GNSS Data Processing Lab Exercises

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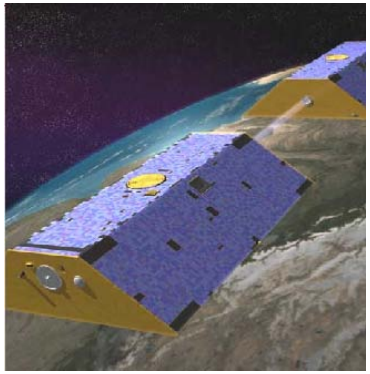
Slides associated to
***gLAB* version 2.0.0**

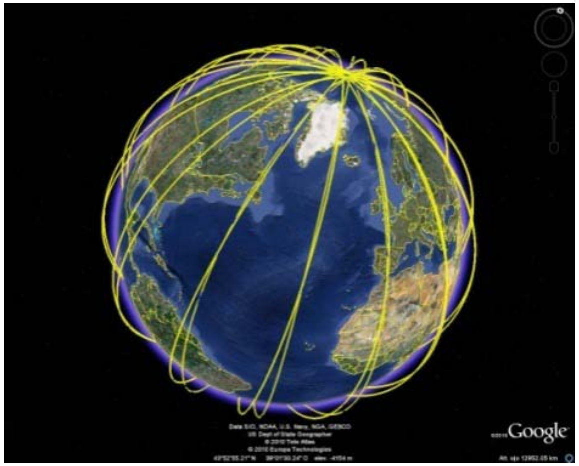
OVERVIEW

- **Introduction**
- **The gLAB tool suite**
- **Examples of GNSS Positioning using gLAB**
- **Laboratory session organization**



LABORATORY Session

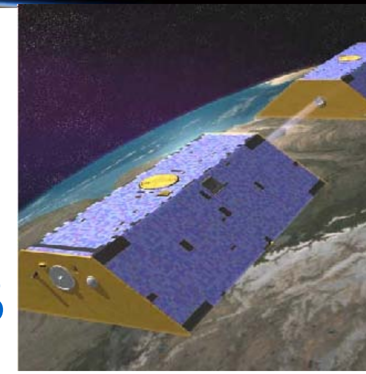
- **Starting-up your laptop**
- **Basic:** Introductory lab exercises
- **Medium:** Laboratory Work Project:
  Kinematic positioning of a LEO sat.
- **Advanced:** Homework



Introduction

- **This practical lecture** is devoted to analyze and assess different issues associated with Standard and Precise Point Positioning with GPS data.
- The laboratory exercises will be developed with actual GPS measurements, and processed with the **ESA/UPC GNSS-Lab Tool suite** (**gLAB**), which is an interactive software package for GNSS data processing and analysis.
- Some examples of gLAB capabilities and usage will be shown before starting the laboratory session.
- All software tools (including ***gLAB***) and associated files for the laboratory session are included in the USB stick delivered to lecture attendants.
- **The laboratory session** will consist in a set of exercises organized in three different levels of difficulty (**Basic**, **Medium** and **Advanced**). Its content ranges from a first glance assessment of the different model components involved on a Standard or Precise Positioning, to the kinematic positioning of a LEO satellite, as well as an in-depth analysis of the GPS measurements and associated error sources.

OVERVIEW



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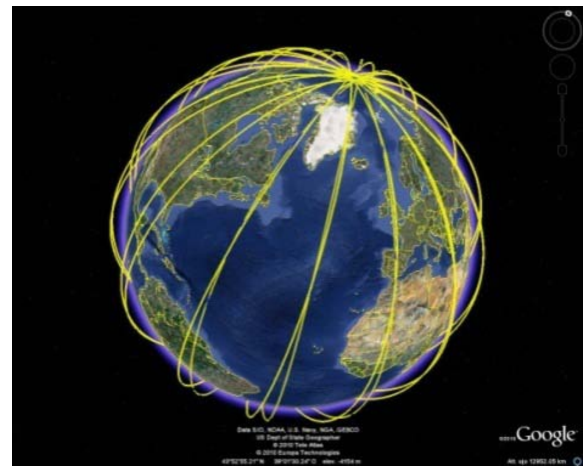

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The gLAB Tool suite

- **The GNSS-Lab Tool suite (gLAB)** is an interactive multipurpose educational and professional package for GNSS Data Processing and Analysis.
- gLAB has been developed under the ESA Education Office contract N. P1081434.
- **Main features:**
  - High Accuracy Positioning capability.
  - Fully configurable.
  - Easy to use.
  - Access to internal computations.

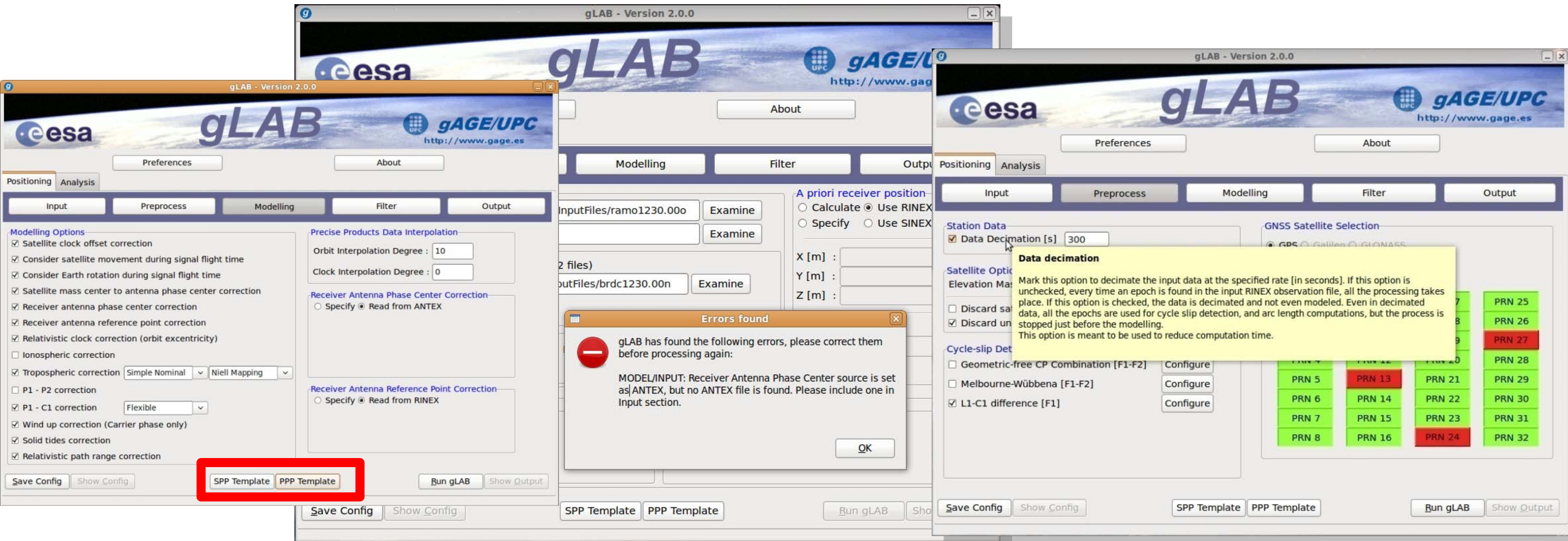
The gLAB Tool suite

- **gLAB** has been designed to cope with the needs of two main target groups:
  - Students/Newcomers: User-friendly tool, with a lot of explanations and some guidelines.
  - Professionals/Experts: Powerful Data Processing and Analysis tool, fast to configure and use, and able to be included in massive batch processing.

The gLAB Tool suite

Students/Newcomers:

- Easiness of use: Intuitive GUI.
- Explanations: Tooltips over the different options of the GUI.
- Guidelines: Several error and warning messages. Templates for pre-configured processing.



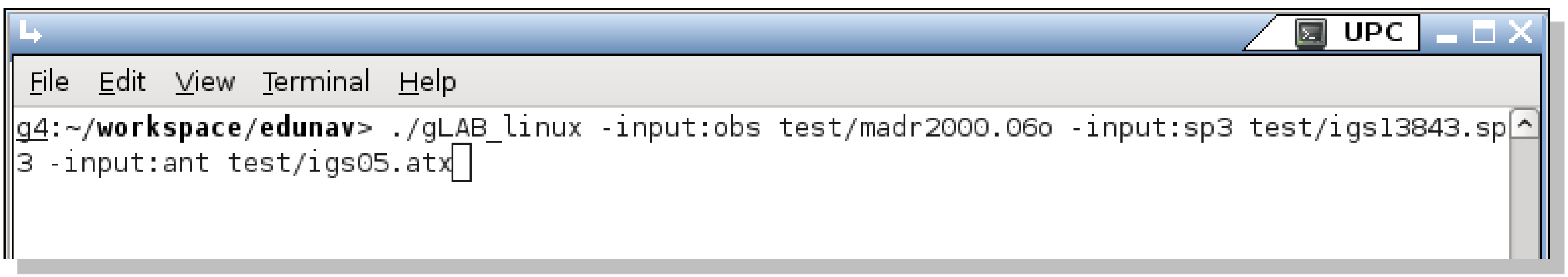
The gLAB Tool suite

Students/Newcomers:

- Easiness of use: Intuitive GUI.
- Explanations: Tooltips over the different GUI options.
- Guidelines: Several error and warning messages. Templates for pre-configured processing.

Professionals/Experts:

- Powerful tool with High Accuracy Positioning capability.
- Fast to configure and use: Templates and carefully chosen defaults.
- Able to be executed in command-line and to be **included in batch processing**.



The gLAB Tool suite

- **In order to broad the tool availability, gLAB Software has been designed to work in both Windows and Linux environments.**

- **The package contains:**
  - Windows binaries (with an installable file).
  - Linux .tgz file.
  - Source code (to compile it in both Linux and Windows OS) under an Apache 2.0 license.
  - Example data files.
  - Software User Manual.
  - HTML files describing the standard formats.

The gLAB Tool suite

Read files capability:

- RINEX observation v2.11 & v3.00
- RINEX navigation message.
- SP3 precise satellite clocks and orbits files
- ANTEX Antenna information files.
- Constellation status.
- DCBs files.
- GPS_Receiver_Type files.
- SINEX position files.

Pre-processing module:

- Carrier-phase prealignment.
- Carrier-phase / pseudorange consistency check.
- Cycle-slip detection (customizable parameters)
  - Melbourne-Wübbena.
  - Geometry-free CP combination.
  - L1-C1 difference (single frequency).
- Pseudorange smoothing.
- Decimation capability.
- On demand satellite enable/disable.
- Elevation mask.
- Frequency selection.
- Discard eclipsed satellites.

Modelling module:

- Fully configurable model.
- Satellite positions.
- Satellite clock error correction.
- Satellite movement during signal flight time.
- Earth rotation during signal flight time.
- Satellite phase centre correction.
- Receiver phase centre correction. (frequency dependent).
- Relativistic clock correction.
- Relativistic path range correction.
- Ionospheric correction (Klobuchar).
- Tropospheric correction
  - Simple and Niell mappings.
  - Simple and UNB-3 nominals.
- Differential Code Bias corrections.
- Wind up correction.
- Solid tides correction (up to 2nd degree).

The gLAB Tool suite

Filtering module:

- Able to chose different measurements to process (1 or more), with different weights. This design could be useful in future Galileo processing, where processing with different measurements may be desired.
- Fixed or elevation-dependant weights per observation.
- Troposphere estimation on/off.
- Carrier-Phase or Pseudorange positioning.
- Static/Kinematic positioning (full Q/Phi/P0 customization).
- Able to do a forward/backward processing.
- Able to compute trajectories (no need for a priori position).

Output module:

- Cartesian / NEU coordinates.
- Configurable message output.

Other functionalities:

- Computation of satellite coordinates and clocks from RINEX and SP3 files.
- Satellite coordinates comparison mode. For instance RINEX navigation vs. SP3, or SP3 vs. SP3 (along-track, cross-track and radial orbit errors, clock errors, SISRE).
- Show input mode. No processing, only parsing RINEX observation files.

- **Current version allows full GPS data processing, and partial handling of Galileo and GLONASS data.**
- **Future updates may include full GNSS data processing.**

GNSS learning material package

Includes three different parts, allowing to follow either a guided or a self-learning GNSS course:

- **GNSS Book**: Complete book with theory and algorithms (Volume 1), and with a Lab. course on GNSS Data Processing & Analysis (Volume 2).

- **gLAB tool suite**: Source code and binary software files, plus configuration files, allowing processing GNSS data from standard formats. The options are fully configurable through a GUI.

- **gAGE-GLUE**: Bootable USB stick with a full environment ready to use; based on LINUX (Ubuntu) OS.

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Basic: Introductory Lab. Exercises

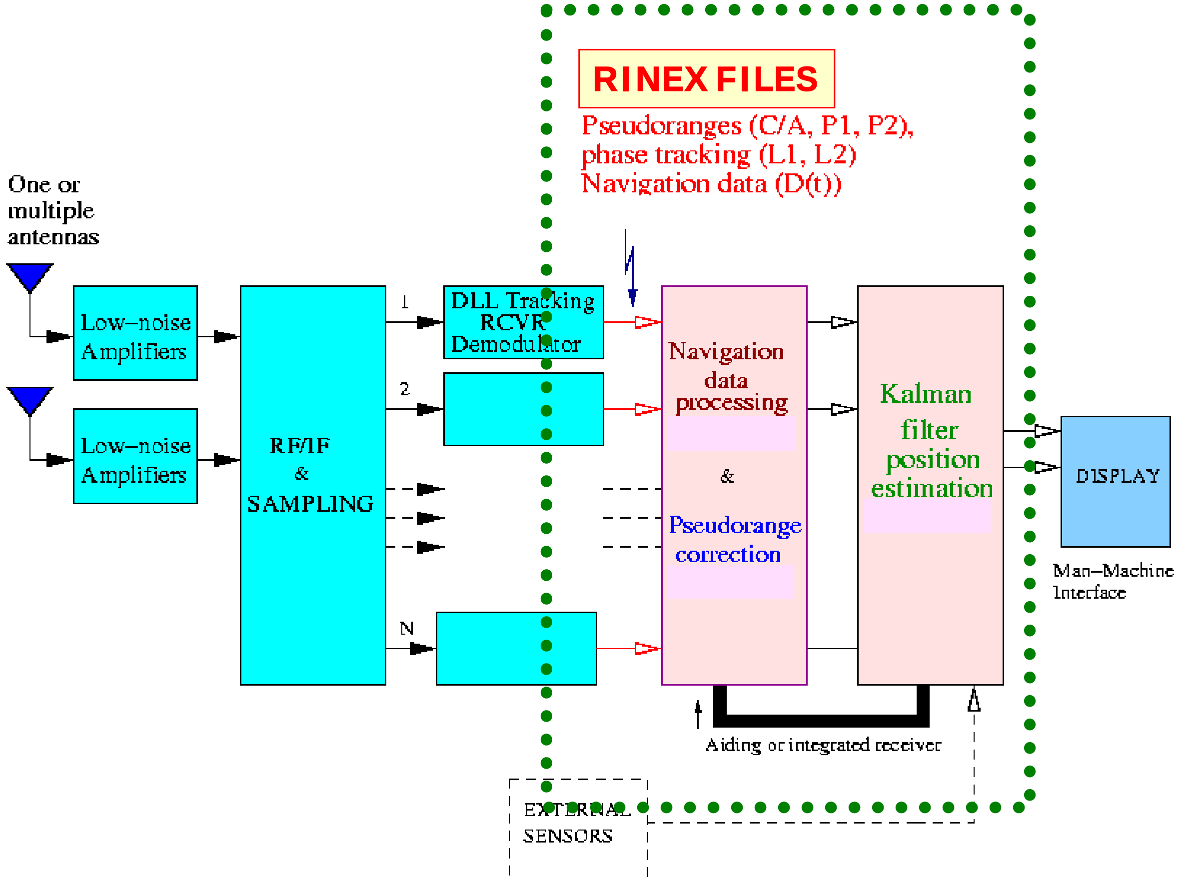
Standard and Precise Point Positioning

- To Illustrate how easy to process GNSS data using gLAB, a GPS receiver will be positioned in the next examples using:
  - Example 1: Broadcast orbits and clocks (**SPP,** kinematic).
  - Example 2: Precise Orbits and clocks (**PPP,** static).
  - Example 3: Precise Orbits and clocks (**PPP,** kinematic).

- Solutions will be compared with an accurate reference value of receiver coordinates to asses the positioning error.

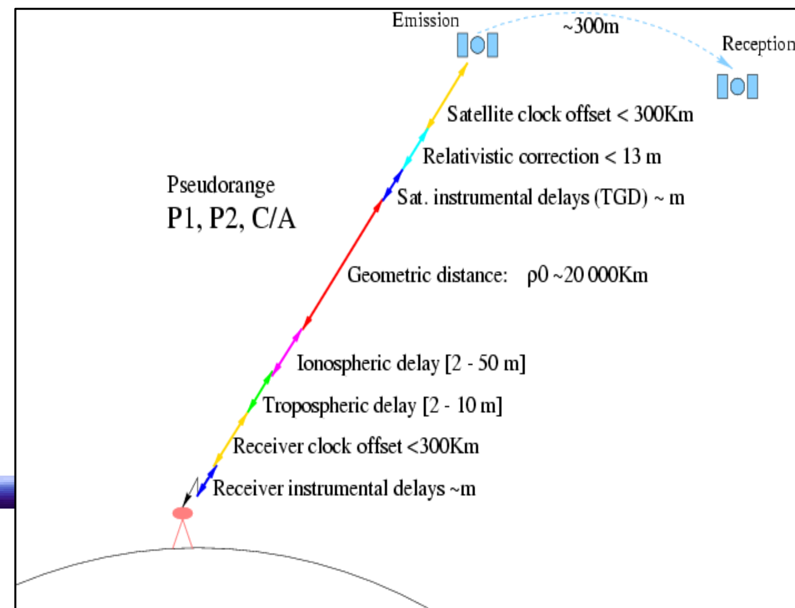
Note: the receiver coordinates were keep fixed during the data collection.

We will work after the correlator: Our input data are code and carrier measurements and satellite orbits and clocks.



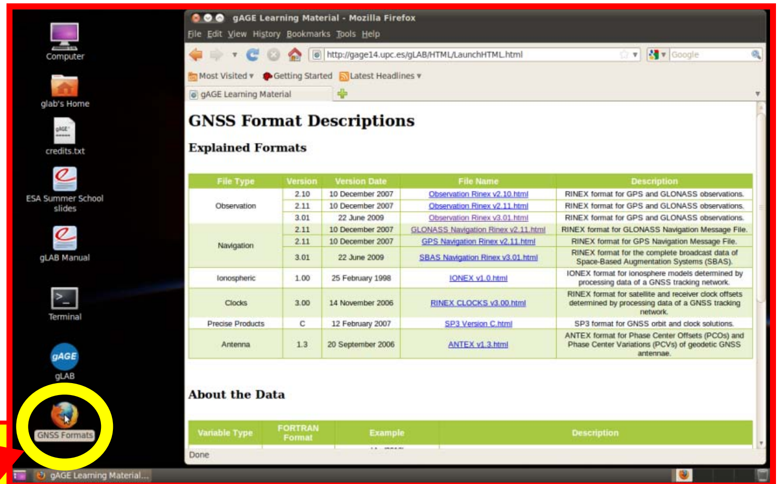
Ficheros RINEX: observables

```
     2              OBSERVATION DATA    G (GPS)             RINEX VERSION / TYPE
RGRINEXO V2.4.1 UX  AUSLIG              10-JAN-97 10:19     PGM / RUN BY / DATE
Australian Regional GPS Network (ARGN) - COCOS ISLAND       COMMENT
BIT 2 OF LLI (+4) FLAGS DATA COLLECTED UNDER "AS" CONDITION COMMENT
        -0.000000000103        HARDWARE CALIBRATION (S)     COMMENT
        -0.000000054663        CLOCK OFFSET (S)             COMMENT
COCO                                                        MARKER NAME
AU18                                                        MARKER NUMBER
mrh                 auslig                                  OBSERVER / AGENCY
126                 ROGUE SNR-8100      93.05.25 / 2.8.33.2 REC # / TYPE / VERS
327                 DORNE MARGOLIN T                        ANT # / TYPE
  -741950.3241  6190961.9624 -1337769.9813                  APPROX POSITION XYZ
        0.0040        0.0000        0.0000                  ANTENNA: DELTA H/E/N
     1     1                                                WAVELENGTH FACT L1/2
     5    C1    L1    L2    P2    P1                        # / TYPES OF OBSERV
SNR is mapped to signal strength [0,1,4-9]                  COMMENT
 SNR:    >500  >100   >50   >10    >5    >0   bad   n/a     COMMENT
 sig:       9     8     7     6     5     4     1     0     COMMENT
    30                                                      INTERVAL
  1997     1     9     0     7   30.0000000                 TIME OF FIRST OBS
  1997     1     9    23    59   30.0000000                 TIME OF LAST OBS
                                                            END OF HEADER
 97  1  9  0  7 30.0000000  0  7  1 25  9  5 23 17  6
  22127685.105  -14268715.899 8 -11118481.28445  22127685.4014  <==== 1
  22672158.746  -11510817.892 7  -8969469.30045  22672158.5184  <==== 25
  22594902.367  -12949753.825 7 -10090708.53945  22594903.7394  <==== 9
  22731128.796  -11621184.951 7  -9055464.16945  22731130.0094  <==== 5
  24610920.702    -924108.174 6   -720085.67045  24610920.0404  <==== 23
  20718775.074  -18605935.474 9 -14498133.97346  20718775.6074  <==== 17
  20842713.610  -19083282.892 9 -14870090.55546  20842713.4814  <==== 6
```



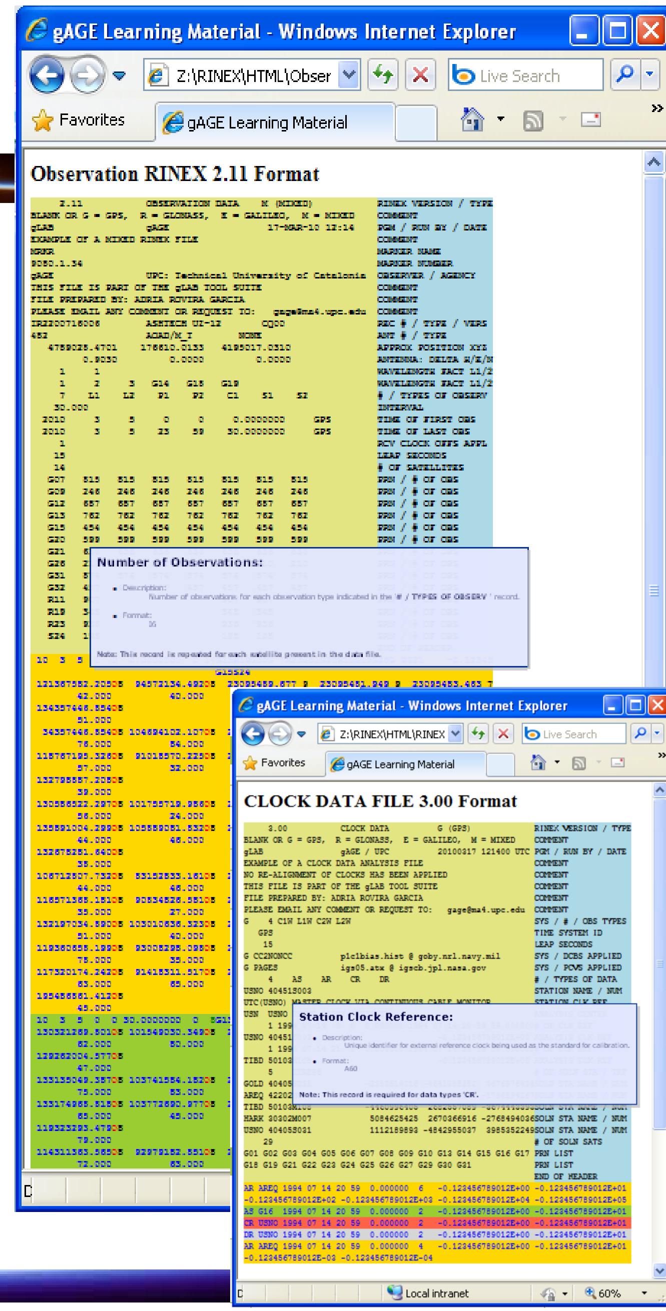
GNSS Format Descriptions

- **GNSS data files follow a well defined set of standards formats: RINEX, ANTEX, SINEX…**
- **Understanding a format description is a tough task.**
- **These standards are explained in a very easy and friendly way through a set of html files.**
- **Described formats:**
  - Observation RINEX
  - Navigation RINEX
  - RINEX CLOCKS
  - SP3 Version C
  - ANTEX



Open GNSS Formats

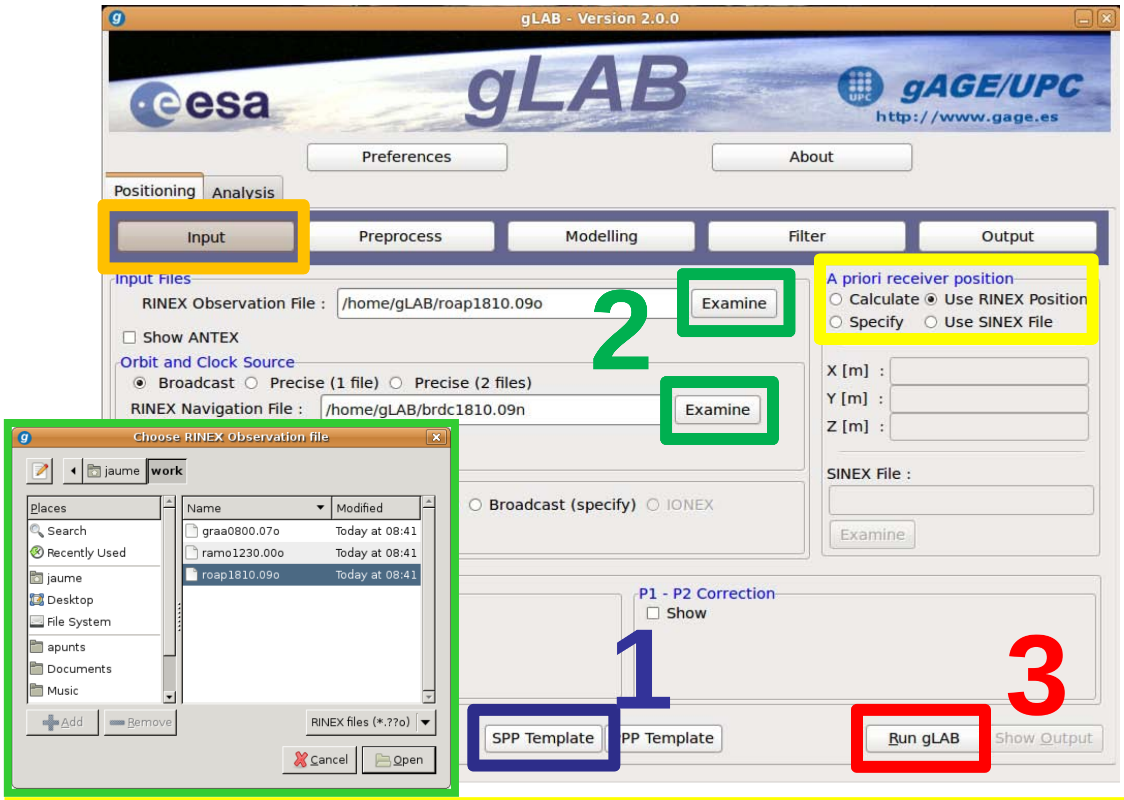
with **Firefox** internet browser



More details at: `http://www.gage.es/gLAB`

Example 1: Standard Point Positioning (SPP)

SPP Template: Kinematic positioning with single freq. C1 code + broadcast orbits and clocks.



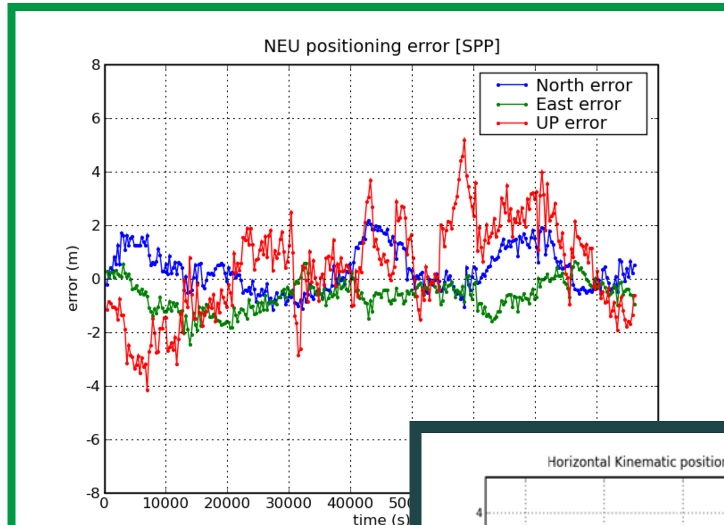
1. Select the **SPP Template**
2. **Upload the RINEX** files:
   - Measurement : `roap1810.09o`
   - Navigation: `brdc1810.09n`
3. **RUN** gLAB

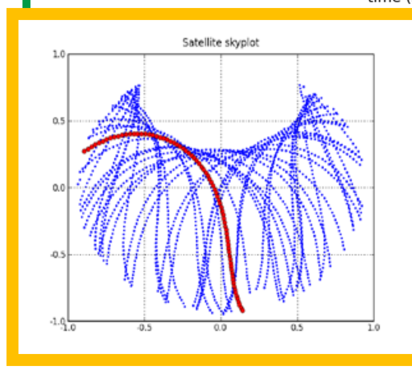
Default output file:
gLAB.out

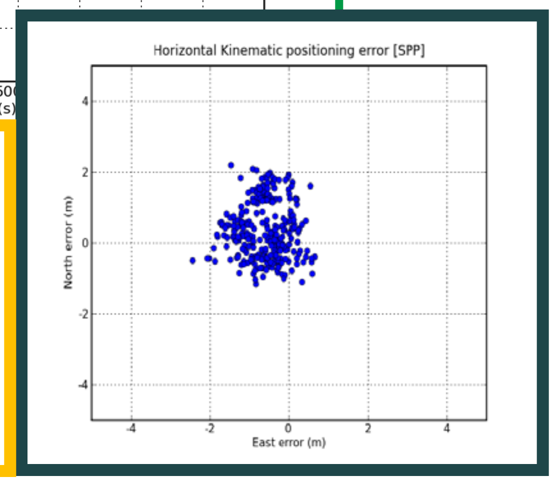
Note: Reference coordinates are from RINEX

Example 1: Standard Point Positioning (SPP)

Plotting Results







Positioning with few meters of error is achieved **in kinematic SPP mode.**

- Receiver navigated as a rover in pure kinematic mode.
- Single frequency C1 code is used.
- Broadcast orbits and clocks.

Example 2: Static Precise Point Positioning (PPP)

PPP Template: Static positioning with dual freq. code & carrier (ionosphere-free combination PC,LC) + post-processed precise orbits & clocks.

1. Select the **PPP Template**
2. **Upload data** files:
   - Measurement : `roap1810.09o`
   - ANTEX: `igs05_1525.atx`
   - Orbits & clocks: `igs15382.sp3`
   - SINEX: `igs09P1538.snx`
3. **RUN** gLAB

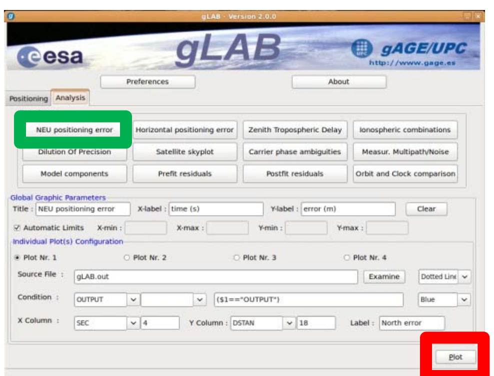
Default output file:

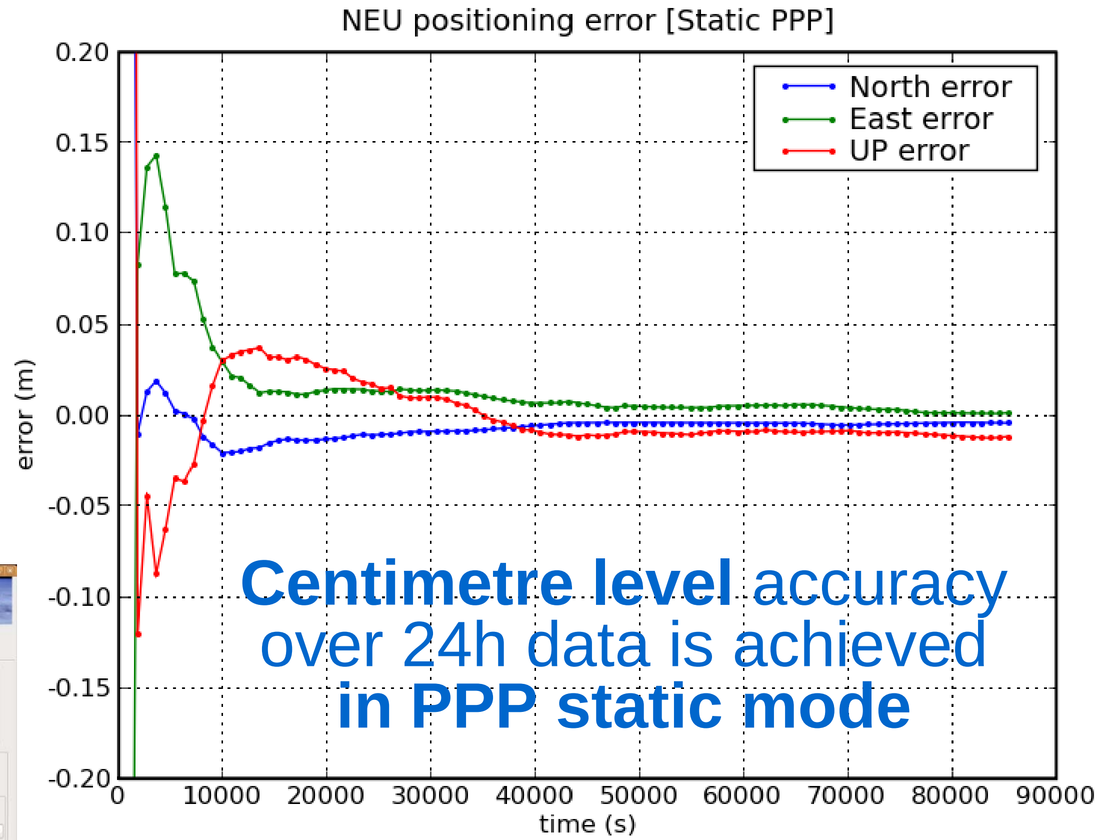
gLAB.out

Example 2: Static Precise Point Positioning (PPP)

Plotting Results

- Coordinates are taken as constants in nav. filter.
- Dual frequency Code and Carrier measurements.
- Precise orbits and clocks.
- Measurements modelling at the centimetre level.



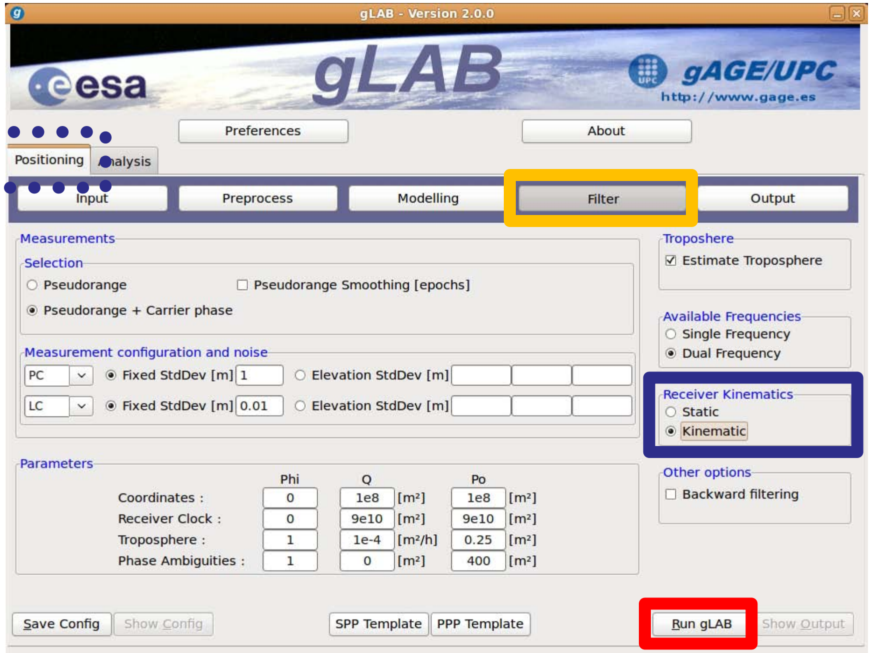


Centimetre level accuracy over 24h data is achieved **in PPP static mode**

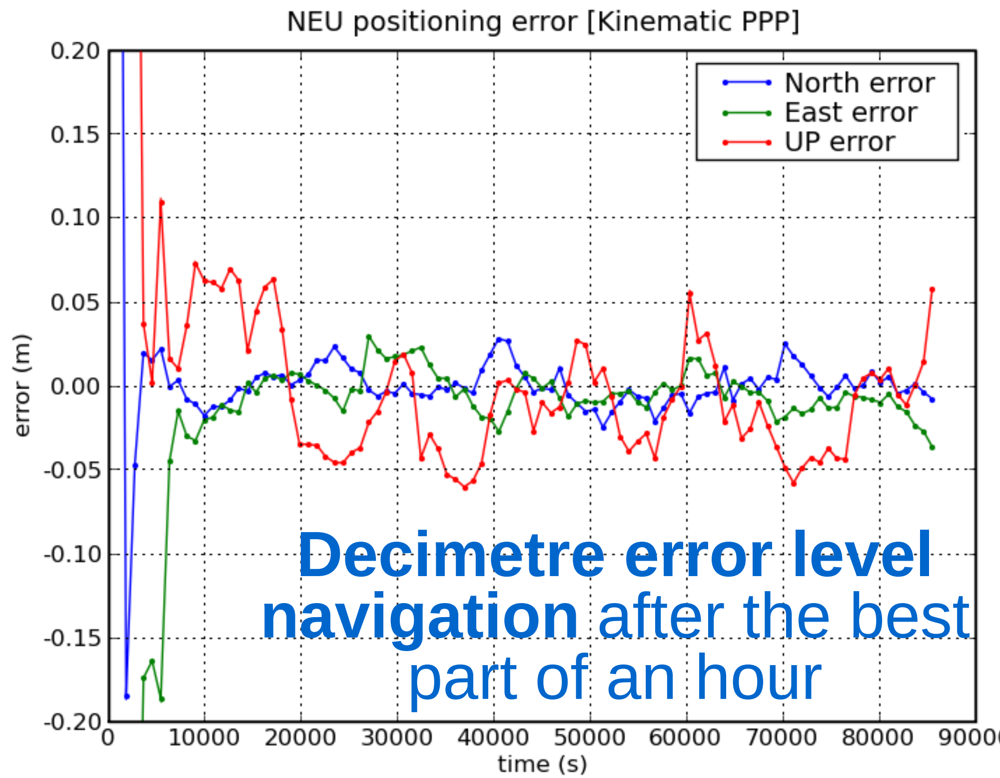
Example 3: Kinematic Precise Point Positioning

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.



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Laboratory session organization

- The laboratory session is organized as an **assisted activity** were a set of **exercises must be developed individually or in groups of two**.

- As they are conceived as self-learning work, a detailed guide is provided in the slides (pdf file) to develop the exercises.

- A set of questions is presented, and the answers are also included in the slides.

- Teachers will attend individual (or collective) questions that could arise during exercise resolution.

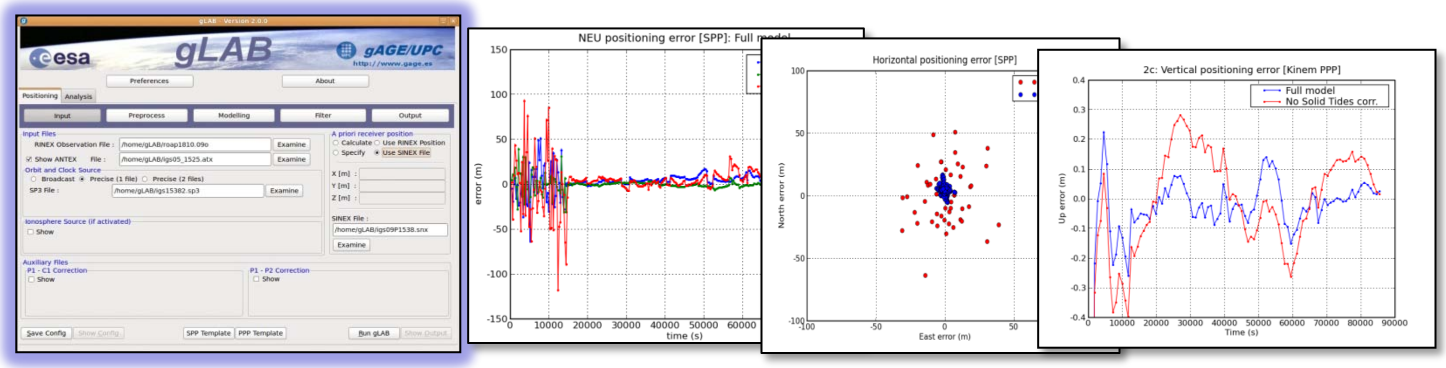
Laboratory session organization

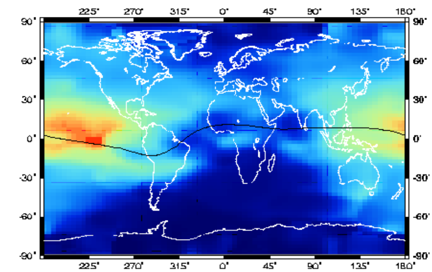
- The exercises are organized in **<u>three different levels of difficulty</u>**. The student can choose the level of exercises to do, although at least an introductory exercise is recommended to learn basic **gLAB** usage.

