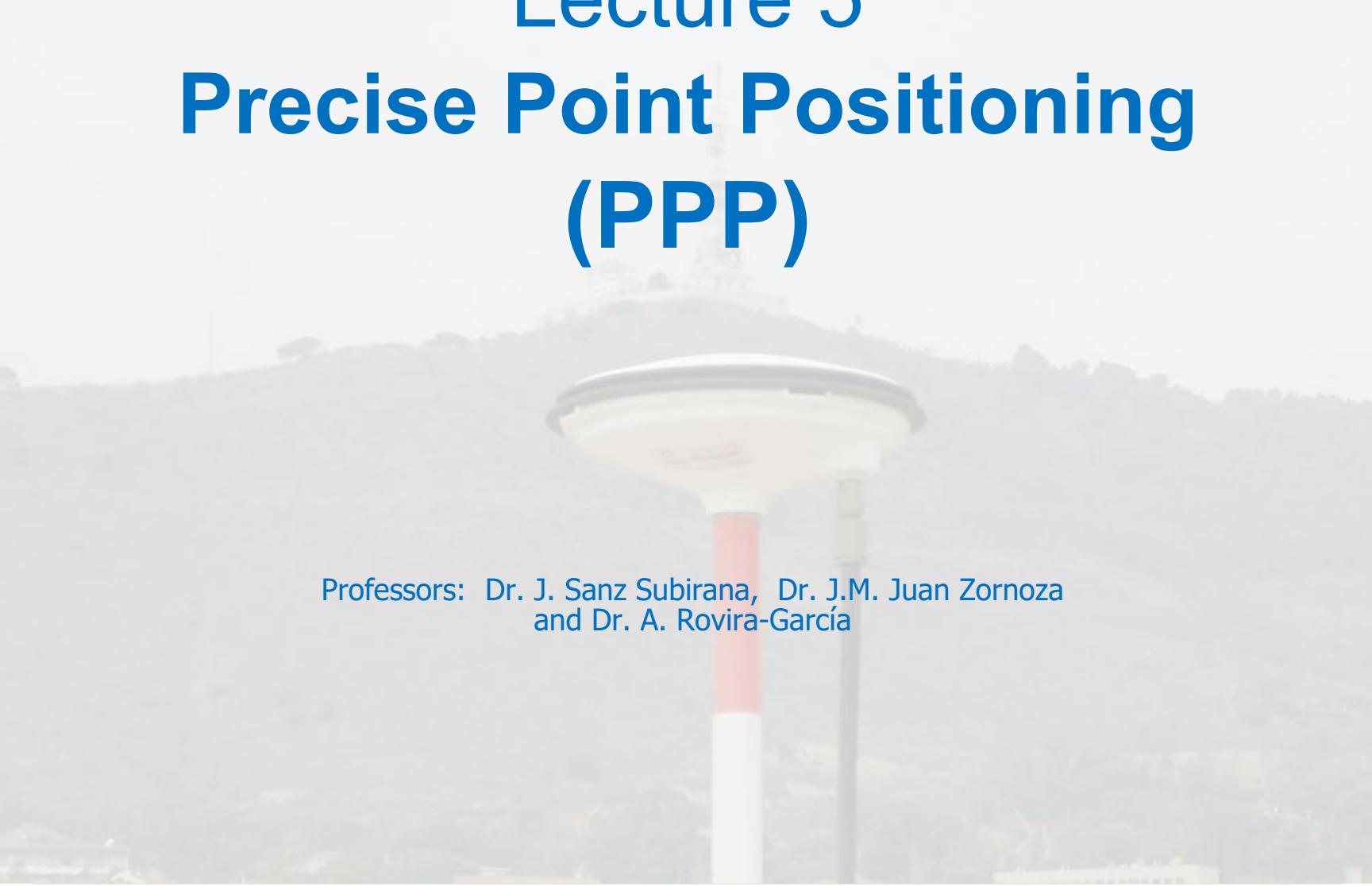


Lecture 5

Precise Point Positioning

(PPP)



Professors: Dr. J. Sanz Subirana, Dr. J.M. Juan Zornoza
and Dr. A. Rovira-García

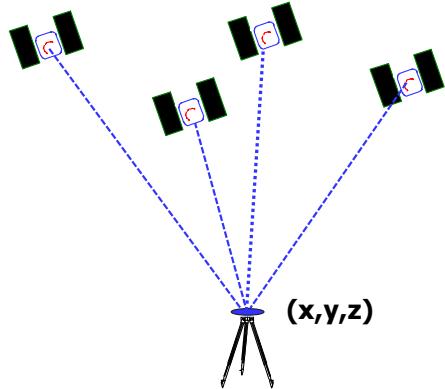
Contents

Precise Point Positioning (PPP)

1. Introduction
2. Orbits and Clocks: Broadcast and Precise
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5. Parameter estimation: Floating Ambiguities
6. Carrier Ambiguity fixing concept: DD and undifferenced
7. Accelerating Filter convergence with accurate ionosphere

Code based positioning

Standard Point Positioning (SPP)

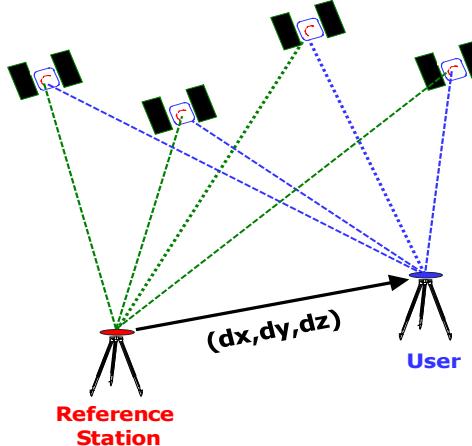


**Few meters.
World wide.
Single epoch.**

Carrier based Differential positioning

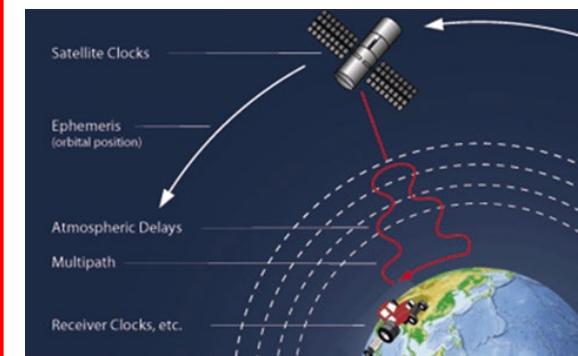
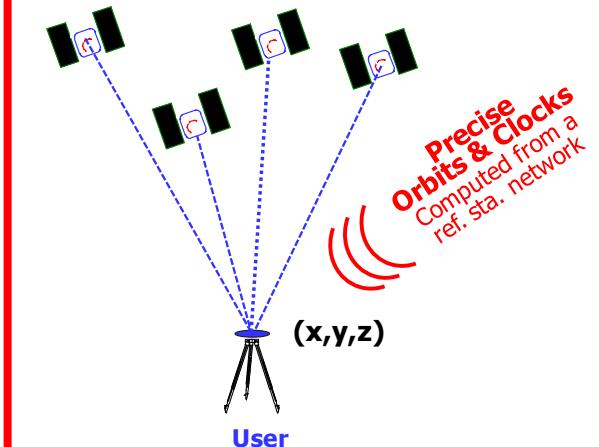
High Accuracy

Relative Positioning (RTK)



**Few centimetres.
Local Area (few km).
Few seconds.**

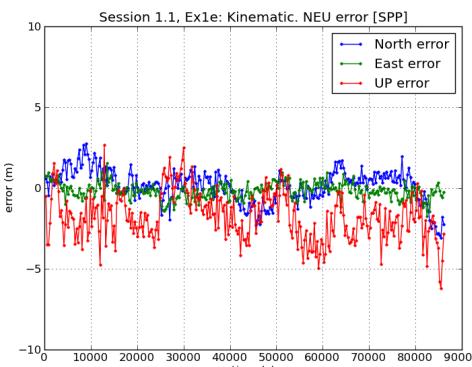
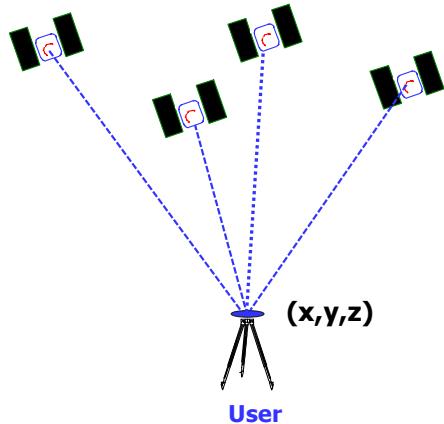
Precise Point Positioning (PPP)



**cm – dm level.
World wide.
Best part of one hour.**

Code based positioning

Standard Point Positioning (SPP)

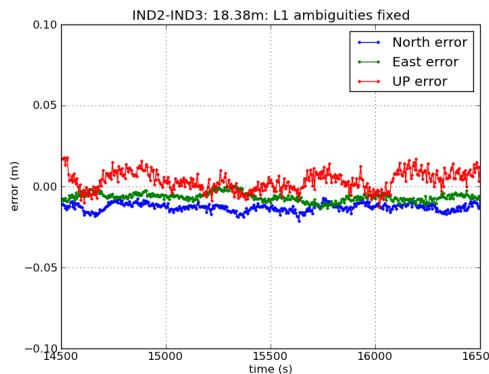
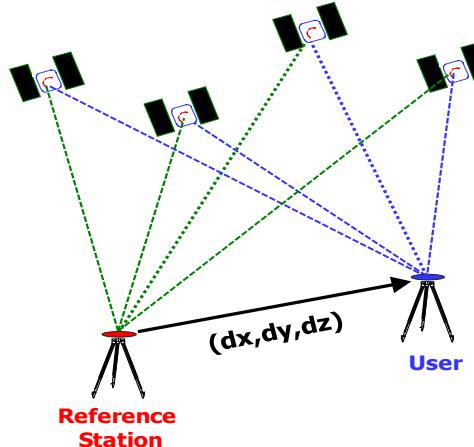


Few meters.
World wide.
Single epoch.

Carrier based Differential positioning

High Accuracy

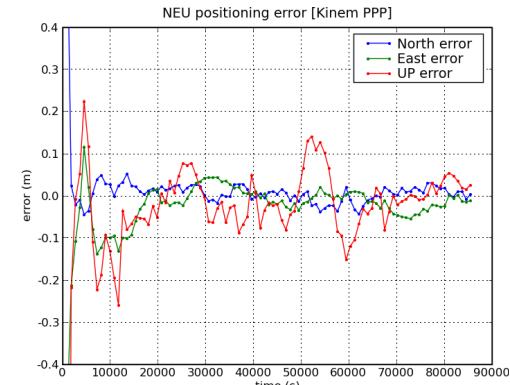
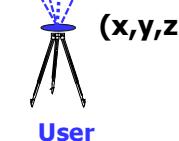
Relative Positioning (RTK)



Few centimetres.
Local Area (few km).
Few seconds.

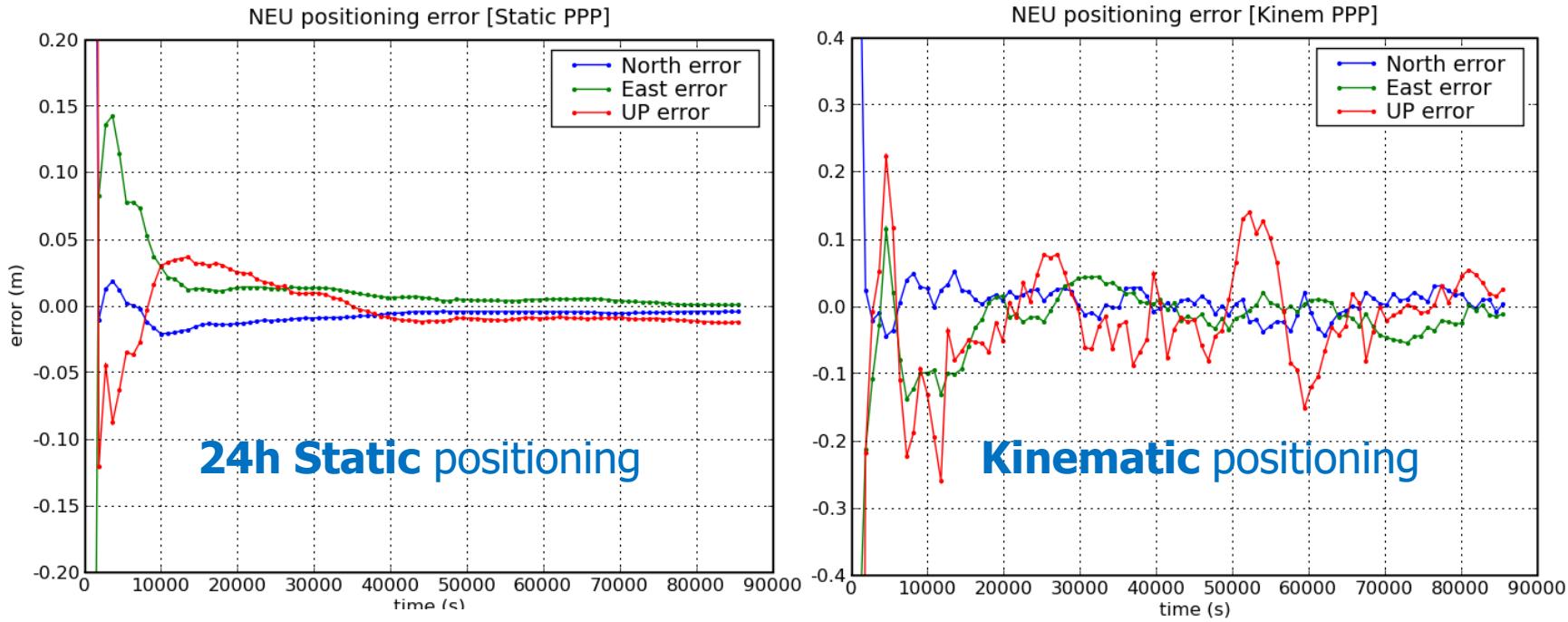
Precise Point Positioning (PPP)

Precise
Orbits & Clocks
Computed from a
ref. sta. network



cm – dm level.
World wide.
Best part of one hour.

The PPP technique allows **centimetre-level** accuracy to be achieved for static positioning and **decimetre level, or better, for kinematic positioning, after the best part of one hour.**



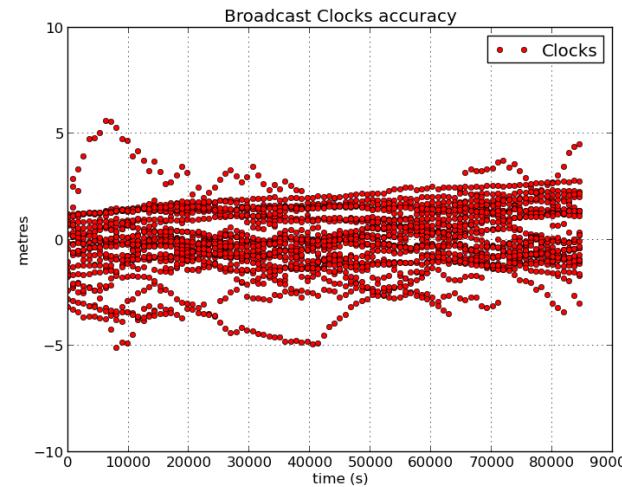
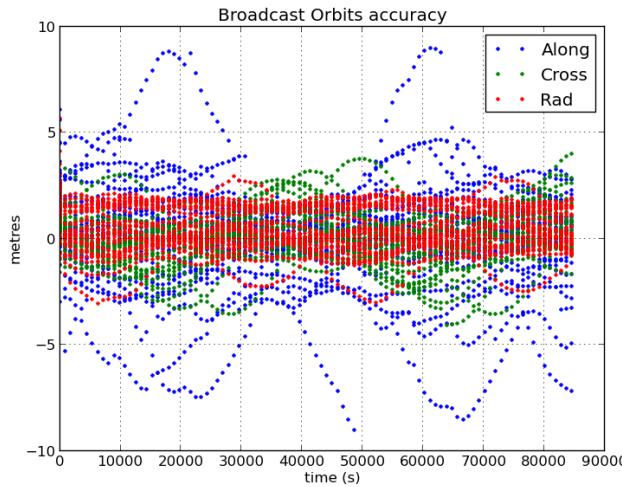
This high accuracy requires the use of code and carrier measurements and an accurate measurement modelling up to centimetre level or better.

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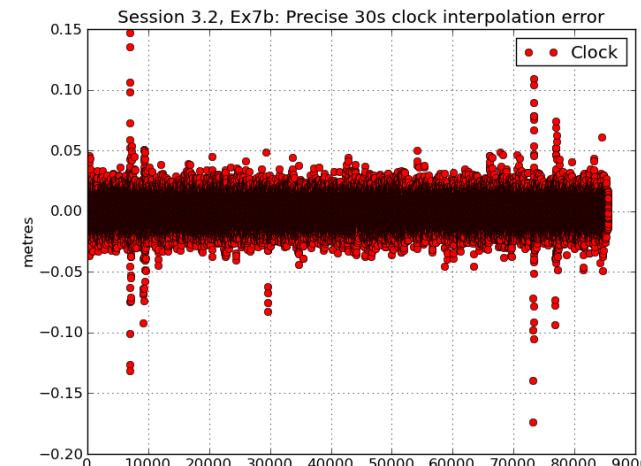
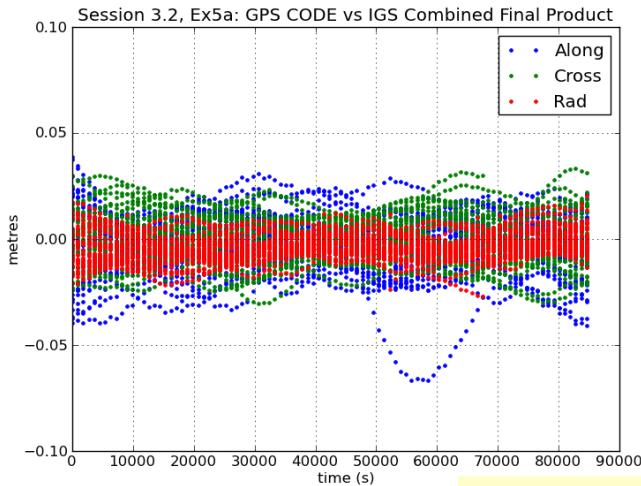
Satellite Orbit and clock accuracies



Broadcast:
Few metres of accuracy for broadcast orbits and clocks

Transmitted in the satellite navigation message.

POST-PROCESS Products



Precise:
Few centimetres of accuracy for precise orbits and clocks

Precise clocks for GPS satellites can be found on the International GNSS Service (IGS) server <http://igscb.jpl.nasa.gov>

IGS Precise orbit and clock products:

RMS accuracy, latency and sampling

Products (delay)	Broadcast (real time)	Ultra-rapid Predicted (real time)	Observed (3–9 h)	Rapid (17–41 h)	Final (12–18 d)
Orbit GPS (sampling)	~100 cm (~2 h)	~5 cm (15 min)	~3 cm (15 min)	~2.5cm (15 min)	~ 2.5 cm (15 min)
Glonass (sampling)					~5 cm (15 min)
Clock GPS (sampling)	~5 ns (daily)	~3 ns (15 min)	~150 ps (15 min)	~75 ps (5 min)	~75 ps (30 s)
Glonass (sampling)					~ TBD (15 min)

