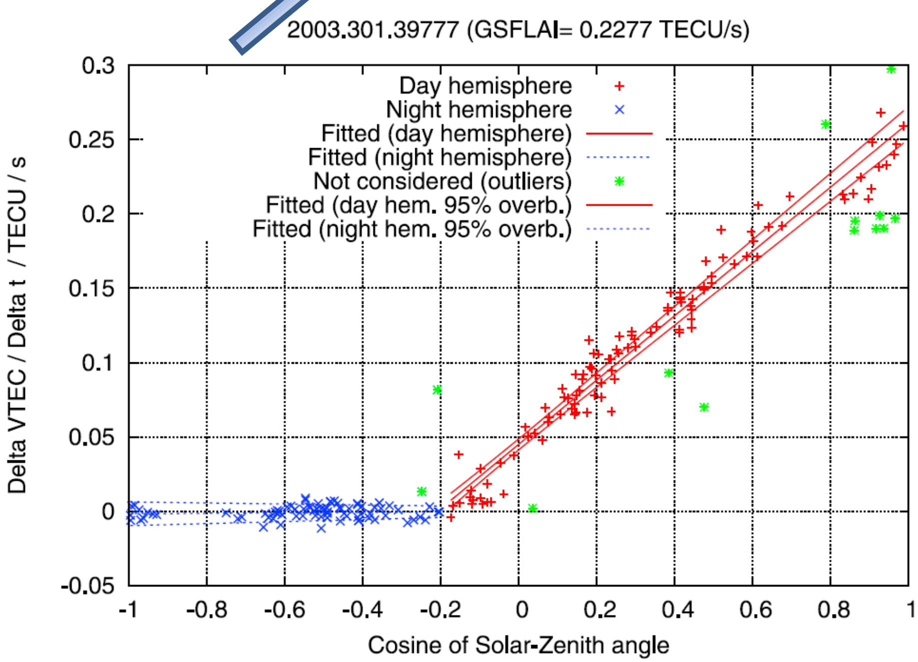
$$\dot{V} = a_1 \cos\chi + a_2$$

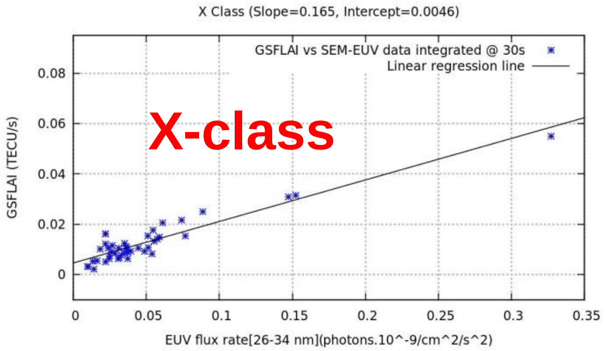


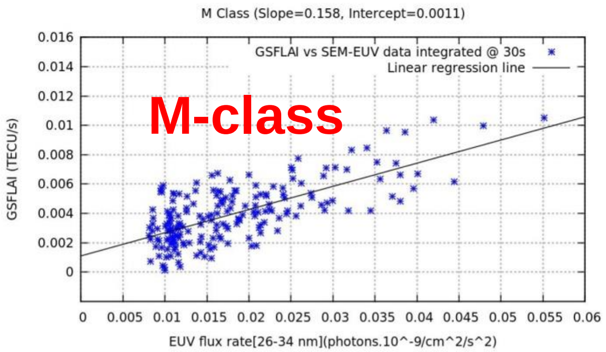


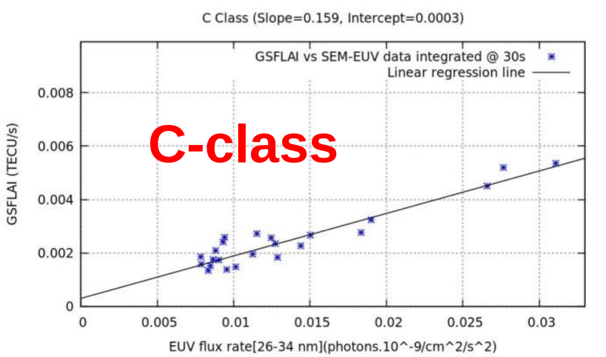
During the next day major geomagnetic storm peak, the higher variations doesn't follow the SF spatial pattern, and GSFLAI (=0) performs again well.


GSFLAI / TECU/(15s)
GSFLAI integrated @ 15s / TECU/15s
SEM-EUV flux rate at [21,34] nm (rescaled units)
3.5
3
2.5
2
1.5
1
0.5
0
39800
40000
40200
40400
40600
GPS Time / seconds (301, 2003)


2003.301.39777 (GSFLAI= 0.2277 TECU/s)
Day hemisphere
Night hemisphere
Fitted (day hemisphere)
Fitted (night hemisphere)
Not considered (outliers)
Fitted (day hem. 95% overb.)
Fitted (night hem. 95% overb.)
Delta VTEC / Delta t / TECU / s
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Cosine of Solar-Zenith angle







The GSFLAI, a proxy of EUV flux rate for X, M & C-class S. Flares

- GSFLAI (point with fastest increase per flare, if above the GNSS measurement error) vs. EUV flux rate data (from SOHO-SEM in 26-34 nm range).

- From top to bottom: X, M and C class Solar Flares meeting the criteria since 2001 until 2014.

- Regression lines, with **slopes 0.165, 0.157 and 0.159 for X, M & C-class** => high consistency of the simple physical model & technique.

Singh, T., M. Hernandez-Pajares, E. Monte, A. Garcia-Rigo, and G. Olivares-Pulido (2015), *GPS as a solar observational instrument: Real-time estimation of EUV photons flux rate during strong, medium, and weak solar flares*, J. Geophys. Res. Space Physics, 120, doi:10.1002/2015JA021824.

Flares		Slope		Intercept		Corr. Factor	
Class	Number	All	Peaks	All	Peaks	All	Peaks
X	60	0.184	0.165	0.0022	0.0046	0.83	0.94
M	320	0.127	0.157	0.0012	0.0012	0.63	0.70
C	300	0.111	0.159	0.0008	0.0003	0.46	0.94

[a] The units are $TECU/s$ for GSFLAI and $photons.10^-9/cm^2/s^2$ for EUV flux rate.

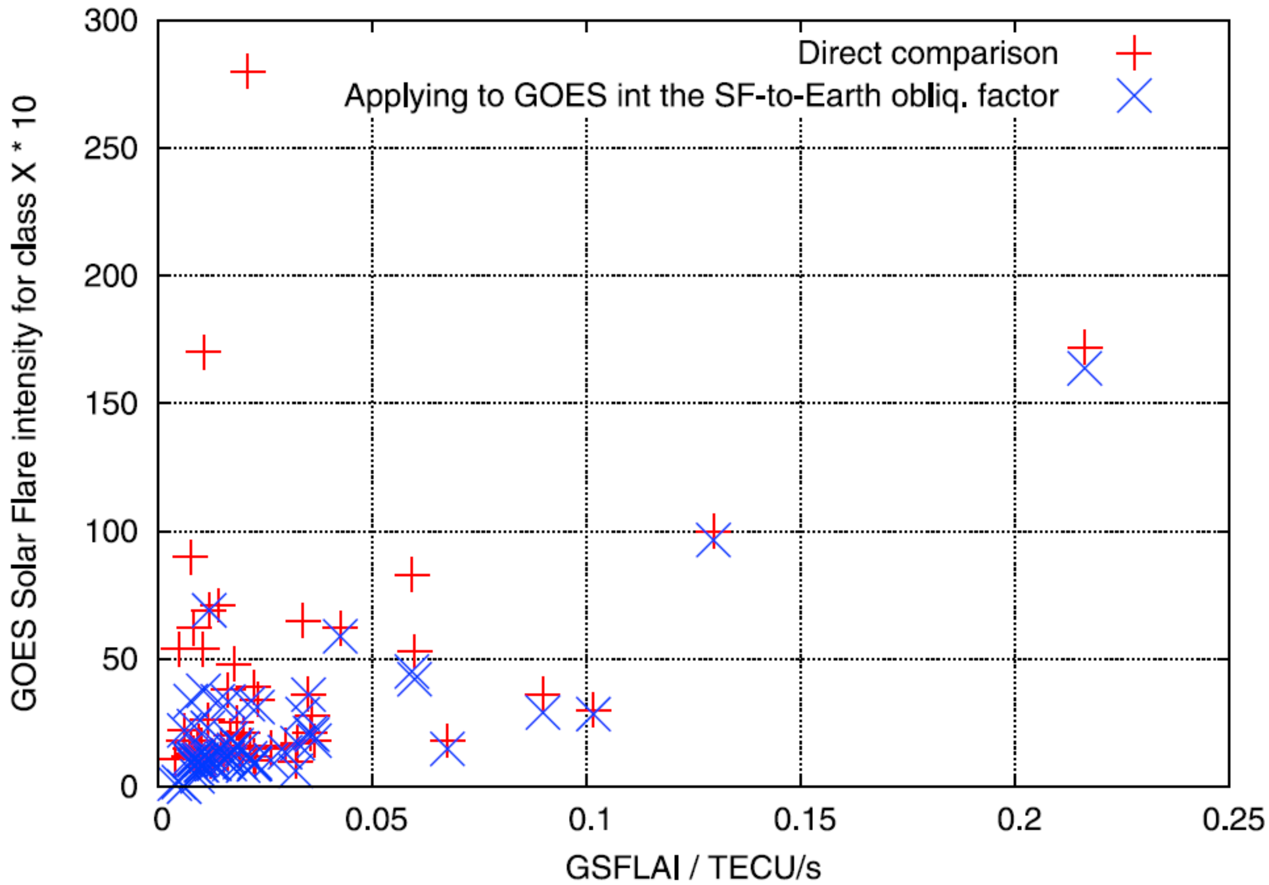
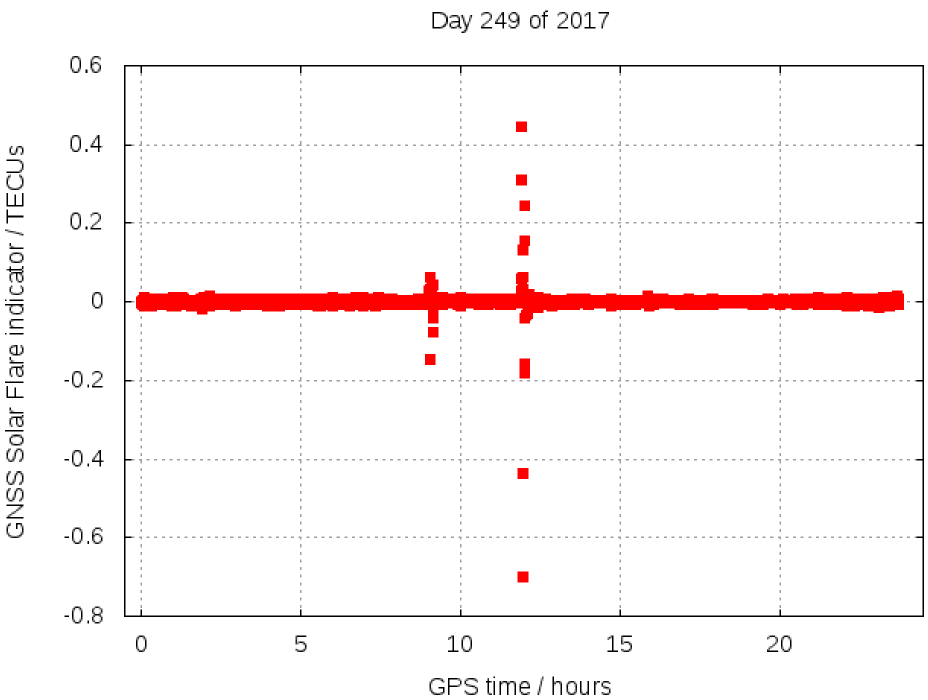
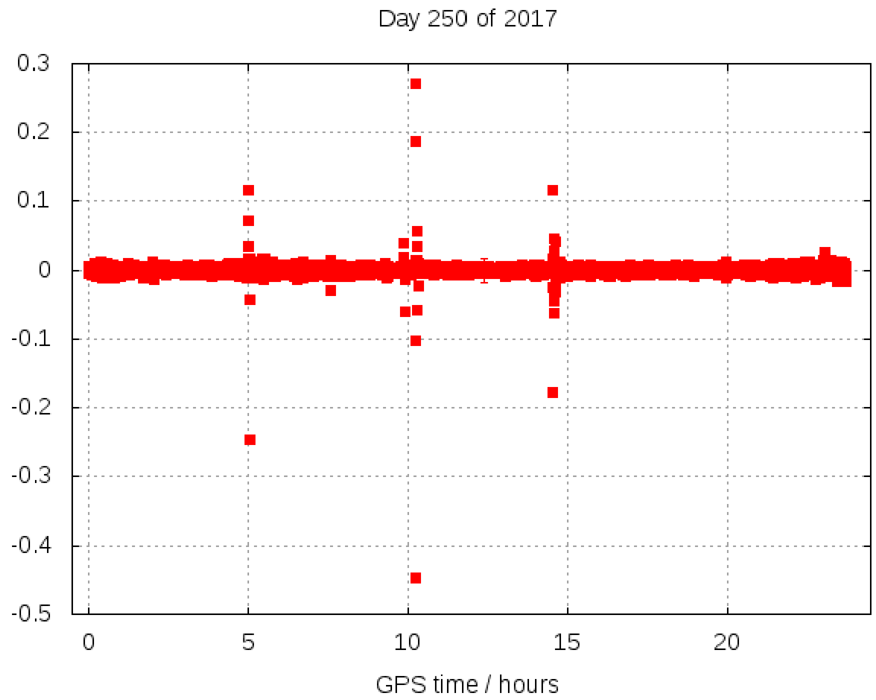