- **1. <u>Basic</u>: Introductory exercises 1 & 2.**

  They consist in simple exercises to assess the model components for Standard and Precise Point Positioning.

  "Background information" slides are provided, summarizing the main concepts associated with these exercises.





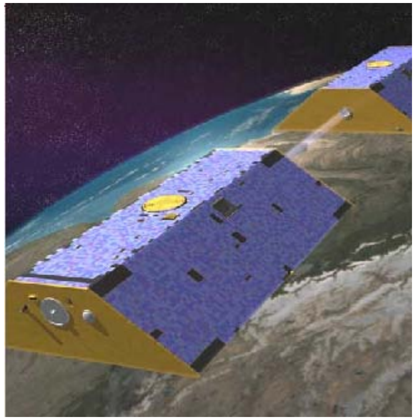
Brief summaries of fundamentals in backup slides

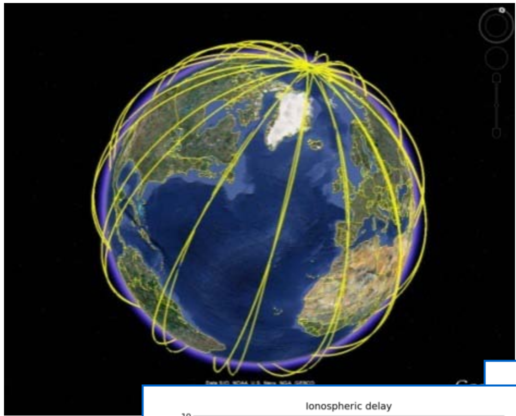
Laboratory session organization

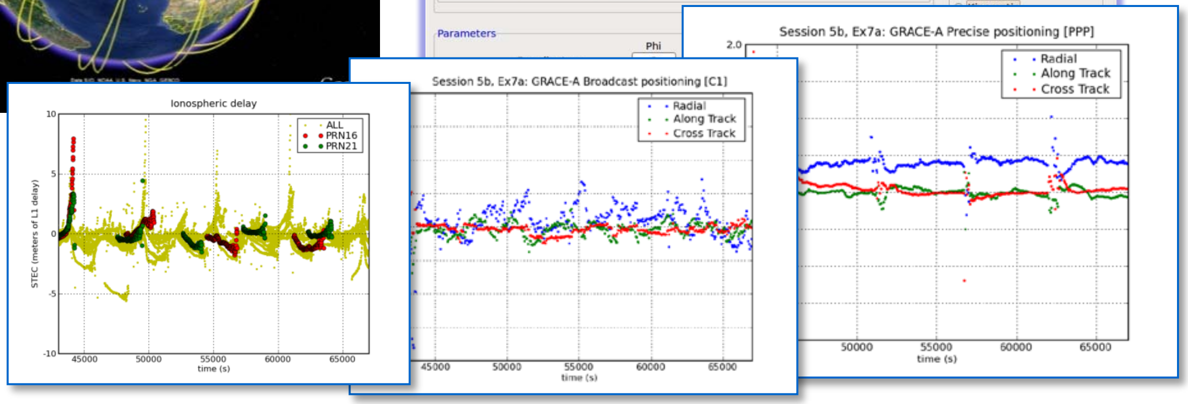
- **2. <u>Medium</u>: Laboratory work project.**

  It consists in the kinematic positioning of a Low Earth Orbit satellite.

  Different positioning modes are analyzed and different modeling options will be discussed.







Given that session time is limited to 3h, students who feel comfortable using gLAB, can skip part of the previous basic exercises (Ex1, Ex2) and jump to the <u>Lab. Work Project.</u>

Laboratory session organization

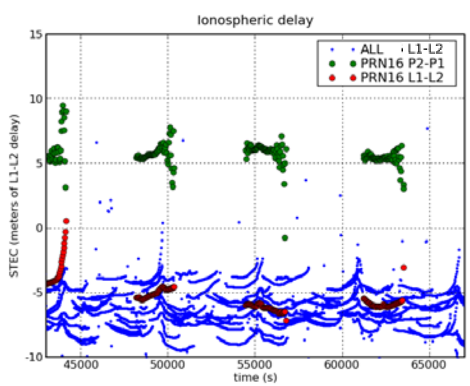
- **3 . <u>Advanced</u>:** Labeled as **“Homework exercises”**

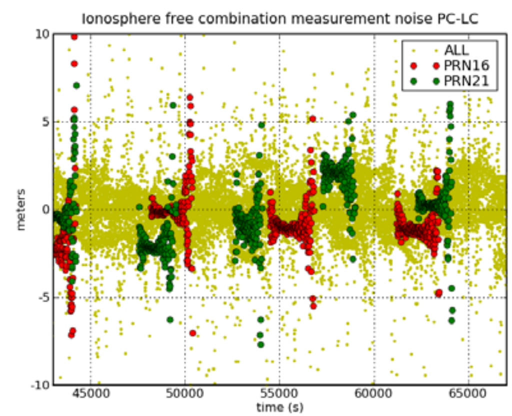
A set of additional exercises addressed to those students that already have a solid background on GPS data processing.

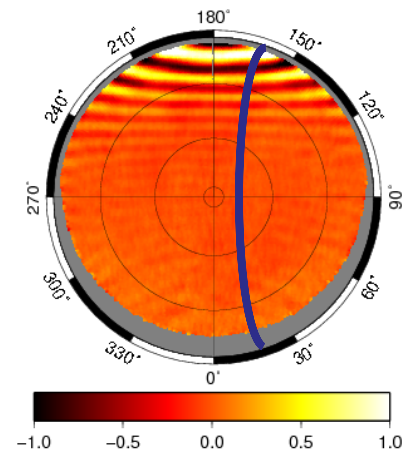
These exercises are <u>out of the scope of this 3h laboratory session</u>, and are posed for a possible further discussion…

As in the previous cases, the answers to the posed questions are also included as BACKUP slides.

A minimum knowledge of UNIX (e.g., awk) is required for these homework exercises.








```
gawk 'BEGIN{g=(77/60)^2}{print $6, $4, (g*($13-$14)-($15-$16))/(g-1)}' meas.txt > PC.txt
```

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Starting-up your laptop

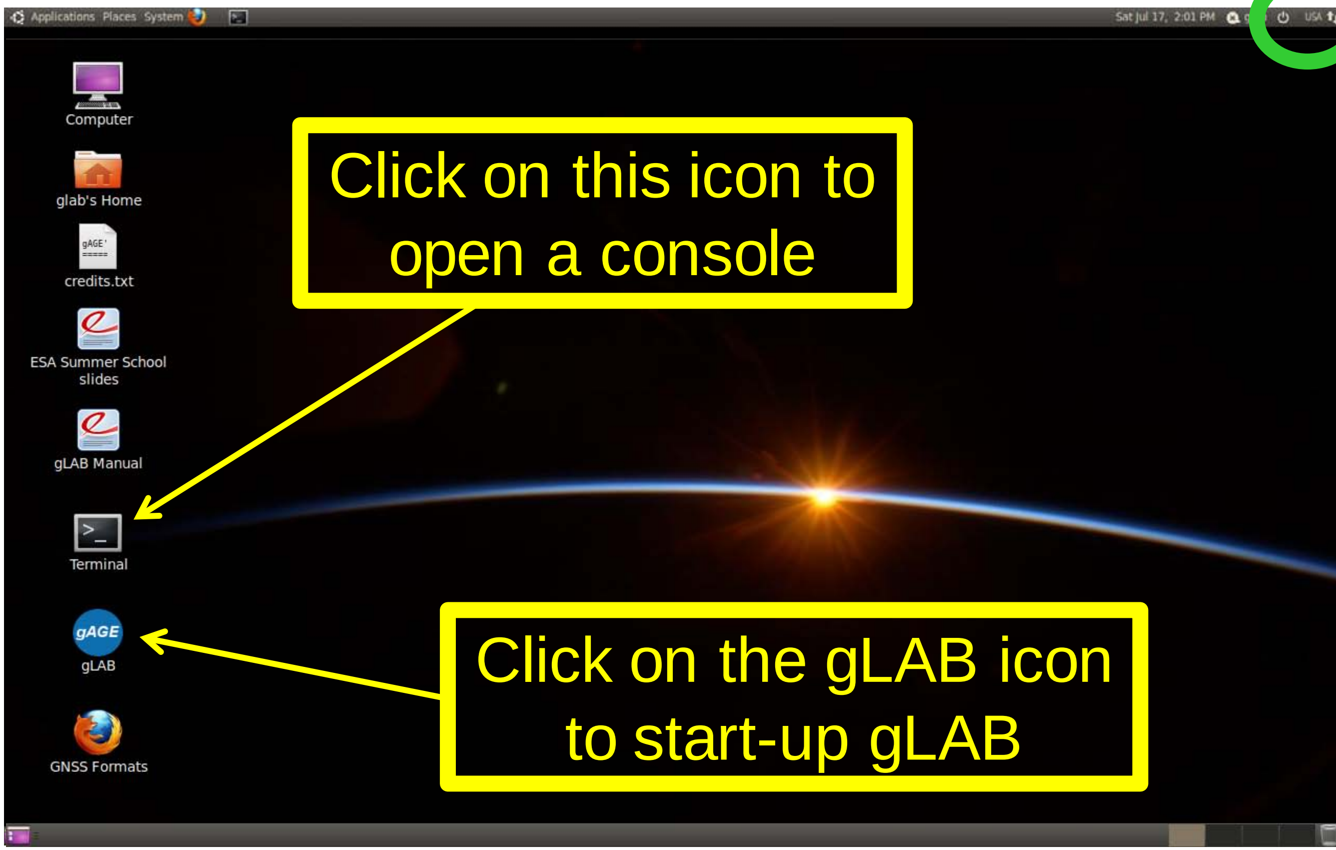
1. **Plug the stick into an USB port and *boot your laptop from the stick*.**

2. **Access the Boot Device Menu when starting-up the laptop.**

   Note: The way to do it *depends on your computer*:
   Usually, you should press **[ESC]** or **[F4]**, **[F10]**, **[F12]**....

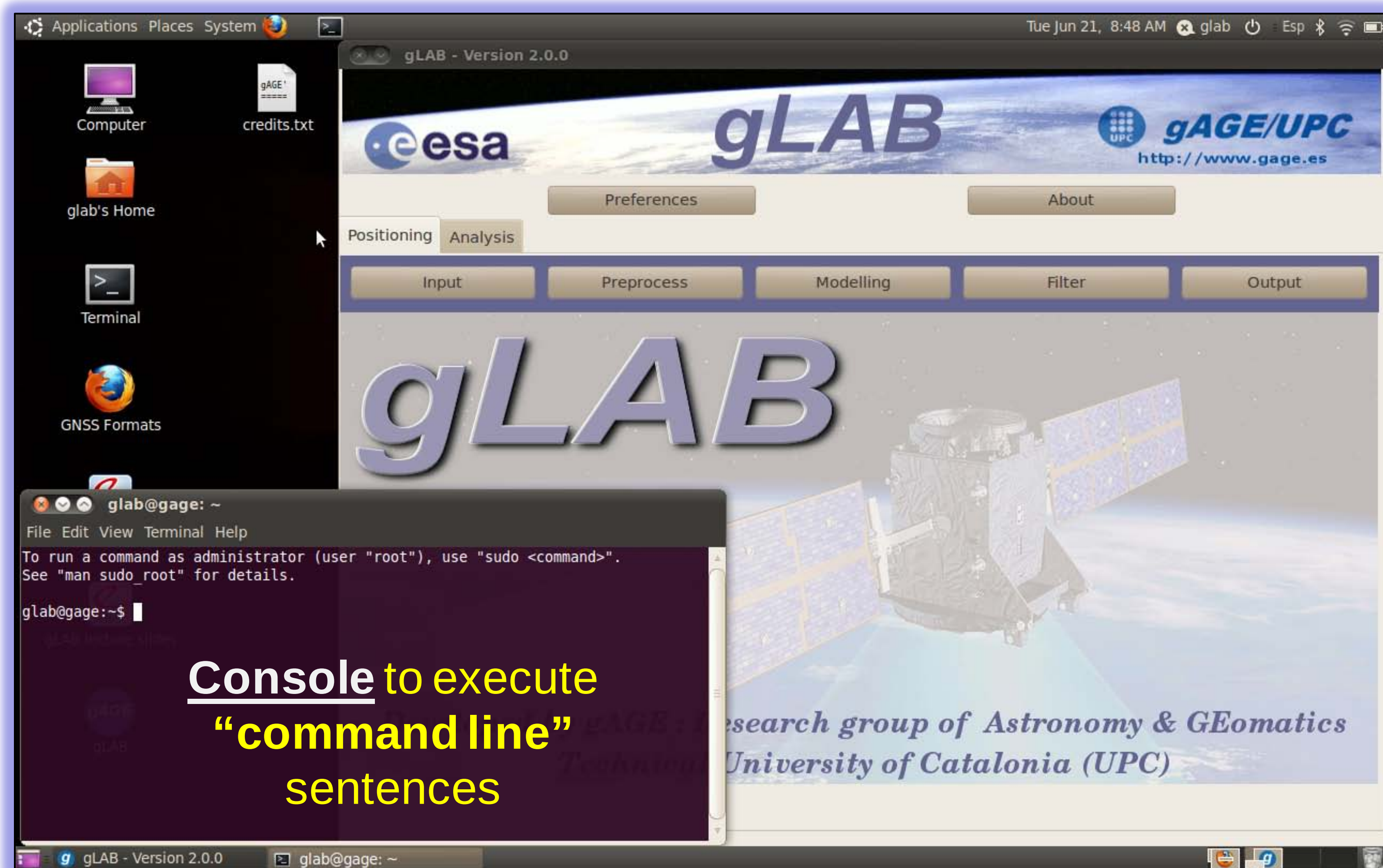
Starting-up your laptop

3. The following screen will appear after about 2 minutes:



The US keyboard is set by default. You can change it by clicking on the upper right corner.

Starting-up your laptop



Now, the system is ready to start working!

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Exercise 1: Model components analysis for SPP

- This exercise is devoted to analyze the different model components of measurements (ionosphere, troposphere, relativity, etc.). This is done both in the Signal-In-Space (SIS) and User Domains.

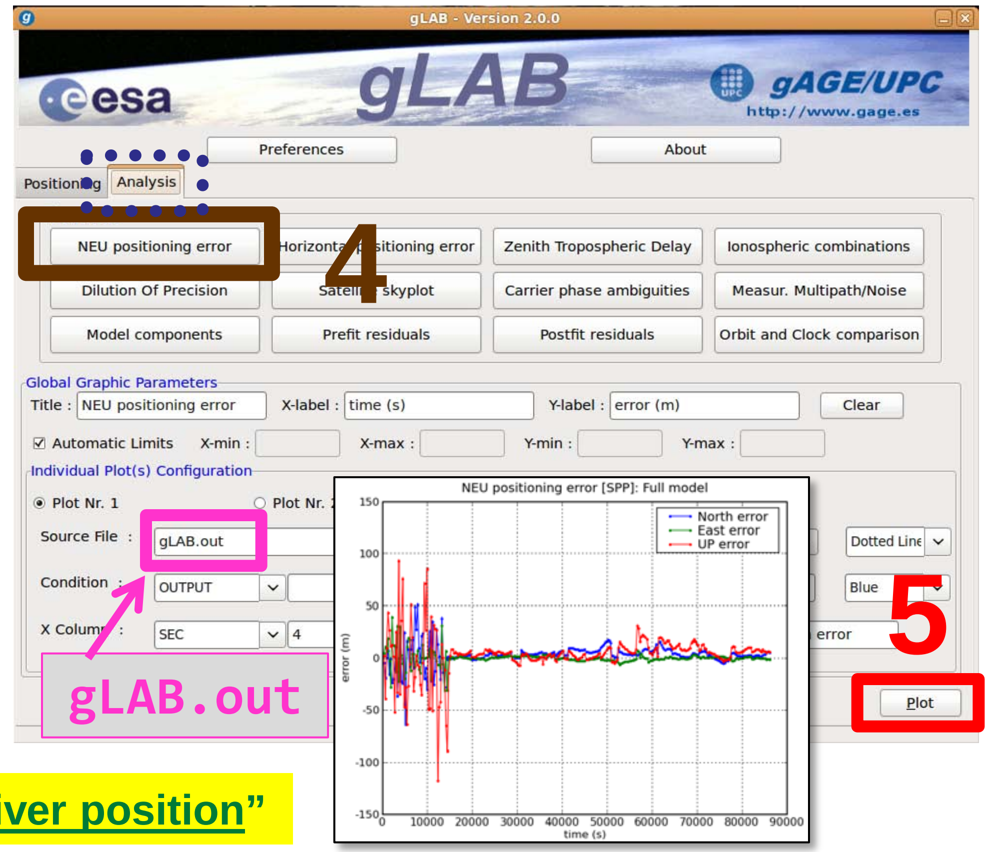
- To asses the modelling needs in terms of the GPS positioning service accuracy, the impact of neglecting each model component will be evaluated in a S/A on/off scenario.

Note: **Selective Availability (S/A)** was an intentional degradation of public GPS signals implemented for US national security reasons. S/A was turned off at May 2nd 2000 (Day-Of-Year 123).

Given that session time is limited to 3h, students who feel comfortable using gLAB, can skip part of the basic exercises (Ex1, Ex2) and jump to the Lab. Work Project.

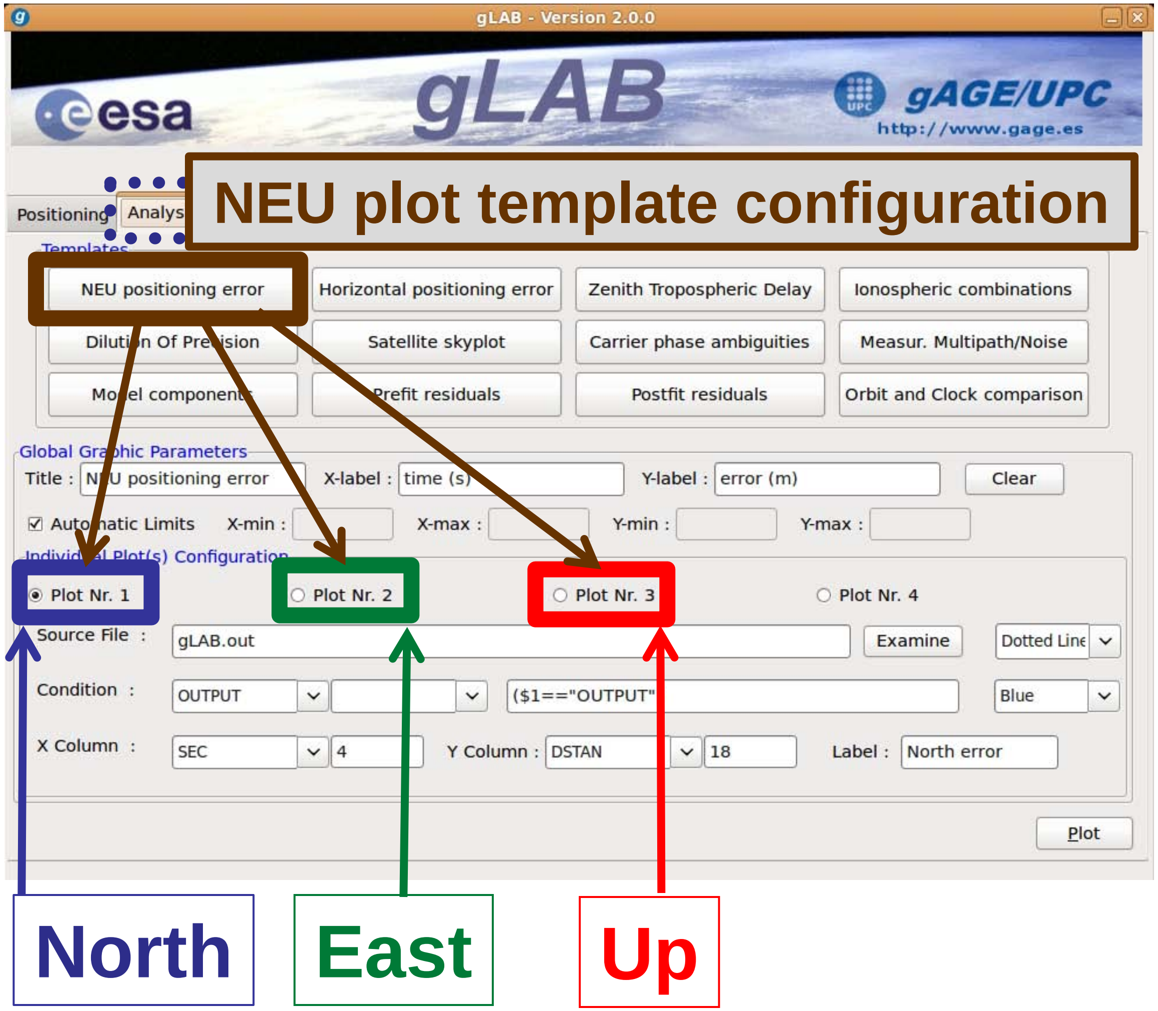
Exercise 1: SPP Model components analysis

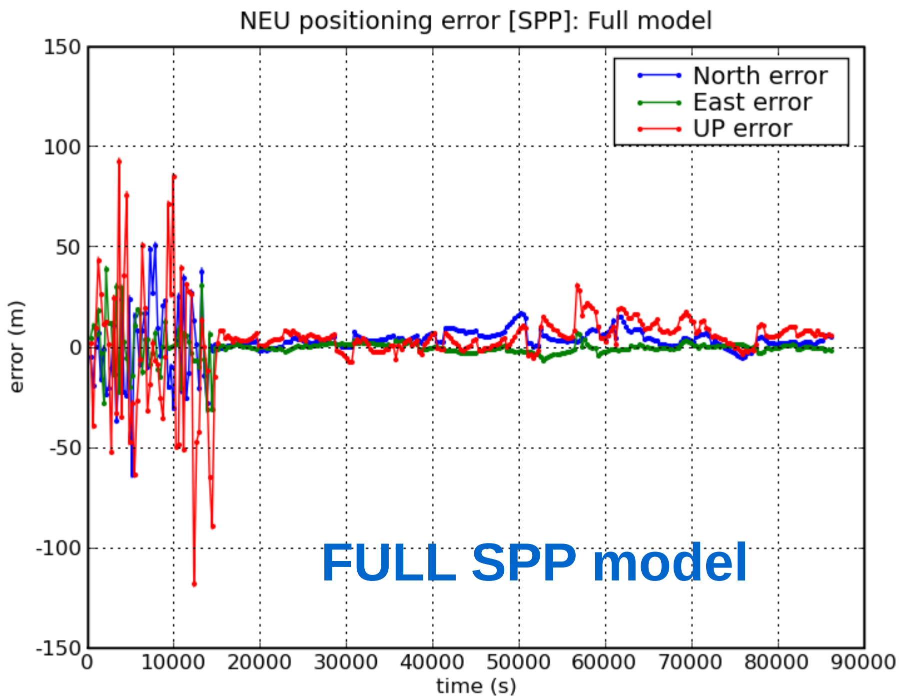
1. **Compute SPP using files:** `ramo1230.00o,brdc1230.00n, igs00P1060.snx.`



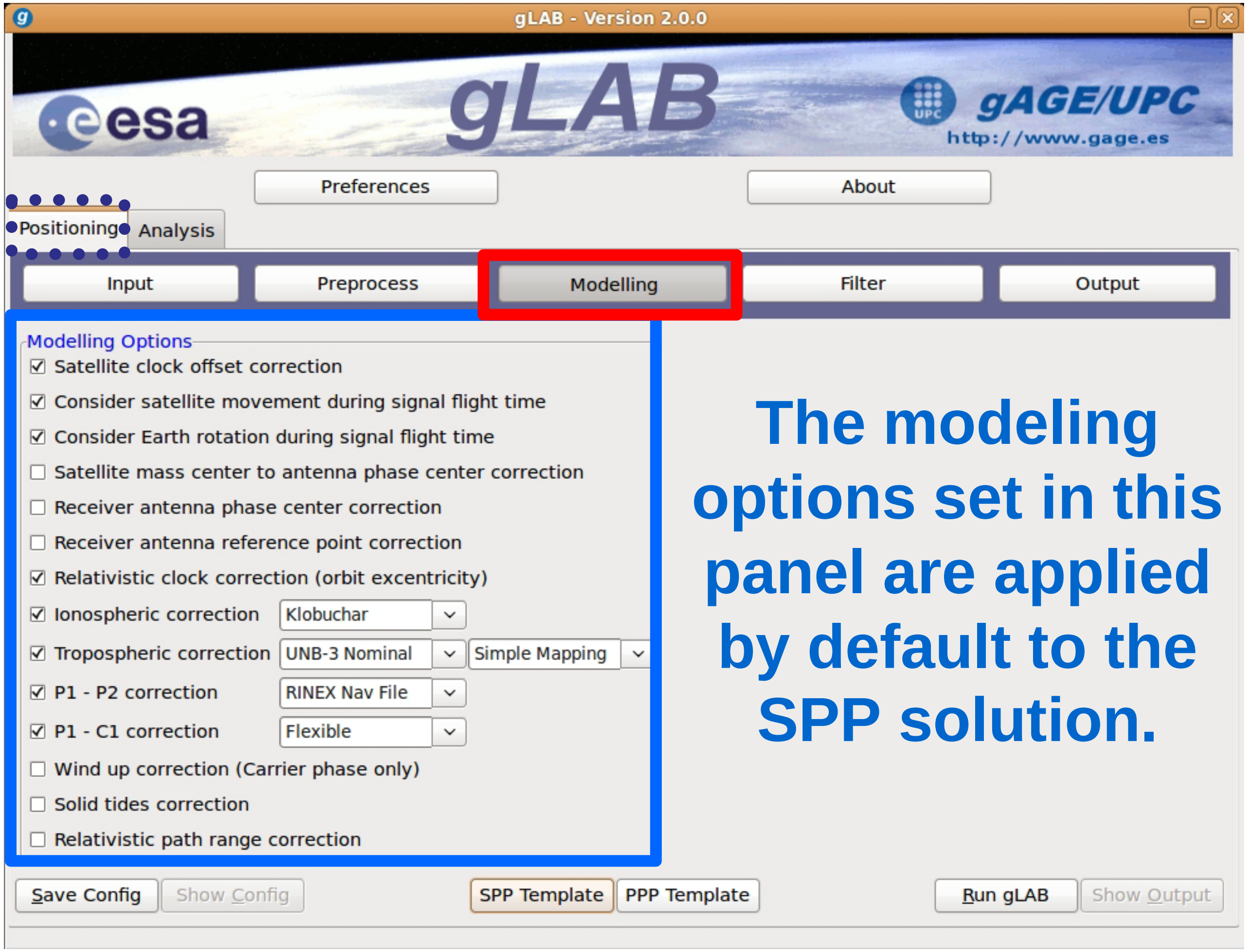
Note: Be sure of using the SINEX for "a priory receiver position"

NEU Position Error plot from gLAB.out





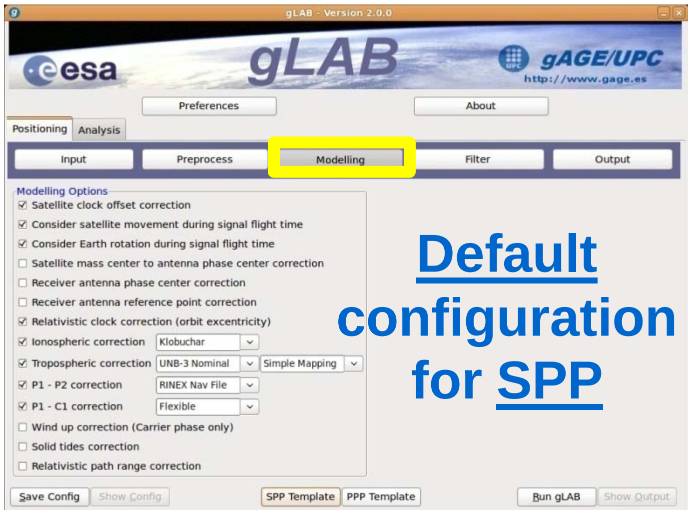
Exercise 1: SPP Model components analysis



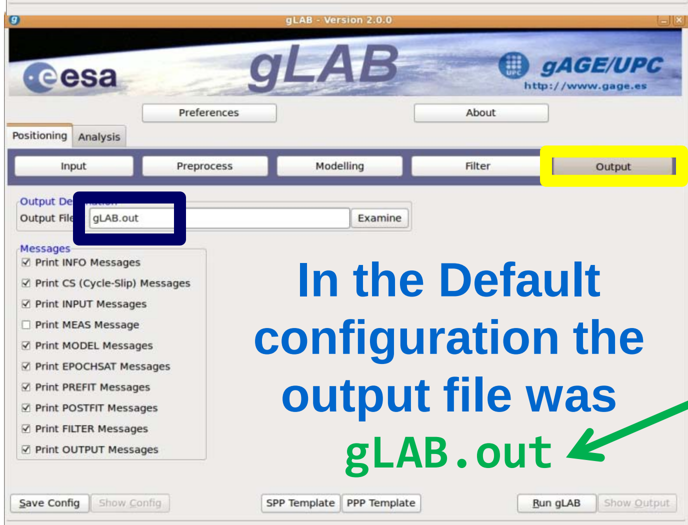
The different model components will be analyzed with gLAB:

- Using the previous data file, the impact of neglecting each model component will be evaluated in the Range and Position domains
- A baseline example of this analysis procedure for the ionospheric correction is provided as follows.
- The same scheme must be applied for all model terms.

Example of model component analysis: **IONO.**



Default configuration for SPP



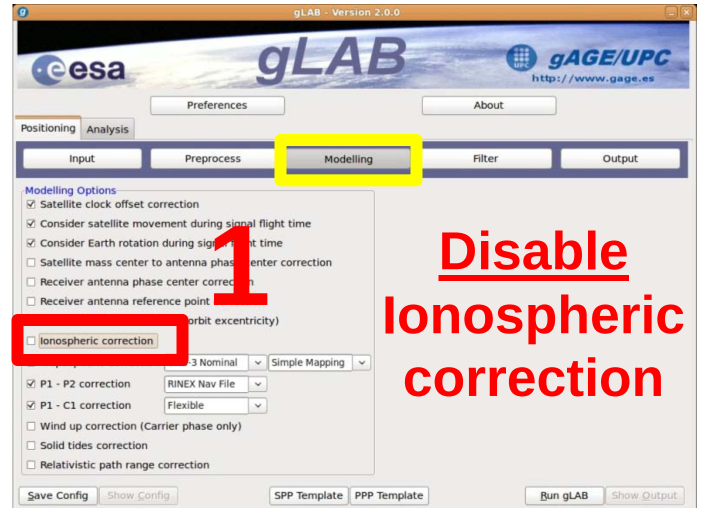
In the Default configuration the output file was `gLAB.out`

The procedure explained here is applicable for all the cases: iono, tropo…

1. **In Modeling** panel, disable the model component to analyze.
   (in this example: disable **Ionospheric correction**)

2. **Save** as **`gLAB1.out`** the associated output file.

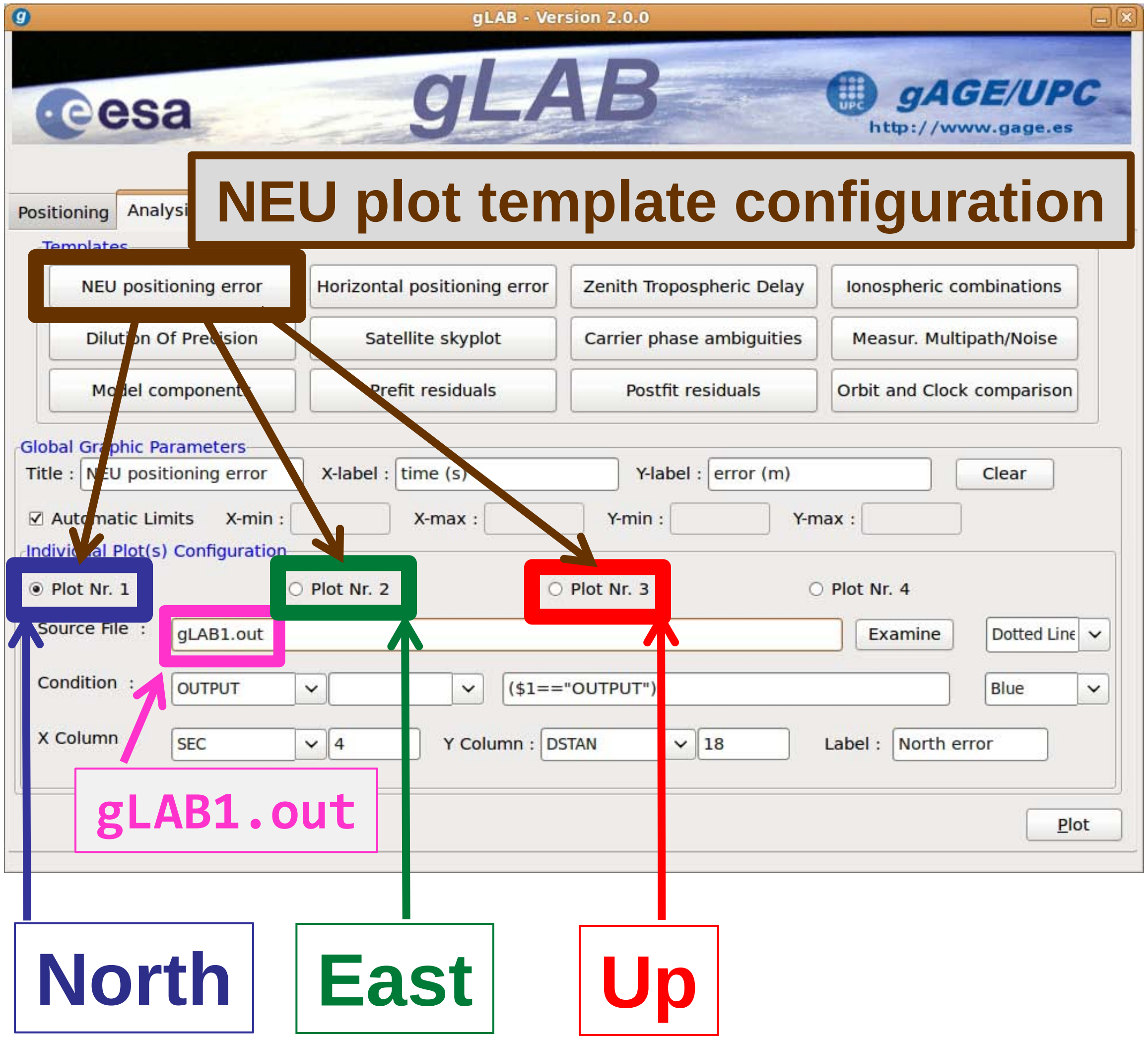
Notice that the **`gLAB.out`** file contains the processing results with the **FULL model**, as it was set in the default configuration.

