Final Presentation

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Outline

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2. **IONO4HAS tool design and algorithms**
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    b) Unambiguous STEC computation
    c) Ionospheric Modelling
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6. **Potential studies using the outputs of IONO4HAS**
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    b) South-hemisphere TEC anomalies
    c) Possibility of using HAS SL1 corrections in IONO4HAS
7. **Conclusions**
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1. Introduction: Project main objective

Implementation of a prototype of 3D High Precision Ionospheric Correction Real-Time caster tool on a continental scale, allowing assessing different real-time computation strategies for different geographic locations, network sizes and different ionospheric messages to achieve high-accuracy ionospheric estimates.

1. Introduction: Work to be performed (SoW)

Task 1: Study High precision 3D ionosphere models.

Task 2: Advanced algorithms for Real-Time 3D ionosphere models.

Task 3: 3D ionospheric and interfrequency bias dissemination message selection.

Task 4: Design of a modular e-RTICC.

Task 5: Implementation of the e-RTICC.

Task 6: ESA Real-Time Ionospheric Continental Caster (e-RTICC) campaigns.

1. Introduction: Organization of the work

IONO4HAS project

- **WP00** Management
- **WP10** Revision SoA and Requirements
- **WP20** Algorithm Evaluation
- **WP30** Message Selection
- **WP40** Algorithm Design
- **WP50** Implementation
- **WP60** E-RTICC Campaigns
- ***Further Studies***

List of documents	*Corresponding WP*
TN1.1 State-of-art 3D models for ionospheric determination	WP10
TN1.2 Consolidated Requirements document	WP10
TN2 Algorithms for Real-Time 3D ionosphere determination	WP20
TN3 3D ionosphereand interfrequencybias dissemination messages	WP30
TN4.1 e-RTICC Justification Design Document	WP40
TN4.2 e-RTICC Design Document	WP40
TN4.3 e-RTICC Validation Plan	WP40
TN5.1 e-RTICC implementation	WP50
TN5.2 e-RTICC user manual	WP50
TN5.3 e-RTICC deployment manual	WP50
TN5.4 e-RTICC Validation results	WP50

List of documents	*Corresponding WP*
TN6.1 e-RTICC operation report	WP60
TN6.2 e-RTICC performance report	WP60
TN6.3 e-RTICC feedback report	WP60
SW1 e-RTICC source code (pre-processing)	WP30, Contact Closure
SW2 e-RTICC source code (ionospheric part)	WP30, Contact Closure
SW3 e-RTICC source code (Frame)	WP30, Contact Closure
SW4 e-RTICC Deployment Package	WP30, Contact Closure
Technology Achievement Summary	Final Review
Final Report	Final Review
Summary Report	Final Review
Executive Summary Report	Final Review

1. Introduction: Consolidated requirements (1)

Requirements		
development of a prototype tool for Real-Time 3D ionosphere corrections, e-RTICC		*High Level Requirements*
able to process Galileo and GPS satellites (optional Beidou and GLONASS)		
Shall be modular; each calculation step shall be independent from previous one.		*Functional Requirements*
able to connect to private/public stream of data		
able to use simultaneously several streams of data		
able to be deployed with minimum intervention		
shall be used with RINEX data for testing purposes.		
shall be used as post-process tool		
able to introduce new ionosphere/biases messages in a modular way.		

1. Introduction: Consolidated requirements (2)

Requirements	
process as a minimum L1/E1, L2, L5/E5a, E5B, E5, E6 (may process B1, B2, B3)	
able to process carrier phase data and code pseudorange observables	
process the data with a 3D ionosphere model	
produce ionospheric corrections with an error estimate	
produce interfrequency bias products for dual frequency CDMA combinations with an error estimate (GPS: L1/L2 , L1/L5. GAL: E1/E5a, E1/E5b, E1/E5. BDS: B1/B2 , B1/B3)	
biases selection has to be done by the operator	
generate message for ionosphere to be broadcast from MEO satellite (400 bit maximum for one satellite, using up to 2 satellites).	
generate message for ionosphere to be broadcast from GEO/IGSO satellite (400 bit maximum for one satellite with continuous visibility)	
generate message for ionosphere to be broadcast from terrestrial networks (unlimited bandwidth)	
generate message for interfrequency biases to be broadcast from MEO satellite (400 bit maximum for one satellite, using up to 2 satellites)	

Technical Requirements

1. Introduction: Consolidated requirements (3)

Requirements	
generate message for interfrequency biases to be broadcast from GEO/IGSO satellite (400 bit maximum for one satellite with continuous visibility)	
generate message for interfrequency biases to be broadcast from terrestrial networks (*unlimited* bandwidth)	
shall produce ionosphere data with the appropriate sampling, 300 seconds	
shall produce interfrequency bias data with the appropriate sampling, 300 seconds	
Latency of the end-to-end has to be monitored.	
Latency should be less than 1 minute (95%)	

Technical Requirements

1. Introduction: Consolidated requirements (4)

Requirements	
The e-RTICC shall be validated with independent VTEC data	
The e-RTICC shall be validated with STEC post-processed data	
The e-RTICC shall be validated for its impact on single frequency users PVT	
The e-RTICC shall be validated for its impact on multi-frequency users PVT	
The e-RTICC impact on PVT will be done by means of positioning error	
The e-RTICC impact on PVT will be done by means of convergence time to a 30 cm horizontal, vertical and 3D threshold against its counterpart without the corrections.	

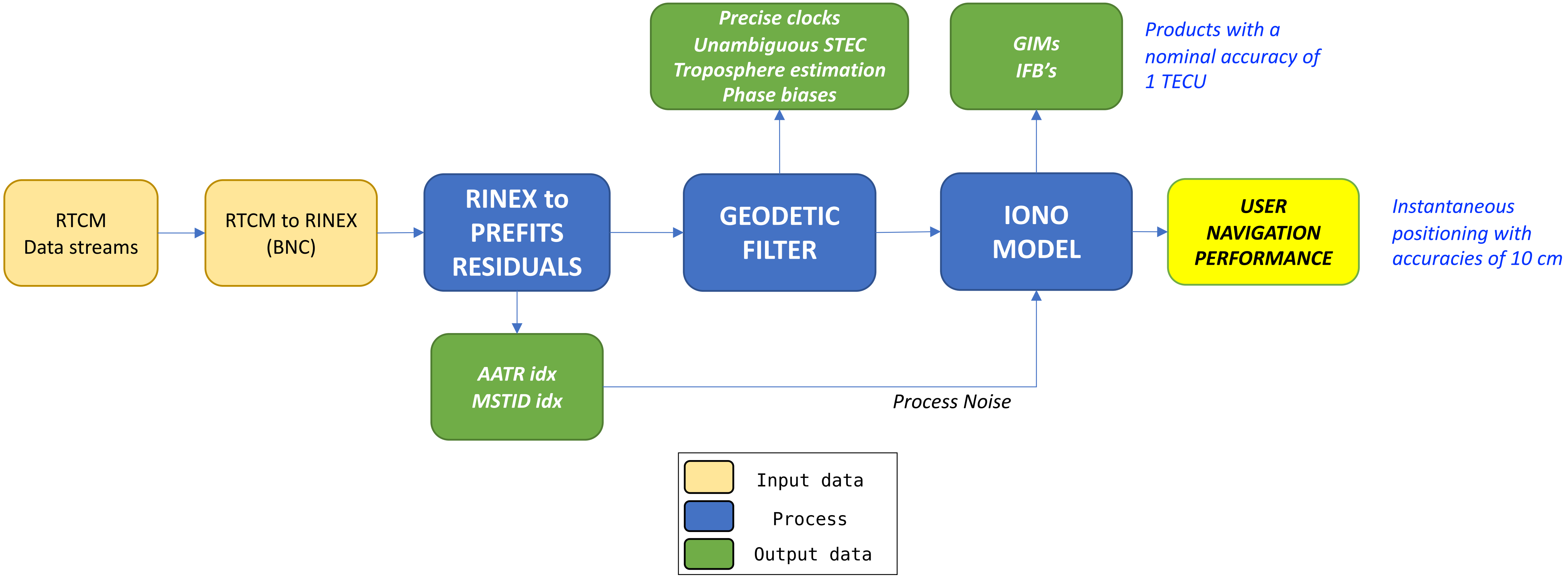
Validation Requirements

1. Introduction: Consolidated requirements (5)

Requirements	
The e-RTICC shall compute VTEC with an accuracy better than 1 TECU 95% of time.	
The e-RTICC shall compute STEC with an accuracy better than 1 TECU 95% of time	
The e-RTICC shall compute Final Interfrequency Biases with an accuracy better than 1 TECU 95% of time	
The e-RTICC PVT derived solution shall converge in less than 100 seconds	
The e-RTICC shall have an availability of 95%	

Performance Requirements

2. IONO4HAS Tool design and algorithms (1)



2. IONO4HAS Tool design and algorithms (2)

From RINEX to prefit residuals

RINEX observation files are corrected from the known effects to generate the prefit residuals:

1. RINEX to plain file text: *converts RINEX observation file to plain text*
2. Cycle slip detector: *detects cycle slips in carrier-phase measurements implementing the geometry-free and Hatch-Melbourne-Wübenna Combinations of carrier-phases.*
3. Time handling process: *manages the real-time acquisition of the clock and orbit corrections and performs the modelling of the measurements.*
4. Computation of the prefits: *computation of the residuals between the measured and the modelled pseudoranges*

2. IONO4HAS Tool design and algorithms (3)

Geodetic Filter

Estimates precise clocks, receivers' zenith tropospheric delay, phase biases and unambiguous carrier-phases. Provides inputs for the ionospheric filter as accurate as possible.

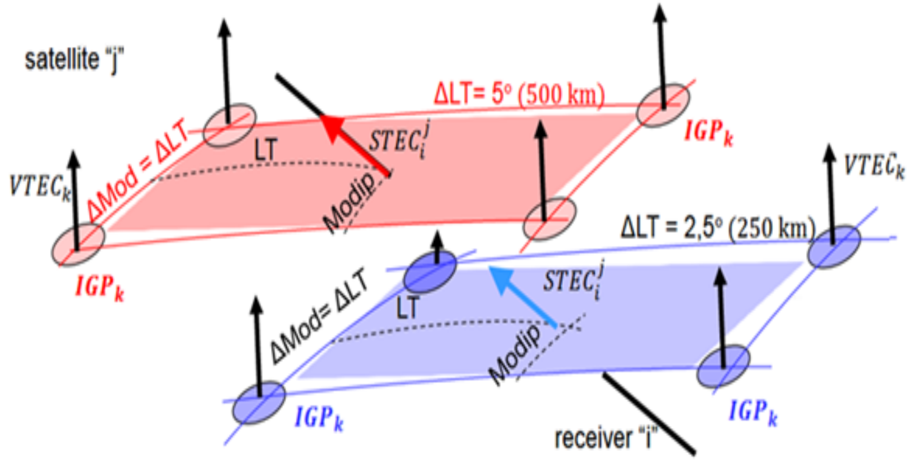
1. Aligning the carrier-phases with the pseudoranges: *estimation of the carrier-phase ambiguities (B_{GF}) as real numbers (floated ambiguities).*
2. Fixing ambiguities: *based on a set of GNSS stations, double differences (DD) of each measurement are performed (corresponding to a specific receiver-satellite pair, with respect to a reference receiver-satellite pair) eliminating phase biases (for both receiver and satellite) and resulting in an integer number for B_{GF}*

2. IONO4HAS Tool design and algorithms (4)

Ionospheric Module

Generates the 3D ionosphere computation, message generation and broadcasting.

1. <u>Modelling the ionospheric delay:</u> *A dual layer ionospheric model, linking the IGP distribution to MODIP and Local Time instead of geographical coordinates.*



Bottom layer: The MODIP step for IGPs is 2.5 degrees. The LT steps are variable depending on the MODIP ensuring a distance between IGPs at around 250 km (projected over the Earth's surface).

Top layer: The MODIP step for IGPs is 5 degrees. The LT steps are variable depending on the MODIP ensuring a distance between IGPs at around 500 km (projected over the Earth's surface).

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2. IONO4HAS Tool design and algorithms (5)

Ionospheric Module

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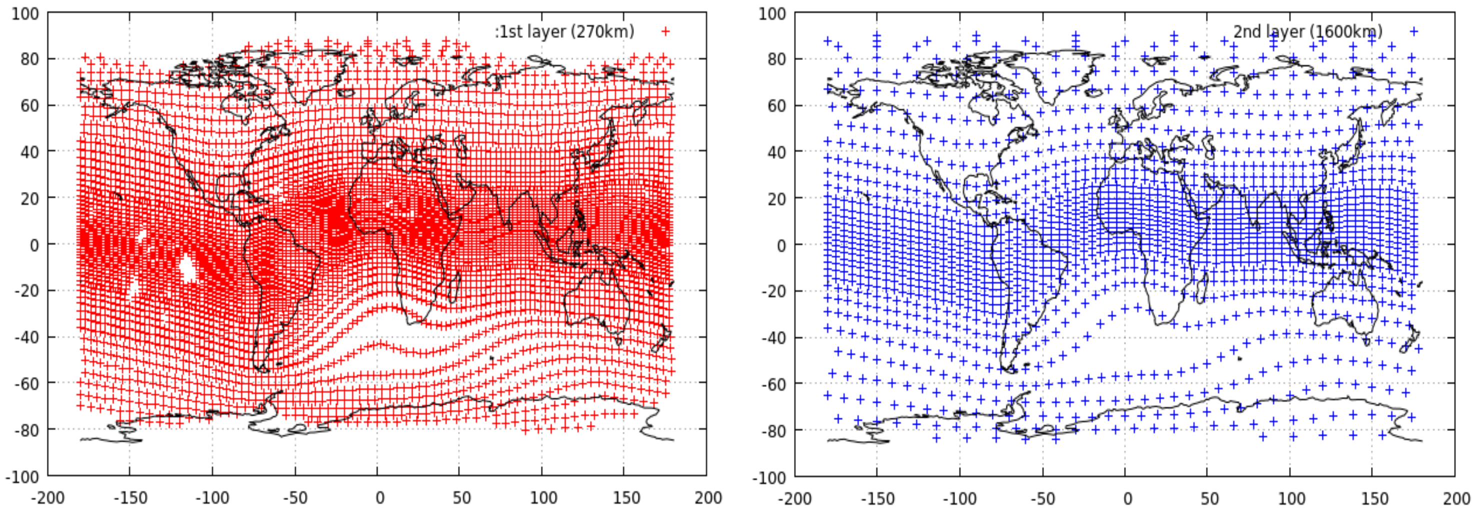


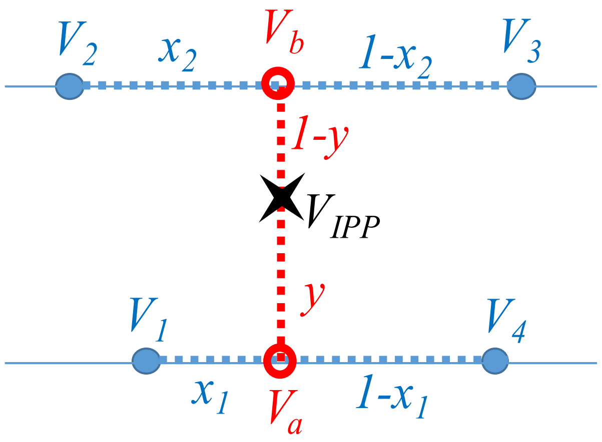
Using MODIP we densify the regions where is expected larger ionospheric activity (at low latitude), reducing the step between MODIP in latitude in the equatorial regions, helping to drop the computational loading and the message bandwidth

2. IONO4HAS Tool design and algorithms (6)

Ionospheric Module

Generates the 3D ionosphere computation, message generation and broadcasting.

1. <u>Modelling the ionospheric delay:</u>



$$V_a = (1 - x_1)\, V_1 + x_1\, V_4$$
$$V_b = (1 - x_2)\, V_2 + x_2\, V_3$$

$$V_{IPP} = (1 - y)\, V_a + y\, V_b$$

That can written as:

$$V_{IPP} = (1 - y) \cdot (1 - x_1) \cdot V_1 + y \cdot (1 - x_2) \cdot V_2 + (1 - y) \cdot x_1 \cdot V_4 + y \cdot x_2 \cdot V_3$$

If the grid were regular (x_1=x_2) , the interpolation would be the standard one in SBAS

2. IONO4HAS Tool design and algorithms (7)

Ionospheric Module

Generates the 3D ionosphere computation, message generation and broadcasting.

1. Ionospheric module output: *broadcasted message of real-time ionospheric model estimates transmitted to the users contains three types of registers:*
   a) Registers with the TIME label: indicating the year, DoY and second when the following parameters have been estimated.
   b) Registers with the SAT label: indicating the satellite identifier, the DCB value (in TECU) and the standard deviation of the DCB estimate (in TECU).
   c) Registers without label: contains the VTEC of each IGP identified by the layer number, its LT and MODIP, the instantaneous longitude and an identifier of the IGP.

2. IONO4HAS Tool design and algorithms (8)

Ionospheric Module

Generates the 3D ionosphere computation, message generation and broadcasting.