Figure 9. X-ray band solar flare intensity, corresponding to the GOES index for all the X-class flares analyzed in this work (those with available data between 2001 and 2011) represented versus the GSFLAI value at the corresponding peak. The red points represent the direct comparison, and the blue points the comparison after applying a solar-earth deprojecting factor, in terms of the solar flare occurrence location in the surface of the Sun.

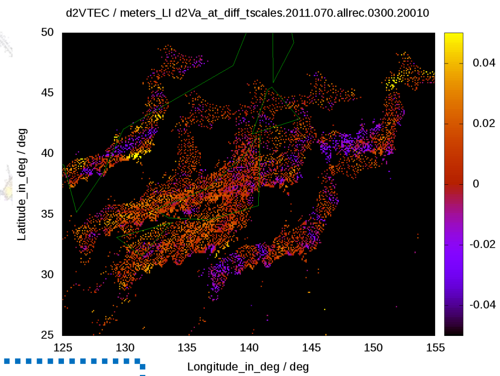
Recent solar flare Sep 6th, 2017: RT detection from global RT GPS measurements with RT-TOMION @ UPC-IonSAT

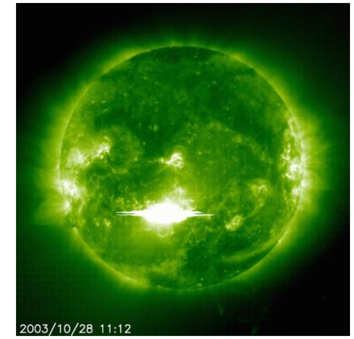




UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

Layout





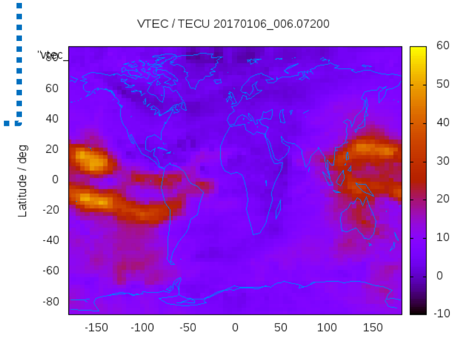
Solar Flare meas. & detection

Potential Tsunami early detection

RT-GNSS datastream

Precise Agriculture

Open Global Ionospheric Maps (IGS)



Border color legend:

Fully implemented & mature

Partially implemented & room for improment

Potentially feasible, to be refined & implemented

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

IonSAT

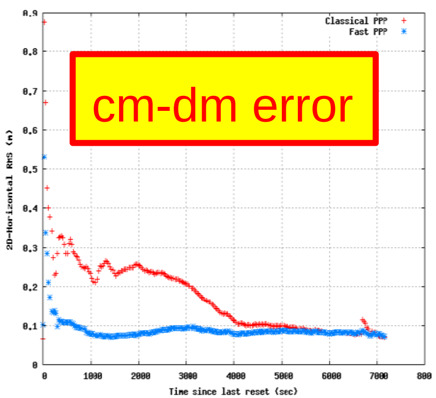
Application #2: Precise Agriculture

- The Wide Area RTK technique is **being implemented** as UPC-IonSAT contribution to Europe Union funded project of the H2020 program.
- It consists on an hybrid geodetic and ionospheric model running RT from a Wide Area GPS data to provide corrections to properly adapted user open-source software receivers.

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

AUDITOR

Title: Advanced Multi-Constellation EGNSS Augmentation and Monitoring
Topic: **GALILEO**-2-2015. Small and Medium Enterprise (SME) based EGNSS applications
Duration: 01/01/2016 – 31/12/2018
Website: http://www.auditor-project.eu
Total cost: 1.157.736,25 €
Partners: ACORDE, UPC, CTTC, Alpha, DGFI, Draxis Environmental S.A. (Greece), DLO (Wageningen University, Holland)



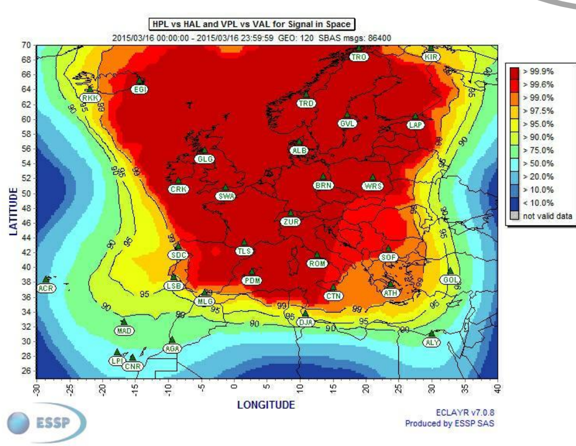
Global Navigation Satellite Systems

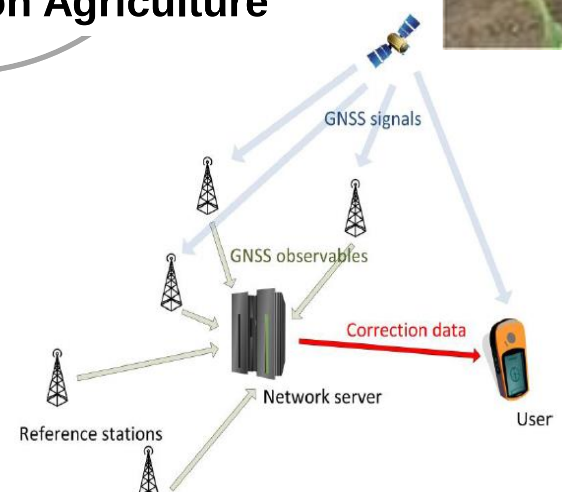
WARTK / FPPP — Low Cost receiver

High Accuracy — RT Network

Fast convergence — User corrections

Services in Precision Agriculture





Scenario and Problem

AUDITOR

Scenario:

✓In Europe (typically at the South):