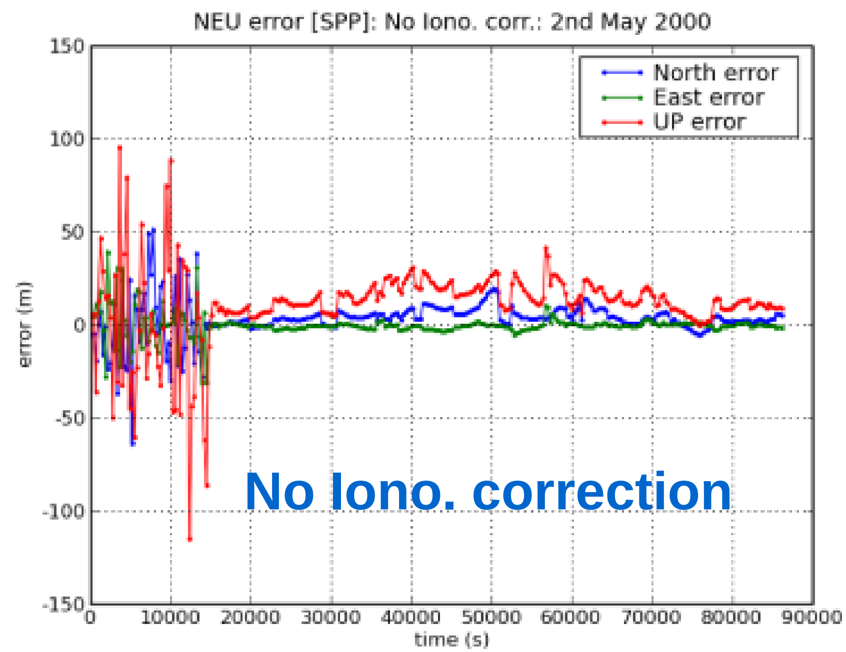


Disable Ionospheric correction

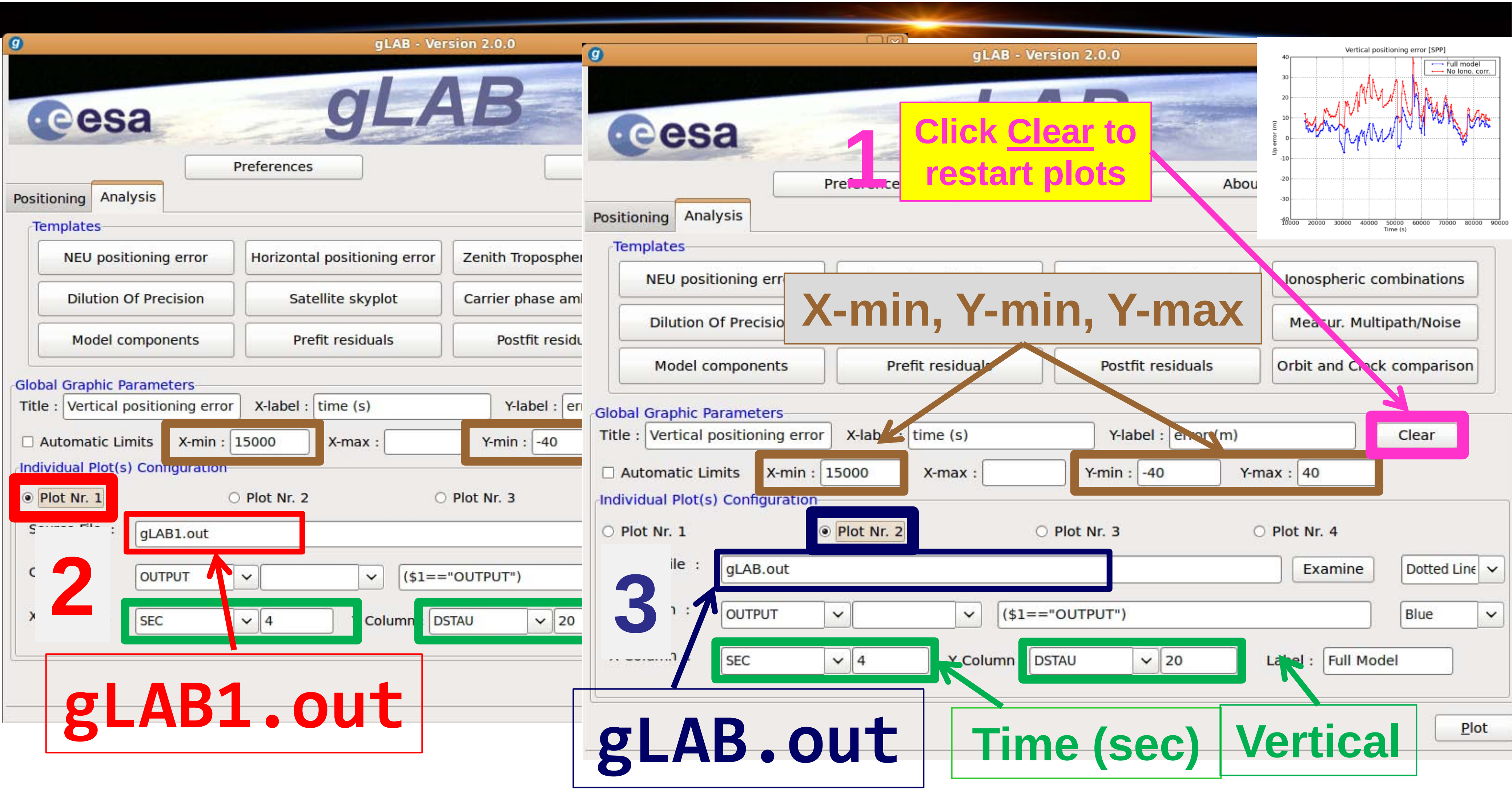
Set output file as `gLAB1.out`

NEU Position Error plot from gLAB1.out

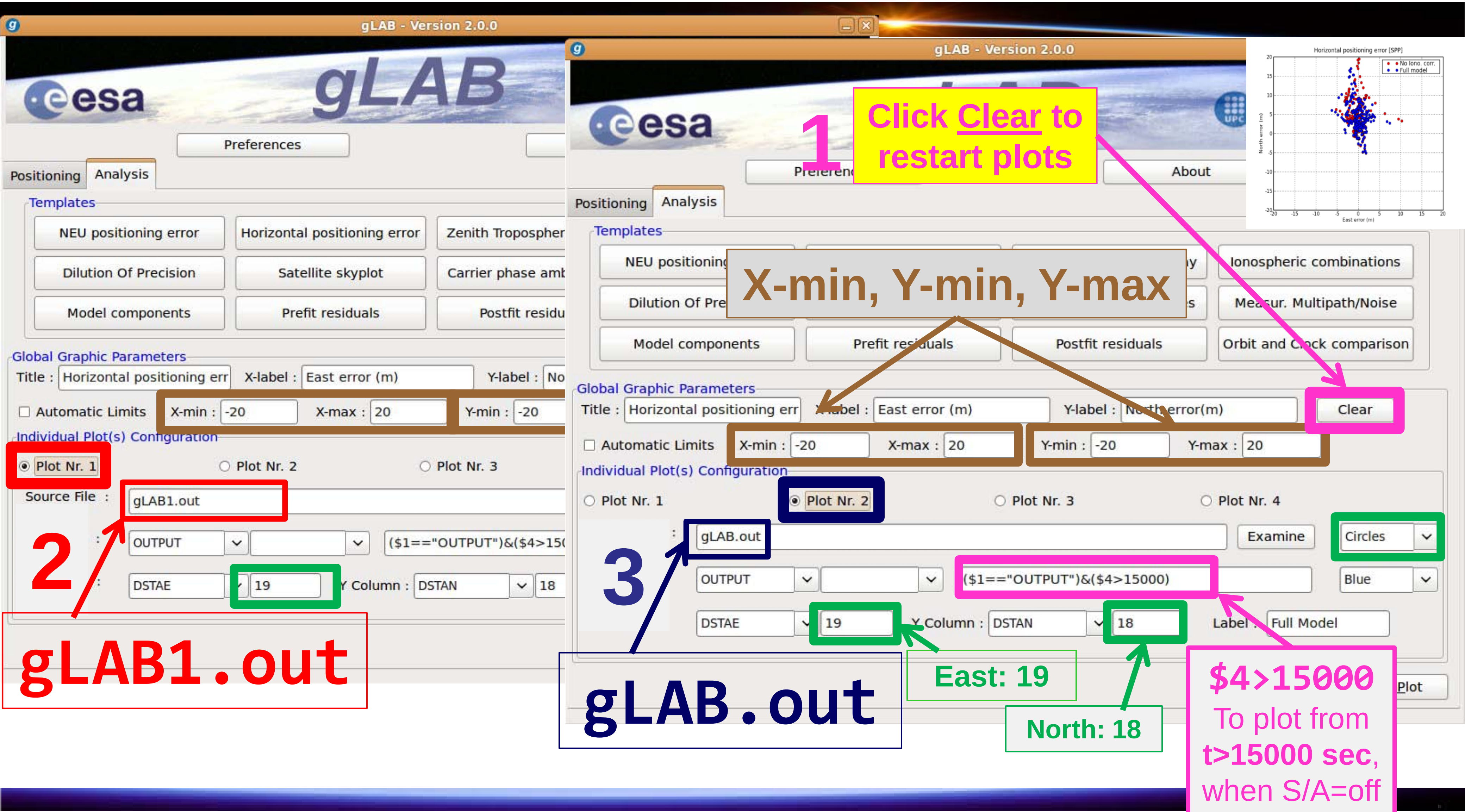




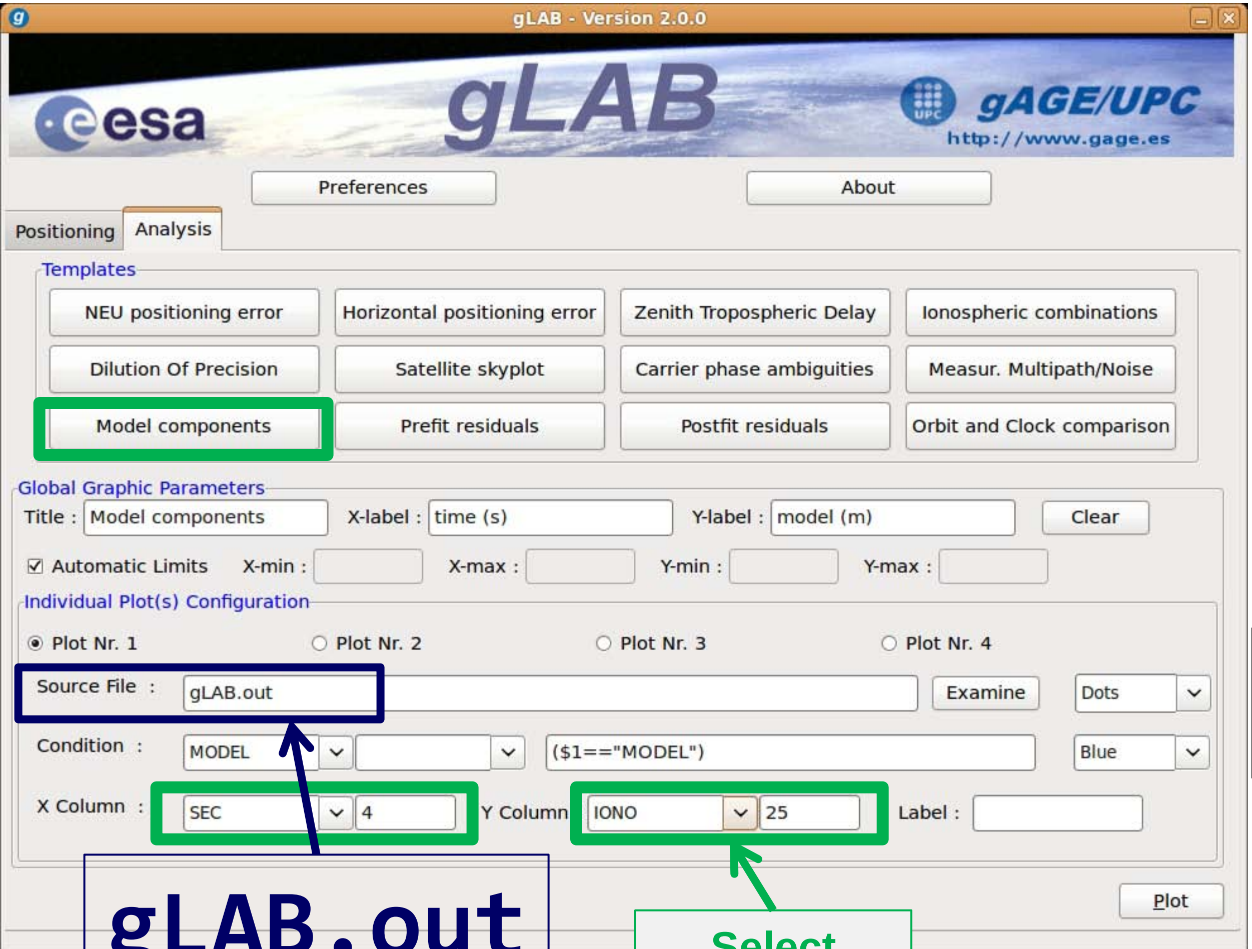
Vertical Position Error plot from gLAB.out, gLAB1.out



Horizontal Position Error plot: gLAB.out, gLAB1.out

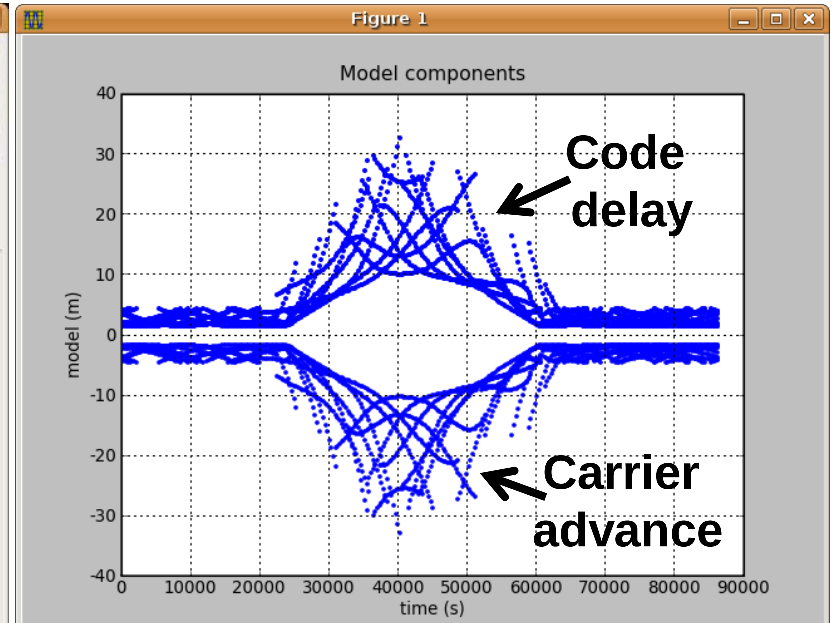


Ionospheric model component plot: **gLAB.out**



gLAB.out

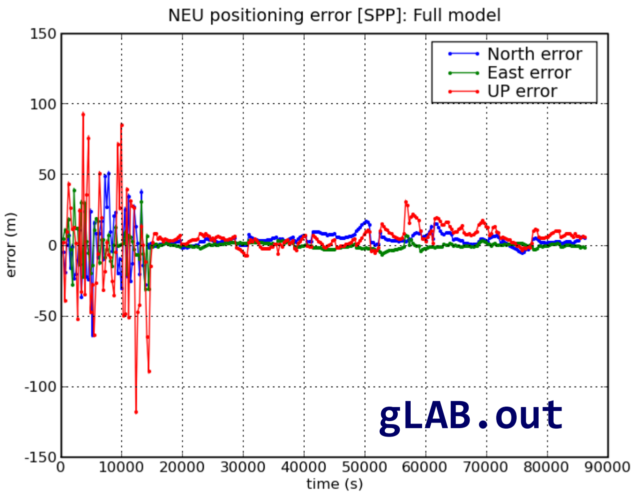
Select IONO

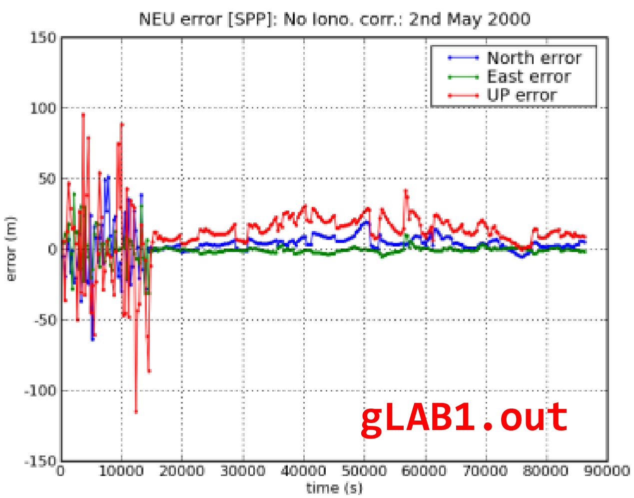


Ionosphere delays code and advances carrier measurements.

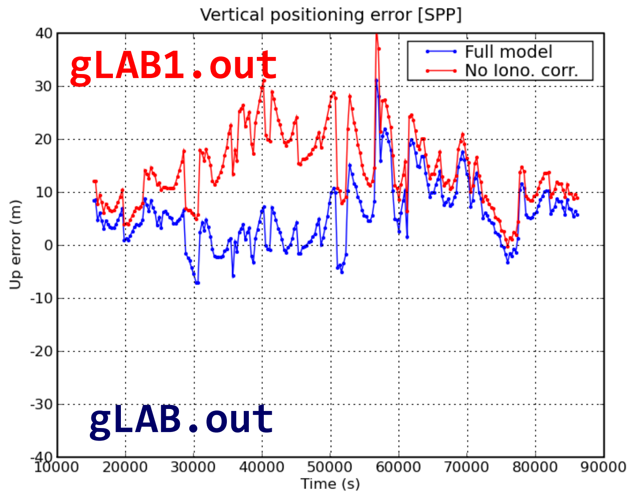
Note: Use the **gLAB.out** file.
In **gLAB1.out** file this model component was switched off.

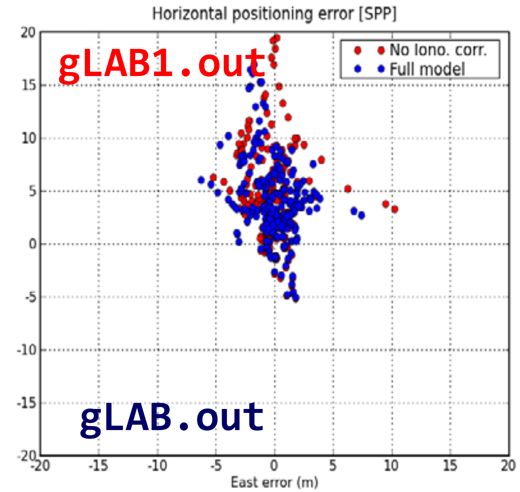
Summary: Iono. model component analysis

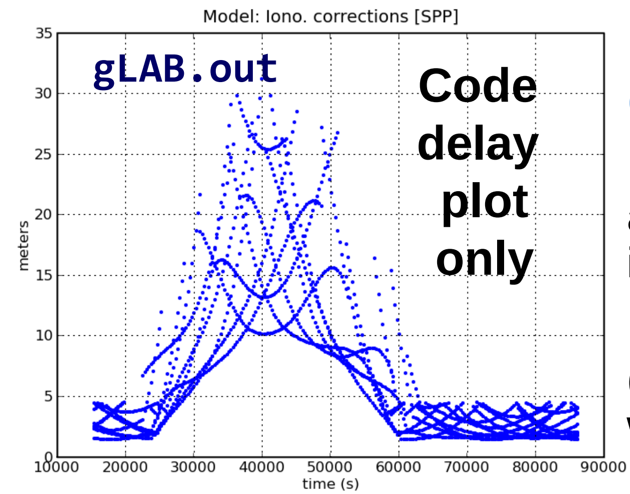




S/A=off Zoom







Ionospheric correction (broadcast Klobuchar)

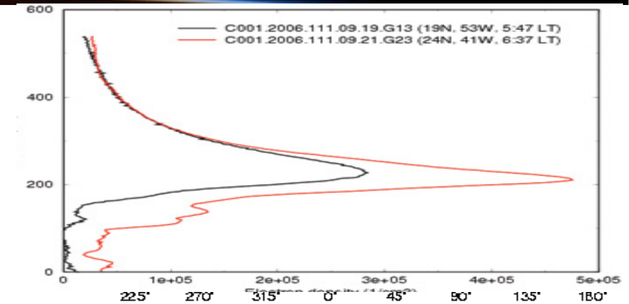
Ionospheric delays are larger at noon due to the higher insulation.

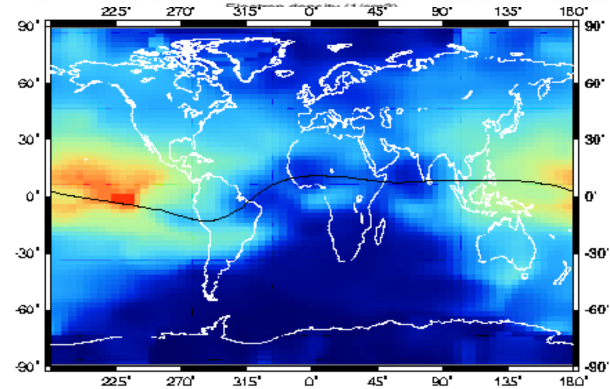
Large positioning errors (mainly in vertical) appear when neglecting iono. corr.

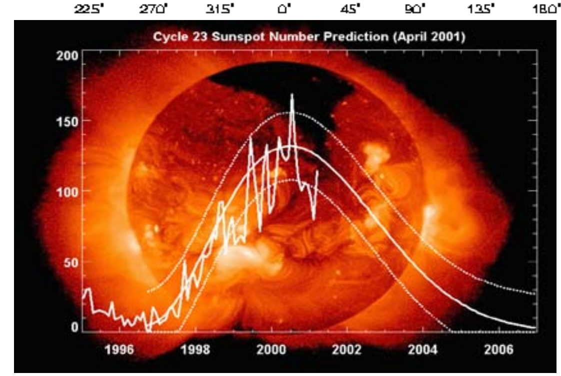
Exercise 1: SPP Model components analysis

Ionospheric delay

The ionosphere extends from about 60 km over the Earth surface until more than 2000 km, with a sharp electron density maximum at around 350 km. The ionospheric refraction depends, among other things, of the location, local time and solar cycle (11 years).







- First order (~99.9%) ionospheric delay δ_{ion} depends on the inverse of squared frequency:

$$\delta_{ion} = \frac{40.3}{f^2} I$$

  where I is the number of electrons per area unit along ray path (STEC: Slant Total Electron Content).

$$I = \int N_e ds$$

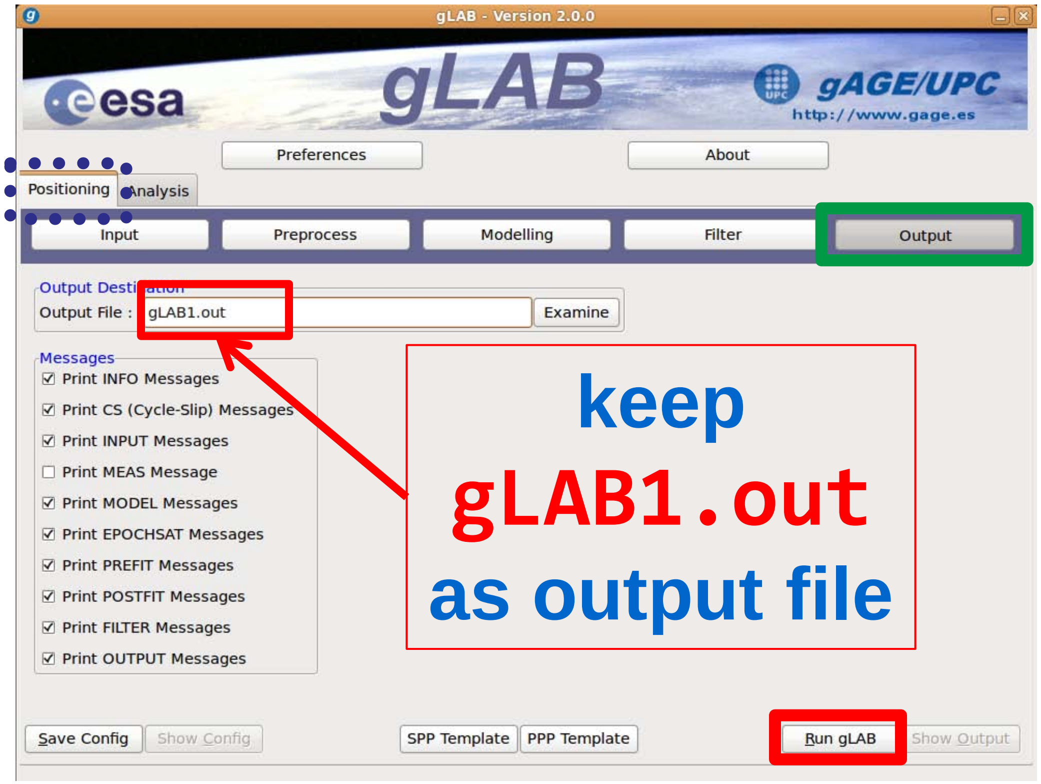
- Two-frequency receivers can remove this error source (up to 99.9%) using ionosphere-free combination of pseudoranges (PC) or carriers (LC).

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

- Single-frequency users can remove about a 50% of the ionospheric delay using the Klobuchar model, whose parameters are broadcast in the GPS navigation message.

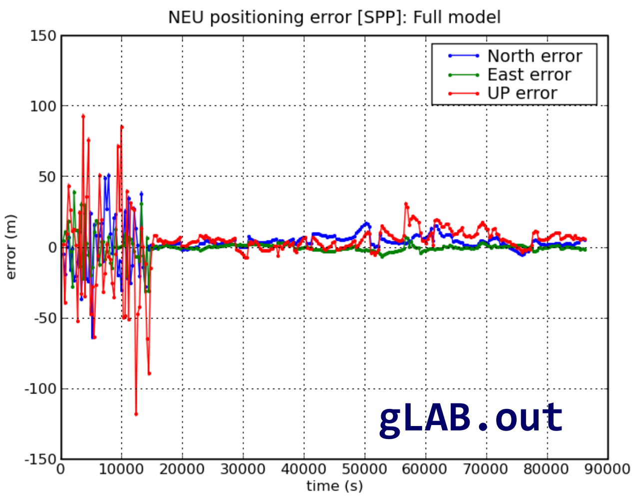
Example of model component analysis: **TROPO.**

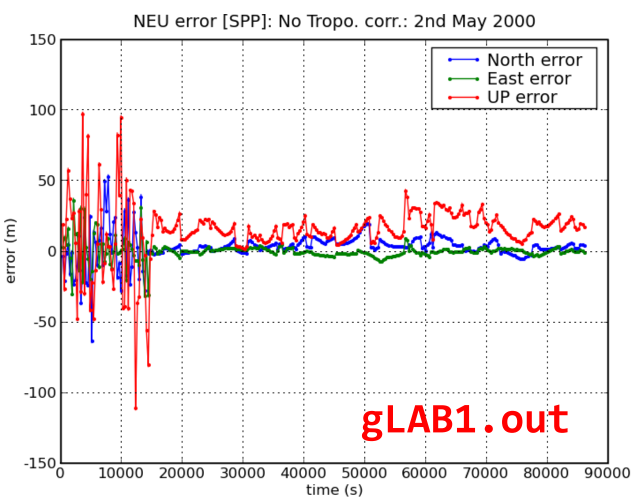
The ***gLAB*** configuration can be set-up as follows, to repeat the processing **without** applying the **tropospheric** correction (but using the ionosphere again!):



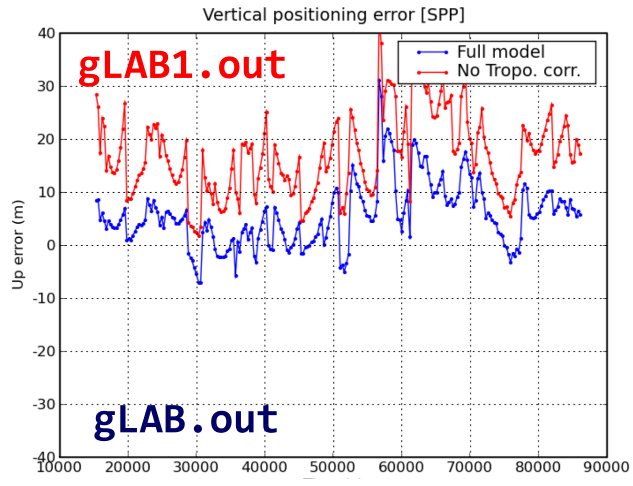
- The same scheme must be applied for all other model terms (TGDs, relat...)

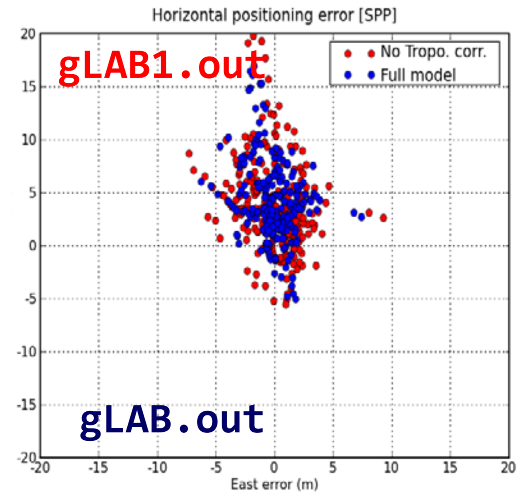
Exercise 1: SPP Model components analysis

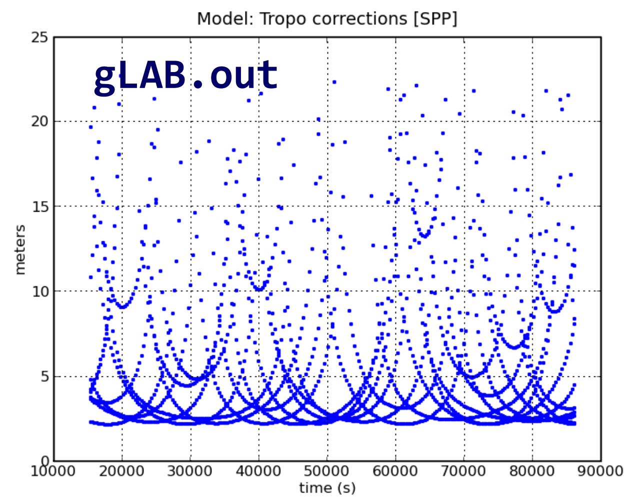




S/A=off Zoom







Tropospheric correction(blind model)

Tropospheric and vertical error are highly correlated.

A displacement of vertical component appears when neglecting tropo. corrections.

Exercise 1: SPP Model components analysis

Tropospheric delay

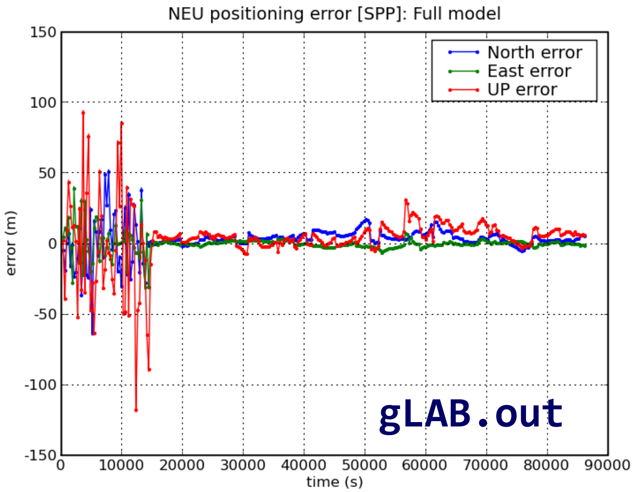
The troposphere is the atmospheric layer placed between Earth's surface and an altitude of about 60 km.

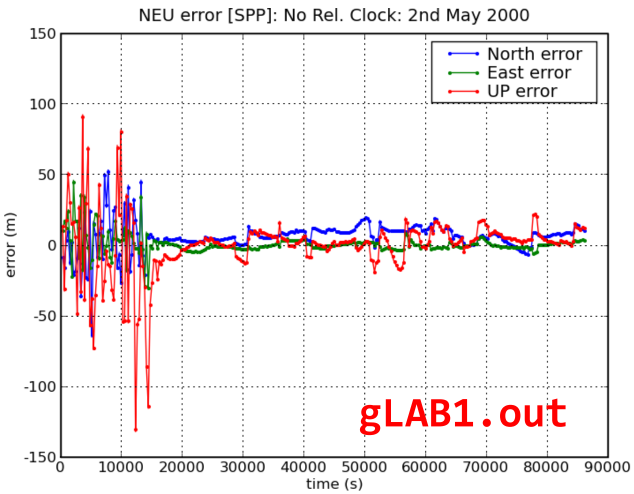
The effect of troposphere on GNSS signals appears as an extra delay in the measurement of the signal travelling from satellite to receiver.

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

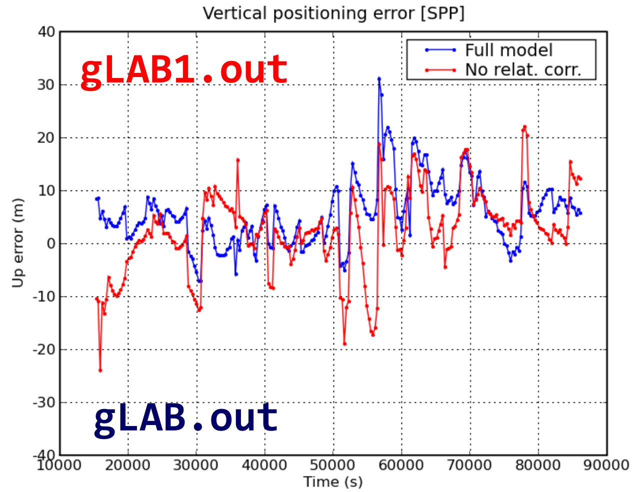
- An **hydrostatic component**, composed of dry gases (mainly nitrogen and oxygen) in hydrostatic equilibrium. This component can be treated as an ideal gas. Its effects vary with the temperature and atmospheric pressure in a quite predictable manner, and it is the responsible of about 90% of the delay.
- A **wet component** caused by the water vapor condensed in the form of clouds. It depends on the weather conditions and varies faster than the hydrostatic component and in a quite random way. For high accuracy positioning, this component must be estimated together with the coordinates and other parameters in the navigation filter.

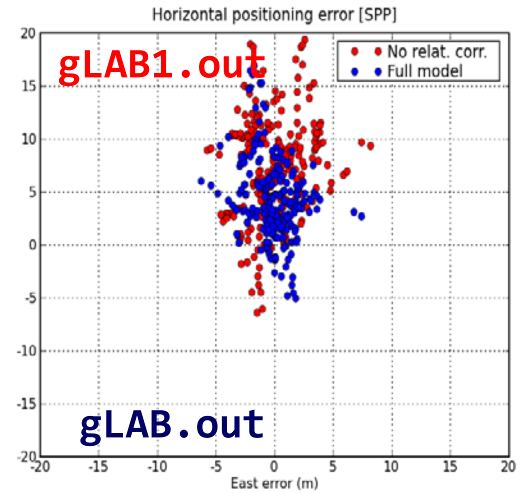
Exercise 1: SPP Model components analysis

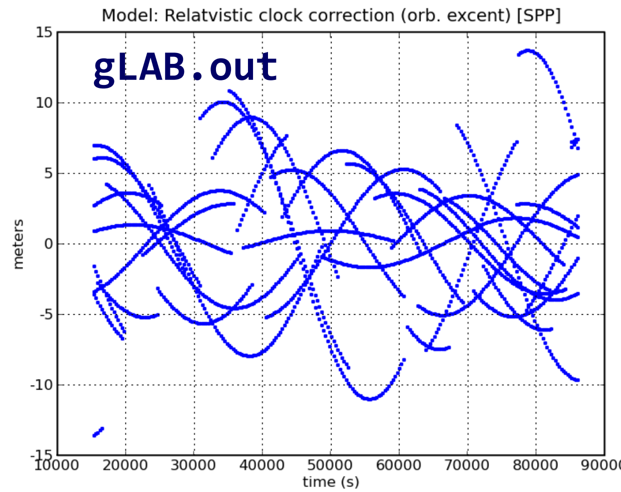




S/A=off Zoom







Relativistic correction on satellite clock due to orbit eccentricity

This is an additional correction to apply at the receiver level. The satellite clock oscillator has been modified to compensate for the main effect (~40μs/day)

Exercise 1: SPP Model components analysis

Relativistic clock correction

1) A constant component, depending only on nominal value of satellite's orbit major semi-axis. It is corrected modifying satellite's clock oscillator frequency:

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

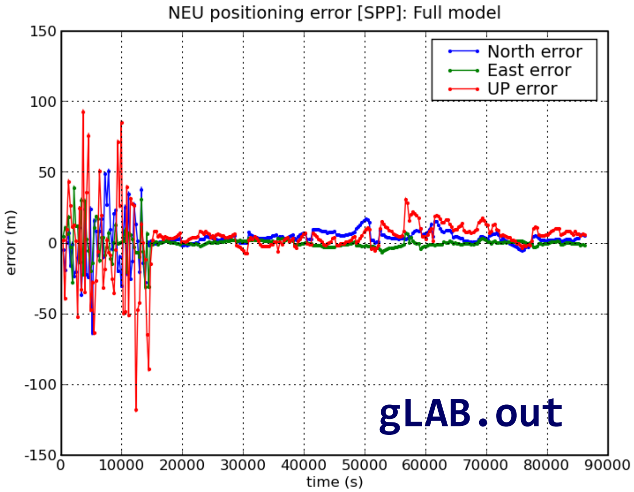
being f_0 = *10.23 MHz*, we have $\Delta f = 4.464\ 10^{-10}\ f_0 = 4.57\ 10^{-3}$ *Hz*. So, satellite should use $f'_0 = 10.22999999543$ *MHz*.

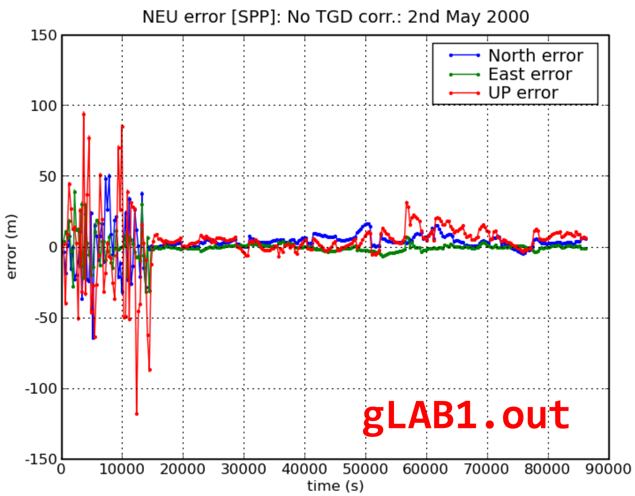
2) A periodic component due to orbit eccentricity must be corrected by user receiver:

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

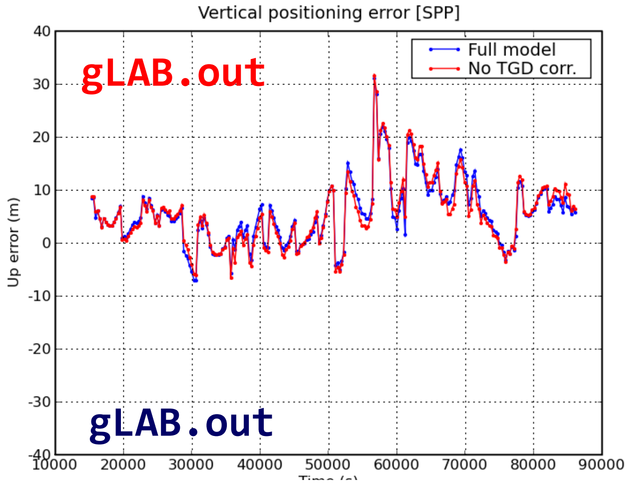
Being $\mu = G\ M_E = 3.986005\ 10^{14}\ (m^3/s^2)$ the gravitational constant, c =299792458 (m/s) light speed in vacuum, a is orbit's major semi-axis, e is its eccentricity, E is satellite's eccentric anomaly, and **r** and **v** are satellite's geocentric position and speed in an inertial system.

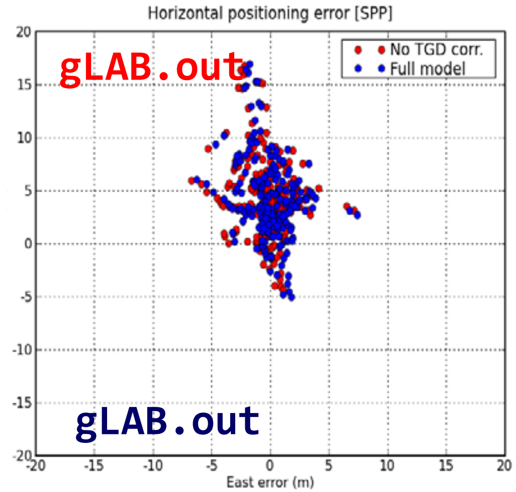
Exercise 1: SPP Model components analysis

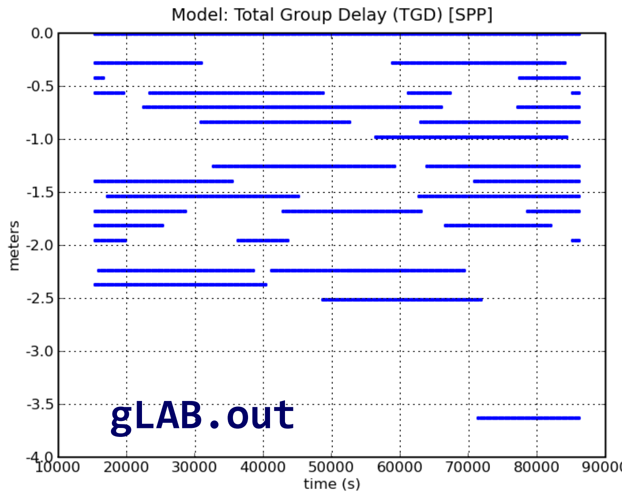




S/A=off Zoom







P2-P1 Differential Code Bias

(Total Group Delay [TGD]) correction.

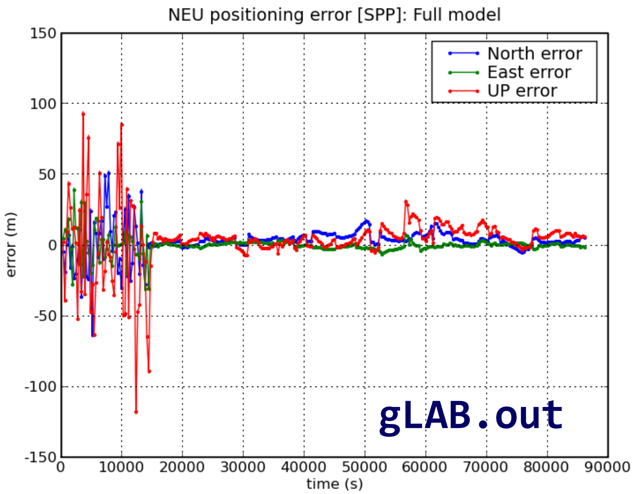
These instrumental delays can affect up to few meters, being the satellite TGDs broadcast in the navigation message for single frequency users.

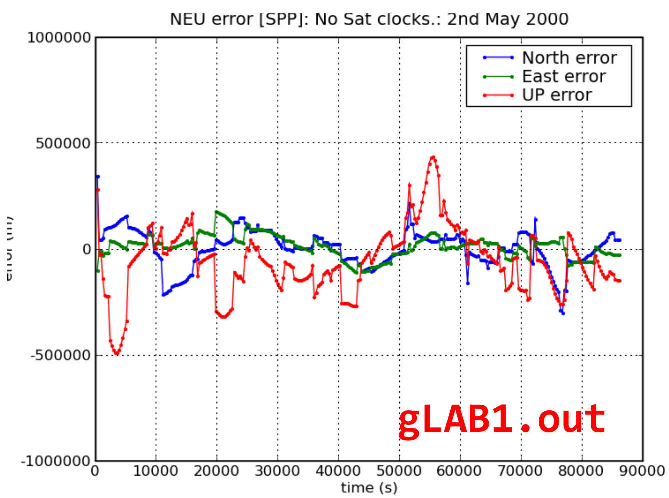
Total Group Delay correction (TGD)

(P2-P1 Differential Code Bias [DCB])

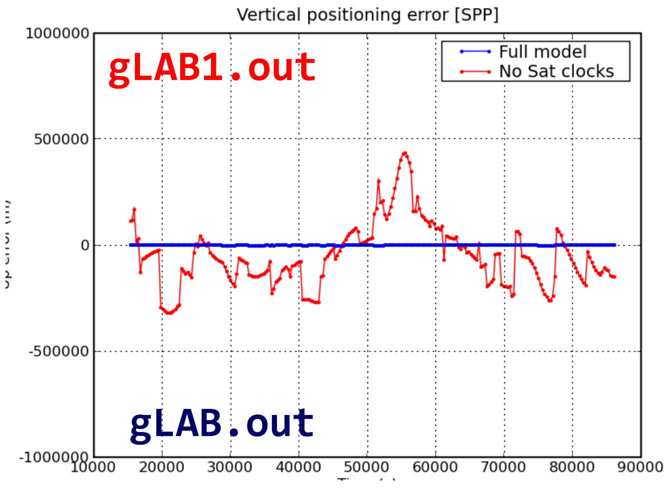
- Instrumental delays are associated to antennas, cables, as well as different filters used in receivers and satellites. They affect both code and carrier measurements.
- Code instrumental delays depend on the frequency and the codes used, and are different for the receiver and the satellites.
- Dual frequency users cancel such delays when using the ionosphere free combination of codes and carrier phases.
- For single frequency users, the satellite instrumental delays (TGDs) are broadcast in the navigation message. The receiver instrumental delay, on the other hand, is assimilated into the receiver clock estimation. That is, being common for all satellites, it is assumed as zero and it is included in the receiver clock offset estimation.

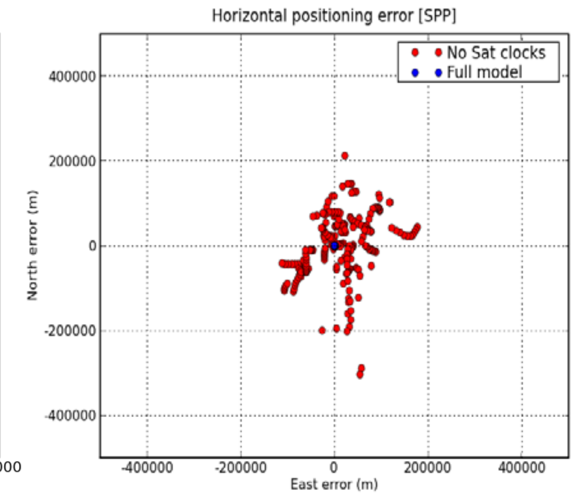
Exercise 1: SPP Model components analysis

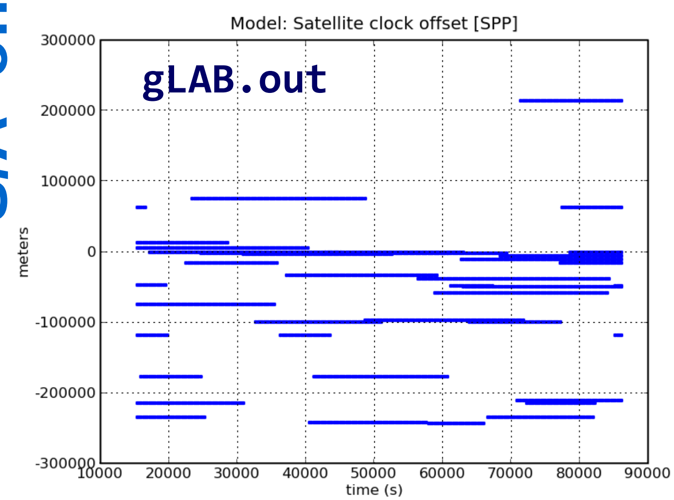




S/A=off Zoom







Satellite clock offsets

This is the largest error source, and it may introduce errors up to a thousand kilometers.