<http://igscb.jpl.nasa.gov/components/prods.html>

GBM0MGXRAP_20240870000_01D_05M_ORB.sp3 - Notepad

```

File Edit View ⚙
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## 2307 259200.00000000 300.00000000 60396 0.0000000000000000
+ 127 C01C02C03C05C06C07C08C09C10C11C12C13C14C16C19C20C21
+ C22C23C24C25C26C27C28C29C30C32C33C34C35C36C37C38C39
+ C40C41C42C43C44C45C46C59C60C62E02E03E04E05E07E08E09
+ E10E11E12E13E14E15E18E19E21E24E25E26E27E30E31E33E34
+ E36G01G02G03G04G05G06G07G08G09G10G11G12G13G14G15G16
+ G17G18G19G20G21G22G23G24G25G26G27G28G29G30G31G32G3202
+ J03J04J07R01R02R03R04R05R07R08R09R11R12R13R14R15R16
+ R17R18R19R20R21R22R24R26 00 00 00 00 00 00 00 00 00 00 00
++ 10 10 10 10 8 9 10 7 7 10 9 7 6 6 5
++ 5 8 6 9 6 5 6 7 5 5 5 6 6 7 7 10 10
++ 10 5 5 5 6 7 6 10 10 5 5 5 6 6 5 5
++ 8 6 5 5 5 6 5 6 5 6 5 6 6 6 6 7 7
++ 6 10 5 5 7 9 8 5 5 6 5 5 6 6 8 6 8
++ 6 6 8 6 8 7 5 6 5 6 7 6 6 5 5 10
++ 10 10 10 7 8 6 5 6 6 6 7 9 10 6 6 8
++ 5 5 10 9 8 8 8 6 0 0 0 0 0 0 0 0 0 0
%cc GPS ccc cccc cccc cccc ccccc ccccc ccccc ccccc
%cc ccc ccc
%f 1.2500000 1.025000000 0.0000000000 0.0000000000000000
%F 0.0000000 0.000000000 0.00000000000 0.000000000000000
%i 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
%o 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
/* PCV:IGS20_2303 OL:AL:FES2014b NONE YN CLK:CoN ORB:CoN
/* GeoForschungsZentrum Potsdam
/*
/*
* 2024 3 27 0 0 0.0000000
PC01 -34336.036084 24438.777260 -1231.133890 889.356019
PC02 4452.079369 41949.450777 -215.804048 547.706076
PC03 -14669.5232025 39528.138951 -896.312620 94.387125
PC05 21960.588387 35990.903906 172.622701 -922.332705
PC06 -14657.215642 25920.703949 29807.194605 301.141003
PC07 -18050.507113 40470.826585 6334.867952 -878.024804
PC08 -213.750720 25160.729290 -33777.600679 28.212208
PC09 -7200.378529 25547.205753 33088.476470 -676.283009
PC10 -4590.928931 42215.515887 -389.533563 27.951339
PC11 15440.448679 -19712.821719 12379.933644 480.413559
PC12 24675.428391 -67000.670006 -5846.610342 -220.791848
PC13 7053.918218 29483.773691 -29089.970369 427.486331
PC14 5639.241823 -24803.361752 11422.523538 498.649416
PC16 -19635.428137 25098.936442 27721.519824 -420.367446
PC19 668.291783 27799.928037 -2502.289575 -917.066145
PC20 -10093.344403 19424.747367 -17313.451174 -297.189398
PC21 15748.393447 1691.285484 22997.260117 -961.666315
PC22 11647.671311 20745.714194 14612.738175 -60.568119
PC23 -19738.657290 -17092.451503 -9854.686336 -775.682122
PC24 17133.610363 -8268.731193 -28426.678427 949.417456
PC25 -2661.792172 -17888.168074 -21270.296170 359.410397
PC26 26217.113289 5313.080894 -7908.883709 -268.457485
PC27 -23890.680701 4840.417906 13550.638755 290.317712
PC28 -14083.846147 -9249.337466 22246.660366 221.637500
PC29 -5972.992704 20351.174467 -18140.555130 259.934856
PC30 -21353.843606 17889.594876 -2208.621634 -44.818235
PC32 -15754.622549 -1613.962058 -22954.875984 -590.164549
PC33 -745.524295 -27758.171989 2649.629004 -962.779907
PC34 20580.342400 -18499.261033 3691.861482 398.823805
PC35 14341.623635 8916.714018 -22237.881148 401.709930

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Ln 1, Col 1

80%

Unix (LF)

UTF-8

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3.00 C RINEX VERSION / TYPE
EPOS-8 GFZ 20240328 181807 LCL PGM / RUN BY / DATE
2 AS AR # / TYPES OF DATA
GFZ GeoForschungsZentrum Potsdam # OF CLK REF
1 mgue 41558M001 ANALYSIS CLK REF
Clocks are re-aligned to broadcast GPS time
125 IGS20 COMMENT
AS G01 2024 3 27 0 0 0.000000 1 0.176177063952E-03 # OF SOLN STA / TRF
AS G02 2024 3 27 0 0 0.000000 1 -0.463729143729E-03
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AS G13 2024 3 27 0 0 0.000000 1 0.637562256337E-03
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AS G15 2024 3 27 0 0 0.000000 1 0.141869701623E-03
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AS G18 2024 3 27 0 0 0.000000 1 -0.583208026783E-03
AS G19 2024 3 27 0 0 0.000000 1 0.459551958960E-03
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AS G21 2024 3 27 0 0 0.000000 1 0.129769753732E-03
AS G22 2024 3 27 0 0 0.000000 1 0.983053431337E-05
AS G23 2024 3 27 0 0 0.000000 1 0.186309799079E-03
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AS R02 2024 3 27 0 0 0.000000 1 -0.226404253130E-04
AS R03 2024 3 27 0 0 0.000000 1 0.970975487824E-04
AS R04 2024 3 27 0 0 0.000000 1 0.229317222267E-03
AS R05 2024 3 27 0 0 0.000000 1 0.129029468731E-03
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```

Ln 8, Col 80

100%

Unix (LF)

UTF-8

Computation of satellite coordinates from precise products.

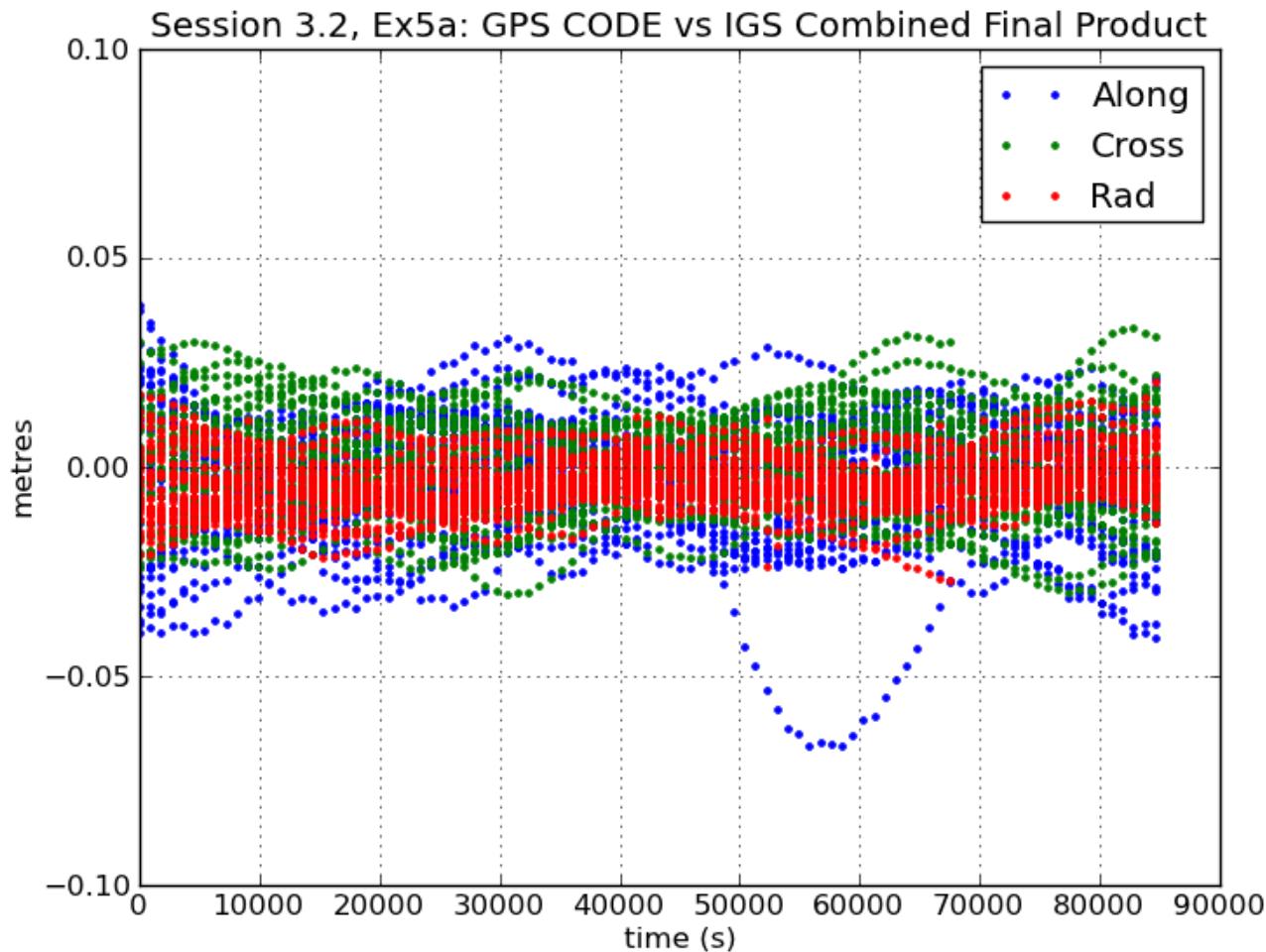
Precise orbits for GPS satellites can be found on the International GNSS Service (IGS) server <http://igscb.jpl.nasa.gov>

Orbits are given by (x, y, z) coordinates with a sampling rate of 15 minutes. The satellite coordinates between epochs can be computed by polynomial interpolation. A 10th-order polynomial is enough for a centimetre level of accuracy with 15 min data.

$$\begin{aligned} P_n(x) &= \sum_{i=1}^n y_i \frac{\prod_{j \neq i} (x - x_j)}{\prod_{j \neq i} (x_i - x_j)} \\ &= y_1 \frac{x - x_2}{x_1 - x_2} \dots \frac{x - x_n}{x_1 - x_n} + \dots \\ &\quad + y_i \frac{x - x_1}{x_i - x_1} \dots \frac{x - x_{i-1}}{x_i - x_{i-1}} \frac{x - x_{i+1}}{x_i - x_{i+1}} \dots \frac{x - x_n}{x_i - x_n} + \dots \\ &\quad + y_n \frac{x - x_1}{x_n - x_1} \dots \frac{x - x_{n-1}}{x_n - x_{n-1}} \end{aligned}$$

