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gAGE/UPC research group of Astronomy and Geomatics
Barcelona**TECH**, Spain

GNSS Error Sources

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and Dr. Adrià Rovira García

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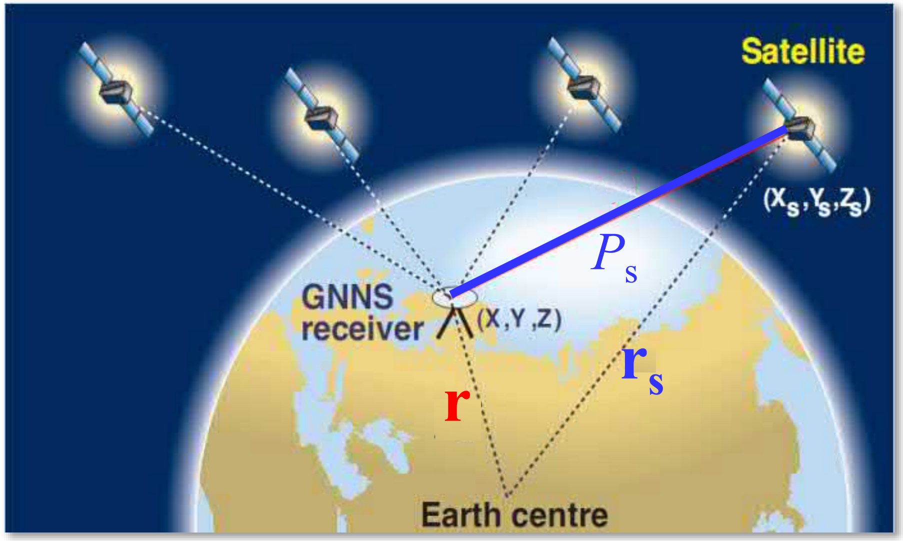
1. Review of the GNSS Positioning Concept



Input:

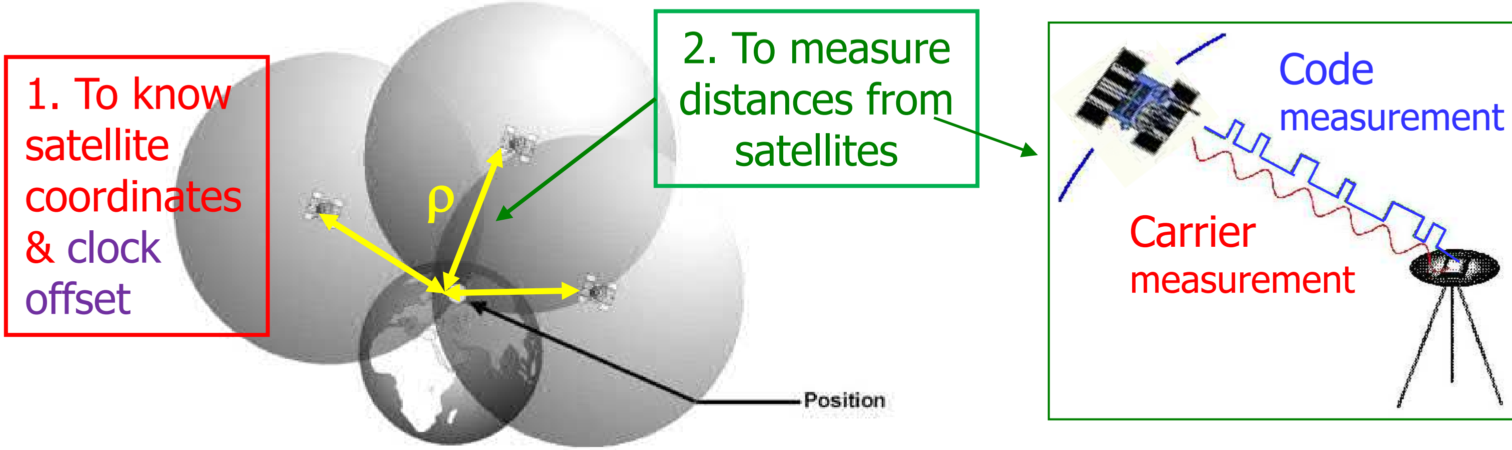
- **Pseudoranges (receiver-satellite j):** P_s
- **Navigation message. In particular:**
  - **Satellites position when transmitting signal:** $\mathbf{r}_s = (x_s, y_s, z_s)$
  - **Offsets of satellite clocks:** dt_s

  (satellites = 1, 2,…n) (n>=4)

Unknowns:

- **Receiver position:** $\mathbf{r} = (x, y, z)$
- **Receiver clock offset:** dT

1. Review of the GNSS Positioning Concept



This picture is from https://gpsfleettrackingexpert.wordpress.com

- GNSS uses technique of "**triangulation**" to find user location
- To "**triangulate**" a GNSS receiver needs:
  - **1.- To know the satellite coordinates** & clock synchronism errors:
    ➔ Satellites broadcast orbits parameters and clock offsets.
  - **2.- To measure distances from satellites (Ranging)**:
    ➔ This is done measuring the **traveling time** of radio signals:
    ("Pseudo-ranges": **Code** and **Carrier** measurements)

    ➔ Measurements must be corrected by several error sources:
    Atmospheric propagation, relativity, clock offsets, instrumental delays…

2.- Satellite Coordinates and Pseudoranges

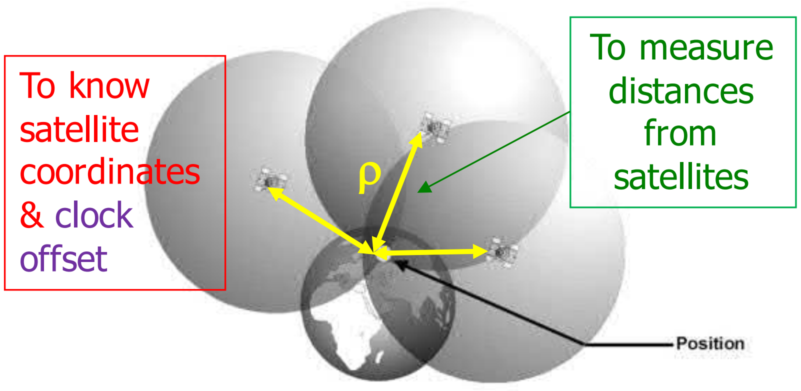
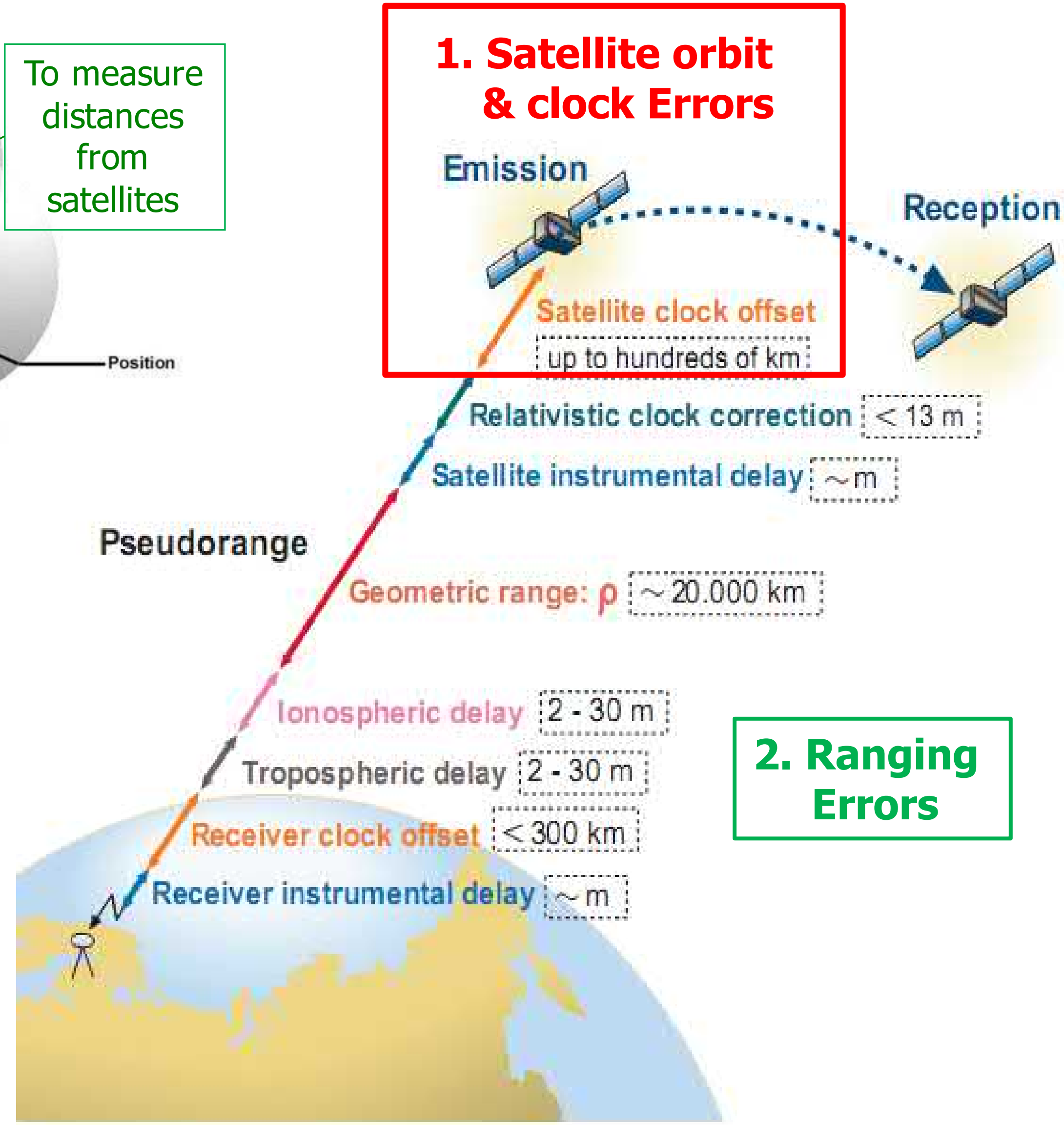
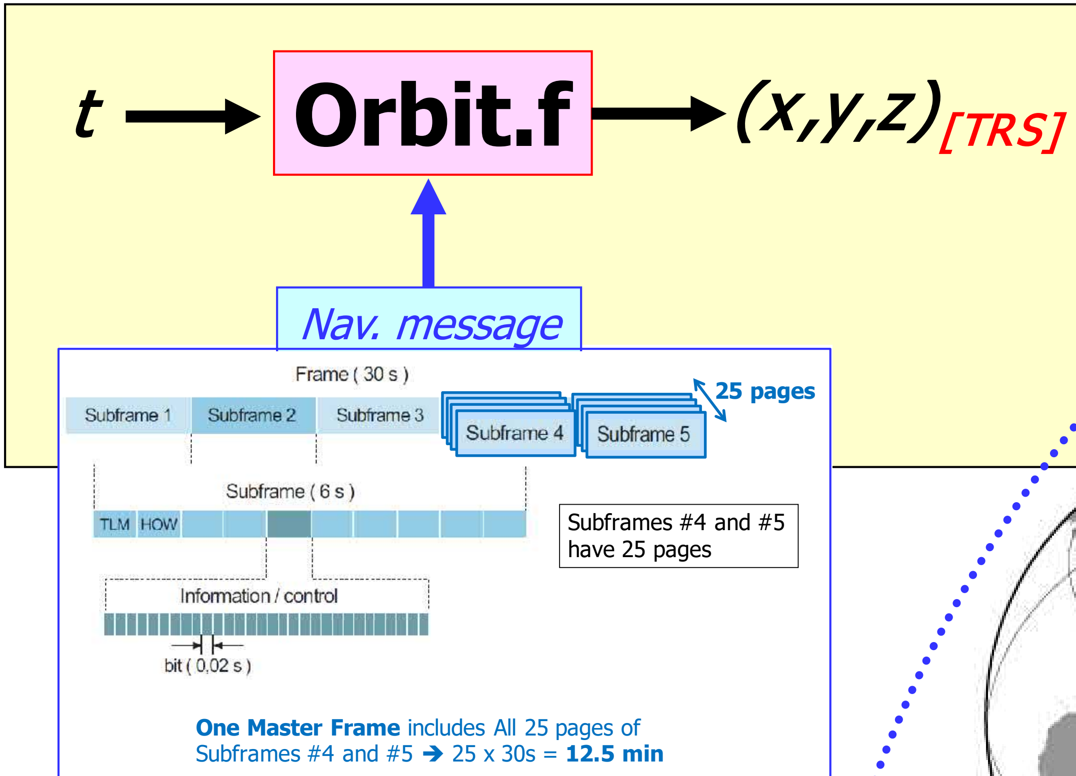


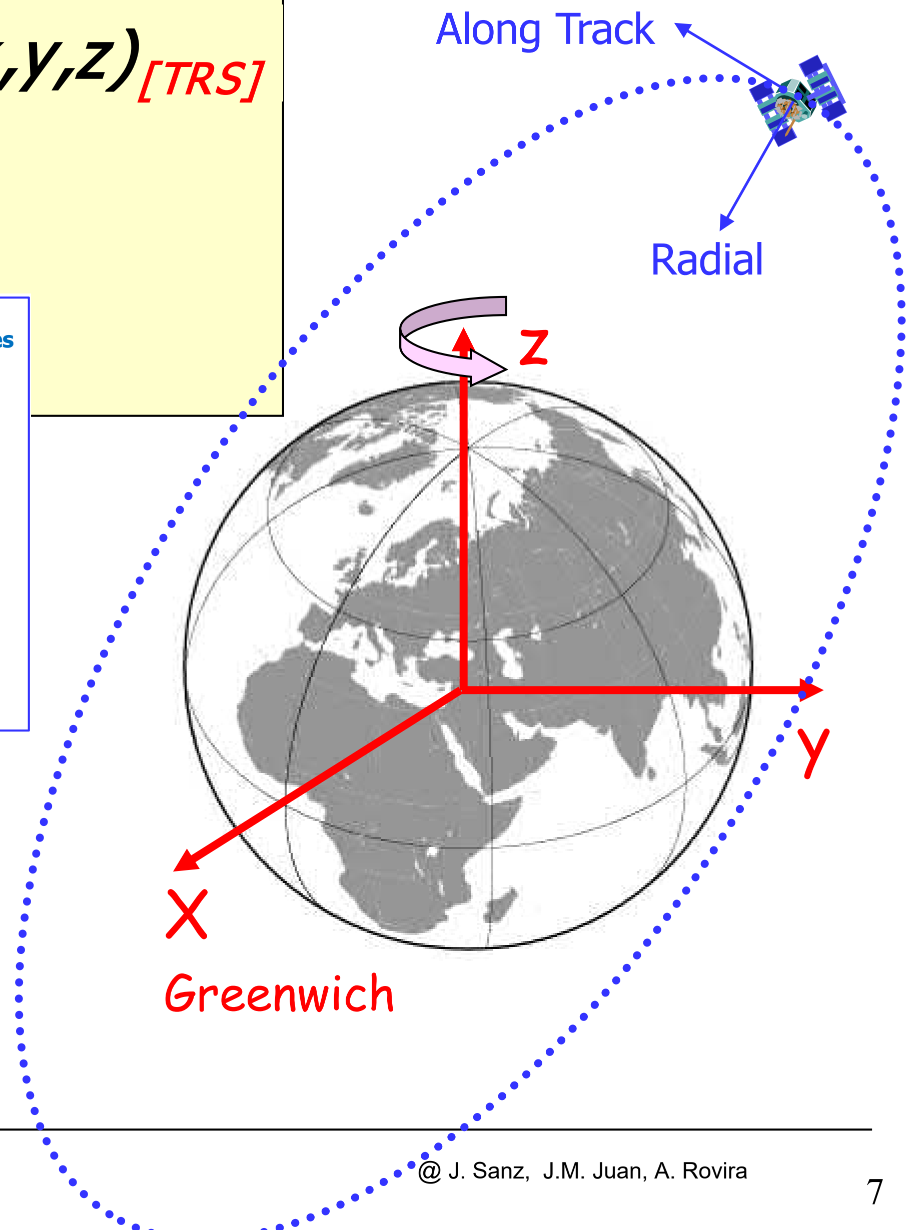
Figure 6: The position is determined at the point where all three spheres intersect



$$C1_{rec}^{sat} = \rho_{rec}^{sat} + c\cdot(dt_{rec} - dt^{sat}) + Trop_{rec}^{sat} + Ion_{1rec}^{sat} + K_{1rec} + TGD^{sat} + \varepsilon_1$$

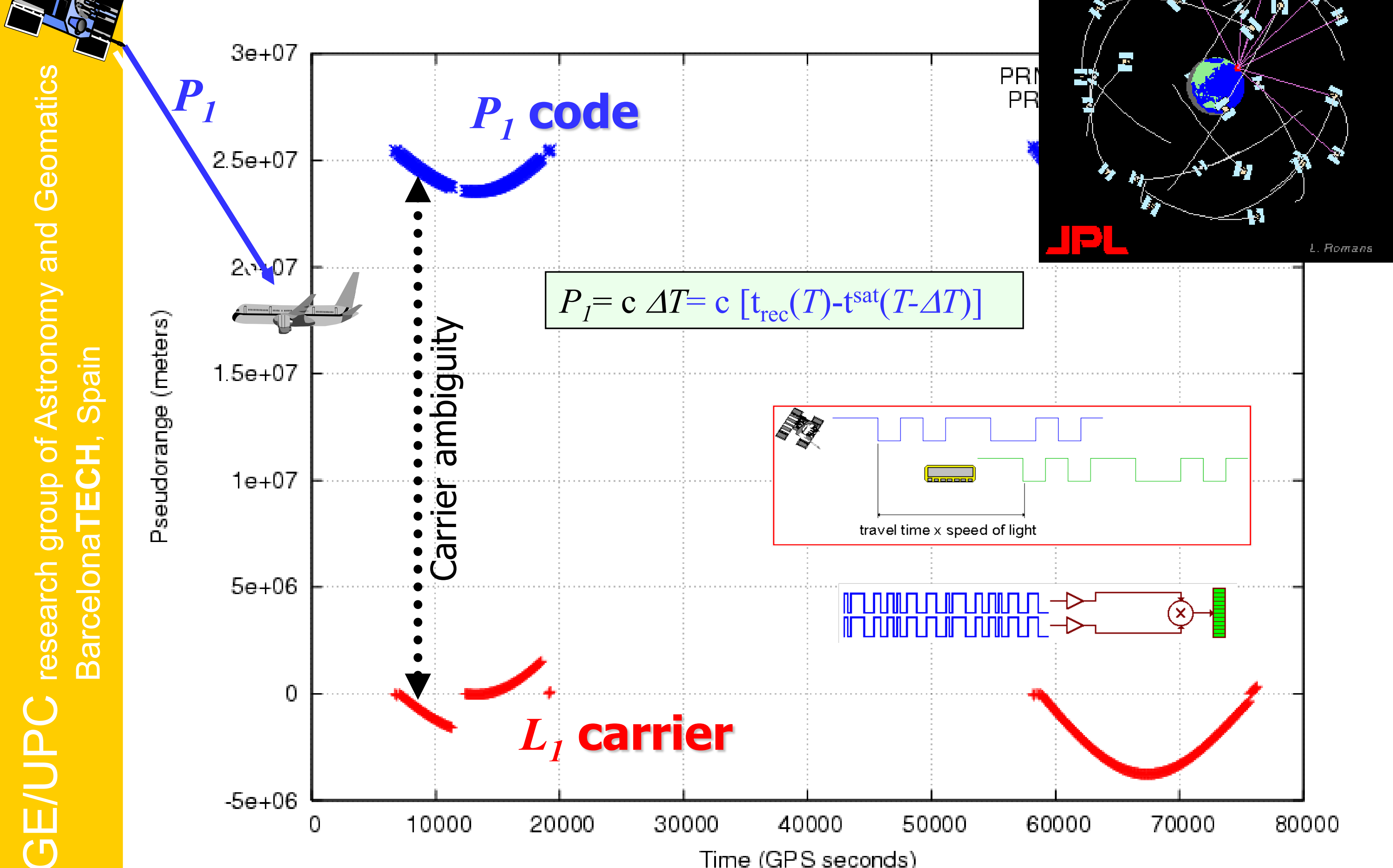
1.- SATELLITE COORDINATES





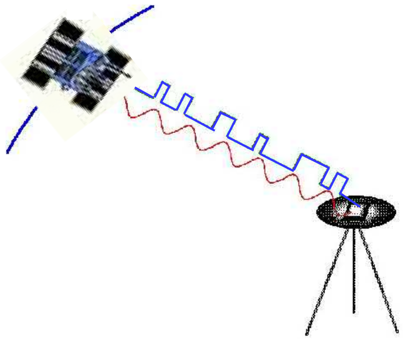
TRS: Earth Centered, Earth-Fixed (ECEF) ➔
This reference system rotates with Earth.