Satellite clock offsets

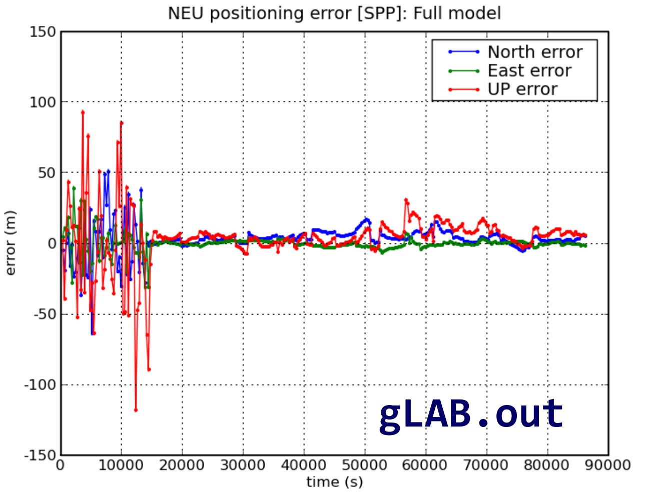
- They are time-offsets between satellite/receiver clocks time and GPS system time (provided by the ground control segment).

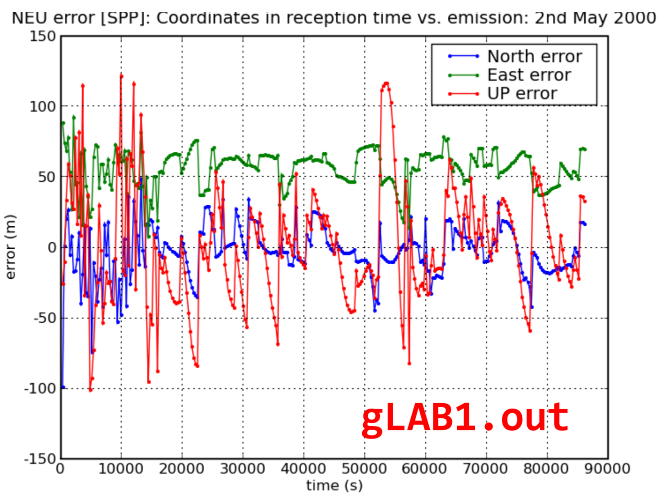
- The receiver clock offset is estimated together with receiver coordinates.

- Satellite clock offset values are provided:
  - In real-time, within the broadcast navigation message with a few meters of error (S/A=off)

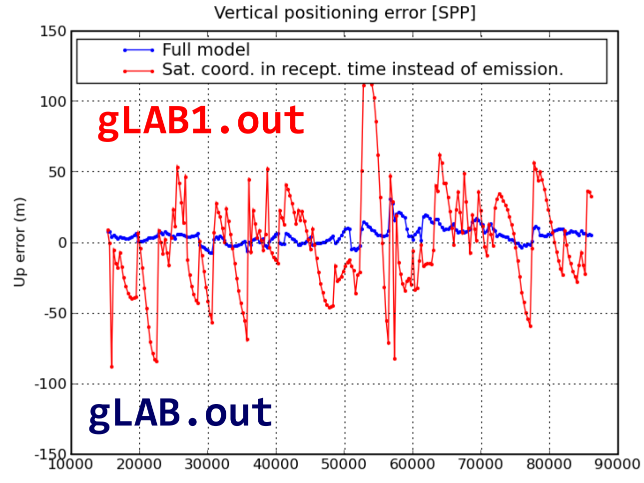
    or,
  - In post-process mode, by IGS precise products with centimeter-level accuracy.

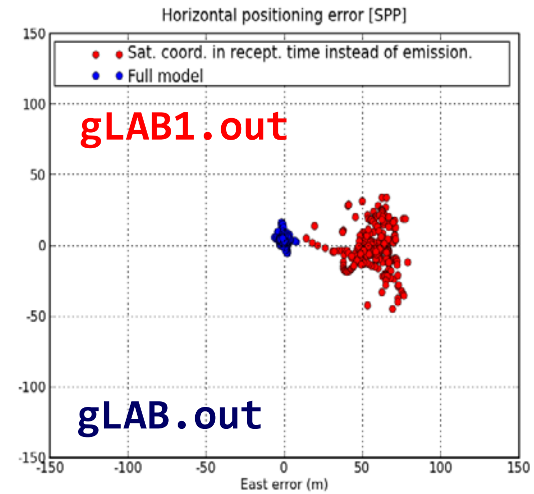
Exercise 1: SPP Model components analysis

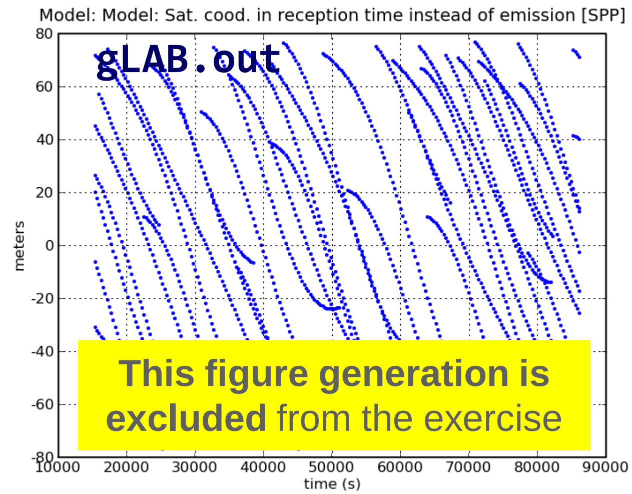




S/A=off Zoom







Satellite coordinates in reception time instead of emission time

Unset both (in gLAB Model):

- **Satellite movement during signal flight time.**
- **Earth rotation during signal flight time.**

Exercise 1: SPP Model components analysis

gLAB implements the following well known algorithm to compute the satellite coordinates (both from broadcast message or IGS precise orbits):

1. From receiver time-tags (i.e., reception time in the receiver clock), compute emission time in GPS system time:

$$T[emission] = t_{rec}(T_R) - (C1/c + dt^S)$$

Notice that code pseudorange is a link between transmission and reception times in the satellite and receiver clocks

$$\mathbf{C1 = c\ \Delta t = c\ [t_{rec}(T_R) - t^{ems}(T^S)]}$$

dt^S : satellite clock-offset
c: light speed in vacuum

2. Compute satellite coordinates at emission time *T[emission]*

$$T[emission] \rightarrow \textbf{[orbit]} \rightarrow (X^{sat}, Y^{sat}, Z^{sat})_{CTS[emission]}$$

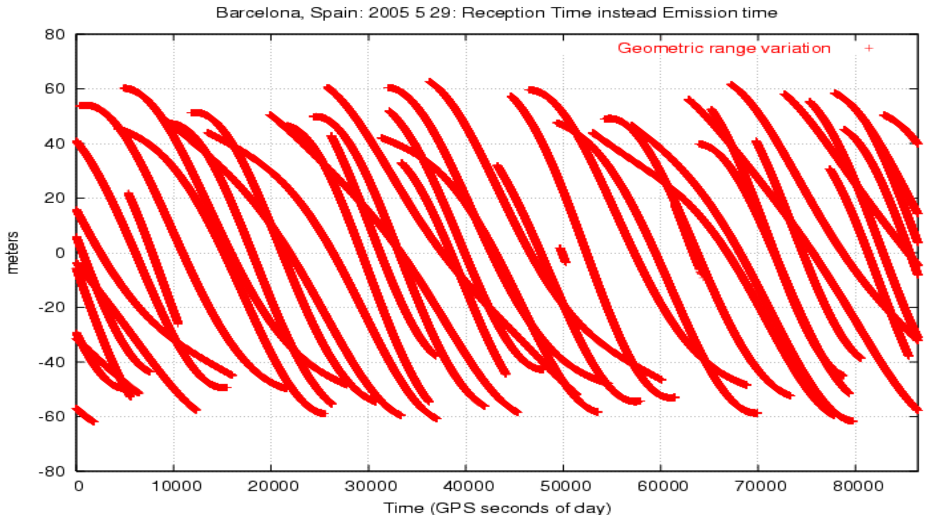
3. Account for Earth rotation during traveling time from emission to reception "**Δt**" *(CTS reference system at* ***reception time is used to build the nav. equations****):*

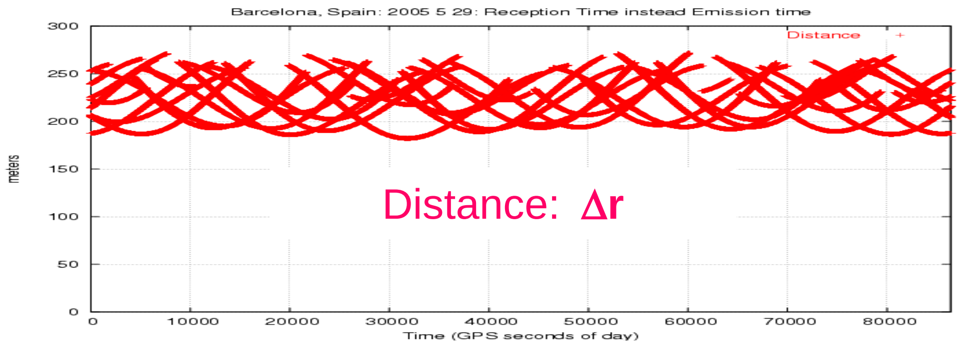
$$(X^{sat}, Y^{sat}, Z^{sat})_{CTS[\mathbf{reception}]} = R_3(\omega_E\ \Delta t) \cdot (X^{sat}, Y^{sat}, Z^{sat})_{CTS[emission]}$$

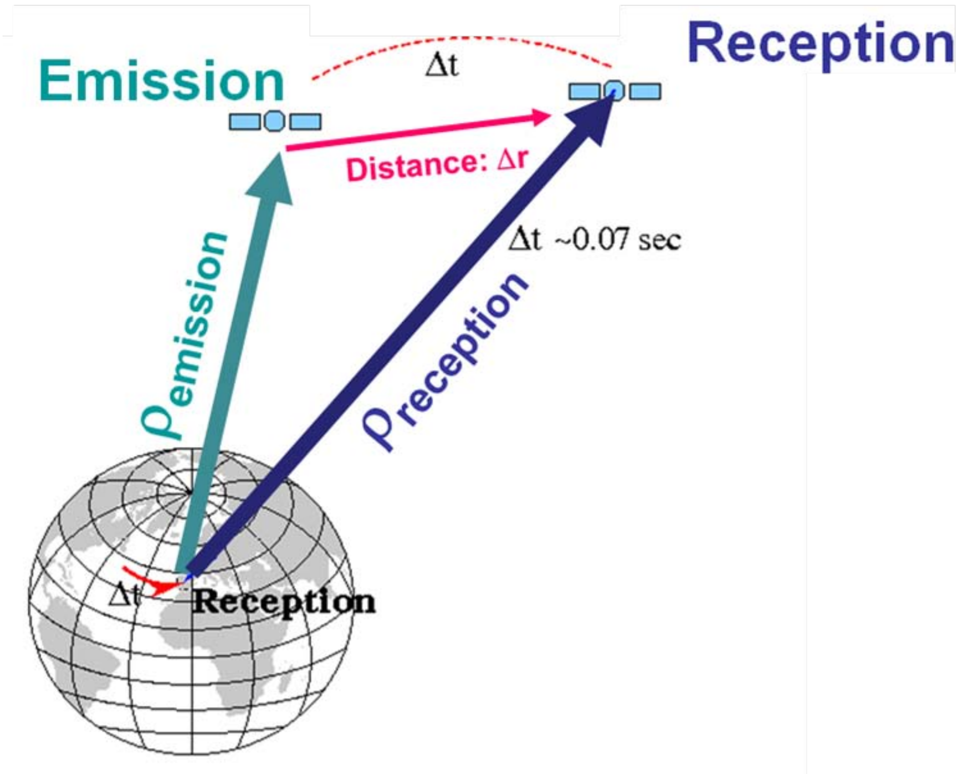
Thence, Satellite movement (i.e, satellite coordinates at emission instead of reception time) and Earth rotation during signal flight time are two important issues to take into account

Exercise 1: SPP Model components analysis

Range variation: $\Delta\rho = \rho_{emission} - \rho_{reception}$



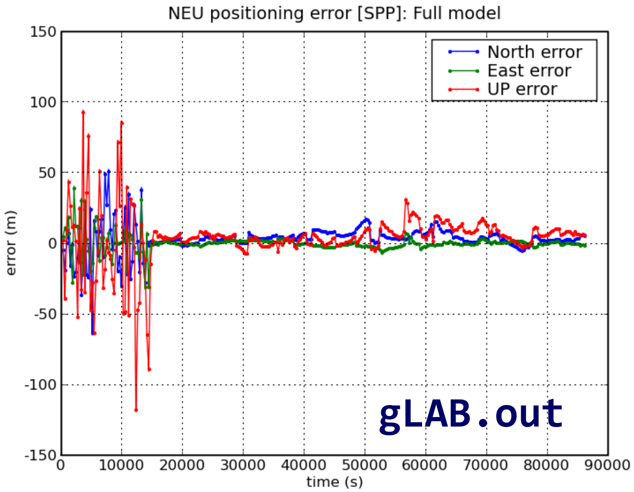


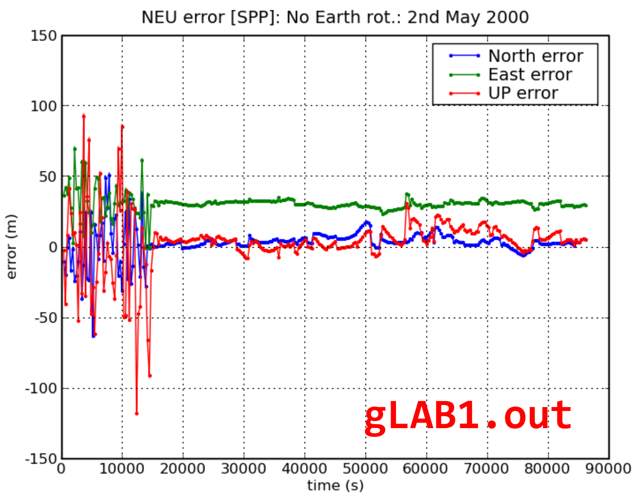


Note: $\rho_{reception}$ is computed unsetting in gLAB:

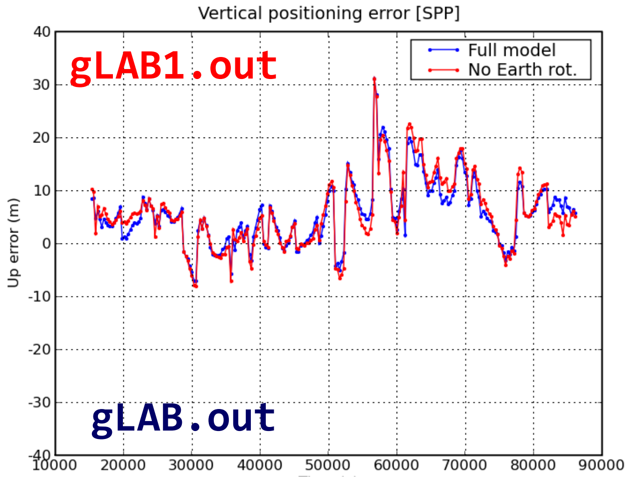
- **Satellite movement during signal flight time.**
- **Earth rotation during signal flight time.**

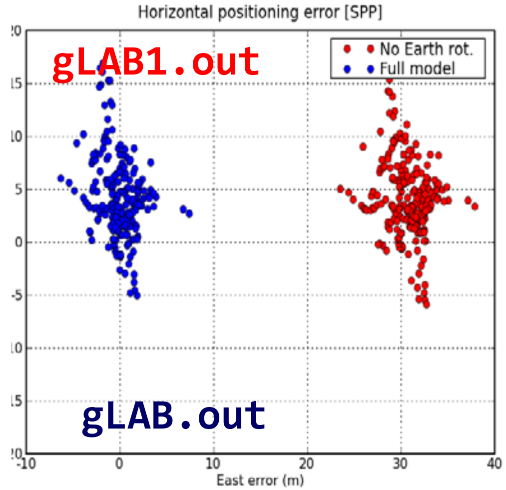
Exercise 1: SPP Model components analysis

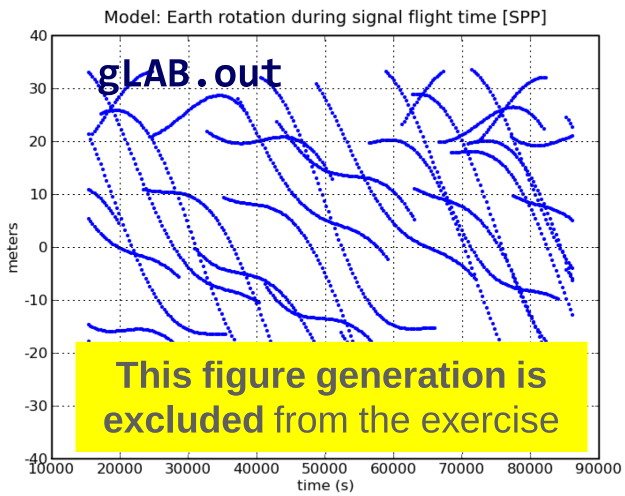




S/A=off Zoom







Earth rotation during signal flight time.

Notice the clear eastward shift when neglecting this term of the model.

Exercise 2: Model components analysis for PPP

- This exercise is devoted to analyze the additional model components used in Precise Point Positioning (the ones which are not required by SPP). This is done in Range and Position Domains.
- Because PPP uses precise orbits and clocks, the positioning accuracy is not affected by the selective availability as with broadcast orbits and clocks, and thence, no distinction will be done with S/A=on or S/A=off.

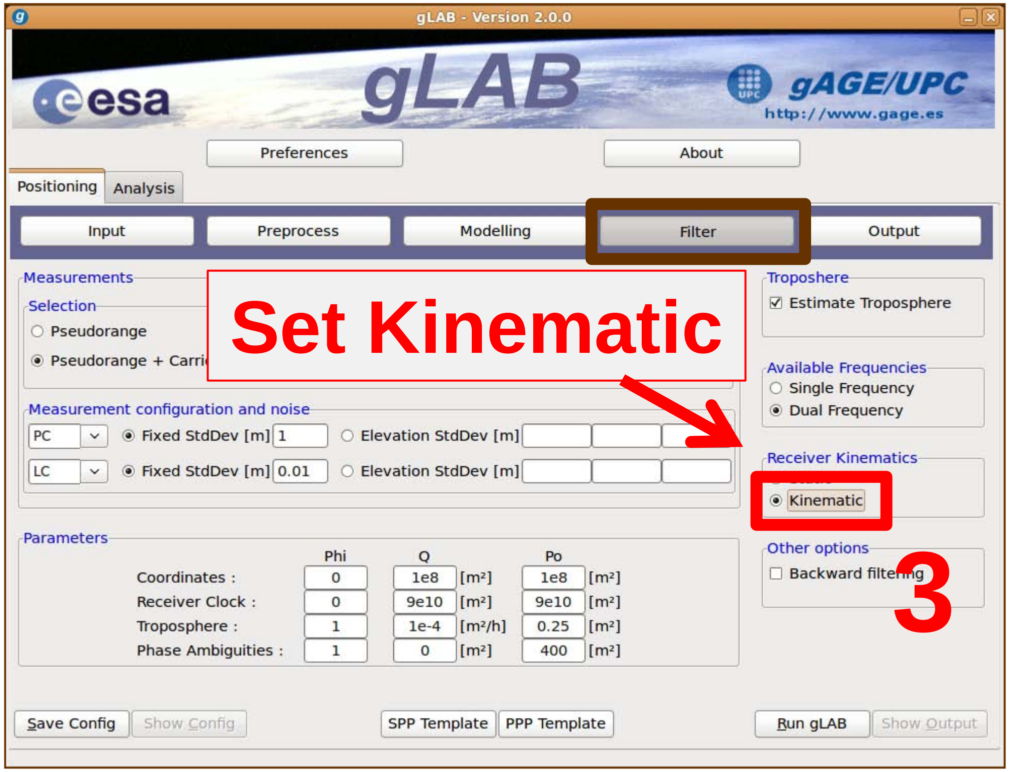
Note: **Selective Availability (S/A)** was an intentional degradation of public GPS signals implemented for US national security reasons. S/A was turned off at midnight May 1st 2000 (Day-Of-Year 123).

Given that session time is limited to 3h, students who feel comfortable using gLAB, can skip part of the basic exercises (Ex1, Ex2) and jump to the Lab. Work Project.

Exercise 2: PPP Model components analysis

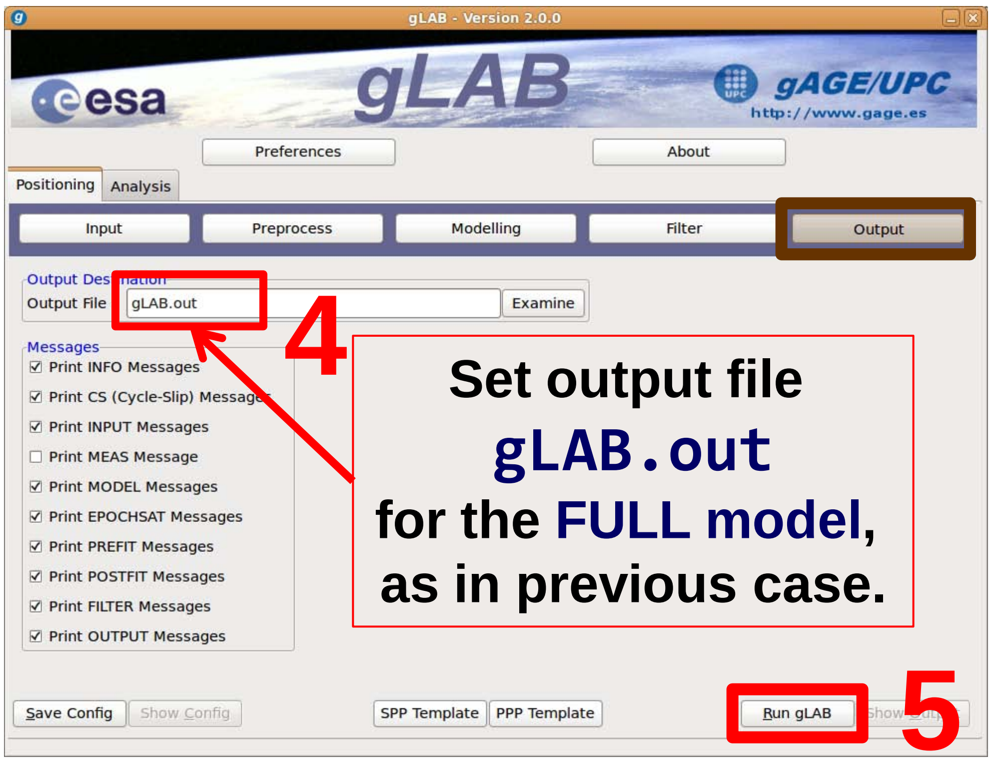
- Compute the **kinematic** PPP solution using files:
  `ramo1230.00o, igs_pre1400.atx, igs10602.sp3, igs00P1060.snx.`

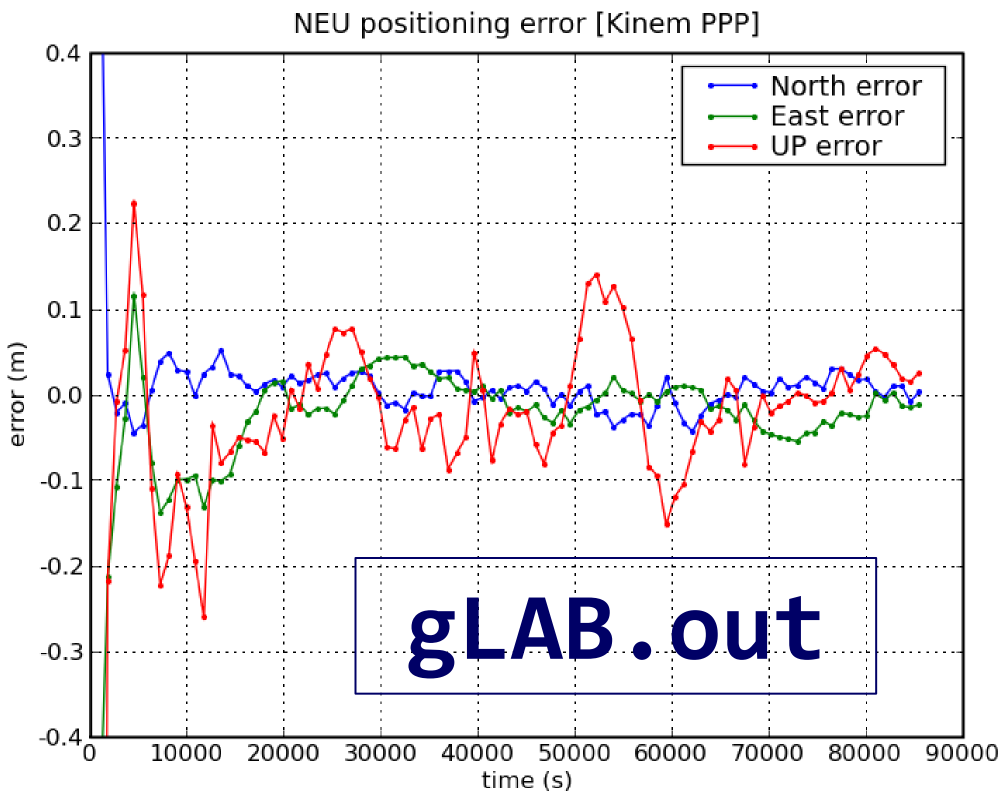
Note: The **`igs_pre1400.atx`** *file contains the APC used by IGS before GPS week 1400.*



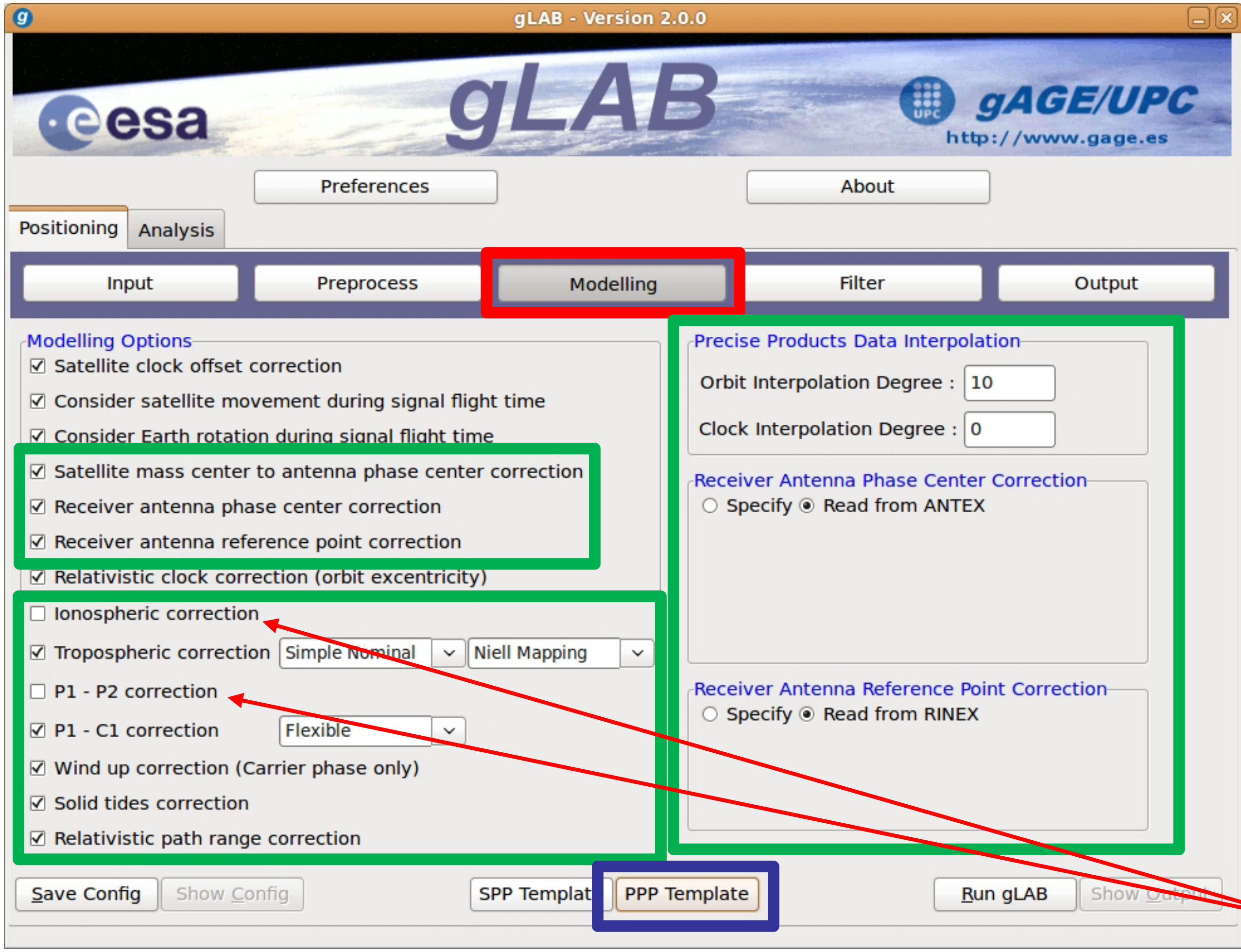
Exercise 2: PPP Model components analysis

Kinematic PPP solution using files `ramo1230.00o`, `igs10602.sp3`, `igs_pre1400.atx`, `igs00P1060.snx`.





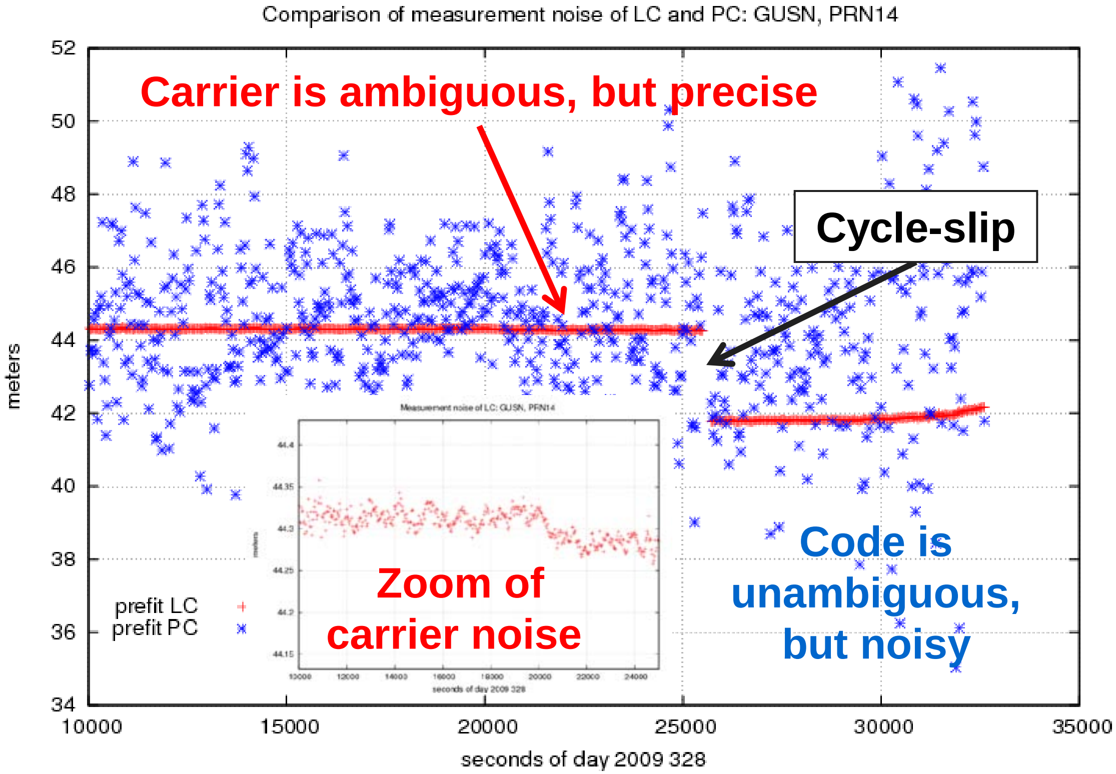
Exercise 2: PPP Model components analysis



- Additional model components are used now in the FULL model to assure a centimeter level modeling.
- **Precise orbits and clocks** instead of broadcast ones.
- **Dual frequency** Code and Carrier data instead of only single frequency code.
- **Iono-free** combination of codes and carriers to **remove ionospheric error** and P1-P2 DCBs.

Exercise 2: PPP Model components analysis

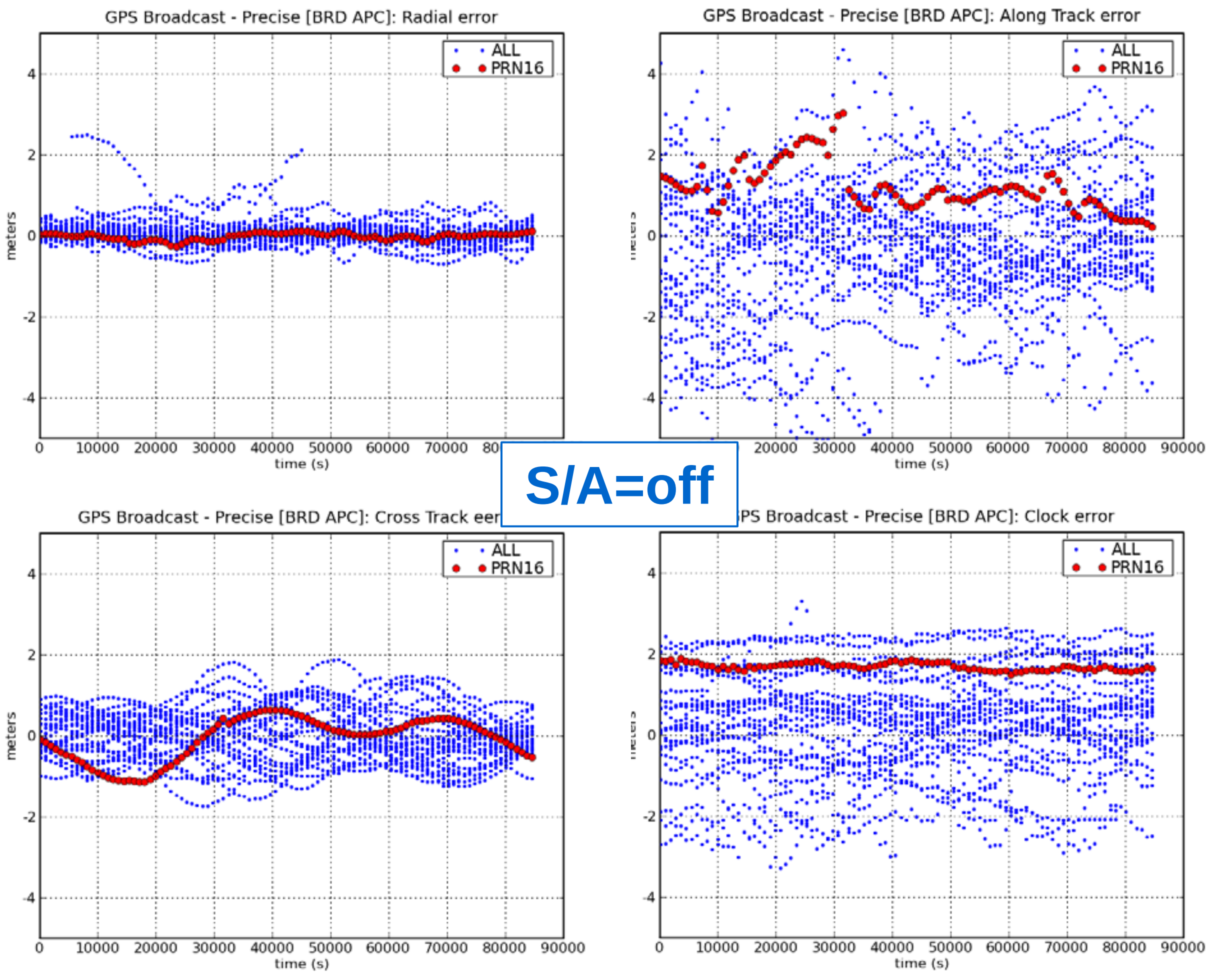
Code and carrier Measurements



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

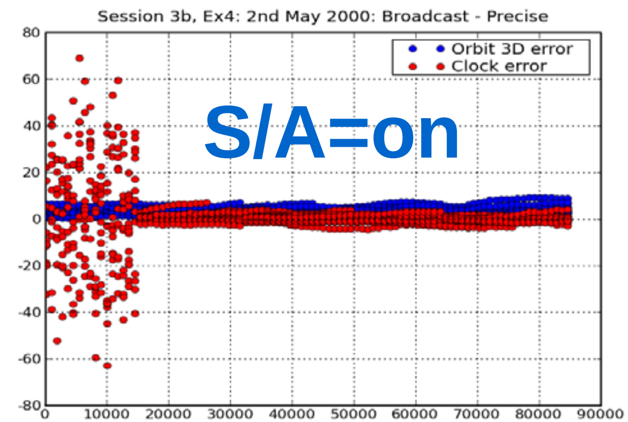
- Code measurements are unambiguous but noisy (meter level measurement noise).
- Carrier measurements are precise but ambiguous, meaning that they have few millimetres of noise, but also have unknown biases that could reach thousands of km.
- Carrier phase biases are estimated in the navigation filter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

Exercise 2: PPP Model components analysis



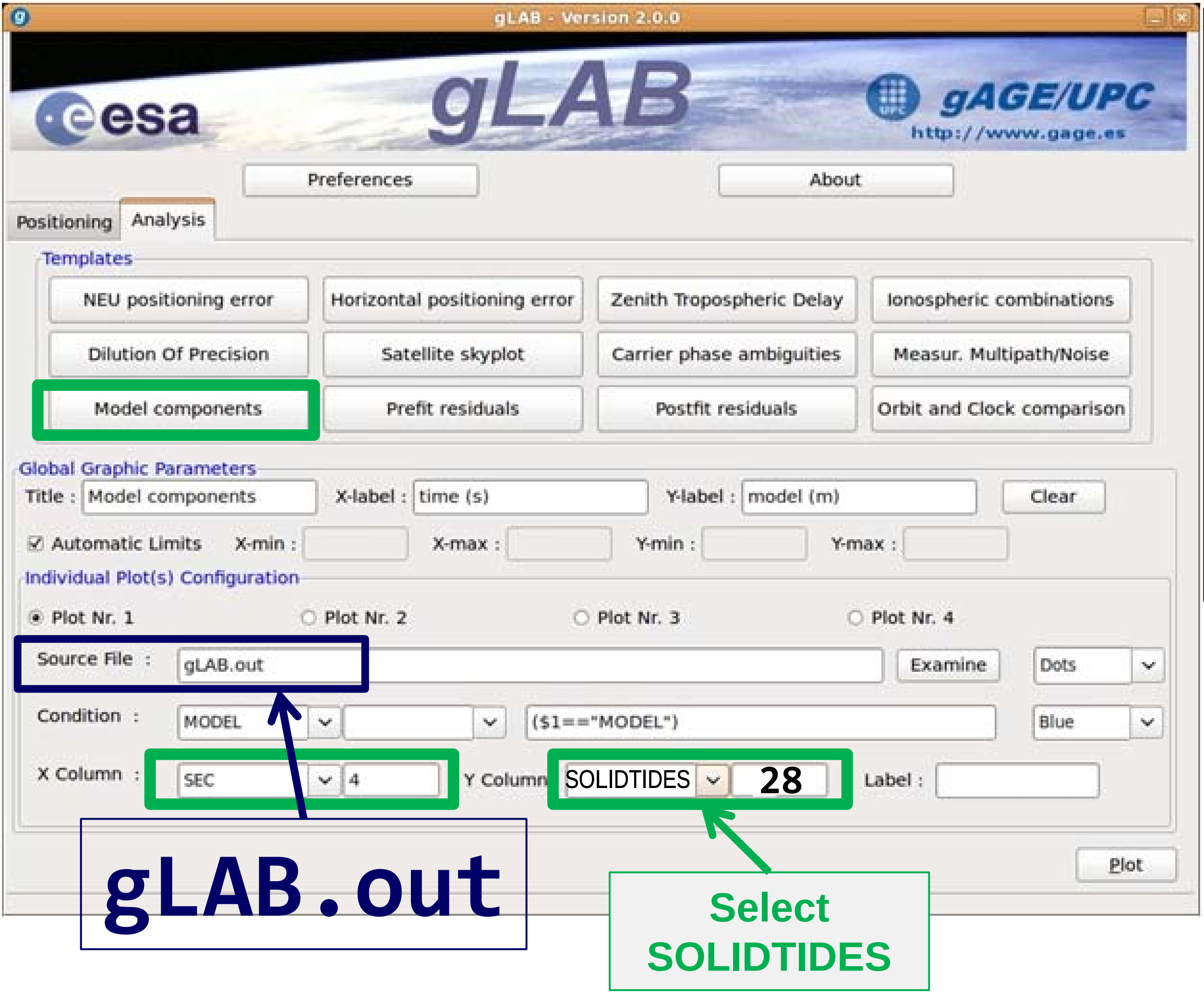
Orbits & clocks

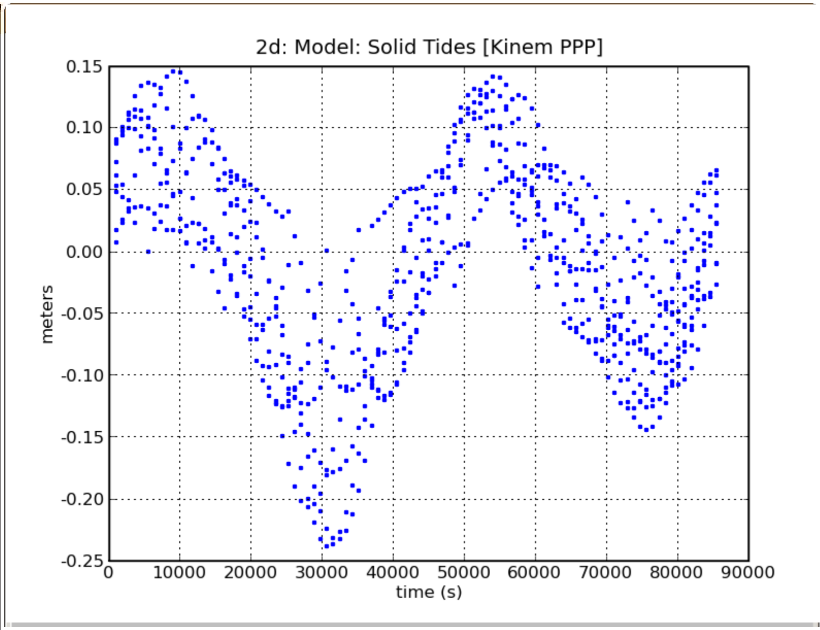
- With S/A=on, clocks were degraded several tens of meters.