IGS orbit and clock products (for PPP):

Discrepancy between the different centres



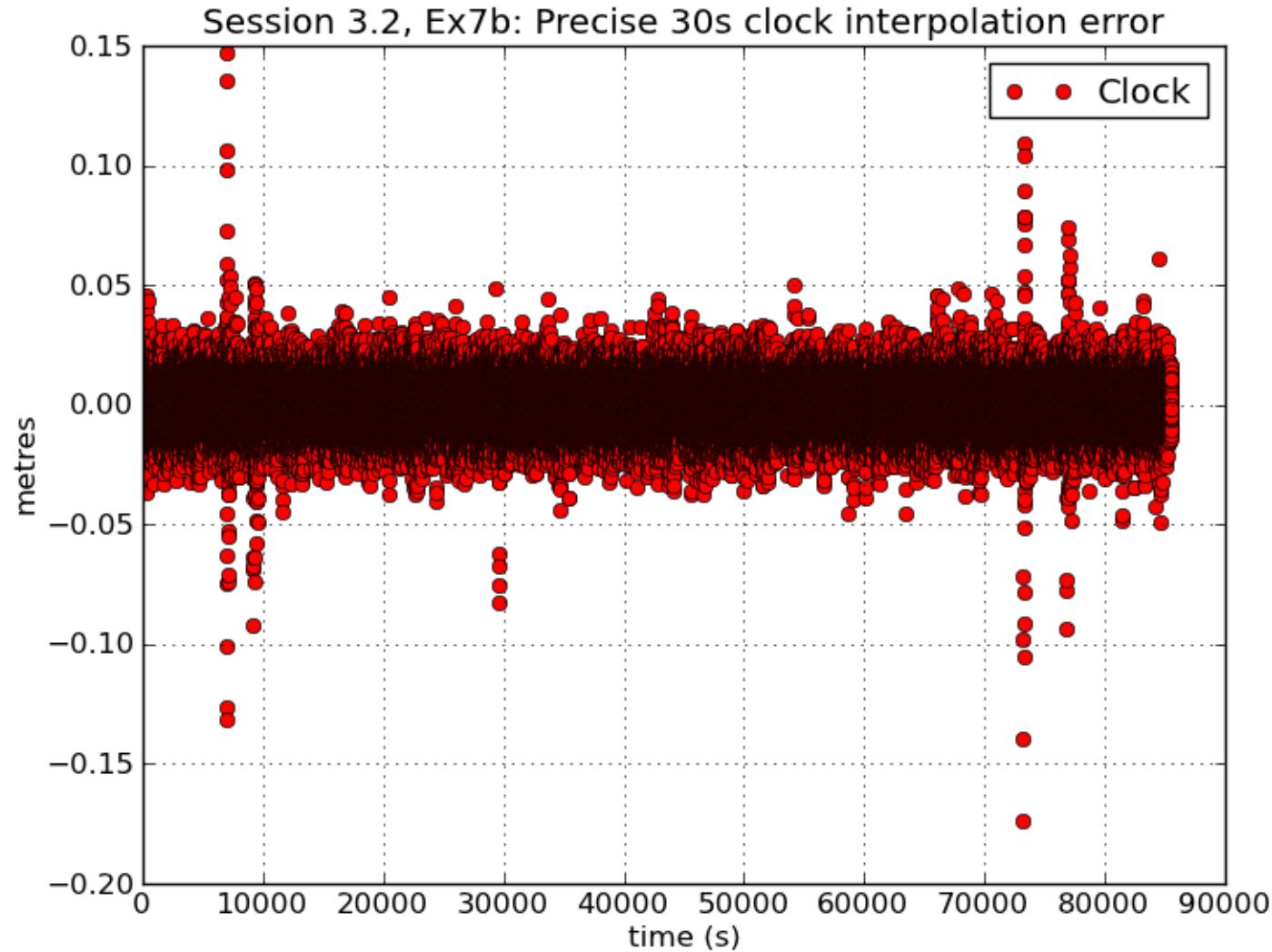
Computation of satellite clocks from precise products

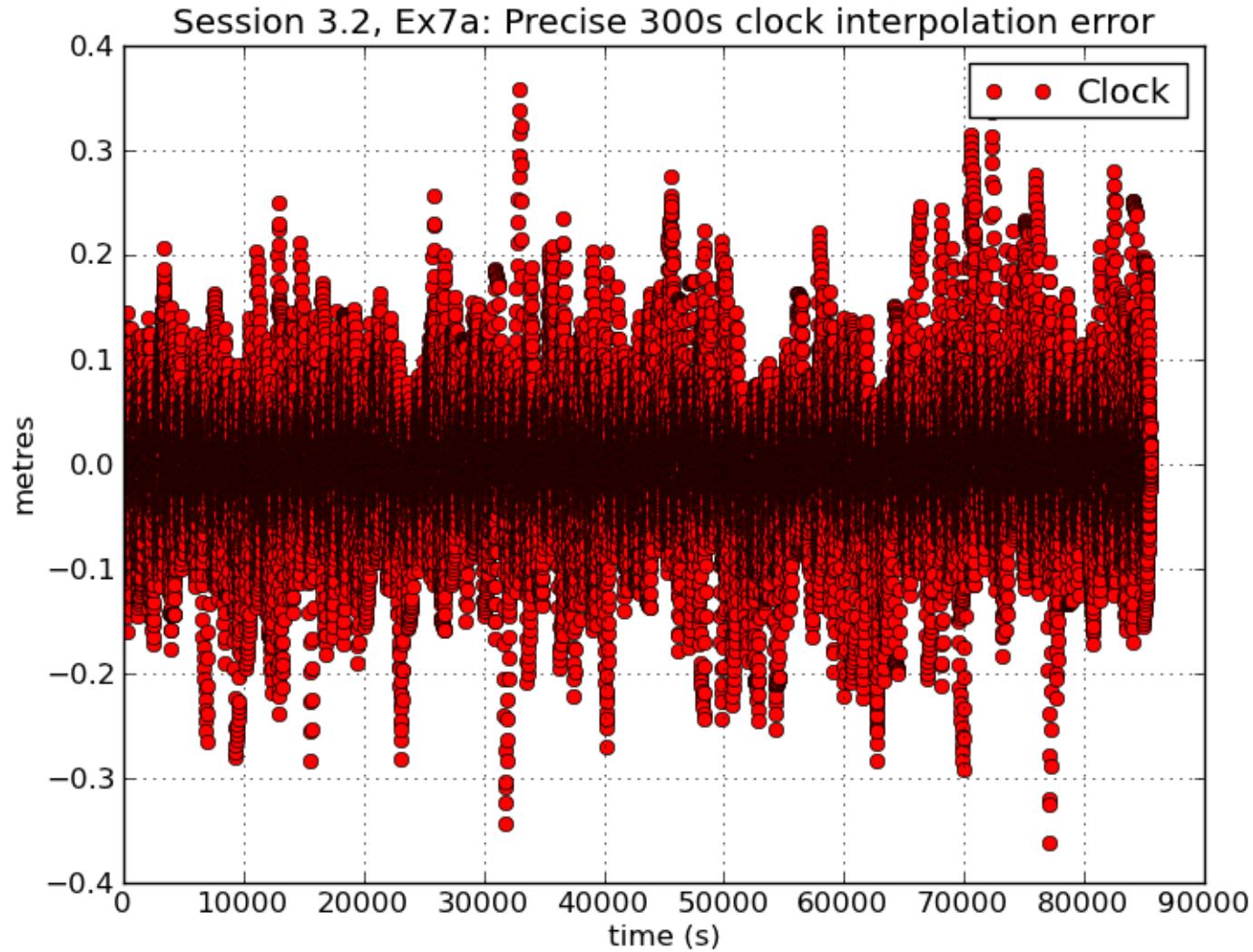
Precise clocks for GPS satellites can be found on the International GNSS Service (IGS) server <http://igscb.jpl.nasa.gov>

IGS is providing precise orbits and clock files with a sampling rate of 15 min, as well as precise clock files with a sample rate of 5 min and 30 sec, in SP3 and CLK formats.

Some centres also provide GPS satellite clocks with a 5 sec sampling rate, like the les obtained from the Crustal Dynamics Data Information System (CDDIS) site.

Stable clocks with a sampling rate of 30 sec or higher can be interpolated with a first-order polynomial to a few centimetres of accuracy. Clocks with a lower sampling rate should not be interpolated, because clocks evolve as random walk processes.



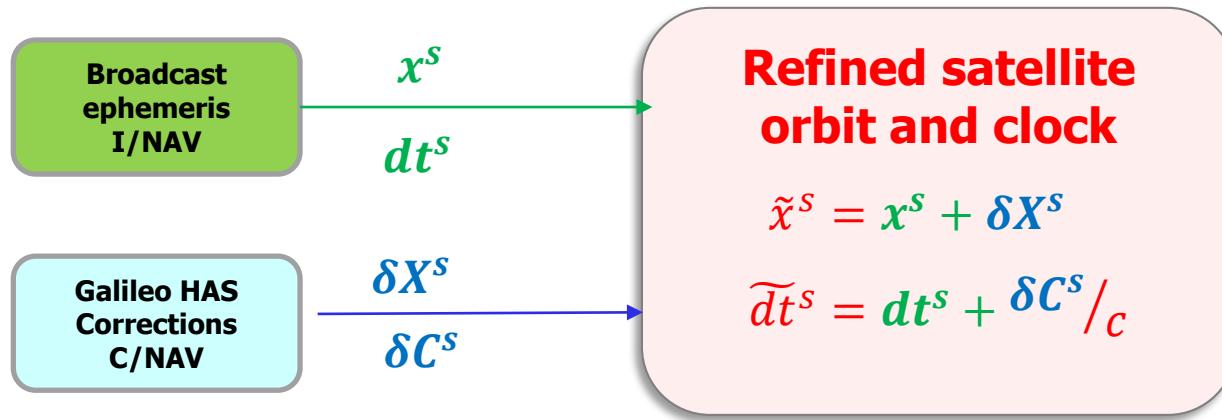


GALILEO High Accuracy Service (HAS)

Enabling **Real-Time** precise Point Positioning (PPP) on a global scale

	Service Level 1	Service Level 2
Coverage	Global	European Coverage Area
Corrections	Orbit, clock, biases (code and phase)	Orbit, clock, biases (code and phase), <u>ionospheric corrections</u>
Constellations	GPS, GALILEO	GPS, GALILEO
Hor. Accuracy (95%)	< 20 cm	< 20 cm
Ver. Accuracy (95%)	< 40 cm	< 40 cm
Convergence Time	< 300 s	< 100 s

Galileo HAS: Orbits and clock Corrections (REAL-TIME)



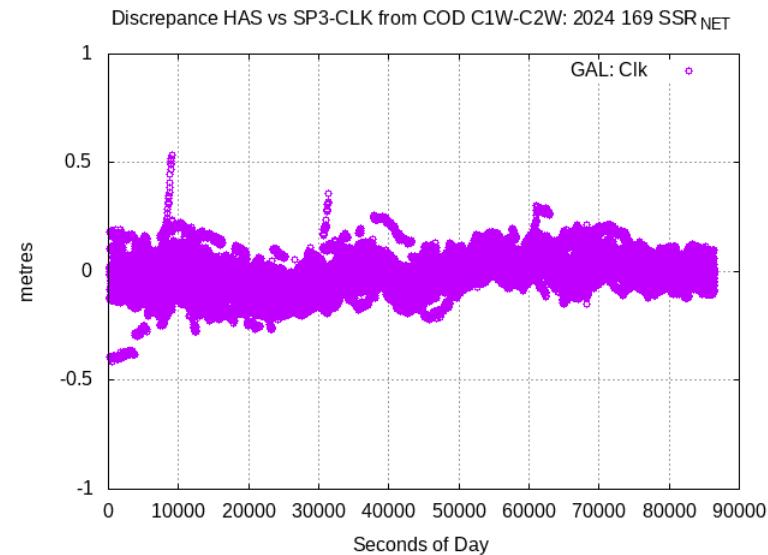
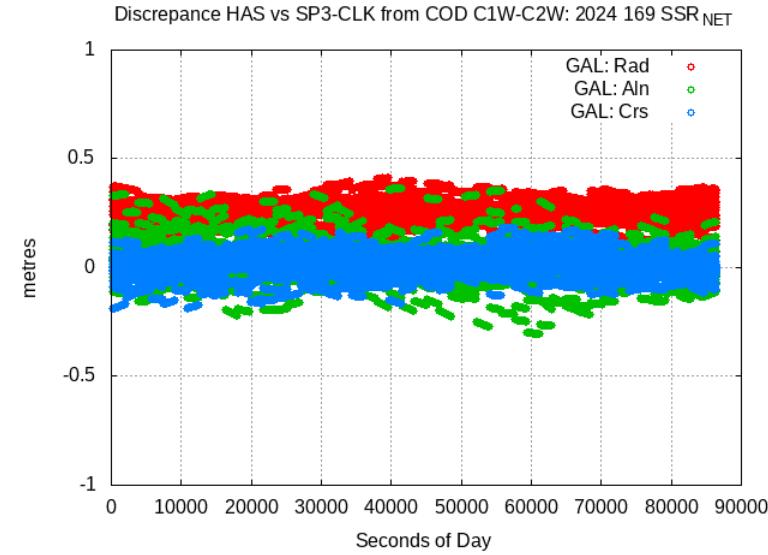
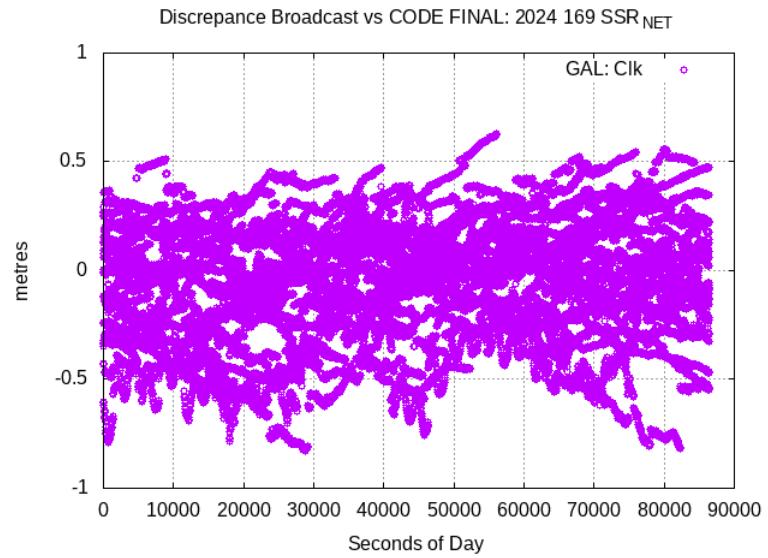
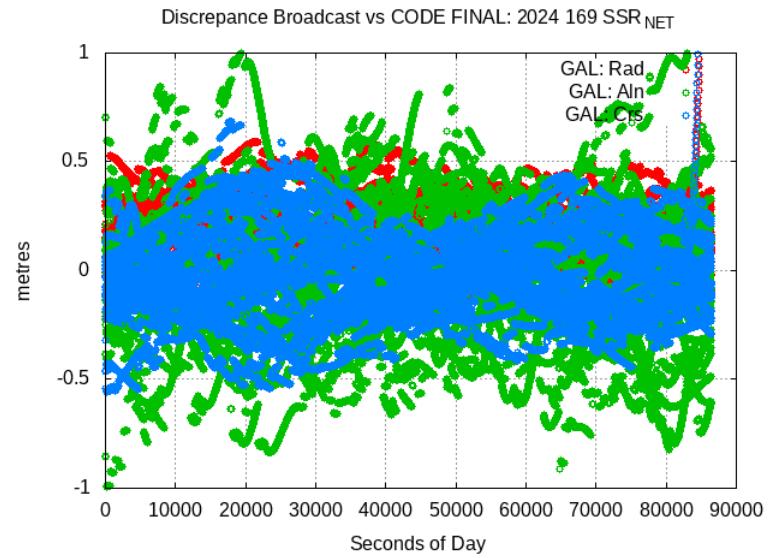
Tangencial: $e_t = \frac{\dot{x}^s}{|\dot{x}^s|}$

In-Track: $e_w = \frac{x^s \times \dot{x}^s}{|x^s \times \dot{x}^s|}$

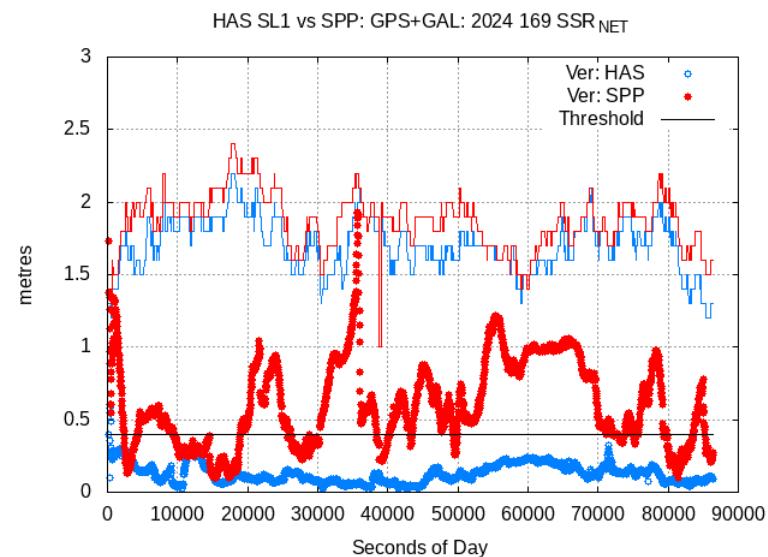
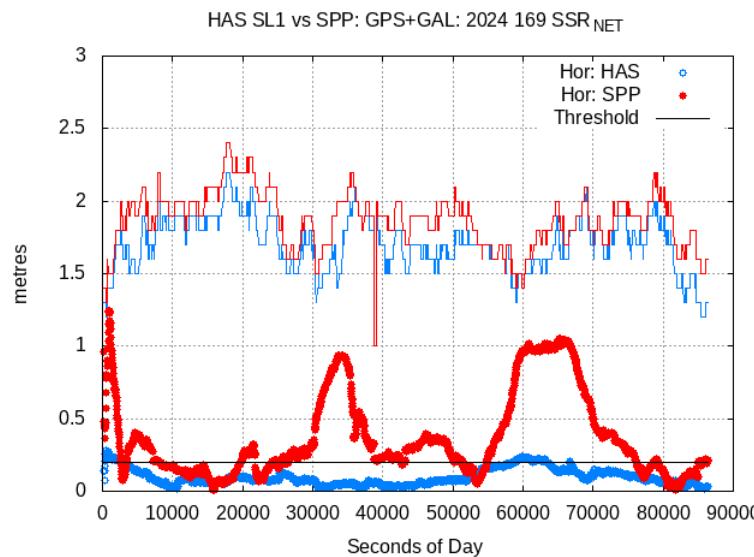
Normal: $e_n = e_t \times e_w$

$$\delta X^s = R_{NTW}^{ECEF} \delta R^s$$

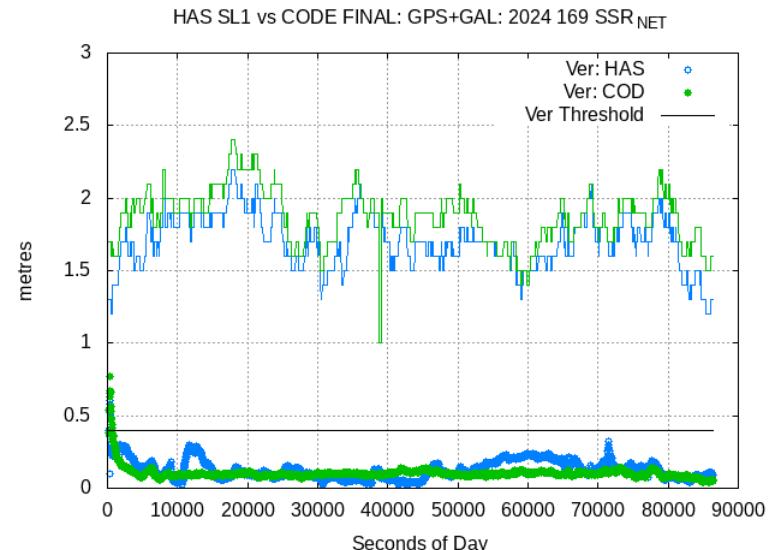
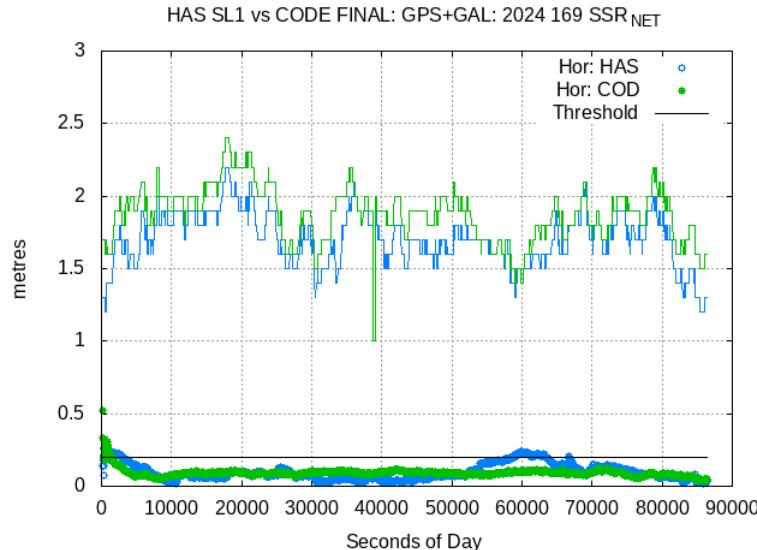
$$R_{NTW}^{ECEF} = [e_n \quad e_t \quad e_w]$$



RT Galileo HAS (SL1) vs RT Broadcast (I/NAV)



RT Galileo HAS (SL1) vs Post-Processed FINAL CODE



Contents

Precise Point Positioning (PPP)

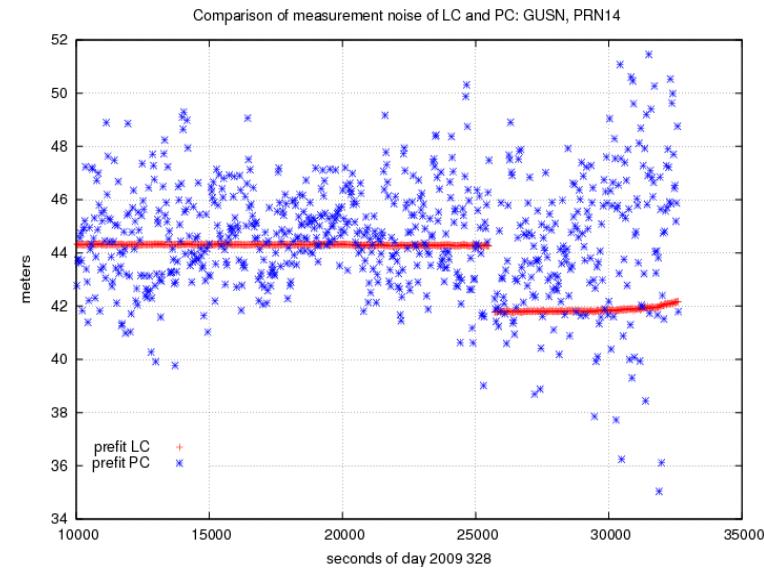
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Measurements: Code and carrier

For high-accuracy positioning, the carrier phase must be used, besides the code pseudorange.

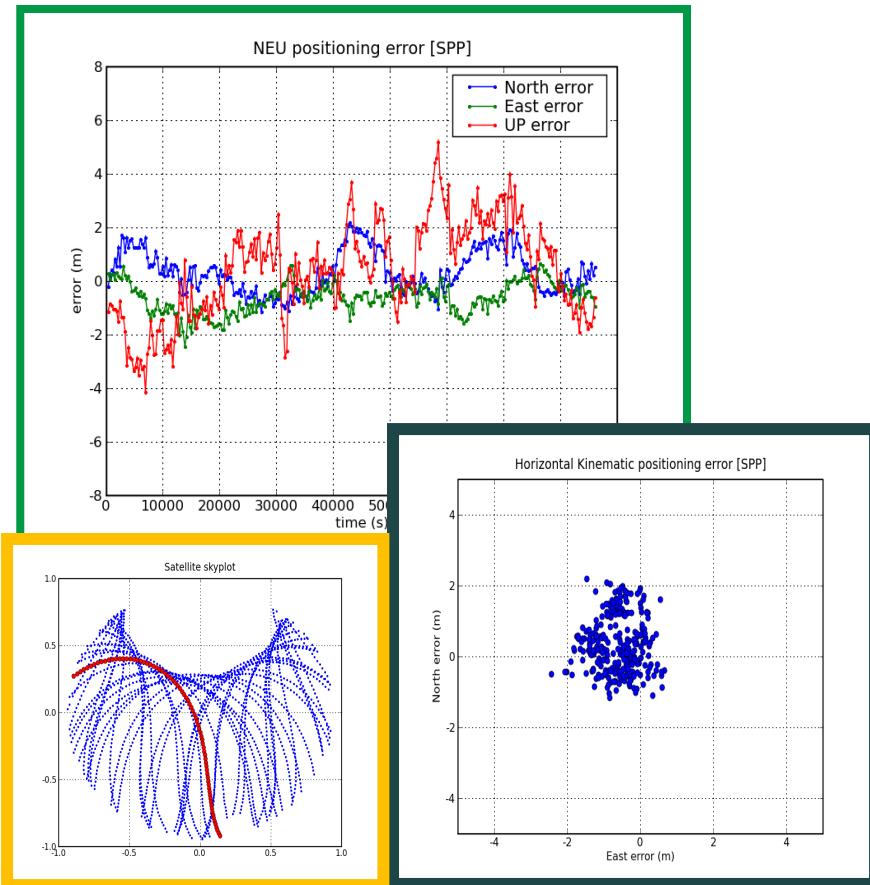
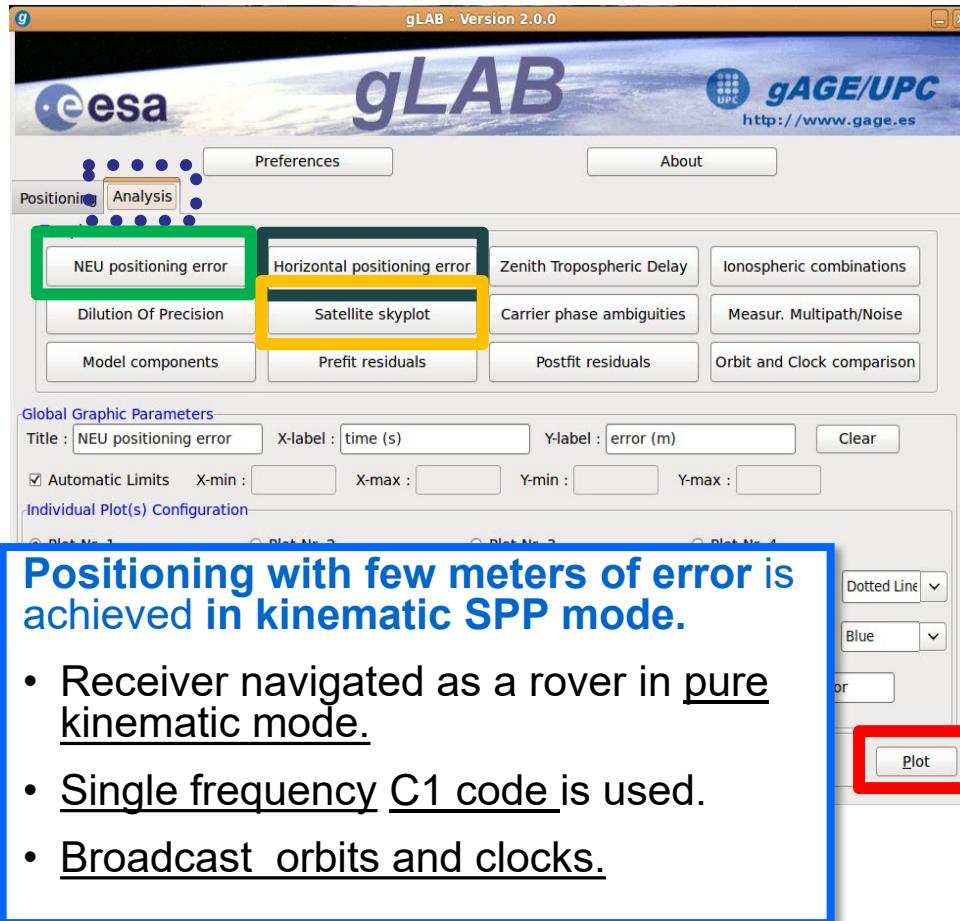
The carrier measurements are very precise, typically at the level of a few millimetres, but contain unknown ambiguities which change every time the receiver locks the signal after a cycle slip.

Nevertheless, such ambiguities can be estimated in the navigation solution, together with the coordinates and other parameters.



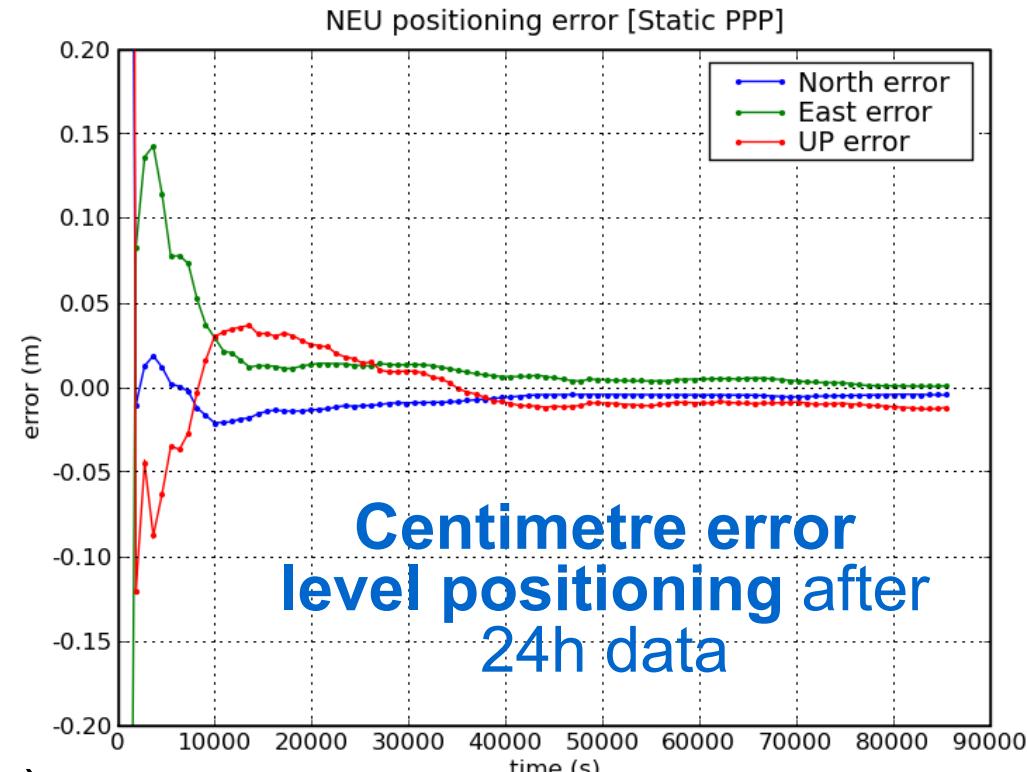
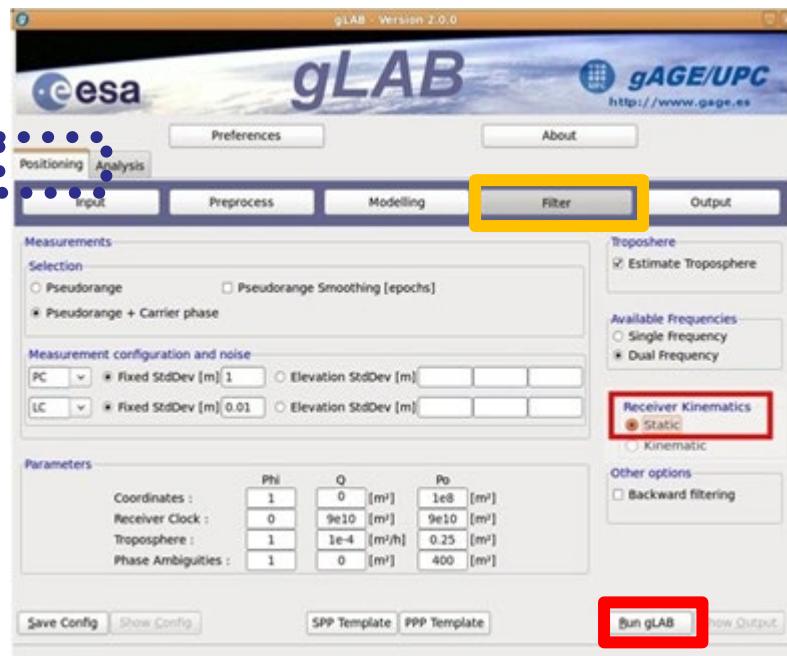
Example 1: Standard Point Positioning (SPP)

Plotting Results



Precise Point Positioning: Static

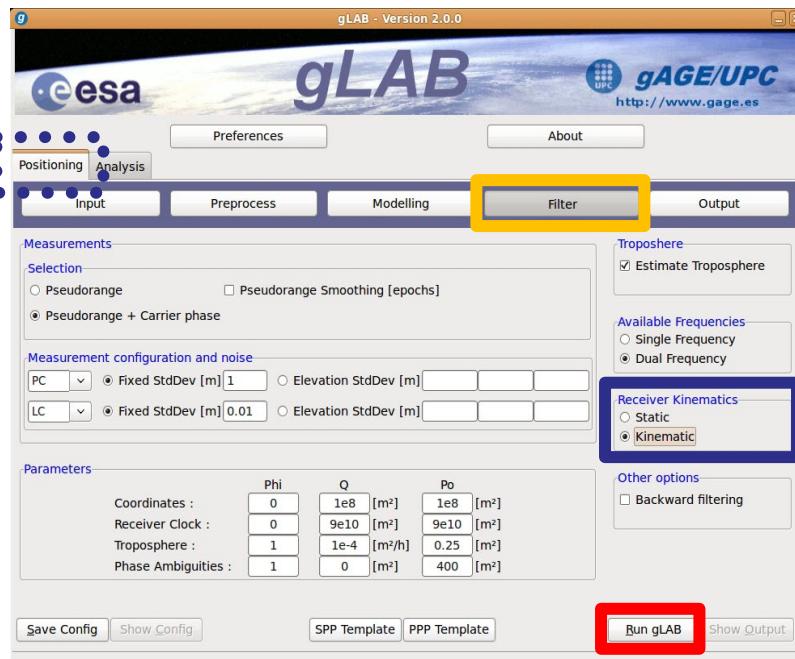
From default configuration of [PPP Template],
Select **Static** in the [Filter] panel. **Run gLAB** and plot results



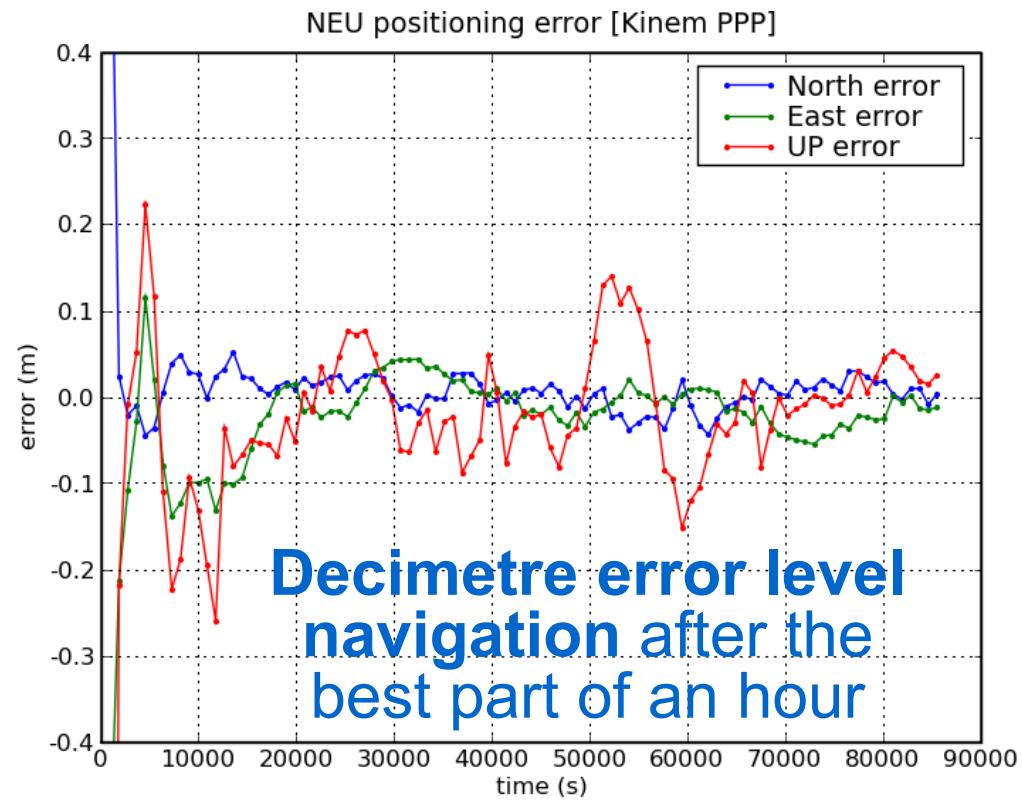
Receiver positioned as a permanent station (static mode)

Precise Point Positioning: Kinematic

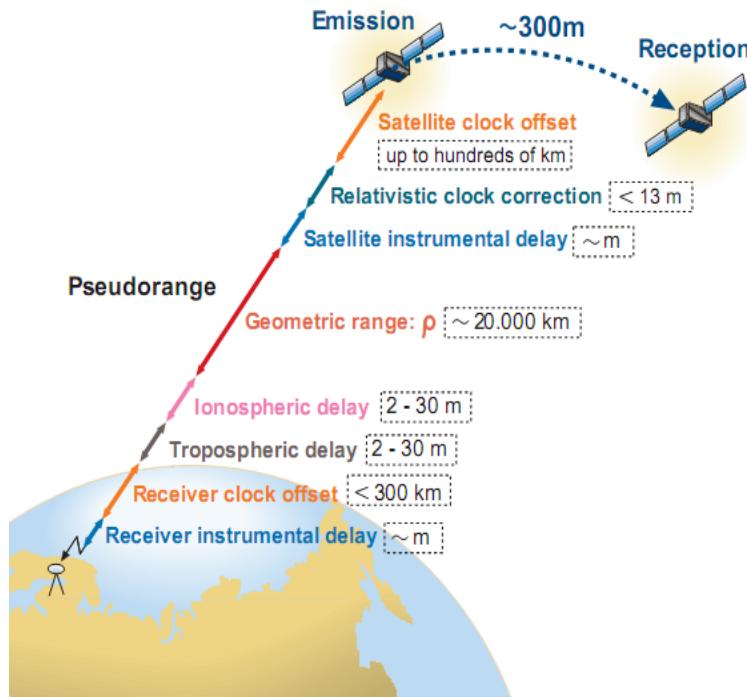
From default configuration of [PPP Template],
Select kinematics in the [Filter] panel. Run **gLAB** and plot results



Receiver navigated as a rover
in a pure kinematic mode.



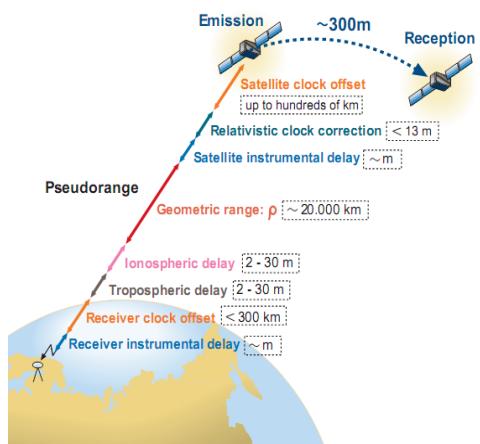
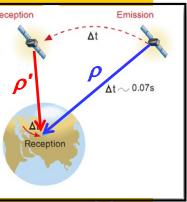
PPP Model components



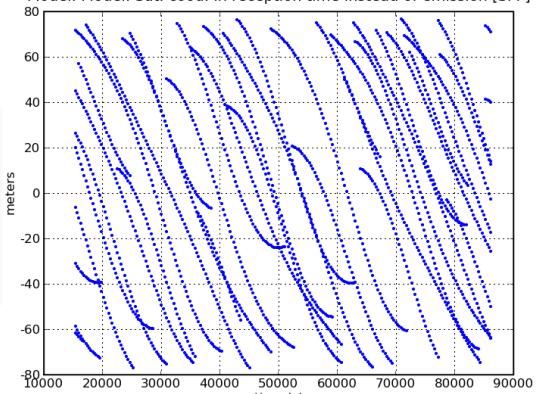
We are going to review first the measurements modelling for the Standard Point Positioning (SPP). A brief summary is given next.

After this summary, we will focus on the additional modelling need for Precise Point Positioning.

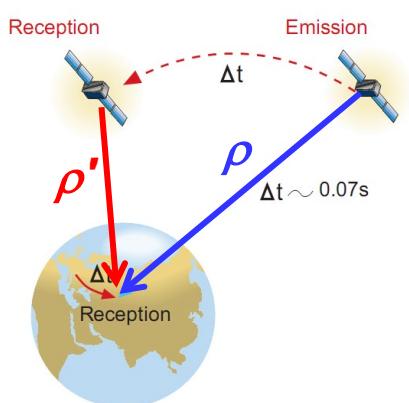
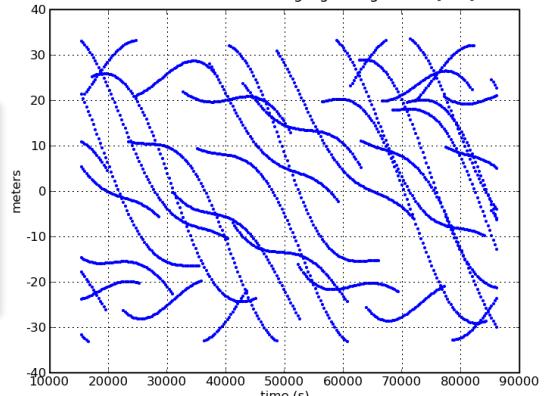
Remember that the error component most difficult to model is the ionosphere. But, in the PPP technique the ionosphere error is removed (more than 99.9%) using dual-frequency measurements in the ionosphere-free combination (Lc,Pc). This combination also removes the Differential Code Bias (or TGD).



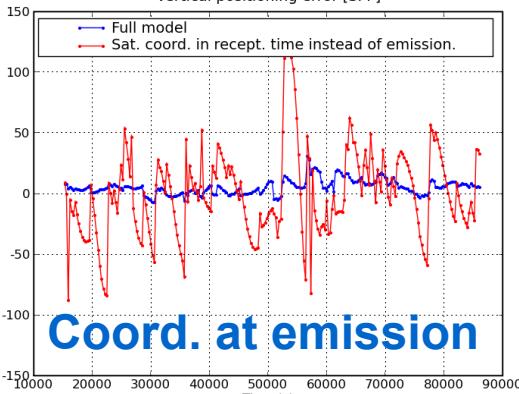
Model: Model: Sat. coord. in reception time instead of emission [SPP]



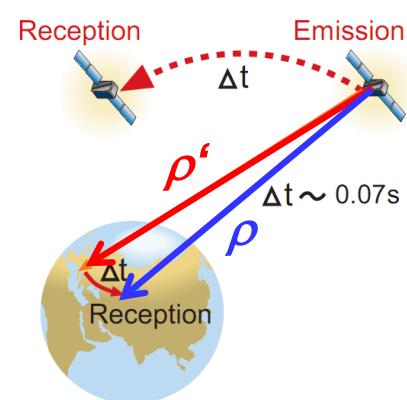
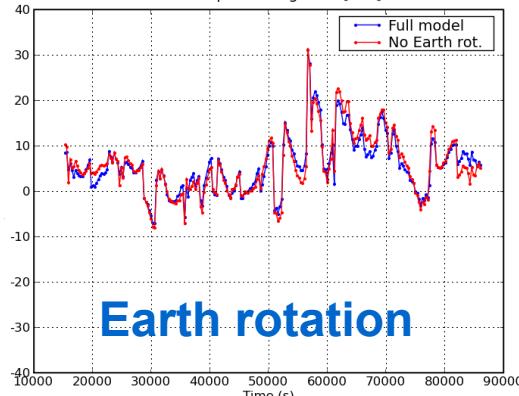
Model: Earth rotation during signal flight time [SPP]



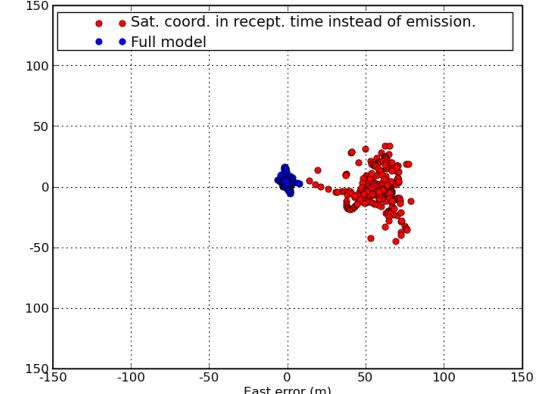
Vertical positioning error [SPP]



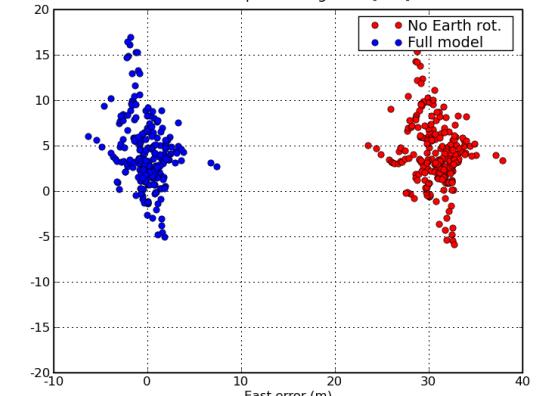
Vertical positioning error [SPP]



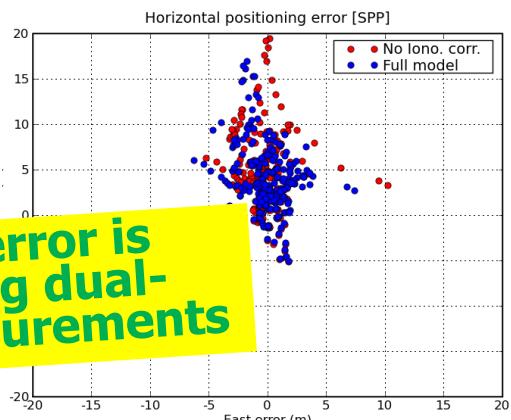
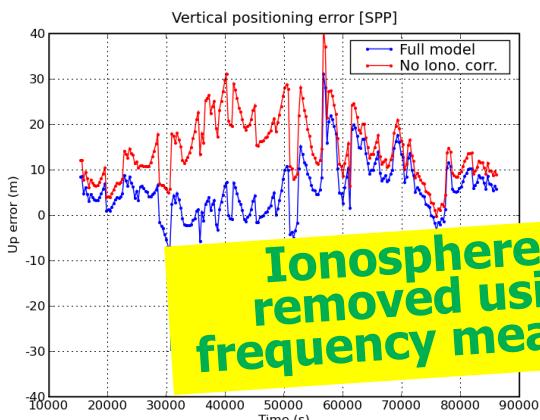
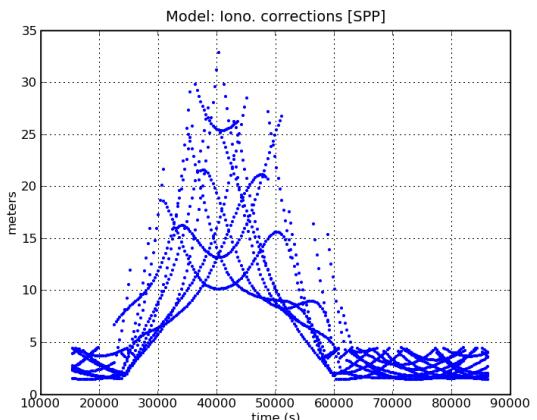
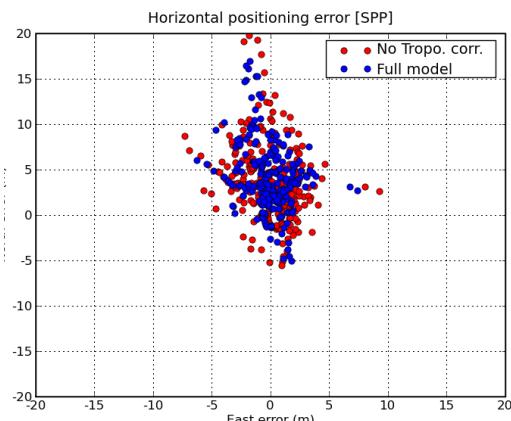
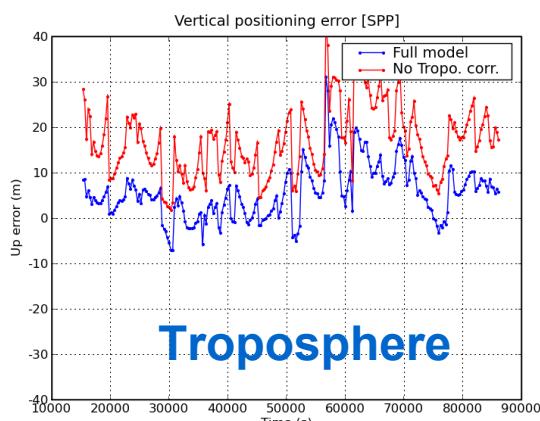
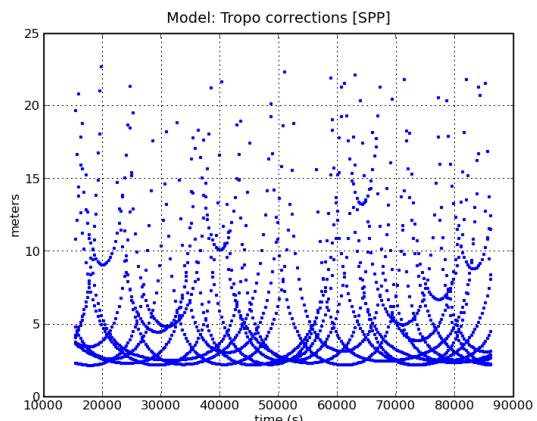
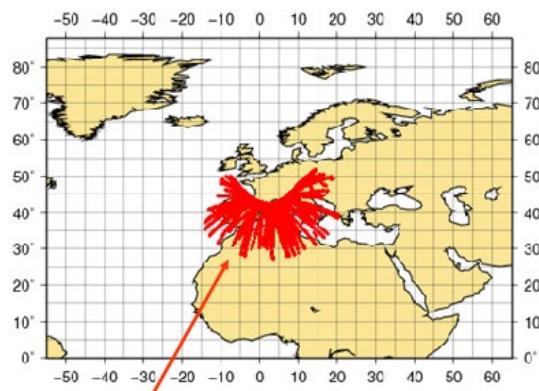
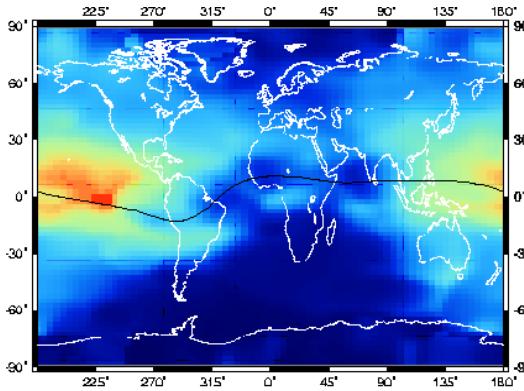
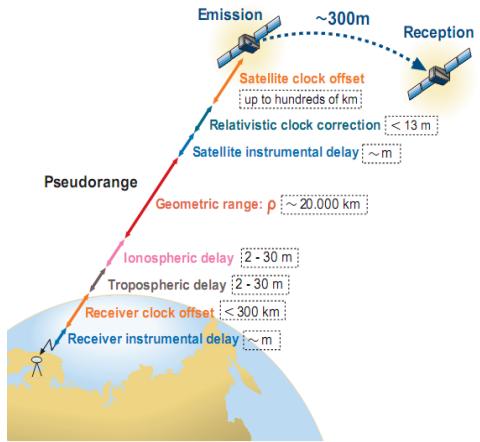
Horizontal positioning error [SPP]



Horizontal positioning error [SPP]