2.- RANGING: Carrier and Code pseudorange measure



L_1 Carrier is Ambiguous measurement. P_1 Code is Not ambiguous

Ranging signals measurement noise



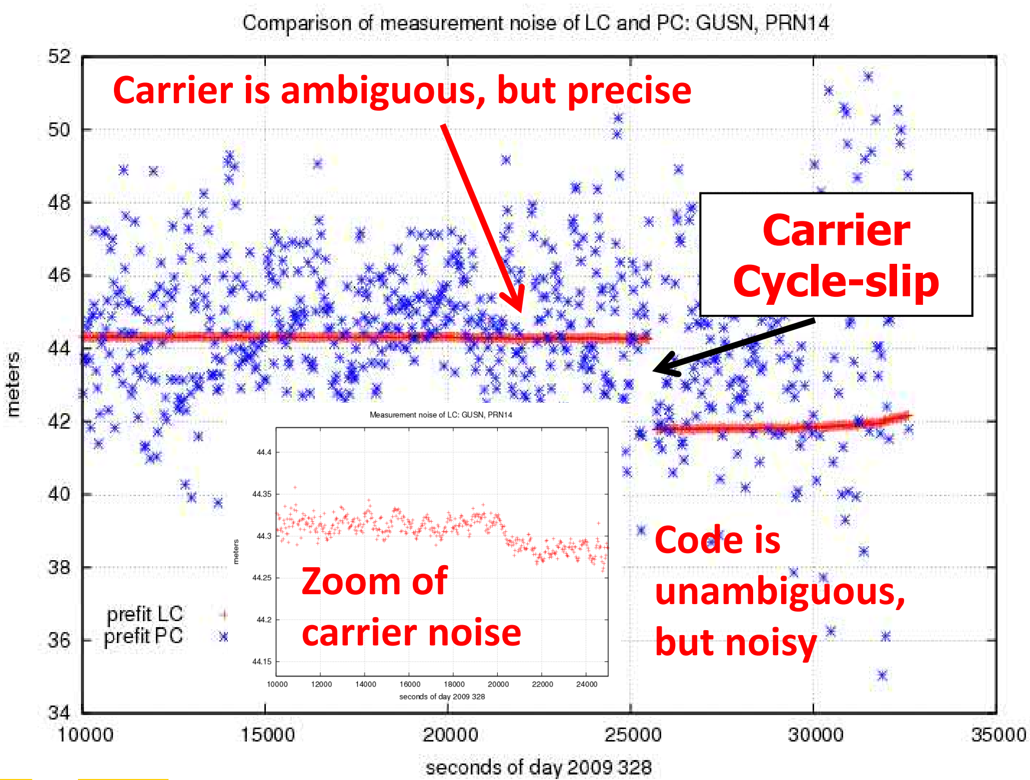
Two different types of measurements:

- **Code measurements are noisy but unambiguous** (metre level measurement noise).

- **Carrier measurements are precise but ambiguous**, meaning that they have some millimetres of noise, but also have "**unknown carrier biases"** that could reach thousands of km.

Carrier biases *are estimated in the navigation filter along with the other parameters (coordinates, clock offsets, etc.).*

Note: Figure shows the noise of code and carrier prefit-residuals, which are the input data for navigation equations.



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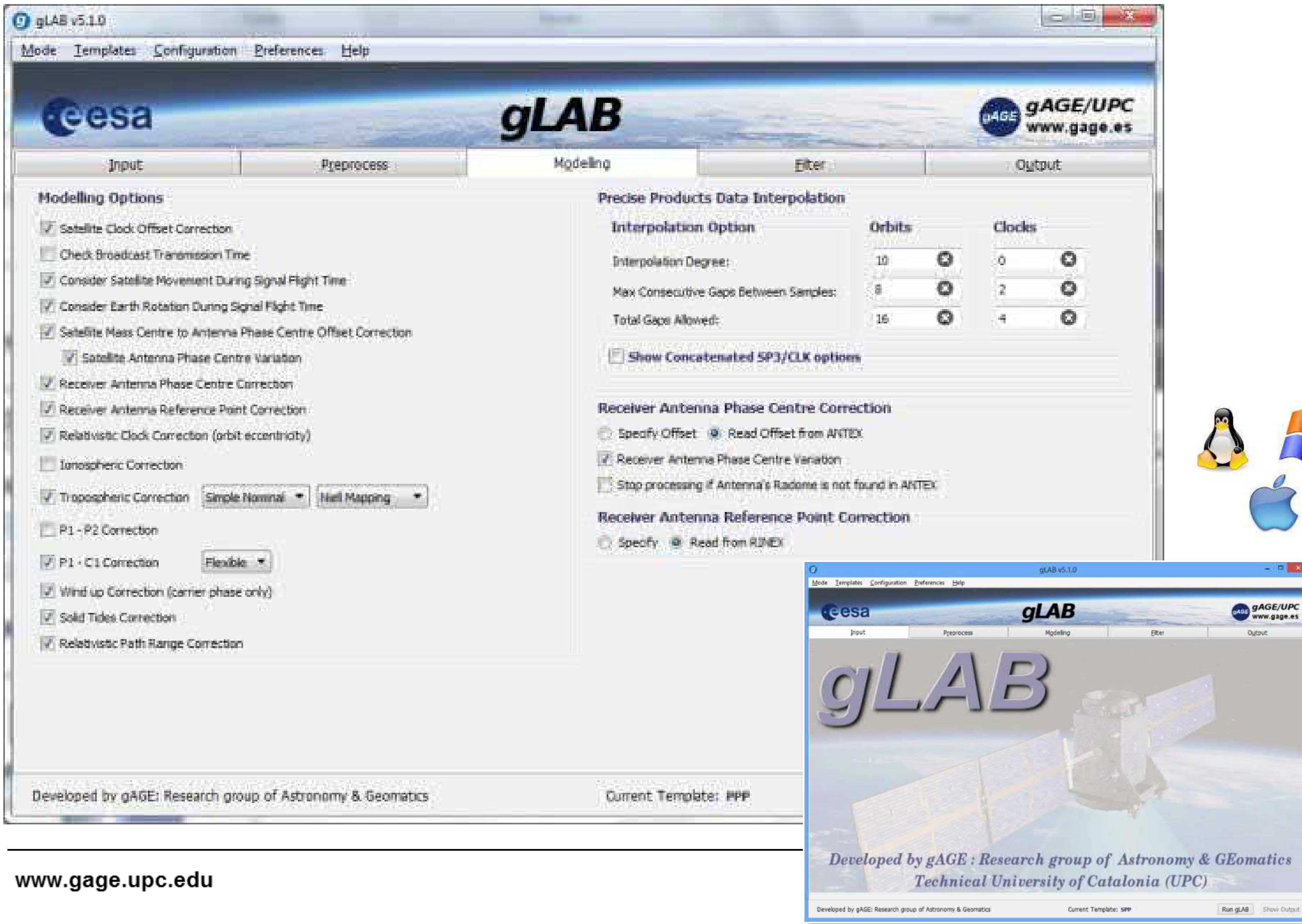
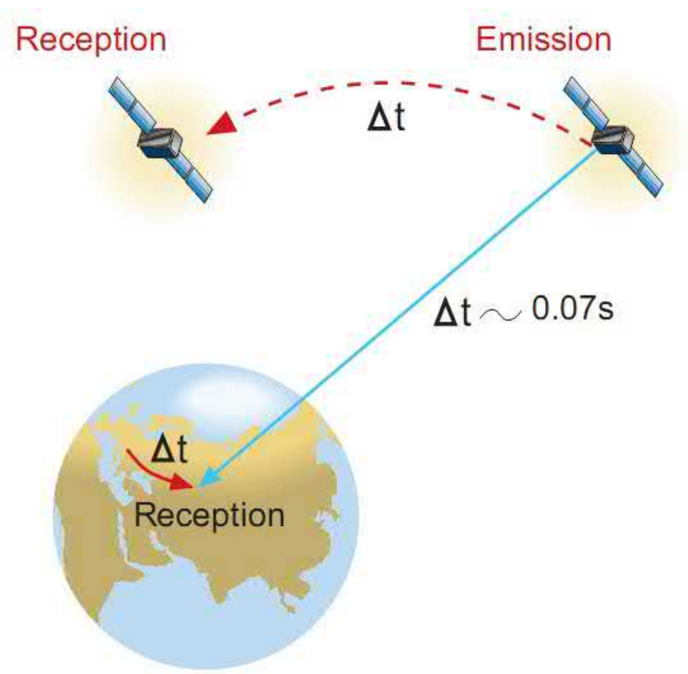
We will introduce the **main error sources** in GNSS Standard Point Positioning.

These error components must be properly modeled by the receivers.

- In the **hands-on laboratory session**, we will reproduce the results by disabling the different model terms in the **gLAB software tool for GNSS positioning**.



ORBIT: ERRORS in satélite coordinates



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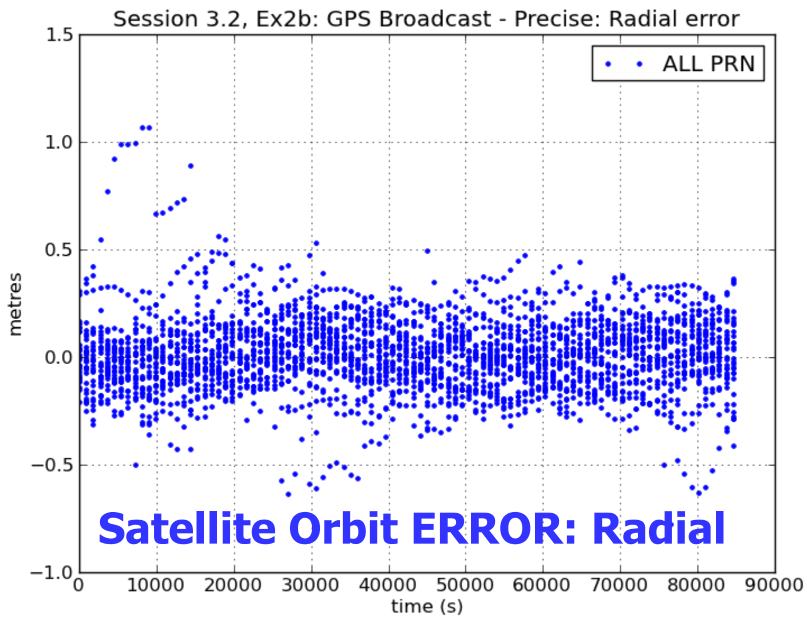
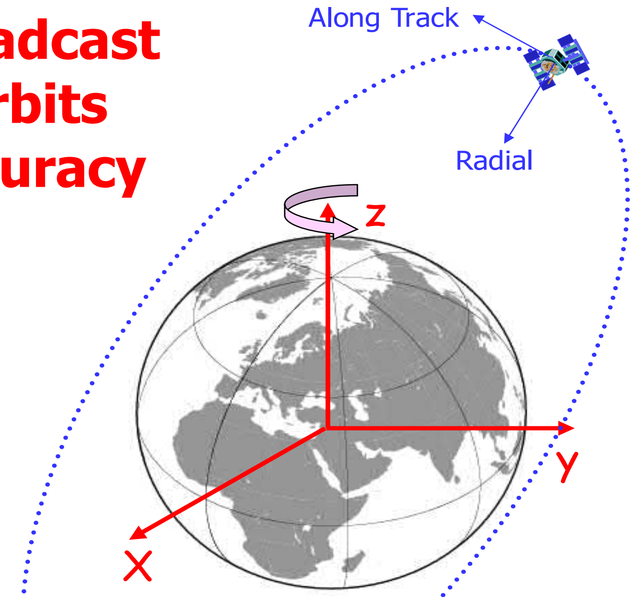
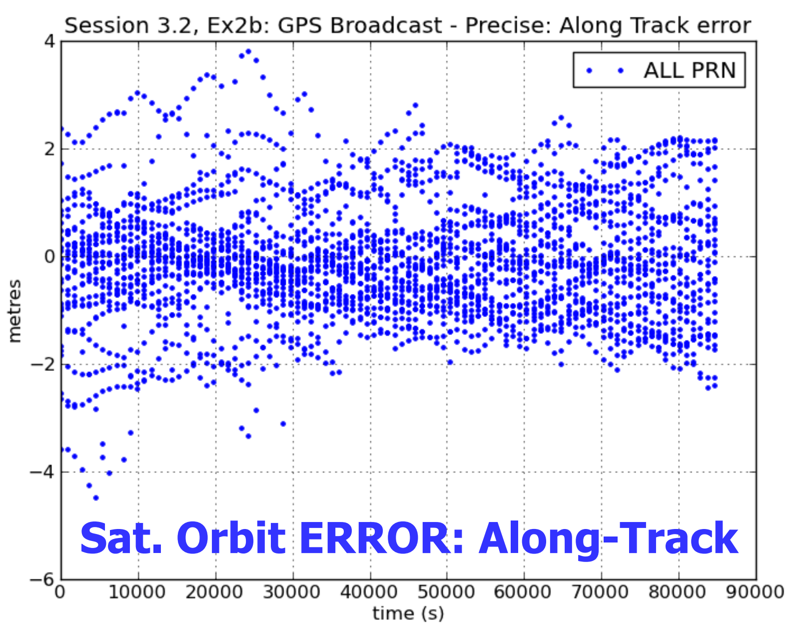
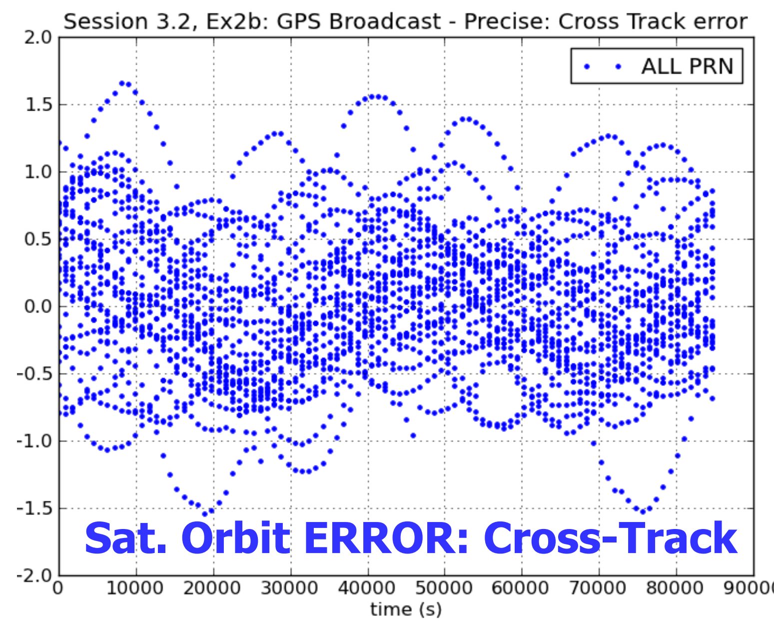
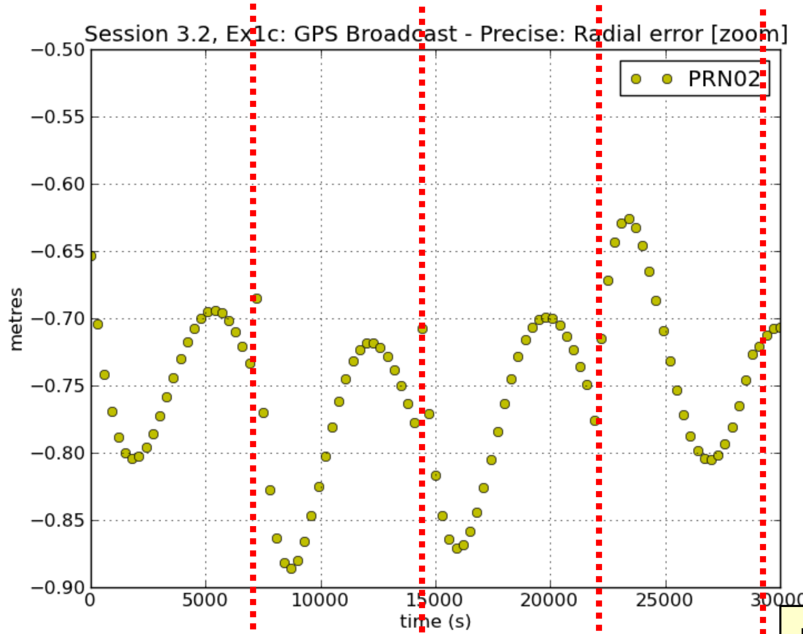
Broadcast Orbits Accuracy