- Under S/A=off , the broadcast orbits and clocks are accurate at few meters level (see plots at left)
- **IGS precise orbits & clocks are accurate at few cm level**

Solid Tides model component plot: `gLAB.out`

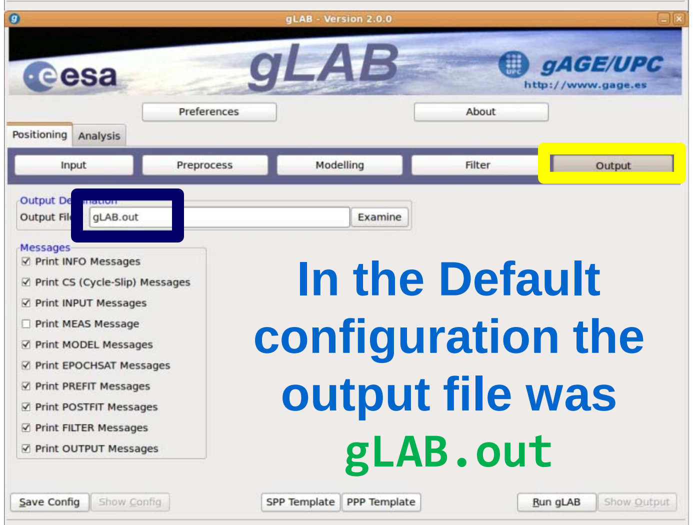




Solid Tides plot

Note: Use the **`gLAB.out`** file. In **`gLAB1.out`** file this model component was switched off.

Example of model component analysis: **Solid Tides**

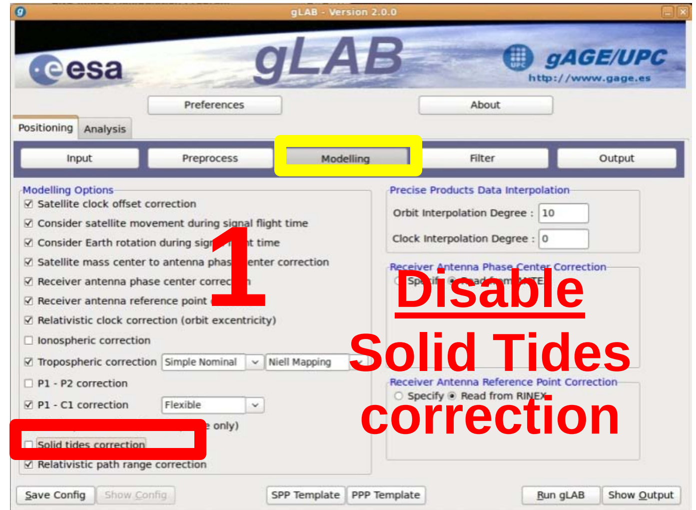


Proceed as in the previous exercise:

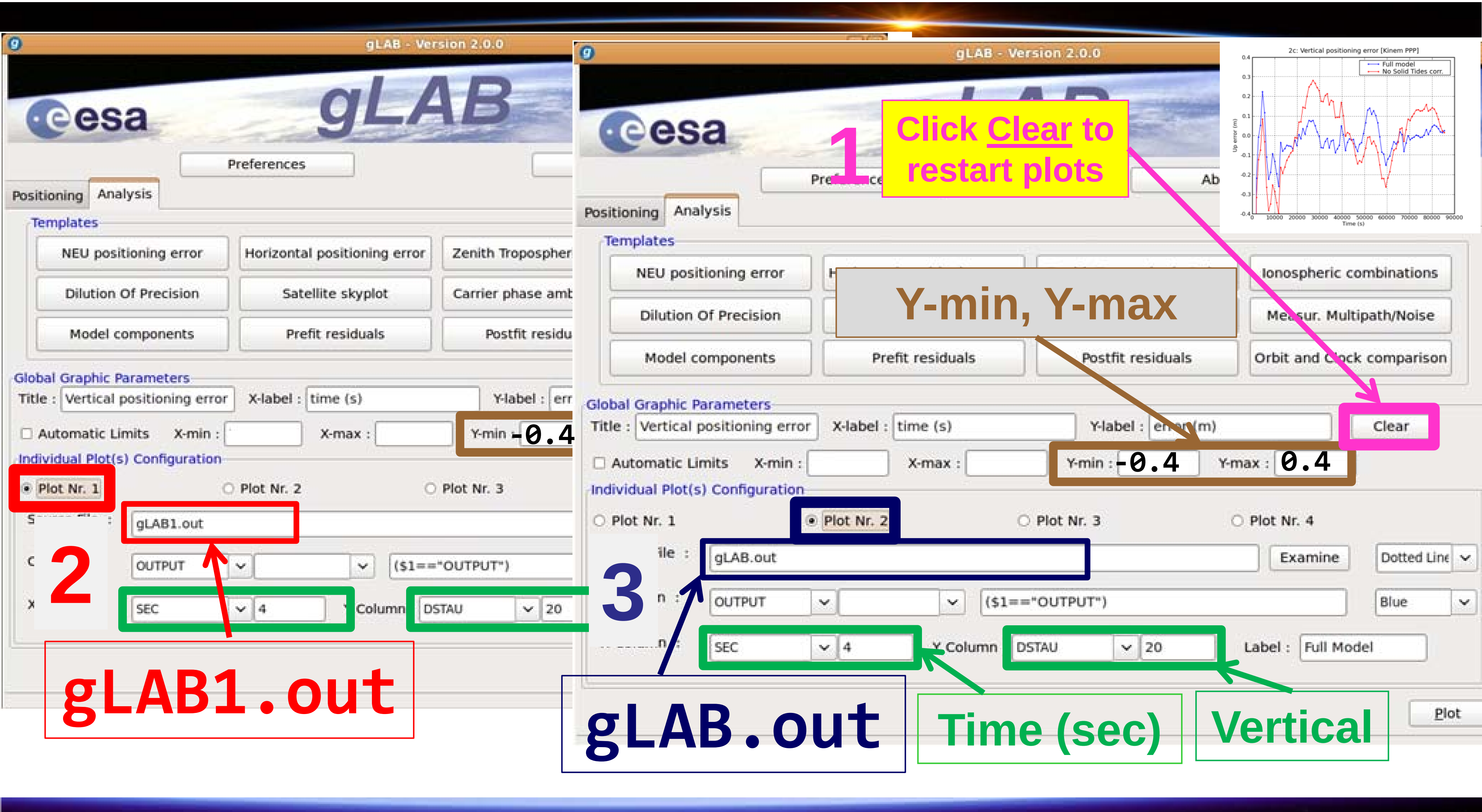
1. **In Modeling** panel, <u>disable</u> the model component to analyze.
2. **Save** as **`gLAB1.out`** the associated output file.

Notice that the **`gLAB.out`** file contains the processing results with the **FULL model**, as it was set in the default configuration.

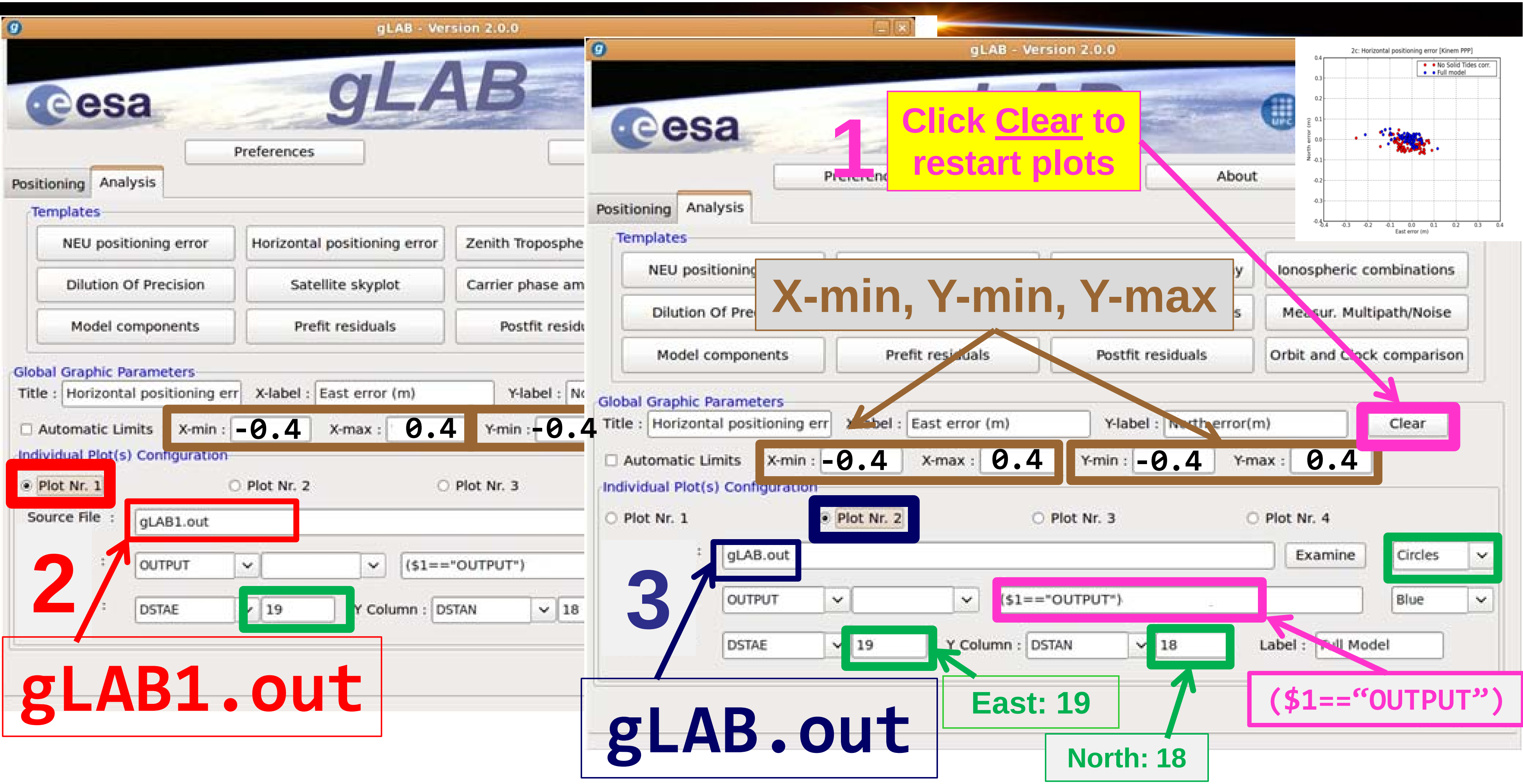
Make plots as in previous exercises (see slides 40-42)



Vertical Position Error plot from gLAB.out, gLAB1.out



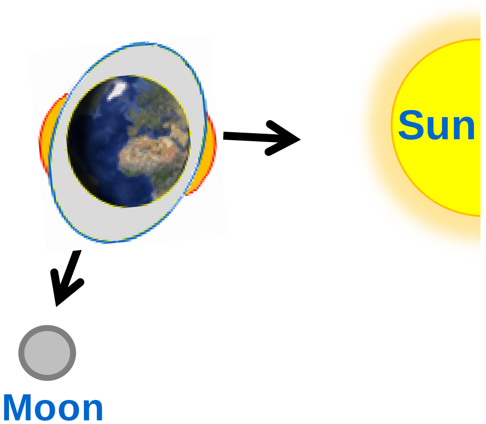
Horizontal Position Error plot: gLAB.out, gLAB1.out

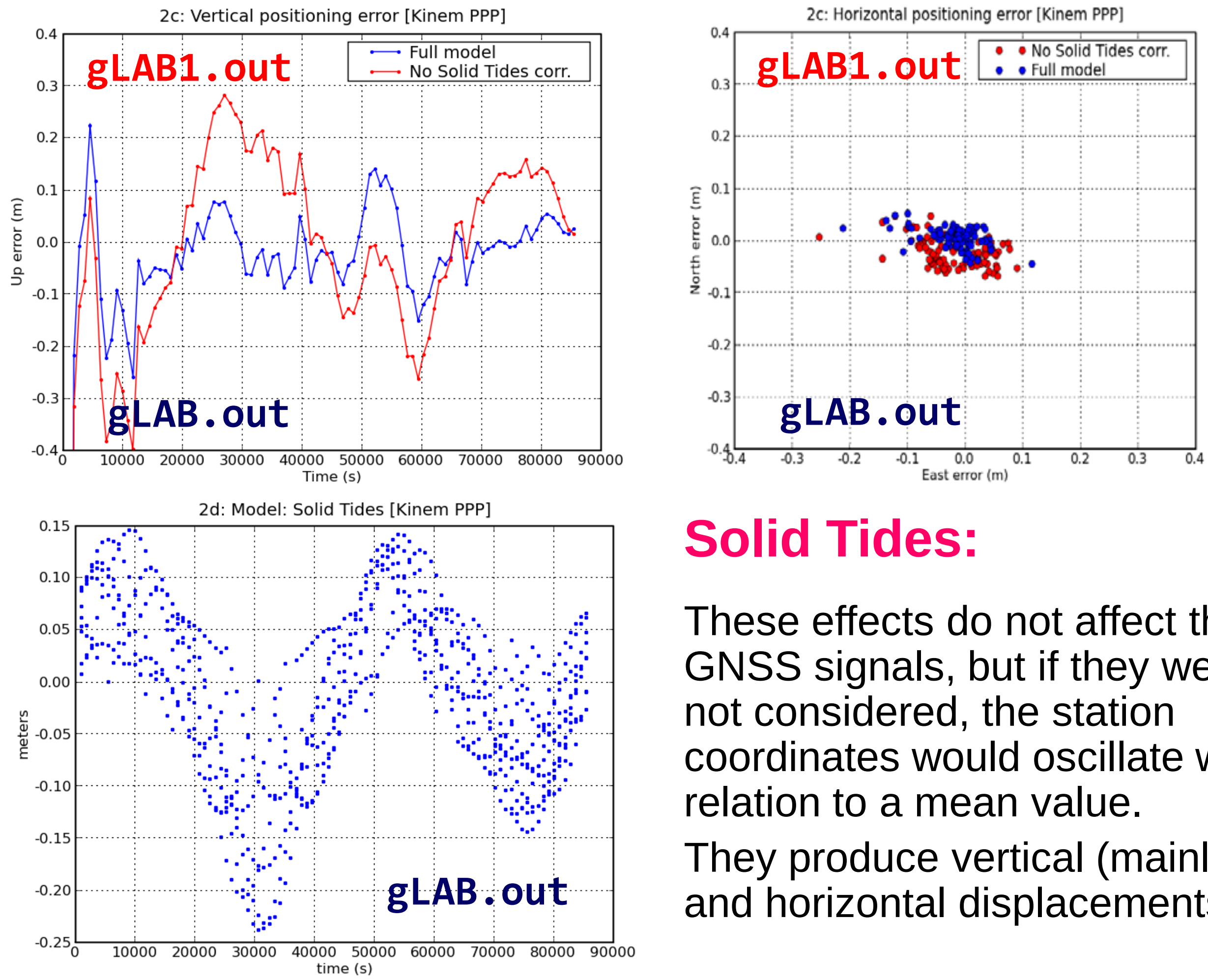


Exercise 2: PPP Model components analysis

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.





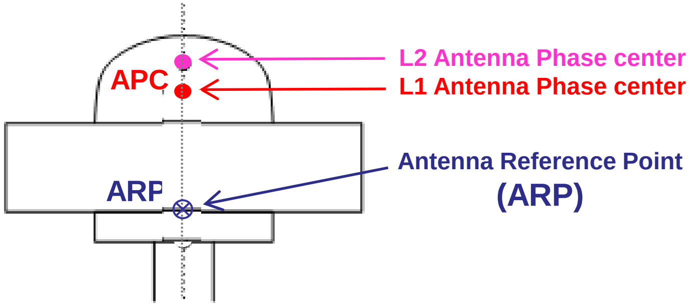
Solid Tides:

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.

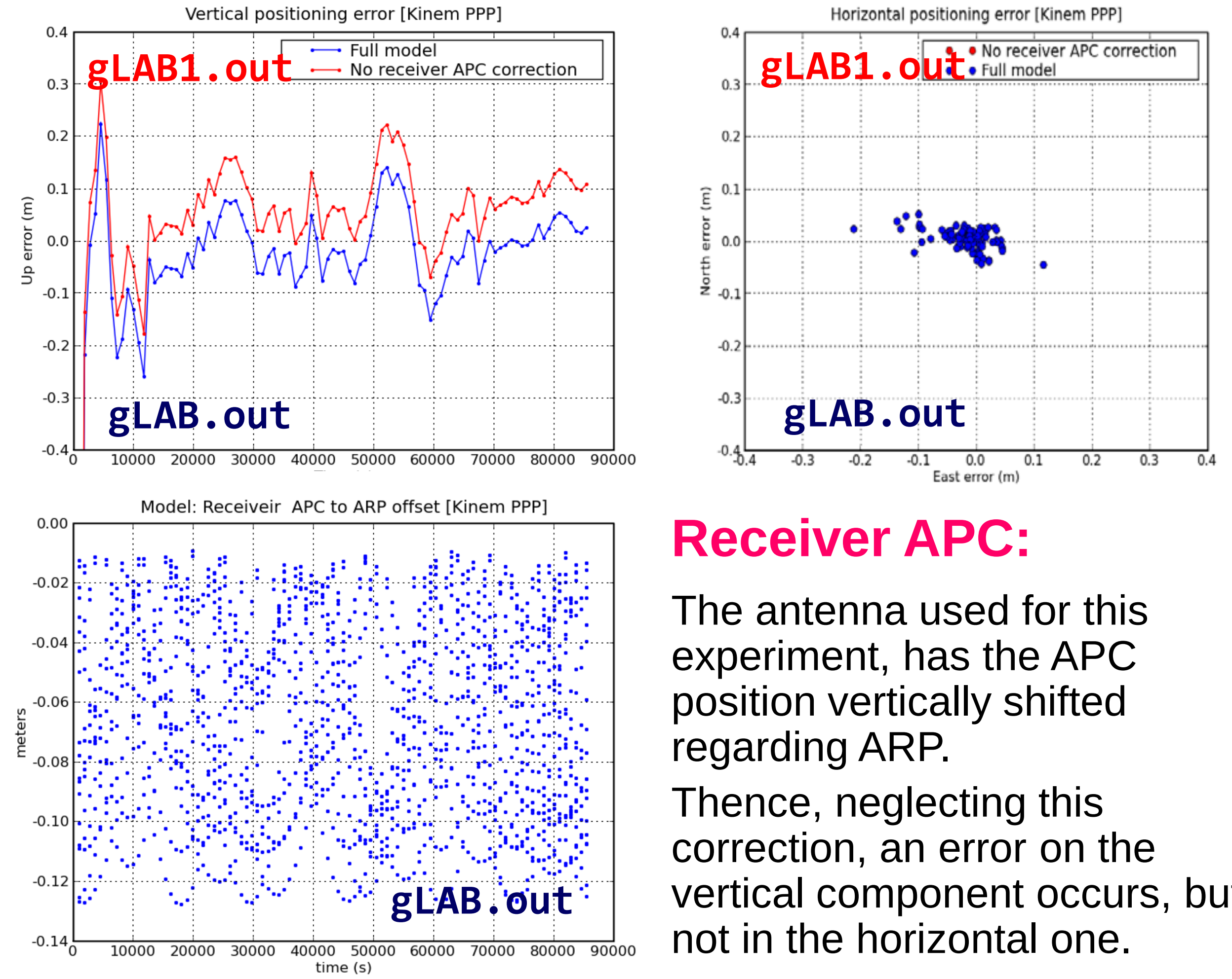
PPP Model Components Analysis

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.

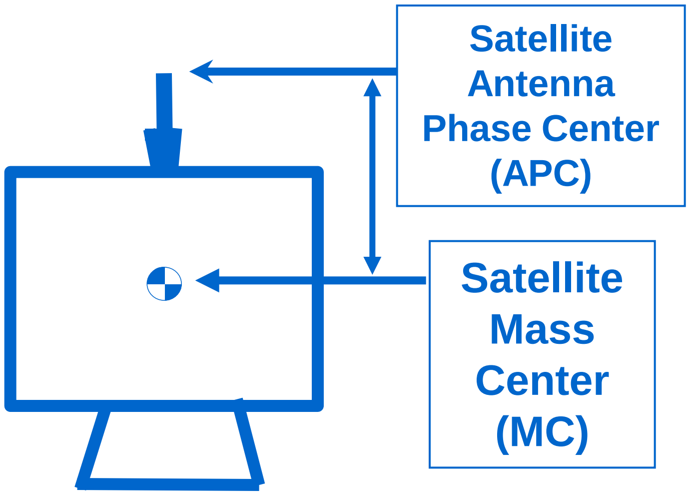


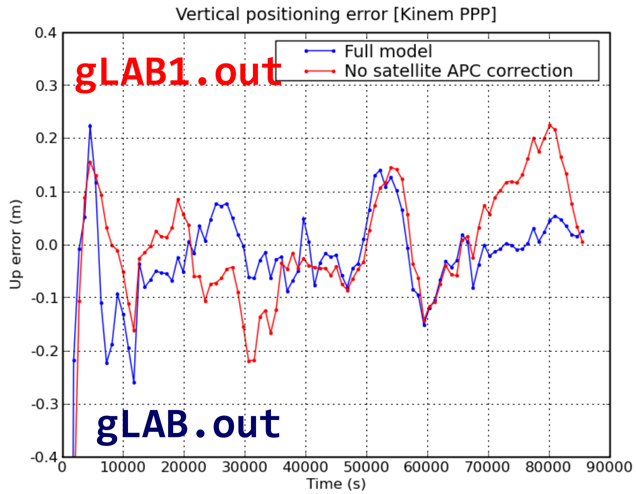
Receiver APC:

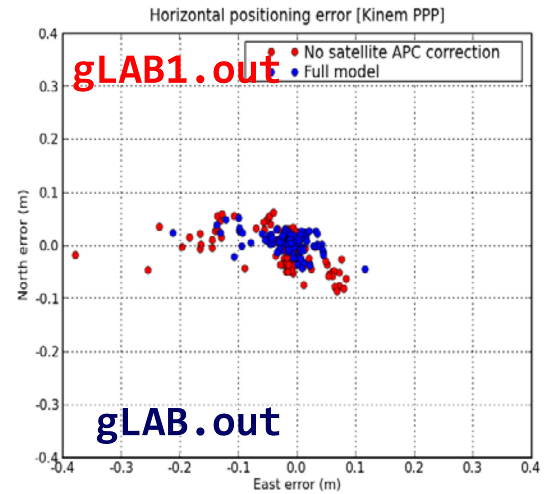
The antenna used for this experiment, has the APC position vertically shifted regarding ARP.

Thence, neglecting this correction, an error on the vertical component occurs, but not in the horizontal one.

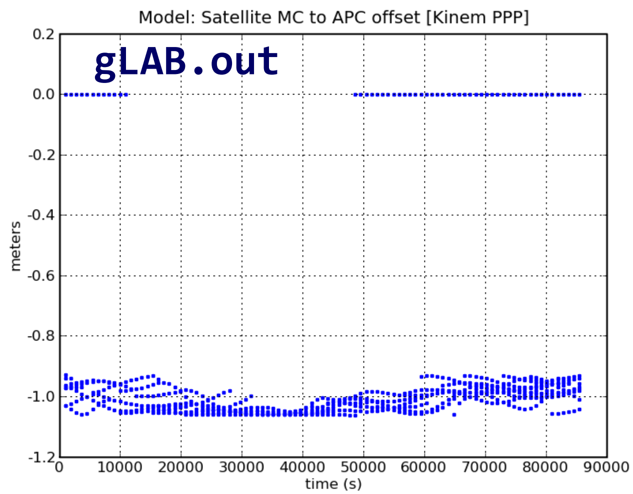
Satellite Mass Center to Antenna Phase Center







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



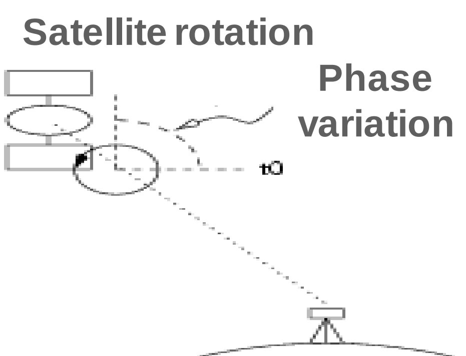
Satellite MC to APC:

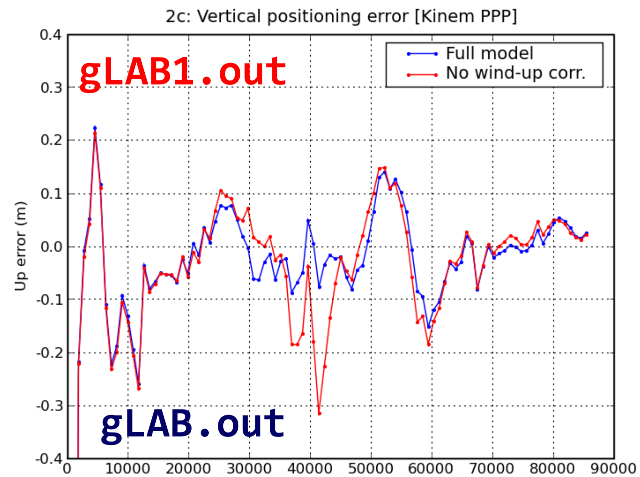
The satellite MC to APC eccentricity vector depends on the satellite. The APC values used in the IGS orbits and clocks products are referred to the iono-free combination (LC, PC) . They are given in the IGS ANTEX files (e.g., `igs05.atx`).

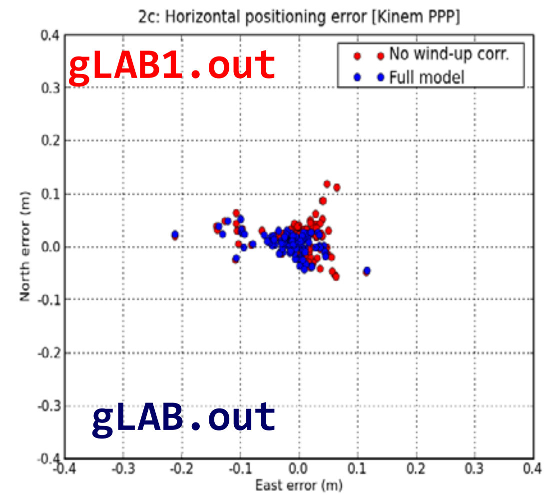
Exercise 2: PPP Model components analysis

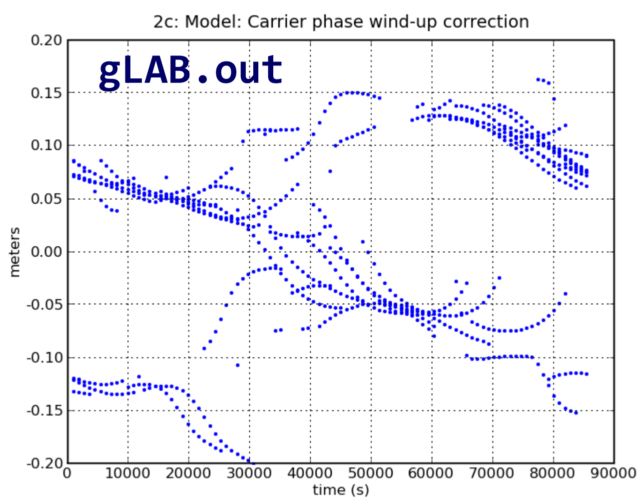
Wind-up affects only carrier phase. It is due to the electromagnetic nature of circularly polarized waves of GNSS signals.

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.

OVERVIEW

- ✓ **Introduction**
- ✓ **The gLAB tool suite**
- ✓ **Examples of GNSS Positioning using gLAB**
- ✓ **Laboratory session organization**

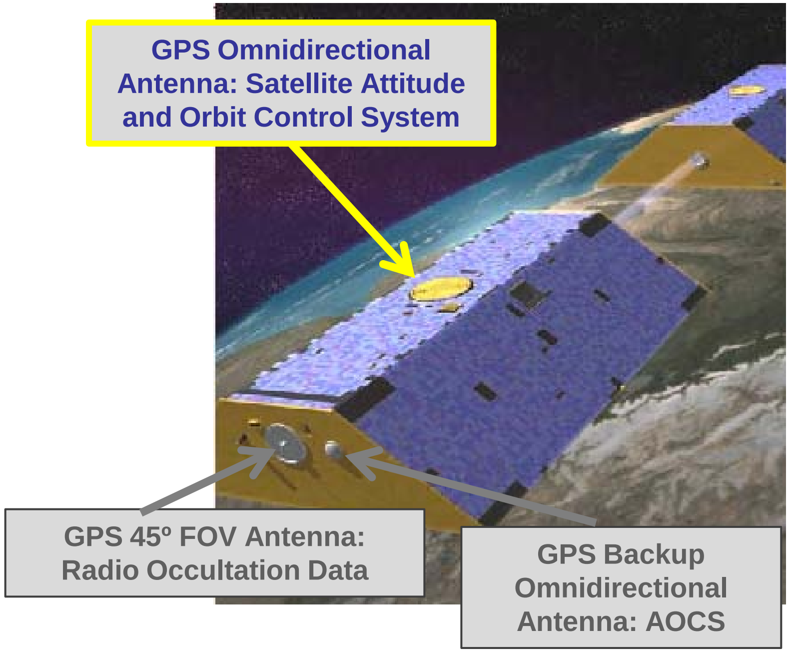
LABORATORY Session

- ✓ **Starting-up your laptop**
- ✓ **Basic:** Introductory laboratory exercises (Ex1, Ex2)
- ➢ **Medium:** Laboratory Work Project (LWP): Kinematic positioning of a LEO satellite
- ⅄ **Advanced:** Homework

LWP: Kinematic positioning of a LEO satellite

- **A kinematic positioning of GRACE-A satellite is proposed in this exercise as a driven example to study and discuss the different navigation modes and modelling options for code or code & carrier positioning of a rover receiver.**

GRACE SATELLITES (A & B)	
Nominal altitude:	460 km
Orbital periode:	1.5 h (aprox.)
Mass:	432 kg
Launch date:	May 17^{th}, 2002
Space Agency:	NASA/GFZ
Designed life-time:	5 years
Receiver pseudorange noise:	40 cm
Receiver carrier-phase noise:	8 mm
Receiver GRAPHIC noise:	12 cm
Antenna phase center:	(0.0, 0.0, -0.414) m



More details at: `http://op.gfz-potsdam.de/grace/index_GRACE.html`

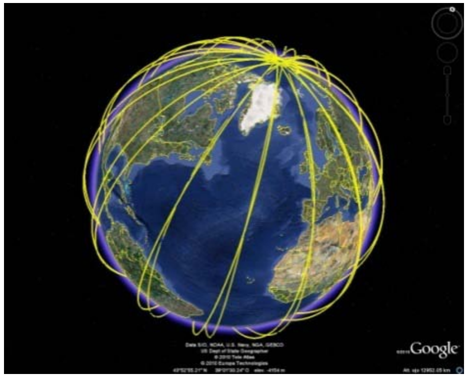
LWP: Kinematic positioning of a LEO satellite

⅄ The following "preliminary" questions are posed:

- Could a LEO satellite like GRACE-A be kinematically positioned as a rover receiver (i.e., car, aircraft...)? Why?
- Would both Standard and Precise Positioning be achievable?

  Note: The RINEX file `graa0800.07o` *contains GPS dual freq. Measurements.*

- Which model components should be set for each positioning mode?
  - Relativistic correction?
  - Tropospheric correction?
  - Ionospheric correction?
  - Instrumental delays (TGDs)?
  - Solid Tides correction?
  - Antenna phase centre corrections?
  - Others ???



- In case of successful positioning, which accuracy is expected?

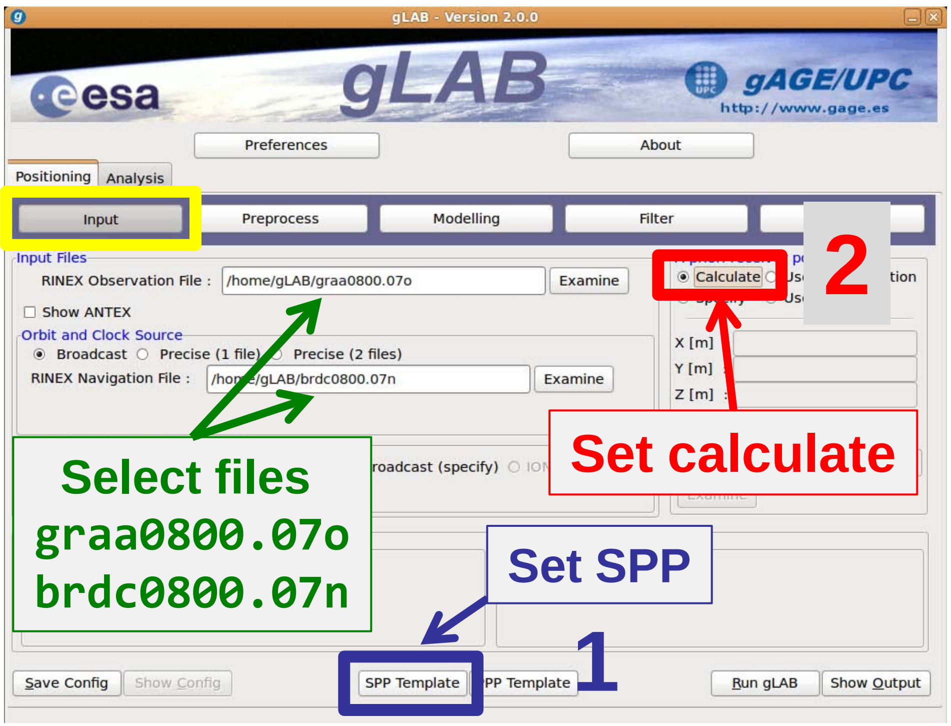
LWP: Kinematic positioning of a LEO satellite

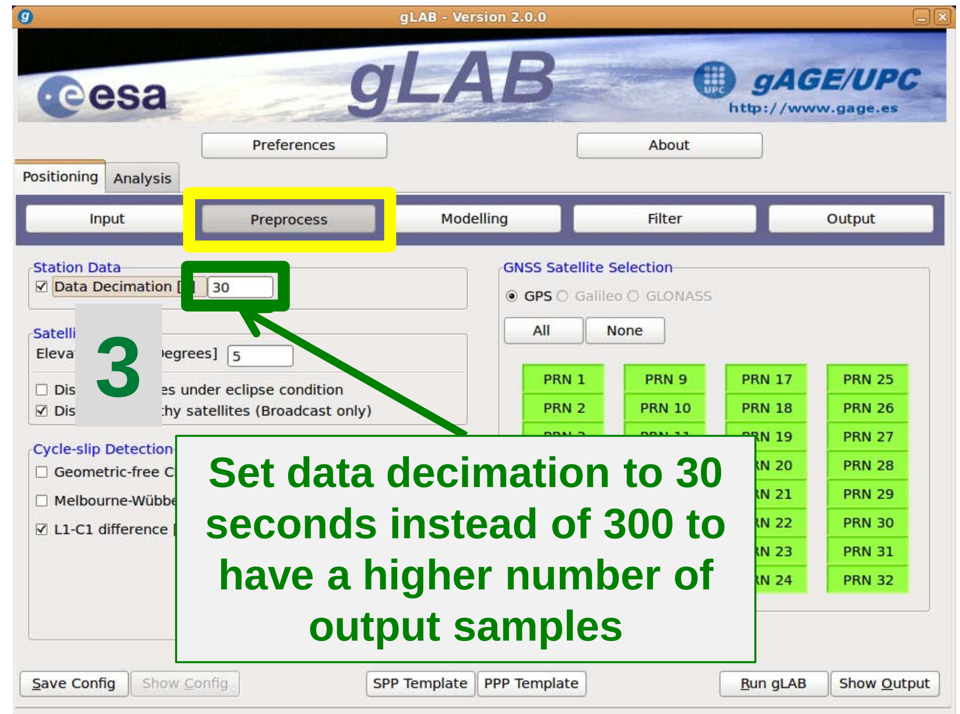
- **The following positioning modes are proposed to be explored:**
  - Code positioning + broadcast orbits:
    1. Single frequency: C1 code (and no ionospheric corrections).
    2. Dual frequency: PC code combination (i.e., ionosphere-free combination)
  - Code and carrier positioning + precise orbits and clocks:
    3. Dual frequency: PC, LC combinations (i.e., ionosphere-free combinations)
    4. GRAPHIC combination of C1 code and L1 carrier phase.
    5. Single frequency: C1 code and L1 carrier (and no ionospheric corrections).
- **Data files:**
  - Measurements file: `graa0800.07o`
  - GPS orbits and clocks:
    - Broadcast: `brdc0800.07n`
    - Precise: `cod14193.sp3`, `cod14193.clk`, `igs05_1402.atx`
  - GRACE-A Precise Reference Orbit file: `GRAA_07_080.sp3`

Mode1: Single frequency C1 code with broadcast orbits & clocks

Example of computation with gLAB:

Code positioning + broadcast orbits: Single frequency, C1 code.

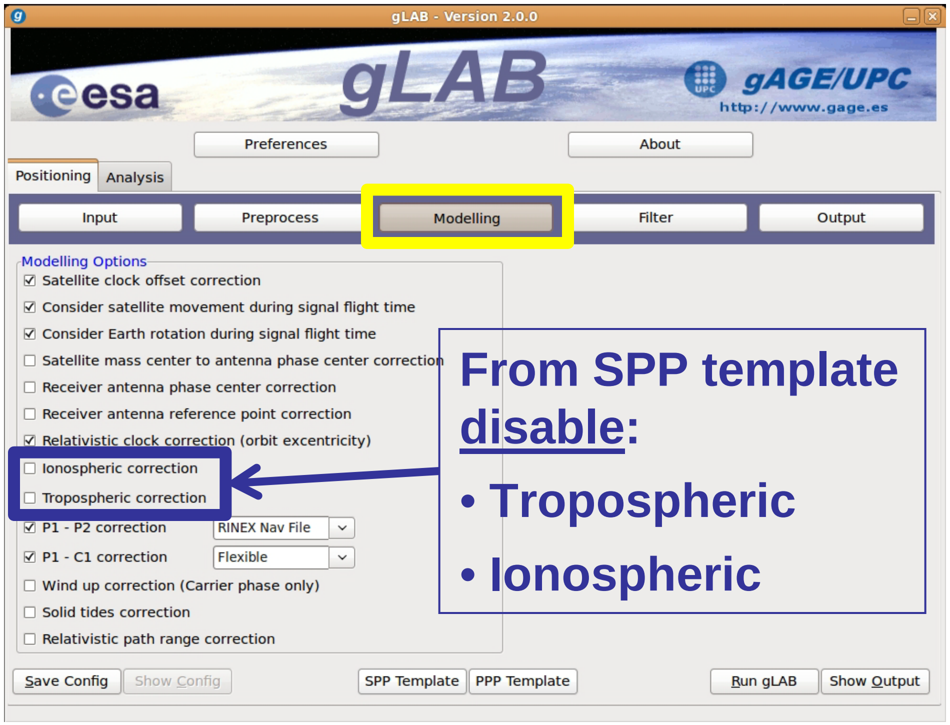


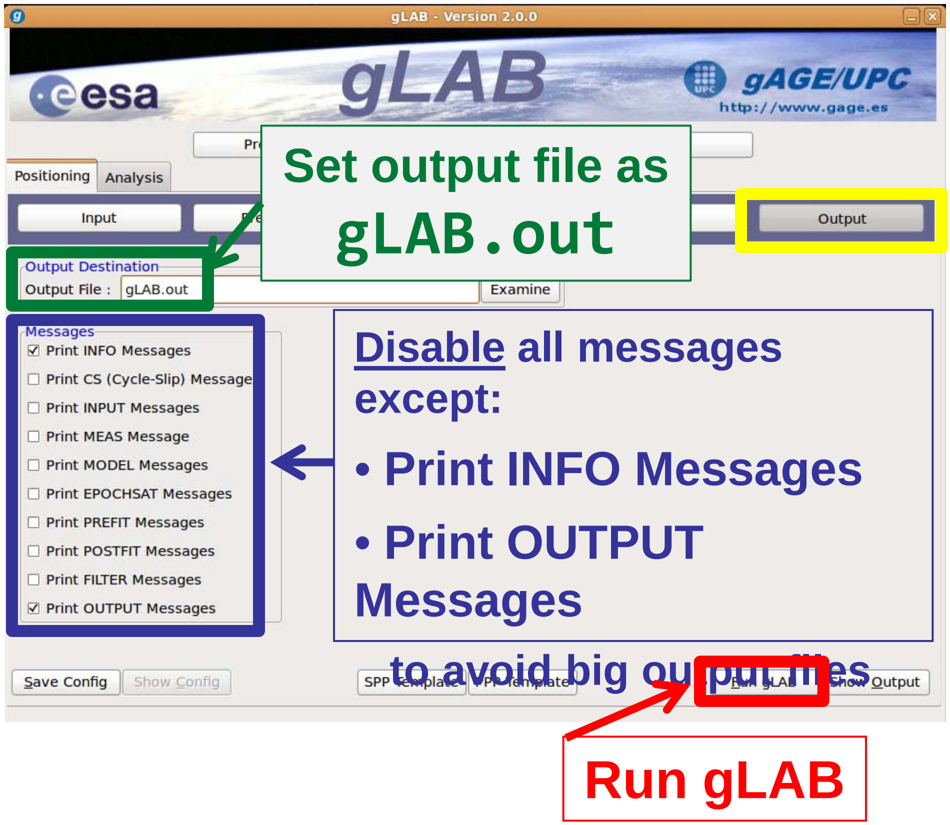


Mode1: Single frequency C1 code with broadcast orbits & clocks

Example of computation with gLAB:

Code positioning + broadcast orbits: Single frequency: C1 code.