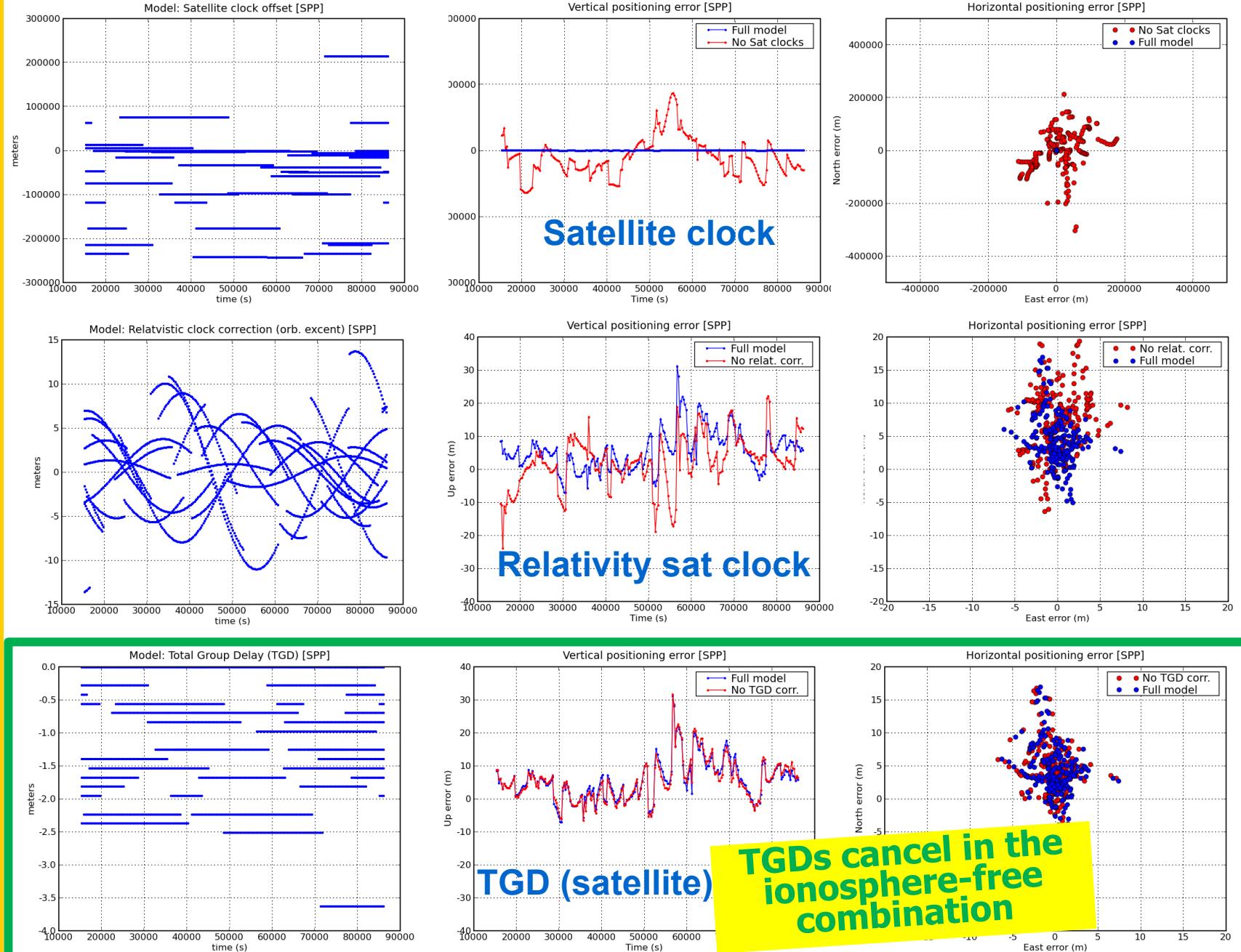


Satellite coordinates computation at signal emission time



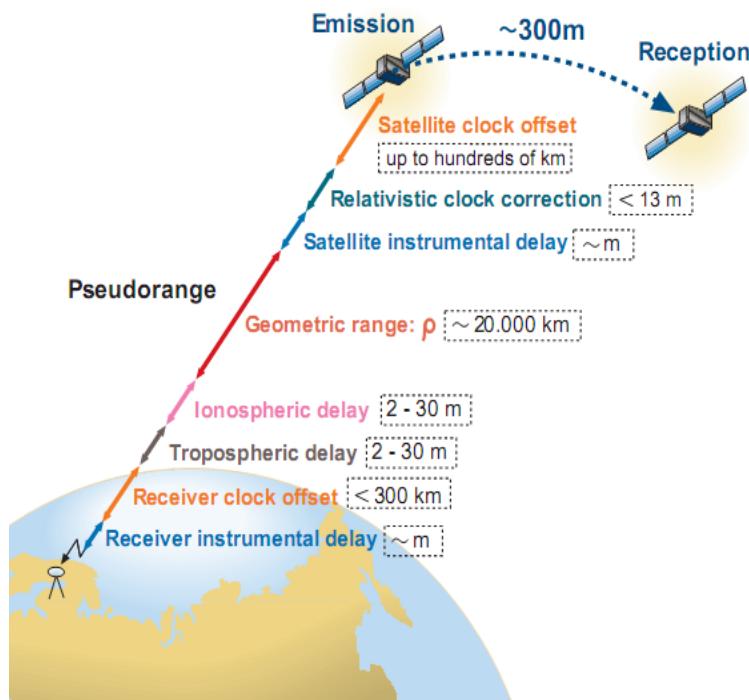
Ionosphere error is removed using dual-frequency measurements

Signal propagation errors on the Atmosphere



Satellite clocks and Total Group Delay (TGD)

Additional Modelling for PPP



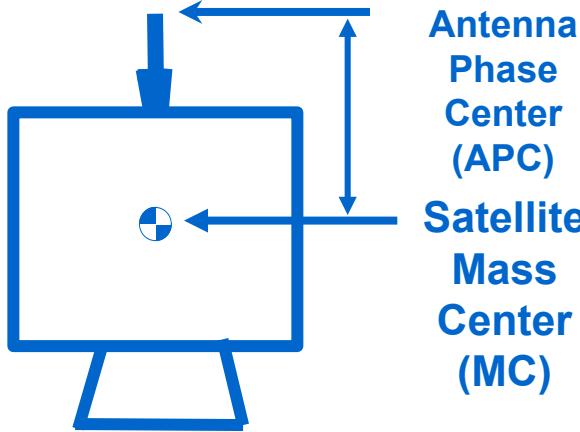
The PPP technique allows centimetre-level of accuracy to be achieved for static positioning and decimetre level, or better, for kinematic navigation.

This high accuracy requires an accurate **modelling “up to the centimetre level or better”**, where all previous model terms must be taken into account (except ionosphere and TGD [*]), **plus some additional terms given next:**

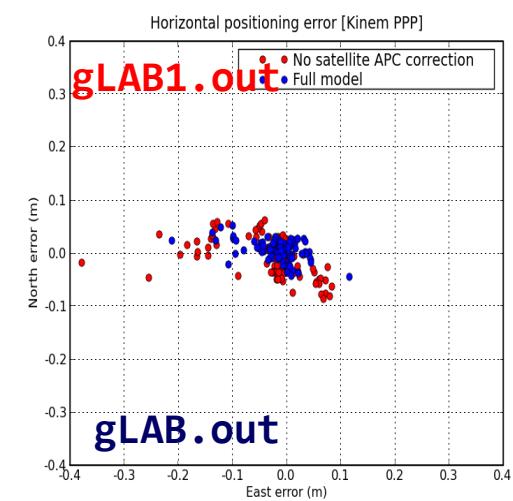
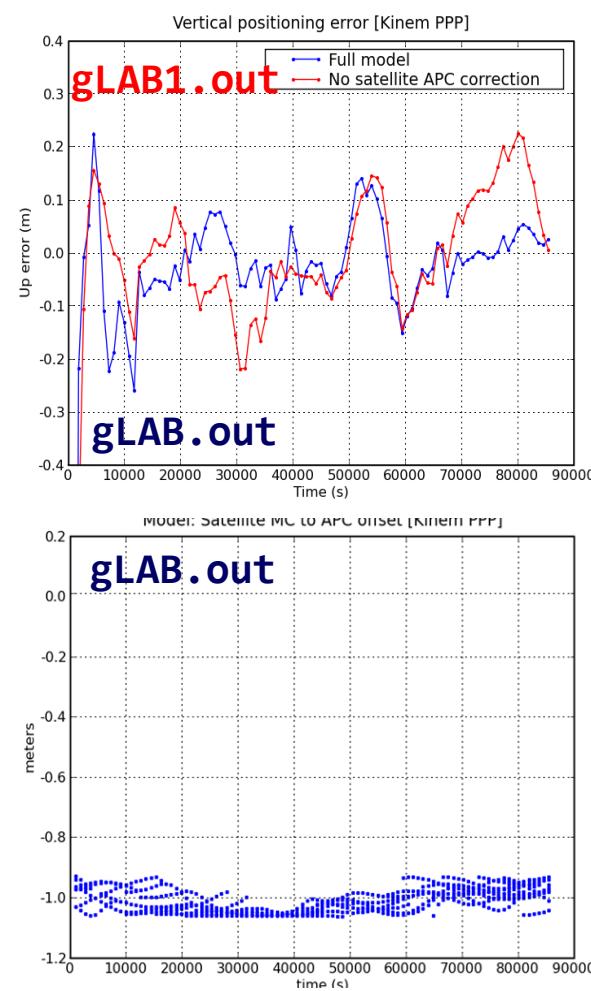
[*] Remember that in the PPP technique the ionosphere error is removed (more than 99.9%) using dual-frequency measurements in the ionosphere-free combination (Lc,Pc). This combination also removes the Differential Code Bias (or TGD).

Additional Modelling for PPP

Satellite Mass Center to Antenna Phase Center



Broadcast orbits are referred to the antenna phase center, but IGS precise orbits are referred to the satellite mass center.

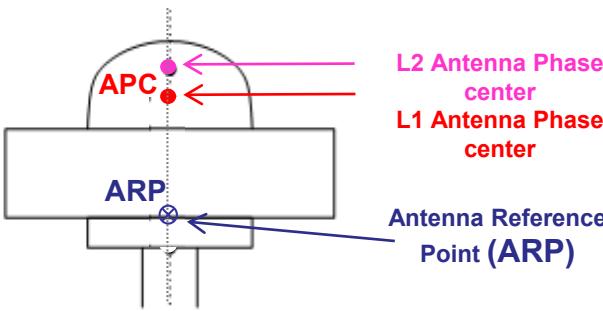


Satellite MC to APC:

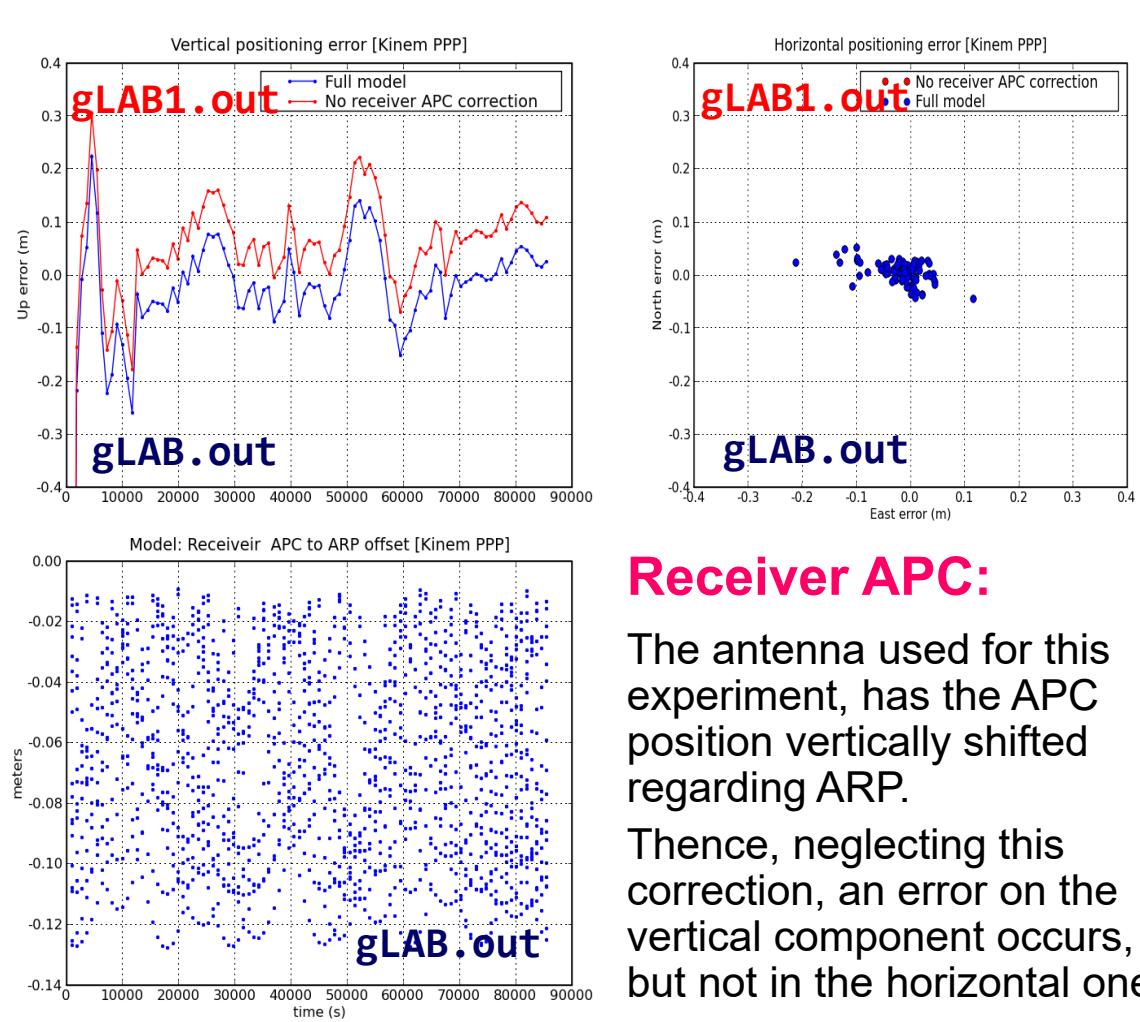
The satellite MC to APC eccentricity vector depends on the satellite. The APC values used in the IGS orbits and clocks products are referred to the iono-free combination (LC, PC). They are given in the IGS ANTEX files (e.g., igs05.atx).

Additional Modelling for PPP

Receiver Antenna Phase center (APC)



GNSS measurements are referred to the APC. This is not necessarily the geometric center of the antenna, and it depends on the signal frequency and the incoming radio signal direction. For geodetic positioning a reference tied to the antenna (ARP) or to monument is used.



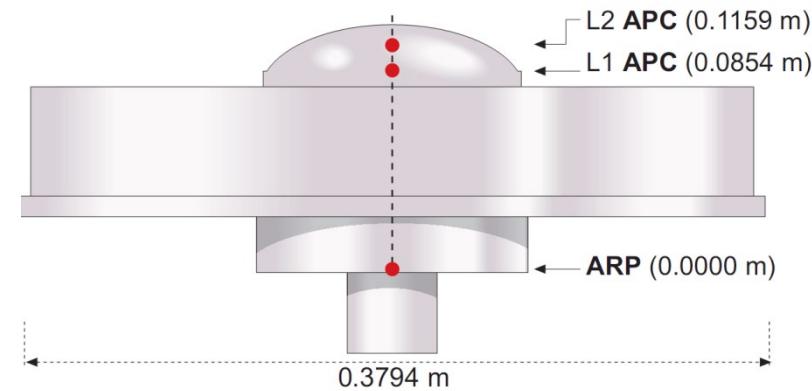
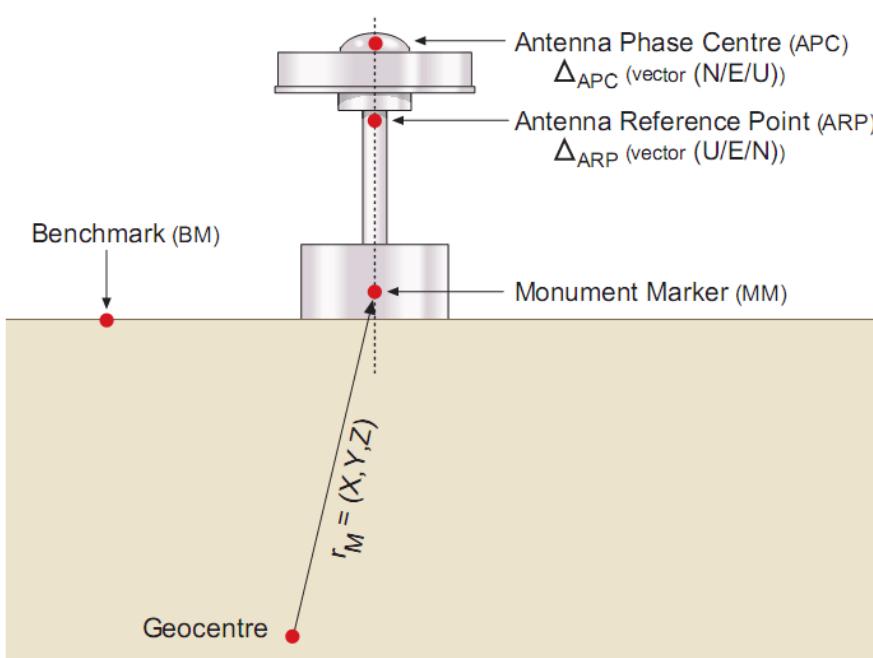
Receiver APC:

The antenna used for this experiment, has the APC position vertically shifted regarding ARP. Thence, neglecting this correction, an error on the vertical component occurs, but not in the horizontal one.

Additional Modelling for PPP: APC

Antenna biases and orientation:

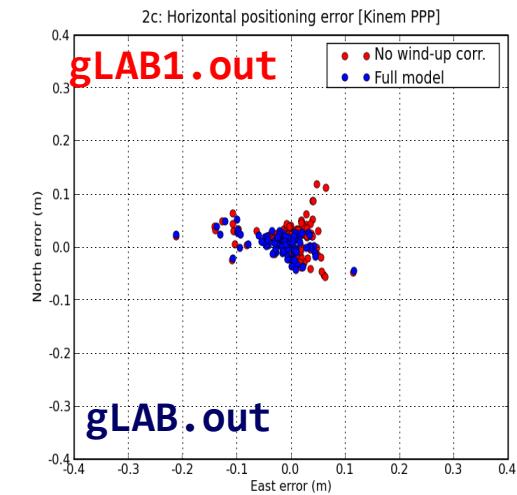
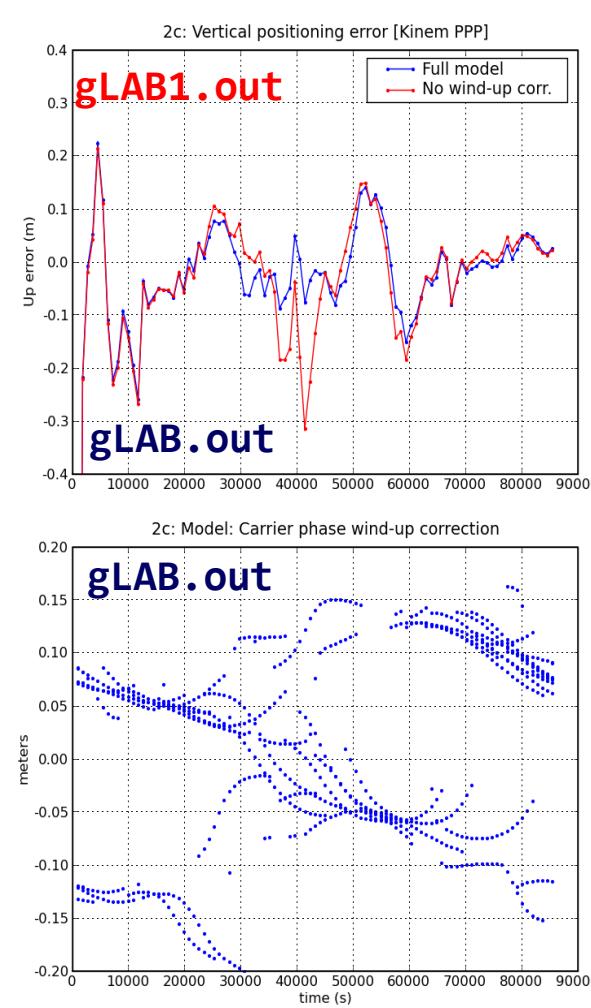
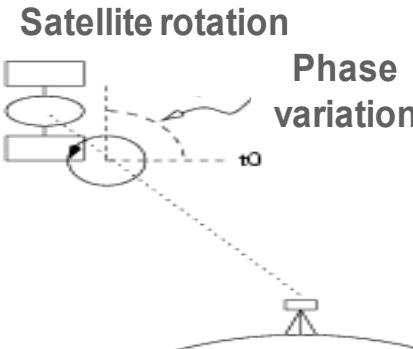
- The satellite and receiver **antenna phase centres (APCs)** can be found in the IGS ANTEX files, after GPS week 1400 (Nov. 2006)
- The **carrier phase wind-up** effect due to the satellite's motion must be taken into account.



Additional Modelling for PPP

Wind-up affects only carrier phase. It is due to the electromagnetic nature of circularly polarized waves of GNSS signals.

As the satellite moves along its orbital path, it performs a rotation to keep its solar panels pointing to the Sun direction. This rotation causes a carrier variation, and thence, a range measurement variation.

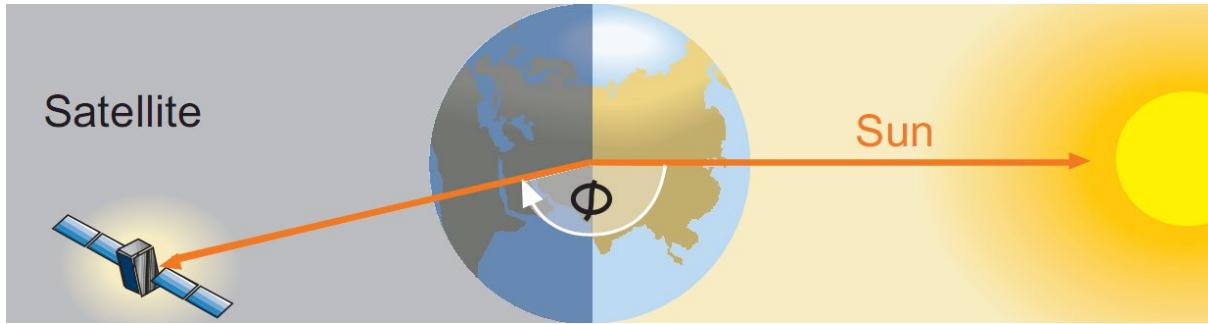


Wind-Up

Wind-up changes smoothly along continuous carrier phase arcs.

In the position domain, wind-up affects both vertical and horizontal components.

Additional Modelling for PPP: Eclipse condition



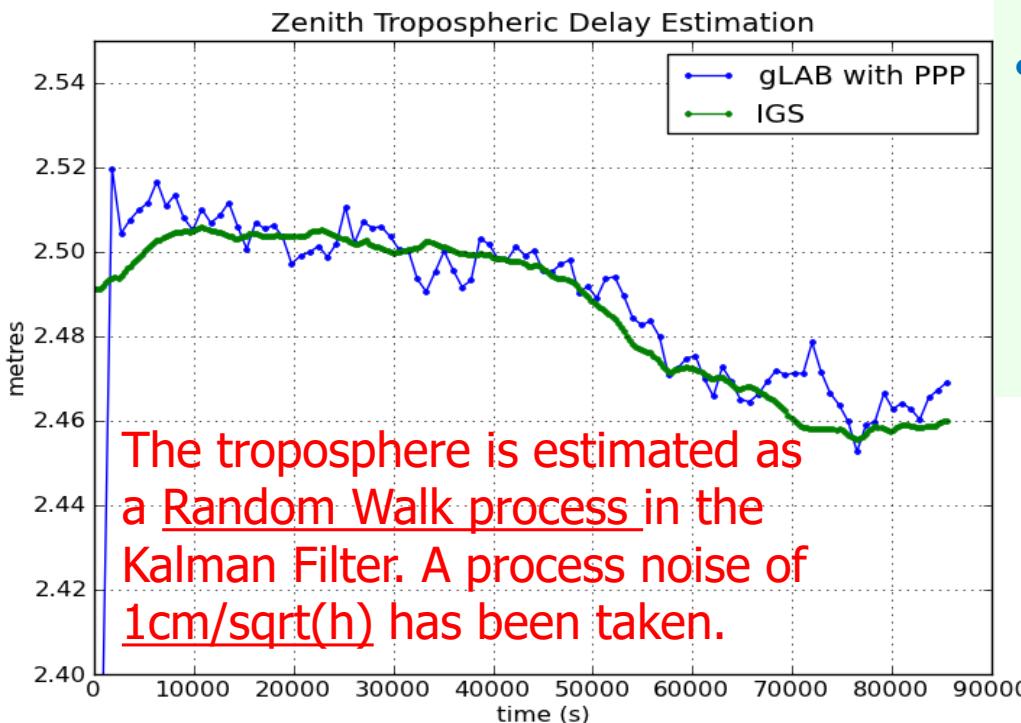
High-accuracy GNSS positioning degrades during the GNSS satellites' eclipse seasons.

- Once the satellite goes into shadow, the radiation pressure vanishes. This effect introduces errors in the satellite dynamics due to the difficulty of properly modelling the solar radiation pressure.
- On the other hand, the satellite's solar sensors lose sight of the Sun and the attitude control (trying to keep the panels facing the Sun).

As a consequence, the orbit during shadow and eclipse periods may be considerably degraded and the removal of satellites under such conditions can improve the high-accuracy positioning results.

Additional Modelling for PPP: Atmospheric Effects

- The **ionospheric refraction and TGDs** are **removed** using the ionosphere-free combination of code and carrier measurements (PC, LC).
- The **tropospheric refraction can be modelled by Dry and Wet components** (and different mappings are usually used for both components, e.g. mapping of Niell).

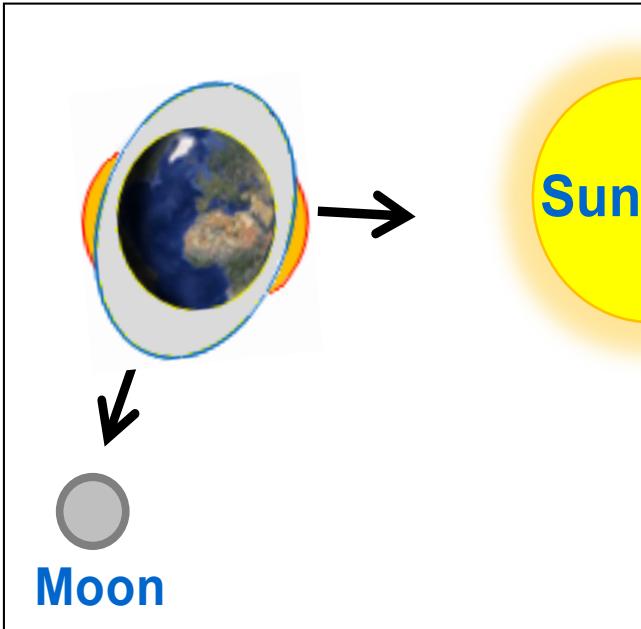


- A **residual tropospheric delay is estimated** (as wet ZTD delay) in the Kalman filter, together with the coordinates, clock and carrier phase ambiguities.

Additional Modelling for PPP: Earth Deformation

Earth deformation effects:

- **Solid tides** must be modelled by equations
- **Ocean loading and pole tides** are second-order effects and can be neglected for PPP accuracies at the centimetre level

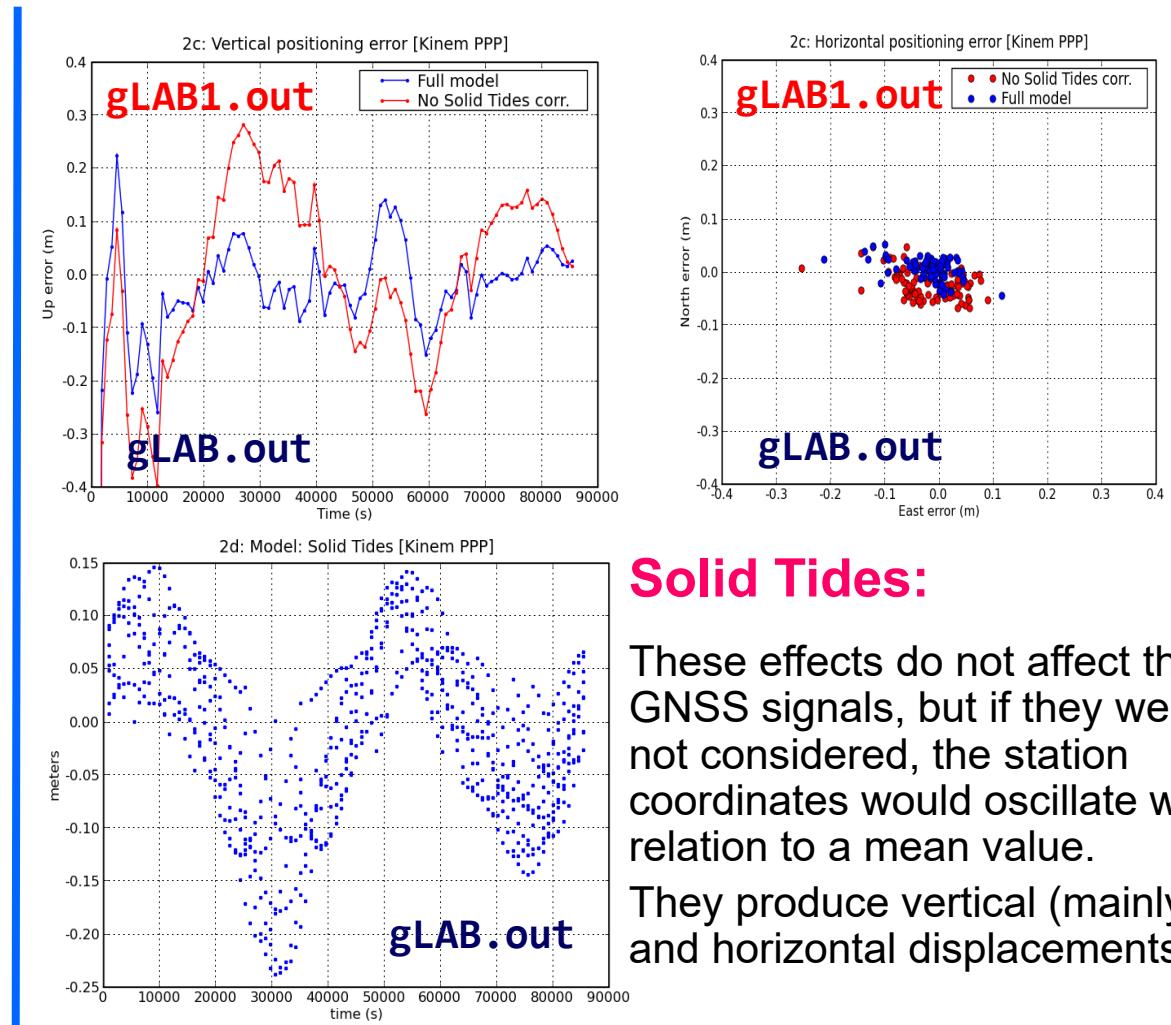
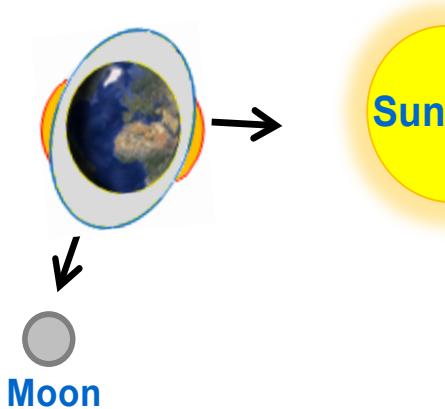


Solid Tides concern the movement of Earth's crust (and thus the variation in the receiver's location coordinates) due to gravitational attractive forces produced by external bodies, mainly the Sun and Moon. Solid tides produce vertical and horizontal displacements that can be expressed by the spherical harmonics expansion (m, n), characterised by the Love and Shida numbers h_{mn} and l_{mn} .

Additional Modelling for PPP

Solid Tides