1. Ionospheric module output: *broadcasted message of real-time ionospheric model estimates transmitted to the users contains three types of registers:*

"TIME" ***label***

label	year	Day of Year	Second of day
TIME	20	61	50100

"SAT" ***label***

label	Satellite id	1st DCB (TECU)	Sigma DCB (TECU)	2nd DCB (TECU)	Sigma DCB (TECU)
SAT	49	0.159	0.21E+00	2.962	0.17E+00
SAT	23	-28.014	0.18E+00	0.000	0.49E+00
SAT	29	-31.282	0.19E+00	0.000	0.49E+00
SAT	53	-2.129	0.25E+00	0.753	0.20E+00

Empty label

layer	LT (º)	MODIP (º)	LON (º)	Electron content (TECU)	Sigma (TECU)	IGP identifier
1	0.0	45.0	150.0	1.371	0.31E+01	6017
1	78.0	45.0	228.0	0.739	0.61E+01	6043
...	...	...	...	...	...	...
2	50.0	0.0	200.0	1.696	0.74E+01	875
2	55.0	0.0	205.0	1.036	0.10E+02	876

2. IONO4HAS Tool design and algorithms (9)

Dissemination Message: Ionospheric Grids Points (IGPs)

Bottom layer at 270km in height:

$$\Delta \text{MODIP} = 2{,}5° \, ; \, \Delta LT \approx \frac{2{,}5°}{\cos \text{MODIP}}$$

	First layer (7.176 IGPs): 270 km in heigh																																						
MODIP	-90	-87,5	-85,0	-82,5	-80,0	-77,5	-75,0	-72,5	-70,0	-67,5	-65,0	-62,5	-60,0	-57,5	-55,0	-52,5	-50,0	-47,5	-45,0	-42,5	-40,0	-37,5	-35,0	-32,5	-30,0	-27,5	-25,0	-22,5	-20,0	-17,5	-15,0	-12,5	-10,0	-7,5	-5,0	-2,5	0,0	2,5	5,0
ΔLT*15	180	30	24	18	12	10	9	8	6	6	5	5	4,5	4,5	4	4	3	3	3	3	3	3	3	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5
N. IGPs	2	12	15	20	30	36	40	45	60	60	72	72	80	80	90	90	120	120	120	120	120	120	120	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144

	First layer (7.176 IGPs): 270 km in heigh																																	
MODIP	7,5	10,0	12,5	15,0	17,5	20,0	22,5	25,0	27,5	30,0	32,5	35,0	37,5	40,0	42,5	45,0	47,5	50,0	52,5	55,0	57,5	60,0	62,5	65,0	67,5	70,0	72,5	75,0	77,5	80,0	82,5	85,0	87,5	90,0
ΔLT*15	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	3	3	3	3	3	3	3	4	4	4,5	4,5	5	5	6	6	8	9	10	12	18	24	30	180
N. IGPs	144	144	144	144	144	144	144	144	144	144	144	120	120	120	120	120	120	120	90	90	80	80	72	72	60	60	45	40	36	30	20	15	12	2

Upper layer at 1600km in height:

$$\Delta \text{MODIP} = 5° \, ; \, \Delta LT \approx \frac{5°}{\cos \text{MODIP}}$$

	Second layer (1.1792 IGPs): 1.600 km in heigh																																			
MODIP	-90,0	-85,0	-80,0	-75,0	-70,0	-65,0	-60,0	-55,0	-50,0	-45,0	-40,0	-35,0	-30,0	-25,0	-20,0	-15,0	-10,0	-5,0	0,0	5,0	10,0	15,0	20,0	25,0	30,0	35,0	40,0	45,0	50,0	55,0	60,0	65,0	70,0	75,0	80,0	85,0	90,0
ΔLT*15	180	30	24	18	12	10	9	8	7,5	6	6	6	5	5	5	5	5	5	5	5	5	5	5	5	5	6	6	6	7,5	8	9	10	12	18	24	30	180
N. IGPs	2	12	15	20	30	36	40	45	48	60	60	60	72	72	72	72	72	72	72	72	72	72	72	72	72	60	60	60	48	45	40	36	30	20	15	12	2

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2. IONO4HAS Tool design and algorithms (10)

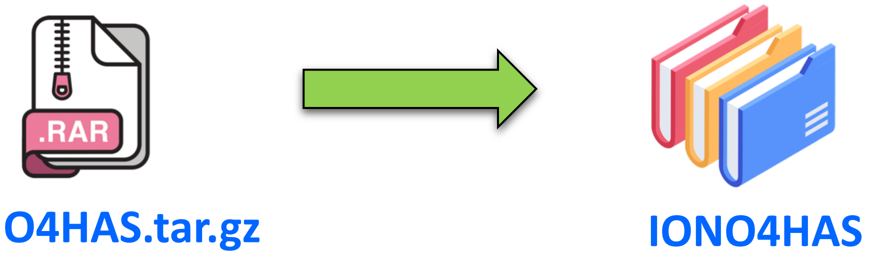
Dissemination Message: two scenarios.

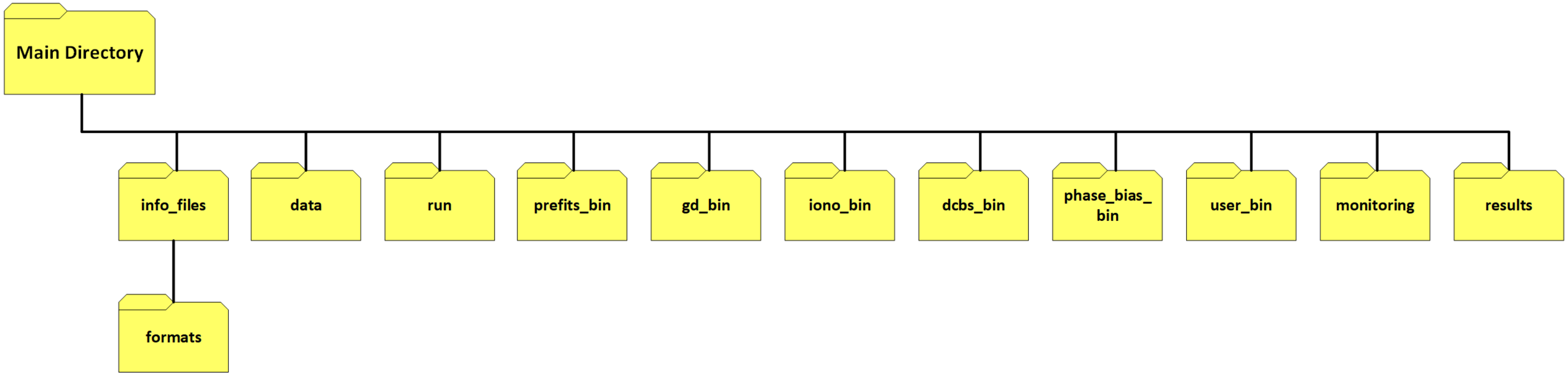
1. Message for an unlimited bandwidth: contains the output of the ionospheric model, without applying any interpolation nor quantization of values. ASCII text file that can be broadcast by internet. Size of this message, containing the full ionospheric model for worldwide users, is less than 2 MBits. The time update is 300 seconds.

2. Message compliant with GNSS standard RTCM SC-104 v3.x with a Data Field length of 1.023 bits: Allows to broadcast the ionosphere and DCBs in less than 30 seconds for European users and in less than 2.5 minutes for worldwide users. The time update is also 300 seconds.

3. IONO4HAS implementation and operation (1)

1. Implementation: The IONO4HAS tool is designed to work in a hierarchical organization on a Linux Operating System.





3. IONO4HAS implementation and operation (2)

2. Operation: IONO4HAS tool execution:

```
> ./run_iono4has.scr
```

run_prefits.scr
computation of the prefit residuals
↓
run_gd_filter.scr
Unambiguos STEC
↓
run_ion_model.scr
Ionospheric corrections
↓
run_idxs.scr
Auxiliary ionospheric indexes
↓
run_pb.scr
Phase biases computaion
↓
run_L1_pos.scr
User positioning assesment using L1
↓
run_LW_pos.scr
User positioning assesment using LW

3. IONO4HAS implementation and operation (3)

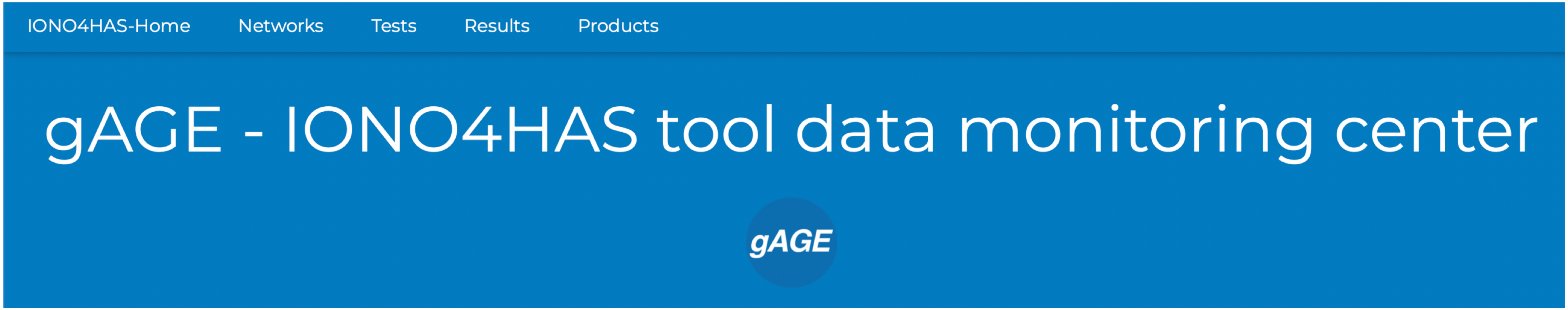
2. Operation: IONO4HAS tool main output files:

File name	Sampling rate (cadence)	Description
rnx2txt.tmp	5 seconds	Concatenation of all the RINEX files available and converted to plain text.
prefits.tmp	30 seconds	Main output of the prefit residuals computation in the pre-processing module.
stec.dat	5 minutes	Main output of the Geodetic filter in the pre-processing module.
iono_model.out	5 minutes	Main output of the Ionospheric modelling (CPF) in the Ionospheric module.
mstid_idx.YEAR.DOY	5 minutes	Output of the complementary module for monitoring regional Ionospheric Activity.
aatr_idx.YEAR.DOY	5 minutes	Output of the complementary module for monitoring local Ionospheric Activity.

3. IONO4HAS implementation and operation (4)

2. Operation: The IONO4HAS tool has been running fot more than 7 months, since the December 2021.

https://gage.upc.edu/iono4has/



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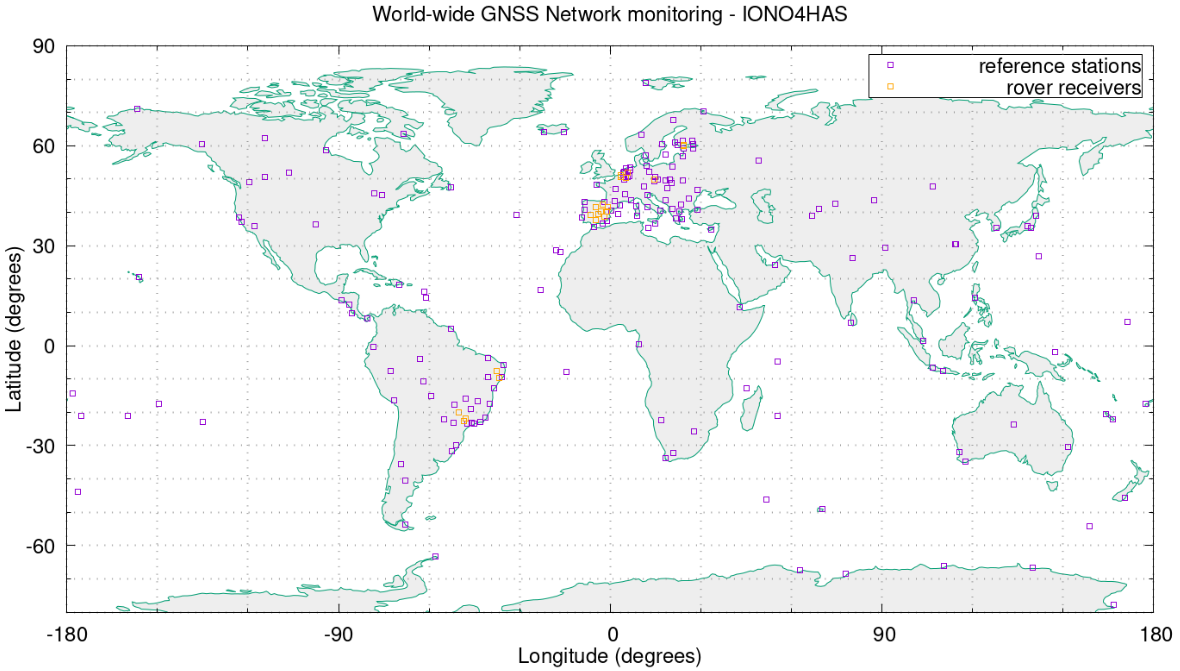
3. IONO4HAS implementation and operation (5)

2. Operation: https://gage.upc.edu/iono4has/

- **Networks:** Definition of the network of implemented GNSS stations, providing information on the stations' location and the data availability in real-time.



- ✓ Ensure a spread worldwide distribution of GNSS stations broadcasting in real-time.
- ✓ Define a dense area of GNSS receivers broadcasting in real-time concentrated in Europe.
- ✓ Define sub-networks of GNSS stations broadcasting in real-time to simulate positioning scenarios using GNSS receivers as users (rovers) of the IONO4HAS model service.

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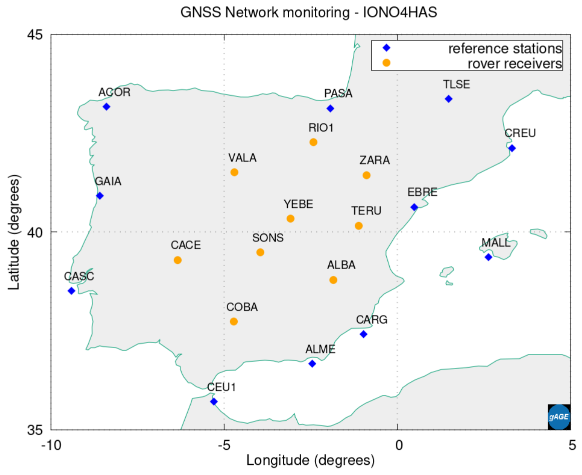
3. IONO4HAS implementation and operation (6)

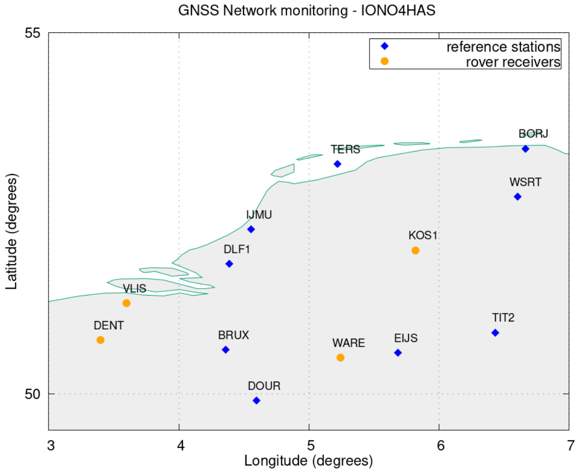
2. Operation: https://gage.upc.edu/iono4has/

- **Networks:** Definition of the network of implemented GNSS stations, providing information on the stations' location and the data availability in real-time.

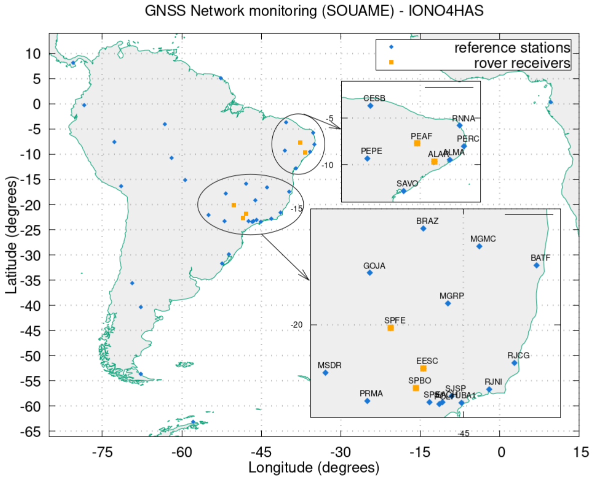
✓ Define sub-networks of GNSS stations broadcasting in real-time to simulate positioning scenarios using GNSS receivers as rovers of the IONO4HAS model service.