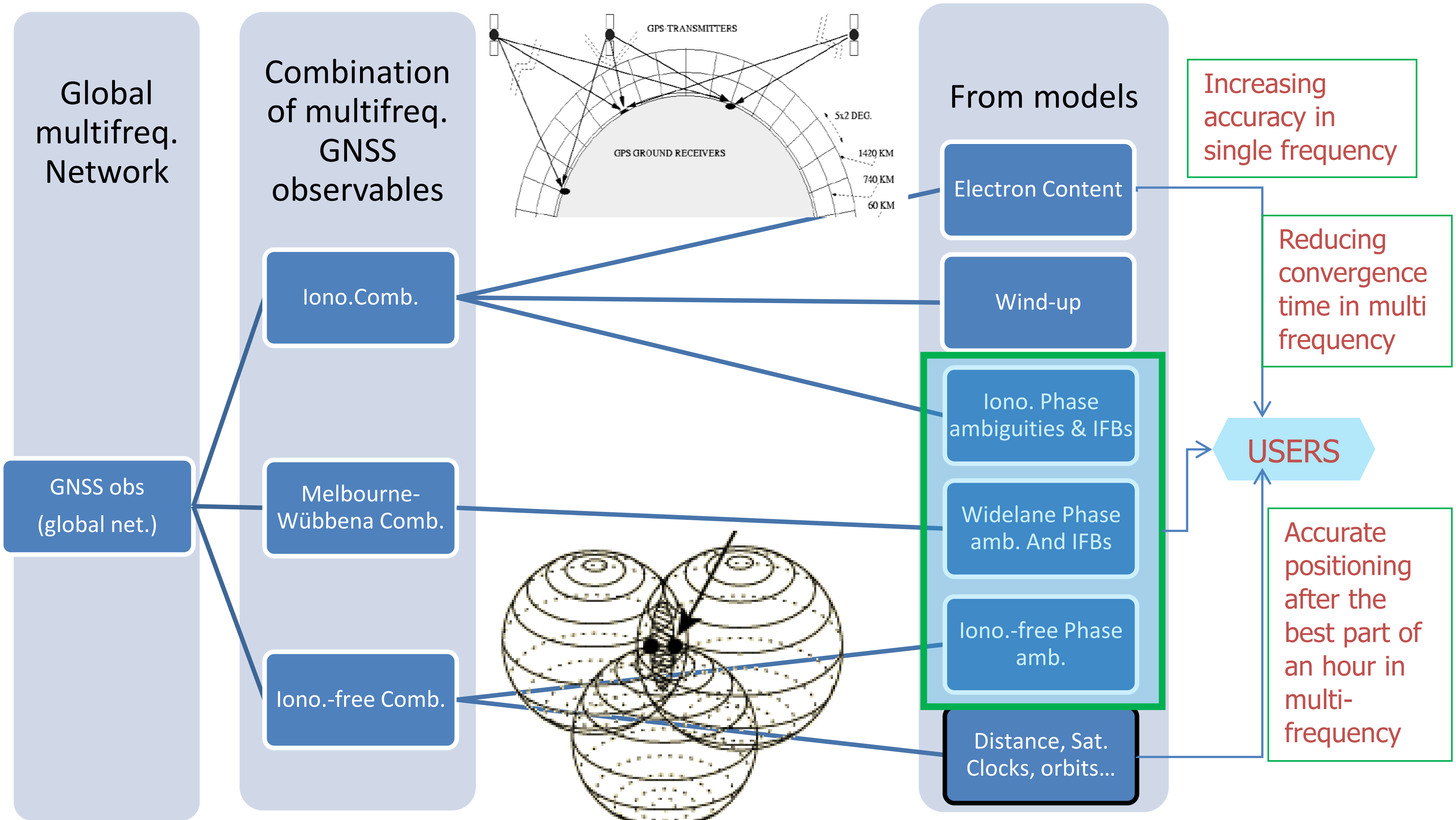
1) The **permanent GNSS networks can be sparse** (up to hundreds of kilometers of distance).
2) The **ionospheric delays can be large**.
3) The economy is not going so well.

Problem:

✓Precise farming in South of Europe will, then, require:

1) Prompt decimeter-error level real-time GNSS positioning at more than 100 km from the nearest GNSS reference site => **Wide Area RTK**
2) Precise real-time ionospheric modelling from the measurements of the GNSS permanent networks => **Dual-layer tomography + Iono. wave modelling** (TOMION).
3) Open source GNSS source receiver, combining flexibility for new GNSS algorithms and affordability.

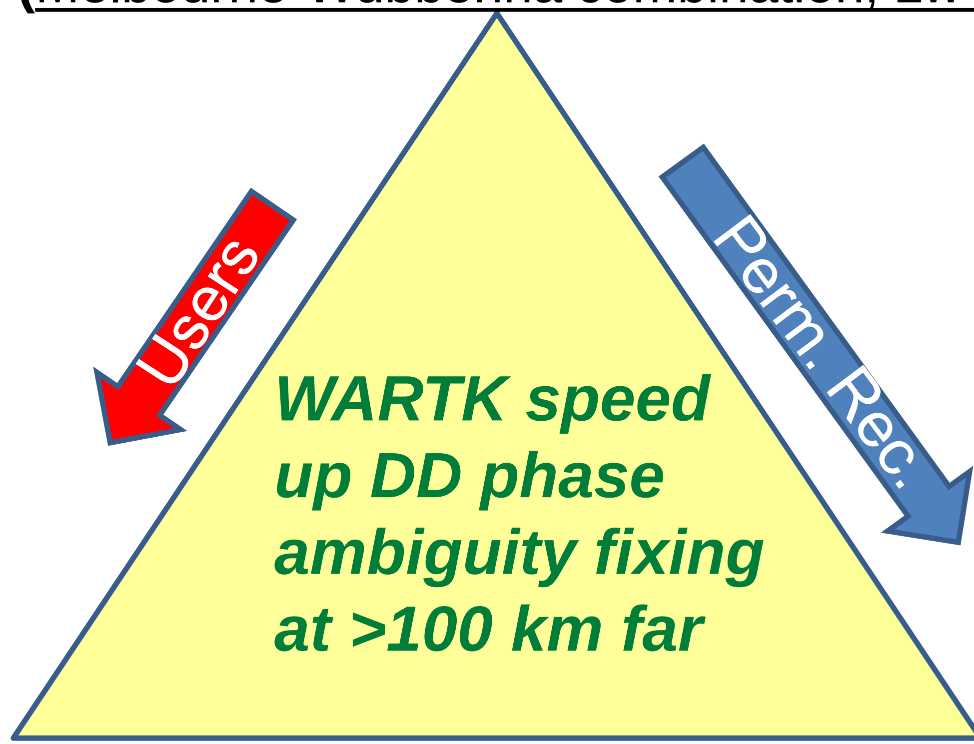
Wide Area RTK / Fast PPP foundamentals
Hybrid ionospheric-geodetic approach



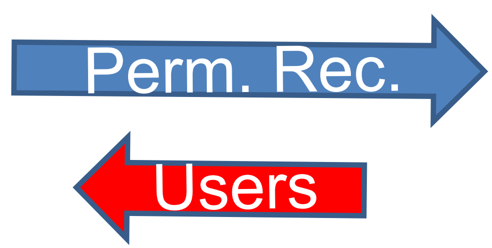
As a consequence of the symbiotic modelling of geometric and ionospheric delay dependences of the GPS, Galileo, GLONASS & Beidou signals: a better positioning service is obtained (cm-accuracy in real-time after short convergence time), and better ionospheric sounding

Wide Area RTK in a nutshell: How to improve the DD phase ambiguity fixing

Geometry- & Ionospheric- free way
(<u>Melbourne-Wubbenna combination, Lw-Pn)</u>



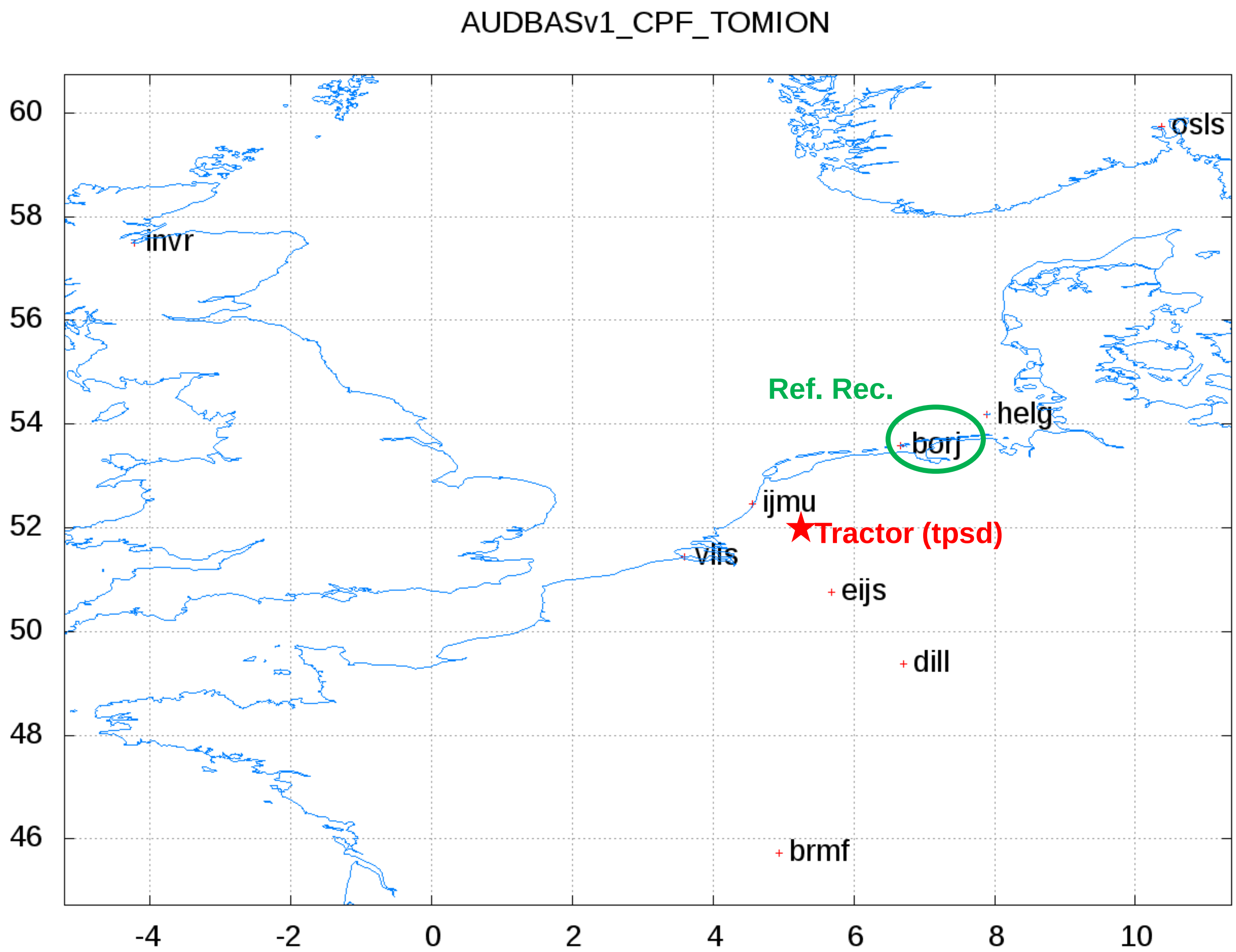
Ionospheric- free way
<u>(Ionospheric-free combination Lc - precise geometric modelling)</u>