It comprises the Earth's crust movement (and thence receiver coordinates variations) due to the gravitational attraction forces produced by external bodies, mainly the Sun and the Moon.



Solid Tides:

These effects do not affect the GNSS signals, but if they were not considered, the station coordinates would oscillate with relation to a mean value.

They produce vertical (mainly) and horizontal displacements.

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Linear observation model for PPP

It is based code and carrier measurements in the ionosphere-free combination (Pc, Lc), which are modelled as follows:

$$P_{Crec}^{sat} = \rho_{rec}^{sat} + c \cdot (dt_{rec} - dt^{sat}) + Trop_{rec}^{sat} + \mathcal{M}_{Pc} + \varepsilon_{Pc}$$

$$L_{Crec}^{sat} = \rho_{rec}^{sat} + c \cdot (dt_{rec} - dt^{sat}) + Trop_{rec}^{sat} + \lambda_N \omega_{rec}^{sat} + B_{Crec}^{sat} + \mathcal{M}_{Lc} + \varepsilon_{Lc}$$

where

$$P_c = \frac{f_1^2 P_1 - f_2^2 P_2}{f_1^2 - f_2^2}; \quad L_c = \frac{f_1^2 L_1 - f_2^2 L_2}{f_1^2 - f_2^2}$$

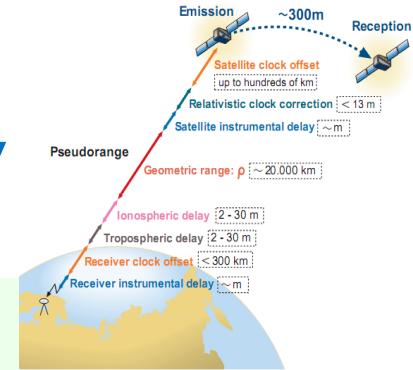
Ionosphere is removed

$$B_c = \lambda_N \left(B_1 + \frac{\lambda_w}{\lambda_2} B_w \right)$$

$$B_w = B_1 - B_2$$

$$\lambda_N = 10.7 \text{ cm}, \lambda_w = 86.2 \text{ cm}$$

Remark, ρ is referred to the Antenna Phase Centres (APC) of satellite and receiver antennas in the ionosphere free combination.



Linear model: For each satellite in view

$$P_{C\ rec}^{sat} = \rho_{rec}^{sat} + c \cdot (dt_{rec} - dt^{sat}) + Trop + \varepsilon$$

Linearising ρ around an 'a priori' receiver position $(x_{rec,0}, y_{rec,0}, z_{rec,0})$

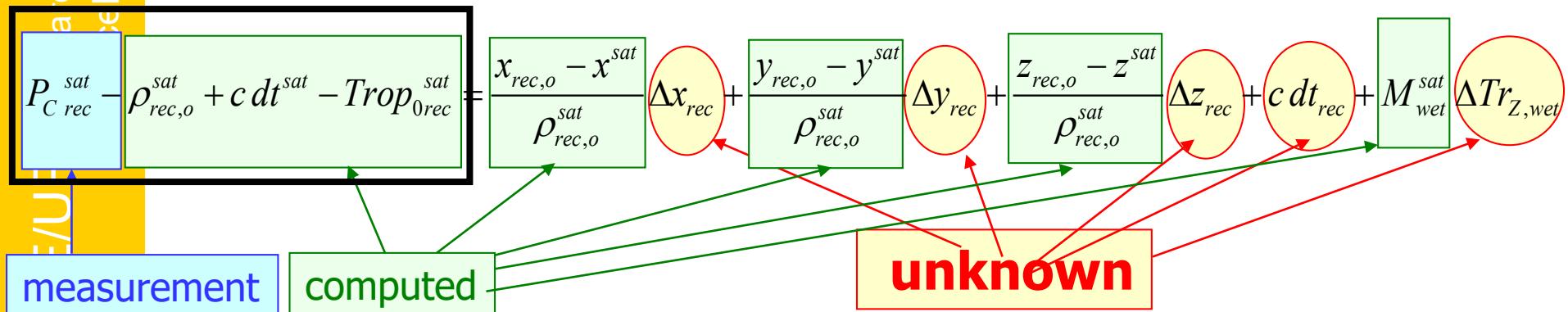
$$= \rho_{rec,o}^{sat} + \frac{x_{rec,o} - x^{sat}}{\rho_{rec,o}^{sat}} \Delta x_{rec} + \frac{y_{rec,o} - y^{sat}}{\rho_{rec,o}^{sat}} \Delta y_{rec} + \frac{z_{rec,o} - z^{sat}}{\rho_{rec,o}^{sat}} \Delta z_{rec} + c(dt_{rec} - dt^{sat}) + Trop$$

where:

$$\Delta x_{rec} = x_{rec} - x_{rec,o} ; \quad \Delta y_{rec} = y_{rec} - y_{rec,o} ; \quad \Delta z_{rec} = z_{rec} - z_{rec,o}$$

and taking: $Trop_{rec}^{sat} = Trop_{0\ rec}^{sat} + M_{wet,rec}^{sat} \Delta Tr_{Z,wet}$

Prefit-residuals (Prefit)



The same for carrier, but adding the ambiguity as an unknown

Remark

$$P_C^{sat} = \rho_{rec}^{sat} + c \cdot (dt_{rec} - dt^{sat}) + Trop + \varepsilon$$

Linearising ρ around an 'a priori' receiver position $(x_{rec,0}, y_{rec,0}, z_{rec,0})$

$$= \rho_{rec,0}^{sat} + \frac{x_{rec,0} - x^{sat}}{\rho_{rec,0}^{sat}} \Delta x_{rec} + \frac{y_{rec,0} - y^{sat}}{\rho_{rec,0}^{sat}} \Delta y_{rec} + \frac{z_{rec,0} - z^{sat}}{\rho_{rec,0}^{sat}} \Delta z_{rec} + c(dt_{rec} - dt^{sat}) + Trop$$

Of course, receiver coordinates $(x_{rec}, y_{rec}, z_{rec})$ are not known (they are the target of this problem). But, we can always assume that an "approximate position $(x_{0,rec}, y_{0,rec}, z_{0,rec})$ is known".

Thence, the navigation problem will consist on:

- 1.- To start from an approximate value for receiver position $(x_{0,rec}, y_{0,rec}, z_{0,rec})$ e.g. the Earth's centre) to linearise the equations
- 2.- With the pseudorange measurements and the navigation equations, compute the correction $(\Delta x_{rec}, \Delta y_{rec}, \Delta z_{rec})$ to have improved estimates:

$$(x_{rec}, y_{rec}, z_{rec}) = (x_{0,rec}, y_{0,rec}, z_{0,rec}) + (\Delta x_{rec}, \Delta y_{rec}, \Delta z_{rec})$$
- 3.- Linearise the equations again, about the new improved estimates, and iterate until the change in the solution estimates is small enough.

Linear model: For each satellite in view

$$P_{C\ rec}^{sat} = \rho_{rec}^{sat} + c \cdot (dt_{rec} - dt^{sat}) + Trop + \varepsilon$$

Linearising ρ around an 'a priori' receiver position $(x_{rec,0}, y_{rec,0}, z_{rec,0})$

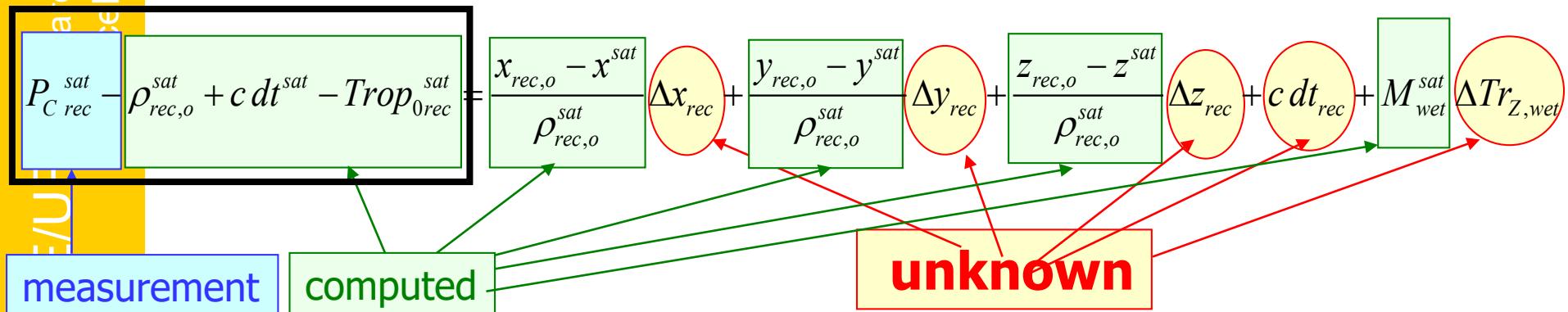
$$= \rho_{rec,o}^{sat} + \frac{x_{rec,o} - x^{sat}}{\rho_{rec,o}^{sat}} \Delta x_{rec} + \frac{y_{rec,o} - y^{sat}}{\rho_{rec,o}^{sat}} \Delta y_{rec} + \frac{z_{rec,o} - z^{sat}}{\rho_{rec,o}^{sat}} \Delta z_{rec} + c(dt_{rec} - dt^{sat}) + Trop$$

where:

$$\Delta x_{rec} = x_{rec} - x_{rec,o} ; \quad \Delta y_{rec} = y_{rec} - y_{rec,o} ; \quad \Delta z_{rec} = z_{rec} - z_{rec,o}$$

and taking: $Trop_{rec}^{sat} = Trop_{0\ rec}^{sat} + M_{wet,rec}^{sat} \Delta Tr_{Z,wet}$

Prefit-residuals (Prefit)



The same for carrier, but adding the ambiguity as an unknown

Linear model: For each satellite in view

$$P_{C\ rec}^{sat} = \rho_{rec}^{sat} + c \cdot (dt_{rec} - dt^{sat}) + Trop + \varepsilon$$

Linearising ρ around an 'a priori' receiver position $(x_{rec,0}, y_{rec,0}, z_{rec,0})$

$$= \rho_{rec,o}^{sat} + \frac{x_{rec,o} - x^{sat}}{\rho_{rec,o}^{sat}} \Delta x_{rec} + \frac{y_{rec,o} - y^{sat}}{\rho_{rec,o}^{sat}} \Delta y_{rec} + \frac{z_{rec,o} - z^{sat}}{\rho_{rec,o}^{sat}} \Delta z_{rec} + c(dt_{rec} - dt^{sat}) + Trop$$

where:

$$\Delta x_{rec} = x_{rec} - x_{rec,o} ; \quad \Delta y_{rec} = y_{rec} - y_{rec,o} ; \quad \Delta z_{rec} = z_{rec} - z_{rec,o}$$

and taking: $Trop_{rec}^{sat} = Trop_{0\ rec}^{sat} + M_{wet,rec}^{sat} \Delta Tr_{Z,wet}$

Prefit-residuals (Prefit)

$$P_{C\ rec}^{sat} - \rho_{rec,o}^{sat} + c dt^{sat} - Trop_{0\ rec}^{sat} = \frac{x_{rec,o} - x^{sat}}{\rho_{rec,o}^{sat}} \Delta x_{rec} + \frac{y_{rec,o} - y^{sat}}{\rho_{rec,o}^{sat}} \Delta y_{rec} + \frac{z_{rec,o} - z^{sat}}{\rho_{rec,o}^{sat}} \Delta z_{rec} + c dt_{rec} + M_{wet}^{sat} \Delta Tr_{Z,wet}$$