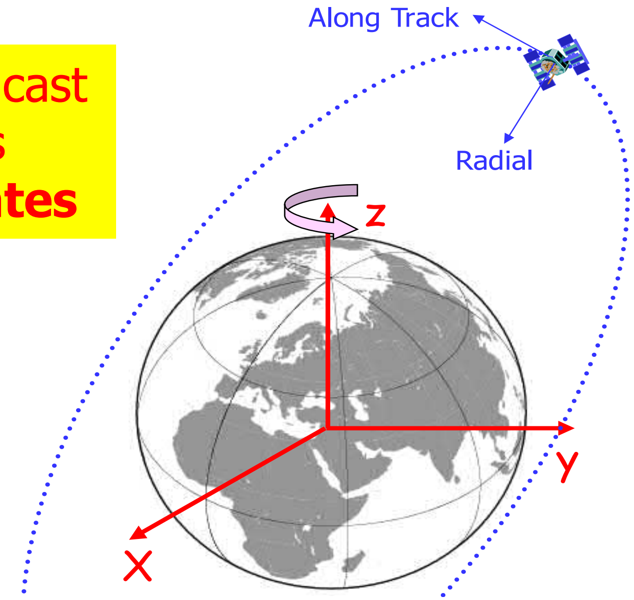




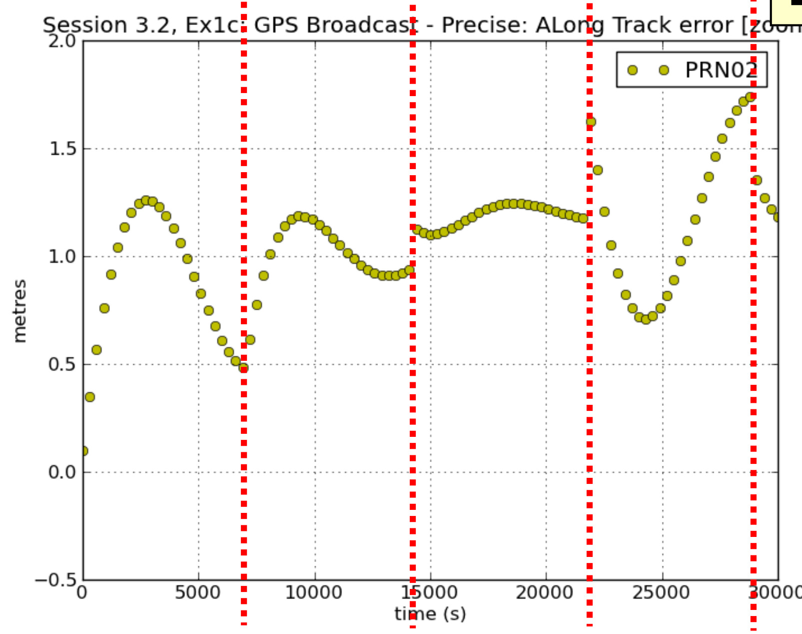


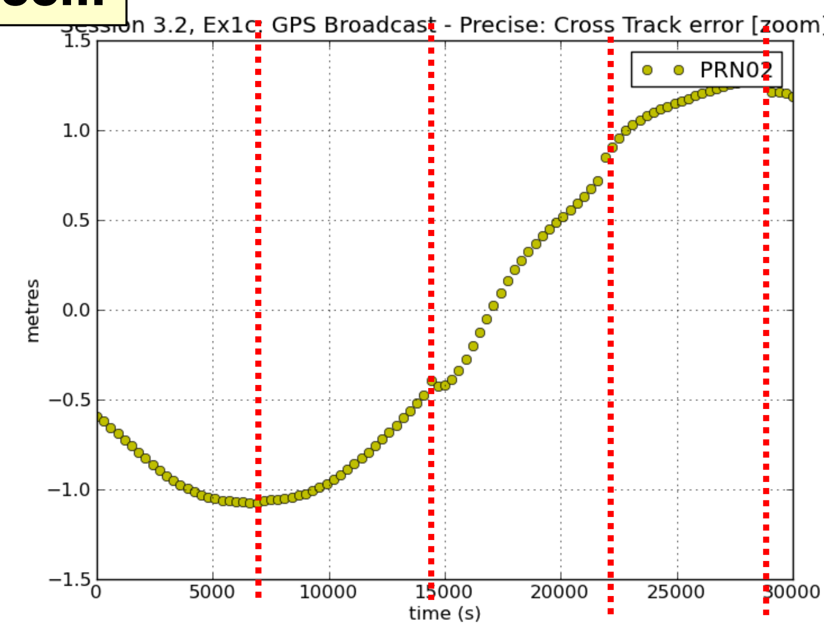


Broadcast Orbits Updates



Zoom





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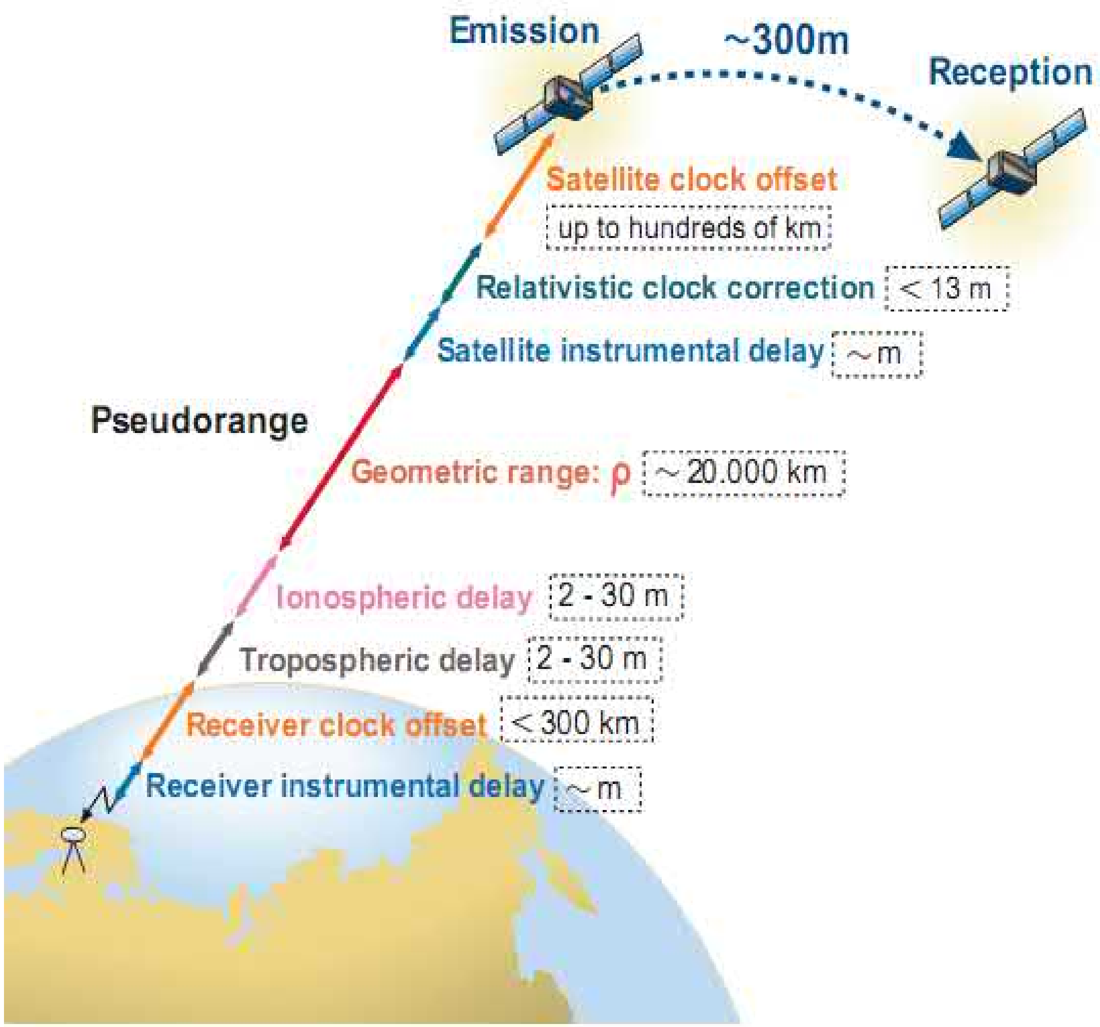
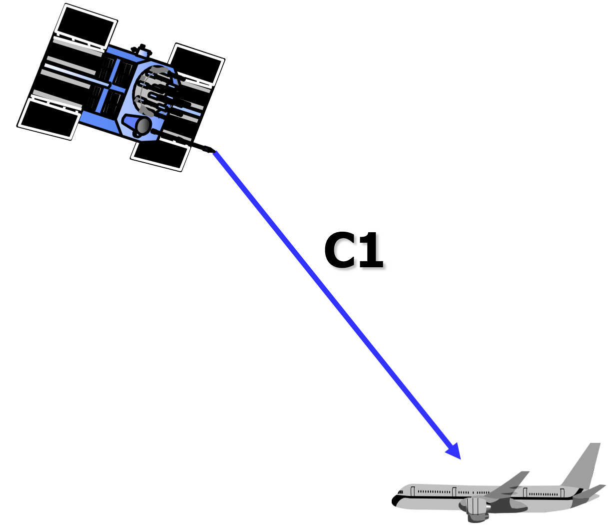
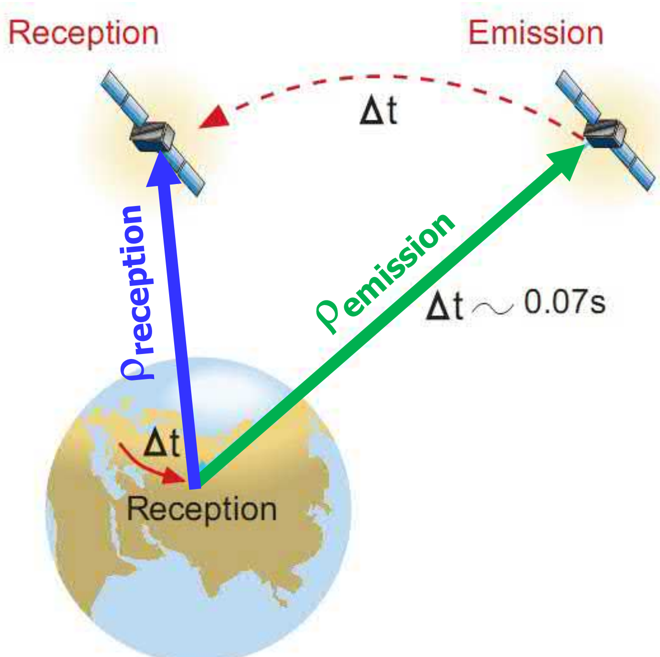
How to determine the satellite coordinates (at emisión time)?

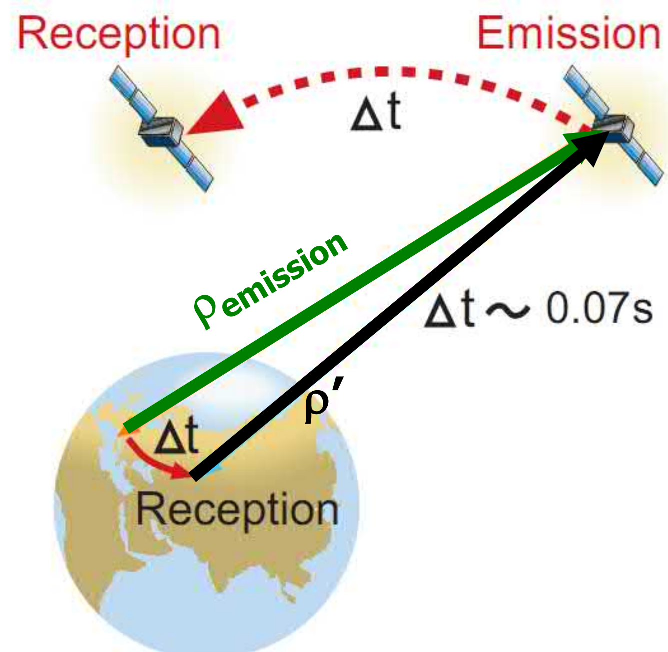


- The GPS signal travels from satellite coordinates at emission time (T_{emis}) to receiver coordinates at reception time (T_{recep}).

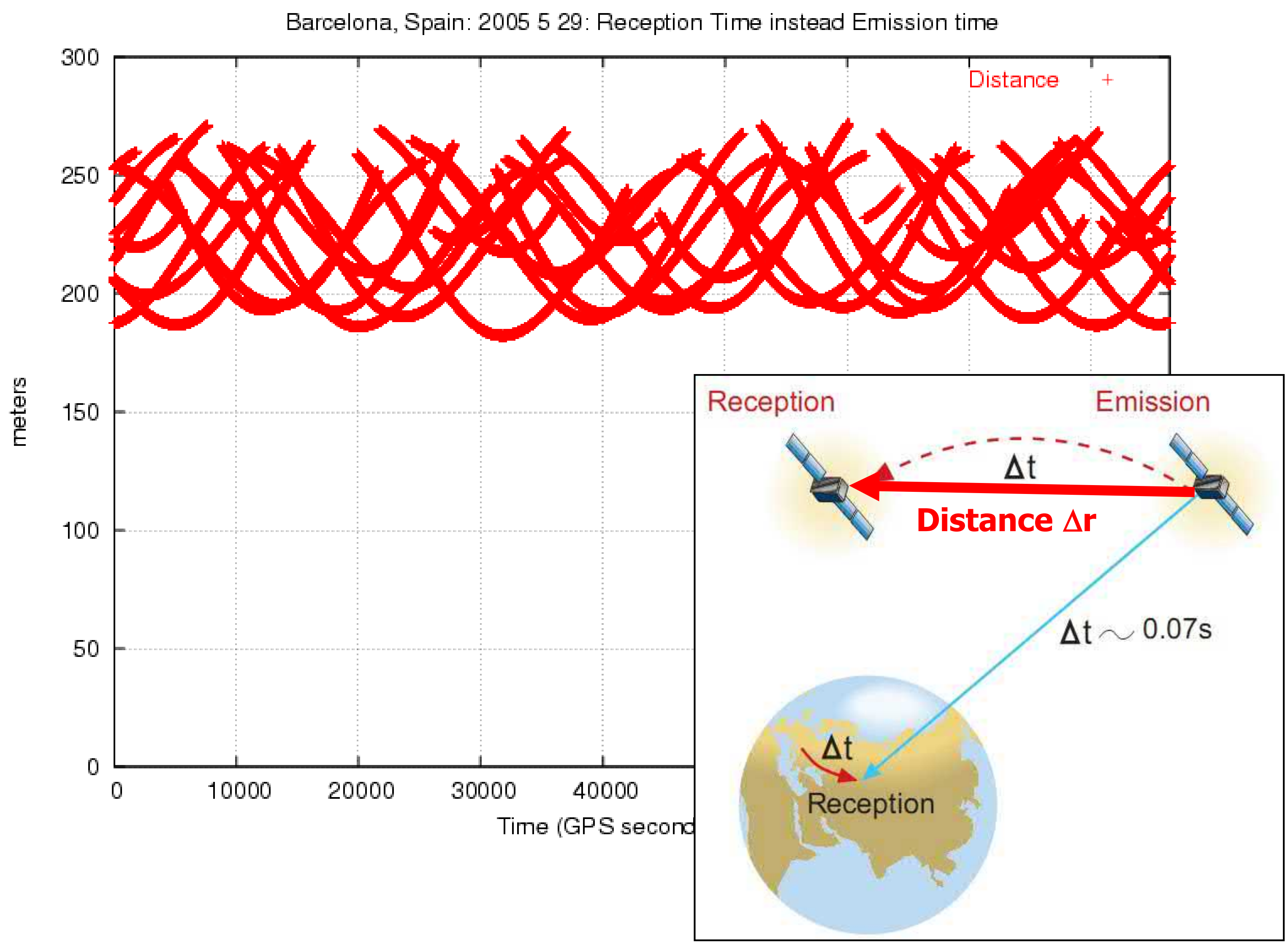
- The satellite can move several hundreds of meters from T_{emis} to T_{recep}.







Distance: Δr



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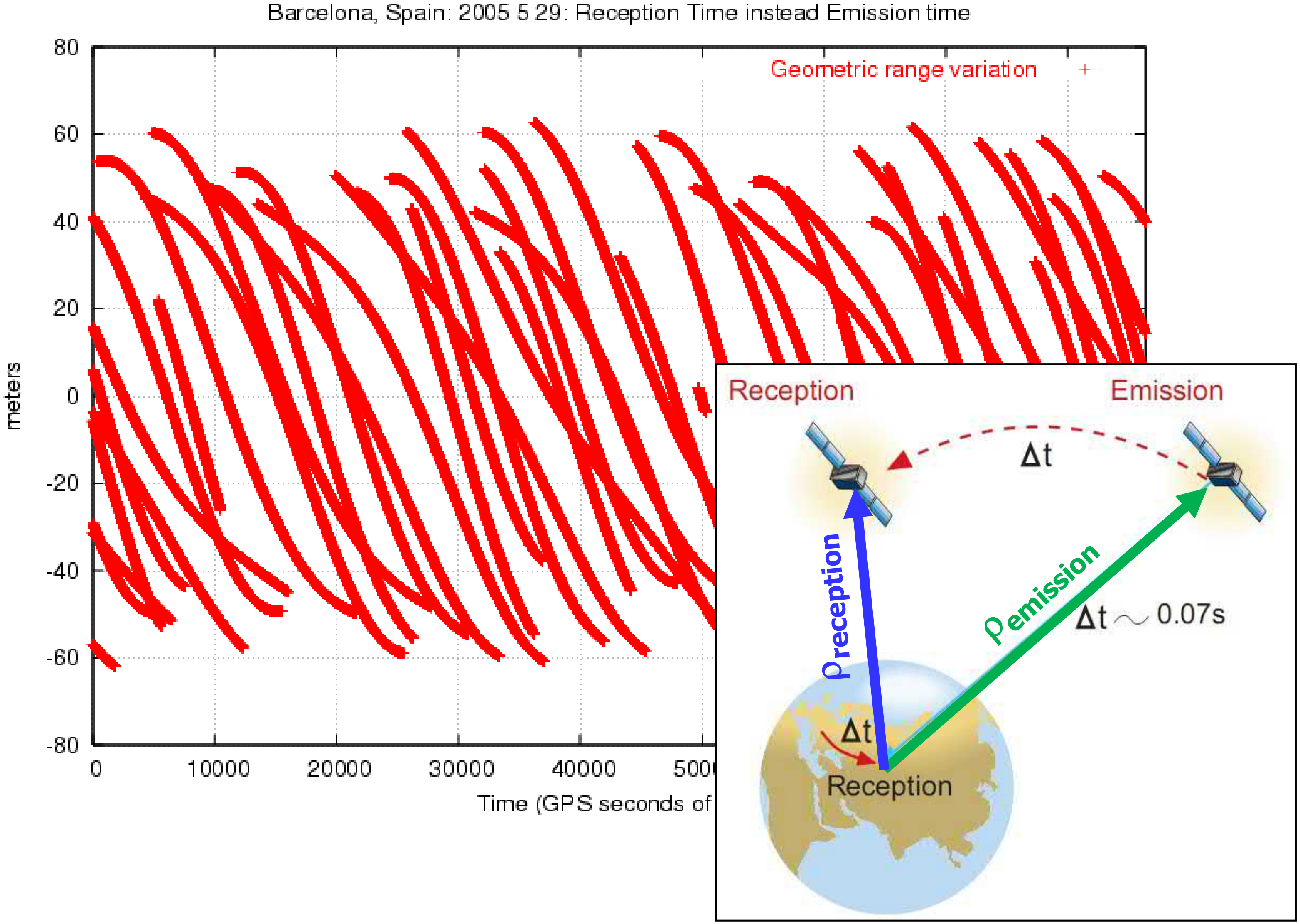
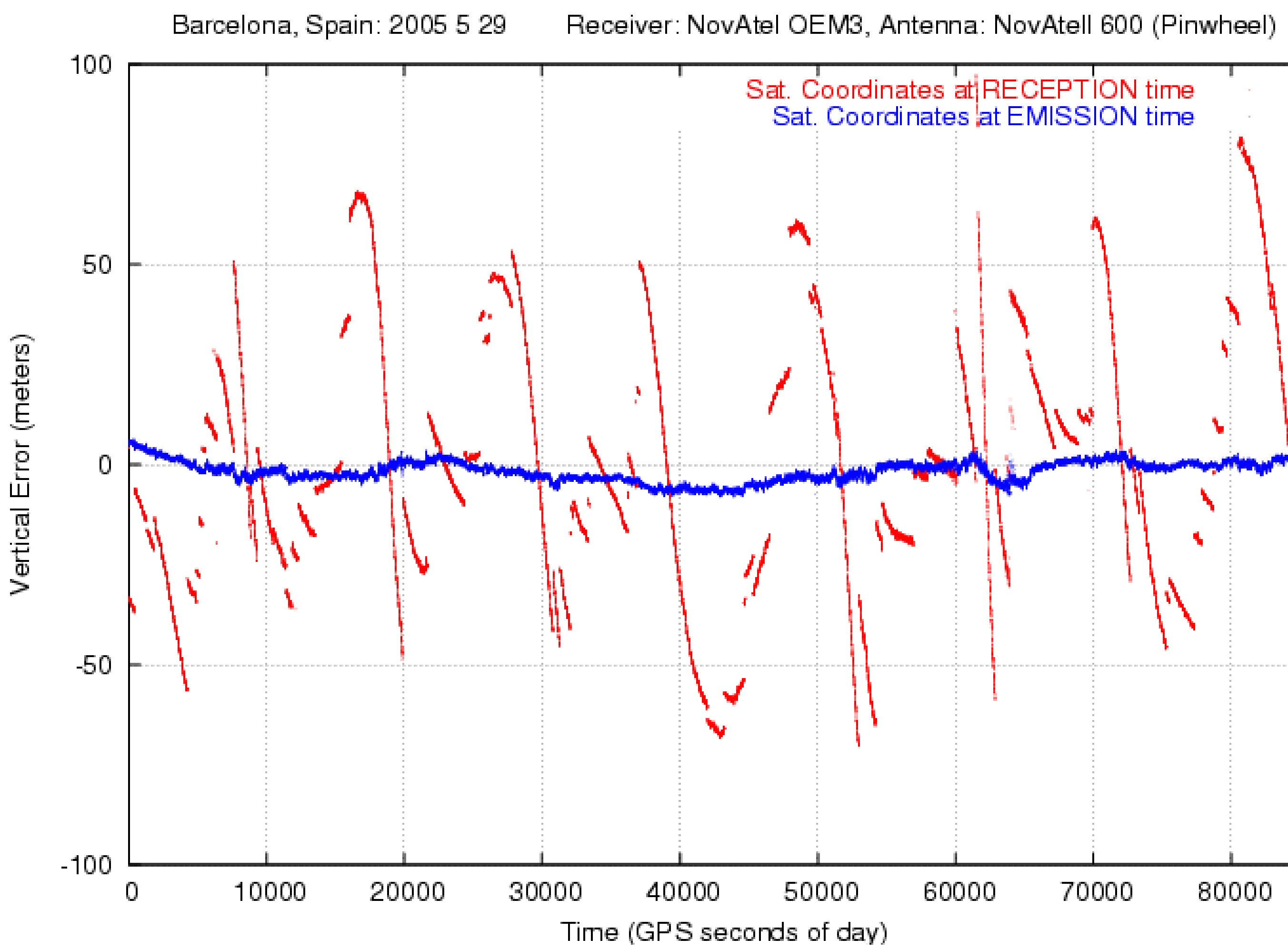
Variation in range: $\Delta\rho = \rho_{emission} - \rho_{reception}$



Vertical error comparison



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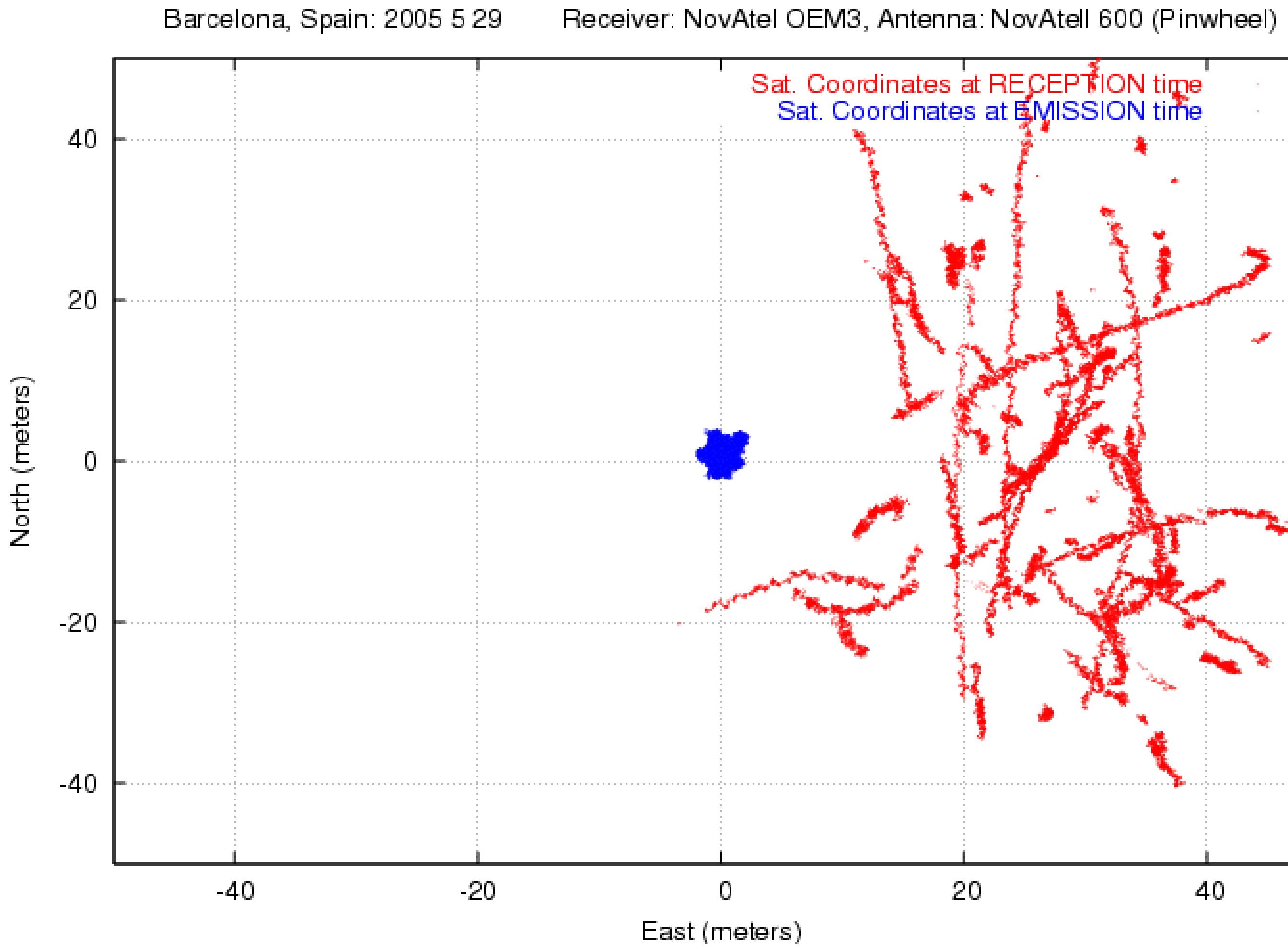
Horizontal error comparison