Geometry- free way
<u>(Ionospheric combination LI - precise ionospheric modelling)</u>

Exp. 170613: Tractor & permanent network

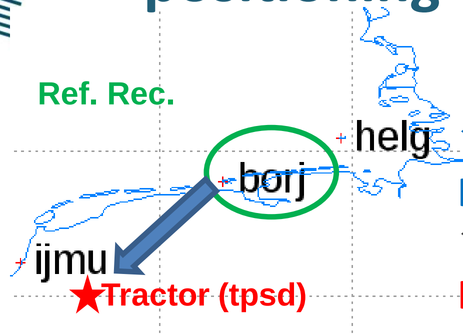
Rec. Id.	Distance to BORJ / km
HELG	104
IJMU	**188**
TPSD	190
VLIS	316
EIJS	321
DILL	468
OSLS	722
INVR	811
BRMF	882



Exp. 170613: Relative RT-mode dual-frequency positioning of Tractor (tpsd) vs Ref. Rec. (borj) with TOMION (1 of 4)

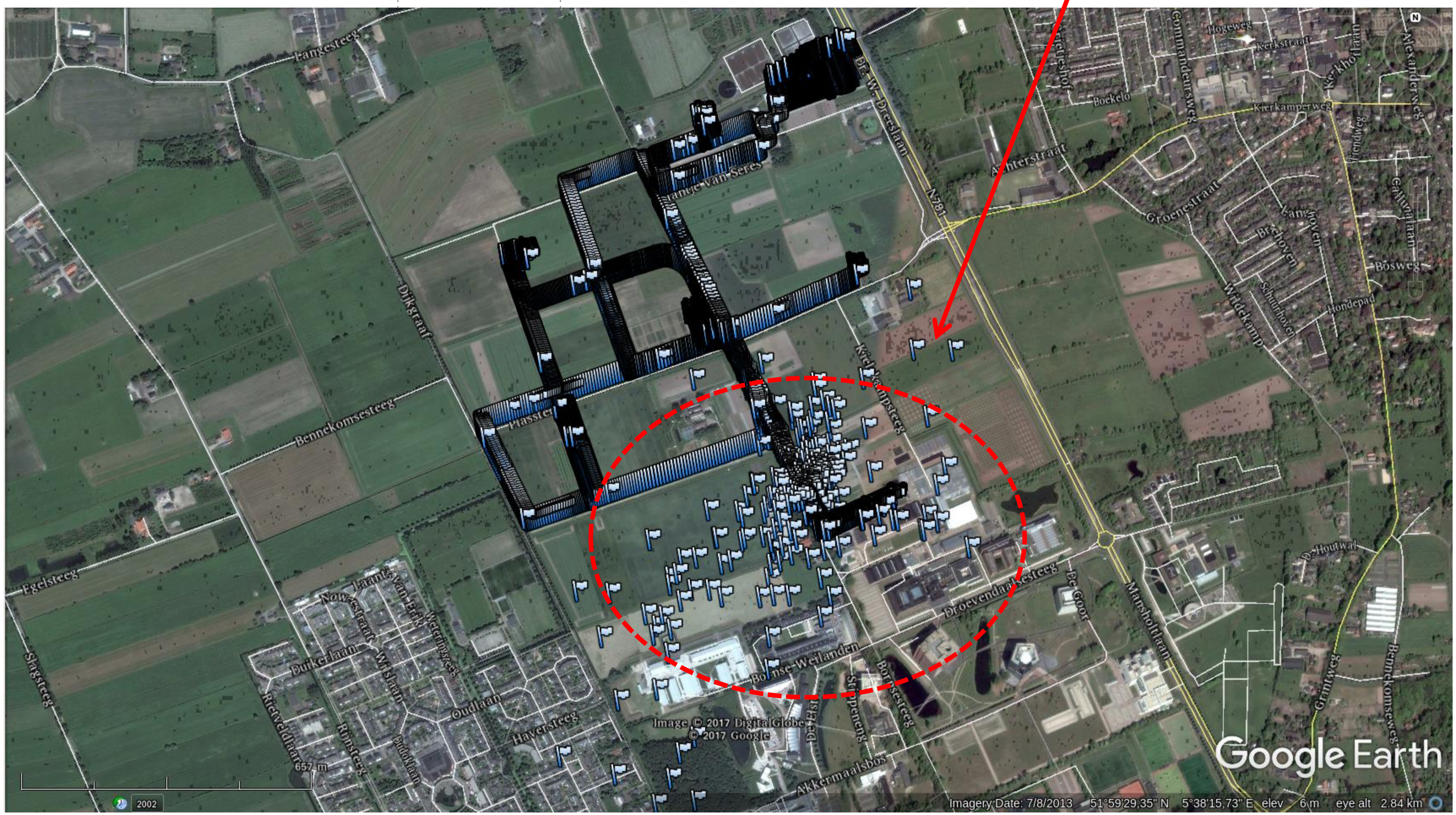
AUDITOR

Rec. Id.	Distance to BORJ / km
IJMU	188
TPSD	190

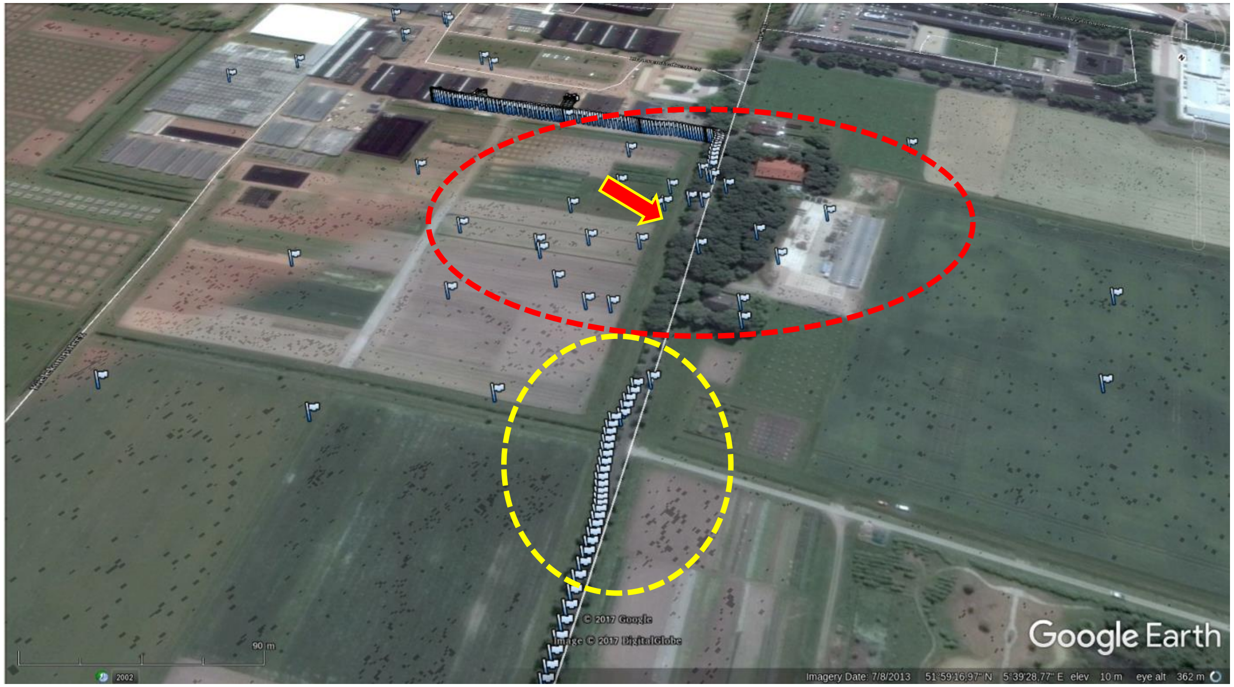


✓Consistency of the most part of positions over the paths compatible with 10cm-error level RT positioning.

✓ But a **cloud of apparently very noisy estimated positions appear**. Why? Cold start? Other reasons?



Exp. 170613: Relative RT-mode dual-frequency positioning of Tractor (tpsd) vs Ref. Rec. (borj) with TOMION (3 of 4)



✓The potential reason of such very large positioning error when moving during the same path (marked by the red arrow) is strongly suggested when the 3D representation is activated at google-earth: **THE CANOPY** (trees densely distributed in such part of the path).

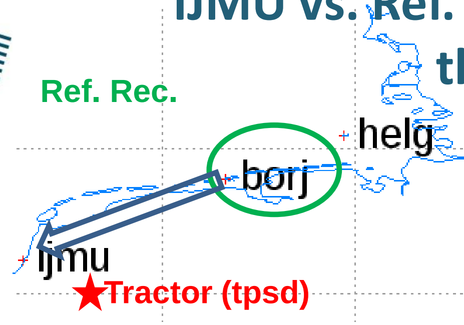
✓The **trees**, affecting to this part of the path, are likely **blocking the signal of many GPS satellites generating cycle-slips and the corresponding re-initialization** of the carrier phase ambiguity estimation.