$$L_{C\ rec}^{sat} - \rho_{rec,o}^{sat} + c dt^{sat} - Trop_{0\ rec}^{sat} - \lambda_N \omega^{sat} = \frac{x_{rec,o} - x^{sat}}{\rho_{rec,o}^{sat}} \Delta x_{rec} + \frac{y_{rec,o} - y^{sat}}{\rho_{rec,o}^{sat}} \Delta y_{rec} + \frac{z_{rec,o} - z^{sat}}{\rho_{rec,o}^{sat}} \Delta z_{rec} + c dt_{rec} + M_{wet}^{sat} \Delta Tr_{Z,wet} + B_C^{sat}$$

Following the same procedure as with the code based positioning (SPP), the linear observation model $\mathbf{y} = \mathbf{G} \mathbf{x}$ for the code and carrier measurements can be written as follows:

$$\mathbf{y} = \mathbf{G} \mathbf{x}$$

$$\begin{bmatrix} \text{Prefit}(Pc)^1 \\ \text{Prefit}(Lc)^1 \\ \dots \\ \text{Prefit}(Pc)^n \\ \text{Prefit}(Lc)^n \end{bmatrix} = \begin{bmatrix} \frac{x_{o,rec} - x^1}{\rho_{0,rec}^1} & \frac{y_{o,rec} - y^1}{\rho_{0,rec}^1} & \frac{z_{o,rec} - z^1}{\rho_{0,rec}^1} & 1 & M_{wet}^1 & 0 & \dots & \dots & 0 \\ \frac{x_{o,rec} - x^1}{\rho_{0,rec}^1} & \frac{y_{o,rec} - y^1}{\rho_{0,rec}^1} & \frac{z_{o,rec} - z^1}{\rho_{0,rec}^1} & 1 & M_{wet}^1 & 1 & \dots & \dots & 0 \\ \dots & \dots \\ \frac{x_{o,rec} - x^n}{\rho_{0,rec}^n} & \frac{y_{o,rec} - y^n}{\rho_{0,rec}^n} & \frac{z_{o,rec} - z^n}{\rho_{0,rec}^n} & 1 & M_{wet}^n & 0 & \dots & \dots & 0 \\ \frac{x_{o,rec} - x^n}{\rho_{0,rec}^n} & \frac{y_{o,rec} - y^n}{\rho_{0,rec}^n} & \frac{z_{o,rec} - z^n}{\rho_{0,rec}^n} & 1 & M_{wet}^n & 0 & \dots & \dots & 1 \end{bmatrix} \begin{bmatrix} \Delta x_{rec} \\ \Delta y_{rec} \\ \Delta z_{rec} \\ cdt_{rec} \\ \Delta Tr_{Z,wet} \\ B_C^1 \\ \dots \\ B_C^n \end{bmatrix}$$

$$\text{Prefit}(P_C)^k = P_C^k - \rho_0^k + cdt^k - Trop_0^k$$

$$\text{Prefit}(L_C)^k = L_C^k - \rho_0^k + cdt^k - Trop_0^k - \lambda_N \omega^k$$

Carrier ambiguities

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Parameter estimation PPP: Floating Ambiguities

The linear observation model $\mathbf{y} = \mathbf{G} \mathbf{x}$ can be solved using the **Kalman filter**. The next stochastic model can be used

- **Carrier phase ambiguities** (B_C) are taken as 'constant' along continuous phase arcs, and as 'white noise' when a cycle slip happens ($\sigma = 10^4 \text{ m}$ can be taken, for instance) → **FLOATED AMB.**
- **Wet tropospheric delay** ($Tr_{z,wet}$) is taken as a random walk process (with $d\sigma^2/dt = 1 \text{ cm}^2/\text{h}$, for instance).
- **Receiver clock** (cdt) is taken as a white-noise process (with $\sigma = 3.10^5 \text{ m}$, i.e. 1 ms for instance).
- **Receiver coordinates** ($\Delta x, \Delta y, \Delta z$)
 - For **static positioning** the coordinates are taken as constants.
 - For **kinematic positioning** the coordinates are taken as white noise or a random walk process.

Comment: Floating Ambiguities

This solution procedure is called **floating ambiguities**. 'Floating' in the sense that the ambiguities are estimated by the filter 'as real numbers'.

The bias estimations \hat{B}_C will converge to a solution after a transition time that depends on the observation geometry, model quality and data noise.

In general, one must expect errors at the decimetre level, or better, in pure kinematic positioning (after the best part of one hour) and at the centimetre level in static PPP over 24h data.

See exercises in the laboratory session (Tutorial 1).

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Carrier Ambiguity Fixing concept

In the previous formulation, the ambiguities have been estimated as real numbers in the Kalman filter, without exploiting its integer nature.

That is, the ambiguities in L_1 , L_2 or L_W signals are an integer number (N) of its associated wavelength (λ) plus a fractional part associated to the satellite and to the receiver.

$$B_{1,rec}^{sat} = \lambda_1 N_{1,rec}^{sat} + b_{1,rec} + b_1^{sat}$$

$$B_{2,rec}^{sat} = \lambda_2 N_{2,rec}^{sat} + b_{2,rec} + b_2^{sat}$$

$$\dots \quad \dots \quad \dots$$

$$N_W = N_1 - N_2$$

$$B_C = \lambda_N \left(N_1 + \frac{\lambda_w}{\lambda_2} N_W \right) + b_{C,rec} + b_C^{sat}$$

B_C is not an integer number of λ_N but can be related with the integers N_1 , N_W

The Ambiguity Fixing techniques take benefit of this INTEGER NATURE of N_1 , N_2 ambiguities to properly fix them, reducing convergence time, and thence, achieving high accuracy quickly.

Carrier Ambiguity Fixing concept

Two different approaches can be considered:

- **Double differenced Ambiguity Fixing (e.g. RTK):**

This is the classical approach which relies in the fact that the fractional part of carrier ambiguities cancels when forming the double differences between receivers and satellites:

→ That is, given: $B_{rec}^{sat} = \lambda N_{rec}^{sat} + b_{rec} + b^{sat}$

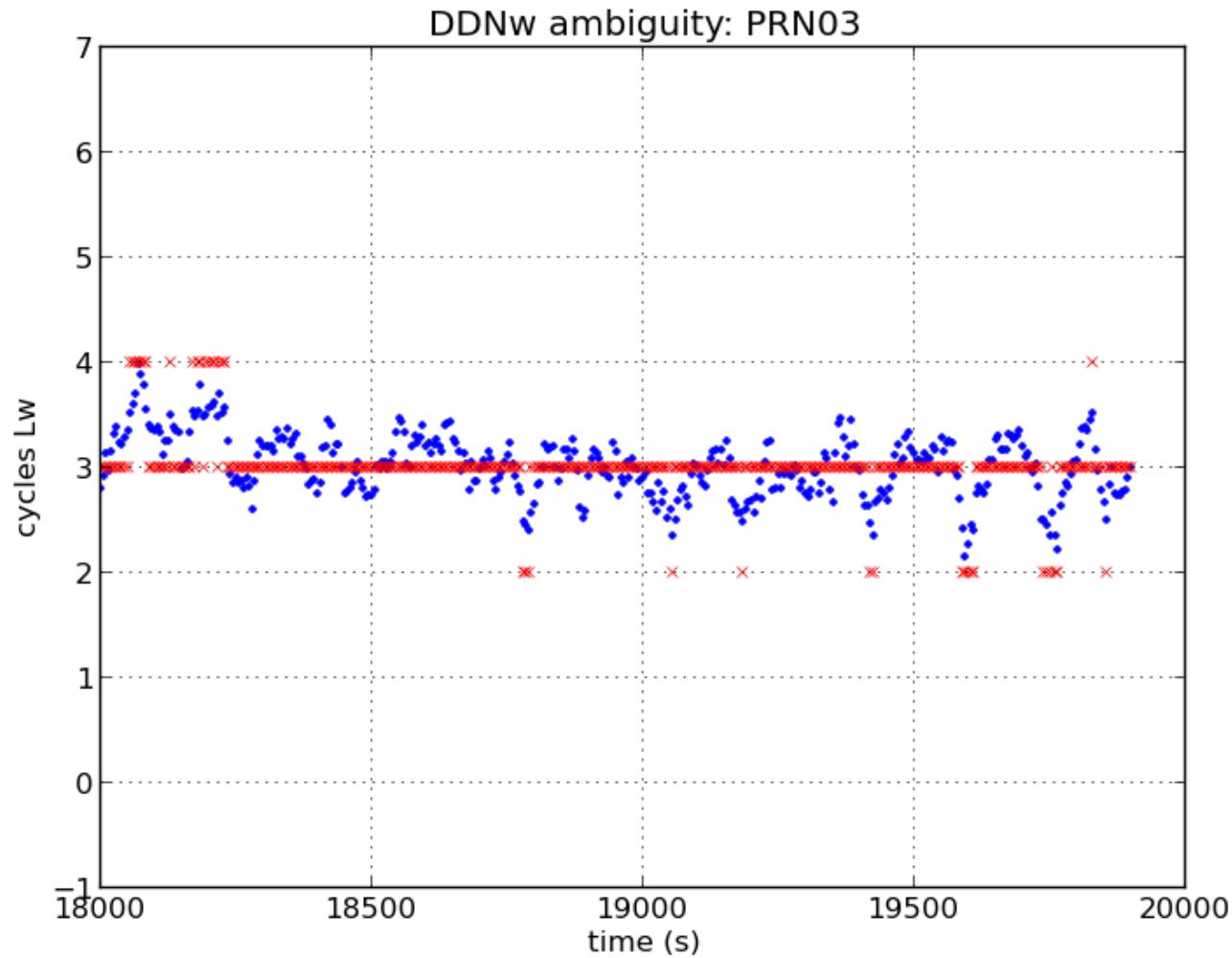
The double differences, regarding a reference receiver and satellite, yield:

$$\Delta \nabla B_{rec}^{sat} = B_{rec}^{sat} - B_{rec,R}^{sat} - (B_{rec}^{sat,R} - B_{rec,R}^{sat}) = \lambda \Delta \nabla N_{rec}^{sat}$$

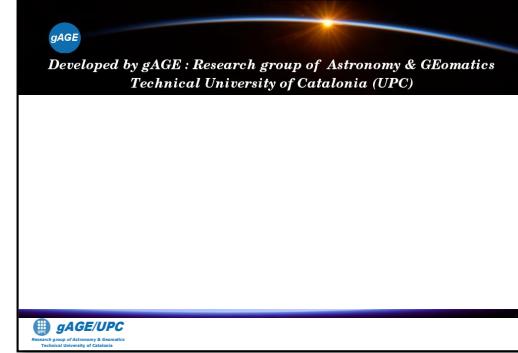
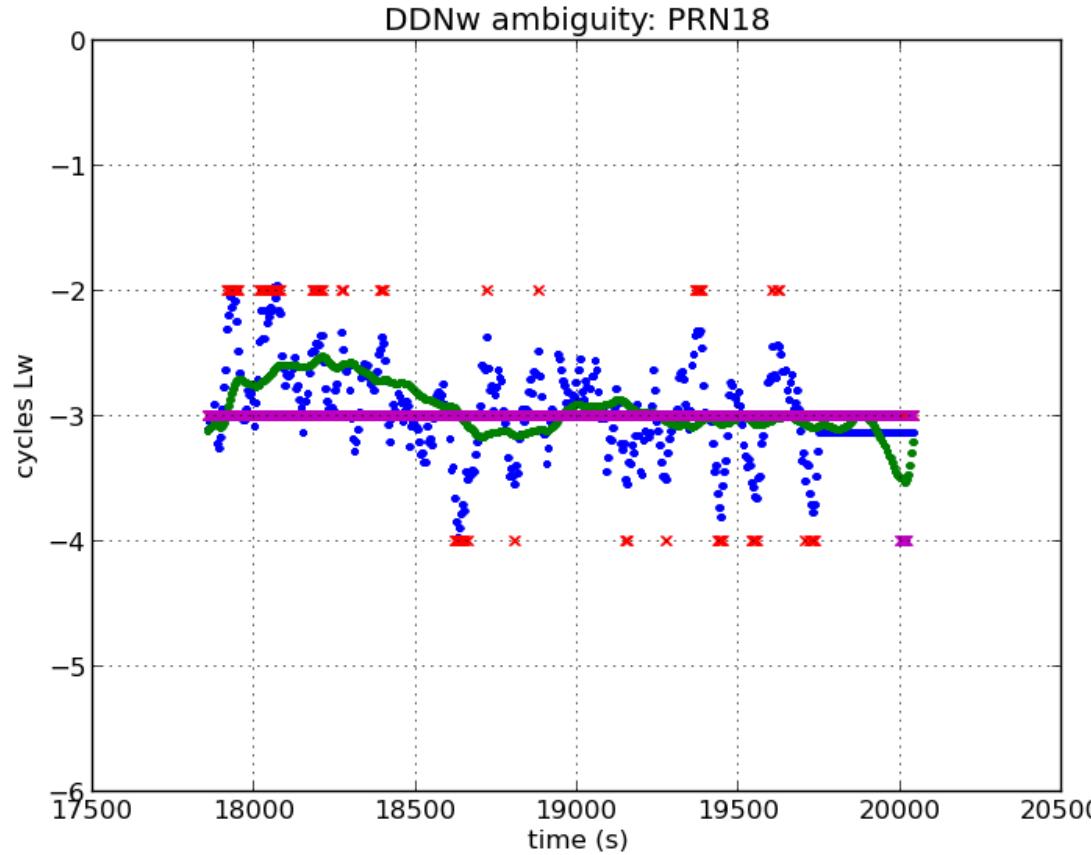
where the satellite and receiver ambiguity terms (b_{rec} , b^{sat}) cancel out.

- **Absolute (or undifferenced) ambiguity fixing (e.g. PPP AR):**