Mode1: Single frequency C1 code with broadcast orbits & clocks

- **Accuracy assessment of the computed solution:**

  Complete the following steps to compare the output solution (from **gLAB.out** file) with the reference coordinates of file **GRAA_07_080.sp3**:

1. **Convert** the output **gLAB.out** file to **sp3** format:

   Execute (in **Console**): `out2sp3 gLAB.out`

   Note: this sentence generates the file: **orb.sp3**

   (see file content with: less orb.sp3)

2. **Compare** the computed coordinates **orb.sp3** with reference **GRAA_07_080.sp3.**

   Note: Use the configuration file **dif.cfg**.

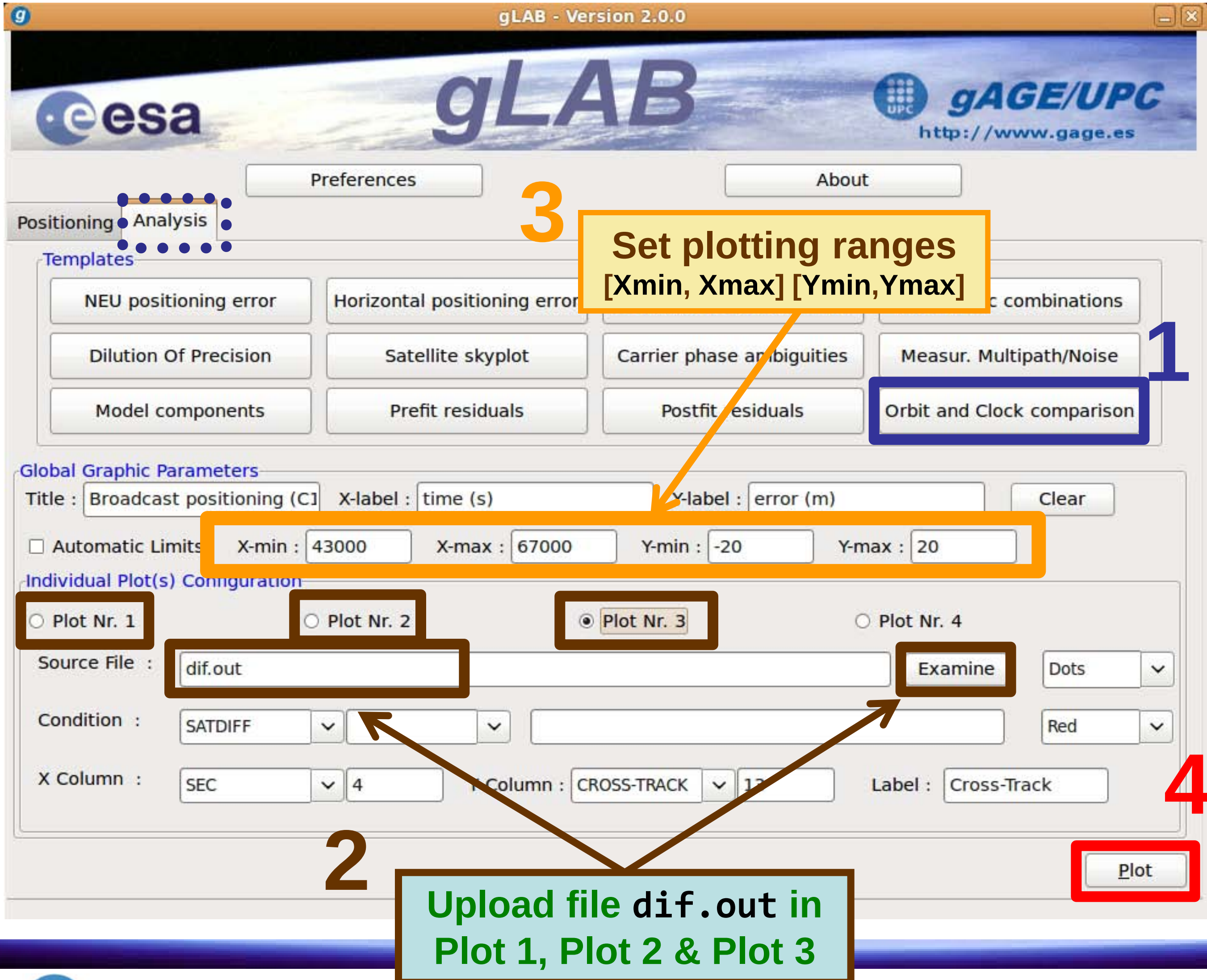
```
gLAB_linux -input:cfg dif.cfg -input:SP3 GRAA_07_080.sp3 -input:SP3 orb.sp3
```

   Note: this sentence generates the file: **dif.out**

3. **Plot** **dif.out** file:

   The Graphic User Interface can be used for plotting

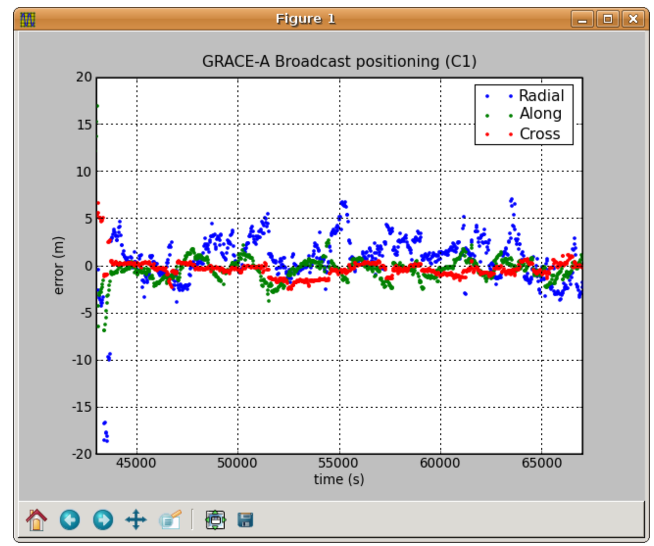
Mode1: Single frequency C1 code with broadcast orbits & clocks



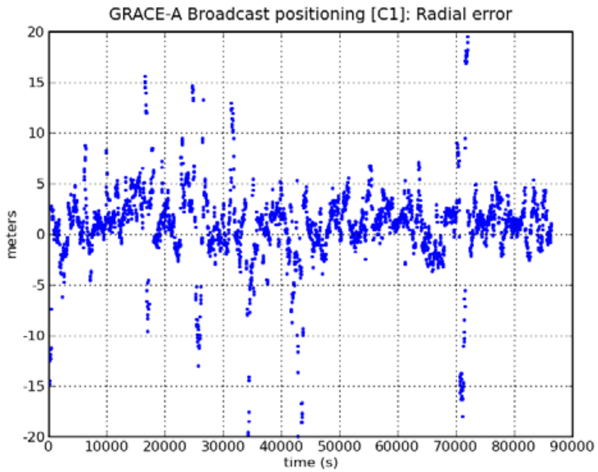
Plotting

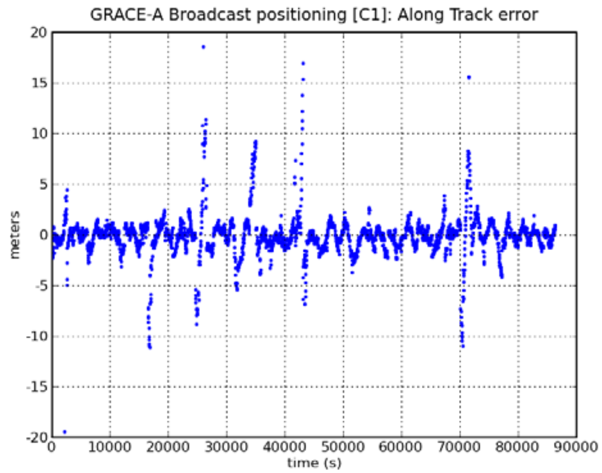
dif.out

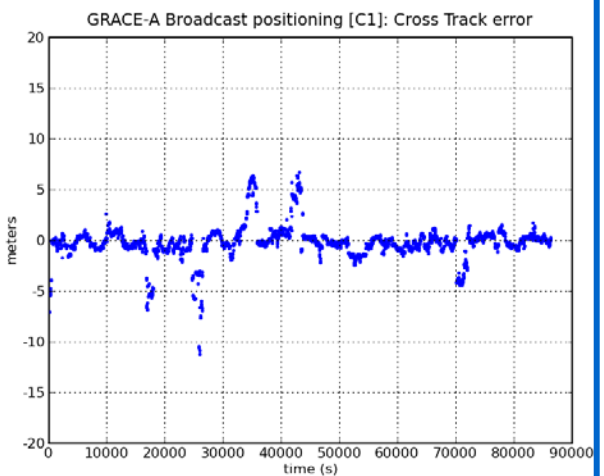
with the GUI

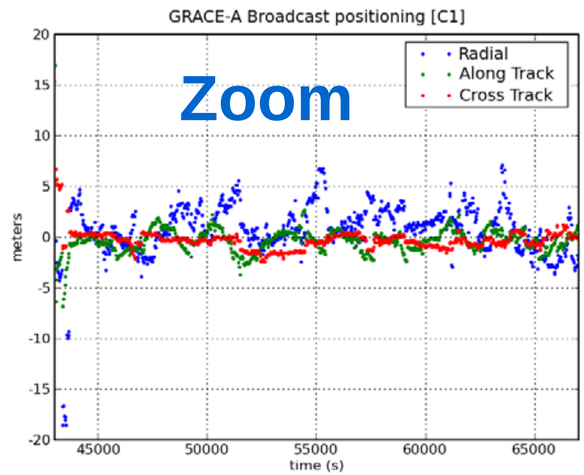


Mode1: Single frequency C1 code with broadcast orbits & clocks









Questions

1. Is it reasonable to <u>disable</u> the tropospheric and ionospheric corrections?

2. Like GPS satellites, LEOs are also affected by relativistic effects. Is it necessary to introduce an additional model term to account for this effect?

3. What could be the reason for the large error peaks seen in the plots?

Mode1: Single frequency C1 code with broadcast orbits & clocks

- **Answer to Question 1:**
  Is it reasonable to disable the tropospheric and ionospheric corrections?
  - Troposphere:

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

    GRACE-A satellite is orbiting at about 450 km altitude, thence no tropospheric error is affecting the measurements.
  - Ionosphere:

    The ionosphere extends from about 60 km over the Earth surface until more than 2000 km, with a sharp electron density maximum at around 350 km.

    GRACE-A satellite, orbiting at about 450 km altitude, is less affected by the ionosphere than on the ground, but nonetheless a few meters of slant delay could be experienced. On the other hand, as the correction from Klobuchar model is tuned for ground receivers, its usage could produce more harm than benefit *(see HW1).*

- **Homework:**
  - **HW1**: Assess the ionospheric delay on the GRACE-A satellite measurements. Compare with the Klobuchar model corrections.

Mode1: Single frequency C1 code with broadcast orbits & clocks

- **Answer to Question 2:**

  In this approach, is it necessary to introduce an additional model term to account for the relativity effect on LEO satellite?

  - GRACE-A clock is affected by general and special relativistic effects (due to the gravitational potential and satellite speed). But this is not a problem, because the receiver clock is estimated along with the coordinates.

    Notice that this relativistic effect will affect all measurements in the same way, and thence, it will be absorbed into the receiver clock offset estimation.

- **Answer to Question 3:**

  What could be the reason for the large error peaks seen in the plots?

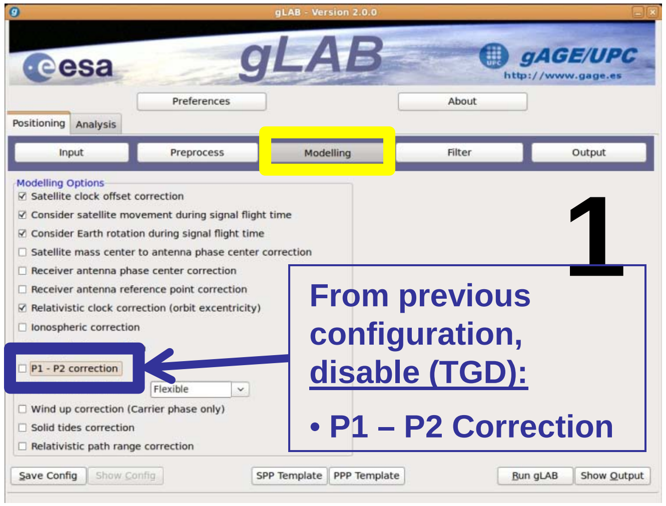
  - The large error peaks are associated to bad GPS-LEO satellite geometries and mismodelling. Notice that the satellite is moving at about 8 km/s and therefore the geometry changes quickly *(see HW2).* Also, the geometry is particularly poor when GRACE-A satellite is over poles.

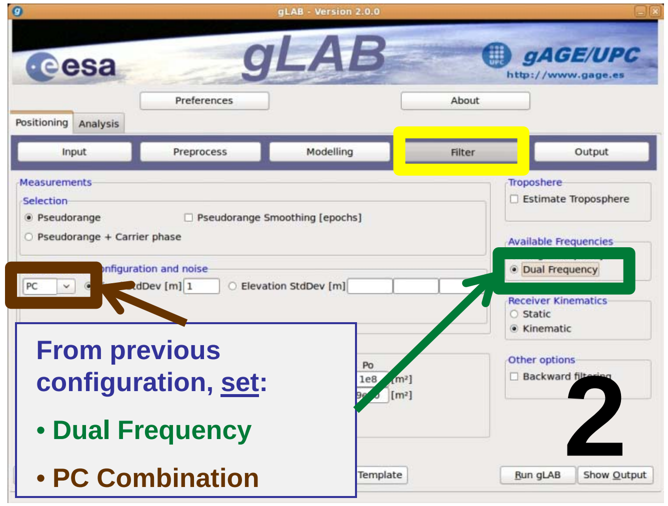
- **Homework:**
  - **HW2:** Plot in the same graph the "True 3D error", the "Formal 3D error" (i.e, the 3D-sigma) and the number of satellites used. Analyze the evolution of the error.

Mode 2. Dual frequency PC code with broadcast orbits & clocks

Example of computation with gLAB:

Code positioning + broadcast orbits: Dual frequency: PC code combination.





1. **Convert** the output **gLAB.out** file to **sp3** format:

   Execute (in **Console**): `out2sp3 gLAB.out`

   ➔ `orb.sp3`

2. **Compare** the computed coordinates **orb.sp3** with reference **GRAA_07_080.sp3**.

   Note: Use the configuration file **dif.cfg**.

```
gLAB_linux -input:cfg dif.cfg -input:SP3 GRAA_07_080.sp3 -input:SP3 orb.sp3
```

   ➔ `dif.out`

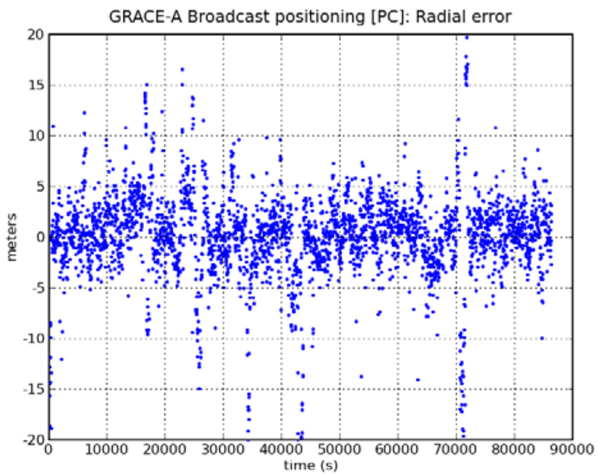
3. **Plot** **dif.out** file:

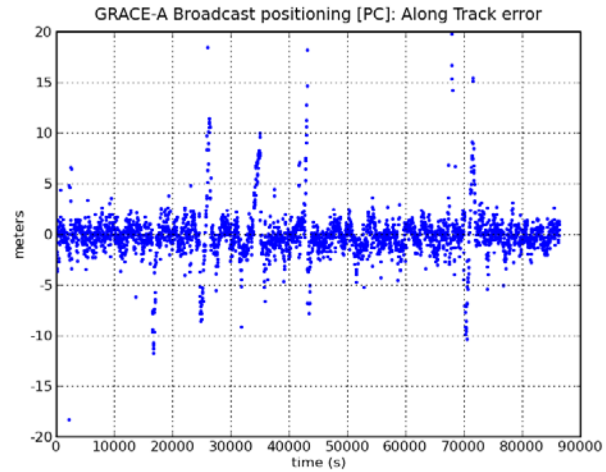
3

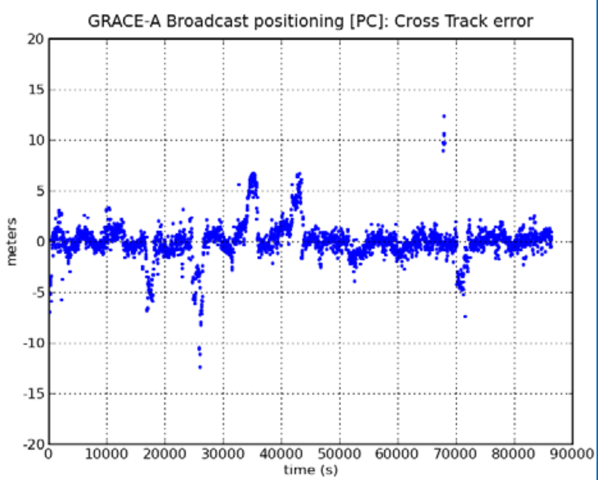
Complete the steps (from previous configuration):

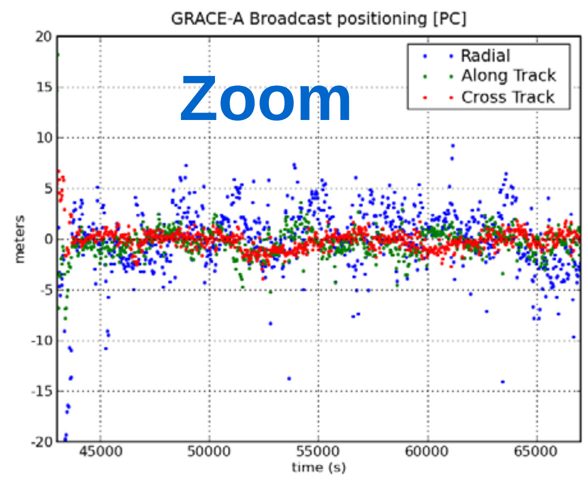
1. [**Modeling**]:
   - Disable **P1-P2** correction
2. [**Filter**]:
   - **Dual Frequency**
   - **PC** combination
3. Run **gLAB**
4. In console mode:
   - **Convert** the **gLAB.out** to **orb.sp3** format file.
   - **Compute differences** with reference file **GRAA_07_080.sp3**

Mode 2. Dual frequency PC code with broadcast orbits & clocks









Plotting

- Make the same plots as in the previous case.

Questions

4. Why is the solution noisier than the previous one with C1 code?
5. Discuss the pros and cons of the ionosphere-free combination of codes (PC), compared with C1 code.
6. How could the performance be improved?

Mode 2. Dual frequency PC code with broadcast orbits & clocks

- **Answer to Question 4:**
  Why the solution is noisier than the previous one with C1 code?

  The iono-free combination of codes P1 and *P2* is computed as: $Pc = \frac{f_1^2 P_1 - f_2^2 P_2}{f_1^2 - f_2^2} := \frac{\gamma P_1 - P_2}{\gamma - 1}$ $\gamma = \left(\frac{77}{60}\right)^2$

  Thence, assuming uncorrelated *P1, P2* measurements with equal noise σ, it follows: $\sigma_{Pc} = 3\sigma$

- **Answer to Question 5:**
  Discuss the pros and cons of the ionosphere-free combination of codes (PC).
  - Combination PC removes about the 99.9% of ionospheric delay, one of the most difficult error sources to model, but two frequency signals are needed. On the other hand, PC is noisier than the individual codes C1, P1 or P2 *(see HW3).*

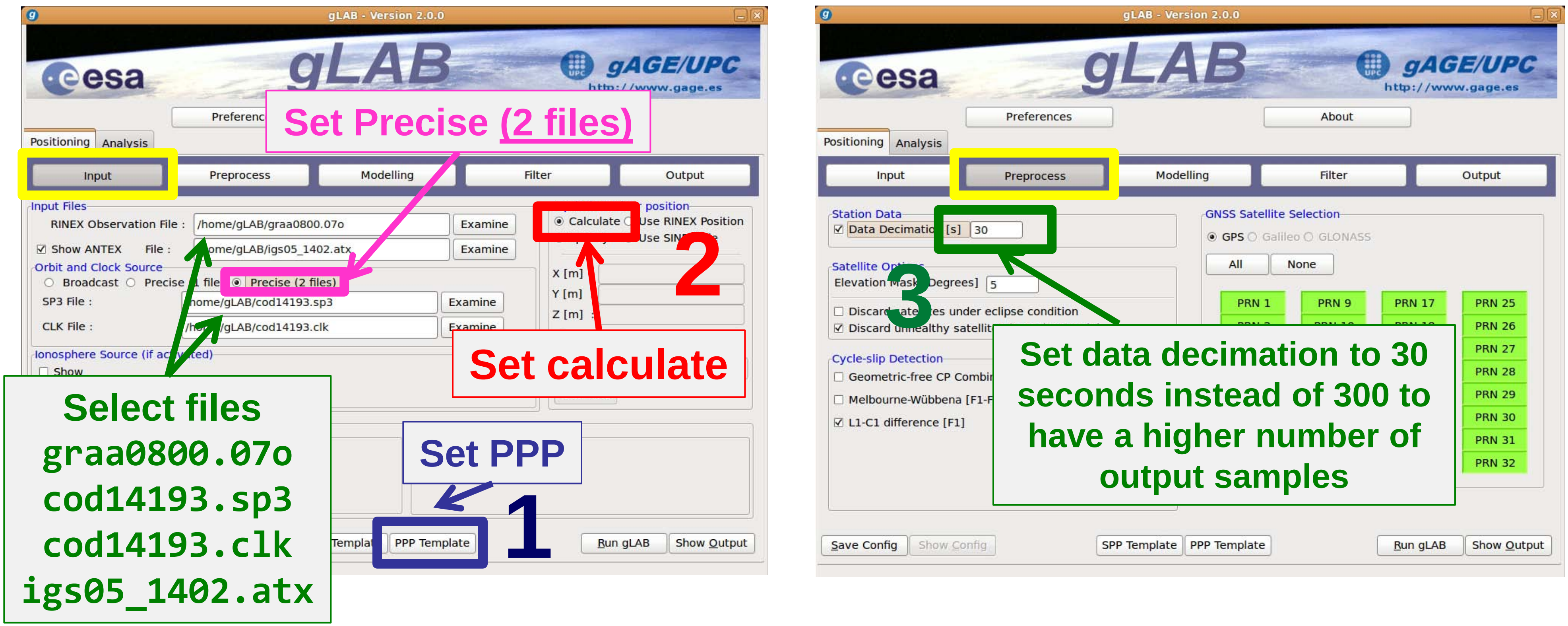
- **Answer to Question 6:**
  How could the performance be improved?
  - Smoothing the code with the carrier and/or using precise orbits and clock products as well.

- **Homework:**
  - **HW3:** Assess the measurement noise on the C1, P1, P2 and PC code measurements.

Mode 3. Dual freq. LC, PC carrier and code with precise orbits & clocks

Example of computation with gLAB:

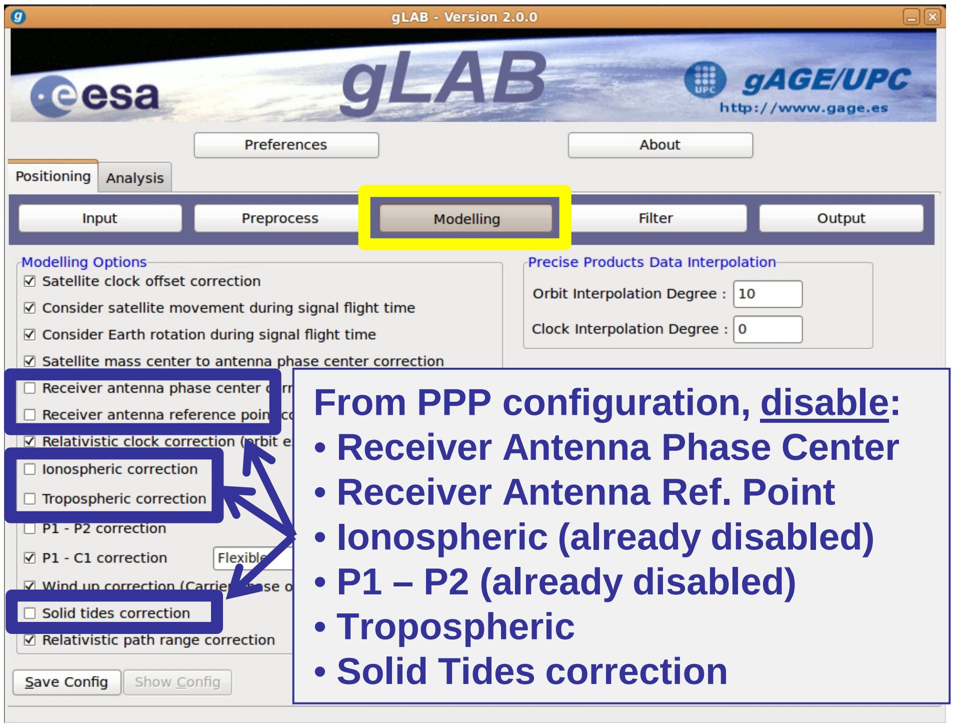
Code & Carrier + precise orbits & clocks: Dual frequency (LC, PC)

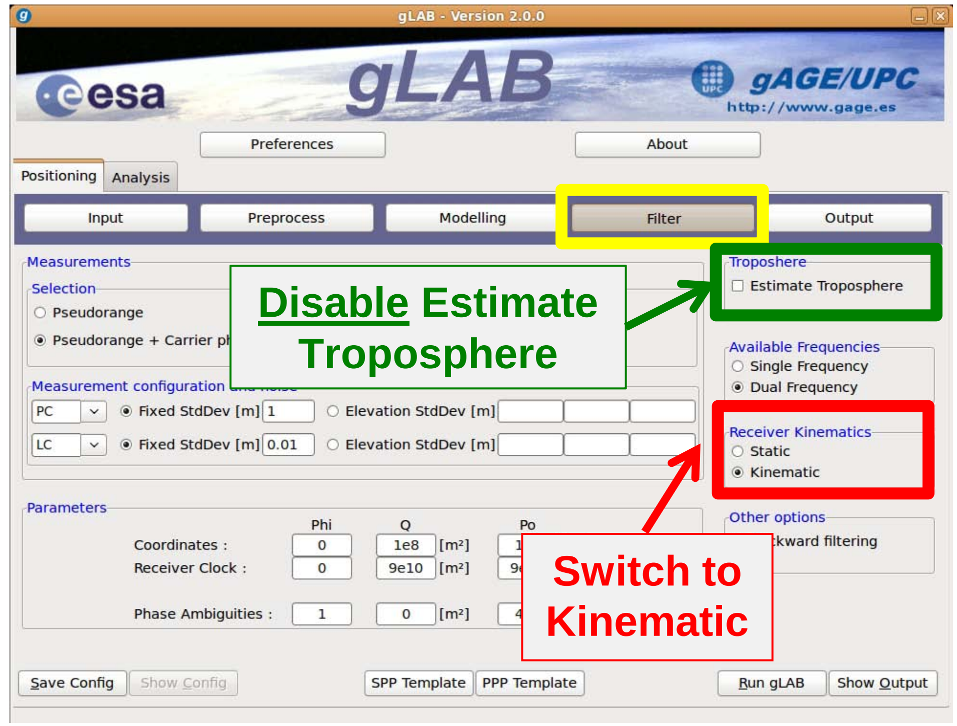


Mode 3. Dual freq. LC, PC carrier and code with precise orbits & clocks

Example of computation with gLAB:

Code & Carrier + precise orbits & clocks: Dual frequency (LC, PC)





Mode 3. Dual freq. LC, PC carrier and code with precise orbits & clocks

Example of computation with gLAB:

Code & Carrier + precise orbits & clocks: Dual frequency (LC, PC)

Run gLAB

1. **Convert** the output **gLAB.out** file to **sp3** format:

   Execute (in **Console**): `out2sp3 gLAB.out`

   ➔ `orb.sp3`

2. **Compare** the computed coordinates **orb.sp3** with reference **GRAA_07_080.sp3**.

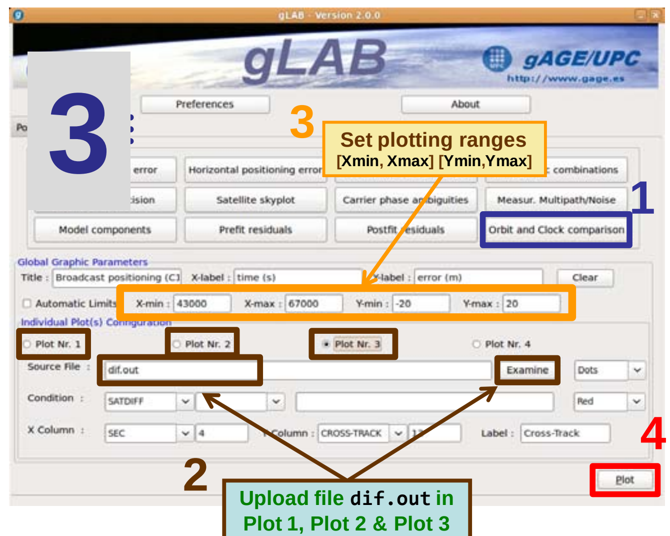
   Note: Use the configuration file `dif.cfg`.

```
gLAB_linux -input:cfg dif.cfg -input:SP3 GRAA_07_080.sp3 -input:SP3 orb.sp3
```

   ➔ `dif.out`

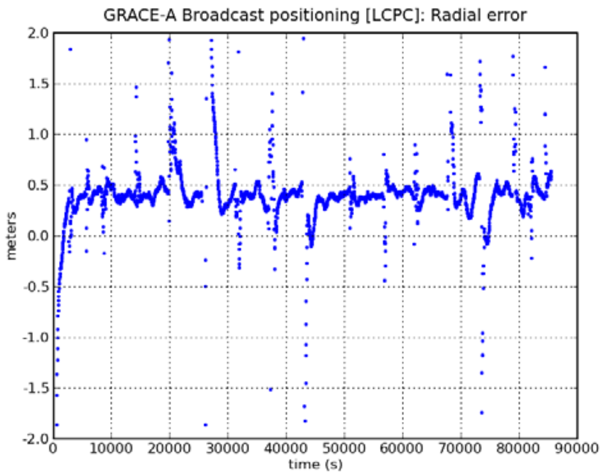
3. **Plot** **dif.out** file:

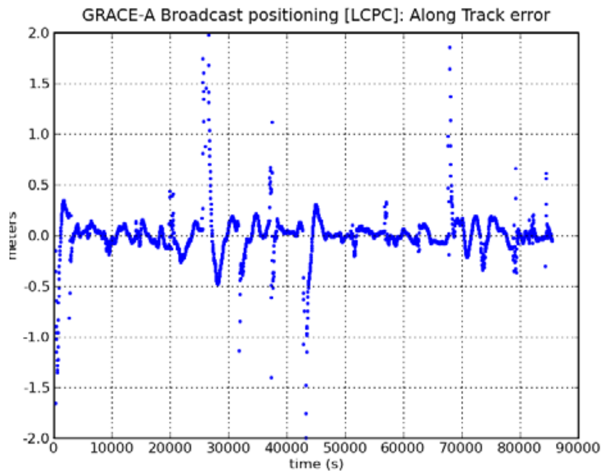
2

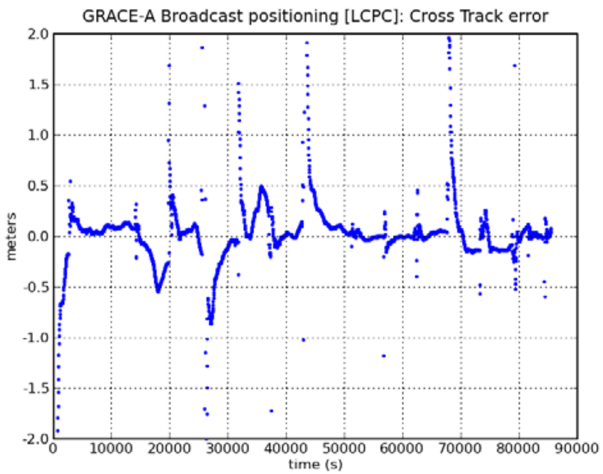


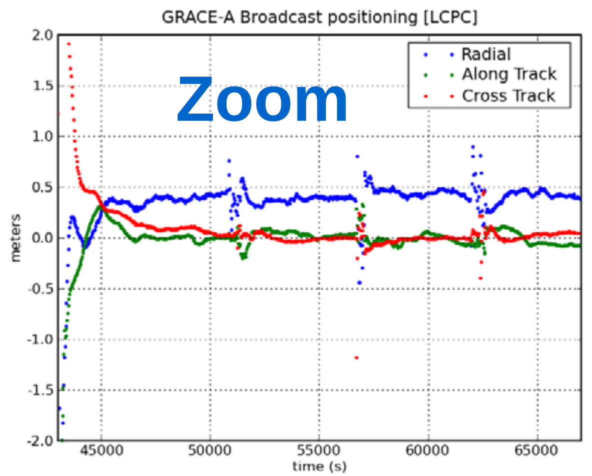
1. **Run gLAB**
2. **Generate dif.out file**
3. **Make plots** as before

Mode 3. Dual freq. LC, PC carrier and code with precise orbits & clocks









Questions

7. Which is the improvement in precise orbits and clocks accuracy, regarding the broadcast case?
8. How do carrier phase measurements allow to improve the accuracy?
9. Why do large peaks appear?
10. Why does a 40-50 cm bias appear in the radial component?
11. Why do wind-up and satellite antenna phase center offset corrections have to be applied? What about the solid tides correction?

Mode 3. Dual freq. LC, PC carrier and code with precise orbits & clocks

- **Answer to Question 7:**

  Which is the improvement in precise orbits and clocks accuracy, regarding the broadcast case?
  - Broadcast orbits and clocks are accurate at the level of few meters.
  - Precise orbits and clocks IGS products are accurate at few centimeter level *(see HW4).*

- **Answer to Question 8:**

  How do carrier phase measurements allow to improve the accuracy?
  - Code measurements are unambiguous but noisy (meter-level measurement noise).
  - Carrier measurements are precise but ambiguous (few millimetres of noise, but with an unknown bias that can reach thousands of kilometres).
  - The carrier phase biases are estimated in the navigation filter along with the other parameters (coordinates, clock offsets, etc.). If these biases were fixed, then measurements accurate at the level of few millimetres, would be available for positioning. However, some time is needed to decorrelate such biases from the other parameters in the filter, and the estimated values are not fully unbiased.

- **Homework:**
  - **HW4:** Assess the broadcast orbits and clock accuracy using the precise products as the truth.

Mode 3. Dual freq. LC, PC carrier and code with precise orbits & clocks

- **Answer to Question 9:**
  Why do large peaks appear?
  - The peaks are related to massive cycle-slips experienced after each revolution (about 1.5 h).
  - After a cycle-slip happens, the filter has to restart the carrier ambiguity. This is not a problem when it occurs on a single satellite (being the others well determined), as its ambiguity is estimated quickly. But when a massive cycle-slip occurs, the filter needs more time to converge *(see HW5).*

- **Answer to Question 10:**
  Why does a 40-50 cm bias appear in the radial component?
  - This is the GRACE-A antenna phase centre offset. Please notice that we are positioning the Antenna Phase Centre (APC), while the coordinates in the SP3 reference file (`GRAA_07_080.sp3`) are referred to the satellite Mass Centre (MC).

- **Homework:**
  - **HW5:** Analyze the carrier phase biases convergence in this kinematic PPP positioning.

Mode 3. Dual freq. LC, PC carrier and code with precise orbits & clocks

- **Answer to Question 11:**
  Why do wind-up and GPS satellite antenna phase center offset corrections have to be applied? What about the solid tides correction?

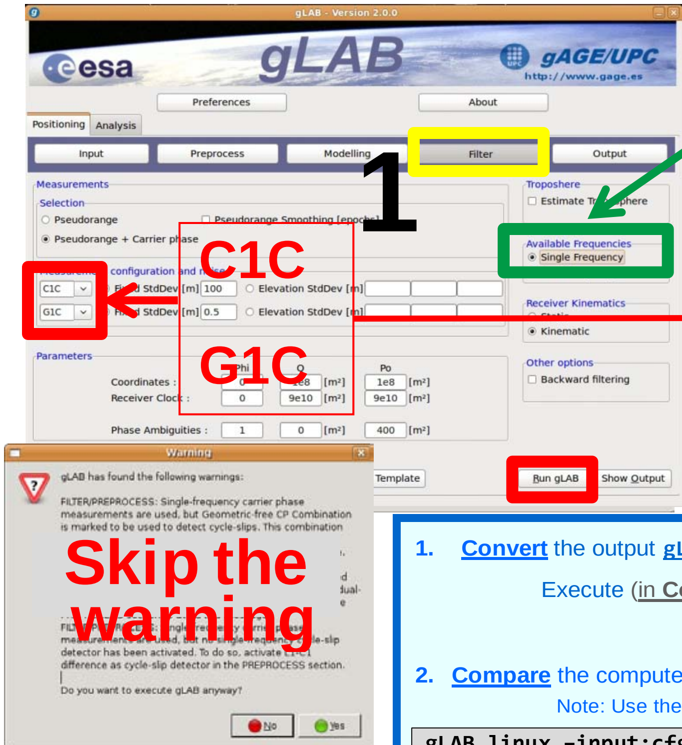
  - **Wind-up correction:** Wind-up only affects the carrier phase measurements, but not the code ones. This is due to the electromagnetic nature of circularly polarised waves of GPS signals.
    The correction implemented in *gLAB* only accounts for the GPS satellites movement relative to a receiver. An additional correction to account for the GRACE-A motion along its orbital path could also be included, but since most part of this effect will be common for all satellites, it will be absorbed by the receiver clock offset estimation.

  - **GPS satellite antenna phase center:** Precise orbits and clocks of IGS products are relative to the GPS satellite mass centre (unlike the broadcast ones, which are relative to the satellite antenna phase centre [APC]). Thence an APC offset vector must be applied.

  - **Solid tides correction:** No Earth's Solid Tides corrections are needed because the rover is not on the ground.

Mode 4. Single freq. with L1, C1 GRAPHIC comb. and precise orbits & clocks

Example of computation with gLAB: Code and Carrier + precise orbits & clocks: Single frequency (GRAPHIC)



Single frequency

[*] Note: C1C **must** be set due to gLAB architecture, but it is *assigned a large sigma* to avoid the C1 code noise and ionospheric error.

σ_{C1}=100 meters

σ_{G1}=0.5 meters

1. **Convert** the output **gLAB.out** file to **sp3** format:

   Execute (in **Console**): `out2sp3 gLAB.out`

   ➔ `orb.sp3`

2. **Compare** the computed coordinates **orb.sp3** with reference **GRAA_07_080.sp3**.