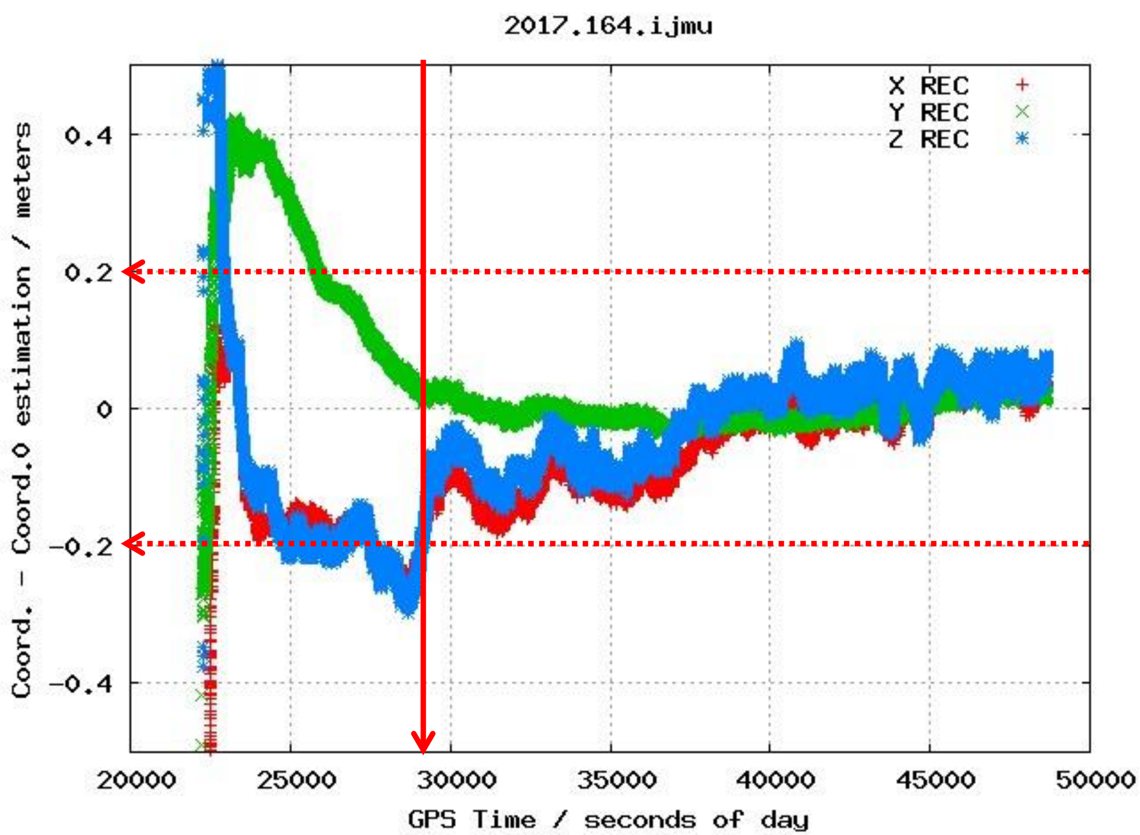
✓The **convergence phase of the positioning can be clearly seen** (within yellow ellipse), lasting for about ~25 seconds.

Exp. 170613: RT Relative dual-frequency positioning of IJMU vs. Ref. Rec. (borj) with TOMION (same time period than Tractor): No Iono. + floating ambiguities

AUDITOR

Rec. Id.	Distance to BORJ / km
IJMU	188
TPSD	190



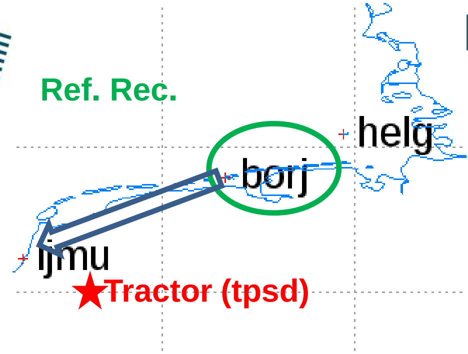


✓Convergence time of ~7000 sec (No Iono. + floating ambiguities)

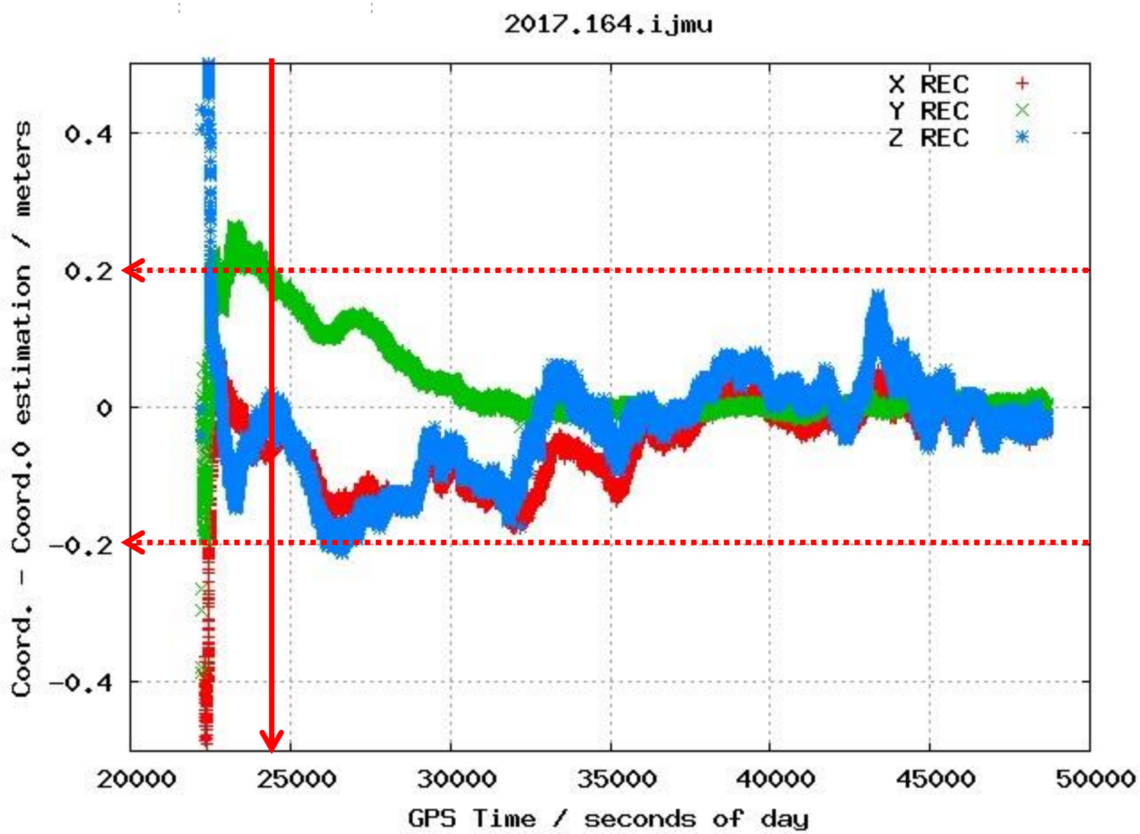
Exp. 170613: RT Relative dual-frequency positioning of f. Rec. (borj) with TOMION (same time period Tractor): ambiguities constrained by RT iono.

AUDITOR

Rec. Id.	Distance to BORJ / km
IJMU	188
TPSD	190



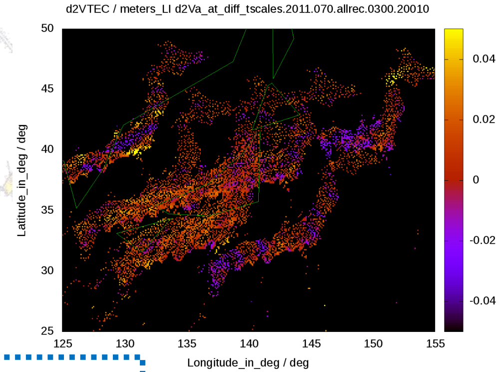
✓Mitigation strategies of GNSS precise positioning under canopy (such as Soloviev & Dickman, 2011) should be considered in future upgrades of the soft. receiver.



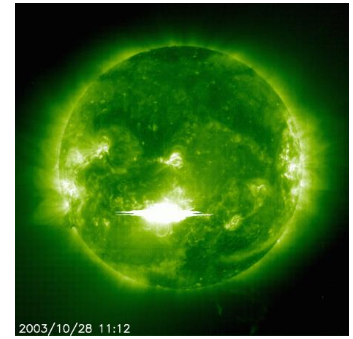
✓When Wide Area RTK, involving precise ionospheric corrections, is applied, the convergence time under full cold start is reduced to less than one third.

✓Convergence time of ~2000 sec (ambiguities constrained by RT iono)

Layout



Solar Flare meas. & detection



Border color legend:

Fully implemented & mature

Partially implemented & room for improment

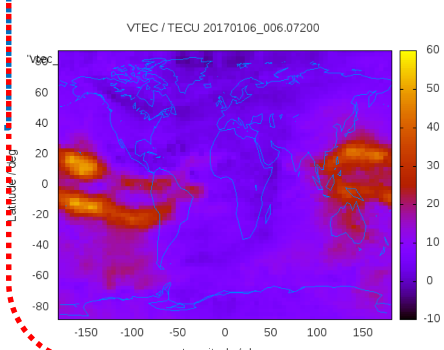
Potentially feasible, to be refined & implemented

Potential Tsunami early detection

RT-GNSS datastream

Precise Agriculture

Open Global Ionospheric Maps (IGS)