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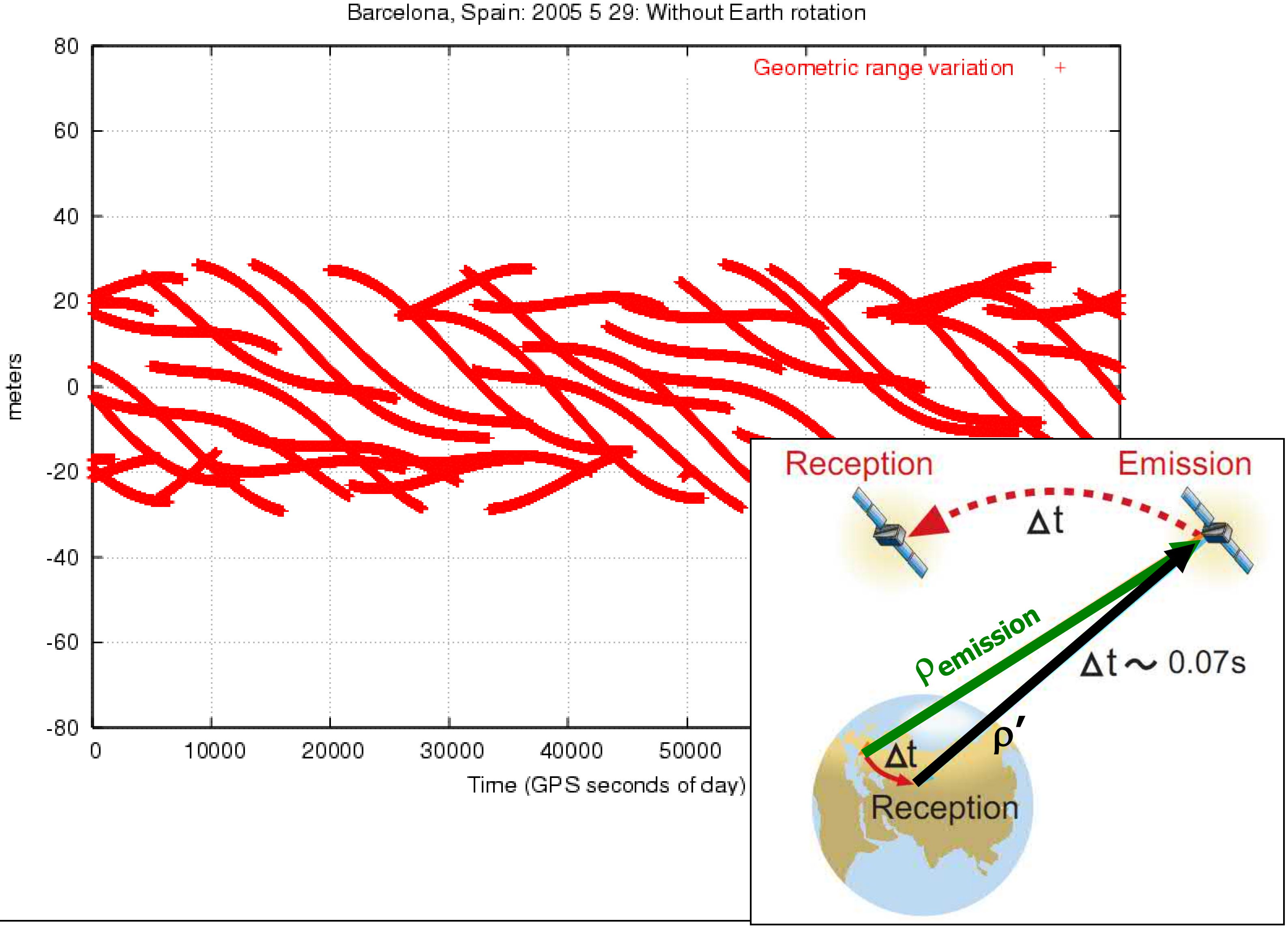
Variation in range: $\Delta\rho = \rho' - \rho_{emission}$



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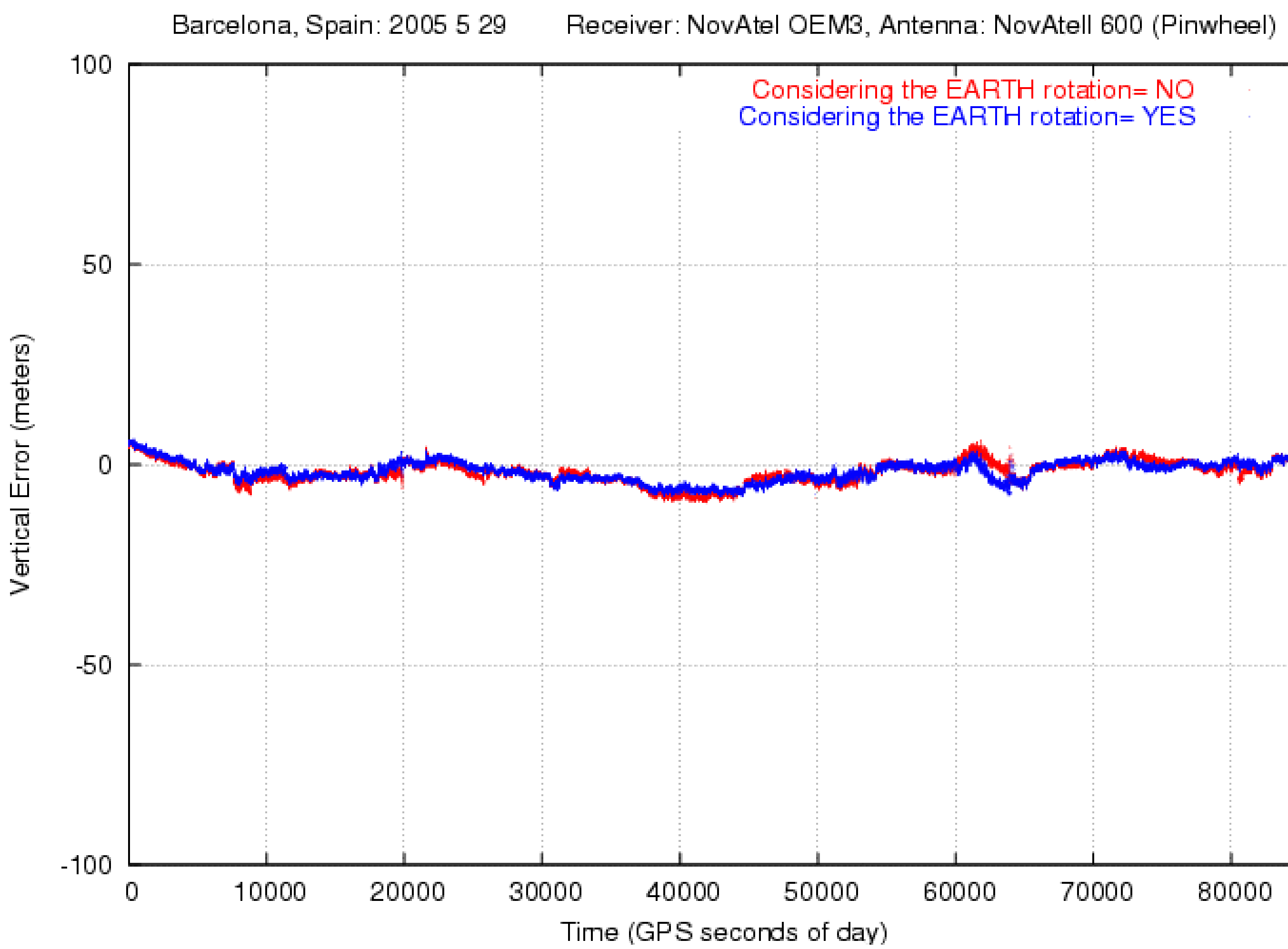
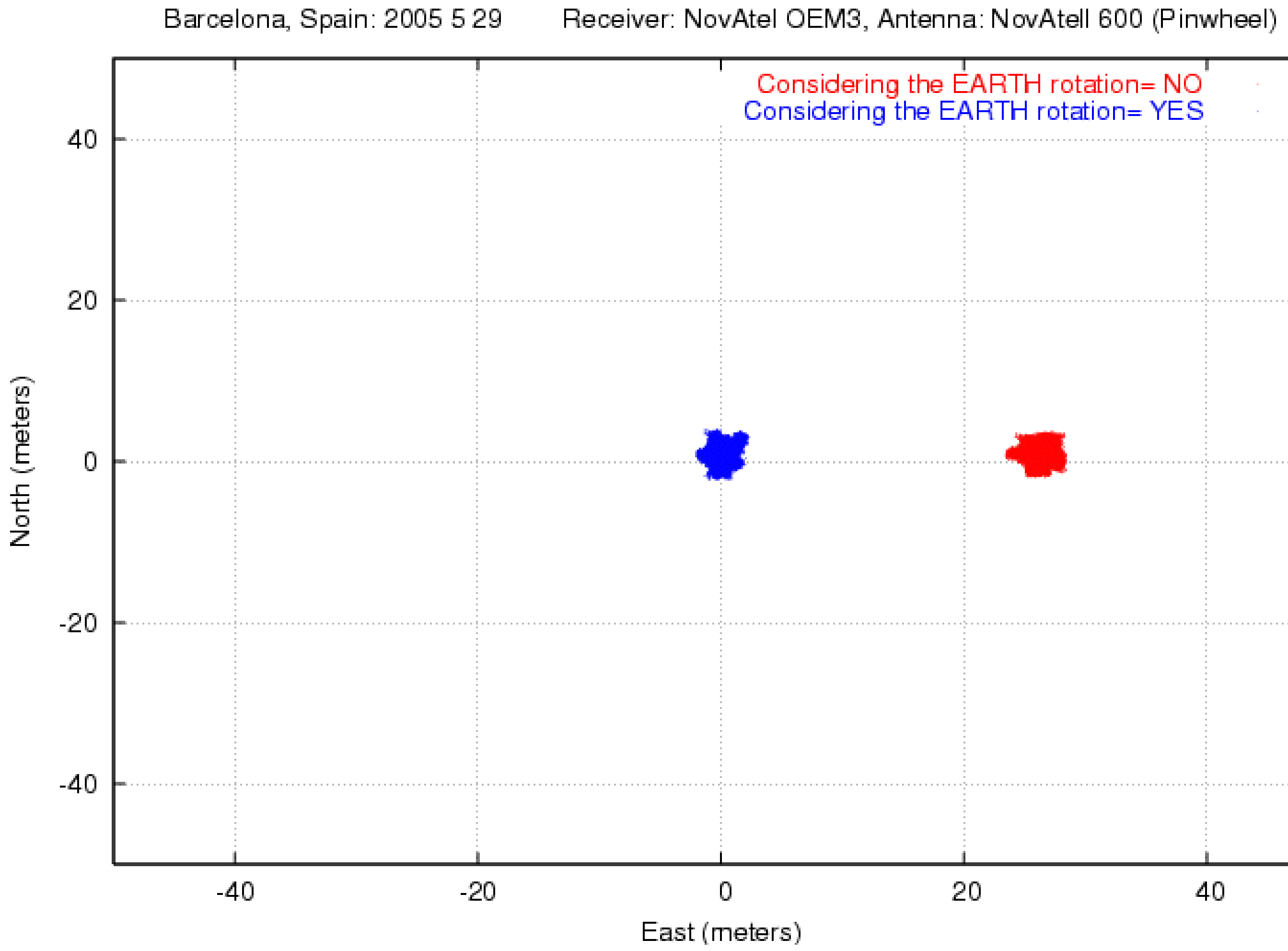
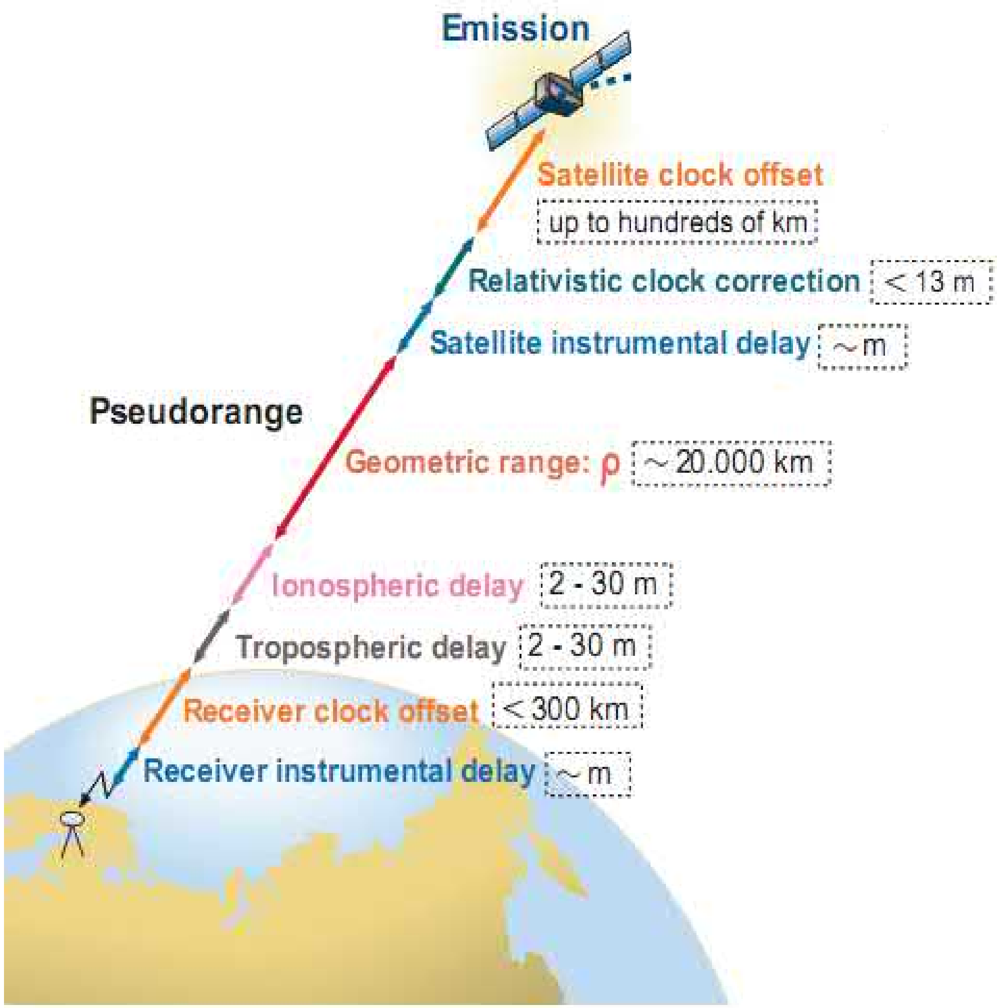
Vertical error comparison



Horizontal error comparison



RANGING ERRORS



Satellite and receiver clock offsets

- They are time-offsets between satellite/receiver time and GPS system time (provided by the ground control segment):

  - The receiver clock offset (dt_{rec}) is estimated together with receiver coordinates.

  - Satellite clock offset (dt^{sat}) may be computed from navigation message plus a Relativistic clock correction

$$dt^{sat} = a_0 + a_1(t - t_0) + a_2(t - t_0)^2 + \Delta rel^{sat}$$

$$C1_{rec}^{sat}[\text{modelled}] = \rho_{rec,0}^{sat} - c\left(\overline{dt}^{sat} + \Delta rel^{sat}\right) + Trop_{rec}^{sat} + Ion_{1rec}^{sat} + TGD^{sat}$$

$$dt^{sat}$$

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$$a_0 + a_1(t-t_0) + a_2(t-t_0)^2$$