   Note: Use the configuration file `dif.cfg`.

```
gLAB_linux -input:cfg dif.cfg -input:SP3 GRAA_07_080.sp3 -input:SP3 orb.sp3
```

   ➔ `dif.out`

3. **Plot** **dif.out** file:

2

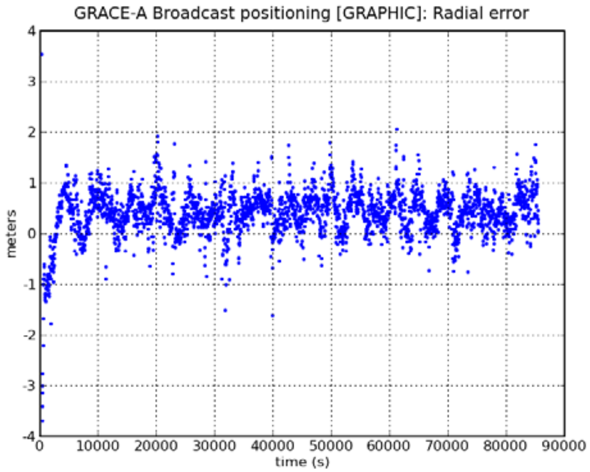
Complete the steps

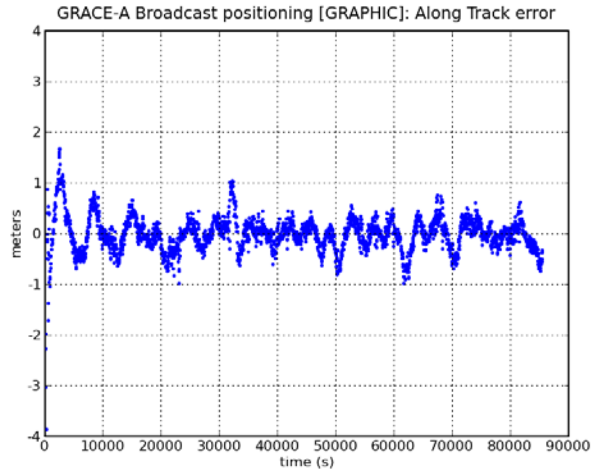
(from previous configuration):

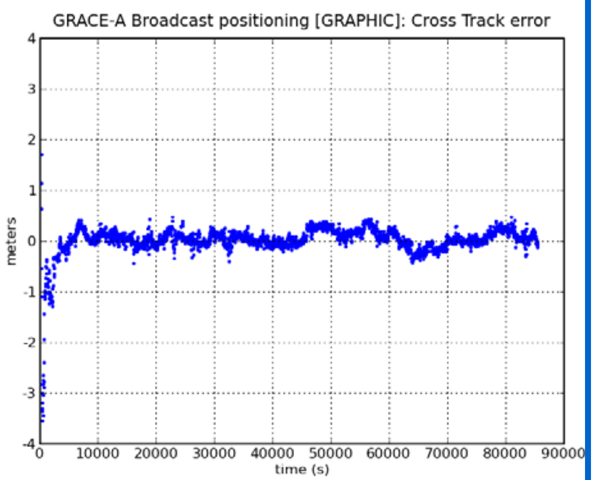
1. [**Model**]:
   - **Disable P1 – P2 Corr.**
2. [**Filter**]:
   - **Single Frequency**
   - **C1C** (C1 code [*])
   - **G1C (GRAPHIC)**
3. Run **gLAB**
4. In console mode:
   - **Convert** the **glab.out** to **orb.sp3** format file.
   - **Compute differences** with reference file **GRAA_07_080.sp3**

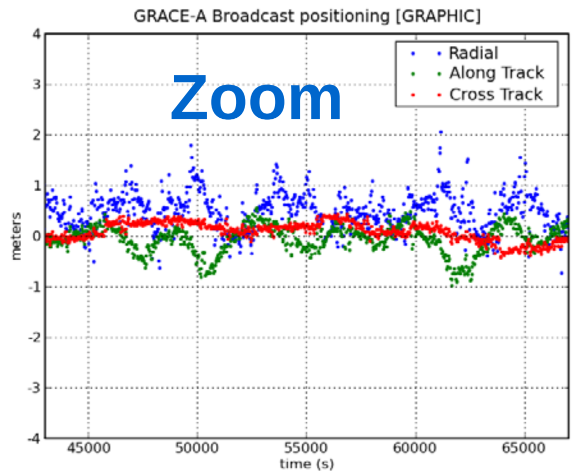
Make plots as before.

Mode 4. Single freq. with L1, C1 GRAPHIC comb. and precise orbits & clocks









Questions

12. Which is the main benefit of the GRAPHIC combination?

13. Why is the solution noisier than the previous one with LC, PC?

14. Would the performance be improved directly using the L1, P1 measurements (like in the LC, PC case)?

Mode 4. Single freq. with L1, C1 GRAPHIC comb. and precise orbits & clocks

- **Answer to Question 12:**
  Which is the main benefit of the GRAPHIC combination?
  - The GRAPHIC combination is defined as: $G=\frac{1}{2}\left(P_1+L_1\right)$
  - Thence, since the ionospheric refraction has opposite sign in code P_1 and carrier L_1, GRAPHIC removes the ionospheric error.
  - On the other hand the code noise is reduced by a factor 2 (i.e., $\sigma_G=1/2\,\sigma$).
  - However, this is an ambiguous measurement due to the unknown carrier phase bias.
  - Note: Due to the gLAB filter design, a code measurement must also be provided to the filter along with the GRAPHIC one. Nevertheless, a large sigma noise is set to this code in order to downweight this measurement in the filter (in this way the solution will be driven by the GRAPHIC combination).

- **Answer to Question 13:**
  Why is the solution noisier than the previous one with LC, PC?
  - Unlike the previous case (where carrier phase data with few millimetres of error were provided), now the most accurate measure provided to the filter is the GRAPHIC combination with tens of centimetres of error.

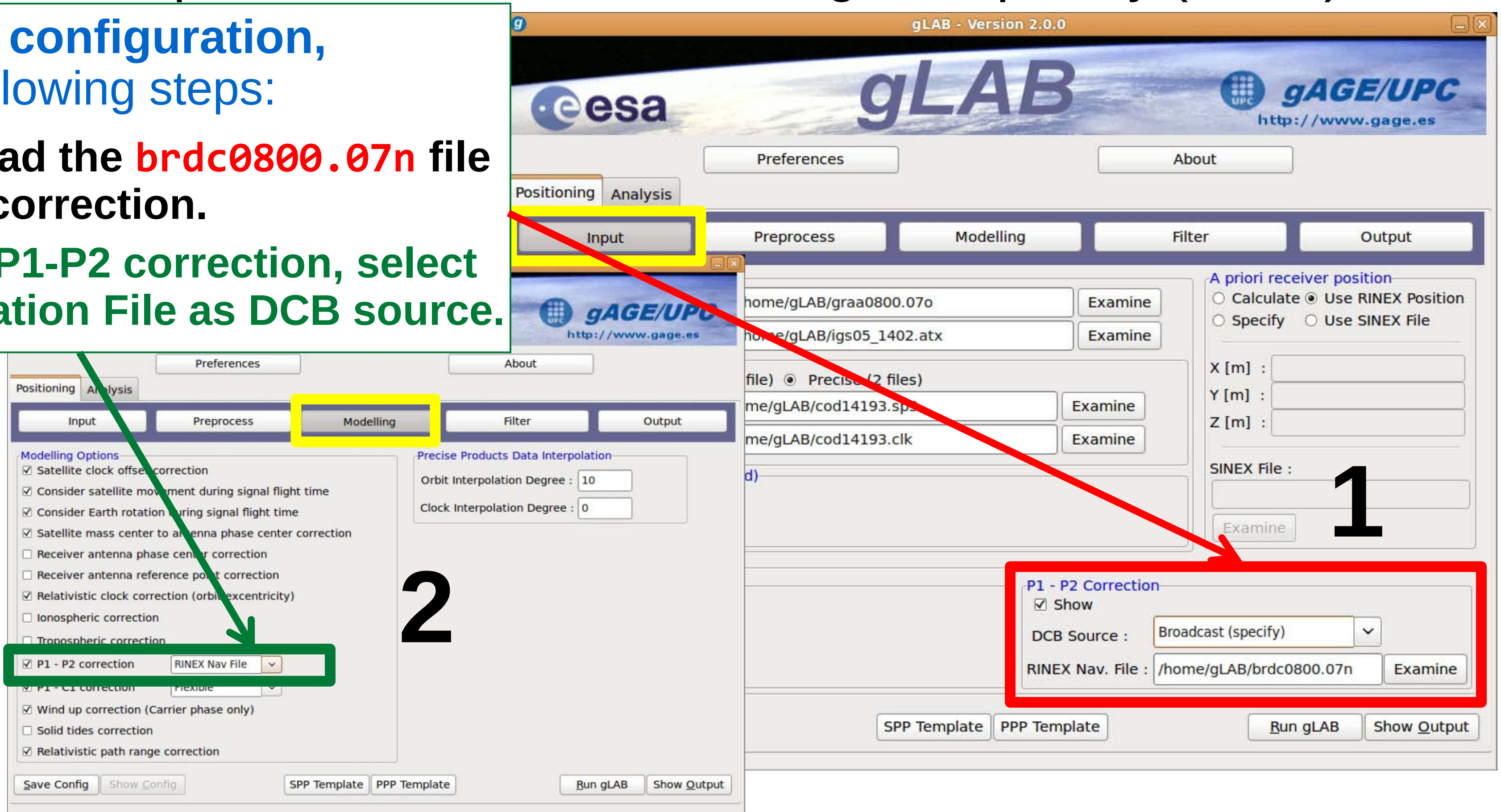
- **Answer to Question 14:** Let's see the next two exercises.

Example of computation with gLAB:

Code and Carrier + precise orbits & clocks: Single frequency (L1, C1)

From previous configuration, complete the following steps:

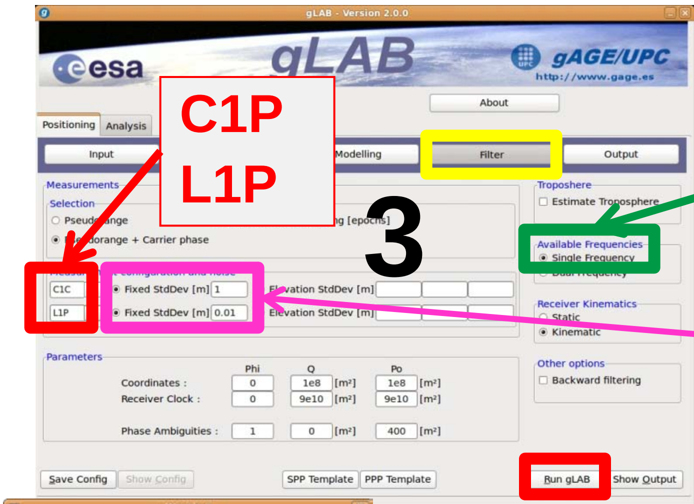
1. **[Input]: Upload the brdc0800.07n file in the P1-P2 correction.**
2. **[Model]: Set P1-P2 correction, select RINEX Navigation File as DCB source.**



Note:
TGDs (i.e, P1-P2 DCBs) are needed for single-frequency positioning.

Example of computation with gLAB:

Code and Carrier + precise orbits & clocks: Single frequency (L1, C1)

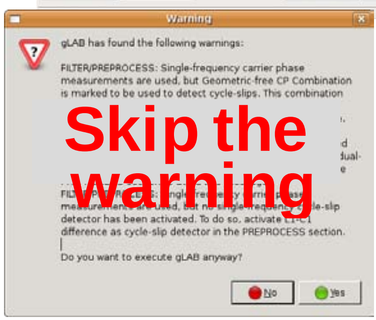


Single frequency

Set

σ_{C1P}=1 meter

σ_{L1P}=0.01 meters



1. **Convert** the output **gLAB.out** file to **sp3** format:

   Execute (in **Console**): `out2sp3 gLAB.out`

   ➔ `orb.sp3`

2. **Compare** the computed coordinates **orb.sp3** with reference **GRAA_07_080.sp3**.

   Note: Use the configuration file **dif.cfg**.

```
gLAB_linux -input:cfg dif.cfg -input:SP3 GRAA_07_080.sp3 -input:SP3 orb.sp3
```

   ➔ `dif.out`

3. **Plot** **dif.out** file:

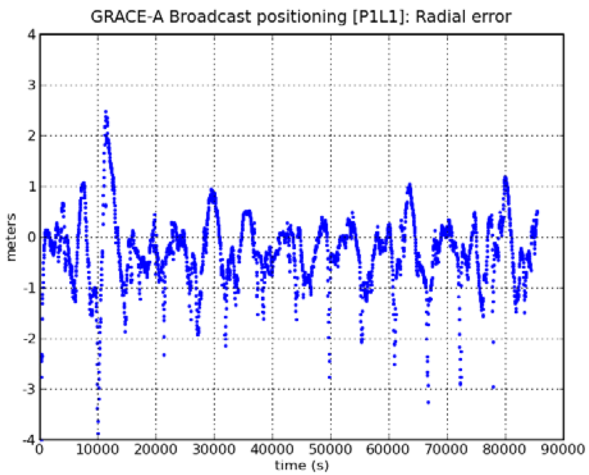
4

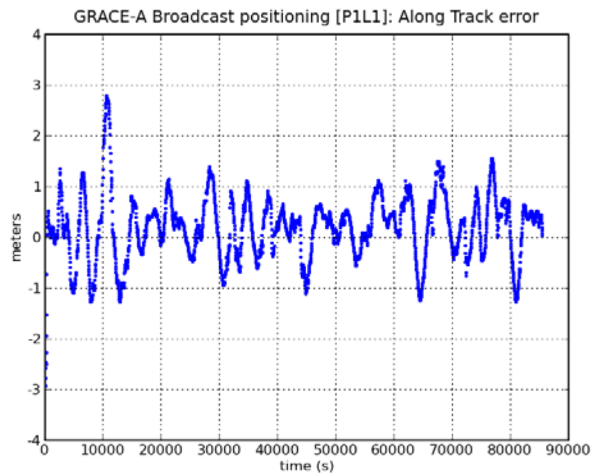
Complete the steps

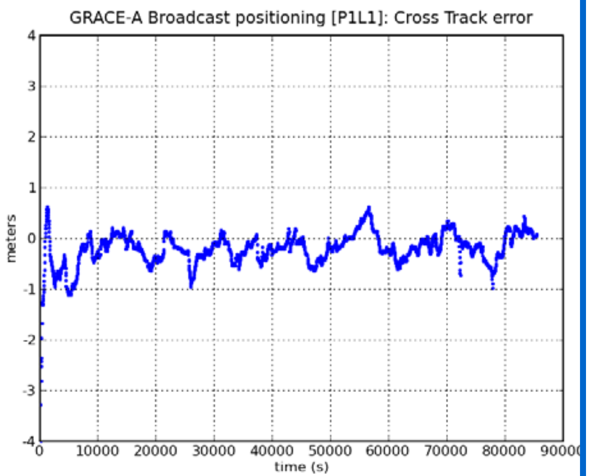
3. [**Filter**]:
   - **Single Frequency measurements**
   - **L1P** (L1 carrier)
   - **C1P** (P1 code)
4. Run **gLAB**
5. In console mode:
   - **Convert** the **gLAB.out** to **orb.sp3** format file.
   - **Compute differences** with reference file **GRAA_07_080.sp3**

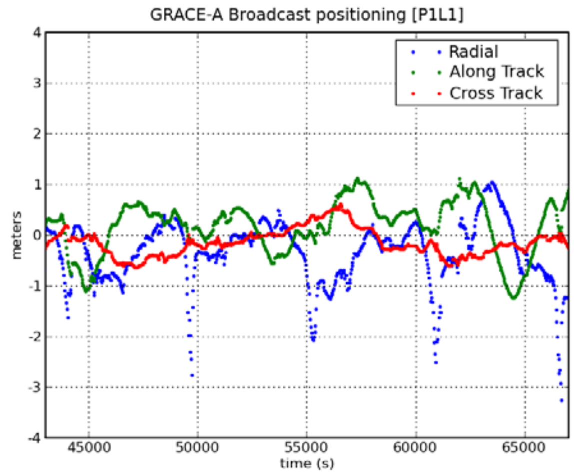
Make plots as before.

Mode 5. Single freq. L1, C1 carrier and code with precise orbits & clocks









Questions

15. Explain why the solution has a more defined pattern, with large oscillations.

16. No ionospheric corrections have been applied in this run. What would happen if the Klobuchar model is applied?

- **Answer to Question 15:**
  Explain why the solution has a more defined pattern, with large oscillations.
  - This effect is due to the error introduced by the ionosphere and the broadcast differential code biases inaccuracy.

- **Answer to Question 16:**
  No ionospheric corrections have been applied in this run. What would happen if the Klobuchar model is applied?
  - In general, the performance will degrade. As commented before, the correction from Klobuchar model is tuned for ground receivers, only removes about the 50% of ionospheric delay, and its usage can produce more harm than benefit. *(see HW6)*.

- **Homework:**
  - **HW6:** Apply the Klobuchar model and discuss the results.
  - **HW7:** Generate a file with the satellite track (in a Earth-Fixed Earth-Centered reference frame) to be viewed with Google earth

OVERVIEW

- ✓ **Introduction**
- ✓ **The gLAB tool suite**
- ✓ **Examples of GNSS Positioning using gLAB**
- ✓ **Laboratory session organization**

LABORATORY Session

- ✓ **Starting-up your laptop**
- ✓ **Basic:** Introductory laboratory exercises (Ex1, Ex2)
- ✓ **Medium:** Laboratory Work Project (LWP): Kinematic positioning of a LEO satellite
- ➢ **Advanced:** Homework

Proposed Homework exercises

- **HW1:** Assess the ionospheric delay on the GRACE-A satellite measurements. Compare with the Klobuchar model corrections.

- **HW2:** Plot in the same graph the “True 3D error”, the “Formal 3D error” (i.e, the 3D-sigma) and the number of satellites used. Analyze the evolution of the error.

- **HW3:** Assess the measurement noise on the C1, P1, P2 measurements and the PC code combination.

- **HW4:** Assess the broadcast orbits and clocks accuracy using the precise products as the truth.

- **HW5:** Analyze the carrier phase biases convergence in this kinematic PPP positioning.

Proposed Homework exercises

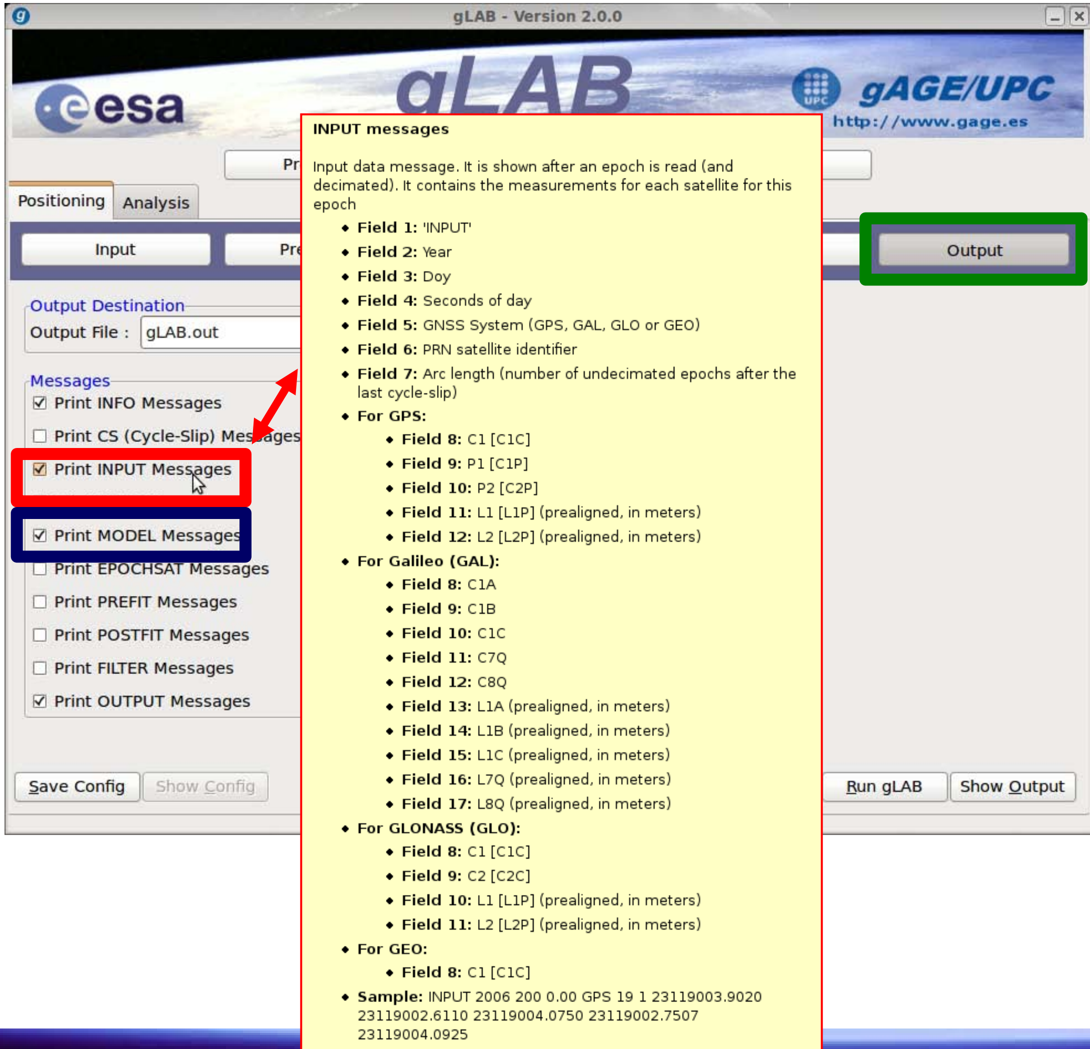
- **HW6:** Apply the Klobuchar model to the L1, P1 positioning with precise orbits and clocks and discuss the results.

- **HW7:** Generate a file with the satellite track (in a Earth-Fixed Earth-Centered reference frame) to be viewed with Google earth.

Backup slides

Homework help and answers

HW1: Assessing the ionospheric delay on the GRACE-A satellite



Configure gLAB as in Mode 1 and complete the following steps:

1. **[Output]: set**
   - **Print INPUT Message**
   - **Print MODEL Message**

   (see message content in the Tooltips)

2. **Run gLAB.**

3. **Make plots:**

   [**Analysis**] section:
   - **Click** on the preconfigured **Ionospheric combinations** option.
   - **Complete** the [Plot1, Plot2, Plot3] panels configuration as indicated in the next slide.

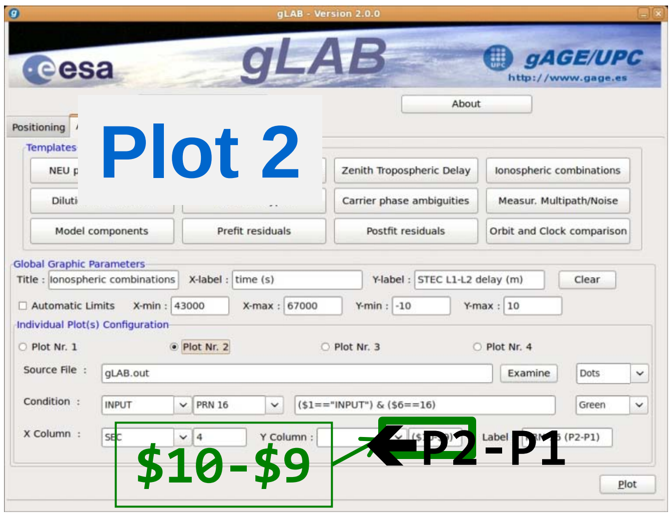
Note: This configuration will provide:

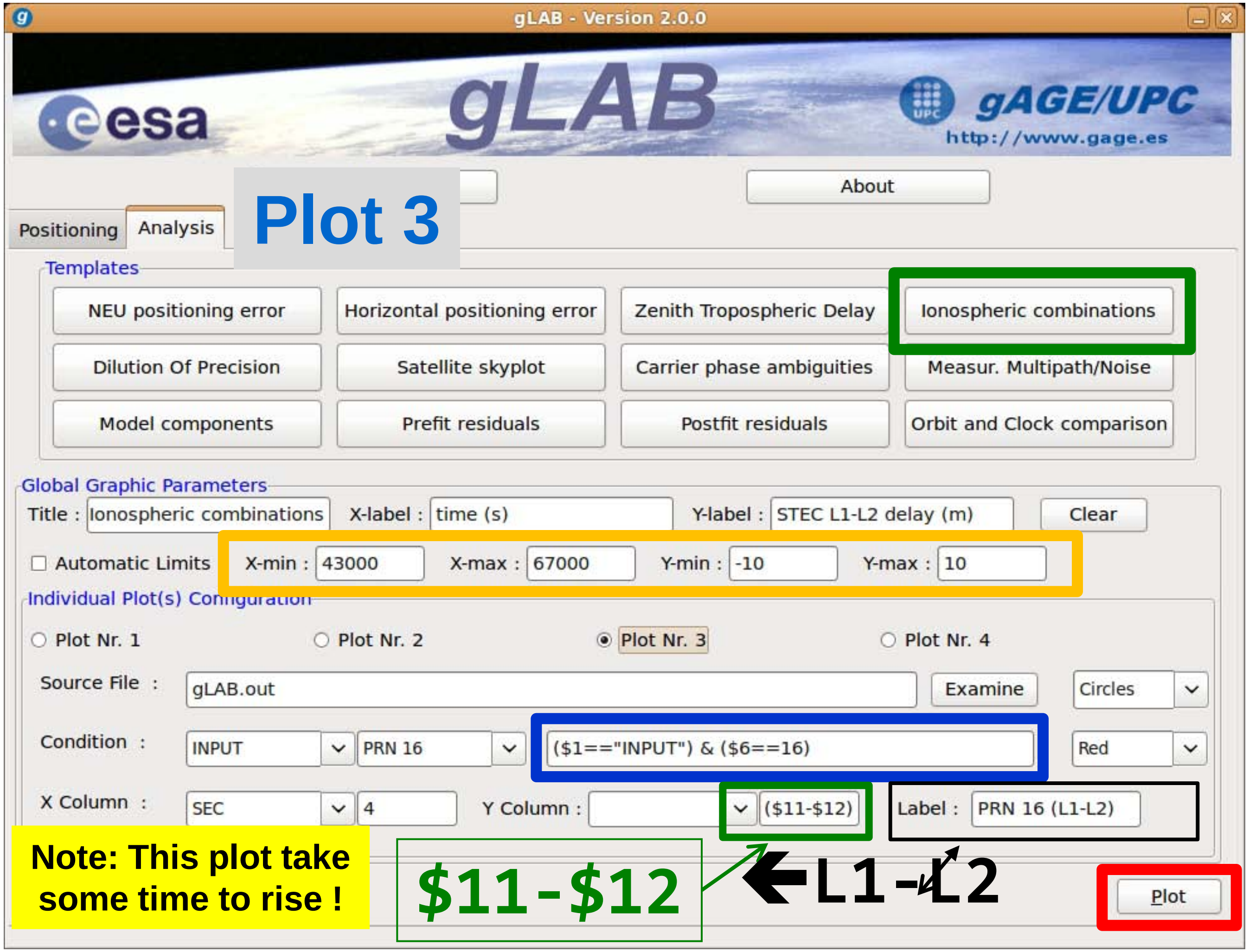
Plot 1: L1-L2 as a function of time for ALL sat.

Plot 2: L1-L2 as a function of time for PRN16.

Plot 3: P2-P1 as a function of time for PRN16

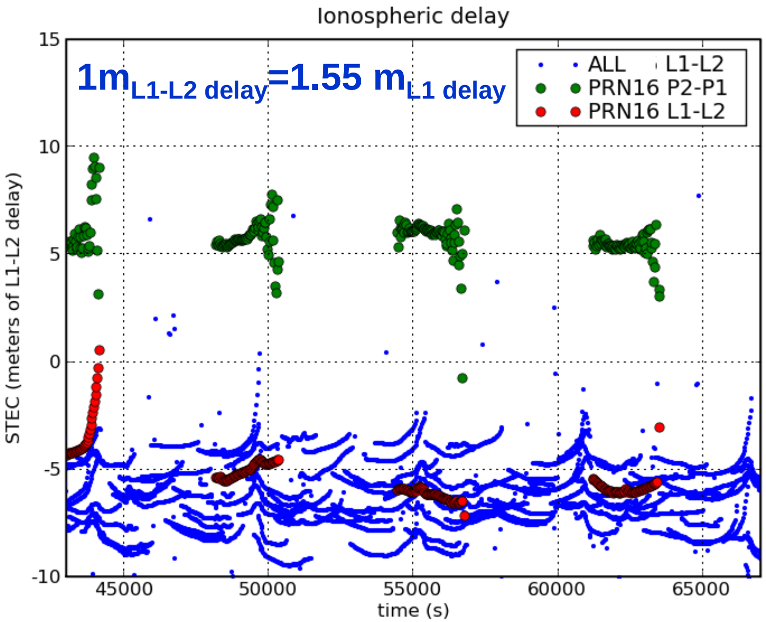
HW1: Assessing the ionospheric delay on the GRACE-A satellite





Note: This plot take some time to rise !

HW1: Assessing the ionospheric delay on the GRACE-A satellite



Plot HW1-a Comments:

- The ionospheric delay (STEC) computed from L1-L2 (aligned) carriers is shown in blue for all satellites.
- The red circles show the L1-L2 delay for sat. PRN16
- The green circles show the ionospheric delay on PRN16 computed from P2-P1 code measurements.

As it is shown in the plot, the STEC variations are typically at the meter level, but in some cases they increase up to several meters.

The code measurement noise and multipath in the P2-P1 combination is typically at the meter level, but in the ends of data arcs (low elevation rays) can reach up to a few meters.

The previous plot can be also generated in console mode as follows (see `graph.py –help`):

```
graph.py -f gLAB.out -c '($1=="INPUT")' -x4 -y'($11-$12)' --l "ALL"
         -f gLAB.out -c '($1=="INPUT")&($6==16)' -x4 -y'($10-$9)'  -so --l "PRN16 P2-P1"
         -f gLAB.out -c '($1=="INPUT")&($6==16)' -x4 -y'($11-$12)' -so --l "PRN16 L1-L2"
         --xn 43000 --xx 67000  --yn -10 --yx 15
```

Working in console mode

The next commands compute the ionospheric delay from C1, L1 measurements:

1. Using the configuration file `meas.cfg`, read the RINEX and generate the MEAS message with data format:

```
[Id YY Doy sec GPS PRN el Az N. list C1C L1C C1P L1P C2P L2P]
 1  2  3   4   5    6  x  x  9  10   11   xx  13  14  15 16 ]
```

   Execute:

```
gLAB_linux -input:cfg meas.cfg -input:obs  graa0800.07o >  meas.txt
```

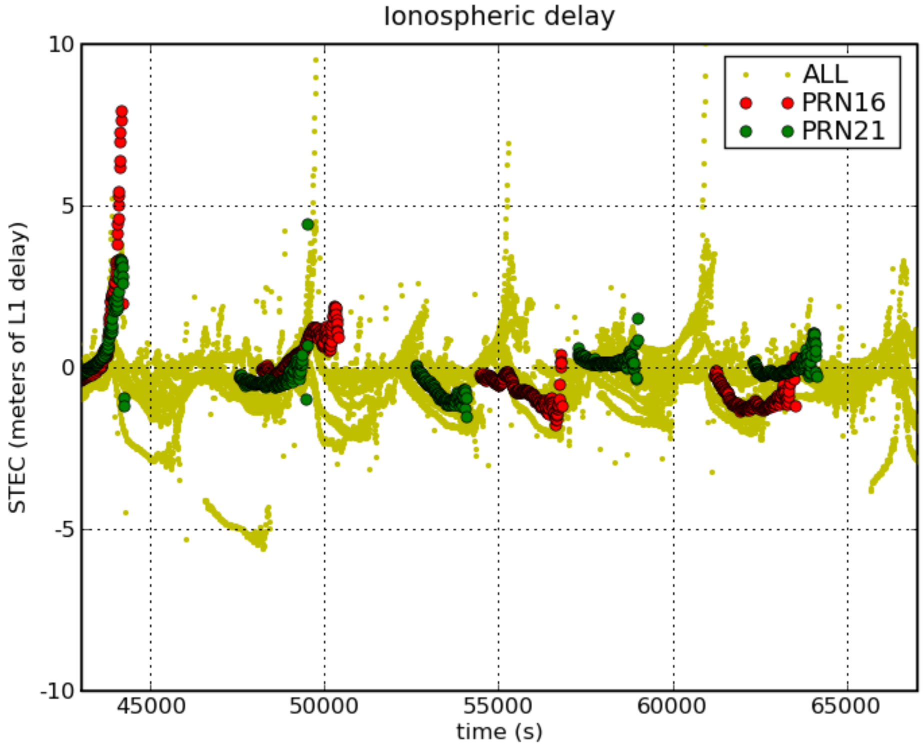
2. From file **`meas.txt`**, compute the ionospheric delay as $I_1 = {}^1\!/_2\,(C1 - L1) + bias$

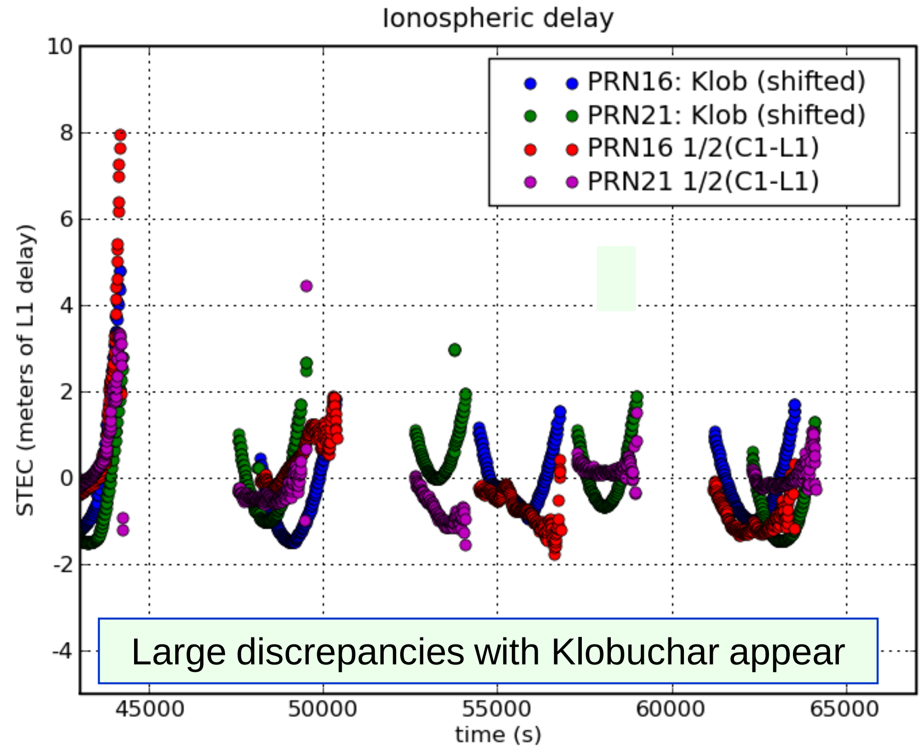
```
gawk '{print $6,$4,($11-$14)/2}' meas.txt > I1.txt
```

3. From previous file, plot the ionospheric delay for the time interval [43000:67000]. Show in the same plot: 1) ALL satellites, 2) PRN16 and 3) PRN21 (see Plot HW1-b in next slide).

```
graph.py -f I1.txt -x2 -y3 -s. --cl y --l "ALL"
         -f I1.txt -c '($1==16)' -x2 -y3 -so --cl r --l "PRN16"
         -f I1.txt -c '($1==21)' -x2 -y3 -so --cl g --l "PRN21"
         --xn 43000 --xx 67000 --yn -10 --yx 10
```

HW1: Assessing the ionospheric delay on the GRACE-A satellite





Plot HW1-b:

STEC variations of few meters are typically experienced , but in some cases they reach up to 8 meters of L1 delay.

Plot HW1-c:

L1-C1 iono estimate is less noisier than the P2-P1. On the other hand, large discrepancies appear when comparing with Klobuchar corrections

Plot HW1-c generation (working with the GUI and in console mode):

1. Using the gLAB configuration of exercise 1, activate the "**Ionospheric Correction**" option in the [**Modelling**] panel and run again gLAB. The program will output the file **`gLAB.out`**.

   (see help and file format executing: **`gLAB_linux -messages`**, *or* **`gLAB_linux -help`**).

2. "grep" the MODEL messages of file **`gLAB.out`**, selecting the C1P [PRN, time Klob_iono] data:

```
grep MODEL gLAB.out |grep C1P|gawk '{print $6,$4,$25-3}' > klob.txt
```

   Note: the Klob_data is shifted by "`-3`" meters to align the curves in the plot

3. Plot in the same graph the ionospheric delays of satellites PRN16 and PRN21 from **`I1.txt`** and **`klob.txt`** file (see Plot HW1-c in the previous slide).

   Note: Both the Graphic User Interface (GUI) panel or the graph.py tool (in console mode) can be used for plotting.

HW2: Plot in the same graph the "True 3D error", the "Formal 3D error" and the number of satellites used. Analyze the result.

Complete the following steps

1. Configure gLAB as in ***Mode1*** and set **Print EPOCHSAT Messages** in **Output panel**.
   (see message content in the Tooltip, or executing **`gLAB_linux –messages`***).*

   Remember that IONO corrections were unable in Mode 1.

2. Run gLAB.
   The program will output the file **`gLAB.out`**.

3. Generate the **`dif.out`** `file from` **`gLAB.out`** as in the previous exercises.

Plot the results:

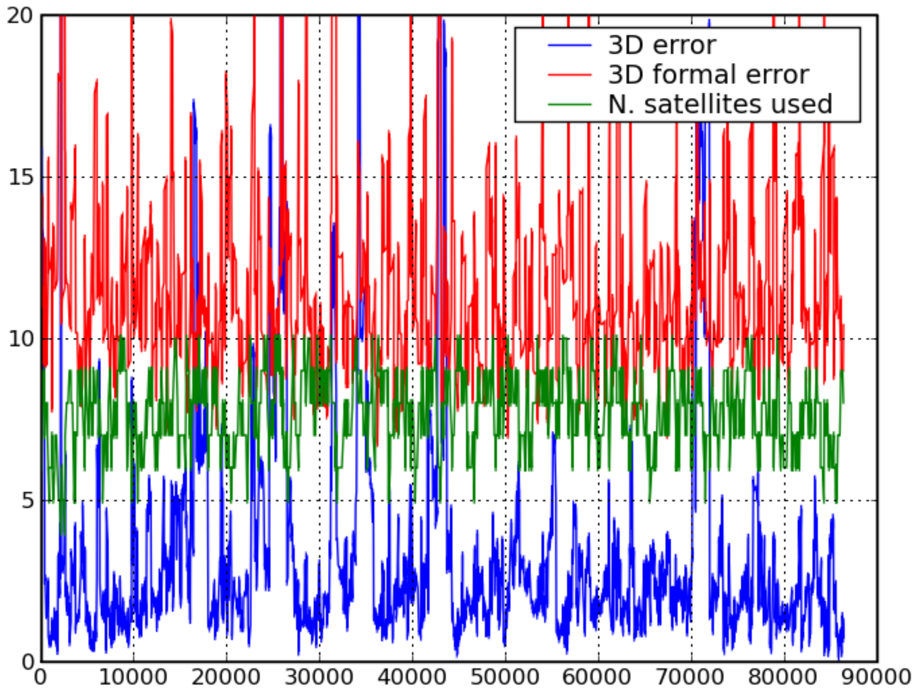
In the same graph, plot the "3D error" [from file **`dif.out`**], the formal error (the 3-D sigma) and the number of satellites used in the computation [from file **`gLAB.out`**].

```
graph.py -f dif.out -x4 -y9 -s- --l "3D error"
         -f gLAB.out -c '($1=="OUTPUT")' -x4 -y'($5*5)' -s- --cl r --l "5*sigma"
         -f gLAB.out -c '($1=="EPOCHSAT")' -x4 -y6 -s- --cl g --l "N. sat. used"
         --xn 43000 --xx 67000  --yn 0 --yx 20
```

Note: *3D-sigma* $\approx \sigma$ *PDOP*

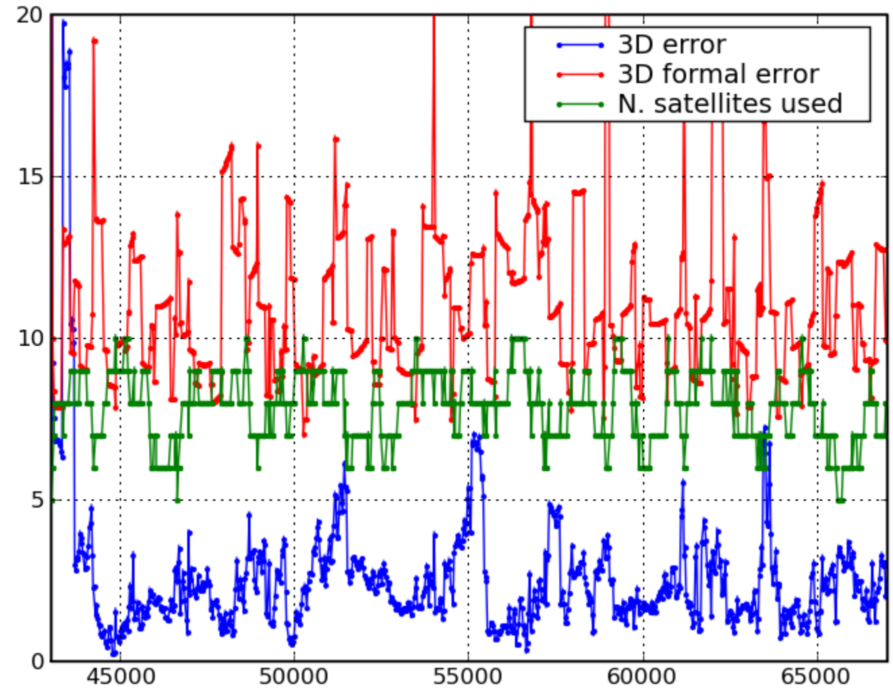
In the previous plot, the 3-D sigma is multiplied by 5 to enlarge the image.

HW2: Plot in the same graph the "True 3D error", the "Formal 3D error" and the number of satellites used. Analyze the result.