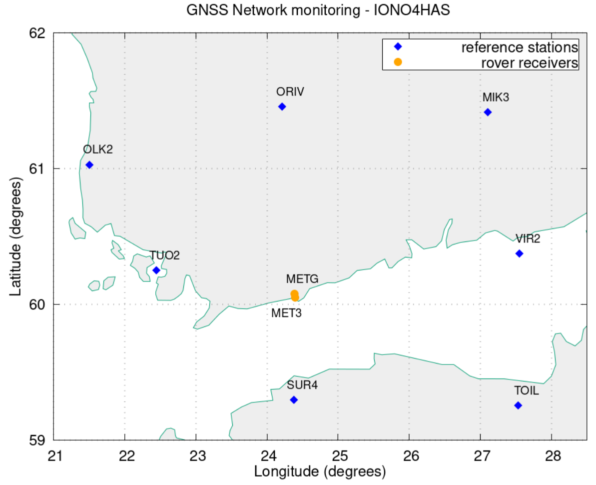
Spanish Network



Belgium Network



Brazilian Network



Finnish Network

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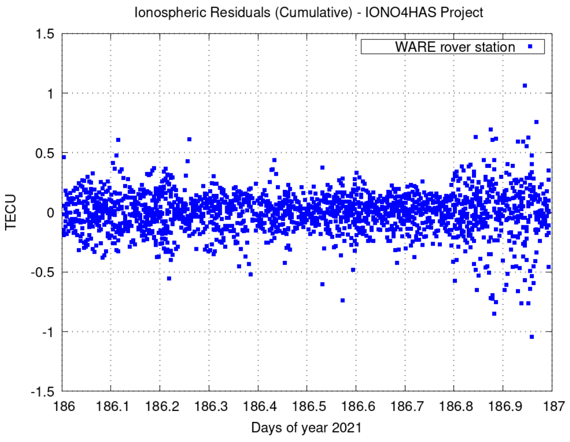
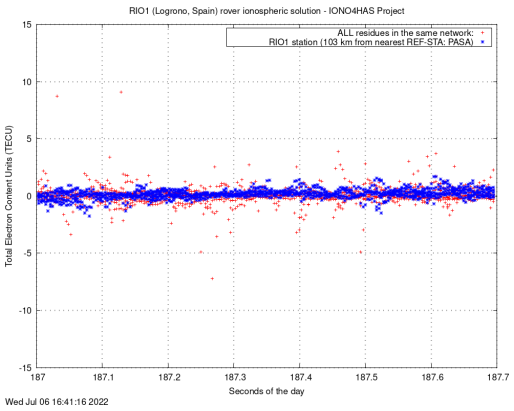
3. IONO4HAS implementation and operation (7)

2. Operation: https://gage.upc.edu/iono4has/

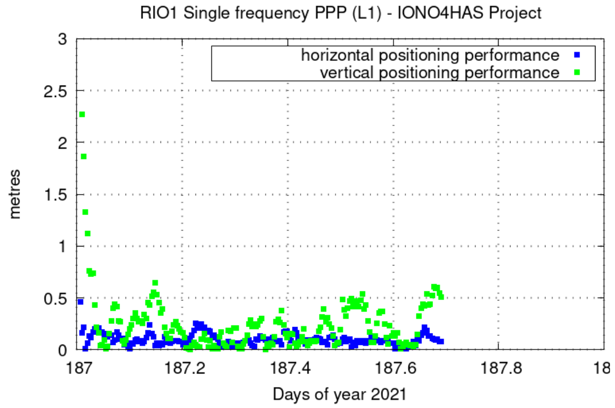
- Tests: IONO4HAS tool correctness is checked testing the residuals at the Geodetic and the ionospheric filter modules. Monitoring of the positioning performance of rover receivers using the ionospheric corrections.

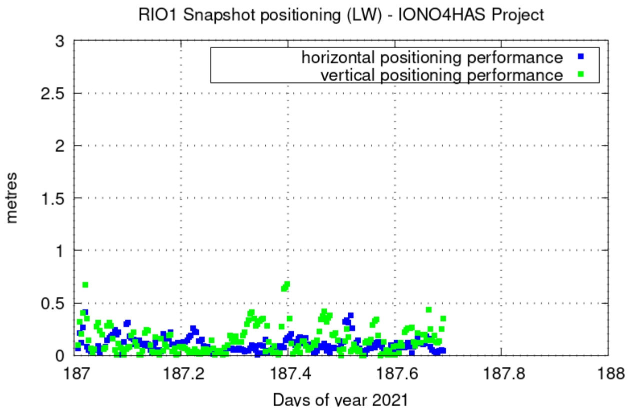


STEC test



IONO residuals



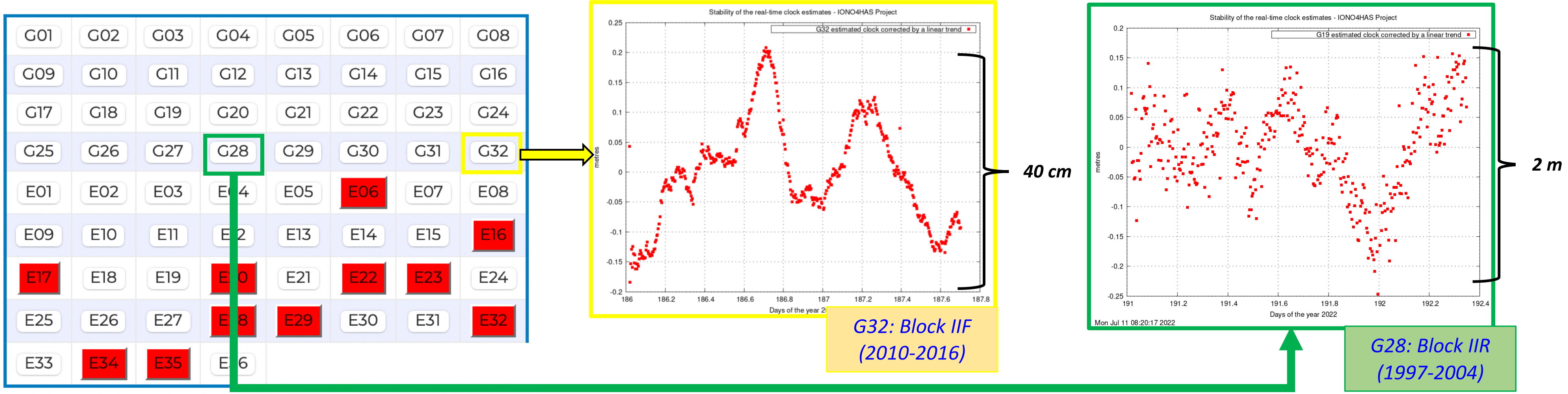


Positioning using L1 (single freq.) and using LW (Snapshot)

3. IONO4HAS implementation and operation (8)

2. Operation: https://gage.upc.edu/iono4has/

- Products: outputs computed in real-time by the IONO4HAS tool:
  - Satellite clock monitoring: Real-time estimates of the satellites clocks. In the plot it is subtracted a linear model in order to facilitate viewing satellite clock stability.



Satellite selectable panel

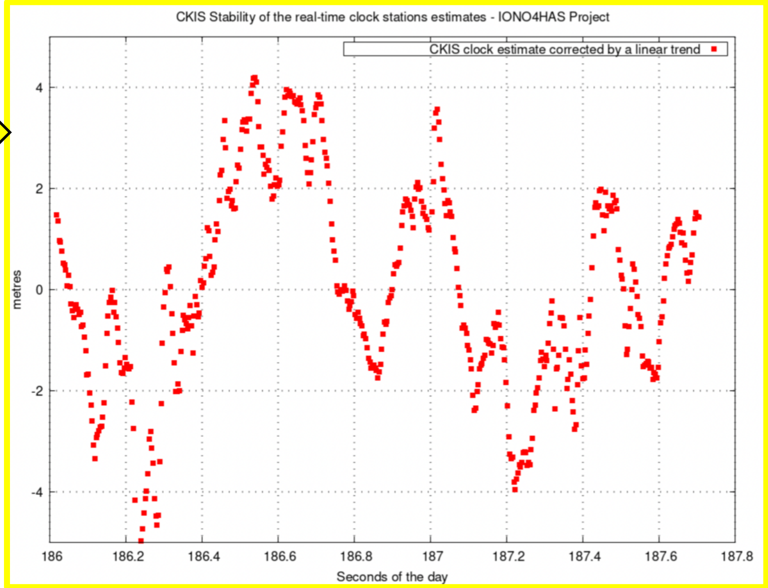
3. IONO4HAS implementation and operation (9)

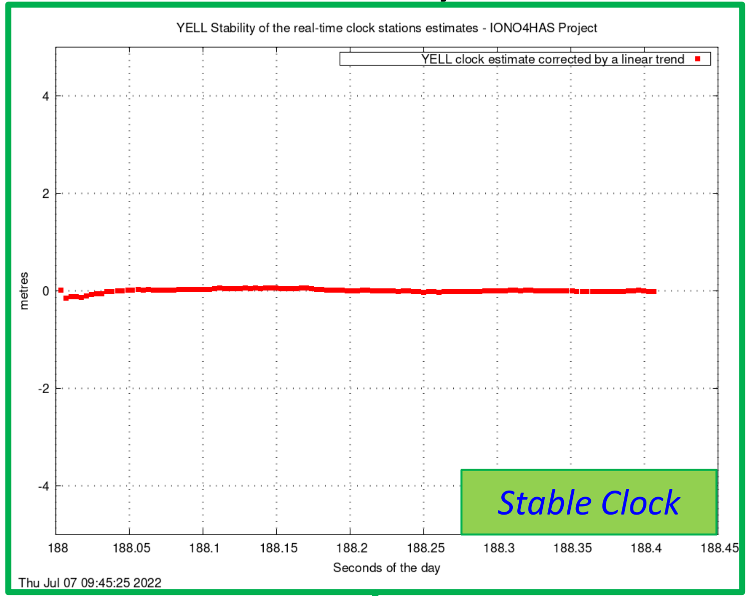
2. Operation: https://gage.upc.edu/iono4has/

- Products: outputs computed in real-time by the IONO4HAS tool:
  - Station clock monitoring: Real-time estimates of the stations clocks. In the plot it is subtracted a linear model in order to facilitate viewing the station clock stability.

ABMF	ACOR	AJAC	ALAR	ALBA	ALBY	ALGO	ALIC	ALMA	ALME
AMCR	ARD2	AREG	ASCG	AUT1	BAKO	BATF	BORJ	BRAZ	BRMF
BRST	BRUX	BUCU	BUTE	CACE	CARG	CAS1	CASC	CCJ2	CESB
CEU1	CFRM	CHPG	CHUR	CKIS					
CPVG	CREU	CRUZ	CTAB	CUT0	CZTG	DAV1	DENT	DJIG	DLF1
DOUR	DRAO	DUMG	DYNG	EBRE	EESC	EIJS	FLRS	FTNA	GAIA
GAMB	GANP	GOJA	GOP6	GRAC	HOFN	HRAG	IGEO	IJMU	IQAL
ISTA	IZAN	JFNG	JOG2	KIR8	KITG	KOS1	KOUC	KOUG	KRA1
KRAW	KRGG	KZN2	LAMA	LAMP	LAUT	LHAZ	LMMF	LPAL	M0SE
MAC1	MAJU	MALL	MAO0	MAR7	MATG	MAW1	MAYG	MET3	METG
METS	MGMC	MGRP	MGV1	MIK3	MIZU	MSDR	MTLA	NICO	NKLG
NMRG	NOT1	NRC1	NRMG	NYA2	OBE4	OHI3	OLK2	ONS1	ORID
ORIV	OUS2	OWMG	P195	PASA	PATO	PEAF	PEPE	PNGM	POAL
POTS	PRDS	PRMA	PTGG	REUN	REYK	RGDG	RIGA	RIO1	RIO2
RJCG	RJNI	RNNA	ROJI	RSPE	SAVO	SCTB	SEYG	SGOC	SGPO
SICO	SIN1	SJSP	SOFI	SONS	SPBO	SPFE	SPS1	SRJV	SSIA
STFU	STJO	SULP	SUR4	SUTM	TASH	TERS	TERU	THTG	TIT2
TLSE	TOIL	TONG	TUO2	UBA1	UCAG	URUM	VALA	VARS	VEN1
VFCH	VIR2	VLIS	WARE	WARN	WHIT	WIND	WSRT	WUH2	YEBE
YELL									

Station selectable panel





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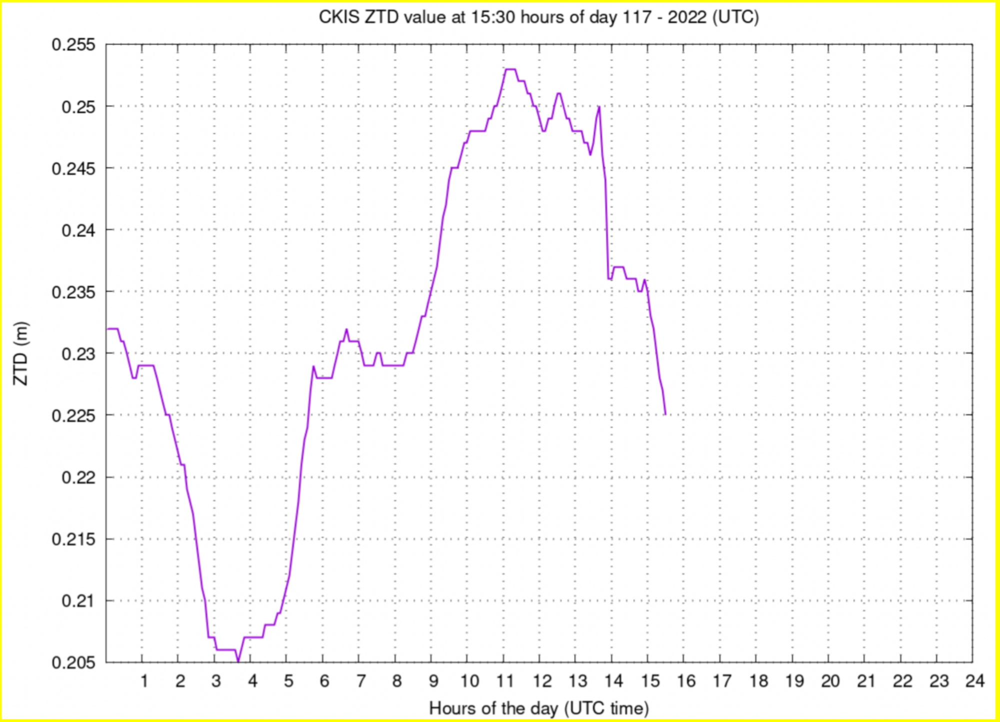
3. IONO4HAS implementation and operation (10)

2. Operation: https://gage.upc.edu/iono4has/

- Products: outputs computed in real-time by the IONO4HAS tool:
  - Station troposphere monitoring: Real-time estimates of Zenith Tropospheric Delay (ZTD) for each station.

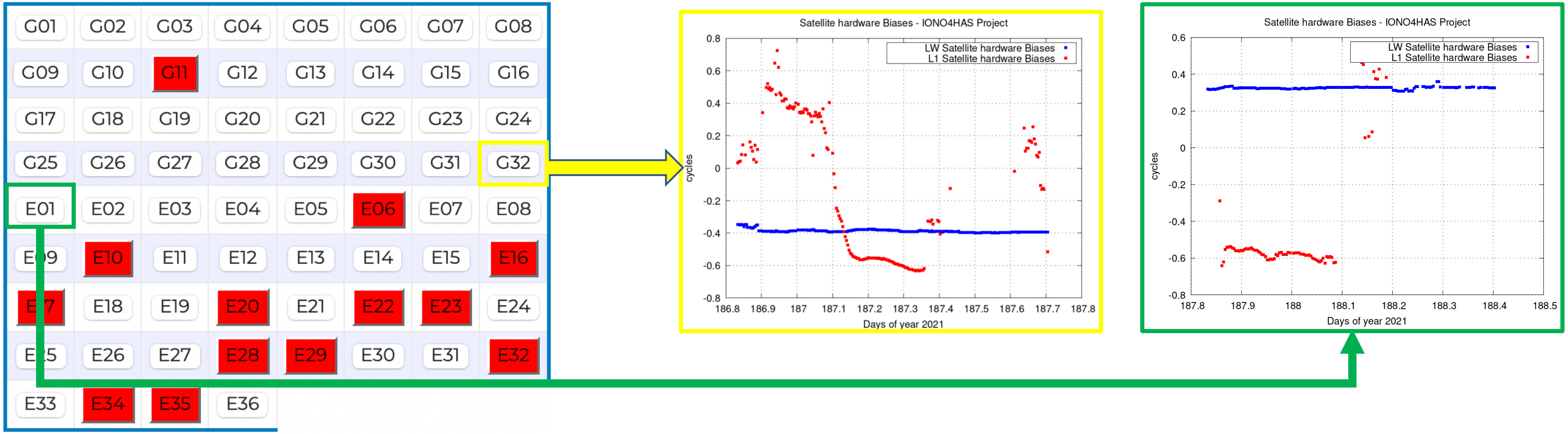
ABMF	ACOR	AJAC	ALAR	ALBA	ALBY	ALGO	ALIC	ALMA	ALME
AMCR	ARD2	AREG	ASCG	AUT1	BAKO	BATF	BORJ	BRAZ	BRMF
BRST	BRUX	BUCU	BUTE	CACE	CARG	CAS1	CASC	CCJ2	CESB
CEU1	CFRM	CHPG	CHUR	CKIS					
CPVG	CREU	CRUZ	CTAB	CUT0	CZTG	DAV1	DENT	DJIG	DLF1
DOUR	DRAO	DUMG	DYNG	EBRE	EESC	EIJS	FLRS	FTNA	GAIA
GAMB	GANP	GOJA	GOP6	GRAC	HOFN	HRAG	IGEO	IJMU	IQAL
ISTA	IZAN	JFNG	JOG2	KIR8	KITG	KOS1	KOUC	KOUG	KRA1
KRAW	KRGG	KZN2	LAMA	LAMP	LAUT	LHAZ	LMMF	LPAL	MOSE
MAC1	MAJU	MALL	MAO0	MAR7	MATG	MAW1	MAYG	MET3	METG
METS	MGMC	MGRP	MGV1	MIK3	MIZU	MSDR	MTLA	NICO	NKLG
NMRG	NOT1	NRC1	NRMG	NYA2	OBE4	OHI3	OLK2	ONS1	ORID
ORIV	OUS2	OWMG	P195	PASA	PAT0	PEAF	PEPE	PNGM	POAL
POTS	PRDS	PRMA	PTGG	REUN	REYK	RGDG	RIGA	RIO1	RIO2
RJCG	RJNI	RNNA	ROJI	RSPE	SAVO	SCTB	SEYG	SGOC	SGPO
SICO	SIN1	SJSP	SOFI	SONS	SPBO	SPFE	SPS1	SRJV	SSIA
STFU	STJO	SULP	SUR4	SUTM	TASH	TERS	TERU	THTG	TIT2
TLSE	TOIL	TONG	TUO2	UBA1	UCAG	URUM	VALA	VARS	VEN1
VFCH	VIR2	VLIS	WARE	WARN	WHIT	WIND	WSRT	WUH2	YEBE
YELL	ZARA								