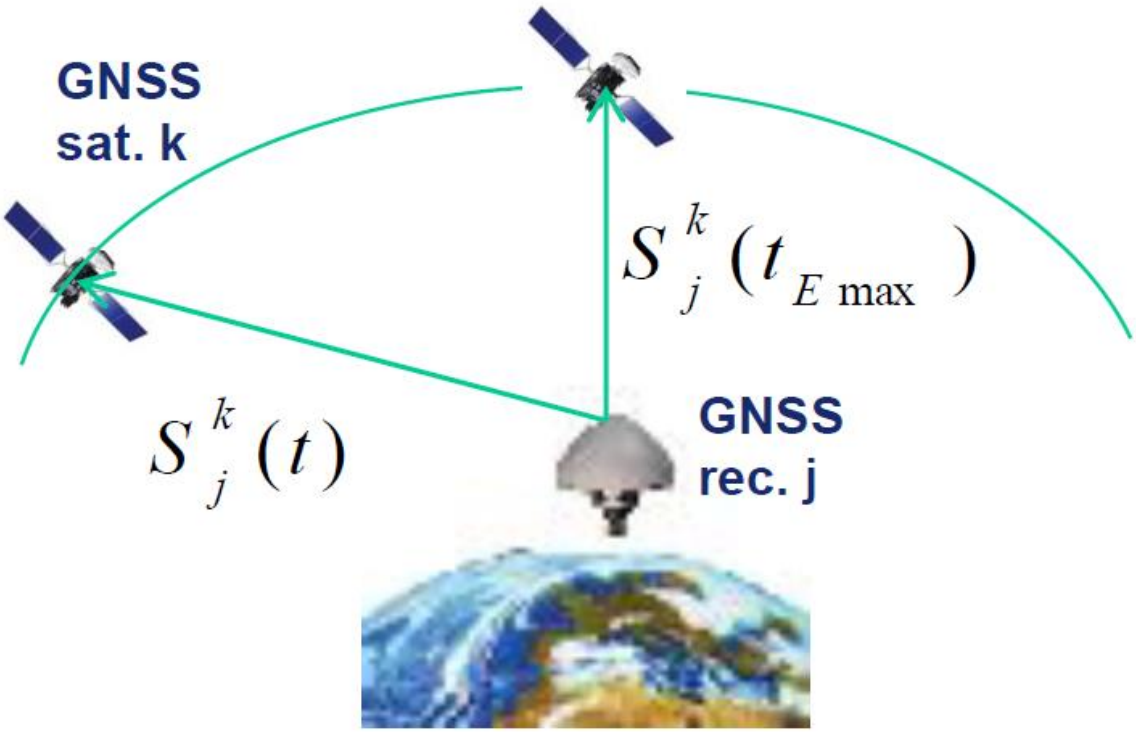


UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

Application #3:
RT- Global Ionospheric Maps

- The GPS datastream of +150 worldwide distributed permanent receivers are being used by UPC-IonSAT **since 2013 to produce experimental RT-GIMs of vertical ionospheric electron content** (i.e. delay).
- The objective, in the context of the International GNSS Service, is to contribute to a first RT combined GIM, in combination with other available RT-GIMs.

dSTEC-GPS layout



1) (Cont) External validation vs dSTEC-GPS @ independent receivers

RT-GIMs (AOEG, CNSG, URTG)

GIM	RMS [TECU]	RMS max [TECU]	RMS min [TECU]	BIAS [TECU]
AOEG	11.8	22.6	4.8	-1.43
CNSG	9.2	18.8	3.0	0.21
URTG	8.2	14.9	3.4	0.30
DGFI	5.6	10.8	1.8	-0.57
IGSG	6.2	11.6	1.9	-1.01
UQRG	4.6	9.1	1.1	-0.61

35 GPS stations have been used. The dSTEC RMS has been calculated for the days of year 2016 from 45 to 59.

2) Analysis centers which might contribute to a combined IGS RT-GIM soon

CNES already transmits RT-GIM (RTCM iono. Messages from PRODUCTS.IGS-IP NTRIP caster)

UPC-IonSAT already transmits RT-GIM (IONEX format)

WHU already transmits RT-GIM (IONEX format)

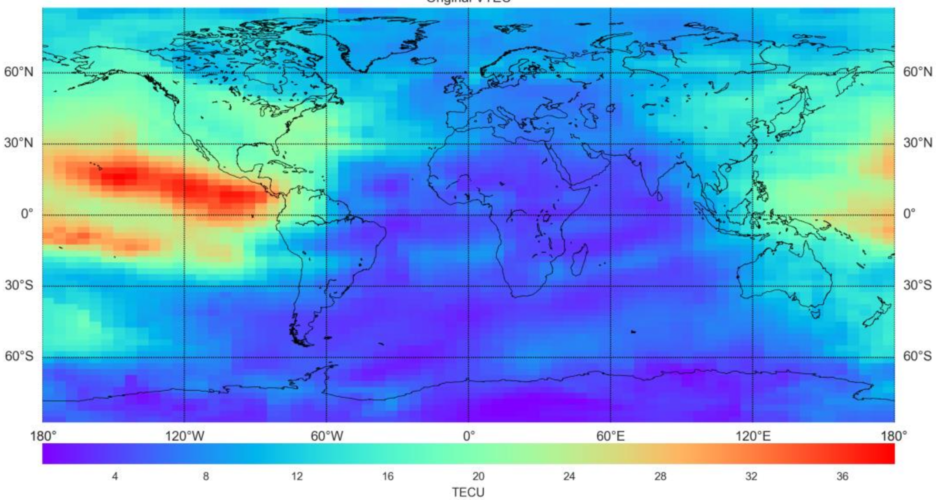
CAS is very interested to transmit RT-GIM by the end 2017 for the RT IGS combination. Currently testing the stability of software, accuracy of RT-GIM, and trying to get more global real-time data streams (internal format, but it can be adapted).

NRCAN interested to join future RT-GIM IGS product. Currently, they produce near-real-time global vTEC maps (IONEX and spherical harmonic coefficients, no schedule yet for RTCM format). An offline comparison and comb. is suggested.

4.(Cont) *Importance of using the right SH order/degree*

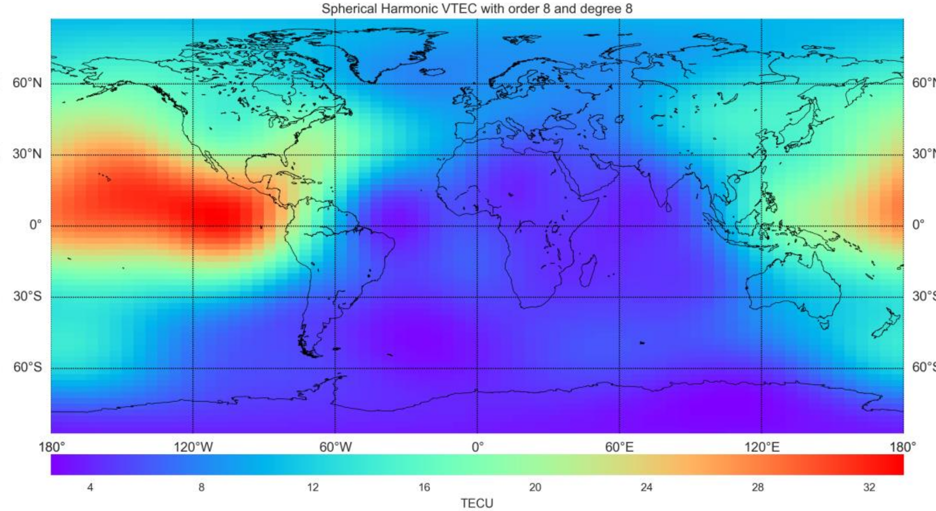
ORIGINAL GIM
(UQRG1480.17i, 00UT)

Original VTEC

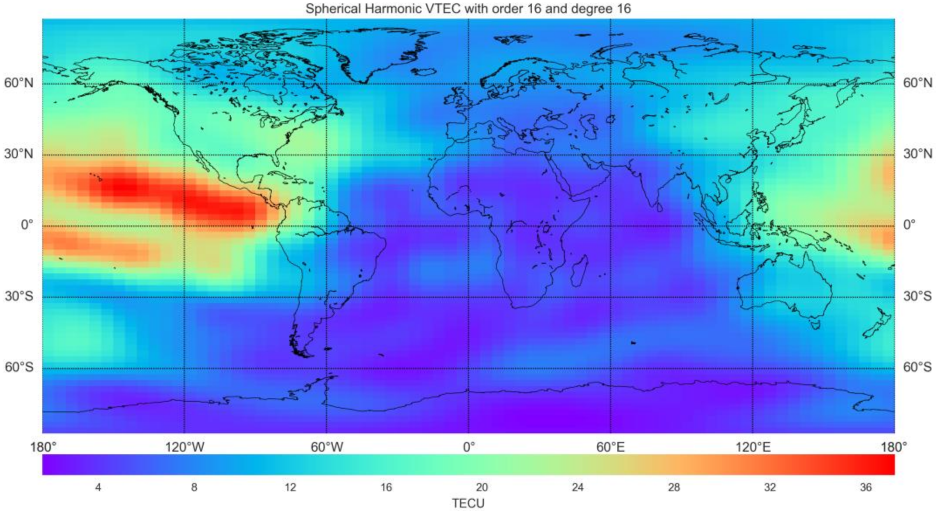


Reconstructed GIM **13% error** **(deg.=8 & ord.=8)**

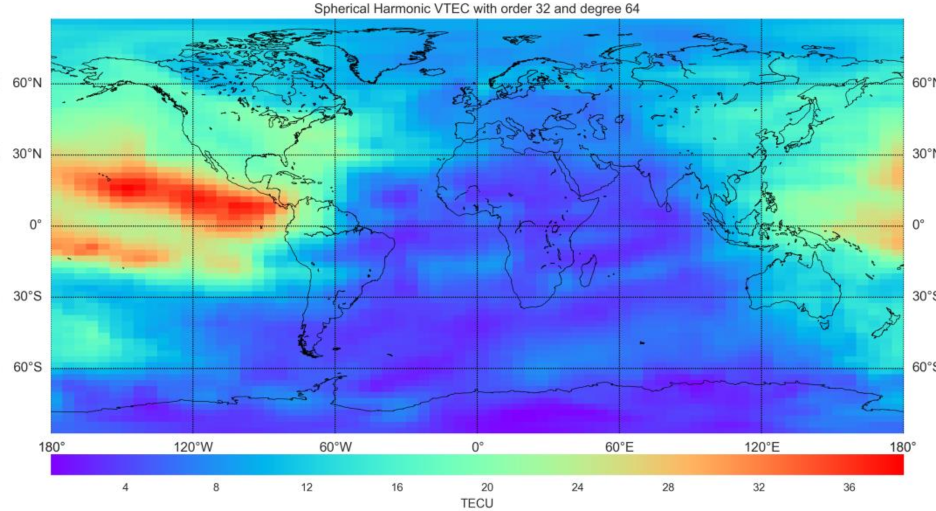
Spherical Harmonic VTEC with order 8 and degree 8