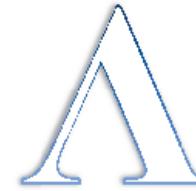
Example of Ambiguity Fixing by rounding



300 seconds smoothing



The LAMBDA METHOD



LAMBDA software package

Matlab implementation, Version 3.0

Sandra Verhagen and Bofeng Li



Mathematical Geodesy and Positioning, Delft University of Technology



Carrier Ambiguity Fixing concept

Two different approaches can be considered:

- **Double differenced Ambiguity Fixing (e.g. RTK):**

This is the classical approach which relies in the fact that the fractional part of carrier ambiguities cancels when forming the double differences between receivers and satellites:

→ That is, given: $B_{rec}^{sat} = \lambda N_{rec}^{sat} + b_{rec} + b^{sat}$

The double differences, regarding a reference receiver and satellite, yield:

$$\Delta \nabla B_{rec}^{sat} = B_{rec}^{sat} - B_{rec,R}^{sat} - (B_{rec}^{sat,R} - B_{rec,R}^{sat}) = \lambda \Delta \nabla N_{rec}^{sat}$$

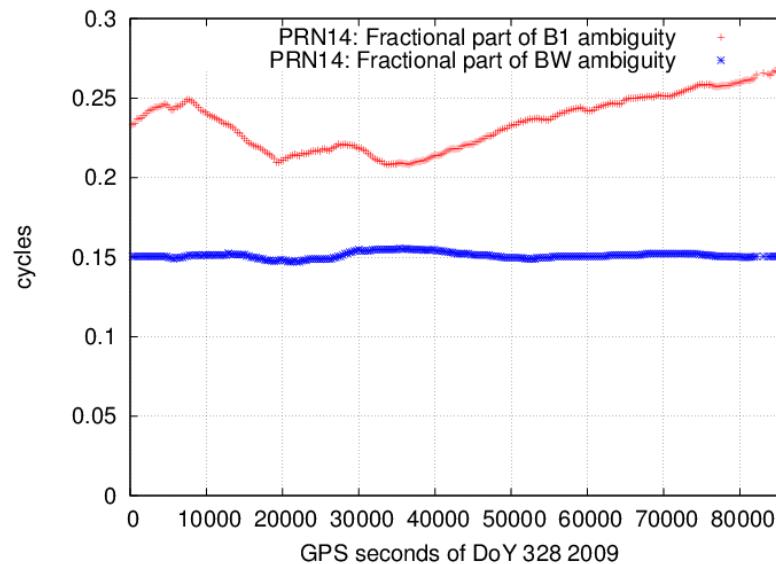
Absolute (or undifferenced) ambiguity fixing (e.g. PPP AR):

This is a new approach, where the fractional part of the ambiguities are estimated from a global network of permanent stations and provided to the users. Thus, the user can remove this fractional part and fix the remaining ambiguity as an integer number.

$$B_{rec}^{sat} = \lambda N_{rec}^{sat} + b_{rec} + b^{sat}$$

Absolute (or undifferenced) ambiguity fixing

Nevertheless, these carrier hardware biases (or fractional part of carrier ambiguities) can be estimated together with the orbits, clocks, ionosphere and DCBs from measurements of a worldwide reference stations network.



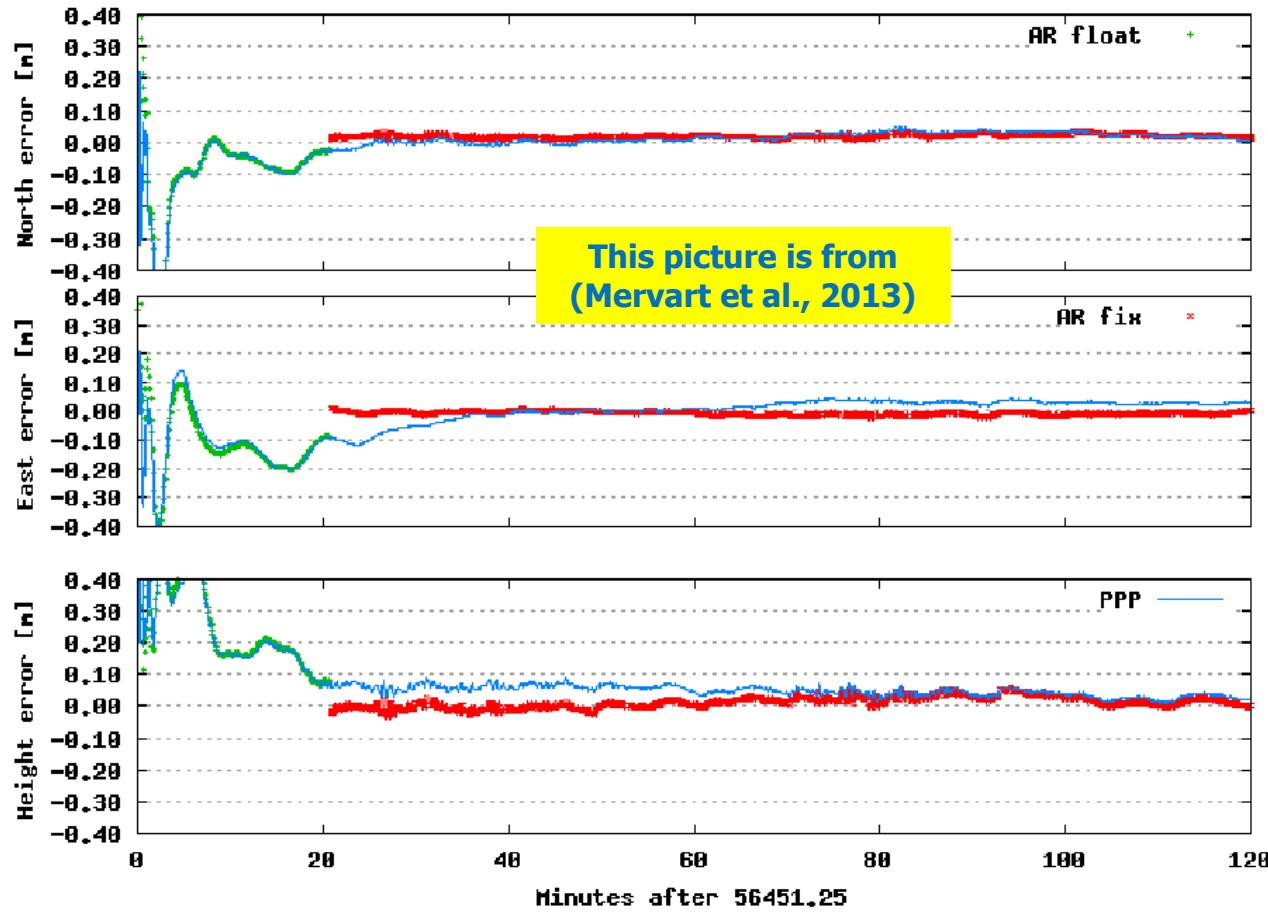
These carrier hardware biases are slow varying parameters and can be broadcast to the user, together with the other differential corrections (orbits, clocks, ionosphere...) from a reference station network.

Then, the user can remove them and estimate the remaining ambiguities as integer numbers.

This can allow world-wide PPP users to perform ambiguity fixing, without baseline length limitation, improving accuracy and reducing convergence time.

Note: These carrier hardware biases are canceled in RTK when forming Double-Differences of measurements between pairs of satellites and receivers.

June 2013



The main weakness of PPP is the large convergence time, which depend on satellites geometry, quality of data (code noise, cycle-slips...). There is a sudden improvement when fixing carrier ambiguities, but still several tens of minutes are needed to achieve centimeter level of accuracy.

L. Mervart, C. Rocken, T. Iwabuchi, Z. Lukes and M. Kanzaki (2013). Precise Point Positioning with Fast Ambiguity Resolution – Prerequisites, Algorithms and Performance. *Proceedings of the 27th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2013), Nashville, Tennessee, September 16-20, 2013.*

Contents

Precise Point Positioning (PPP)

1. Introduction
2. Orbits and Clocks: Broadcast and Precise
3. Code and carrier measurements and modelling errors
4. Linear observation model for PPP
5. Parameter estimation: Floating Ambiguities
6. Carrier Ambiguity fixing concept: DD and undifferenced
7. Accelerating Filter convergence with accurate ionosphere

gAGE-UPC SWM server.gage.upc.edu/iono4has/tests.html

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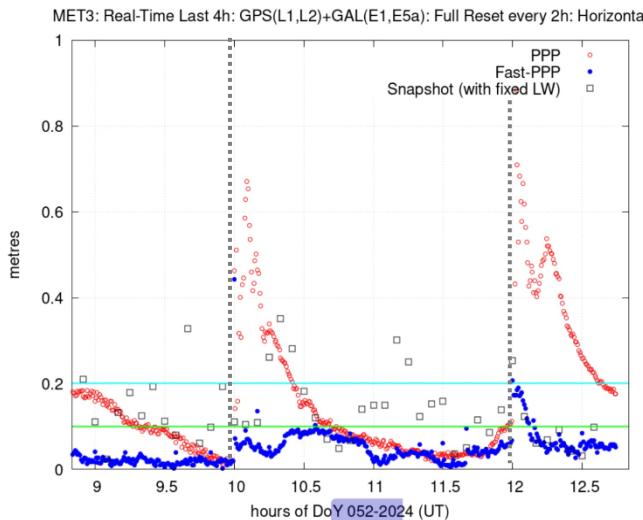
IONO4HAS-Home Networks Tests Results Products +Info

Assessing the IONO4HAS model

Only the wide-lane ins fixed
(but not the short-lane to reduce the probability of miss-fixing ambiguity)

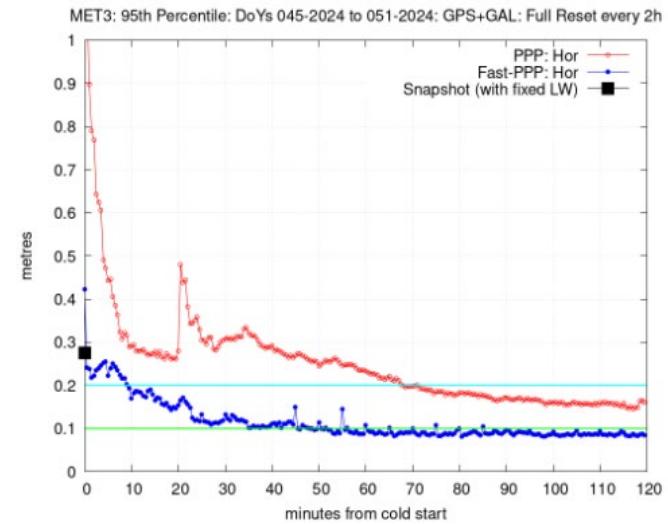
Depicted data corresponds to last 4 hours
Full reset every 2 hours

Horizontal component



Statistics during the last 7 days

95th Percentile



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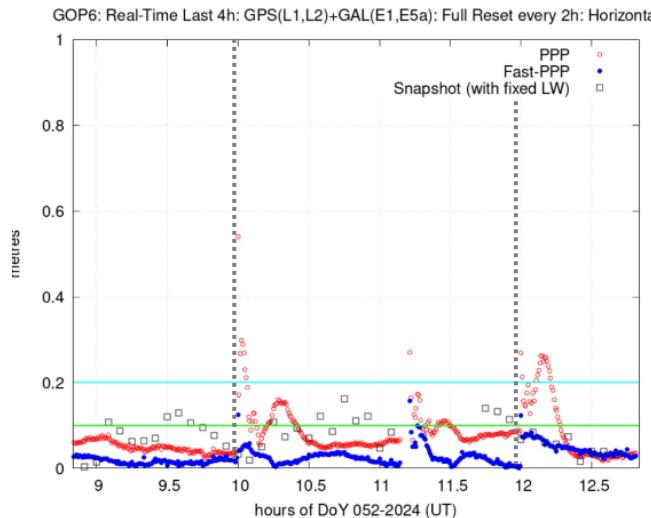
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Assessing the IONO4HAS model

The “Fast-PPP” and the technique is protected by an ESA patent since 2011. (PCT/EP2011/001512)

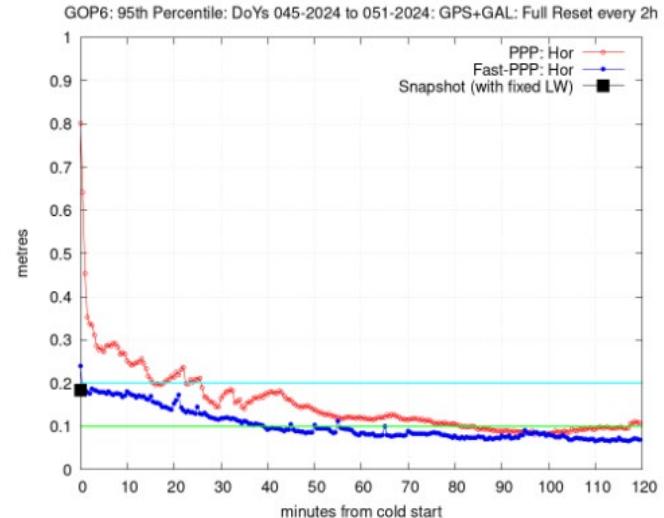
Depicted data corresponds to last 4 hours
Full reset every 2 hours

Horizontal component



Statistics during the last 7 days

95th Percentile



- **How the ionosphere helps the filter convergence in Fast-PPP?**

→ In the classical PPP, the navigation filter convergence is driven by the convergence of the floated iono-free ambiguity (B_C), which, at the beginning, depends on the code noise.

- 1) There is a constraint between the wide-lane ambiguity (B_w), the iono-free ambiguity (B_C) and the ionospheric refraction (STEC) and DCB.

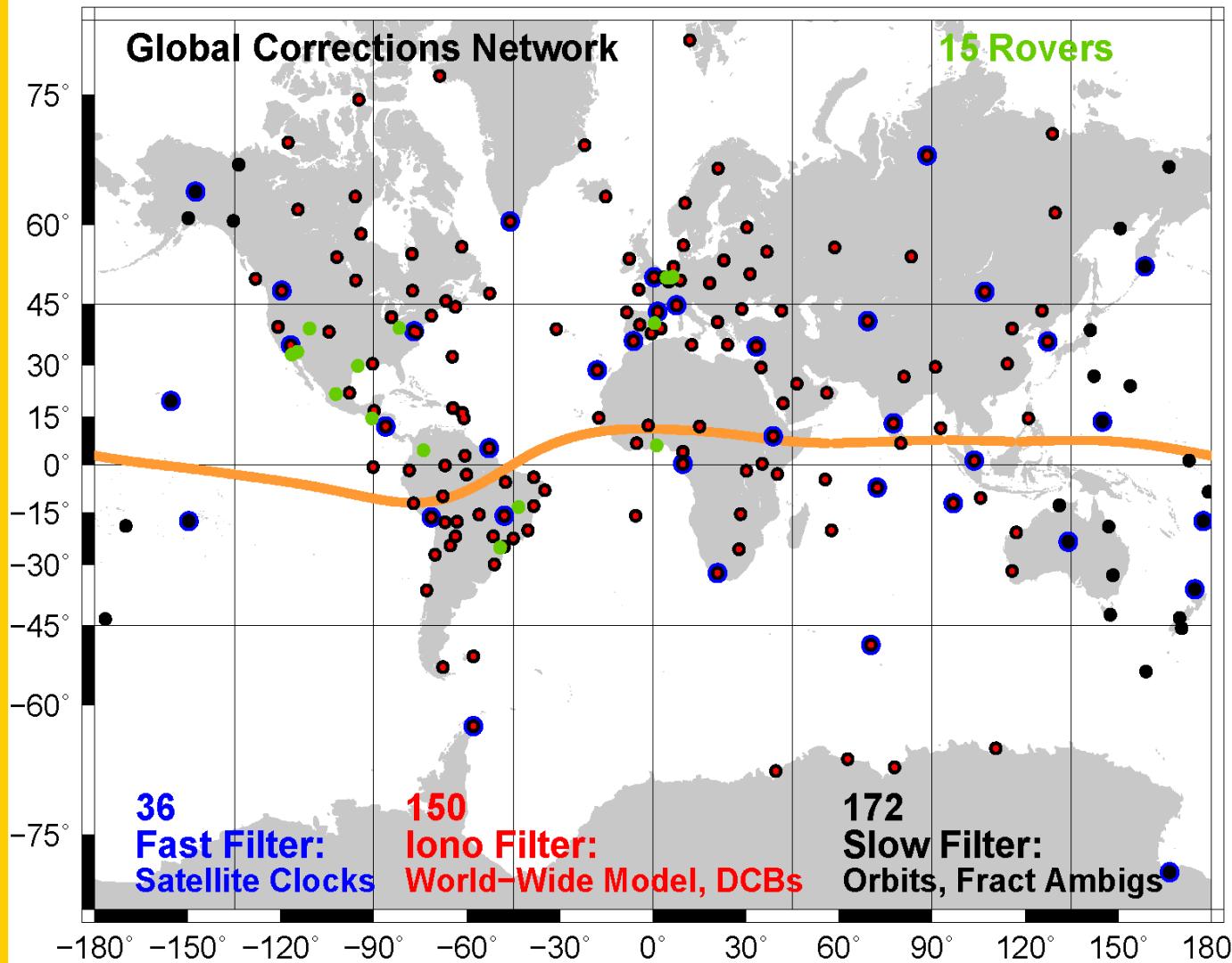
$$B_C = B_w - 1.98 (L_1 - L_2 - STEC - DCB)$$

- 2) The wide-lane ambiguity (B_w) is estimated/fixed quickly (~5 minutes with 2-freq and in single epoch with 3-freq. signals).
- 3) The ionosphere (STEC) is the bridge (through the mentioned constraint) to transfer the quick accuracy achieved in the wide-lane ambiguity (B_w) computed value to the iono-free ambiguity (B_C) estimation, accelerating in this way the filter convergence.

→ Thence, in Fast-PPP the convergence time is strongly reduced thanks to the quick wide-lane ambiguity fixing and the accurate ionospheric corrections. It allows to achieve High Accuracy quickly (~5 minutes with 2-freq & single epoch with 3-freq).