3. IONO4HAS implementation and operation (11)

2. Operation: https://gage.upc.edu/iono4has/

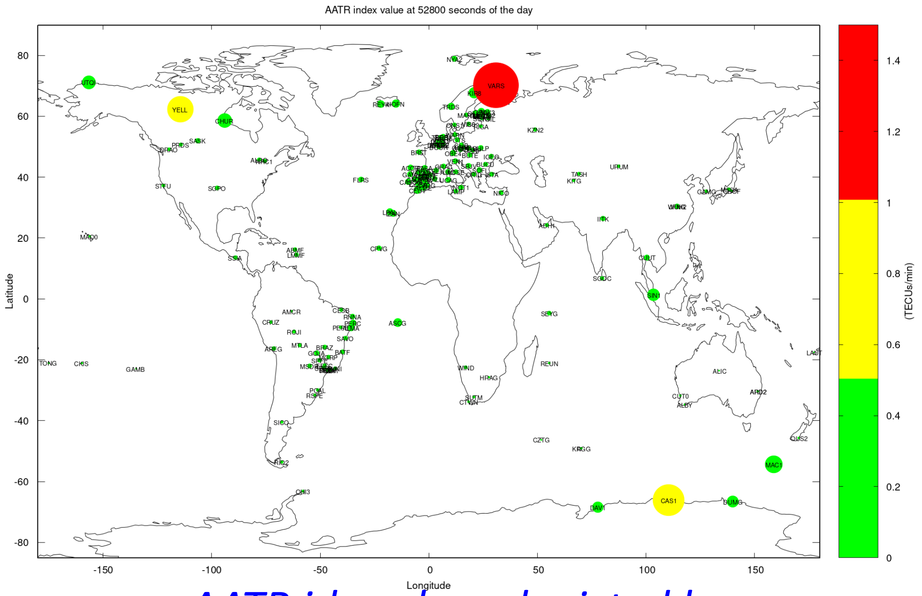
- Products: outputs computed in real-time by the IONO4HAS tool:
  - Satellite phase-biases monitoring: L1 and LW phase biases computed for each one of the satellites to allow any receiver to fix its ambiguities.



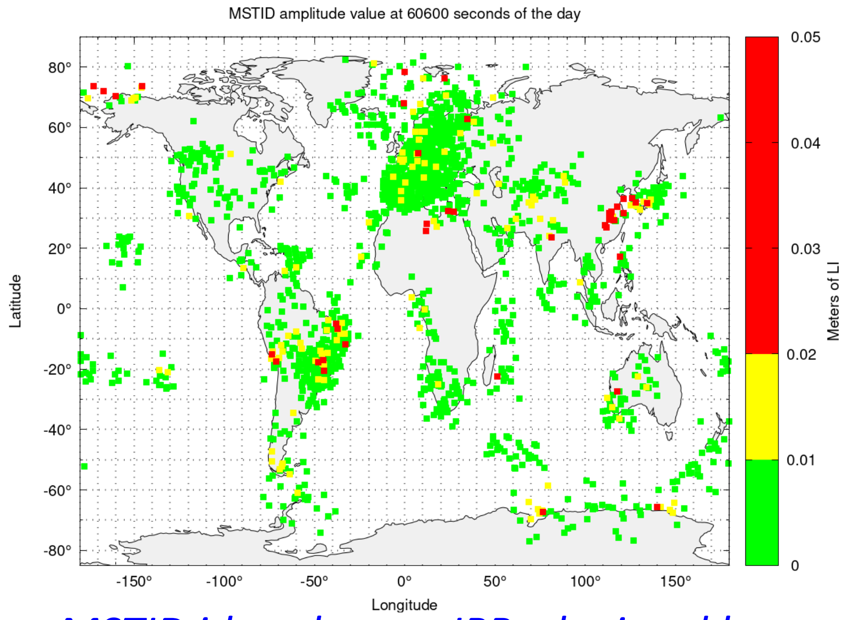
3. IONO4HAS implementation and operation (12)

2. Operation: https://gage.upc.edu/iono4has/

- Products: outputs computed in real-time by the IONO4HAS tool:
  - The AATR and MSTID indexes: monitoring local and regional the ionosphere.

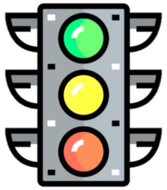


AATR idx values depicted by colour code and point size



MSTID idx values at IPPs depicted by colour code

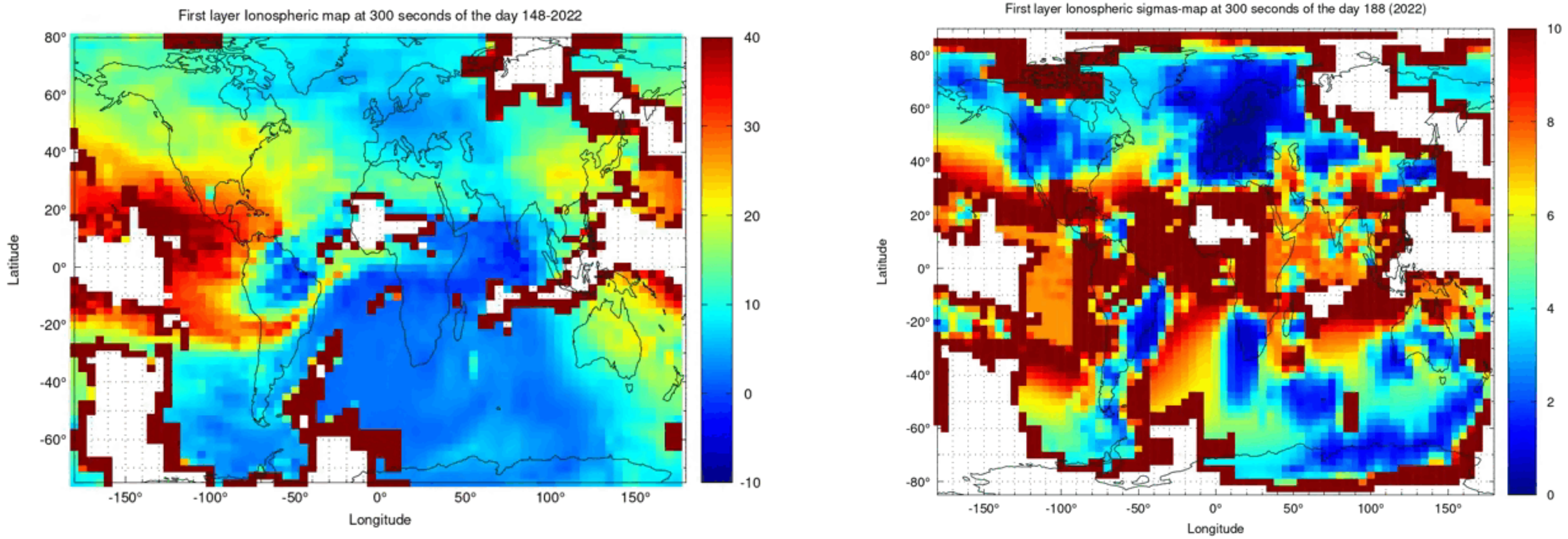
quiet/slow
moderate/medium
strong/high



3. IONO4HAS implementation and operation (13)

2. Operation: https://gage.upc.edu/iono4has/

- Products: outputs computed in real-time by the IONO4HAS tool:
  - Real-time ionospheric plots: Provided corrections and modelling of the ionosphere is given using a two layer model.



Ionospheric modelling and its corresponding sigma values

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3. IONO4HAS implementation and operation (14)

2. Operation: https://gage.upc.edu/iono4has/

- Products: historical outputs computed in real-time by the IONO4HAS tool the real-time ionospheric plots.

Data base for the two layer model

4. Experimentation (1)

Once the IONO4HAS tool has been successfully deployed, and a stable version of the code was achieved, several stages were ready to implement:

1. Campaigns definition
2. Validation stage
   1. STEC test
   2. DCBs
3. Positioning Results

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4. Experimentation (2)

1. Campaigns definition:

Two campaigns in 2022: -DoY **002 to 050**- and -DoY **131 to 170**-

Rover Station	Closest Ref. Station	Distance (km)
ALBA	CARG	171.6
COBA	CEU1	230.5
RIO1	PASA	103.4
SONS	ALME	339.8
TERU	EBRE	146.5
VALA	PASA	290.6
YEBE	EBRE	304.6
ZARA	EBRE	146.3
CACE	GAIA	263.0

Spanish Network

Rover Station	Closest Ref. Station	Distance (km)
DENT	BRUX	69.2
VLIS	DLF1	81.5
WARE	BRUX	63.7
KOS1	IJMU	91.9

Belgium Network

Rover Station	Closest Ref. Station	Distance (km)
EESC	SPBO	108.6
SPFE	GOJA	306.6
SPBO	SPS1	124.9
PEAF	ALMA	284.1
ALAR	ALMA	98.4

Brazilian Network

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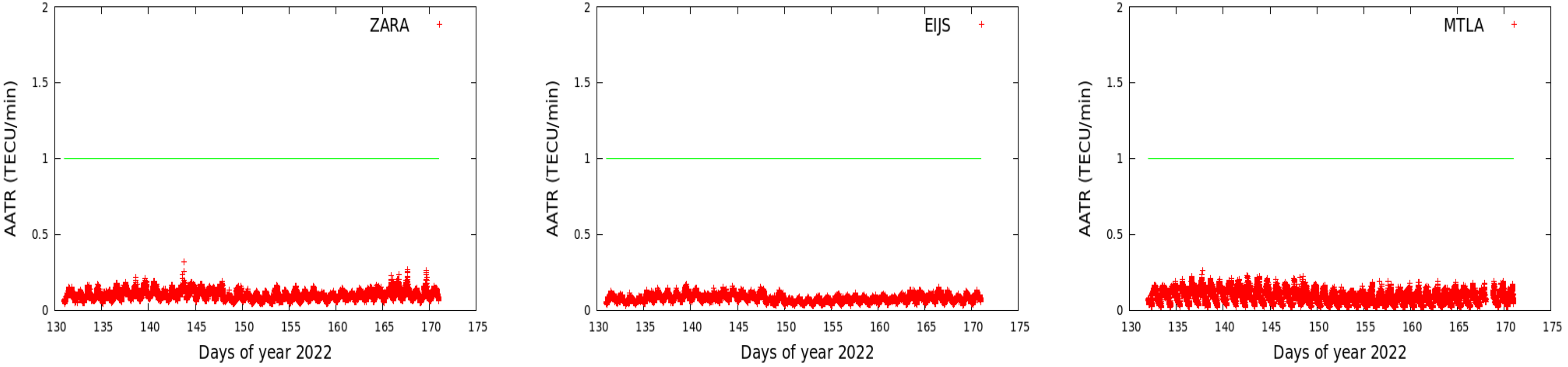
4. Experimentation (3)

1. Campaigns definition: Ionospheric activity levels

Ionospheric activity during the period of time analysed is not particularly high. There is no evidence of sudden perturbations or alterations.



4. Experimentation (4)

2. Validation stage

a) Ionospheric model

- Evaluation of the IONO4HAS model predictions using the unambiguous STEC (from the Geodetic Filter).
- DCBs computed by IONO4HAS: Daily computation of DCBs to be implemented in post-processed mode
- Positioning assessment through the navigation error of rover receivers with well known coordinates.

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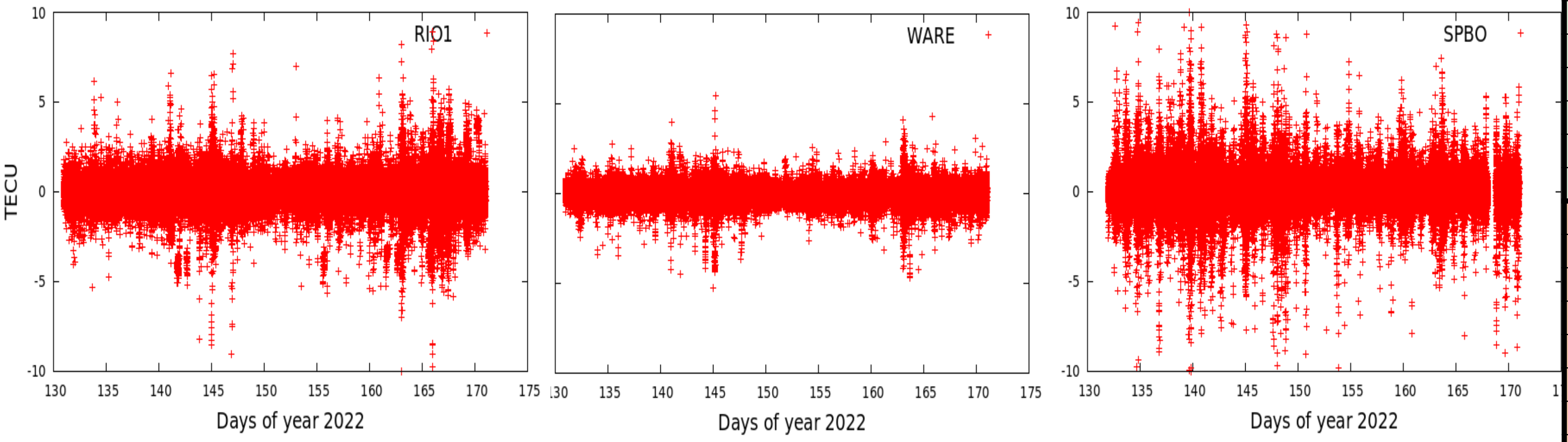
4. Experimentation (5)

2. Validation stage: STEC test

Residuals with respect to the unambiguous STEC at the Geodetic Filter

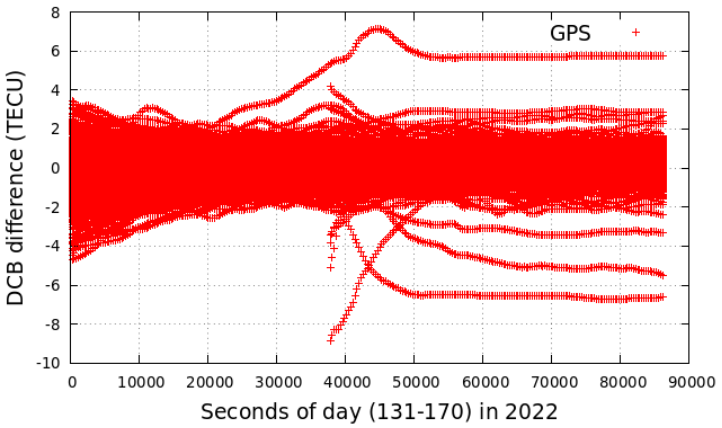


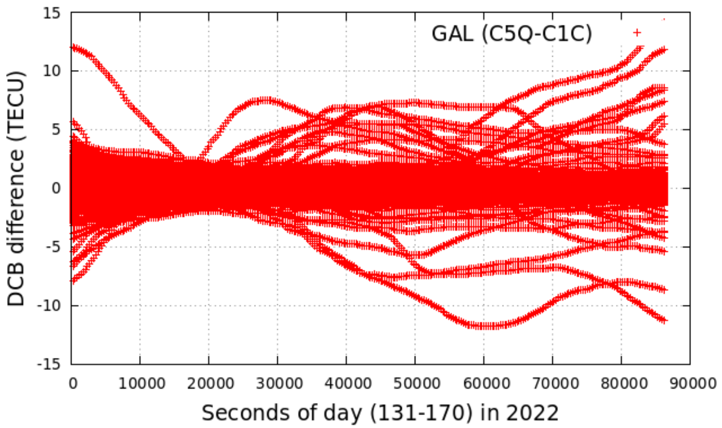
ROVER	Residual RMS (TECU)	Residual 95th (TECU)
METG	0.66	0.86
MET3	0.59	0.77
KOS1	0.39	0.56
VLIS	0.51	0.71
DENT	0.45	0.63
WARE	0.40	0.55
GOP6	0.66	0.84
RIO1	0.81	1.11
VALA	0.81	1.16
ZARA	0.62	0.82
YEBE	0.71	1.00
TERU	0.68	0.92
SONS	0.81	1.11
CACE	1.07	1.60
ALBA	0.79	1.14
COBA	0.81	1.16
PEAF	1.35	2.03
ALAR	1.31	1.90
SPFE	1.39	2.03
EESC	1.28	1.68
SPBO	1.03	1.46

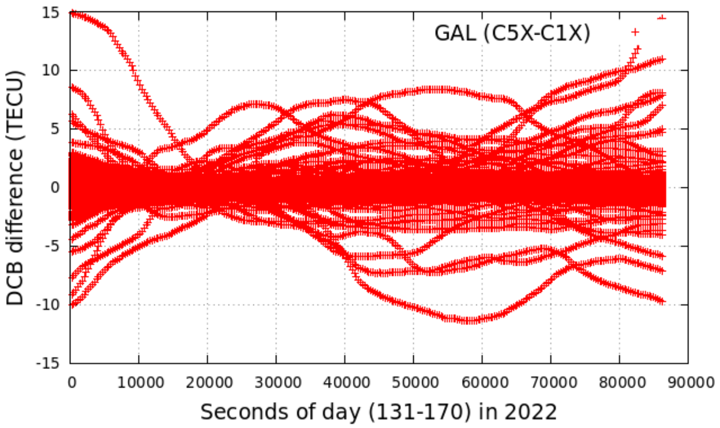
4. Experimentation (6)

2. Validation stage: DCBs computed by the IONO4HAS

Computed DCBs during a day: GPS (C1C-C1W) ang GALILEO (C5Q-C1C and C5X-C1X).