PRN

t0 — YY MM DD H M S

a0

a1

a2

```
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    9.636381916043D-01 2.153437500000D+02 3.056960010495D+00-8.030691653399D-09
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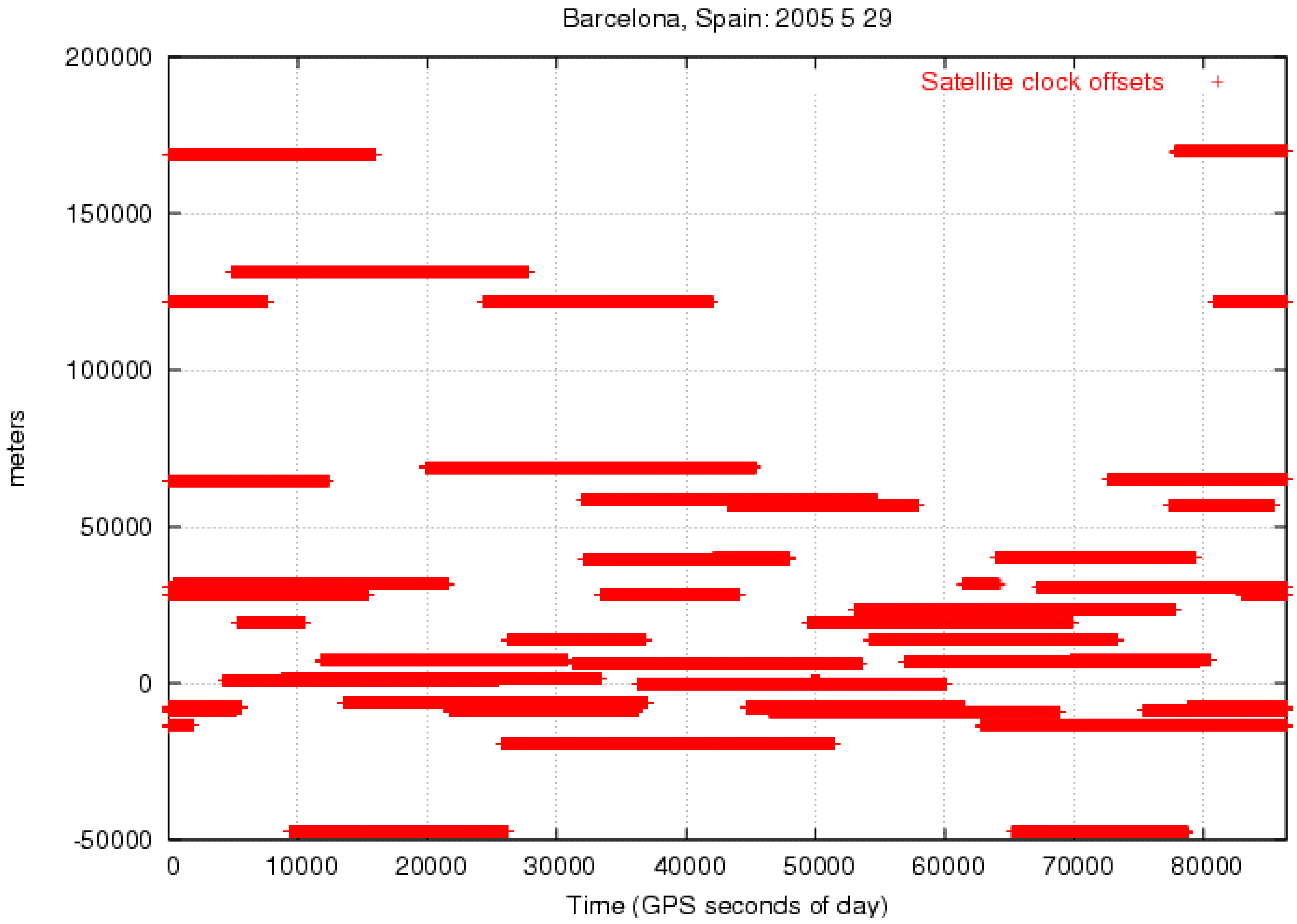
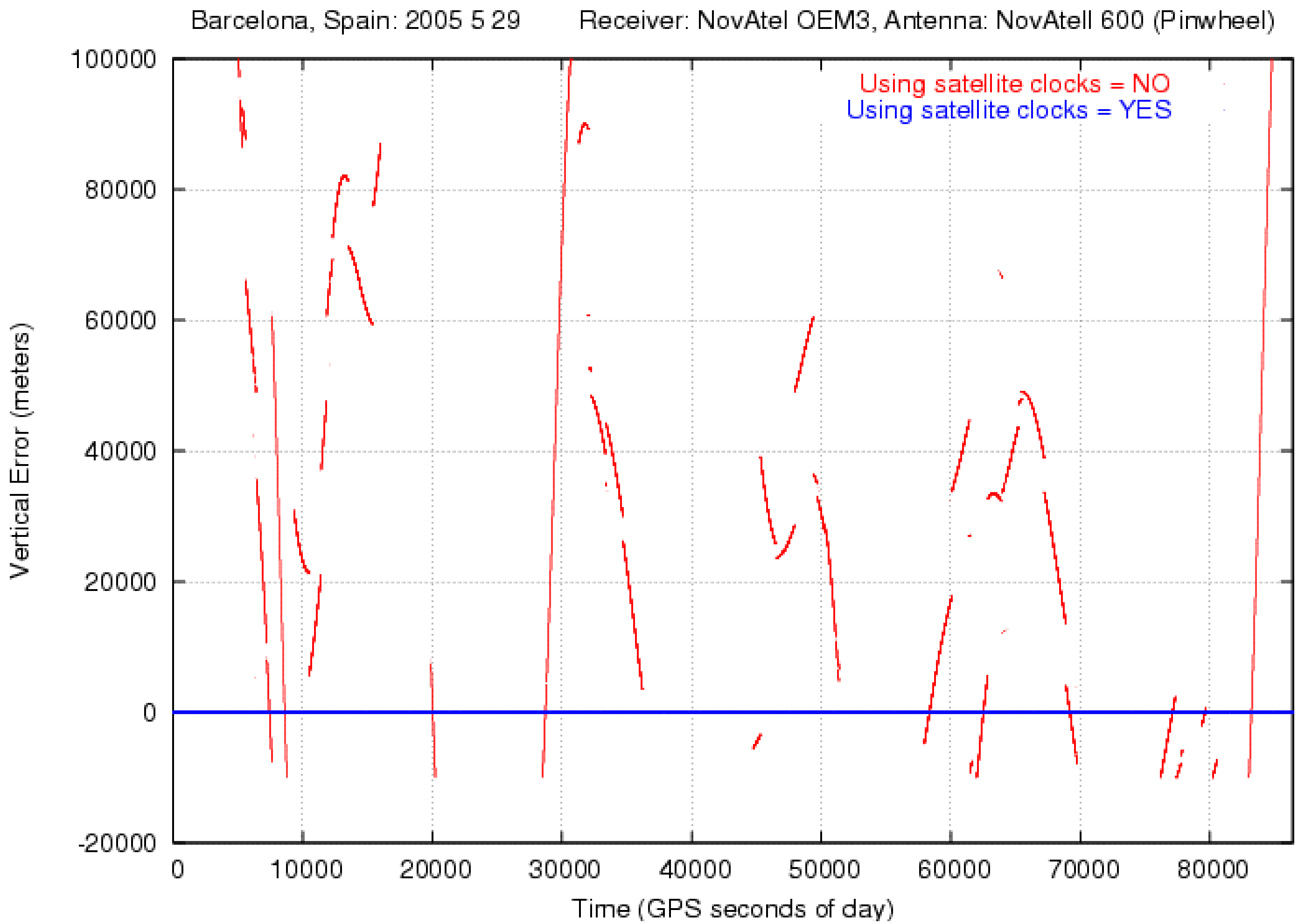
Broadcast Navigation message

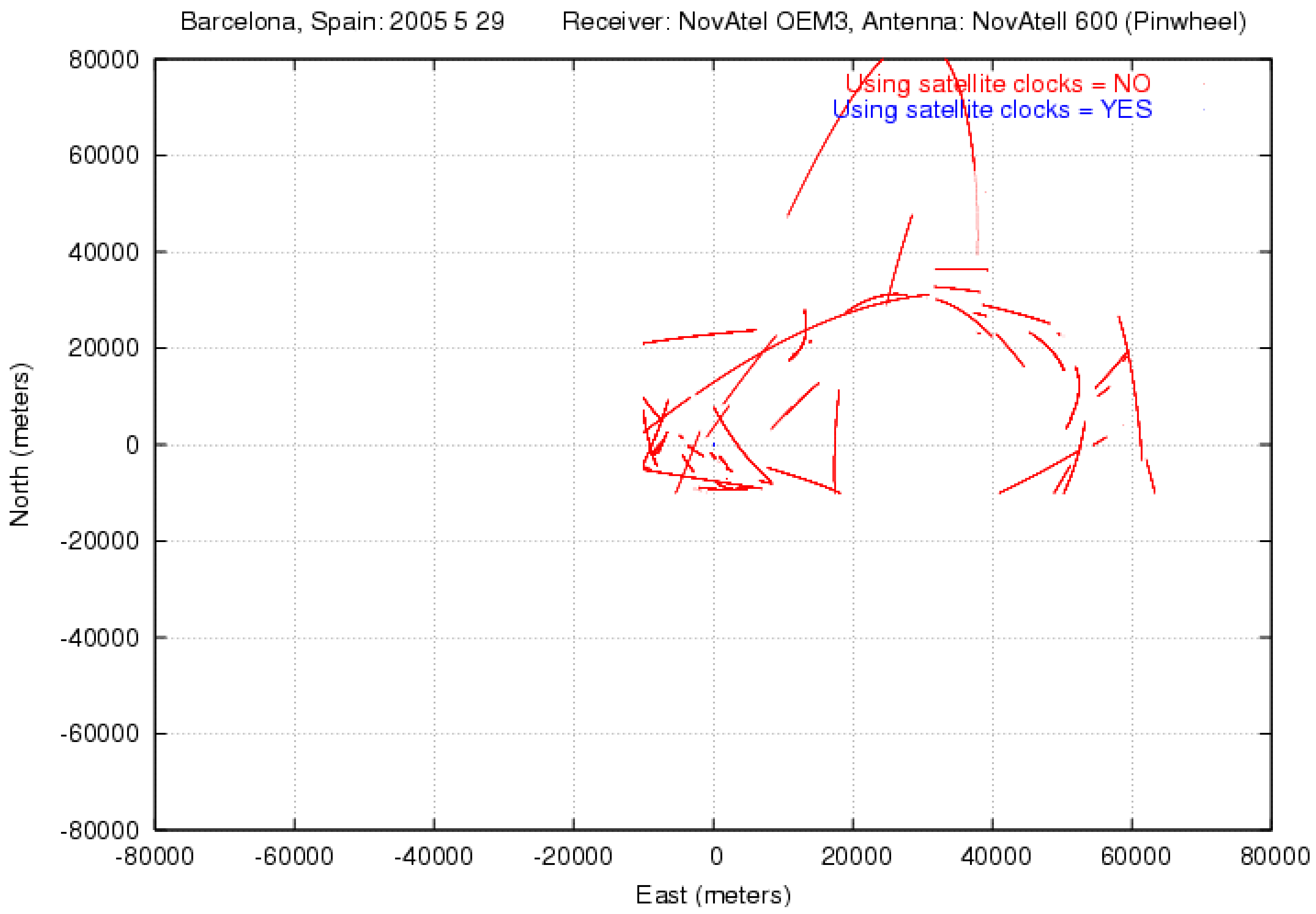
Range variation: satellite clocks



Vertical error comparison



Horizontal error comparison



Relativistic clock correction (Δ_{rel})

- A constant component depending only on nominal value of satellite's orbit major semi-axis, being corrected modifying satellite's clock oscillator frequency*:

$$\frac{f_0^{'} - f_0}{f_0} = \frac{1}{2}\left(\frac{v}{c}\right)^2 + \frac{\Delta U}{c^2} = -4.464 \cdot 10^{-10}$$

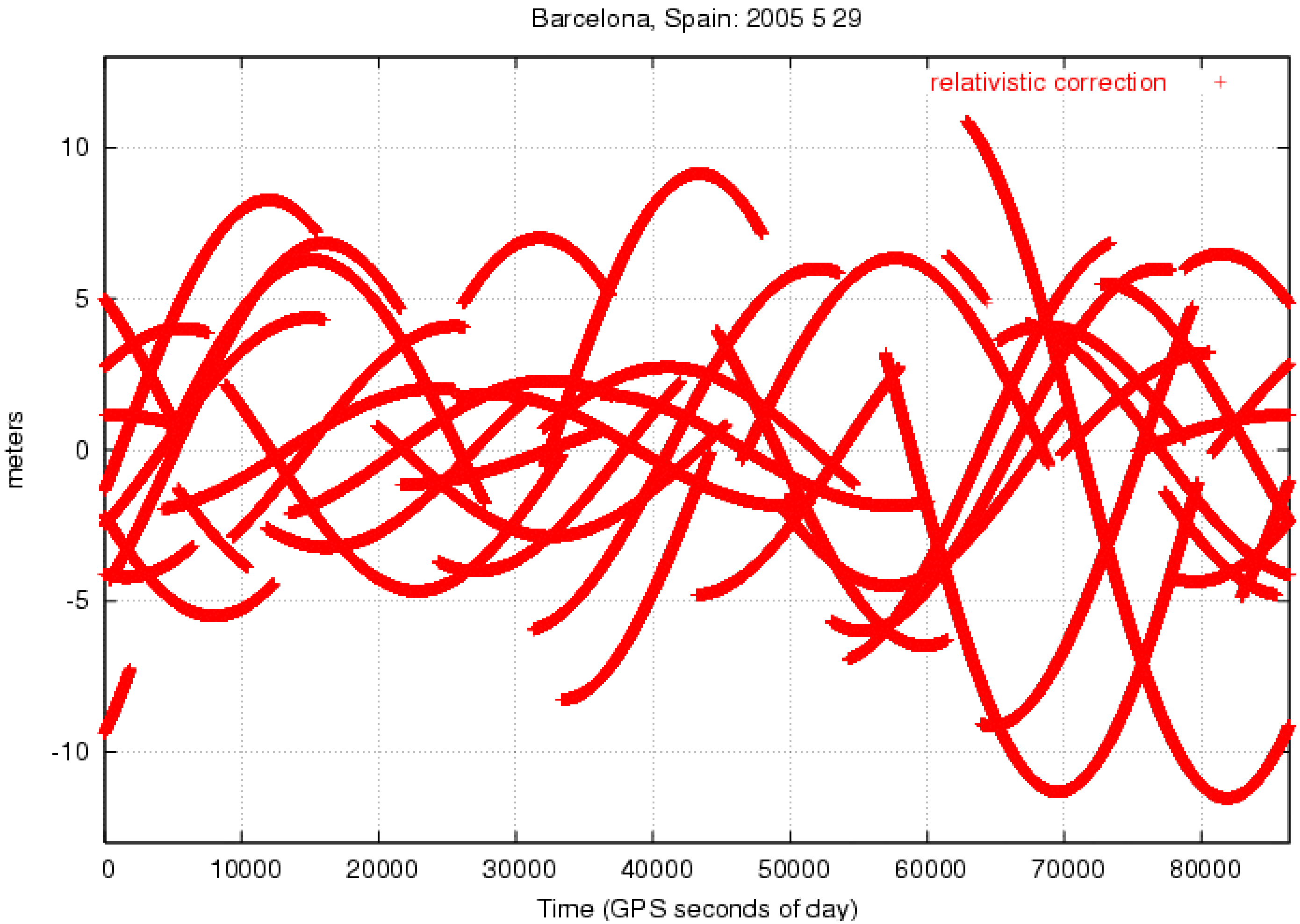
- A periodic component due to orbit eccentricity (to be corrected by user receiver):

$$\Delta_{rel} = -2\frac{\sqrt{\mu a}}{c^2} e \sin(E) = -2\frac{\mathbf{r} \cdot \mathbf{v}}{c^2} (seconds)$$

Being μ=3.986005 10^{14} (m^3/s^2) universal gravity constant, *c* =299792458 *(m/s)* light speed in vacuum, *a* is orbit's major semi-axis, *e* is its eccentricity, *E* is satellite's eccentric anomaly, and *r* and *v* are satellite's geocentric position and speed in an inertial system.

*being f_0 = 10.23 MHz, we have $\Delta f = 4.464\ 10^{-10}\ f_0 = 4.57\ 10^{-3}$ *Hz* so satellite should use *f'o=10.22999999543 MHz*.

Range variation: relativistic correction



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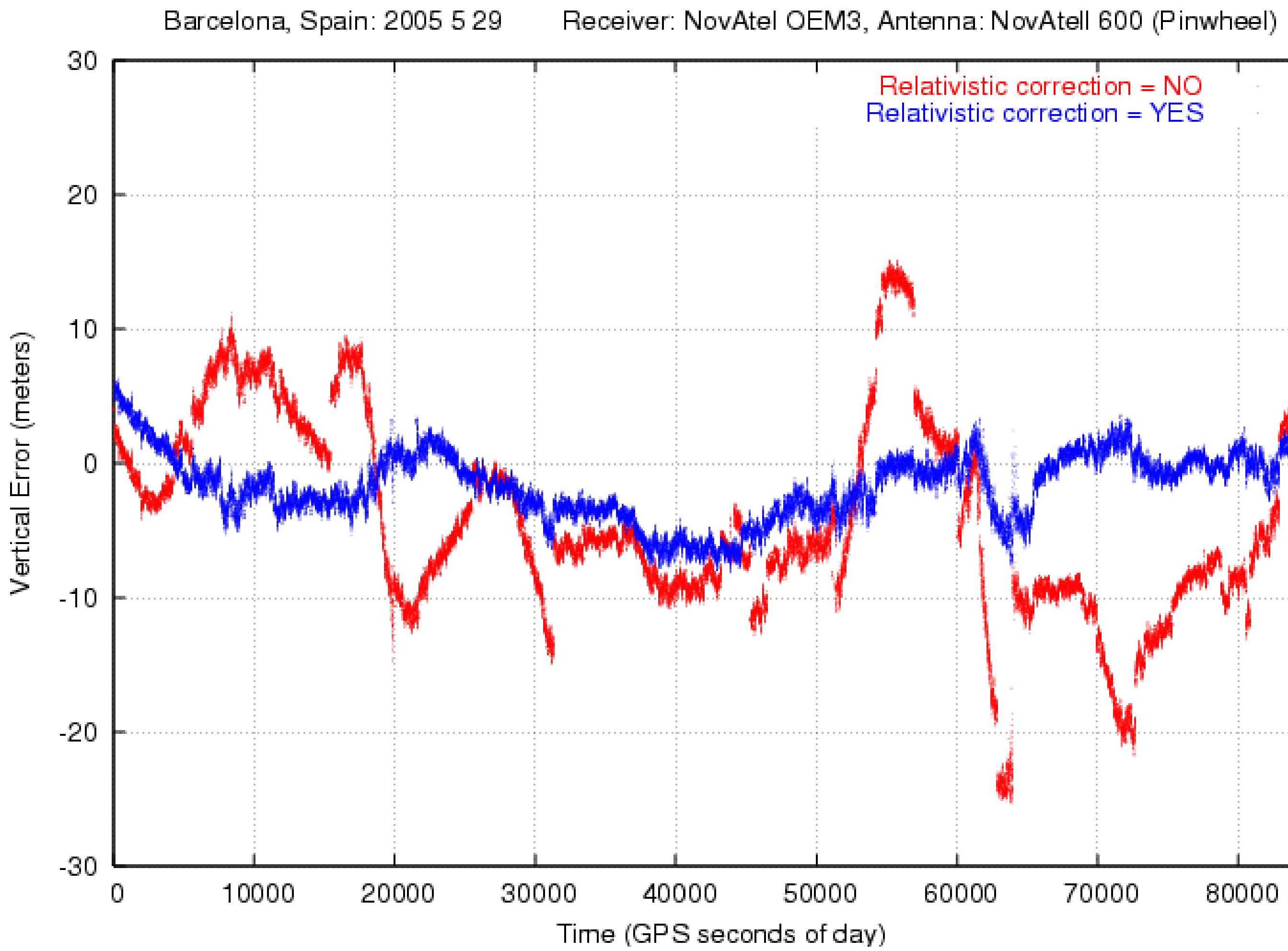
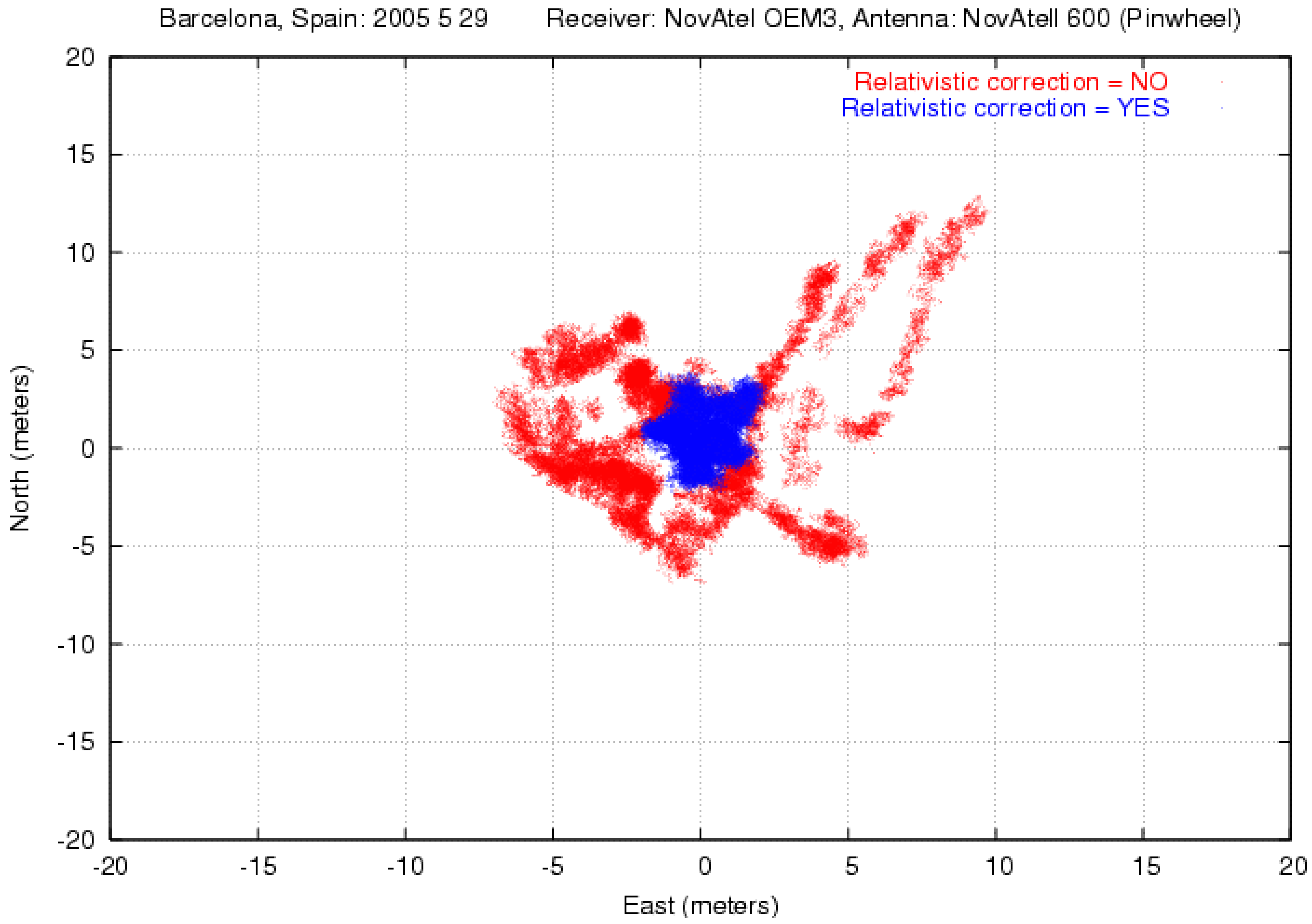
Vertical error comparison



Horizontal error comparison



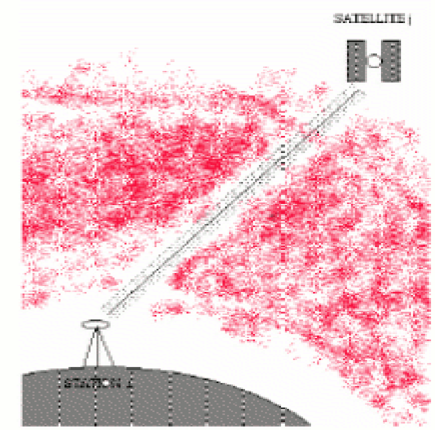
Ionospheric Delay

The ionosphere extends from about 60 km in height until more than 2000 km, with a sharp electron density maximum at around 350 km.

The ionosphere delays code and advances carrier by the same amount.

The ionospheric delay depends on signal frequency as given by:

$$Ion_{1\,rec}^{\,sat} = \frac{40.3}{f_1^2} I$$



Where I is number of electrons per area unit in the direction of observation, or STEC (*Slant Total Electron Content*)

$$I = \int_{rec}^{sat} N_e \, ds$$

- For two-frequency receivers, it may be cancelled (99.9%) using ionosphere-free combination

$$LC = \frac{f_1^2 L1 - f_2^2 L2}{f_1^2 - f_2^2}$$

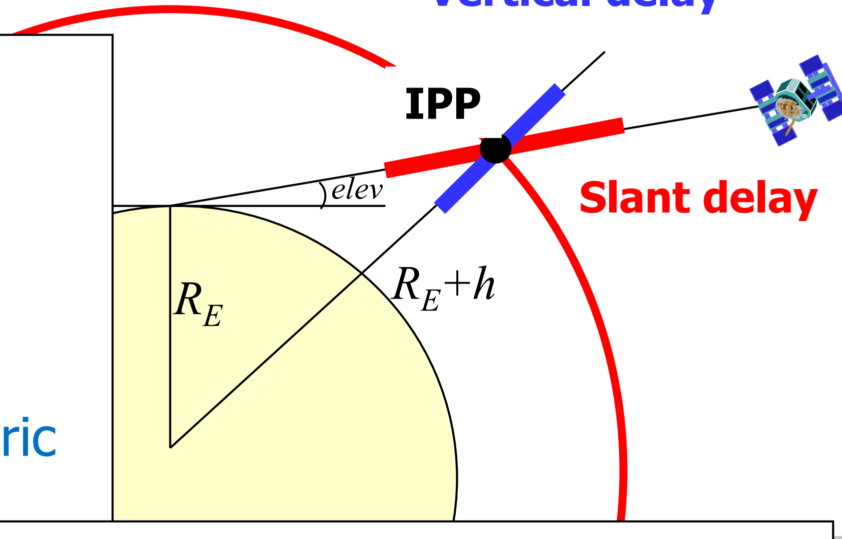
- For one-frequency receivers, it may be corrected (about 60%) using Klobuchar model (defined in GPS/SPS-SS), whose parameters are sent in navigation message. (See program klob.f)

$$C1_{rec}^{sat}[\text{modelled}] = \rho_{0,rec}^{sat} - c\left(d\bar{t}^{\,sat} + \Delta rel^{sat}\right) + Trop_{rec}^{sat} + Ion_{1rec}^{sat} + TGD^{sat}$$

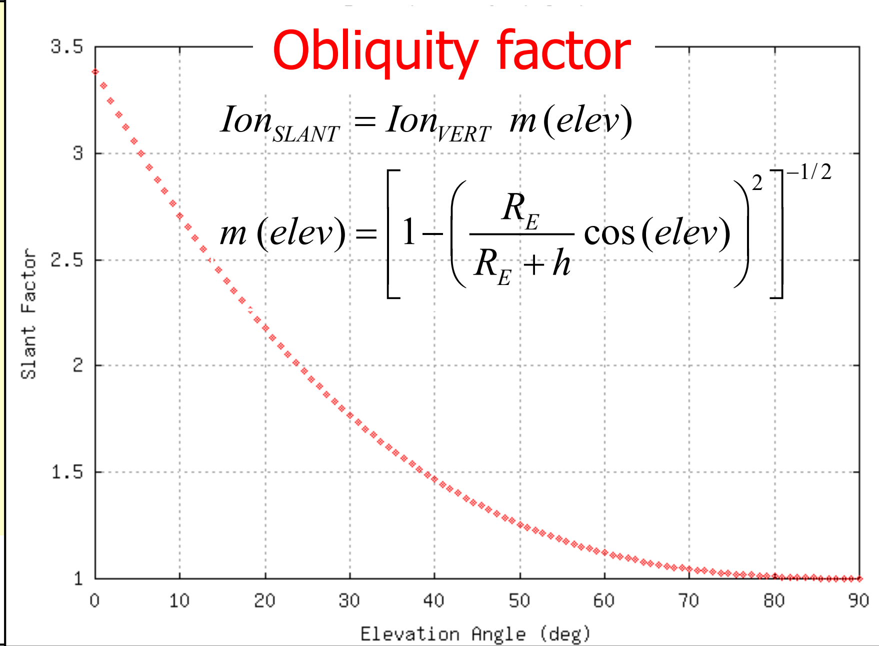
Klobuchar model (klob.f)

It was designed to minimize user computational complexity.

- Minimum user computer storage
- Minimum number of coefficients transmitted on satellite-user link
- At least 50% overall RMS ionospheric error reduction worldwide.



- It is assumed that the electron content is concentrated in a thin layer at 350km in height.
- The slant delay is computed from the vertical delay at the Ionospheric Pierce Point (IPP), multiplying by the obliquity factor.



$$Ion_{SLANT} = Ion_{VERT}\; m(elev)$$

$$m(elev) = \left[1 - \left(\frac{R_E}{R_E + h}\cos(elev)\right)^2\right]^{-1/2}$$

$(time, r_{sta}, r^{sat}, \alpha 0, \alpha 1, \alpha 2, \alpha 3, \beta 0, \beta 1, \beta 2, \beta 3) \rightarrow [Klob] \rightarrow Iono$

elev, ϕ