Spherical Harmonic VTEC with order 16 and degree 16



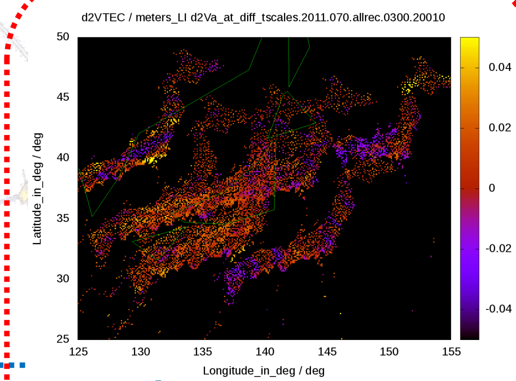
Spherical Harmonic VTEC with order 32 and degree 64



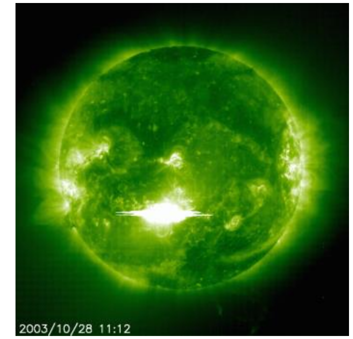
Reconstructed GIM **5.8% error**
(deg=16 & ord=16, max. RTCM)

Reconstructed GIM **1.8% error**
(degree=64 & order=32)

Layout



Solar Flare meas. & detection

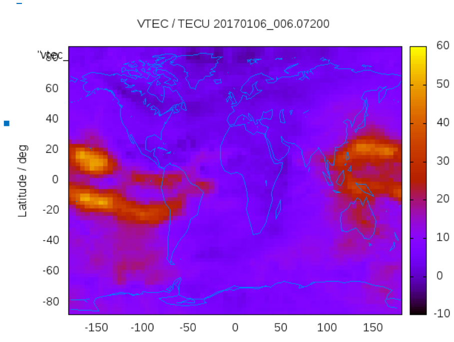


Potential Tsunami early detection

RT-GNSS datastream

Precise Agriculture

Open Global Ionospheric Maps (IGS)



Border color legend:

Fully implemented & mature

Partially implemented & room for improment

Potentially feasible, to be confirmed & implemented

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

IonSAT

Application #4:

Monitoring of co-seismic generated ionospheric signals & potential Tsunami warnings

- Application of RT ionospheric sounding for potential Tsunami warnings, with GNSS dense (Tohoku and mid earthquakes, EQ) and sparse networks (Chile 2015 EQ)..

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

IonSAT

Scenario A: Dense wide networks (GEONET, SCIGN). Two case-studies of major and mid earthquakes

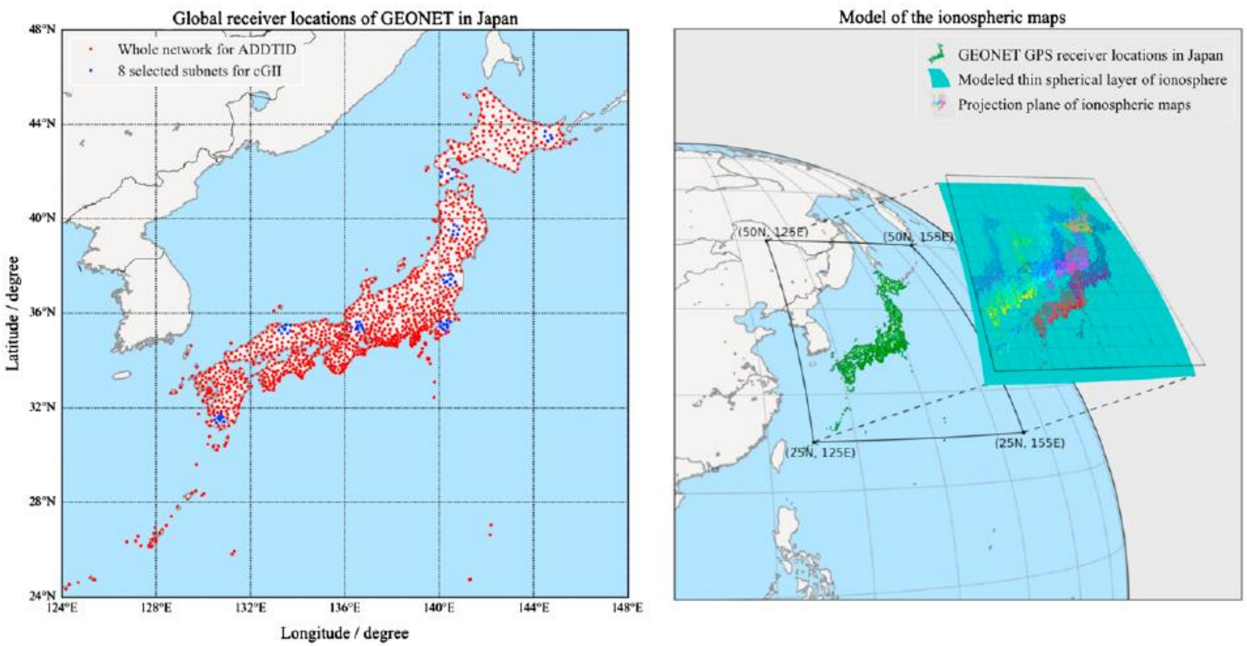
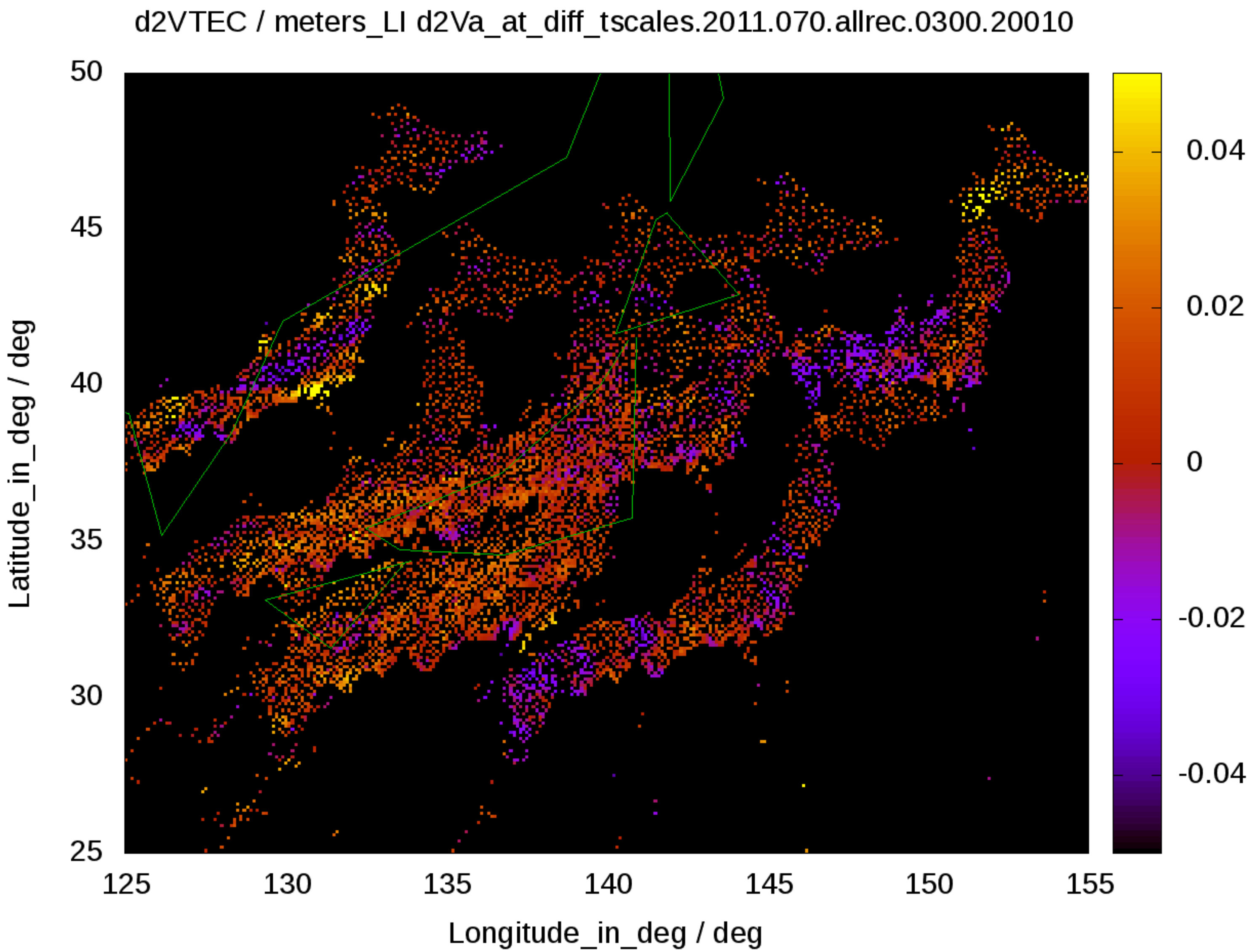


Figure 1. (left) Distribution of GPS receivers in the Japan GEONET network and (right) IPPs distribution in the ionospheric map for different satellites.

(Extracted from Yang, H., E. Monte-Moreno, and M. Hernández-Pajares (2017), *Multi-TID detection and characterization in a dense Global Navigation Satellite System receiver network,* J. Geophys. Res. Space Physics, 122, doi:10.1002/2017JA023988.)