Values bounded under 5 TECU

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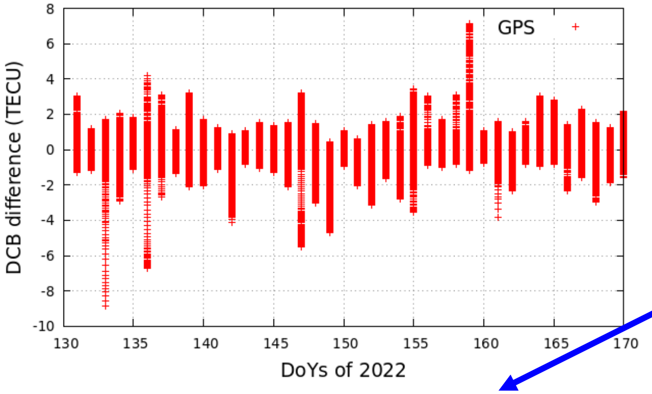
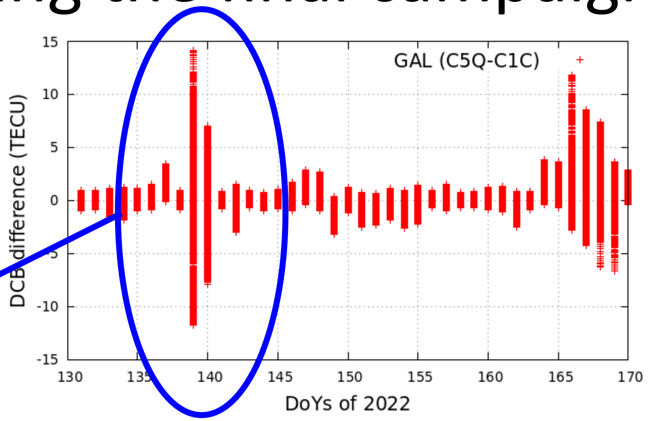
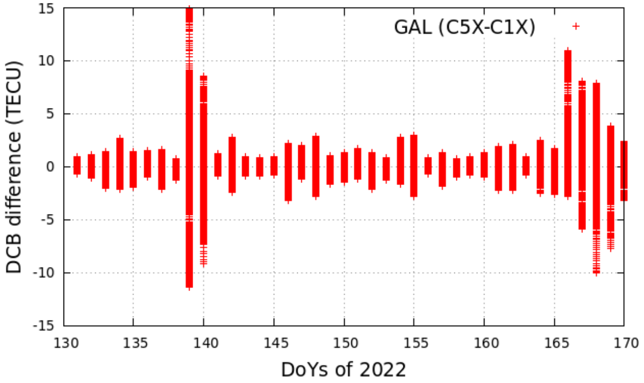
4. Experimentation (7)

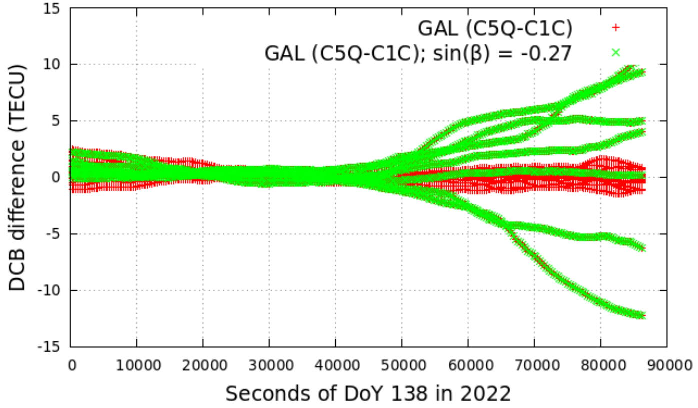
2. Validation stage: DCBs computed by the IONO4HAS

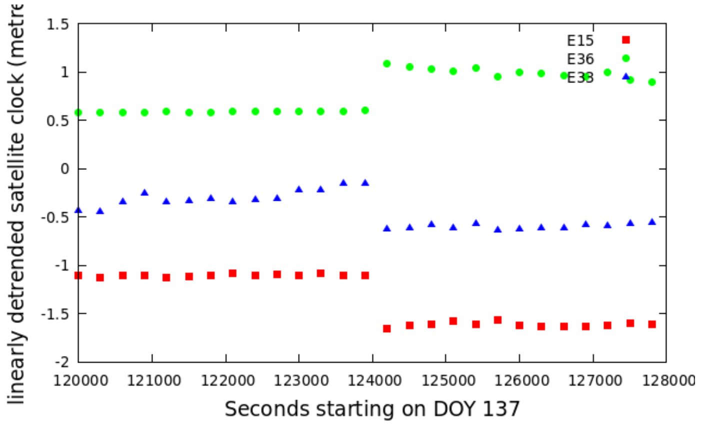
GPS and Galileo DCBs during the final campaign

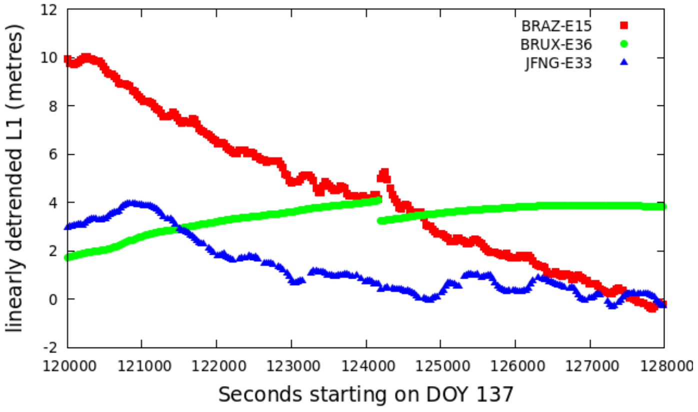












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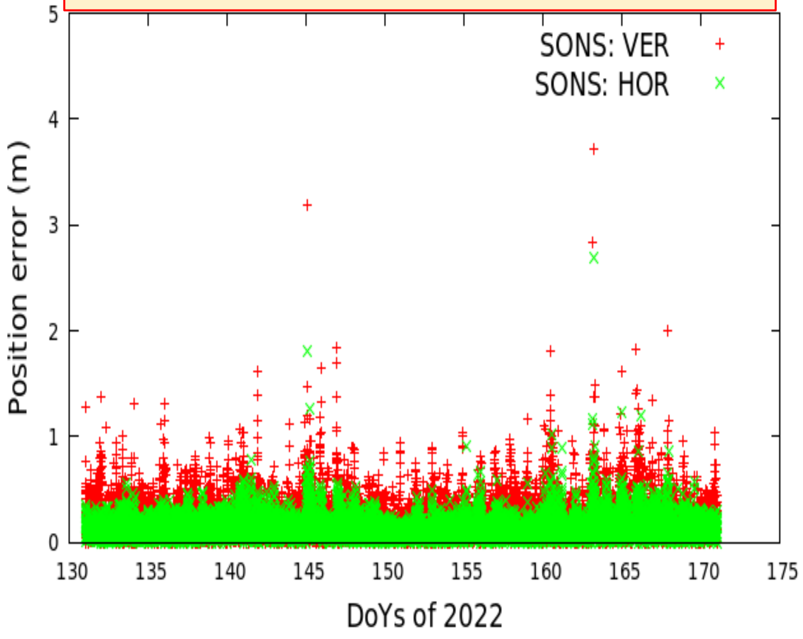
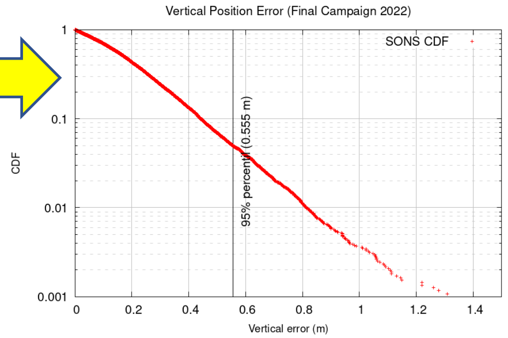
4. Experimentation (8)

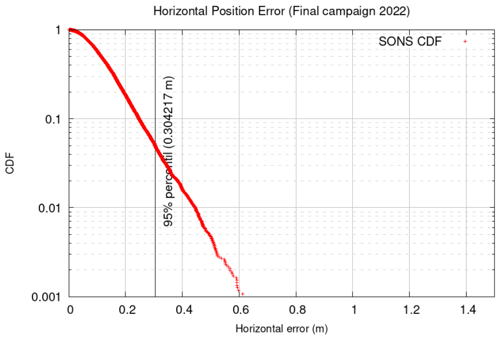
3. Positioning Results

Instantaneous positioning using **unambiguous LW** (snapshot) combination.

Rover	Horizontal positionig error		Vertical positioning error		3D positioning error	
	RMS (m)	95th Perc. (m)	RMS (m)	95th Perc. (m)	RMS (m)	95th Perc. (m)
METG	0.10	0.20	0.15	0.29	0.18	0.33
MET3	0.11	0.20	0.19	0.38	0.22	0.42
KOS1	0.09	0.15	0.18	0.34	0.20	0.36
VLIS	0.09	0.16	0.18	0.33	0.20	0.36
DENT	0.10	0.18	0.20	0.37	0.22	0.40
WARE	0.09	0.16	0.17	0.33	0.19	0.35
GOP6	0.09	0.17	0.15	0.31	0.18	0.34
RIO1	0.14	0.25	0.30	0.56	0.33	0.60
VALA	0.15	0.28	0.35	0.65	0.38	0.69
ZARA	0.14	0.25	0.29	0.56	0.32	0.58
YEBE	0.32	0.29	0.38	0.73	0.50	0.77
TERU	0.15	0.27	0.33	0.62	0.36	0.66
SONS	0.18	0.33	0.39	0.77	0.43	0.80
CACE	0.43	0.44	0.49	0.90	0.65	0.99
ALBA	0.16	0.30	0.33	0.62	0.37	0.68
COBA	0.19	0.36	0.39	0.73	0.43	0.78
PEAF	0.27	0.49	0.52	1.06	0.58	1.13
ALAR	0.24	0.44	0.49	0.98	0.54	1.03
SPFE	0.23	0.44	0.50	0.94	0.55	1.02
EESC	0.23	0.40	0.45	0.89	0.51	0.95
SPBO	0.16	0.30	0.37	0.69	0.40	0.73