The ionosphere will help provided that its quality (noise/error) is better than the code

Actual GNSS Data the entire Year 2014



**World wide
Iono. model**

Rovers are located at distances are orders of magnitude greater than RTK baselines

Close to maximum Solar Cycle conditions

Moderate Geomagnetic Dst Values

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- [RD-3] Pratap Misra, Per Enge. Global Positioning System. Signals, Measurements, and Performance. Ganga –Jamuna Press, 2004.
- [RD-4] B. Hofmann-Wellenhof et al. GPS, Theory and Practice. Springer-Verlag. Wien, New York, 1994.
- [RD-5] Juan, J.M., Hernandez-Pajares, M., Sanz, J., Ramos- Bosch, P., Aragon-Angel, A., Orus, R., Ochieng, W., Feng, S., Coutinho, P., Samson, J. and Tossaint, M., 2012a. Enhanced Precise Point Positioning for GNSS Users. IEEE Transactions on Geoscience and Remote Sensing PP, issue 99, pp. 1-10.
- [RD-6] Sandra Verhagen and Bofeng L., LAMBDA software package. MATLAB implementation, Version 3.0. Mathematical Geodesy and Positioning, Delft University of Technology.

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- [RD-8] Fast-PPP: [International Patent Application PCT/EP2011/001512](#). International patent: G01S19/44 (ESA ref.: ESA/PAT/566).
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- [RD-10] Rovira-Garcia A., Juan J. M., Sanz J., González-Casado G. (2015). "[A World-Wide Ionospheric Model for Fast Precise Point Positioning](#)", [IEEE Transactions on Geoscience and Remote Sensing](#), Volume: 53, Issue: 8, pp 4596-4604, DOI10.1109/TGRS.2015.2402598 (Open Access).

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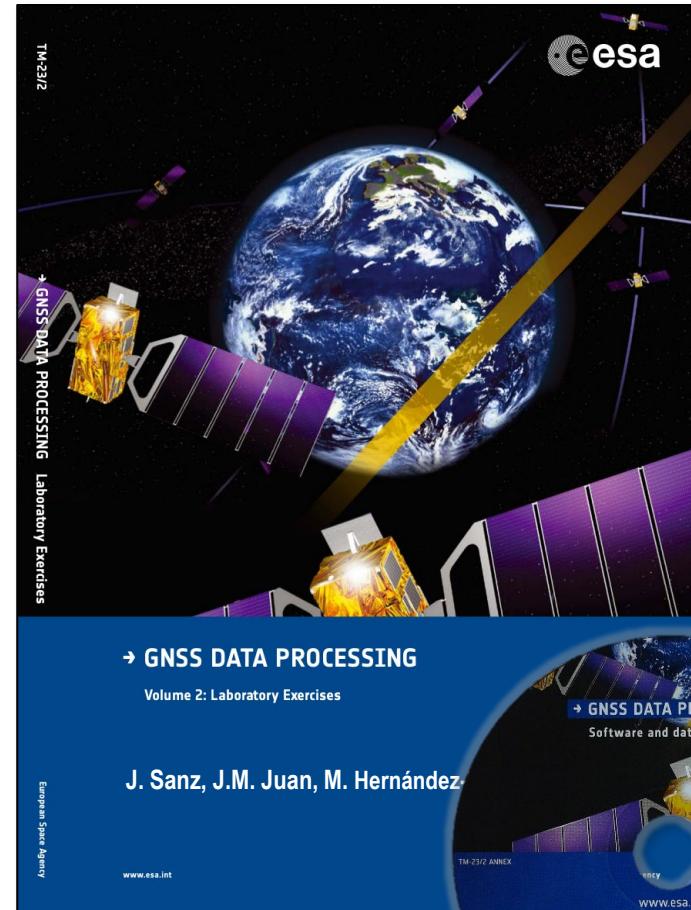
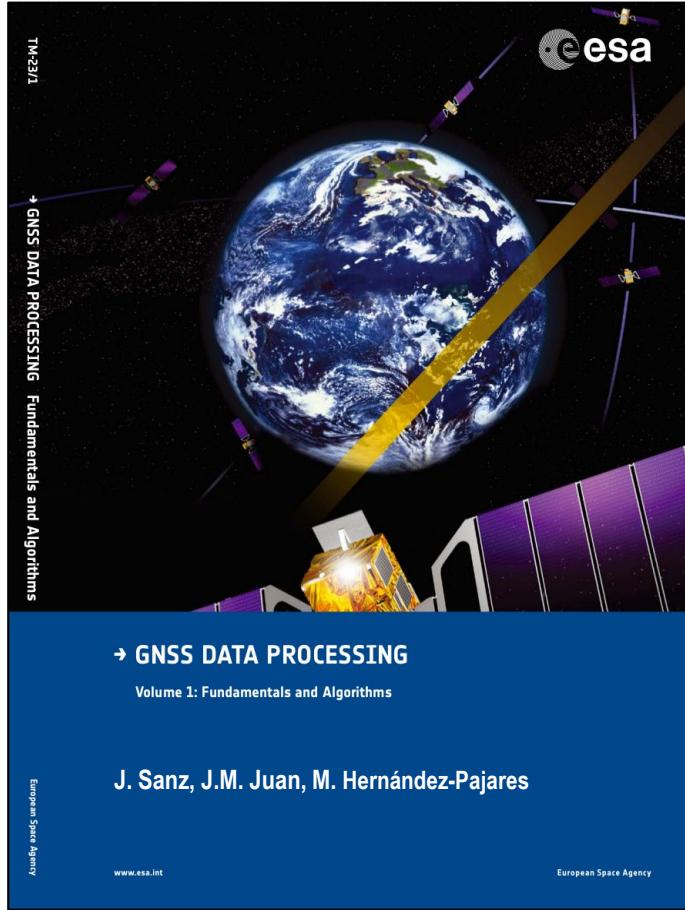
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Fast-PPP Ionospheric Model

technique's core

1.- Derived from the geometry-free combination of **carrier-phases**:

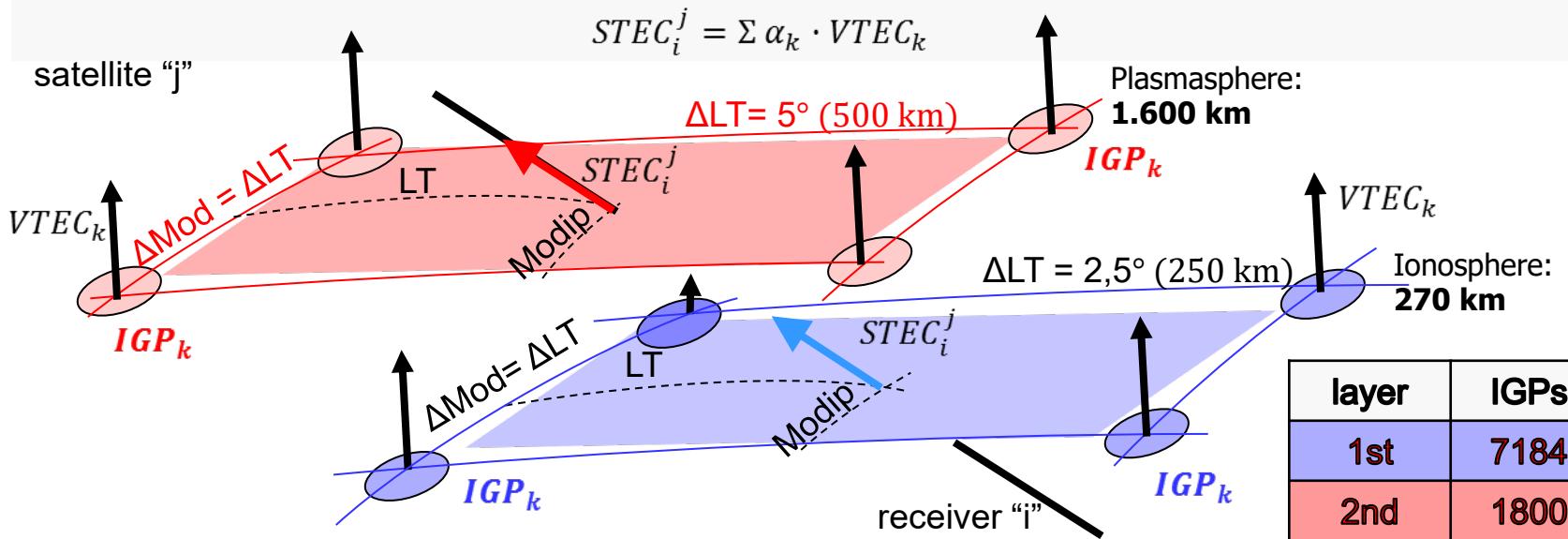
$$LI = L1 - L2$$

2.- Ambiguities are fixed (thanks to the CPF accurate geodetic modelling):

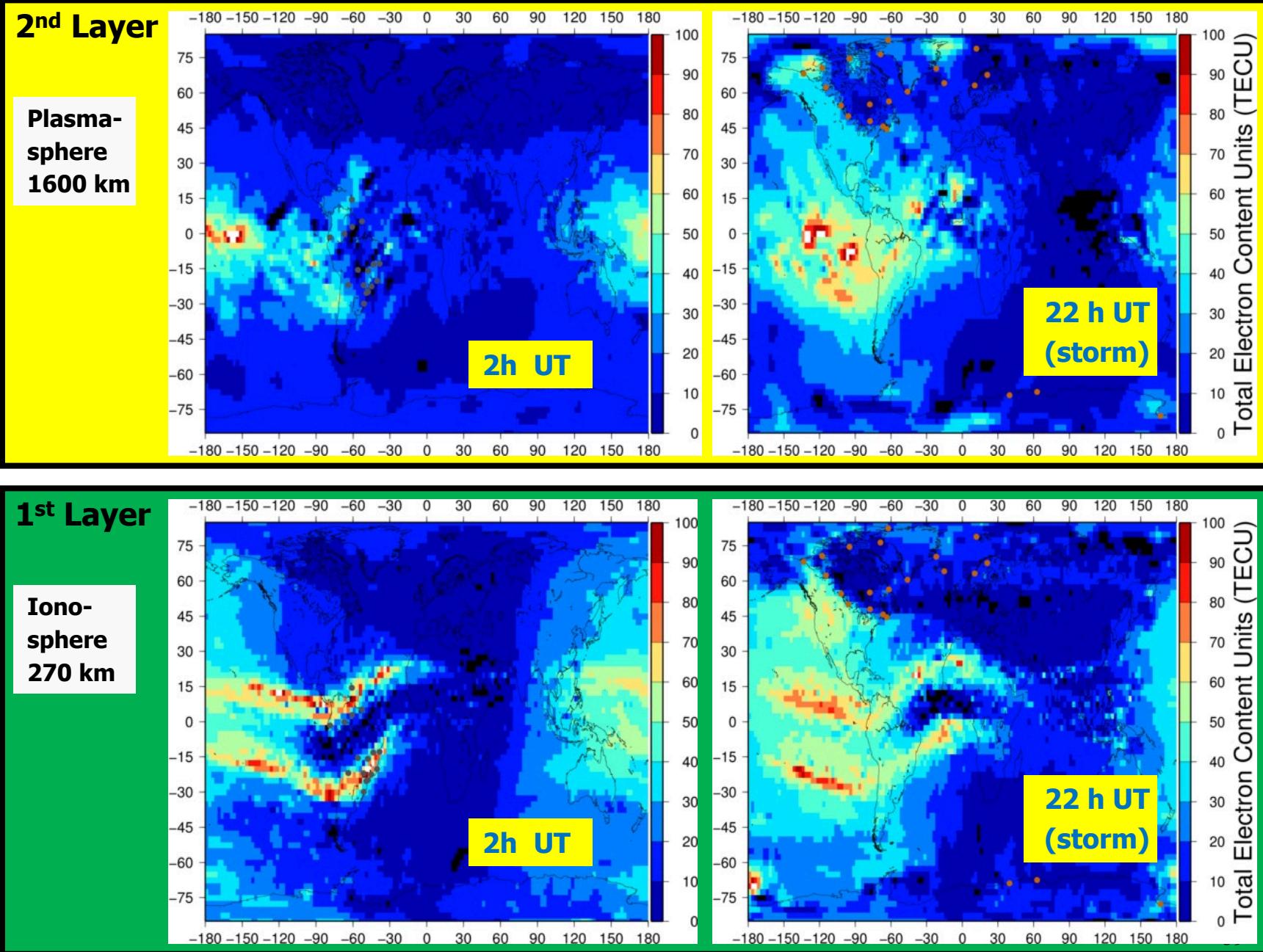
**Unambiguous
Carrier-phase noise (mm)**

$$LI_i^j - BI_i^j = STEC_i^j + DCB_i - DCB^j$$

3.- The Slant Total Electron Content (STEC) is estimated with Vertical STEC (VTEC) on each “k” Ionospheric Grid Point (IGP) at the **two-layers**:



2-Layer Ionospheric Maps during Storm of DoY 058-2014



Agreement Electron Contents of dual-layers between GIM derived from “earth” data and “space-borne” data

Independent data

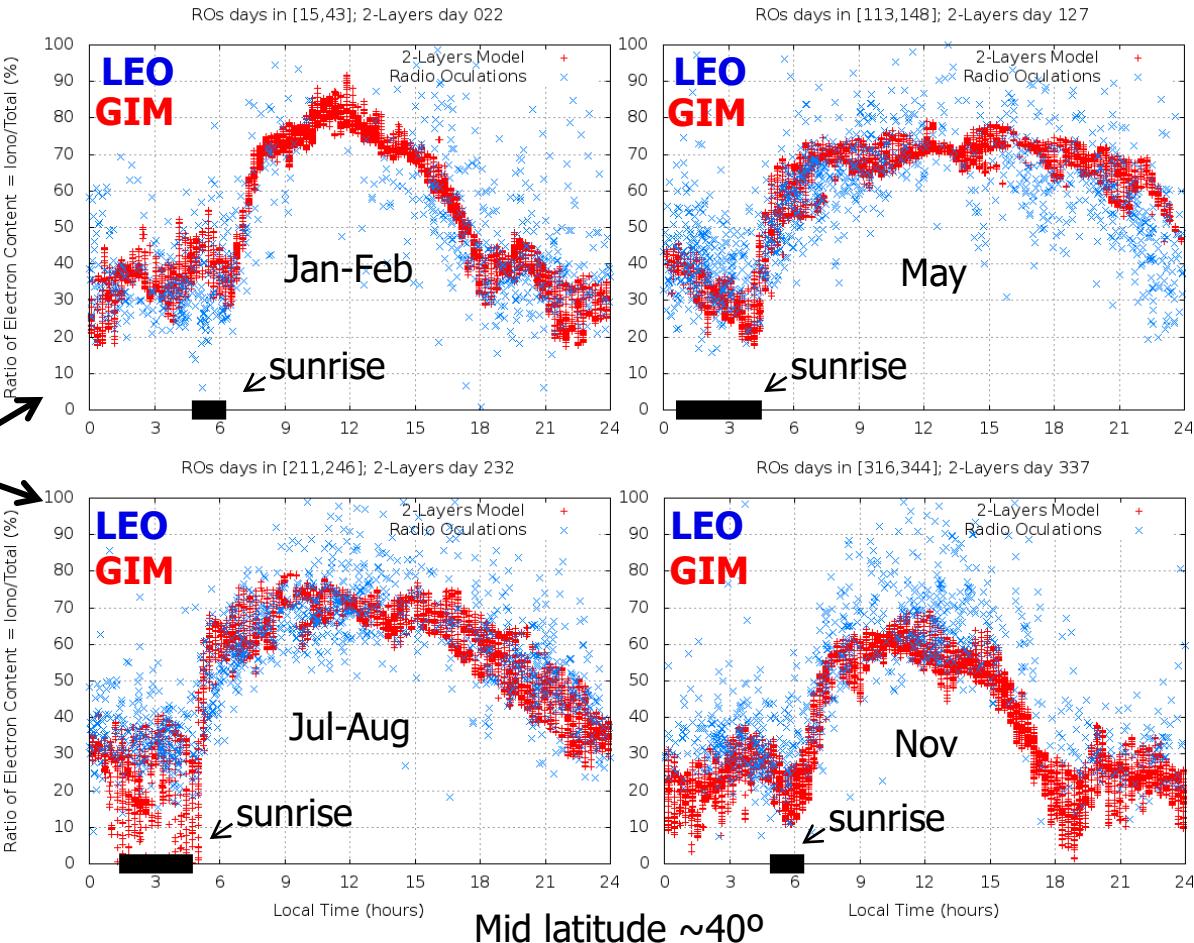
4 weeks of Low Earth Orbit Radio Occultations year 2007.

1 day of gAGE dual-layer GIM.

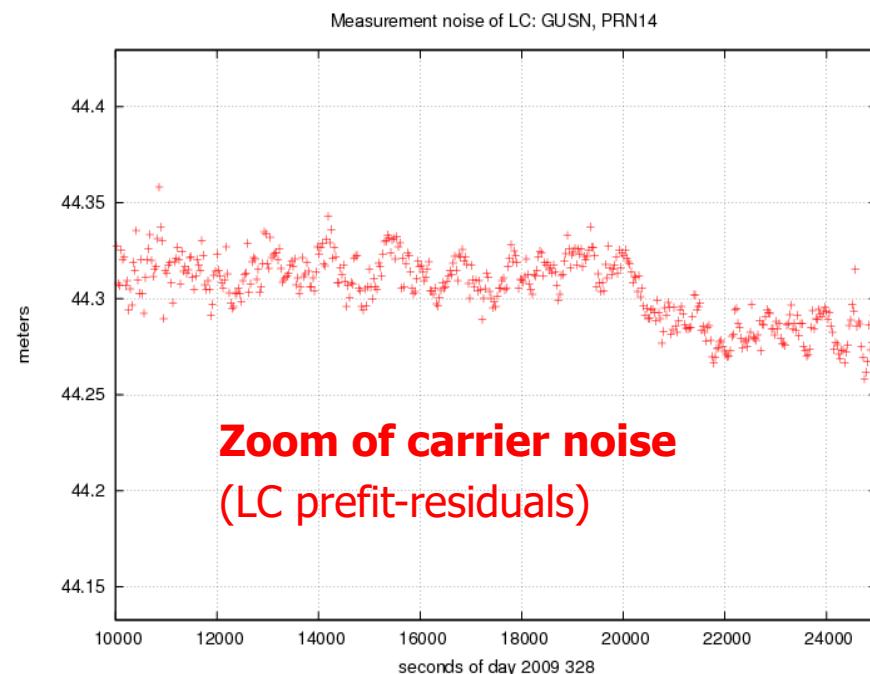
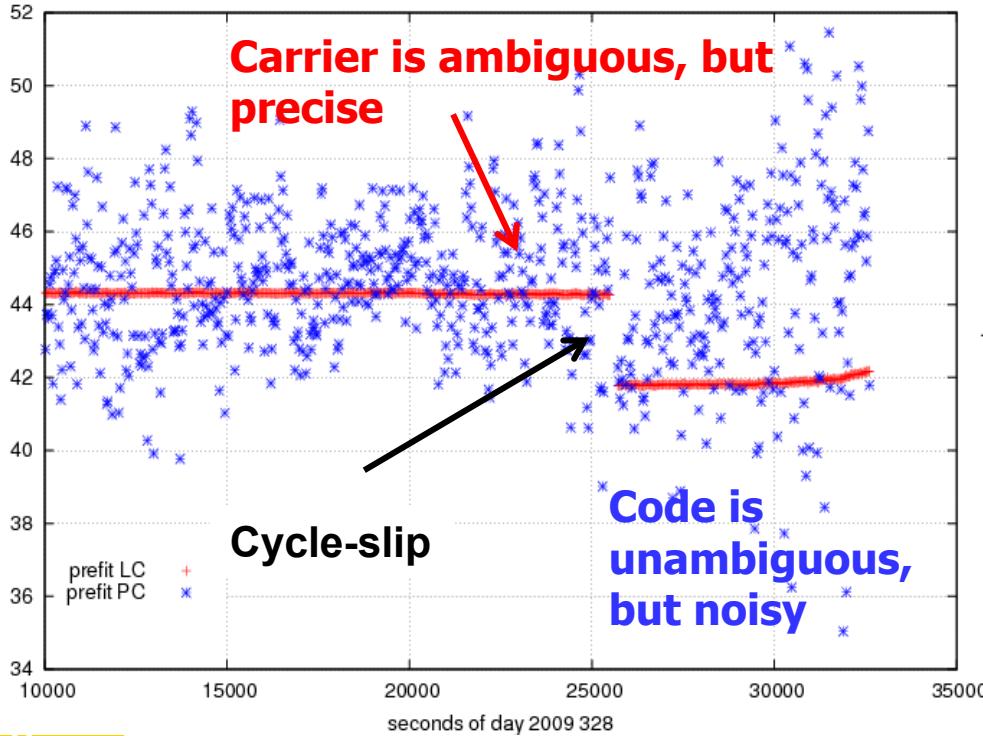
TEC ratio:

<i>Iono TEC</i>
<i>Iono TEC + Plasma TEC</i>

Neglecting this effect, introduce a miss-modelling degrading navigation.



G. González-Casado, J. M. Juan, J. Sanz, A. Rovira-García, and A. Aragón-Angel. "Determination of the Ionospheric and Plasmaspheric contributions to the Total Electron Content using Radio Occultations and Global Ionospheric Maps" Journal of Geophysical Research, 101002/2014JA020807.



- **Code measurements are unambiguous but noisy (meter level noise).**
- **Carrier measurements are precise (few millimetres of noise) but ambiguous (the unknown ambiguities can reach thousands of km).**
- **Carrier phase ambiguities are estimated in the navigation filter along with the other parameters (coordinates, clock offsets, etc.).** If these ambiguities were fixed, measurements accurate to the level of few millimetres would be available for positioning. However, some time is needed to decorrelate such ambiguities from the other parameters in the filter, and the estimated values are not fully unbiased.

Convergence: DoYs 169-200 of 2014

6 Positioning modes per rover, resets every 2h:

- a) Reference Iono-Free sol
- b) Iono Sol: IONEX (IGS-GIM):
- c) Iono Sol. Fast-PPP IONO:

(Close to Solar Maximum)

GRAPHIC 1F

PPP 2F

+

IONEX 1F

PPP+IONEX 2F

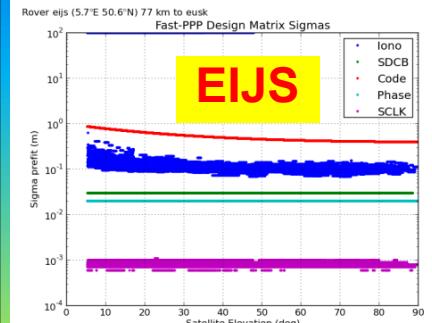
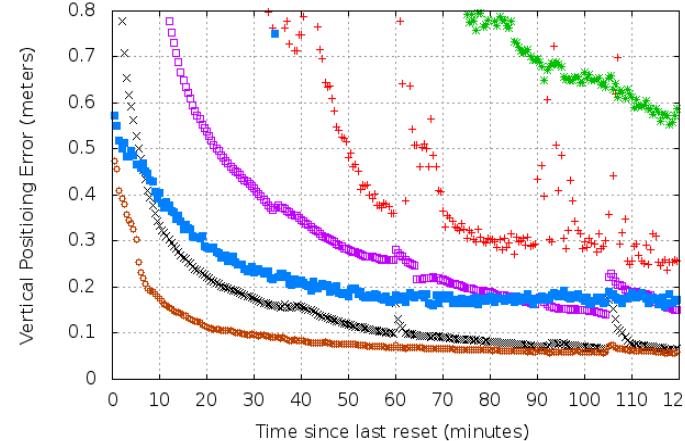
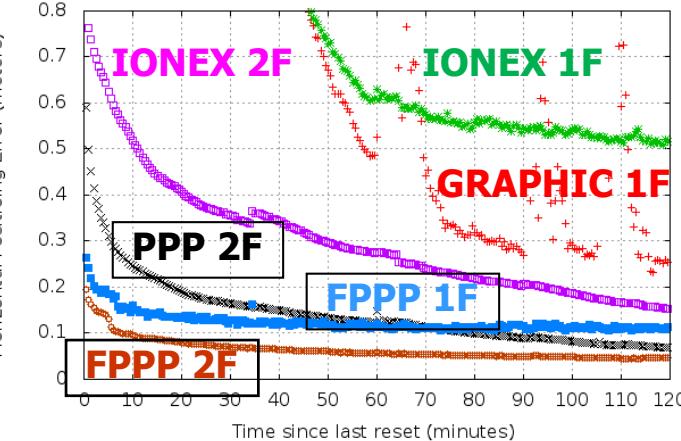
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Fast-PPP 1F

Fast-PPP 2F

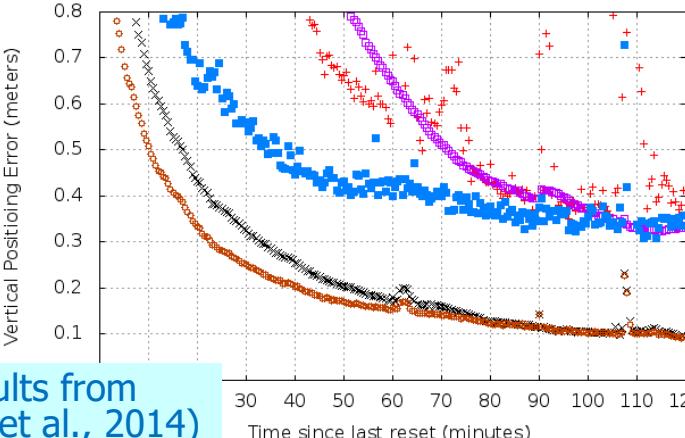
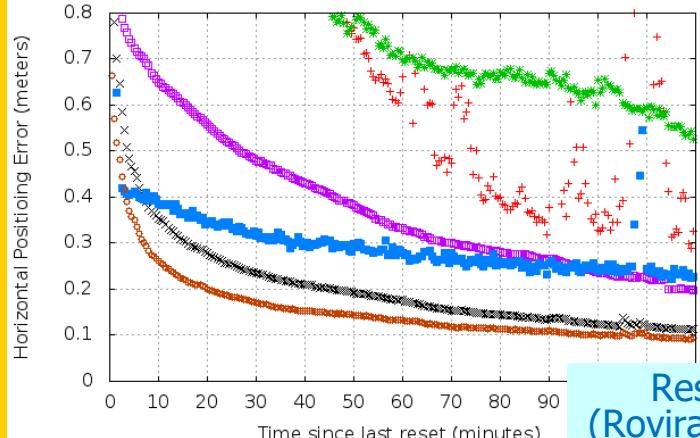
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Rover EIJS (5°E, 50°N): Mid Latitude, 76 km

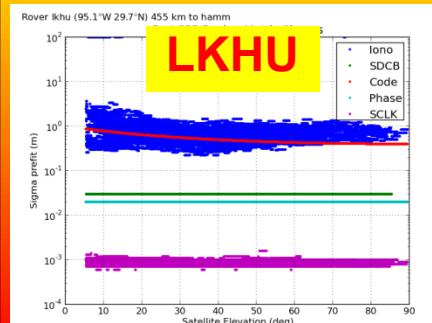


Benefits of applying external ionospheric corrections are expected, provided its quality is superior to that of code noise.

Rover LKHU (95°W, 29°S): Low latitude, 455 km



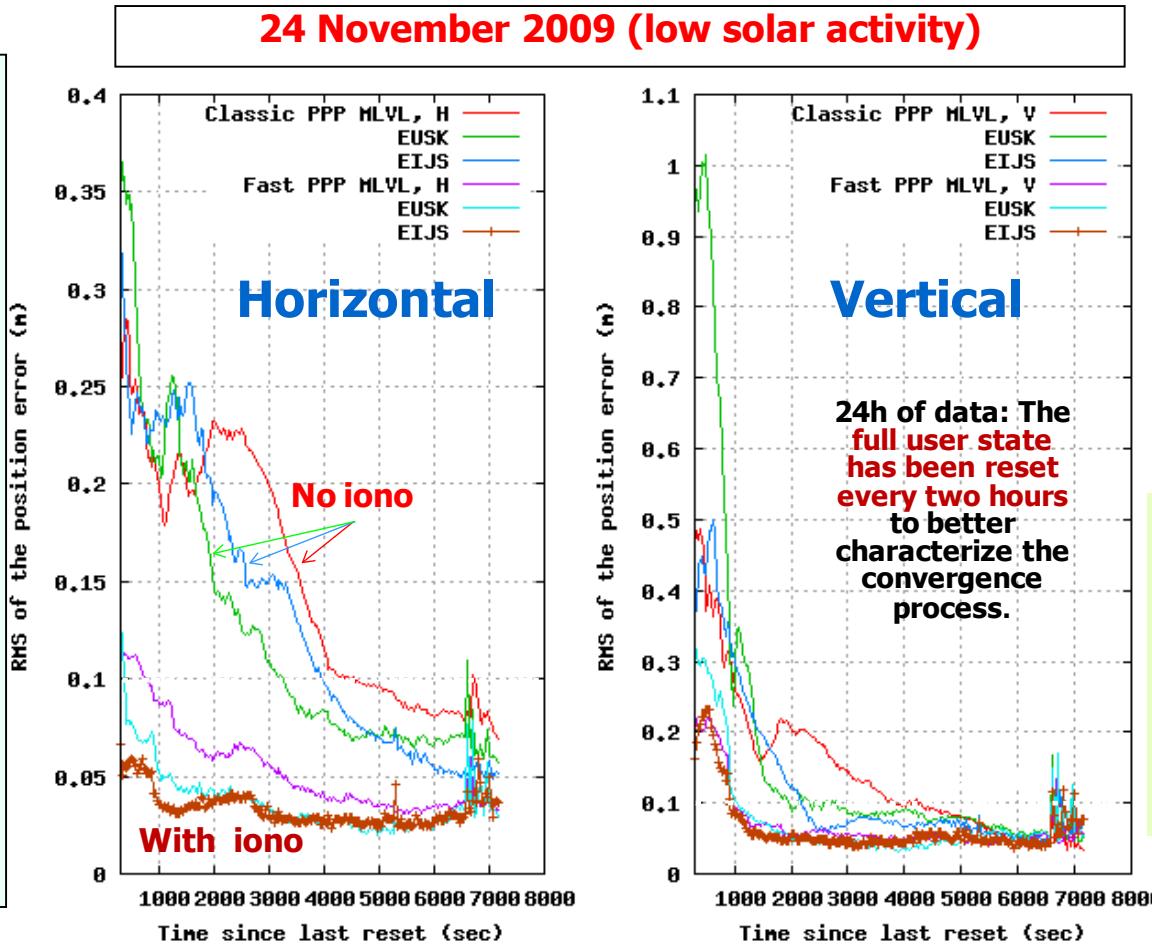
Results from
(Rovira et al., 2014)



Fast-PPP: Accelerating convergence with IONO

- During the early 2000s gAGE/UPC developed a two layers grid model, and afterwards assessed its suitability to help the PPP convergence.

These figures are from (Juan et al, 2012)



This last study was done in the context of ESA project “**Fast-PPP**” and the technique is protected by an **ESA patent since 2011**.
(PCT/EP2011/001512)

More recently, the accurate ionospheric model has been extended to **worldwide**
(Rovira, et al 2014)

MLVL (252km), **EUSK** (170km) and **EIJS** (95km)
(km from the nearest reference receiver)