Ionospheric signature associated to the major earthquake Tohoku / Tsunami (from d2VTEC300s)

- firefox ftp://newg1.upc.es/.4dimitar_and_sergey/201309_30.first_study_on_Fukushima_events/d2Va_at_diff_tscales.2011.070.0300.2.gif



Circular ionospheric waves approx. centered in middle intensity earthquake (M4.6 & M4.9) epicenter happens few hundreds of second after

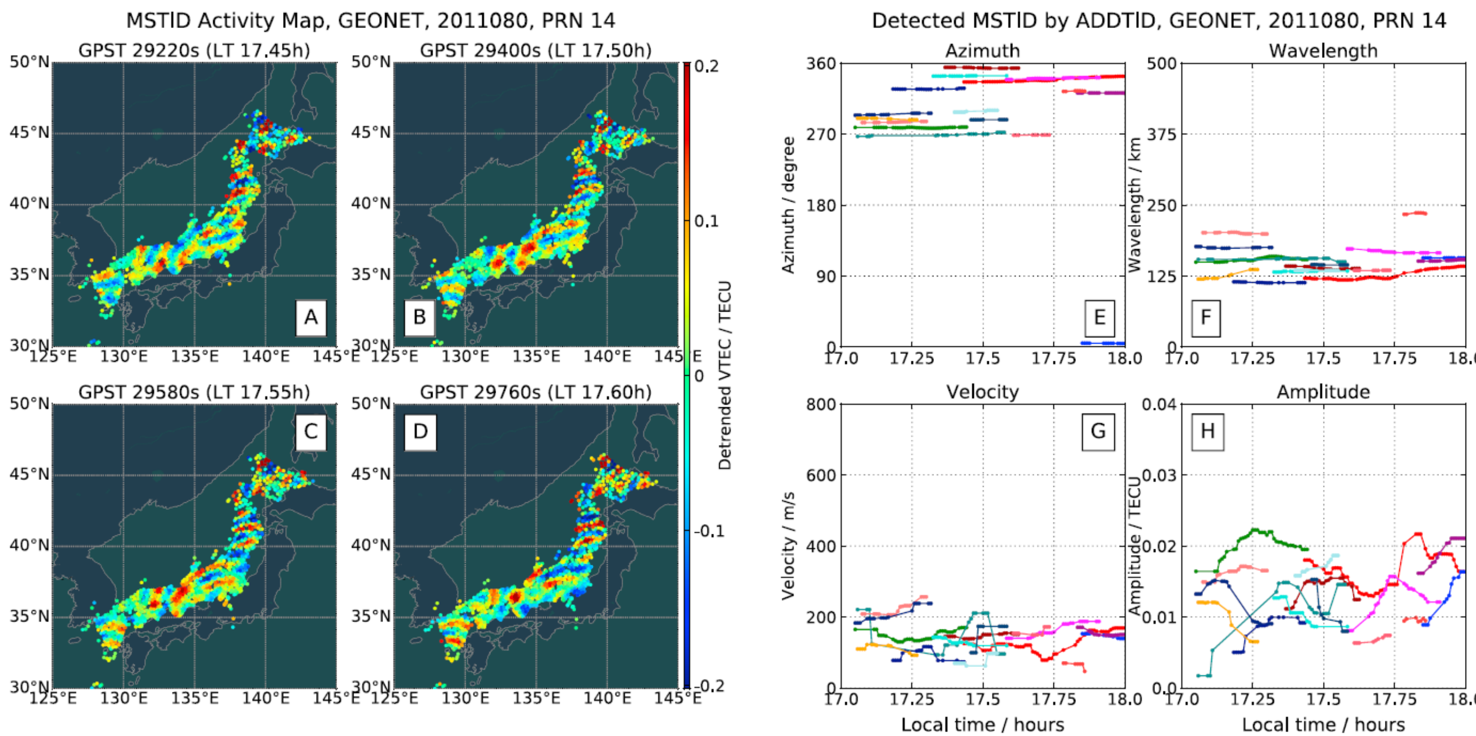


Figure 11. Circular-like MSTIDs during the evening solar terminator about 17:30 LT, from the GEONET, for satellite PRN 14, on the 80th day of 2011. (a–d) Circular MSTID in the detrended VTEC maps (in TECUs) at evening time (17:27–17:36 LT), for four snapshots at GPS time 29,220, 29,400, 29,580, and 29,760 s. (e–h) The time evolution of the estimated parameters during the time interval 17:00–18:00 LT, by azimuth, wavelength, velocity, and amplitude.

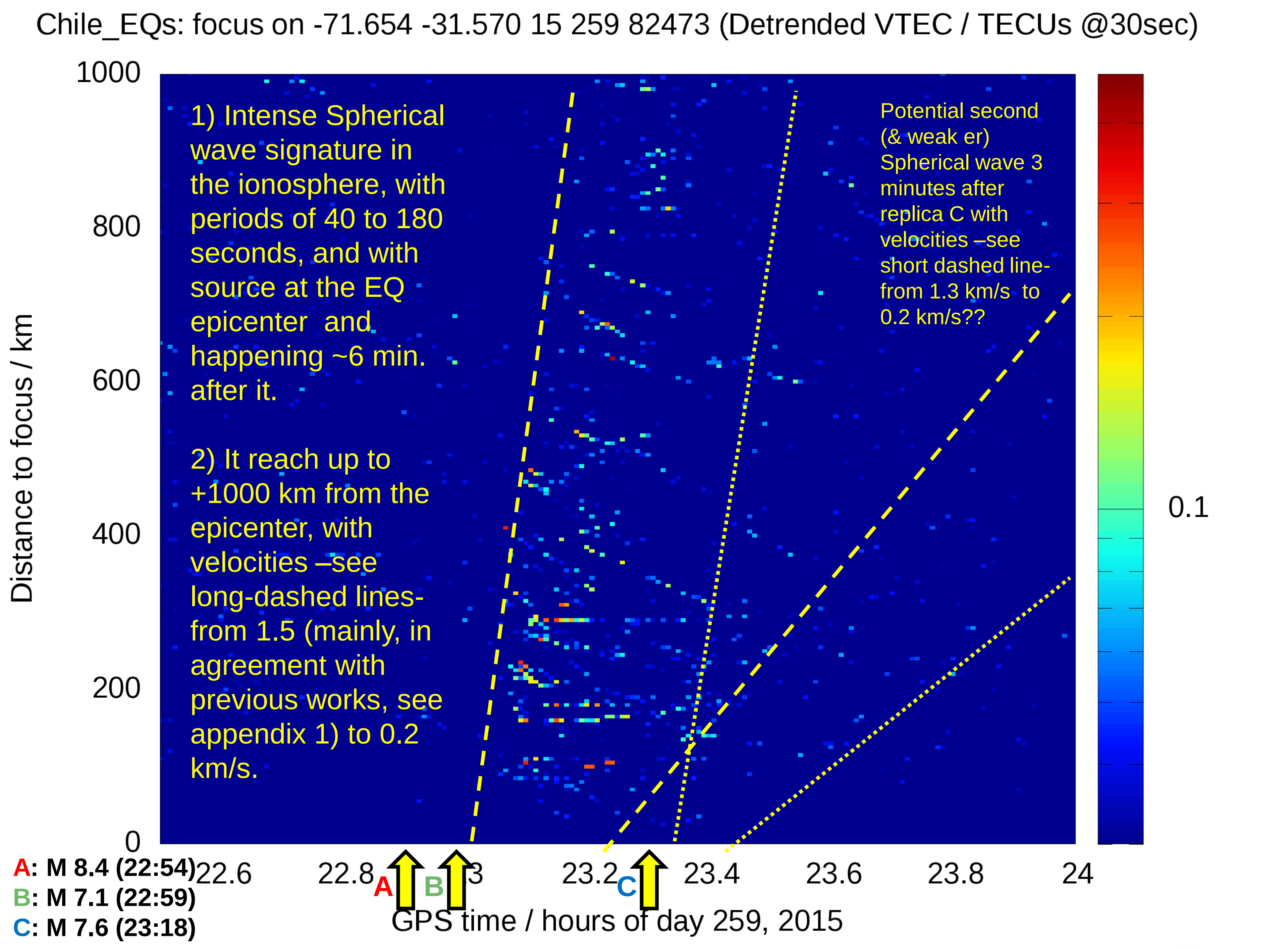
(Extracted from Yang, H., E. Monte-Moreno, and M. Hernández-Pajares (2017), *Multi-TID detection and characterization in a dense Global Navigation Satellite System receiver network,* J. Geophys. Res. Space Physics, 122, doi:10.1002/2017JA023988.)

Scenario 2: Wide not dense GPS network. Case study of major Illapel earthquake on Chile, 2015

- Earthquake happened at Chile on Sep., 16th 2015, 22:54 UTC.

- Gathered from dual-frequency GPS observations taken on few dozens of Argentina & Chile permanent GPS receivers.

- The next results were mainly computed from double-time-difference of VTEC @ 300s (i.e. d2VTEC300s, mainly focused on ionospheric periods from 400 to 1200s).


Chile_EQs: focus on -71.654 -31.570 15 259 82473 (Detrended VTEC / TECUs @30sec)
1000
800
600
400
200
0
Distance to focus / km
22.6
22.8
3
23.2
23.4
23.6
23.8
24
GPS time / hours of day 259, 2015
0.1
1) Intense Spherical wave signature in the ionosphere, with periods of 40 to 180 seconds, and with source at the EQ epicenter and happening ~6 min. after it.
2) It reach up to +1000 km from the epicenter, with velocities –see long-dashed lines- from 1.5 (mainly, in agreement with previous works, see appendix 1) to 0.2 km/s.
Potential second (& weak er) Spherical wave 3 minutes after replica C with velocities –see short dashed line- from 1.3 km/s to 0.2 km/s??
A
B
C
A: M 8.4 (22:54)
B: M 7.1 (22:59)
C: M 7.6 (23:18)

Conclusions

- The RT ionospheric sounding with GNSS is playing an increasing role in improving different areas, such as precise real-time positioning, space weather monitoring, earthquake signatures and potential tsunami detection, among others.

- The above mentioned RT contributions are implemented thanks to the availability of hundreds of worldwide GNSS datastreams.

- Other UPC-IonSAT RT-applications are running as well in a stable way (ROTI scintillation & MSTID activity indices, sidereal-day VTEC variation)

MANY THANKS FOR YOUR ATTENTION!