```
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   -0.2842D+05 -0.2150D+05 -0.1096D+06  0.4301D+06          ION BETA
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                                                            END OF HEADER
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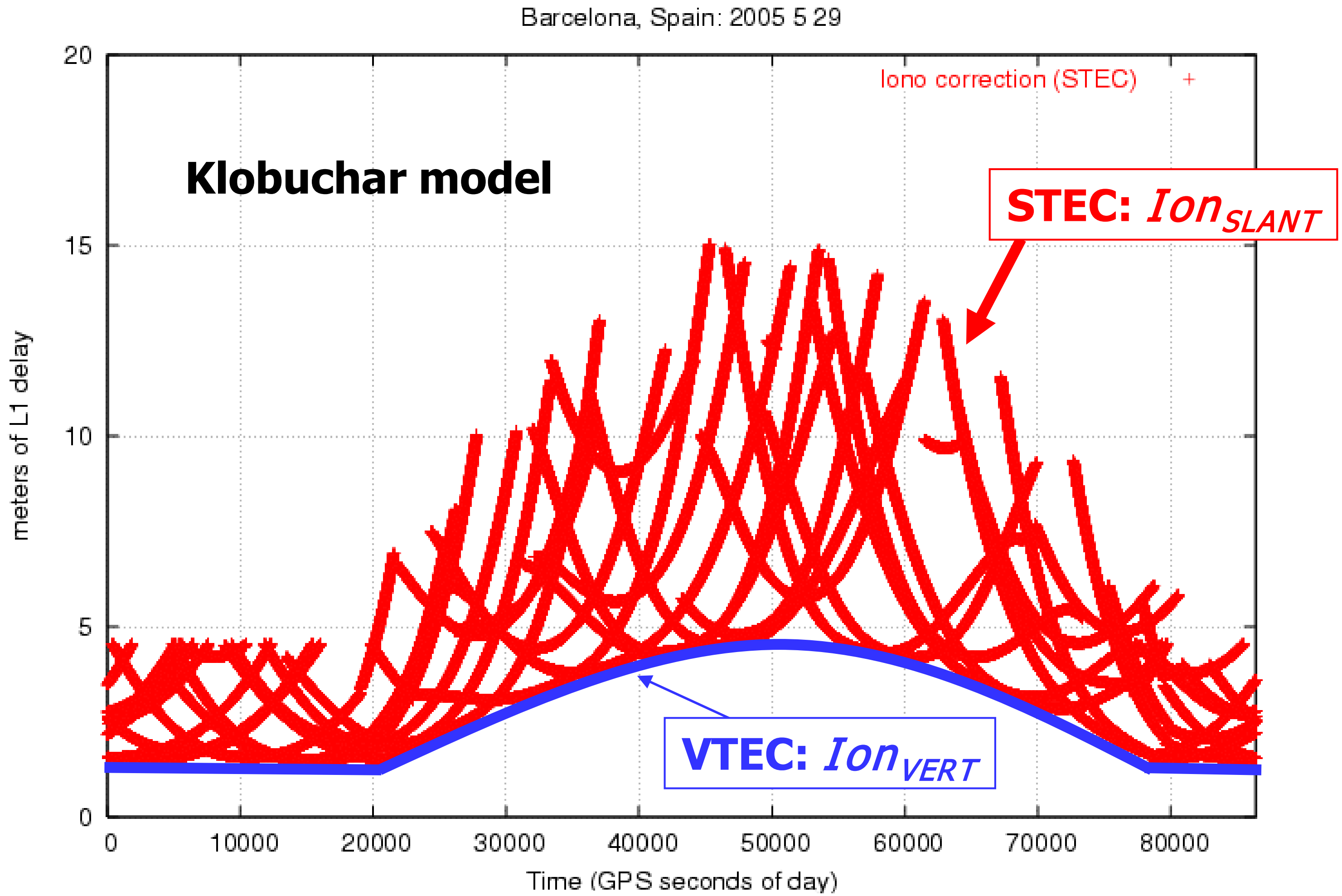
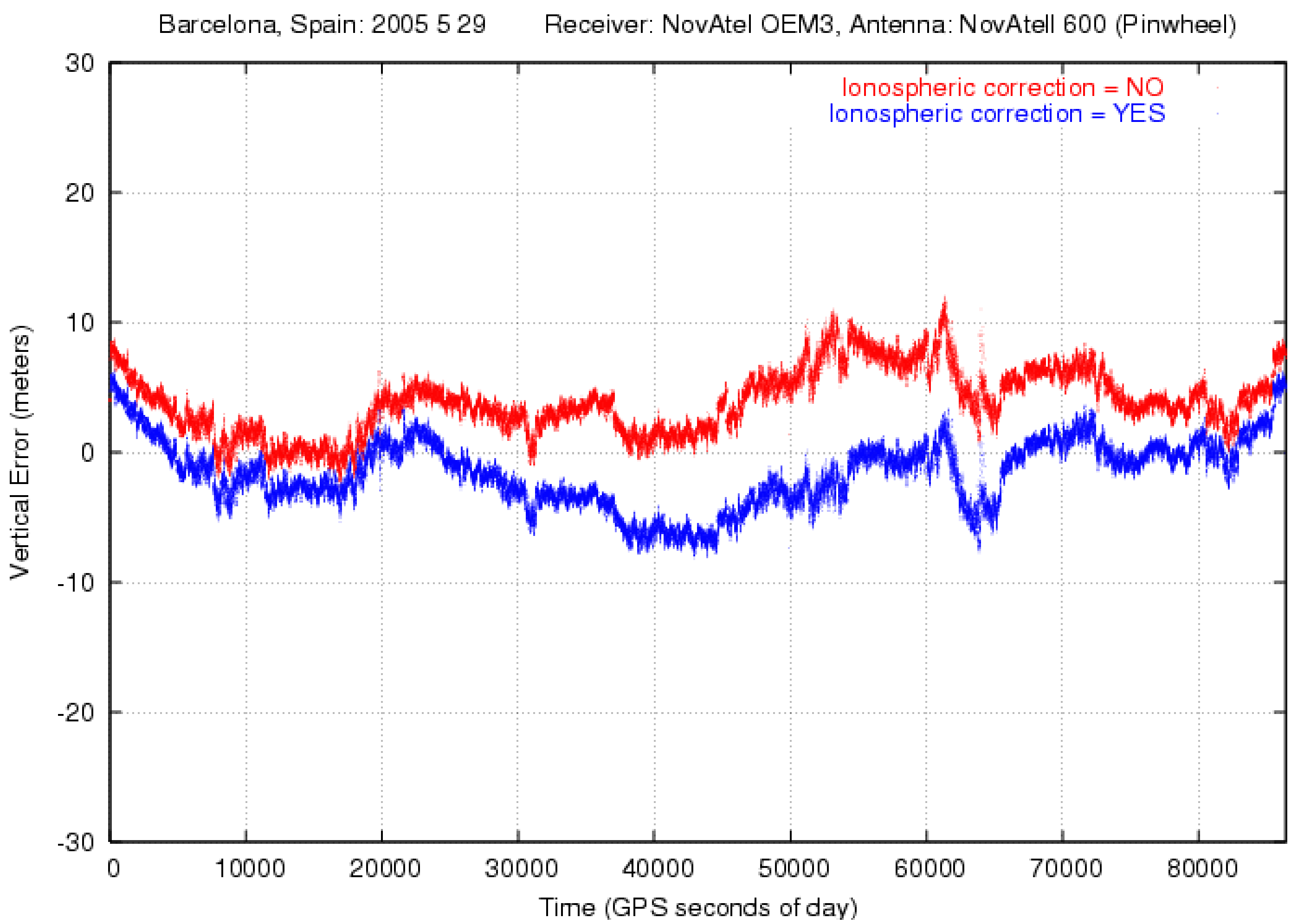
Range variation: Ionospheric correction



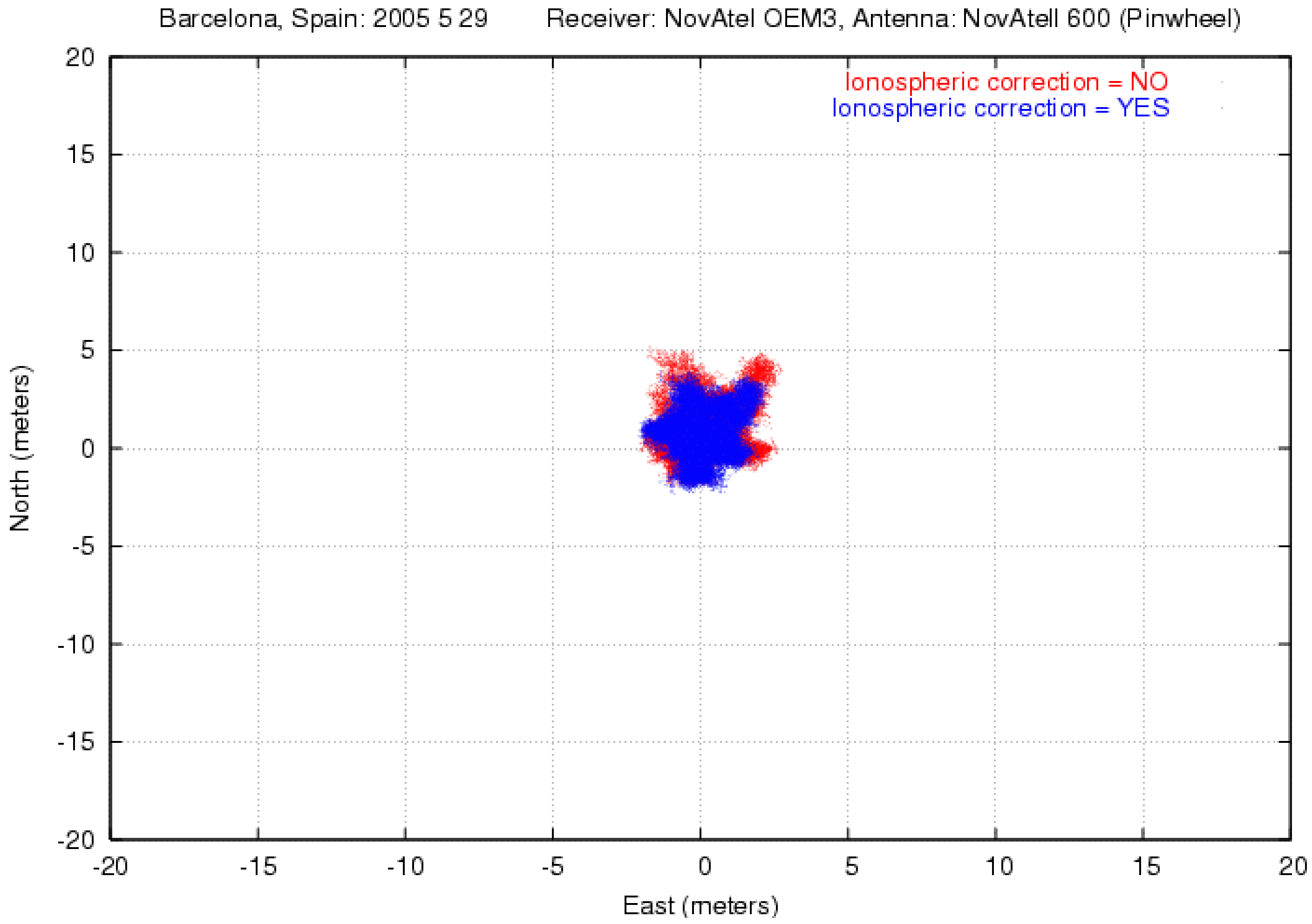
$$Ion_{SLANT} = Ion_{VERT}\ m(elev)$$

$$m(elev) = \left[1 - \left(\frac{R_E}{R_E + h}\cos(elev)\right)^2\right]^{-1/2}$$

Vertical error comparison



Horizontal error comparison



Ionospheric models used by the GNSSs

GPS	Klobuchar model
GLONASS	No ionospheric model is broadcasted
BeiDou	Klobuchar model (with layer height at 375km instead of 350km)
Galileo	NeQuick model

Tropospheric Delay

Troposphere is the atmospheric layer placed between Earth's surface and an altitude of about 60km.

The tropospheric delay does not depend on frequency and affects both the code and carrier phases in the same way. It can be modeled (about 90%) as:

- d_{dry} corresponds to the vertical delay of the dry atmosphere (basically oxygen and nitrogen in hydrostatical equilibrium)
  ➔ It can be modeled as an ideal gas.
- d_{wet} corresponds to the vertical delay of the wet component (water vapor) ➔ difficult to model.

A simple model is:

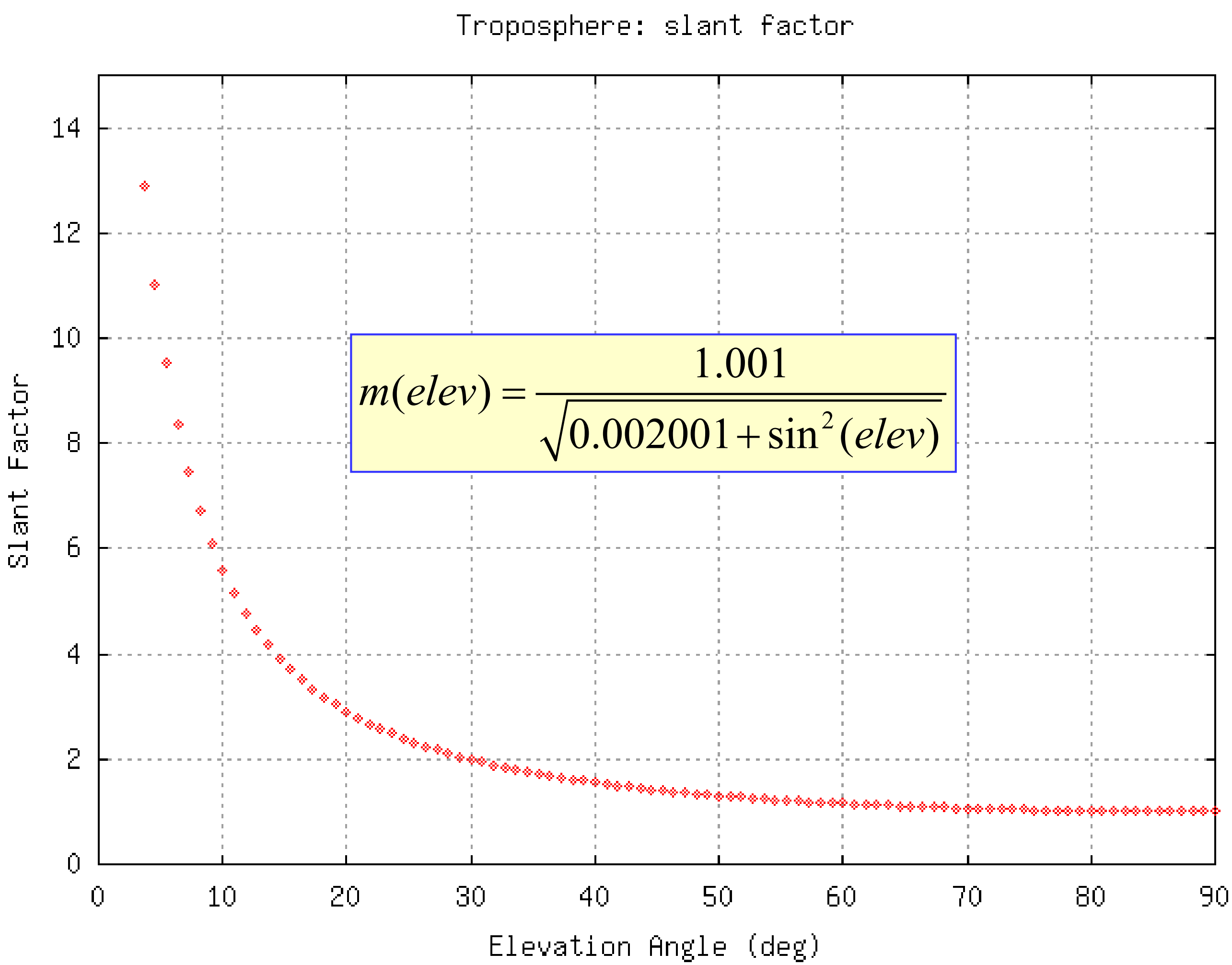
$$Trop_{rec}^{sat} = (d_{dry} + d_{wet}) \cdot m(elev)$$

$$d_{dry} = 2.3 \exp(-0.116 \cdot 10^{-3} H) \;\; meters$$

$$d_{wet} = 0.1 m \quad [H : height\ over\ the\ sea\ level]$$

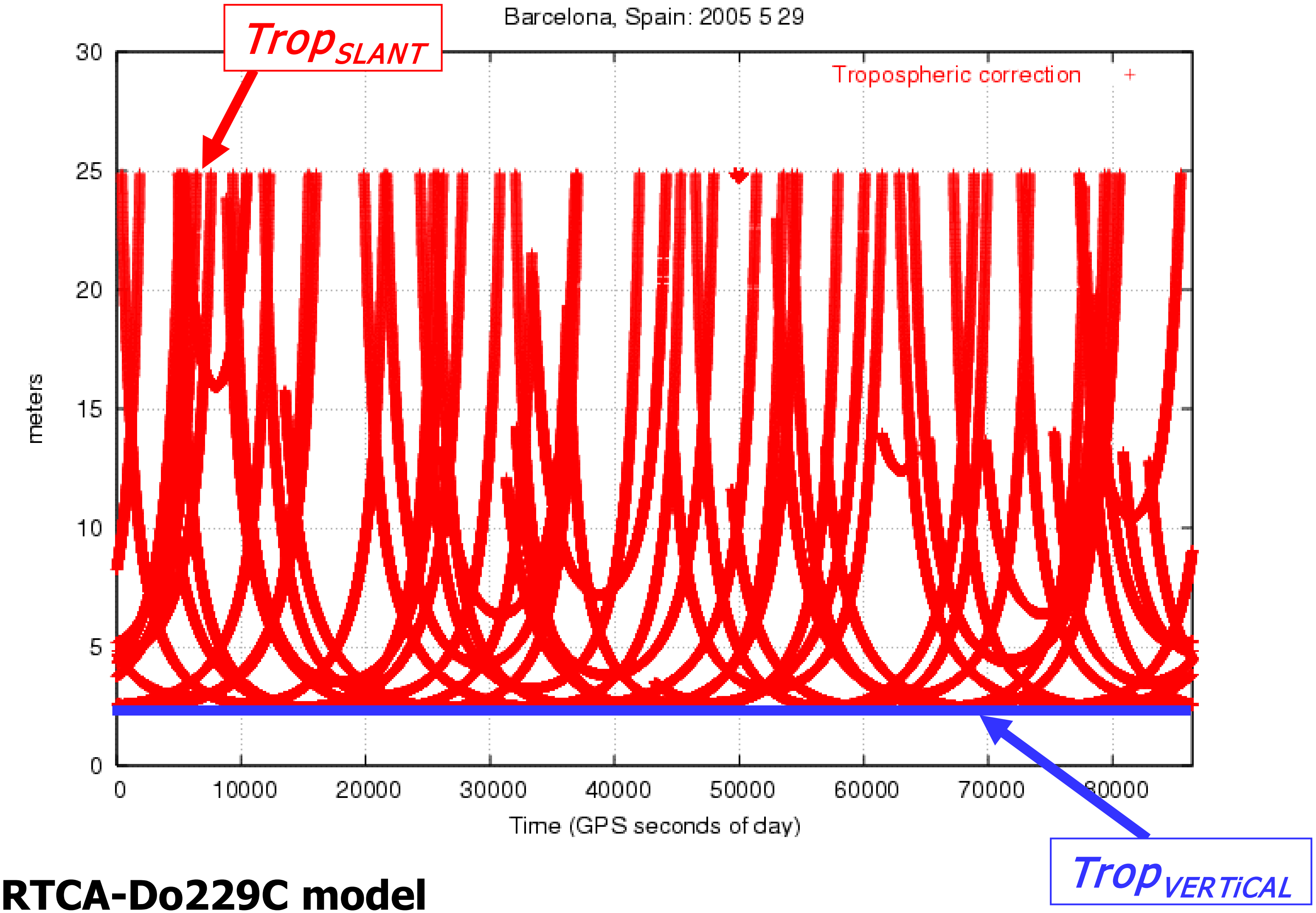
$$m(elev) = \frac{1.001}{\sqrt{0.002001 + \sin^2(elev)}}$$

$$C1_{rec}^{sat}[\text{modelled}] = \rho_{0,rec}^{sat} - c\left(d\overline{t}^{\,sat} + \Delta rel^{sat}\right) + Trop_{rec}^{sat} + Ion_{1rec}^{sat} + TGD^{sat}$$