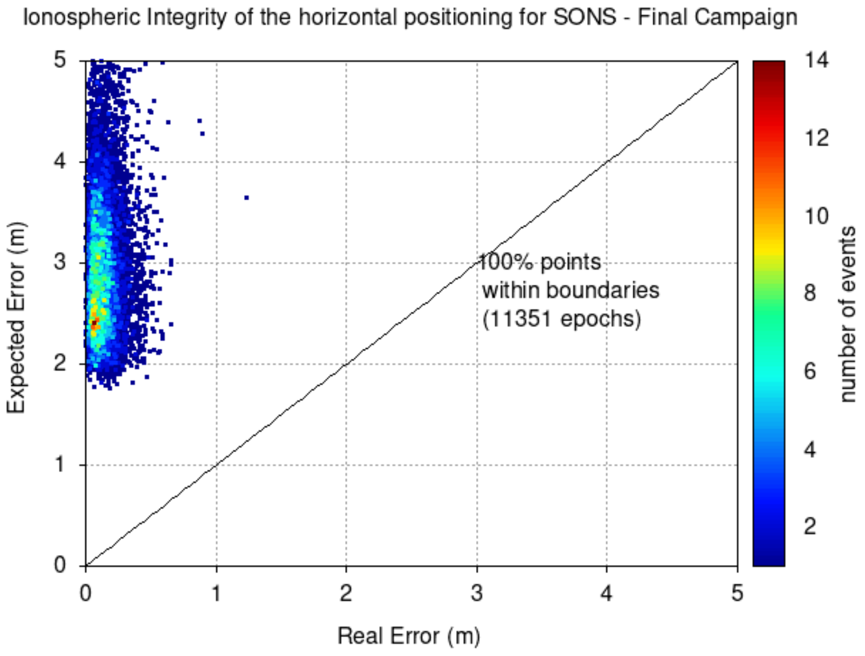


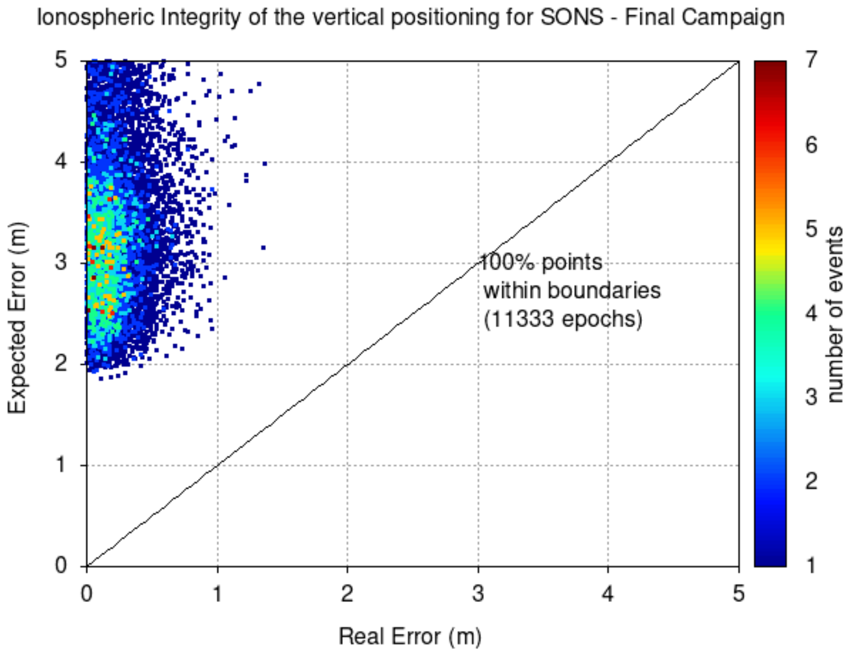


4. Experimentation (9)

3. Positioning results: Confidence level of the corrections

Real error vs Protection level

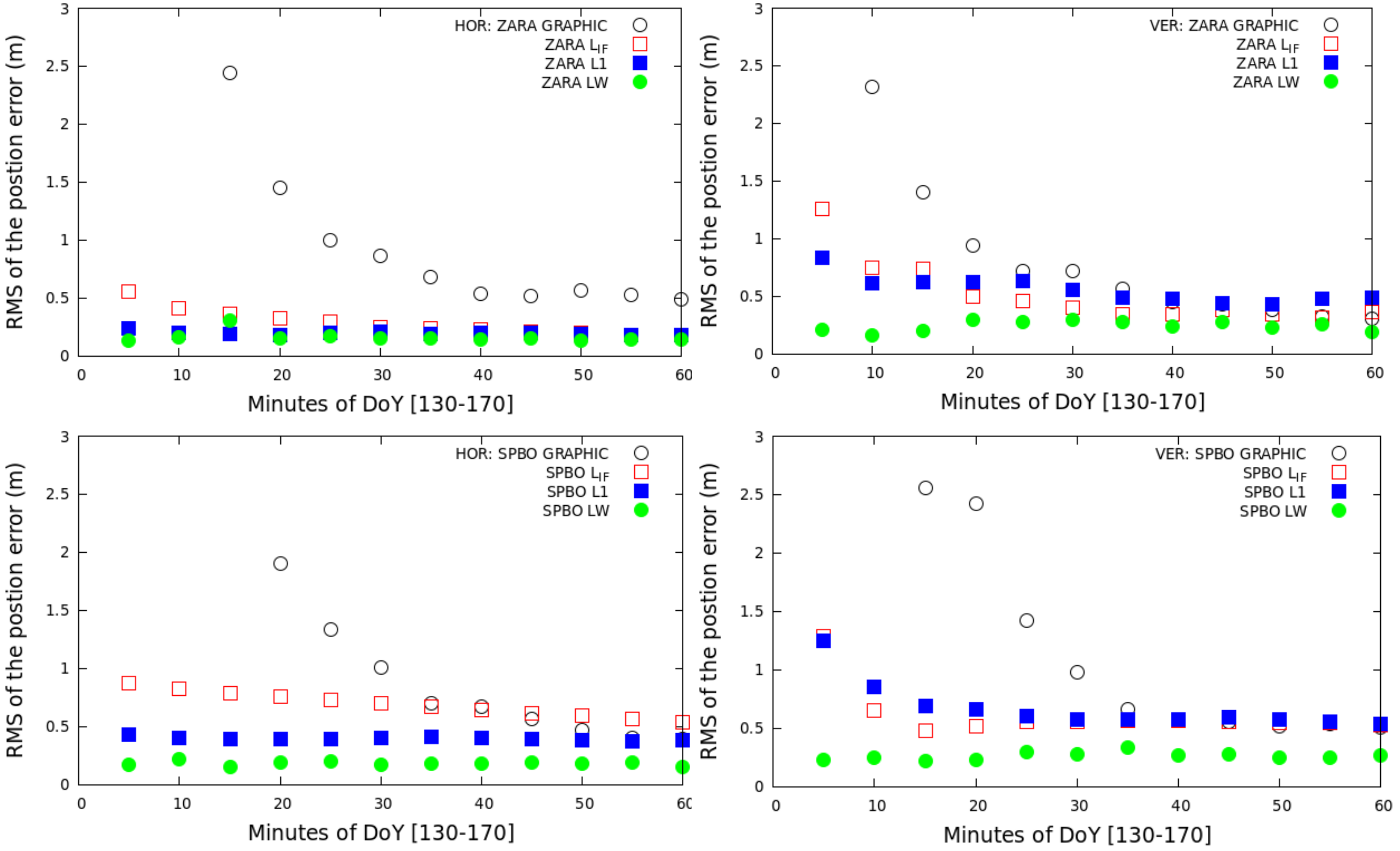




The proposed evaluation relates the computed expected error multiplied by an inflating factor (6 for Horizontal and 5.3 for Vertical, as PL in SBAS), to the real errors using LW.

4. Experimentation (10)

3. Position results: accuracy using LW, L1, L_{IF} and GRAPHIC combination



⚠ *Results during the first hour of solution computation* ⚠

Using unambiguous LW, corrected from ionospheric delay, <u>reports a clear advantage</u>

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4. Experimentation (11)

3. Position accuracy: LW, L1, LIF or GRAPHIC combination

Horizontal

rover	LW HOR position error (m)		L1 HOR position error (m)		L_{IF} HOR position error (m)		GRAPHIC HOR position error (m)	
	RMS	95th	RMS	95th	RMS	95th	RMS	95th
WARE	0.11	0.19	0.19	0.33	0.22	0.36	2.41	4.39
GOP6	0.12	0.23	0.19	0.32	0.17	0.35	0.63	1.34
RIO1	0.17	0.30	0.19	0.35	0.41	0.85	4.38	8.51
ZARA	0.17	0.28	0.20	0.36	0.31	0.61	1.46	2.73
SONS	0.21	0.37	0.18	0.33	0.29	0.52	2.87	6.24
SPFE	0.31	0.57	0.26	0.45	0.38	0.64	4.08	6.20
SPBO	0.18	0.39	0.40	0.67	0.70	0.99	1.79	3.63

Vertical

rover	LW VER position error (m)		L1 VER position error (m)		LIF VER position error (m)		GRAPHIC VER position error (m)	
	RMS	95th	RMS	95th	RMS	95th	RMS	95th
WARE	0.17	0.35	0.39	0.77	0.45	0.88	0.85	1.70
GOP6	0.16	0.32	0.36	0.70	0.31	0.65	0.52	0.93
RIO1	0.27	0.52	0.50	0.92	0.58	1.18	3.69	7.63
ZARA	0.25	0.47	0.57	1.20	0.58	1.16	0.96	2.27
SONS	0.38	0.70	0.58	1.25	0.55	1.07	1.65	3.56
SPFE	0.44	0.94	0.97	1.96	1.07	1.81	3.86	7.11
SPBO	0.26	0.52	0.69	1.44	0.64	1.20	1.78	3.91

⚠*Results of presentative rover receivers at each network during the first hour*⚠

5. Further Studies (1)

Additional analysis of the IONO4HAS tool capabilities:

1. IONO4HAS tool under high ionospheric activity

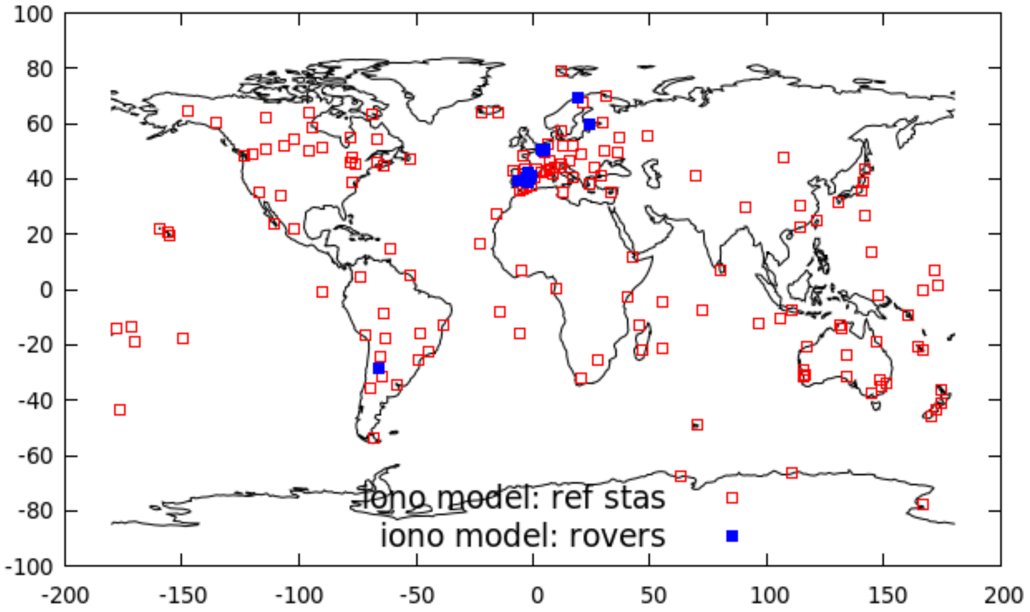
Campaigns in 2022 are close to the solar minimum. Need to test IONO4HAS tool performance under a high ionospheric activity period.

2. Implementation of EGNOS RIMS as input to the IONO4HAS tool

Potential implementation of the EGNOS system to produce an ionospheric model for HAS

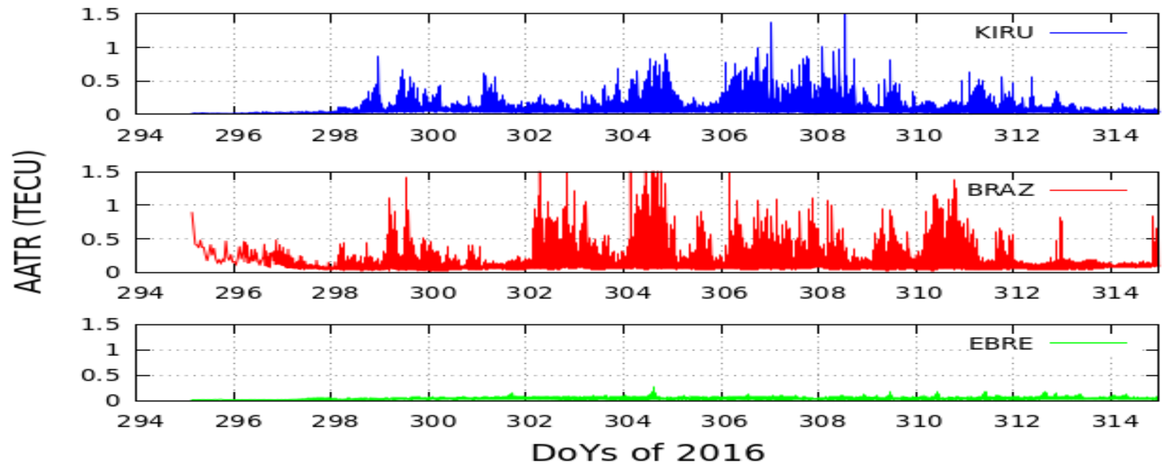
5. Further Studies (2)

1. IONO4HAS tool under high ionospheric activity



162 IGS stations (12 receivers profiled as rovers)
From DoY 300 to 309 in 2016

Determination of high ionospheric activity using the AATR idx

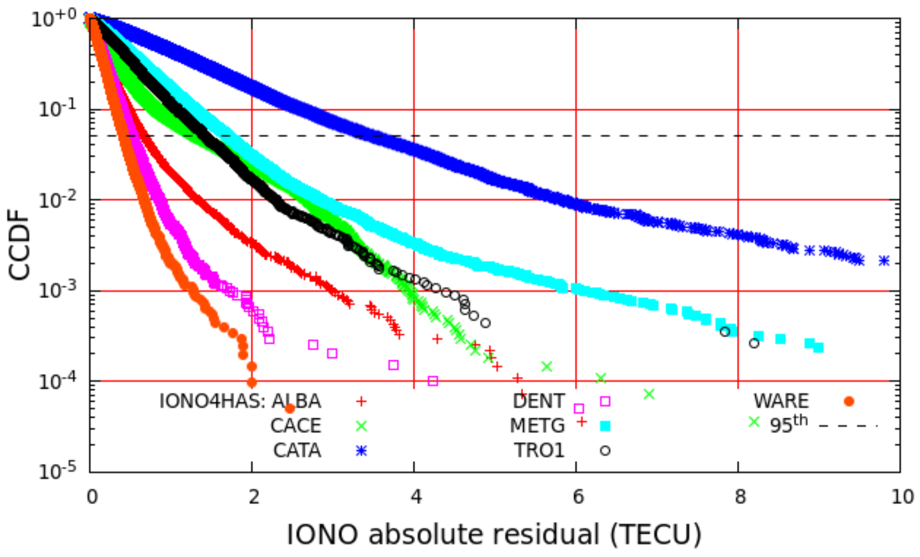


Several days with AATR idx values greater than 0.5 TECU/min (moderate) or even 1 TECU/min (strong) ionospheric activity.

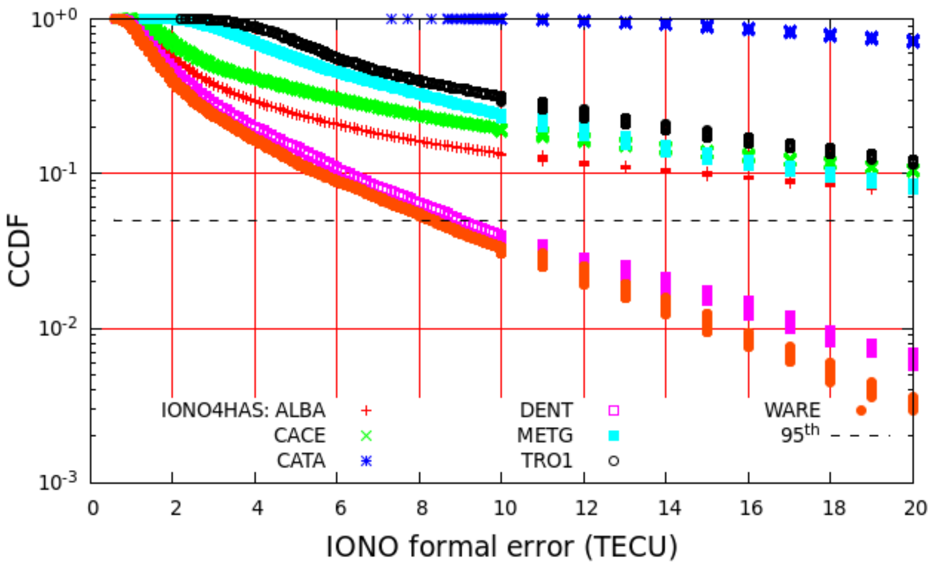
5. Further Studies (3)

1. IONO4HAS tool under high ionospheric activity

Ionospheric model predictions were compared with respect to their unambiguous geometry free combination measurements.



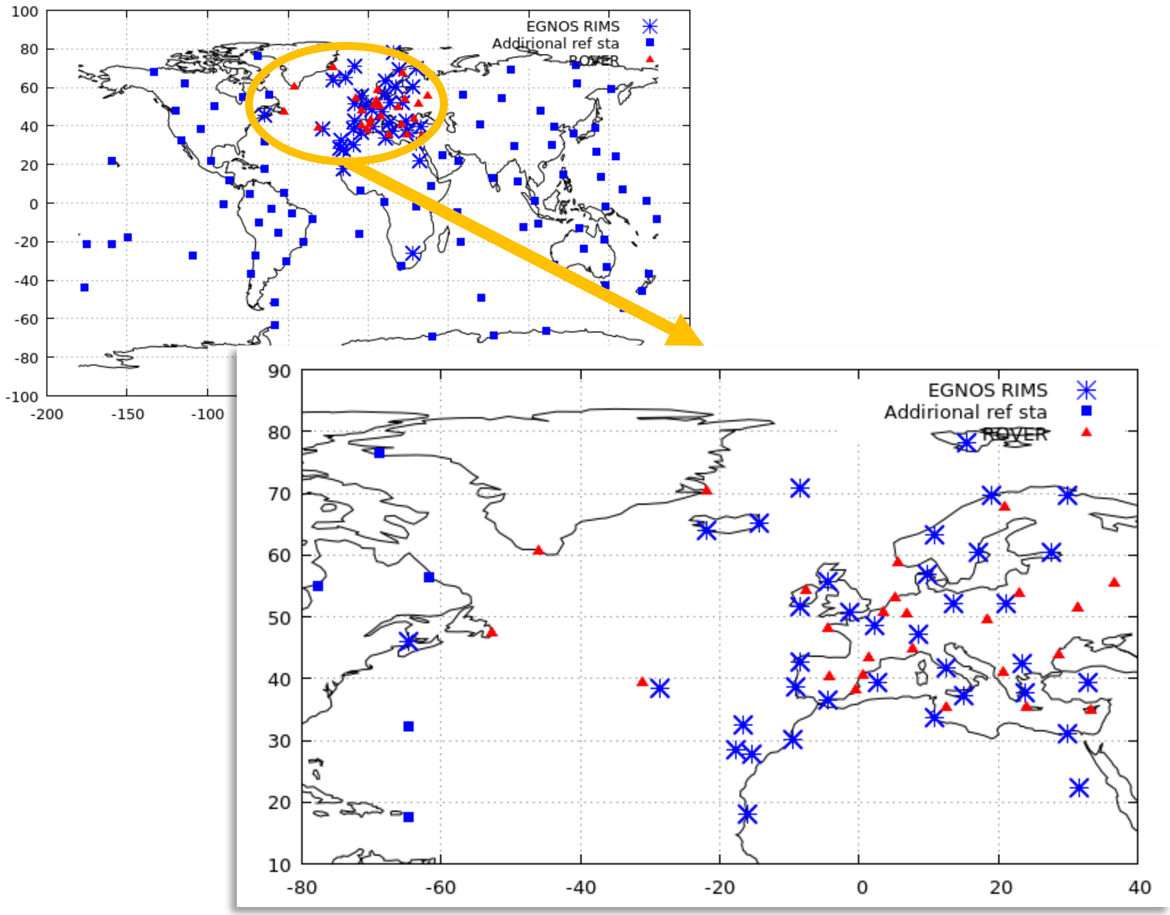
CCDF for the residuals of the STEC test



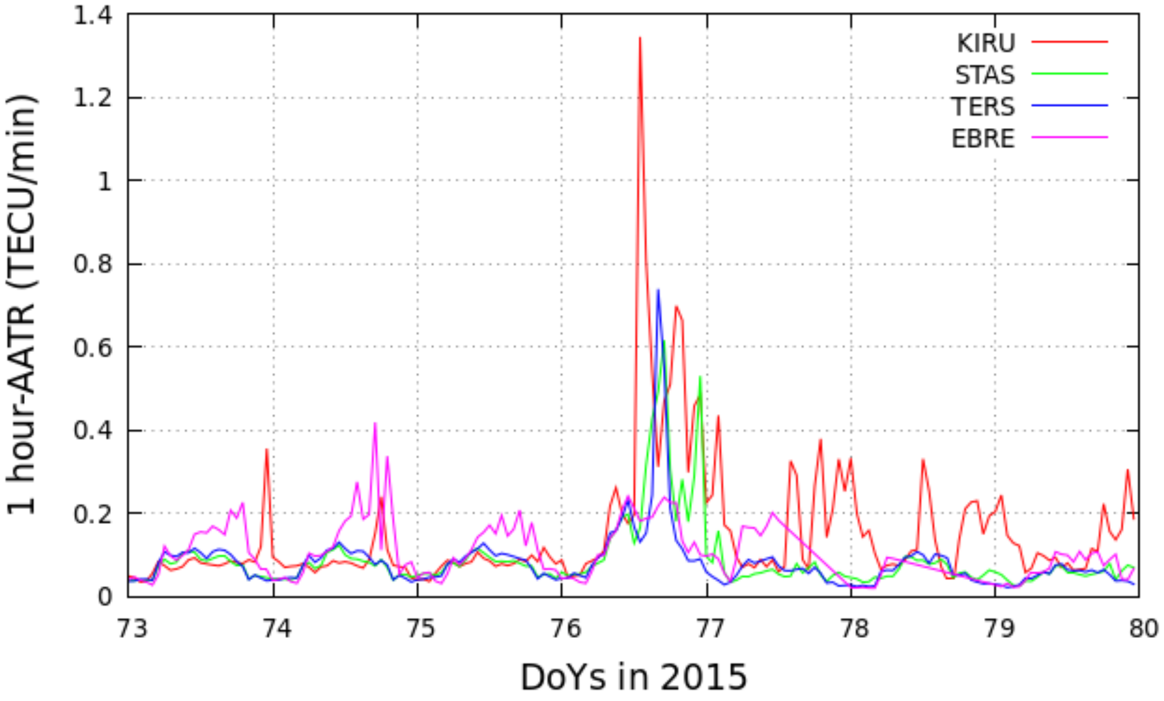
CCDF for the residuals of the confidence values of ionospheric corrections

5. Further Studies (4)

2. Implementation of EGNOS RIMS as input to the IONO4HAS tool



DoYs 073 to 079 in 2015.
Ionospheric activity is characterized by AATR idx.