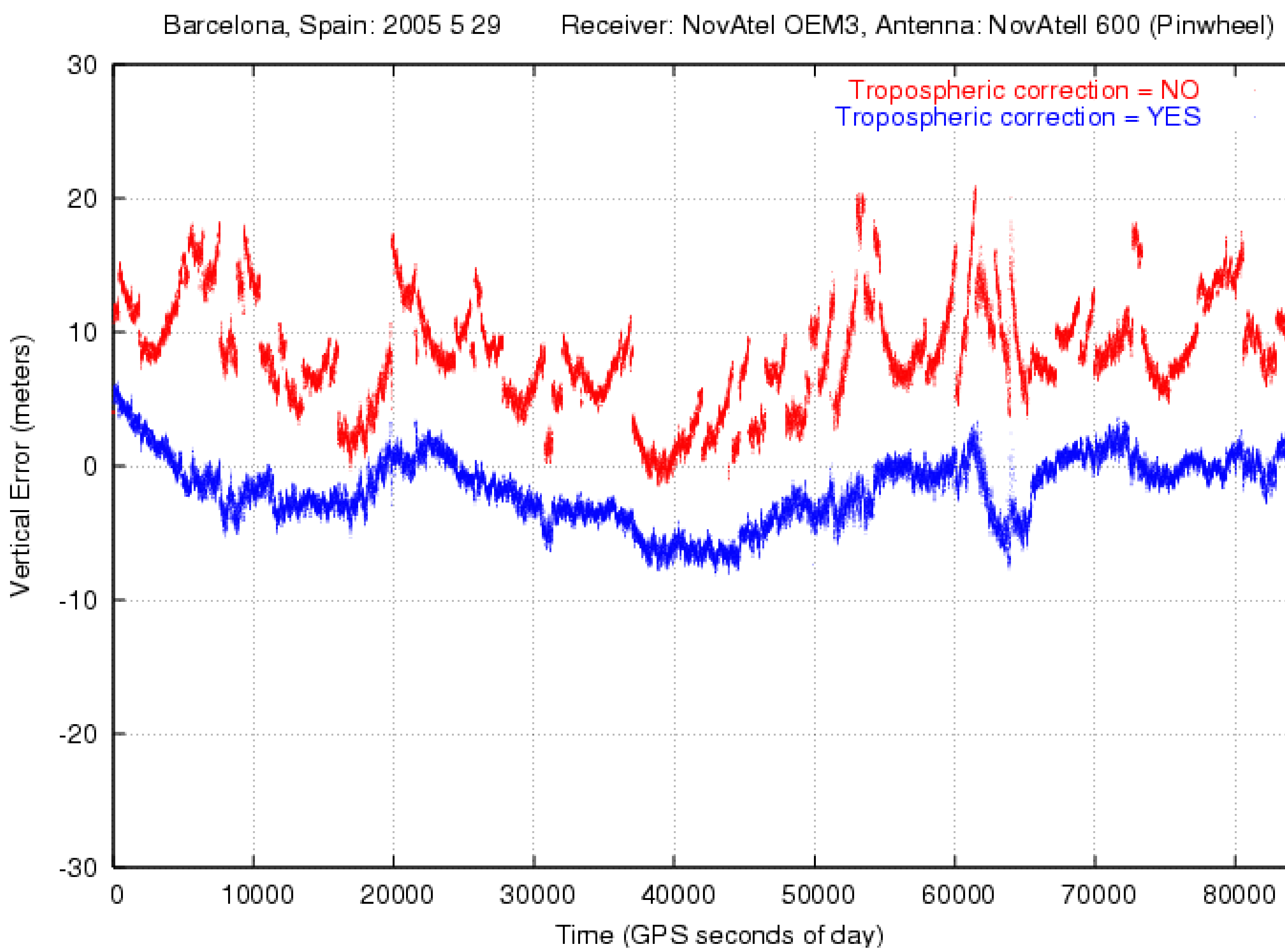
$$m(elev) = \frac{1.001}{\sqrt{0.002001 + \sin^2(elev)}}$$

Range variation: Tropospheric correction

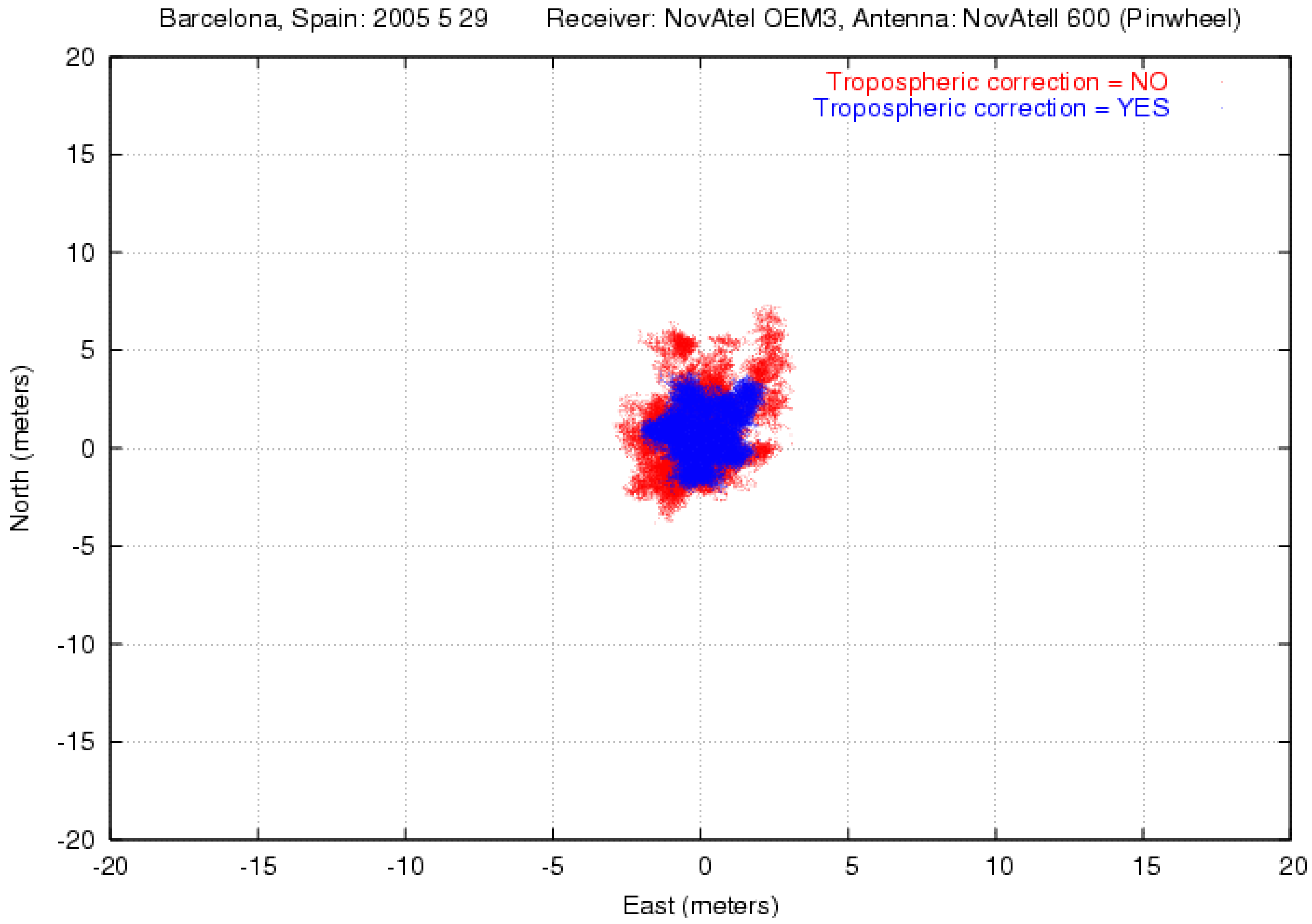


RTCA-Do229C model

Vertical error comparison



Horizontal error comparison



Instrumental Delays

Some sources for these delays are antennas, cables, as well as several filters used in both satellites and receivers.

They are composed by a delay corresponding to satellite and other to receiver, depending on frequency:

$$K_{1,rec}^{sat} = K_{1,rec} + TGD^{sat}$$

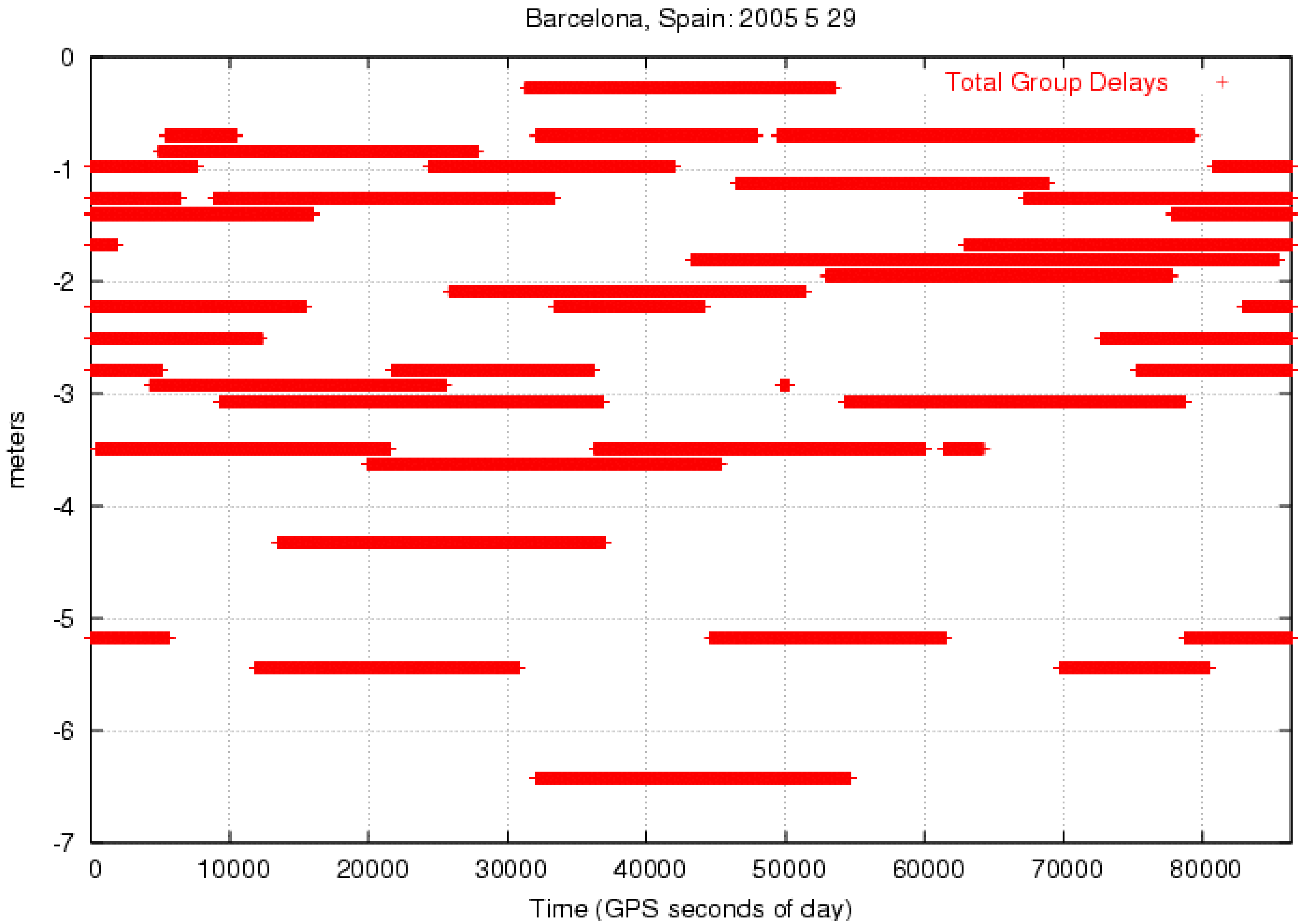
$$K_{2,rec}^{sat} = K_{2,rec} + \frac{f_1^2}{f_2^2} TGD^{sat}$$

- $K1_{rec}$ can be assumed as zero (including it in receiver clock offset).
- TGD^{sat} is transmitted in satellite's navigation message (*Total Group Delay*).

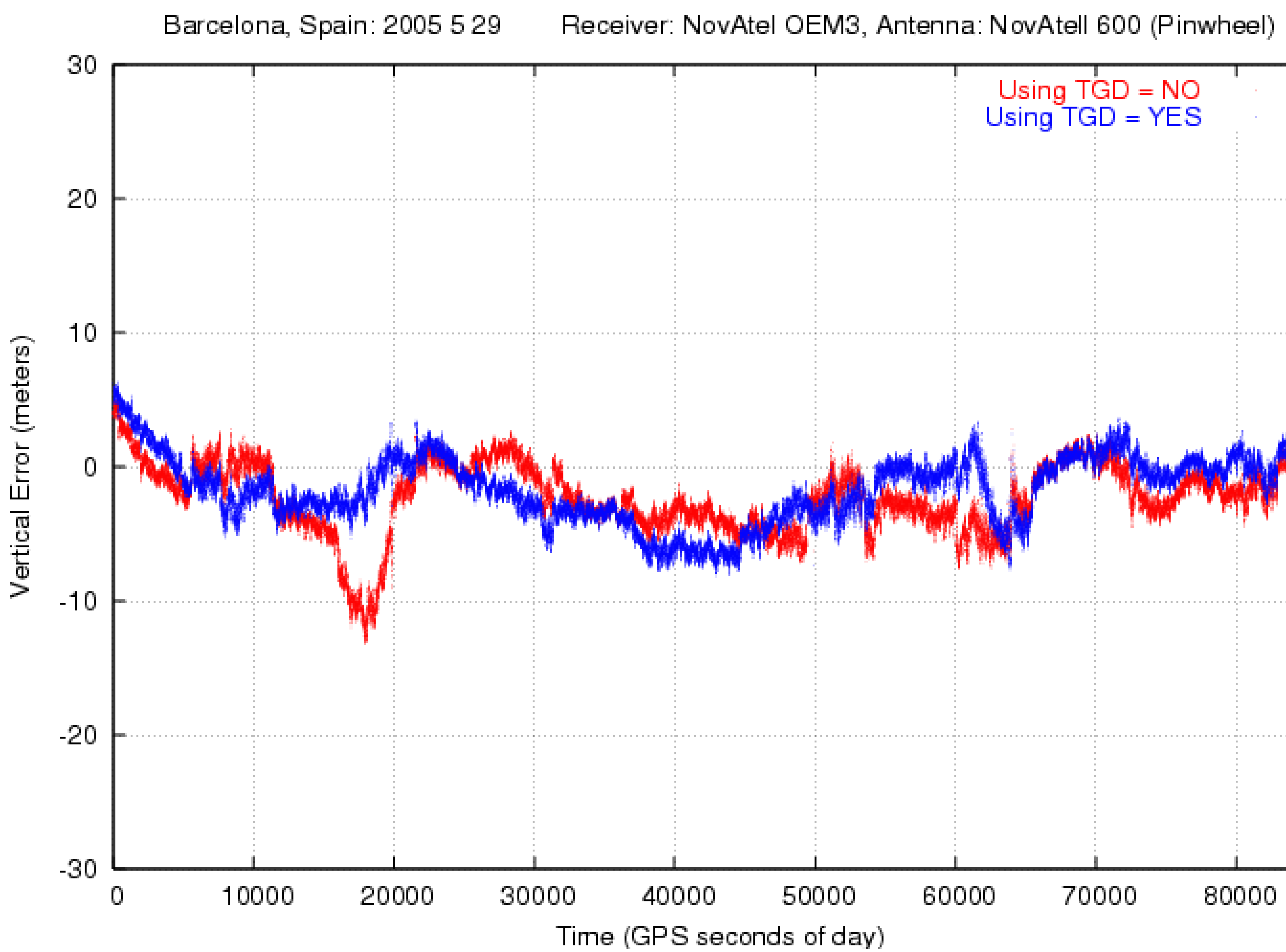
According to ICD GPS-2000, control segment monitors satellite timing, so TGD cancels out when using free-ionosphere combination. That is why we have that particular equation for K_2.

$$C1_{rec}^{sat}[\text{modelled}] = \rho_{0,rec}^{sat} - c\left(\overline{dt}^{sat} + \Delta rel^{sat}\right) + Trop_{rec}^{sat} + Ion_{1rec}^{sat} + TGD^{sat}$$

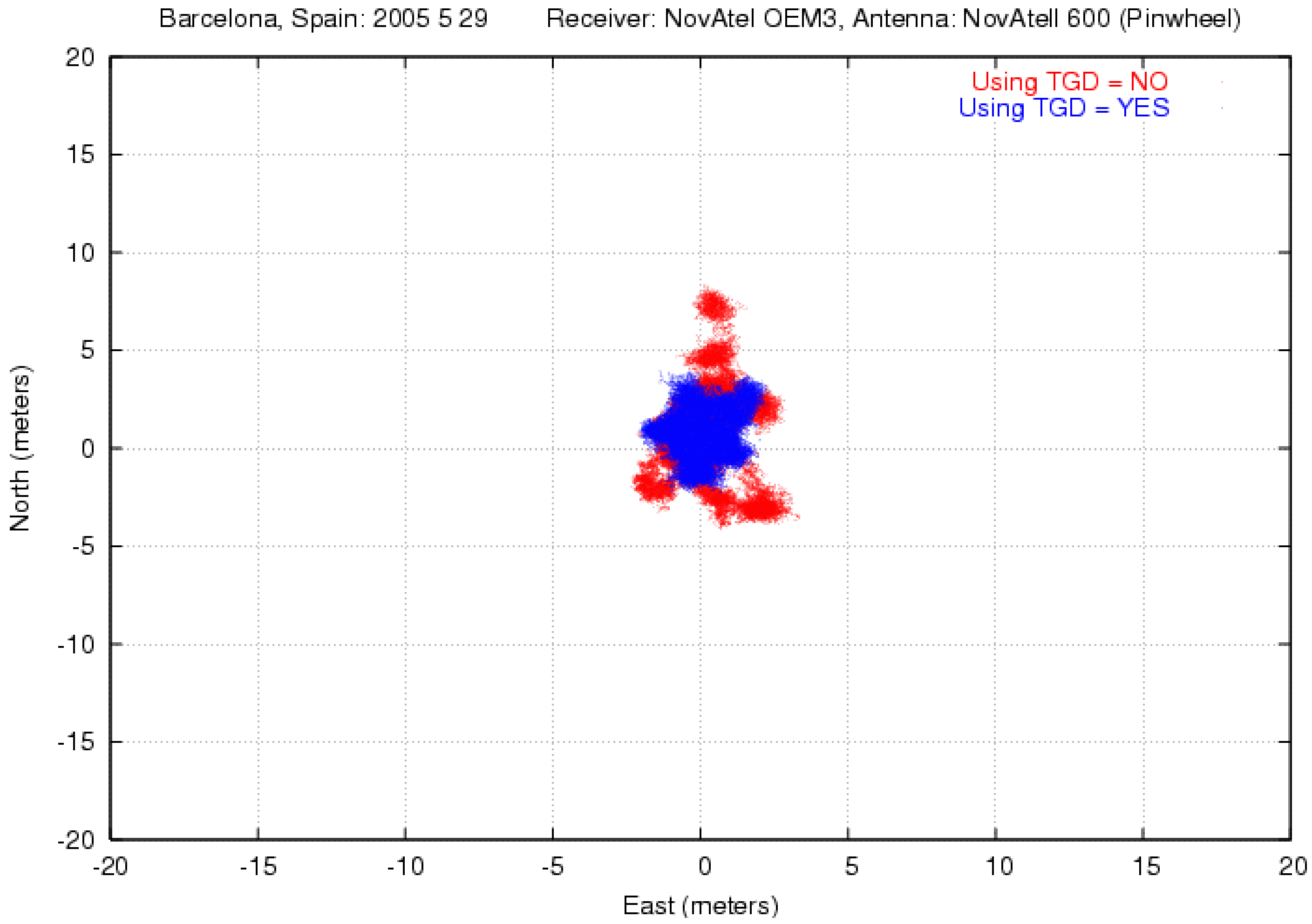
Range variation: Instrumental delays (TGD)