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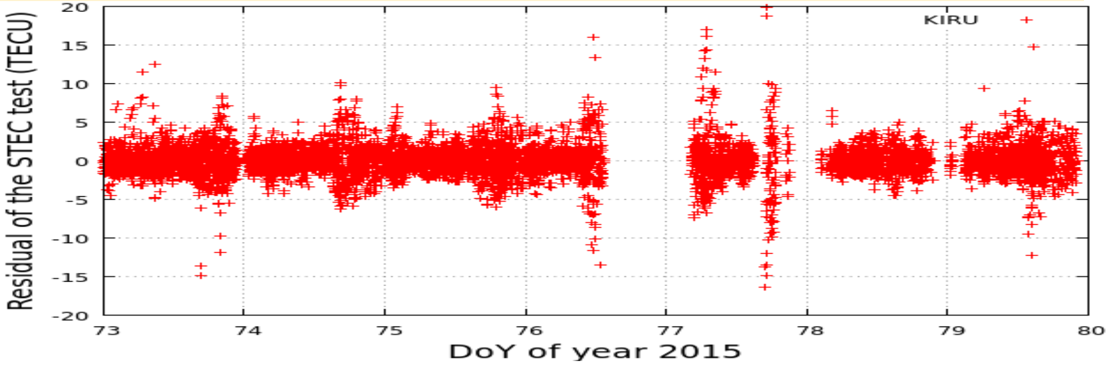
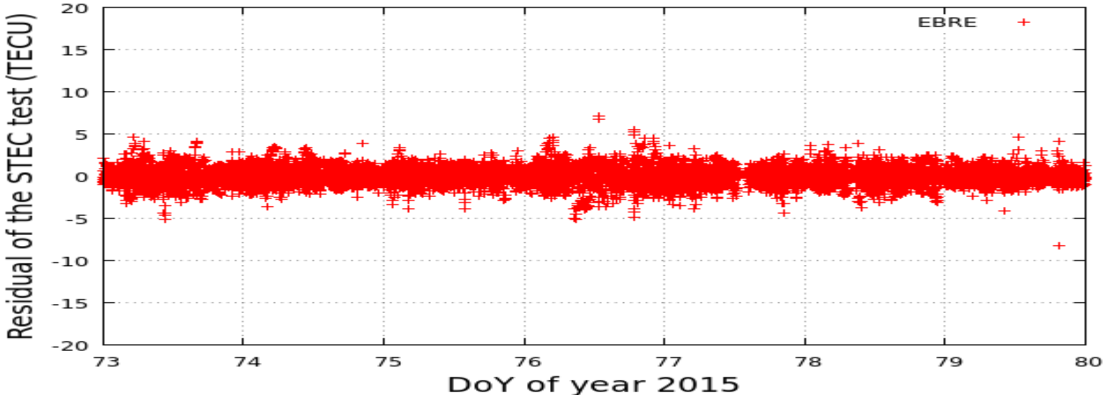
5. Further Studies (5)

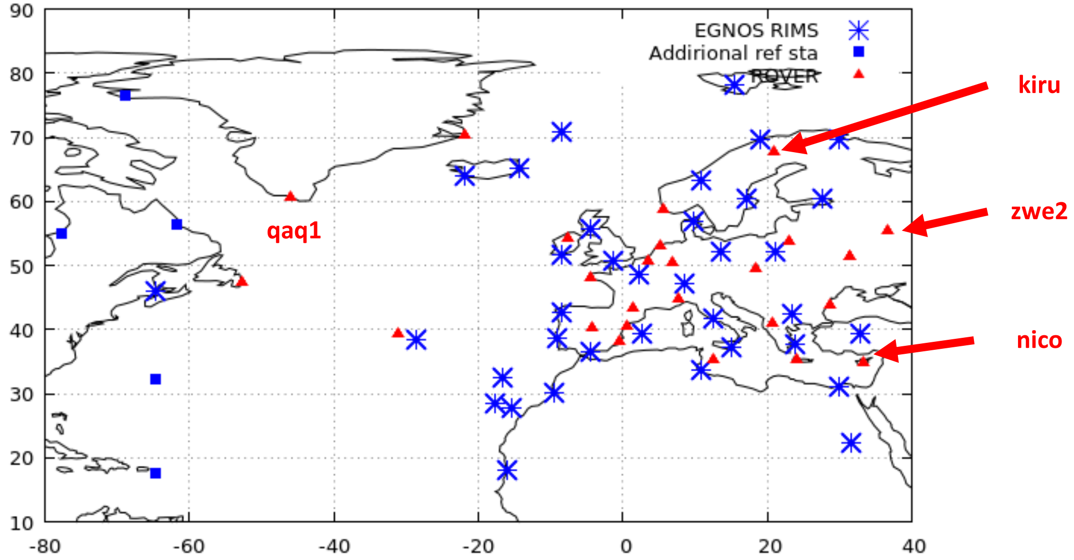
2. Implementation of EGNOS RIMS as input to the IONO4HAS tool

STEC test implemented over the performance of the ionospheric model based on EGNOS RIMs





RCV	074		075		076		077	
ebre	1843	1.0	1846	0.9	1712	1.3	1738	1.0
kiru	1799	1.7	1938	1.7	965	2.3	943	3.4
nico	1918	2.9	1876	3.0	1916	3.6	1866	3.8
qaq1	1345	2.0	1405	2.0	558	1.9	599	2.2
stas	1942	1.1	1931	1.1	1187	1.2	1820	1.7
ters	1925	1.0	1918	1.1	1551	1.4	1913	1.2
zwe2	1874	1.4	1890	1.5	1464	3.2	1748	2.6



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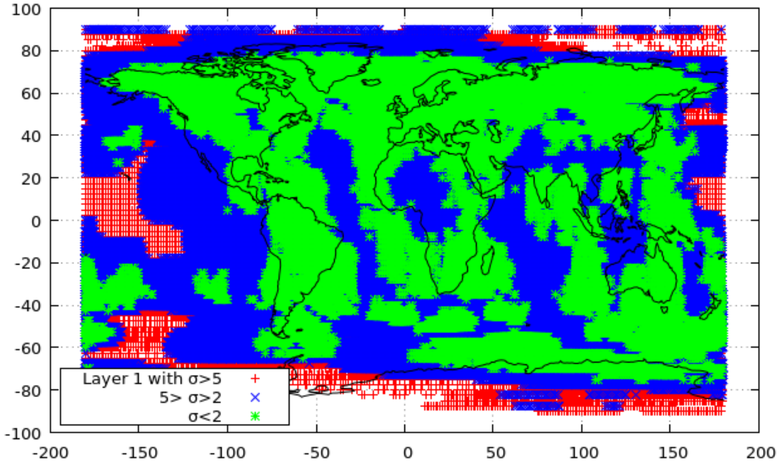
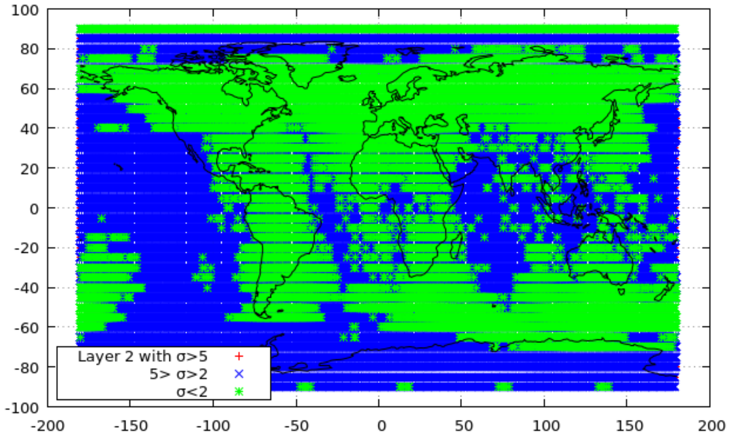
gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain

5. Further Studies (6)

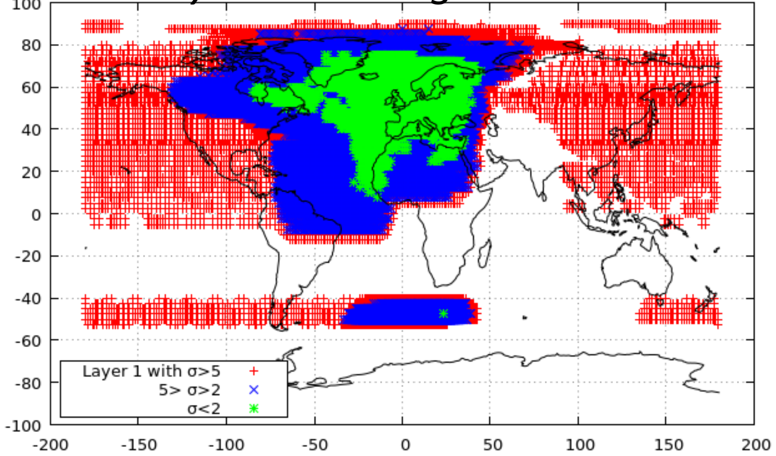
2. Implementation of EGNOS RIMS as input to the IONO4HAS tool

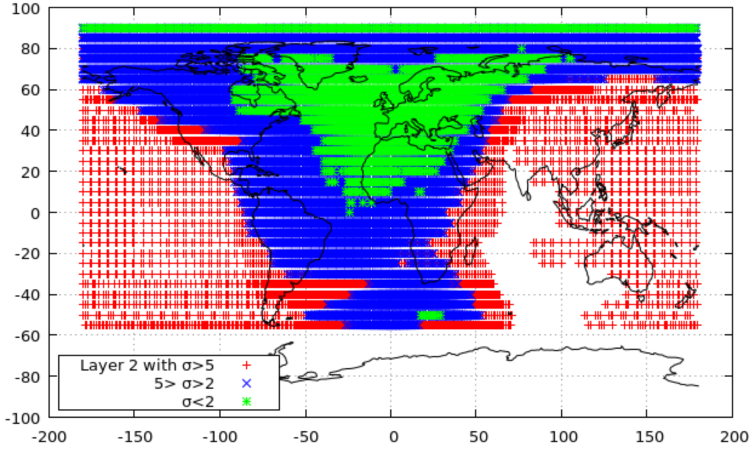
First layer modelling





Second layer modelling





Formal error at the IGPS on DoY 074 of 2015 at 12:00 UT

formal errors > 5 TECU in red
5 TECU > **formal errors** > 2 TECU in blue
formal errors < 2 TECU in green

6. Potential studies using the IONO4HAS outputs (1)

Implementation of IONO4HAS tool opened additional potential capabilities:

1. User Positioning implementing clocks solution at a higher rate (with respect to the actual IONO4HAS rate).
2. Wide area analysis of ionospheric anomalies: *South-Hemisphere TEC anomaly case study*.
3. Possibility of using HAS SL1 corrections in IONO4HAS.

6. Potential studies using the IONO4HAS outputs (2)

1. User Positioning implementing clocks solution at a higher rate (with respect to the actual IONO4HAS rate).

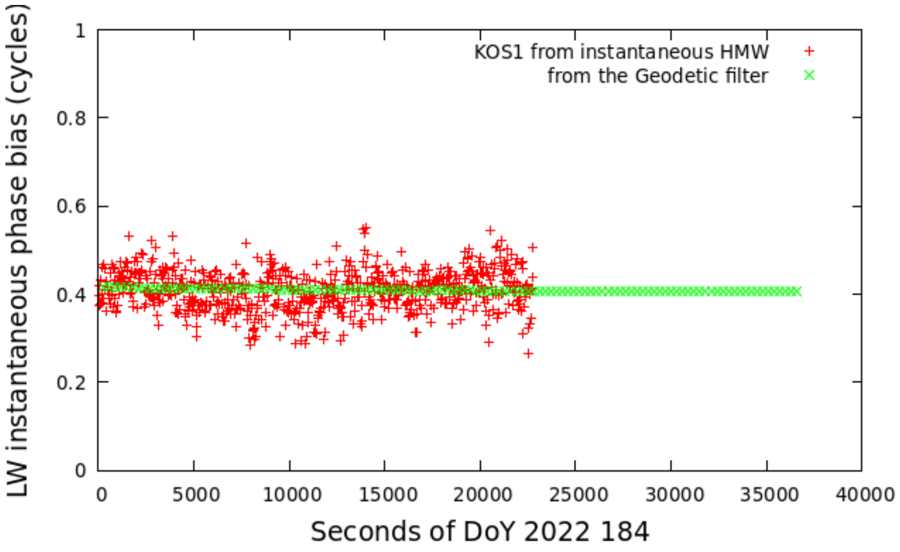
In IONO4HAS project, positioning test takes advantage from the knowledge of satellite and rover phase biases in the WL combination (estimated in the geodetic filter) . From this point, ionospheric delay errors directly impacts on the position accuracy. For a usual rover there appears two issues:

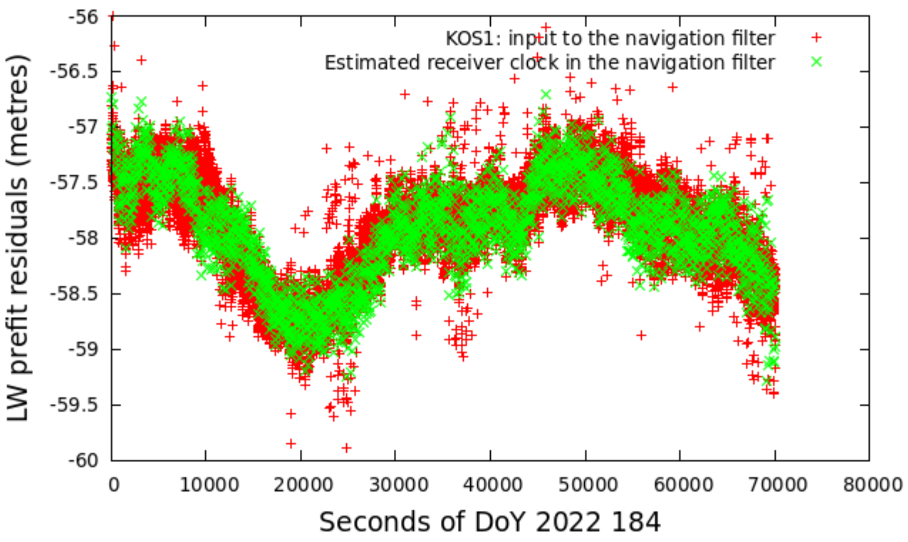
- To reduce the refresh time of the satellite clock estimates, i.e. from 300s to 30s.
- One has to estimate, in RT, the WL phase biases.

These two issues can be solved confidently

6. Potential studies using the IONO4HAS outputs (3)

1. User Positioning implementing clocks solution at a higher rate (with respect to the actual IONO4HAS rate): initial strategies.