Vertical error comparison



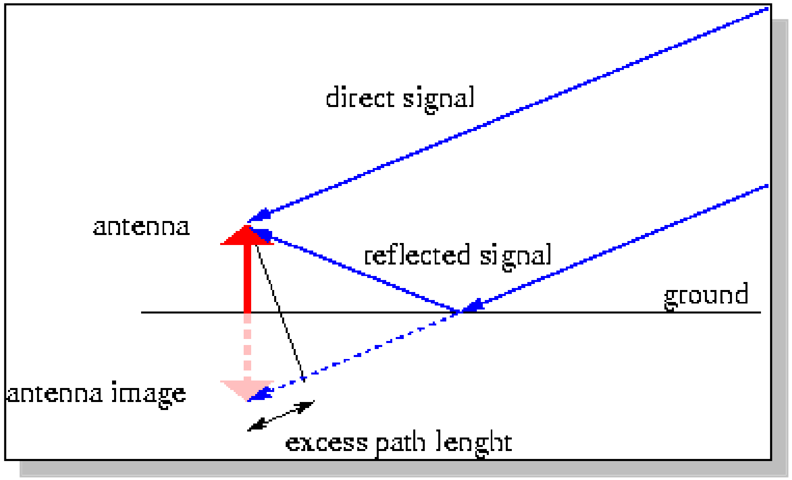
Horizontal error comparison

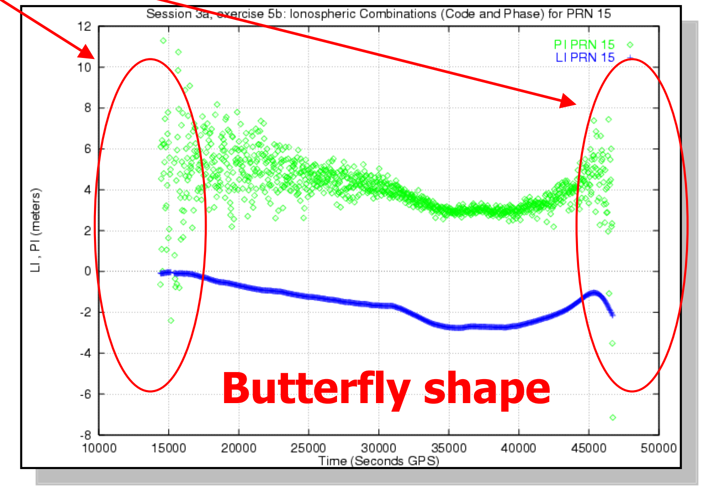


Multipath

- One or more reflected signals reach the antenna in addition to the direct signal. Reflective objects can be earth surface (ground and water), buildings, trees, hills, etc.

- It affects both code and carrier phase measurements, and it is more important at low elevation angles.

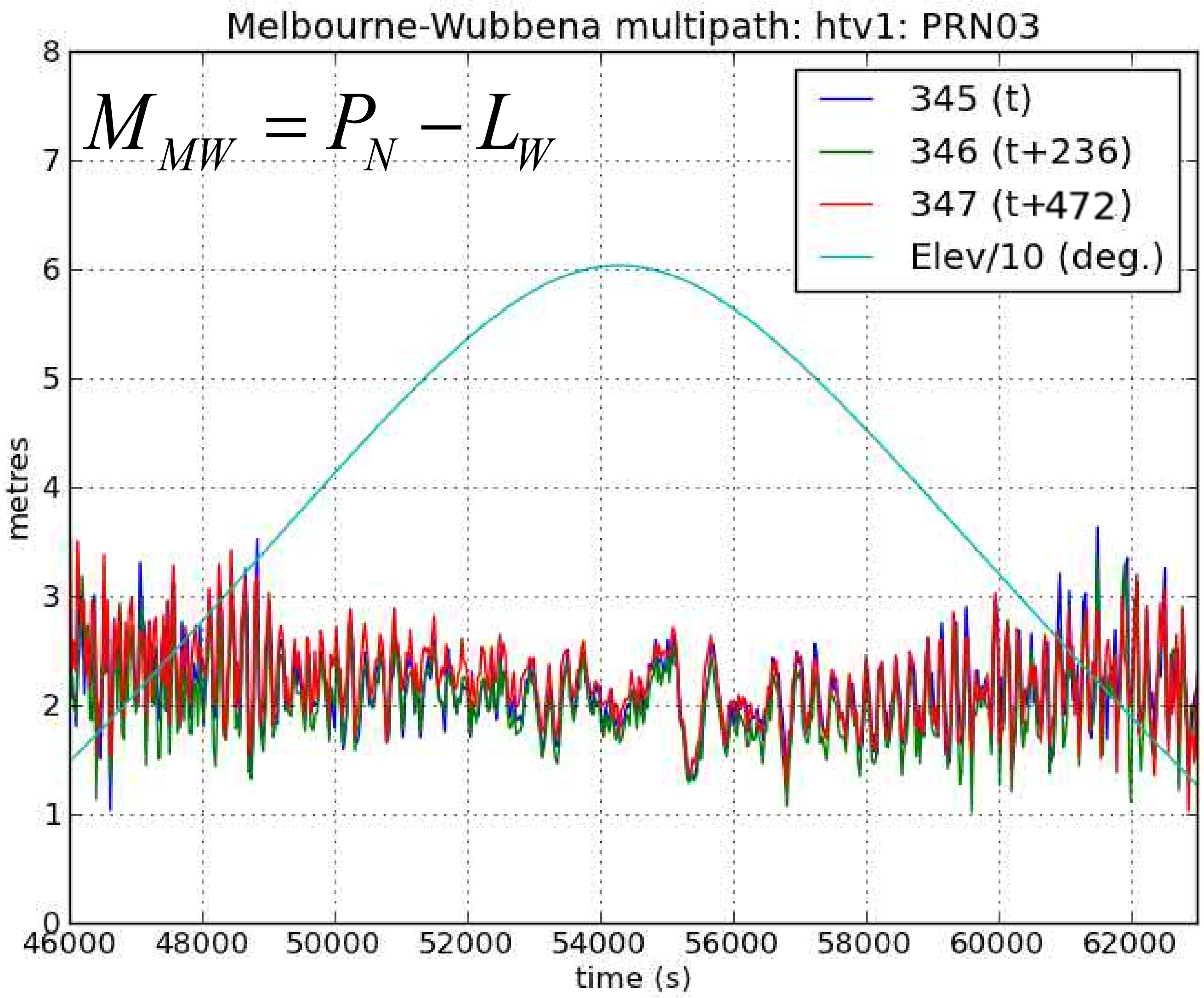




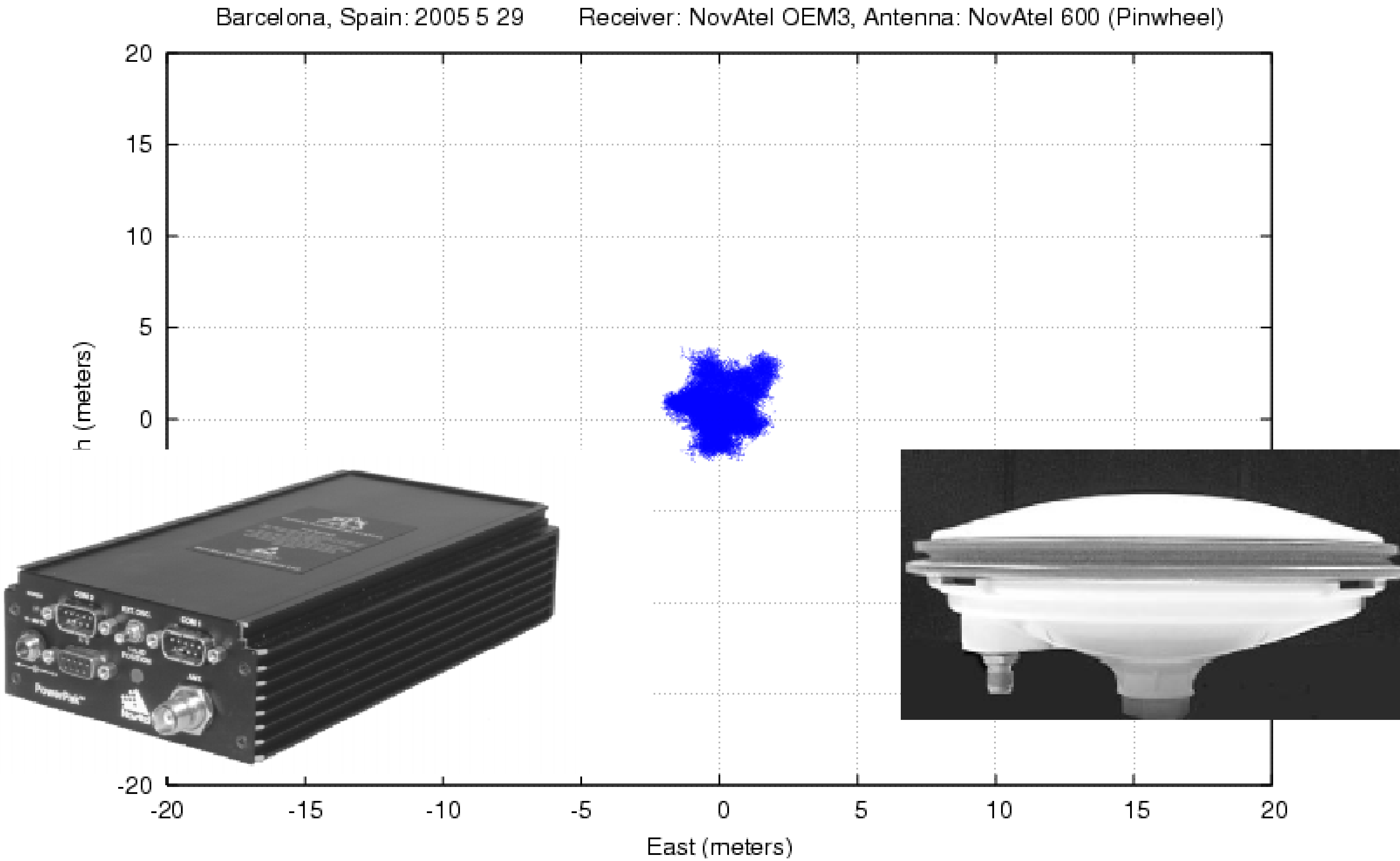
- Code: up to 1.5 chip-length ➔ up to 450m for C1 [theoretically]
  Typically: less than 2-3 m.

- Phase: up to $\lambda/4$ ➔ up to 5 cm for L1 and L2 [theoretically]
  Typically: less than 1 cm

For a stationary receiver, multipath error repeats with the satellite geometry



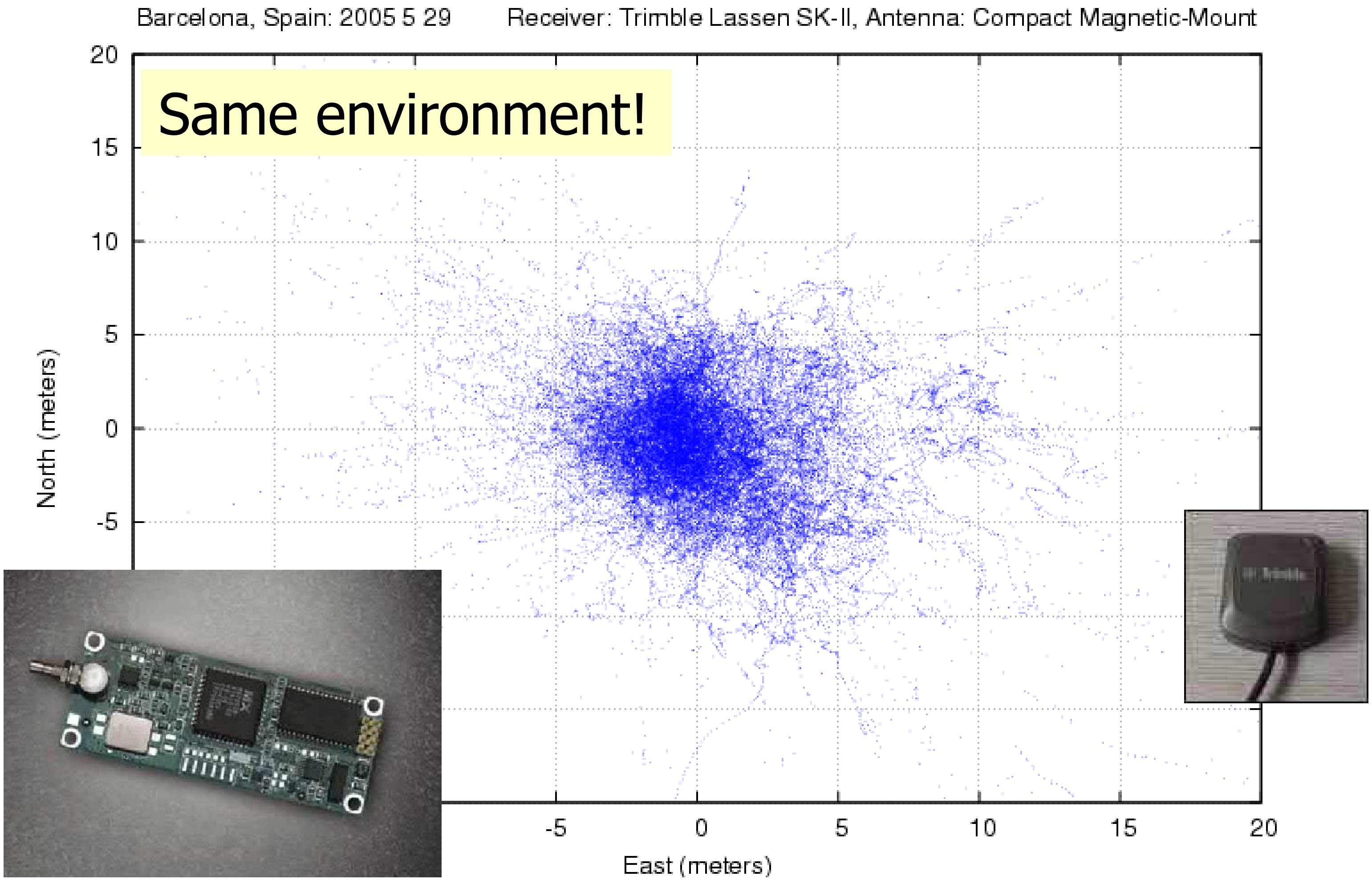
Receiver and multipath noise



GPS standalone (C1 code)

10,000 €

Receiver noise and multipath



GPS standalone (C1 code)

100 €

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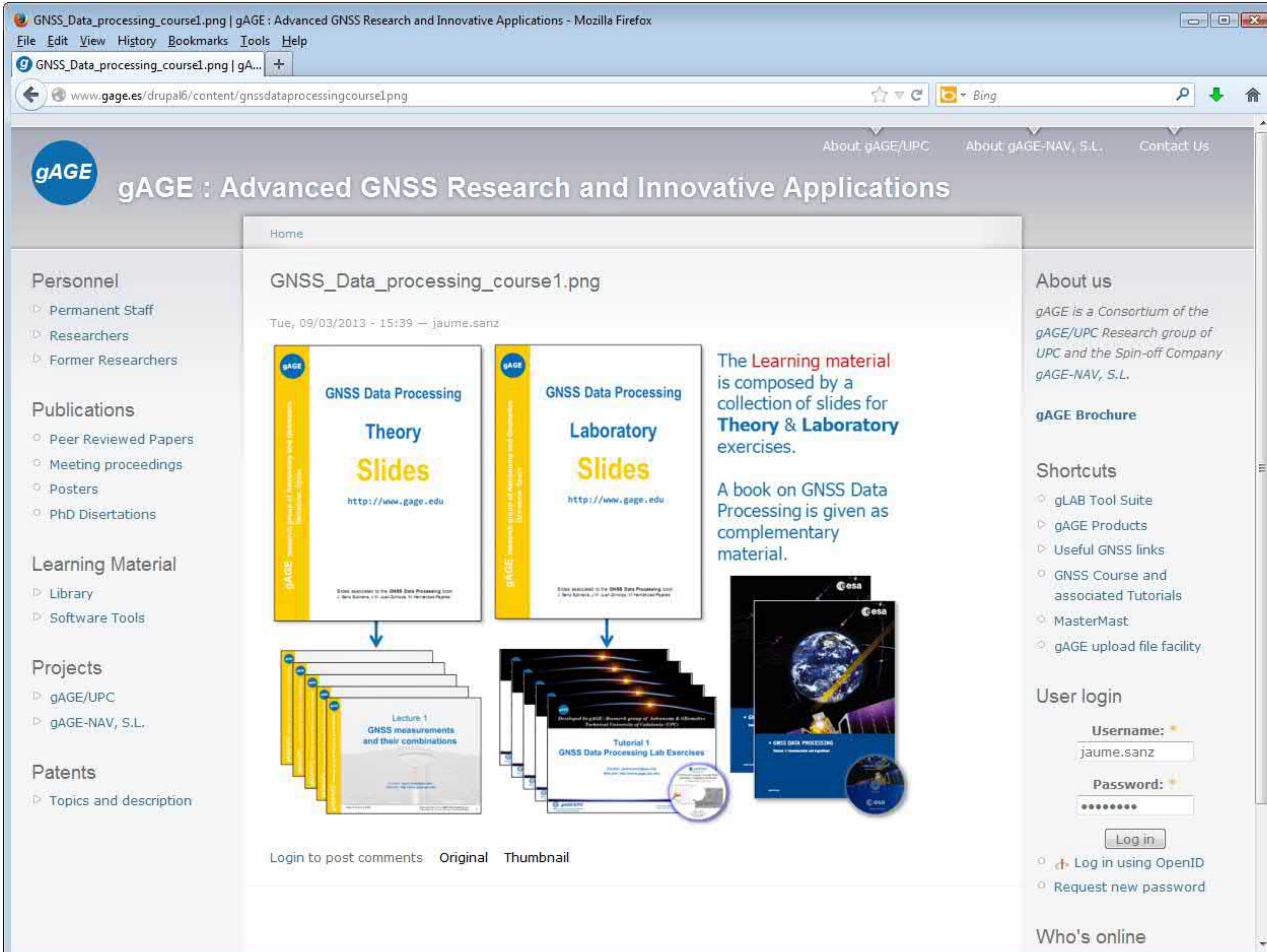
[RD-5] Rovira-Garcia A, Juan J, Sanz J, Gonzalez-Casado G (2015) A Worldwide Ionospheric Model for Fast Precise Point Positioning. Geoscience and Remote Sensing, IEEE Transactions on 53(8):4596{4604, DOI 10.1109/TGRS.2015.2402598, URL http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=7053952

Thank you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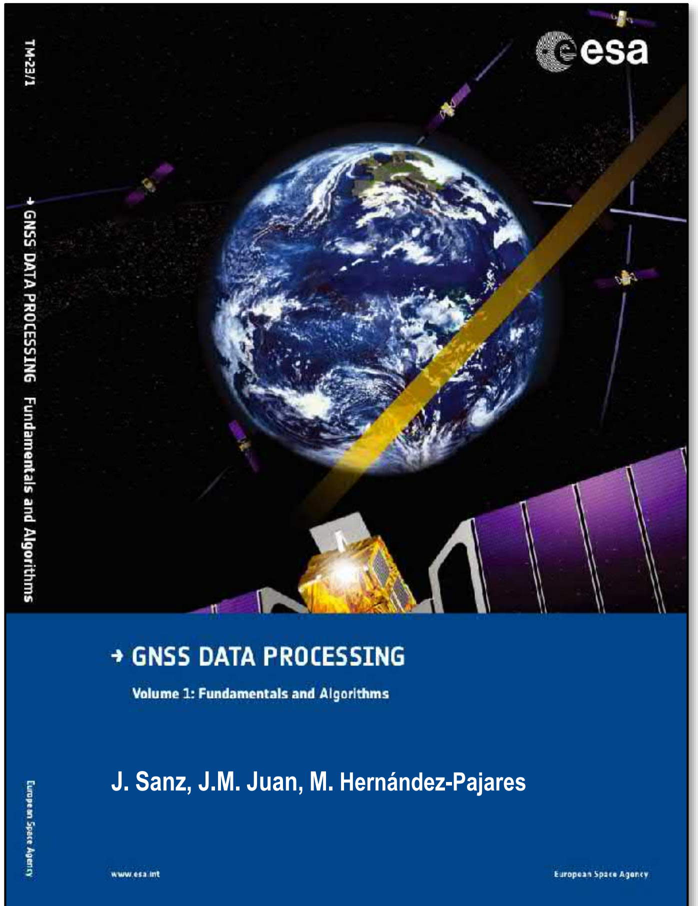

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