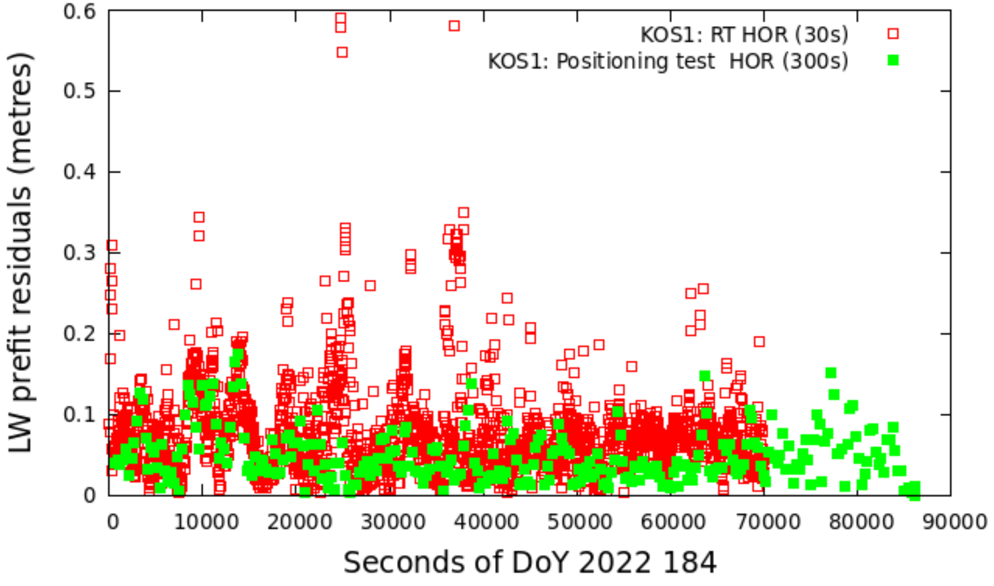


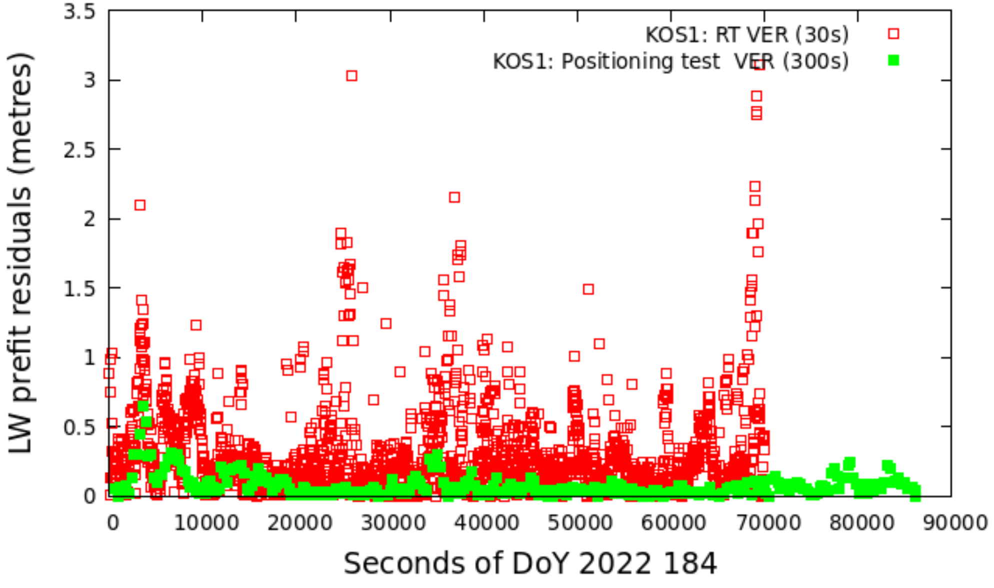


Moreover, one has to extrapolate the satellite clock (refresh time at 30s) and the ionospheric corrections (at 30s) from their last values to the current time: <u>it is necessary to develop strategies for doing such extrapolations minimizing the extrapolation errors.</u>

6. Potential studies using the IONO4HAS outputs (4)

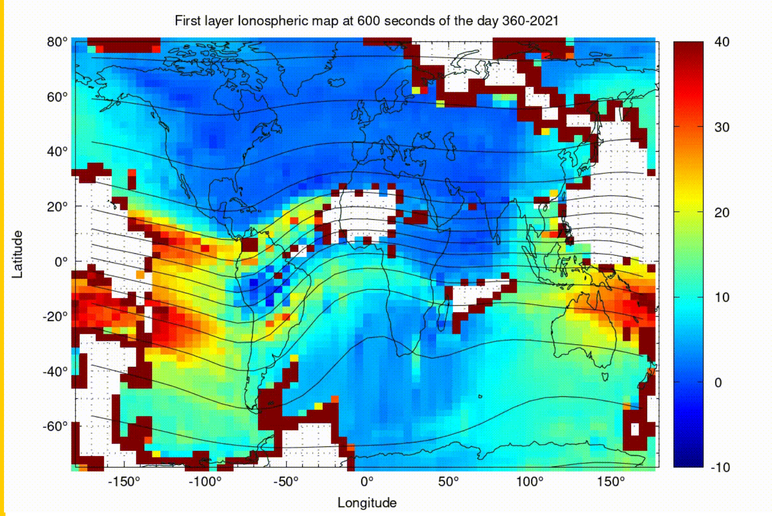
1. User Positioning implementing clocks solution at a higher rate (with respect to the actual IONO4HAS rate): implementation results.



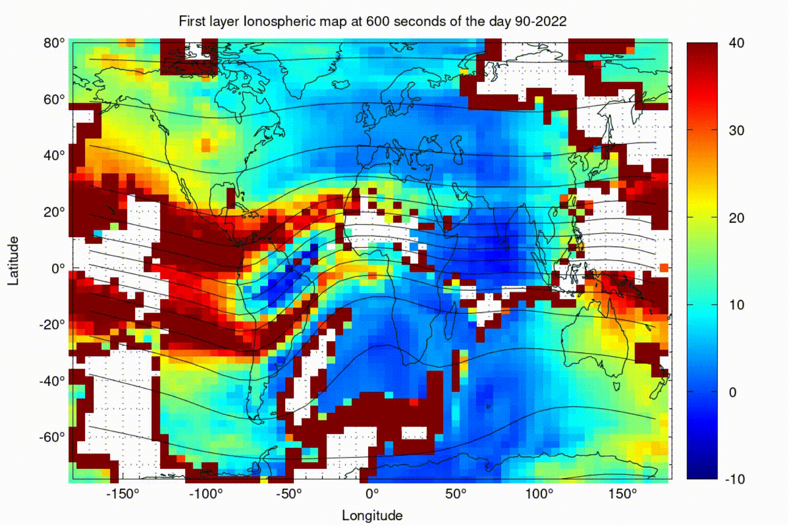


6. Potential studies using the IONO4HAS outputs (5)

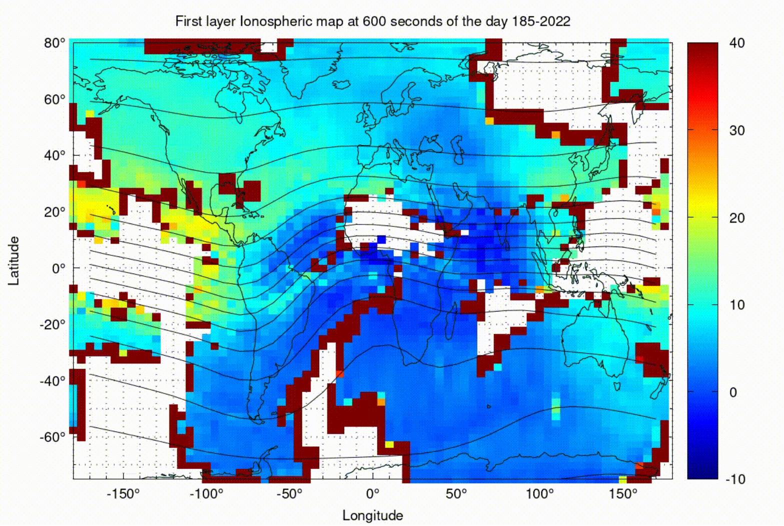
2. Wide area analysis of ionospheric anomalies: *South-Hemisphere TEC anomaly case study.*



December 26th 2022
DoY 360



March 31th 2022
DoY 090

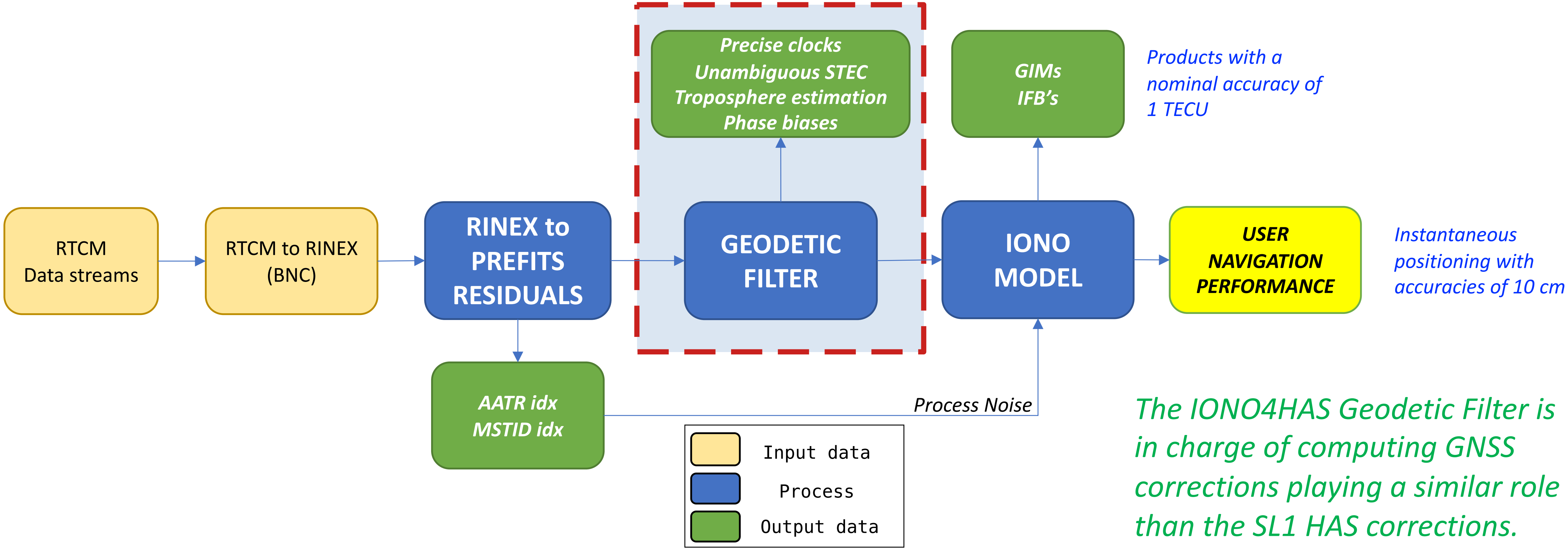


July 4th 2022
DoY 185

6. Potential studies using the IONO4HAS outputs (6)

3. Possibility of using HAS SL1 corrections in IONO4HAS

IONO4HAS Original definition



The IONO4HAS Geodetic Filter is in charge of computing GNSS corrections playing a similar role than the SL1 HAS corrections.

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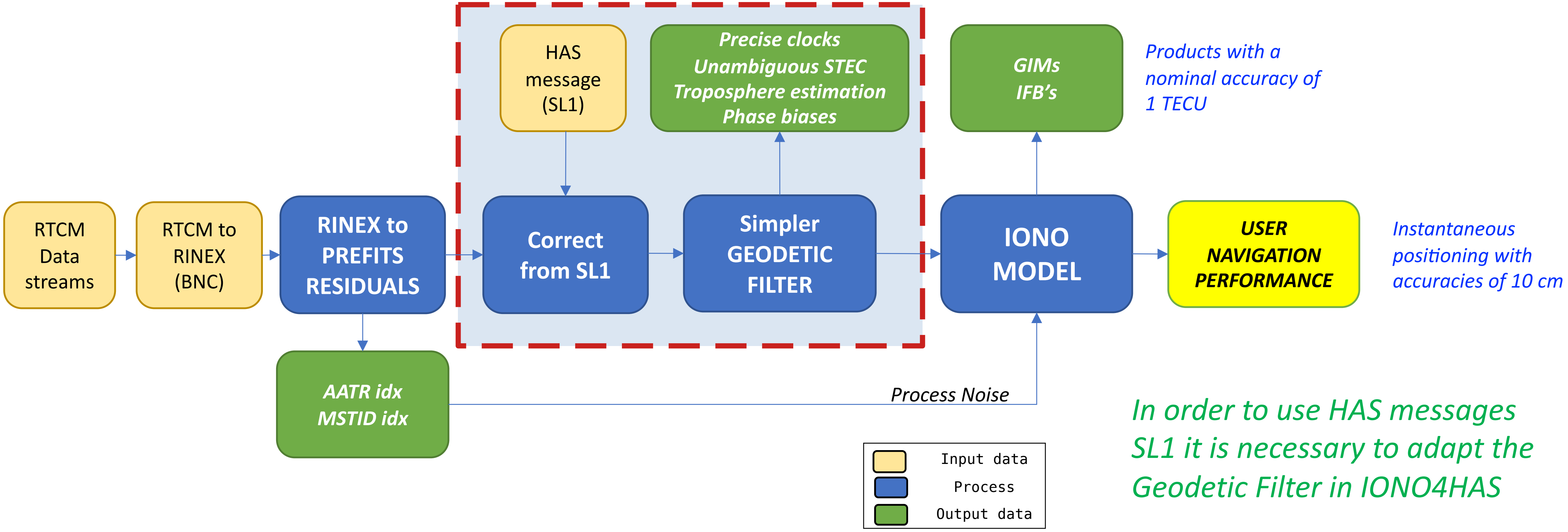
6. Potential studies using the IONO4HAS outputs (7)

3. Possibility of using HAS SL1 corrections in IONO4HAS

IONO4HAS proposed modification



In order to use HAS messages SL1 it is necessary to adapt the Geodetic Filter in IONO4HAS

Conclusions

IONO4HAS is able to build a real time ionospheric model by means of several innovative techniques:

- Use of the ionosphere-free combinations of measurements which allow us to obtain in real time (geodetic filter): Precise satellite clocks which have a similar accuracy to those emitted by several High Precision Positioning Services (for instance IGS-RT), carrier phase biases that allow to any user, into the coverage area, to fix their carrier phase ambiguities, speeding up the convergence of the navigation filter computing the user solution. Unambiguous carrier phase data (unambiguous geometry-free combination of carrier phases).

Conclusions

The IONO4HAS ionospheric model is feed with geometry-free combinations accurately estimated (geodetic filter output). The main characteristics of the developed ionospheric model:

- Consists on a dual layer model, which take into account that the ionospheric delay of a GNSS signal that can occur at different heights.
- It is a grid-based model where the grid points are not regularly distributed, where the grid points are linked to the local time and the MODIP angle.
- Thanks to the reduction in the number of grid points, with a time update of 300 s it is possible to broadcast the ionospheric information and the DCBs in less than 30 seconds for European users and in less than 2.5 minutes for worldwide users.
- Besides the VTEC at each grid point, the ionospheric model also computes the differential DCBs for all the satellites involved in the ionospheric model computation. And even, absolute DCBs are computed for each device involved in the process

Conclusions

- IONO4HAS can handle observations from 5 constellations: GPS, Galileo, Glonass, Beidou and QZSS. In spite of the geodetic filter and the ionospheric model works with 2 frequencies on each constellation, the operator can select the two frequencies for each constellation.
- In order to validate the real time products, we use, routinely, a set of 21 IGS receiver as rover receivers that use the IONO4HAS corrections.
- Two tests have been used for assessing the quality of the IONO4HAS corrections:
    - STEC test. Which compares unambiguous ionospheric free combination of carrier phases with the ionospheric model predictions.
    - Positioning test. Which is based on the unambiguios widelane combination of carrier-phases, corrected from its ionospheric delays.

Conslusions

The IONO4HAS tool is running daily from the last months of 2021. We were able to validate the IONO4HAS products obtaining the following results that for the European rovers :

- The STEC test shows that the error of the ionospheric corrections is smaller than 1 TECU (95^{th} percentile) for the mid/high latitude rovers and around 1 TECU (95^{th} percentile) for the Spanish rovers. Whereas for the Brazilian rovers the 95^{th} percentile can be close to 2 TECU, which is an acceptable error for HAS.
- Applying the positioning test, we obtained an instantaneous positioning with an horizontal error around 20cm (95th percentile) and a vertical error around 30 cm. For the Brazilian rovers arrors are at the level of 50 cm, in horizontal and 1m, in vertical.
- Comparing these instantaneous positioning using the unambiguous wide-lane combination of carrier phases with more classical techniques using single frequency measurements (SFPPP or GRAPHIC) or the ionosphere free combination, we showed that the positioning solutions during the 1^{st} hour of each day, using the unambiguous wide lane combination outperforms the other three techniques.

Conslusions

We have examined the IONO4HAS tool in more challenging scenarios:

- During 10 days of 2016 with periods in some regions presenting strong ionospheric activity (AATR > 1 TECU/min).
- Around the St. Patrick Storm (2015 Doy 076) and using EGNOS RIMs (with larger baselines) data to feed the ionospheric model over the European region.

In both cases, the STEC test reveals a degradation of the performance in these more difficult scenarios. However, the residuals are always around 1 or 2 TECU which is no so far from the results in the real time campaigns. Therefore, it can be concluded that, even in these more complex scenarios, IONO4HAS can help significantly to improve navigation.

Thanks for your attention,

Questions?