Plot HW2-a

Periodic error peaks appear, mostly associated with losing a satellite and/or with bad geometries.



Plot HW2-b: Zoom of Plot HW2-a.

Along the peaks associated to bad geometries, mismodelling is also producing some error trends.

HW3: Code measurements noise assessment: C1, P1, P2 and PC

A) The next commands compute the C1 code noise and multipath:

1. **Using** the configuration file **meas.cfg**, READ the RINEX and generate the MEAS message with data format:

```
[Id YY Doy sec GPS PRN el Az N. list C1C L1C C1P L1P C2P L2P]
 1  2  3   4   5    6  x   x 9  10   11   xx  13  14  15 16 ]
```

   Execute:

```
gLAB_linux -input:cfg meas.cfg -input:obs  graa0800.07o >  meas.txt
```

2. **From meas.txt file,**

   Compute C1 code noise and multipath as:

$$M_{C1} = C1 - L1 - \frac{2}{\gamma - 1}(L1 - L2) \qquad \gamma = \left(\frac{77}{60}\right)^2$$

```
gawk 'BEGIN{g=(77/60)^2}{print $6, $4 , $11-$14-2*($14-$16)/(g-1)}' meas.txt > C1.txt
```

3. **From C1.txt file**,

   Plot the C1 code noise and multipath for time interval [43000:67000]. Show in the same graph: 1) ALL satellites, 2) PRN16 and 3) PRN21 (see Plot HW3-a)

```
graph.py -f C1.txt -x2 -y3 -s. --cl y --l "ALL"
         -f C1.txt -c '($1==16)' -x2 -y3 -so --cl r --l "PRN16"
         -f C1.txt -c '($1==21)' -x2 -y3 -so --cl g --l "PRN21"
         --xn 43000 --xx 67000 --yn 8 --yx 28
```

B) The next commands compute the P1 code noise and multipath:

1. **Using** the **meas.txt** file generated before, with the MEAS message data format:

```
[Id YY Doy sec GPS PRN el Az N. list C1C L1C C1P L1P C2P L2P]
  1  2   3   4   5   6  x  x  9   10  11  xx  13  14  15 16 ]
```

Compute P1 code noise and multipath as:

$$M_{P1} = P1 - L1 - \frac{2}{\gamma - 1}(L1 - L2) \qquad \gamma = \left(\frac{77}{60}\right)^2$$

```
gawk 'BEGIN{g=(77/60)^2}{print $6, $4 , $13-$14-2*($14-$16)/(g-1)}' meas.txt > P1.txt
```

2. **From** previous **P1.txt** file,
   Plot the P1 code noise and multipath for time interval [43000:67000]. Show in the same graph: 1) ALL satellites, 2) PRN16 and 3) PRN21 (see Plot HW3-b)

```
graph.py -f P1.txt -x2 -y3 -s. --cl y --l "ALL"
         -f P1.txt -c '($1==16)' -x2 -y3 -so --cl r --l "PRN16"
         -f P1.txt -c '($1==21)' -x2 -y3 -so --cl g --l "PRN21"
         --xn 43000 --xx 67000 --yn 8 --yx 28
```

C) The next commands compute the P2 code noise and multipath:

1. **Using** the **meas.txt** **file** generated before,, with the MEAS message data format:

```
[Id YY Doy sec GPS PRN el Az N. list C1C L1C C1P L1P C2P L2P]
 1  2  3    4  5    6  x   x 9  10   11   xx  13  14  15 16 ]
```

Compute P2 code noise and multipath as: $M_{P2} = P2 - L2 - \frac{2\gamma}{\gamma - 1}(L1 - L2)$ $\quad \gamma = \left(\frac{77}{60}\right)^2$

```
gawk 'BEGIN{g=(77/60)^2}{print $6, $4 , $15-$16-2*g*($14-$16)/(g-1)}' meas.txt > P2.txt
```

2. **From** previous **P2.txt** **file**,
   Plot the P2 code noise and multipath for time interval [43000:67000]. Show in the same graph: 1) ALL satellites, 2) PRN16 and 3) PRN21 (see Plot HW3-c)

```
graph.py -f P2.txt -x2 -y3 -s. --cl y --l "ALL"
         -f P2.txt -c '($1==16)' -x2 -y3 -so --cl r --l "PRN16"
         -f P2.txt -c '($1==21)' -x2 -y3 -so --cl g --l "PRN21"
         --xn 43000 --xx 67000 --yn 8 --yx 28
```

HW3: Code measurements noise assessment: C1, P1, P2 and PC

D) The next commands compute the PC combination noise and multipath:

1. **Using** the **meas.txt** file generated before, with the MEAS message data format:

```
[Id YY Doy sec GPS PRN el Az N. list C1C L1C C1P L1P C2P L2P]
 1   2  3   4   5   6  x   x  9  10   11   xx  13  14  15 16 ]
```

Compute PC noise and multipath as:

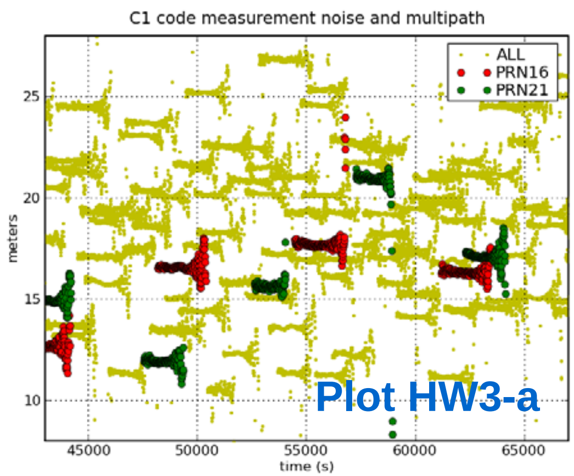
$$M_{Pc} = Pc - Lc \quad \begin{cases} Pc = \dfrac{f_1^2 P_1 - f_2^2 P_2}{f_1^2 - f_2^2} = \dfrac{\gamma P_1 - P_2}{\gamma - 1}; \\[2ex] Lc = \dfrac{f_1^2 L_1 - f_2^2 L_2}{f_1^2 - f_2^2} = \dfrac{\gamma L_1 - L_2}{\gamma - 1} \end{cases}$$

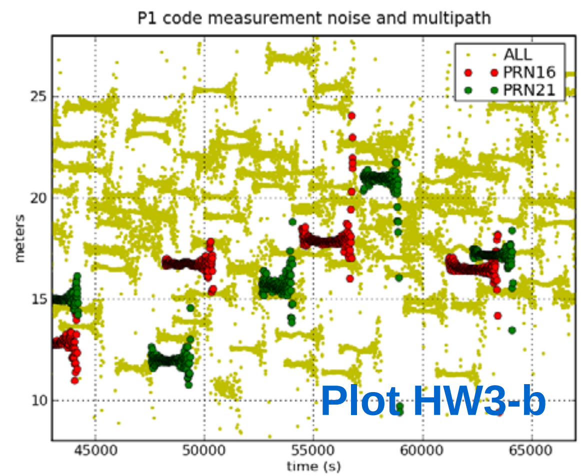
```
gawk 'BEGIN{g=(77/60)^2}{print $6, $4, (g*($13-$14)-($15-$16))/(g-1)}' meas.txt > PC.txt
```

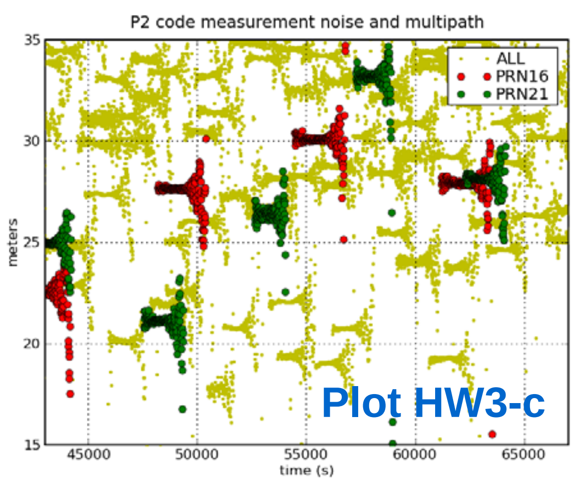
2. **From** previous **PC.txt** file,
   Plot the PC combination noise and multipath for time interval [43000:67000]. Show in the same graph: 1) ALL satellites, 2) PRN16 and 3) PRN21 (see Plot HW3-d)

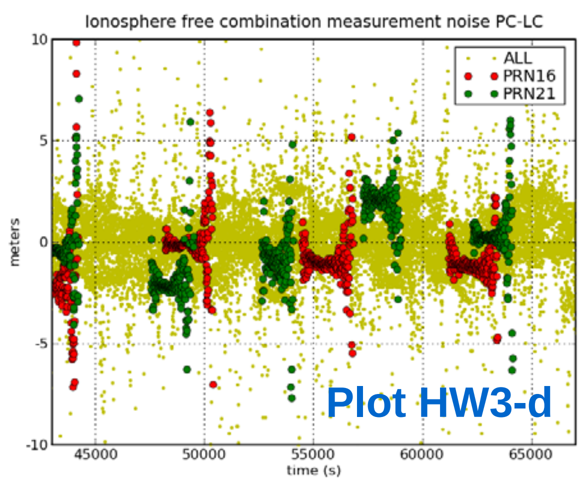
```
graph.py -f PC.txt -x2 -y3 -s. --cl y --l "ALL"
         -f PC.txt -c '($1==16)' -x2 -y3 -so --cl r --l "PRN16"
         -f PC.txt -c '($1==21)' -x2 -y3 -so --cl g --l "PRN21"
         --xn 43000 --xx 67000 --yn 8 --yx 28
```

HW3: Code measurements noise assessment: C1, P1, P2 and PC



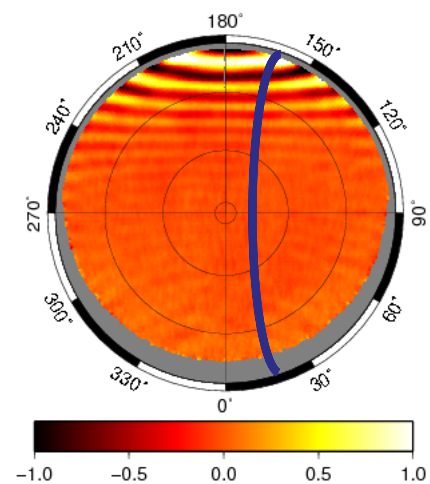






Comments

- Large noise patterns appear at the end of each data arc. This is due to interference cross-talk with other components. The figure at bottom shows the multipath map for the GRACE-A .
- P2 code is noisier than P1 or C1.
- PC code combination is the noisiest one, as expected.



C1 multipath map of sat. GRACE_A.

A GPS satellite track is shown in blue

This figure is from P. Ramos-Bosch PhD dissertation, gAGE/UPC 2008].

HW4: Broadcast orbits and clocks accuracy assessment using the IGS precise products as the accurate reference (i.e, the truth).

Complete the following steps:

File **brdc0800.07n** contains the orbit and clocks data broadcast in the GPS navigation message. Files **cod14193.sp3**, **cod14193.clk** contain the precise orbits and clocks computed in post-process by "CODE" center (IGS precise orbits and clocks products program).

1. **Execute** the following sentence to compute the difference of satellite coordinates and clock offsets between both orbits and clocks sources:

```
gLAB_linux -input:nav brdc0800.07n -input:SP3 cod14193.sp3 -input:ant igs05_1402.atx > dif.tmp
```

2. **Select** the SATDIFF message of **dif.tmp** file:

```
grep SATDIFF dif.tmp > dif.out
```

SATDIFF message content is shown in the table beside. *(see* **gLAB_linux -messages***).*

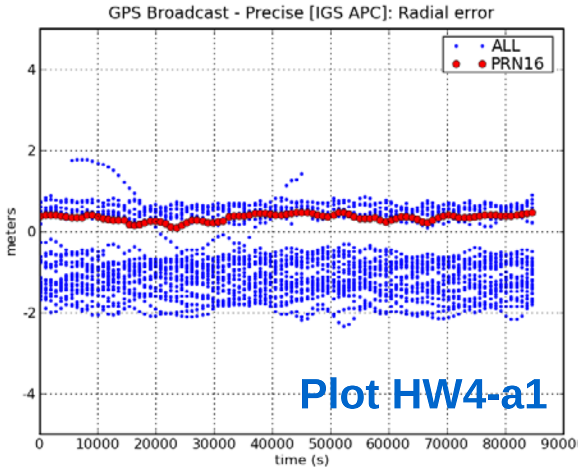
The IGS post-processed products are accurate at few cm level, thence they can be taken as the truth.

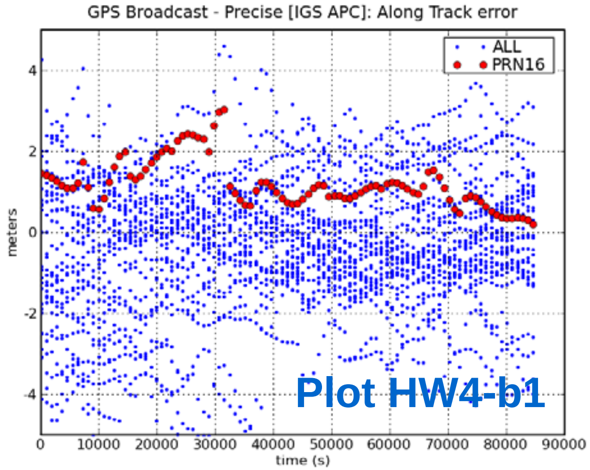
3. **Plot** **dif.out** **file** as in the first exercise.

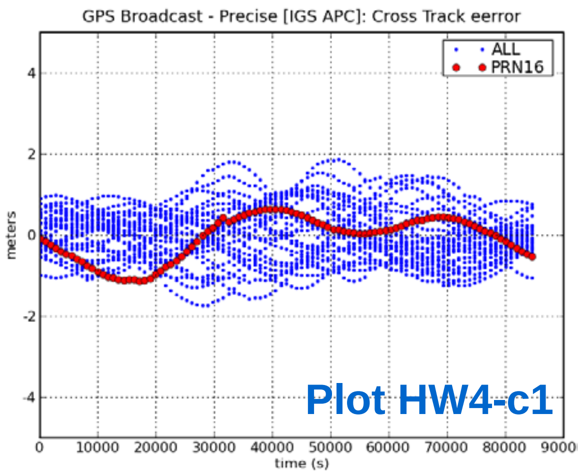
Field	Content
1	'SATDIFF'
2	Year
3	Doy (Days-of-Year)
4	Seconds of day (seconds)
5	GNSS System (GPS, GAL, GLO or GEO)
6	PRN satellite identifier
7	SISRE difference (meters)
8	SISRE orbit-only difference (meters)
9	3D orbit difference (meters)
10	$clkDiff$: Clock difference (meters)
11	$radDiff$: Radial position difference (meters)
12	$atDiff$: Along-track position difference (meters)
13	$ctDiff$: Cross-track position difference (meters)

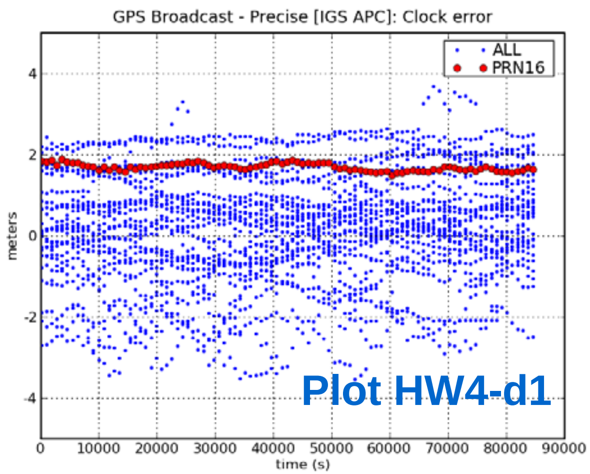
Note: $SISRE = \sqrt{(\Delta\text{Rad} - \Delta\text{Clk})^2 + \frac{1}{49}(\Delta\text{Alon}^2 + \Delta\text{Cross}^2)}$

HW4: Broadcast orbits and clocks accuracy assessment using the IGS precise products as the accurate reference (i.e, the truth).



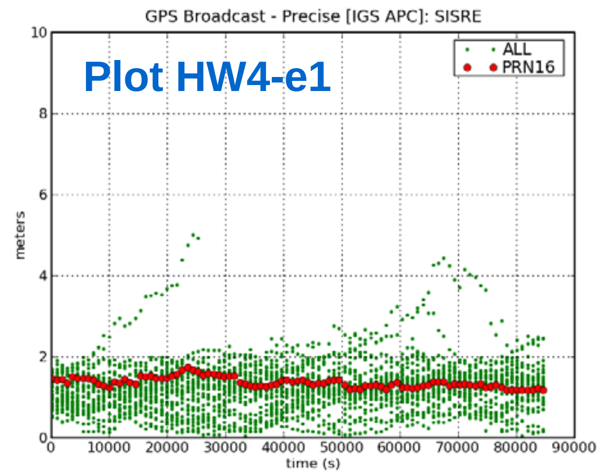




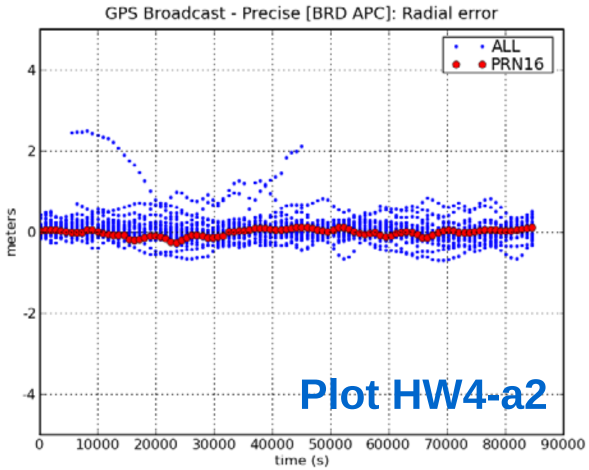


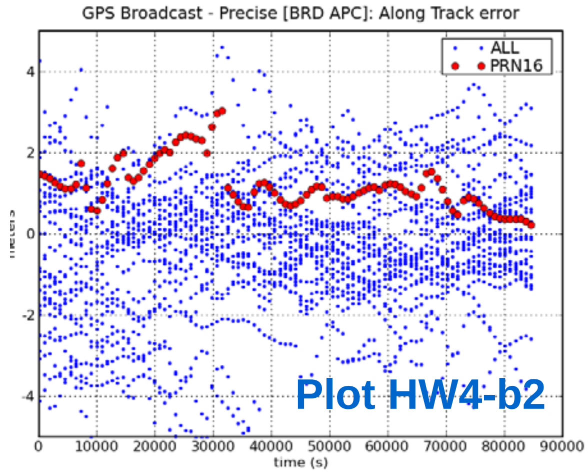
Comments

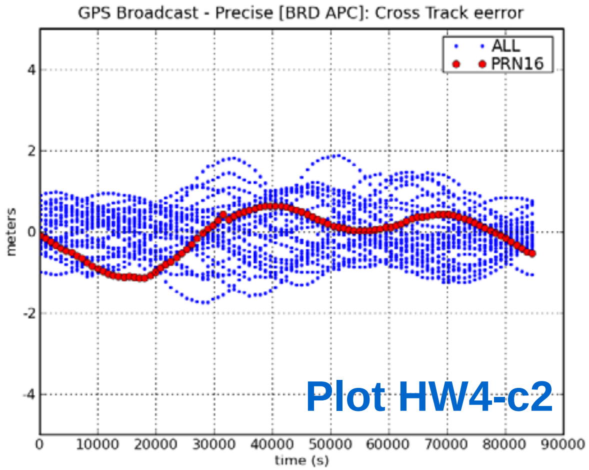
- Meter level errors are found on broadcast orbits and clocks.
- The bias seen in the radial component is due to the different APC's used by the GPS ground segment (i.e, in broadcast orbits) and by IGS (precise products).
- This bias is compensated by a similar shift in clocks.
- For the Signal-In-Space-Range-Error (SISRE), please see the plot below.

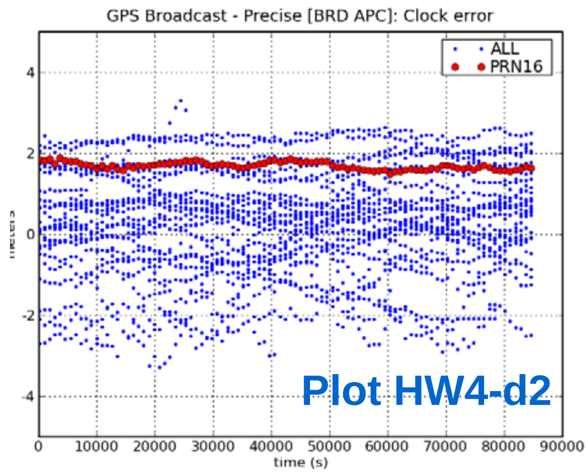


HW4: Broadcast orbits and clocks accuracy assessment using the IGS precise products as the accurate reference (i.e, the truth).







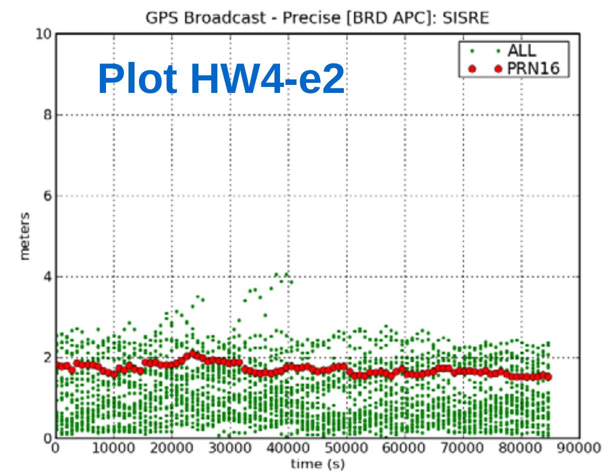


Comments

The previous computations have been repeated, but using the ANTEX file **gps_brd.atx**, instead of **igs05_1402.atx**.

This new ANTEX file contains the GPS antenna phase center offsets used by the GPS ground segment, not the IGS ones.

- Notice that the biases in the radial component have disappeared.



HW5: Analyze the carrier phase biases convergence in the kinematic PPP positioning.

Complete the following steps

1. Configure gLAB as in ***Mode 2*** for the Kinematic PPP positioning. Activate the "**Print POSTFIT messages**" in the OUPUT panel
   (see message content in the Tooltip, or executing **`gLAB_linux –messages`**).

2. Run gLAB.
   The program will output the file **`gLAB.out`**.

3. From **`gLAB.out`**, "grep" the **POSTFIT** message and generate the file **`amb.out`**, containing the estimates of ambiguities for each epoch. Take the last estimated value of the ambiguities for each epoch. This can be done by executing:

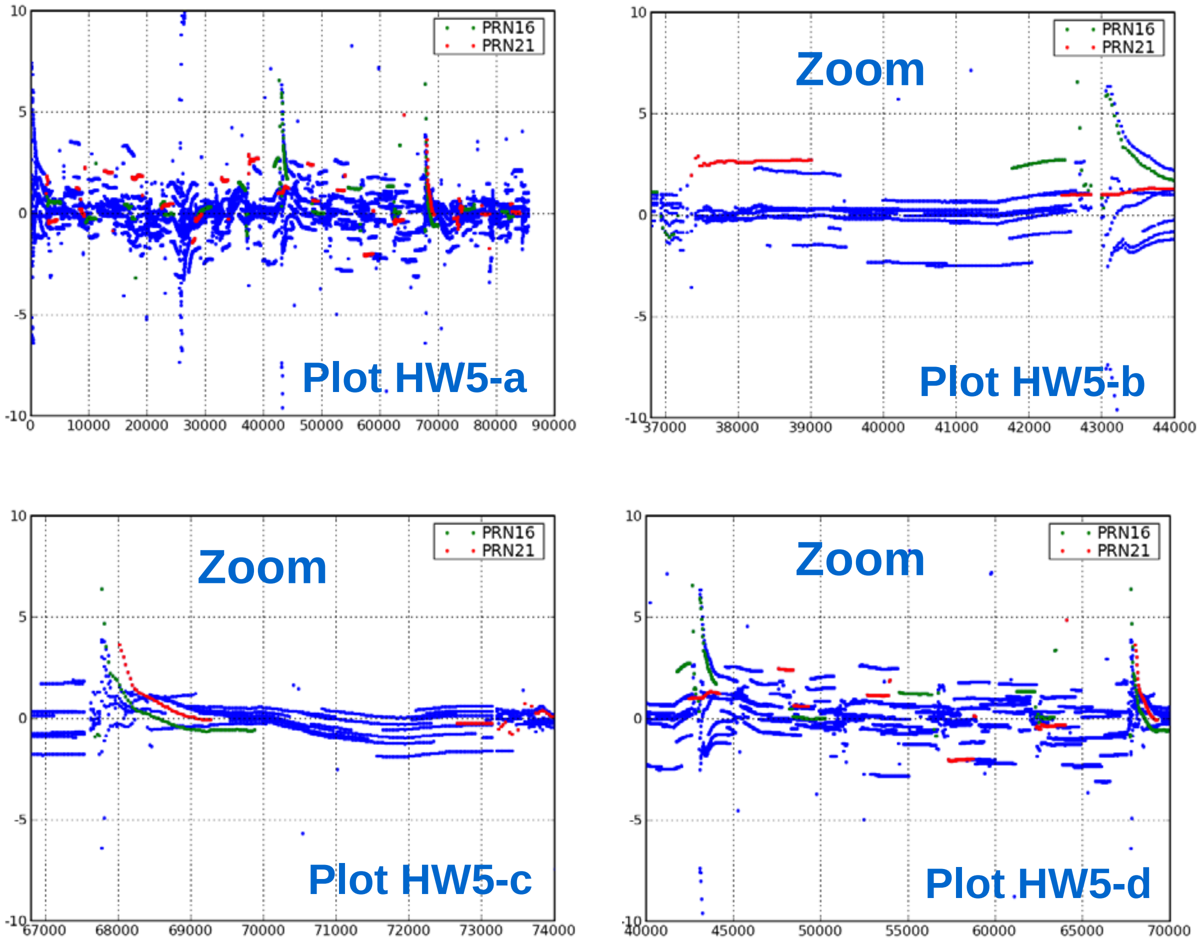
```
grep POSTFIT gLAB.out| gawk '{i=$6" "$4;a[i]=$13}END{for (i in a) print i,a[i]}' |sort -n > amb.out
```

Plot the results: Plot the ionosphere-free bias estimates as a function of time for the time interval [40000:70000]. Show in the same graph: 1) ALL satellites, 2) PRN16 and 3) PRN21 **(see Plot HW5-d).**

Note: The GUI can be used instead of the "graph.py" command.

```
graph.py -f amb.out -x2 -y3
         -f amb.out -x2 -y3 -c '($1==16)' --l "PRN16"
         -f amb.out -x2 -y3 -c '($1==21)' --l "PRN21"
         --xn 40000 --xx 70000 --yn -10 --yx 10
```

HW5: Analyze the carrier phase biases convergence in the kinematic PPP positioning.

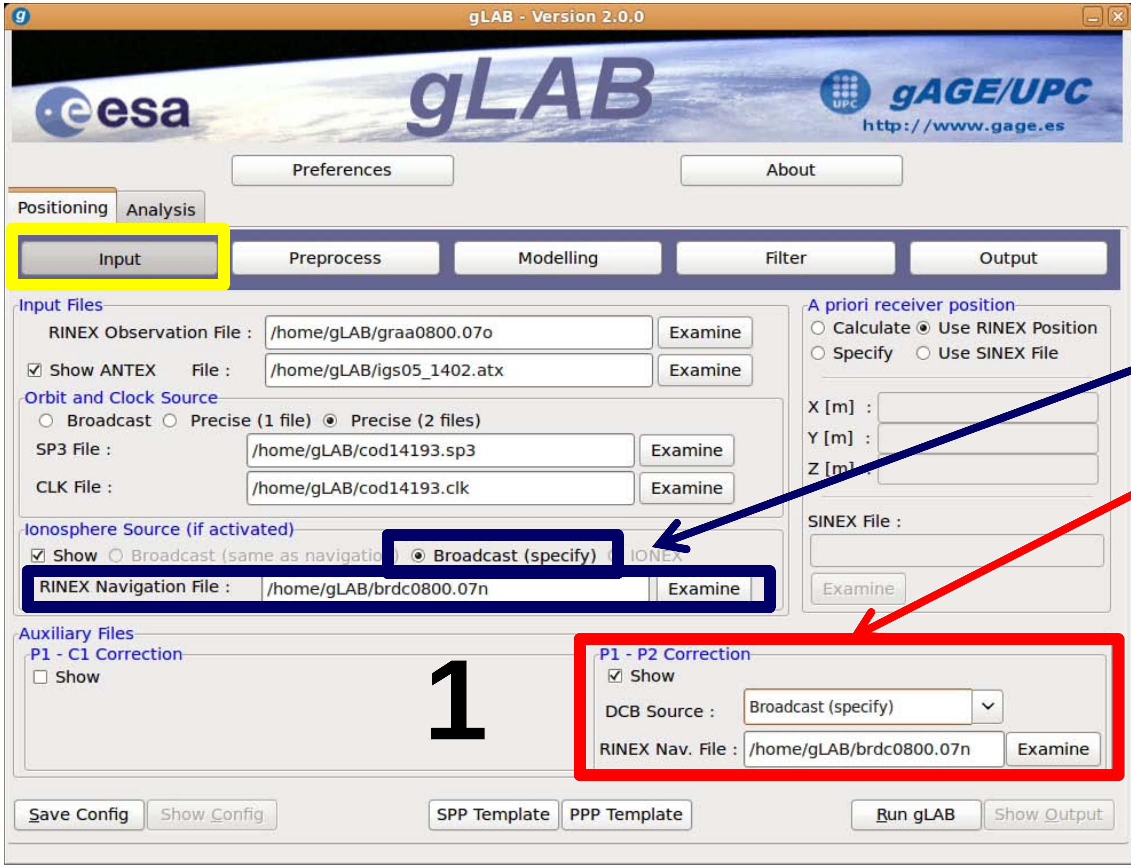


Comments

- Large peaks appear in the carrier phase biases due to massive cycle-slips:
  - Satellite tracking loses happen periodically after each revolution.
  - These satellite loses produce massive cycle slips which leads to a global reinitialization of carrier-phase biases in the navigation (Kalman) filter .
  - After such ambiguities reinitialization, the filter needs some time to converge.
- Carrier phase ambiguities converge quickly thanks to the rapid variation of geometry due to the LEO movement along its orbital path.

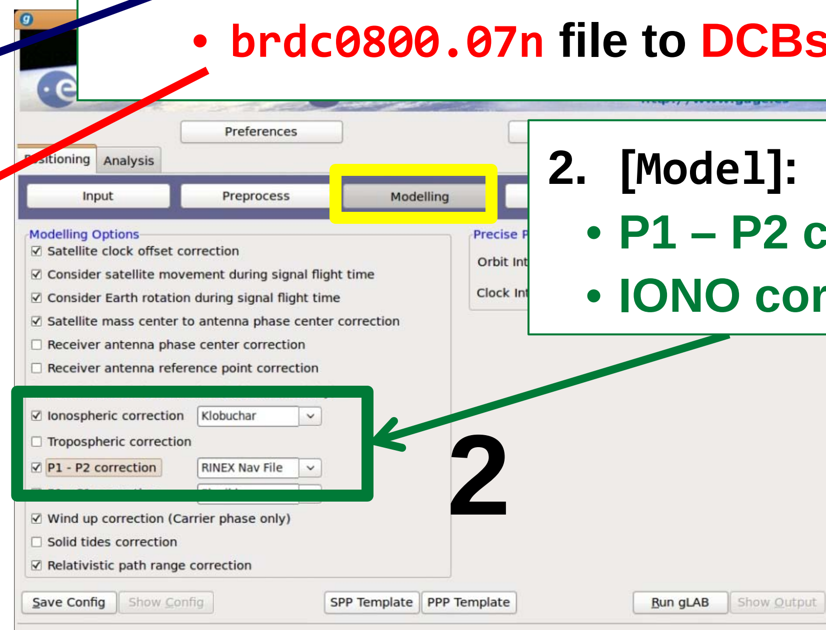
HW6: Single freq. L1, C1 carrier and code with precise orbits & clocks using Klobuchar ionospheric corrections

Code and Carrier + precise orbits & clocks: Single frequency (L1, C1) + Klobuchar ionosphere



Configure gLAB as in Mode 5 and complete the following steps:

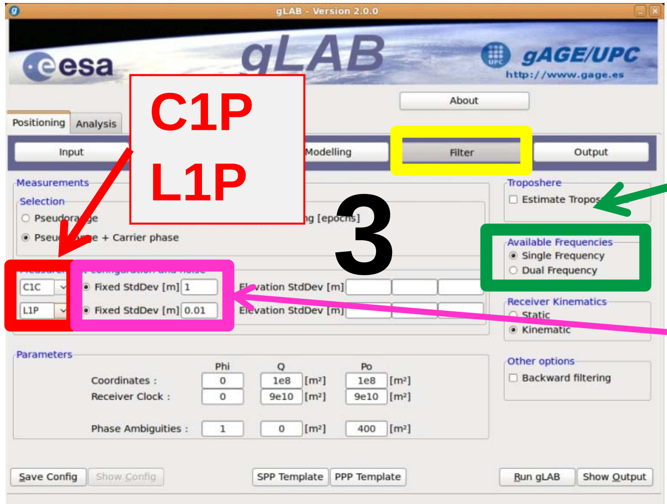
1. **[Input]: Upload the**
   - **brdc0800.07n file to IONO**
   - **brdc0800.07n file to DCBs**



2. **[Model]: set**
   - **P1 – P2 corr.**
   - **IONO corr.**

HW6: Single freq. L1, C1 carrier and code with precise orbits & clocks using Klobuchar ionospheric corrections

Code and Carrier + precise orbits & clocks: Single frequency (L1, C1) + Klobuchar ionosphere



C1P
L1P

3

Single frequency

Set

σ_{C1P} = 1 meter

σ_{L1P} = 0.01 meters

1. **Convert** the output **gLAB.out** file to **sp3** format:

   Execute (in **Console**): `out2sp3 gLAB.out` → `orb.sp3`

4

2. **Compare** the computed coordinates **orb.sp3** with reference **GRAA_07_080.sp3**.

   Note: Use the configuration file **dif.cfg**.

```
gLAB_linux -input:cfg dif.cfg -input:SP3 GRAA_07_080.sp3 -input:SP3 orb.sp3
```

→ `dif.out`

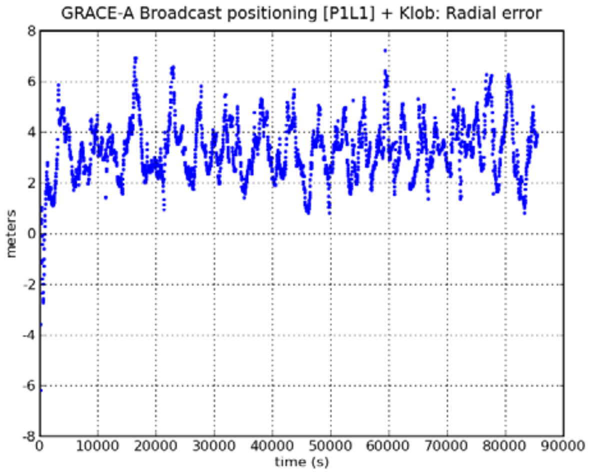
3. **Plot** **dif.out** file:

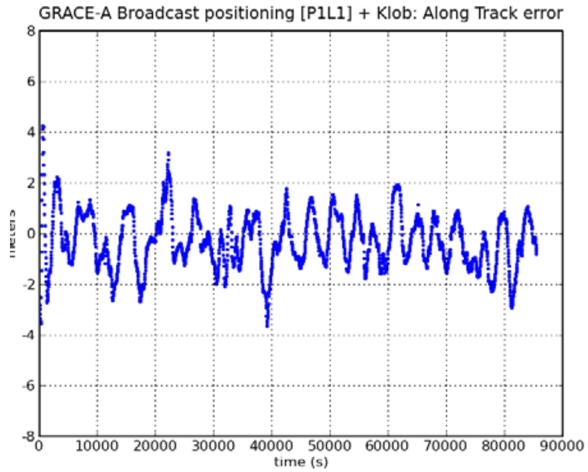
Complete the steps

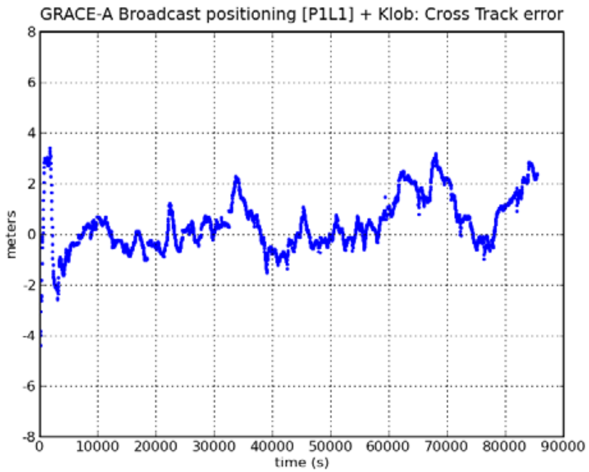
3. [**Filter**]:
   - **Single Frequency measurements:**
   - **L1P** (L1 carrier)
   - **C1P** (P1 code)
4. In console mode:
   - **Convert** the **glab.out** to **orb.sp3** format file.
   - **Compute differences** with reference file **GRAA_07_080.sp3**

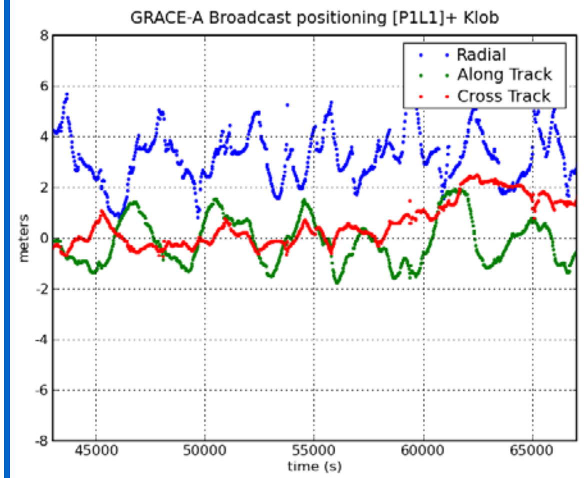
Make plots as before.

HW6: Single freq. L1, C1 carrier and code with precise orbits & clocks using Klobuchar ionospheric corrections



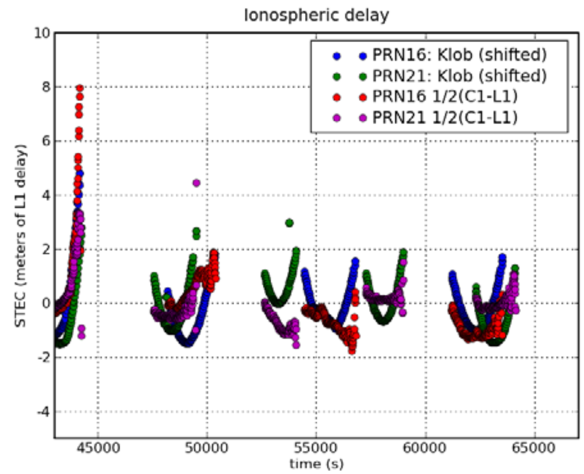






Comments

- A clear degradation is seen when applying the Klobuchar model to the LEO.
- This is due to the large error introduced by this model which was designed for ground receivers, not for LEO's.
- Next plot compares the L1 delay computed from Klobuchar with the STEC experienced by the GPS signal.



HW7: Generate a file with the satellite track (in a Earth-Fixed Earth-Centered reference frame) to be viewed with Google Earth

Complete the following steps

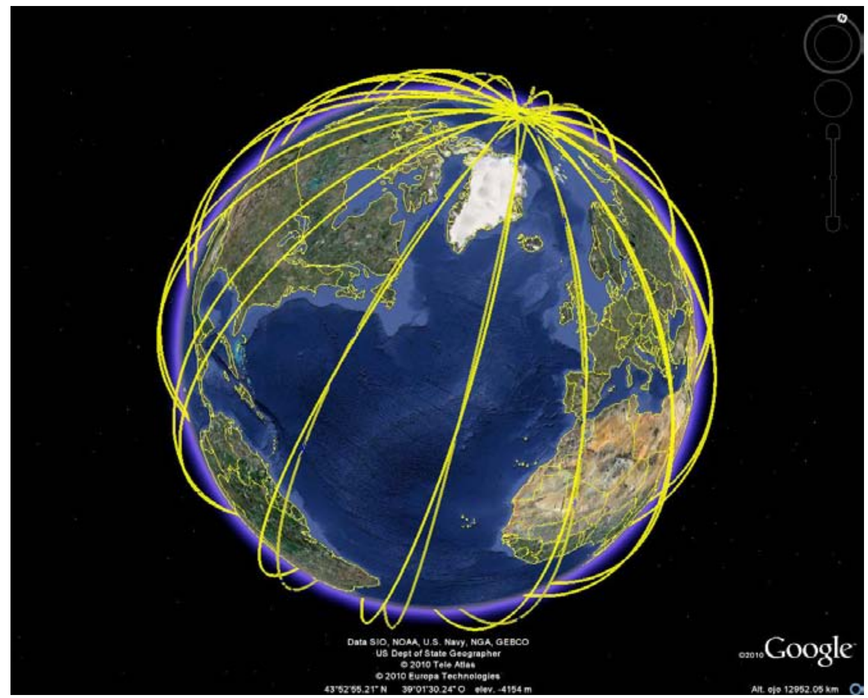
1. Select the satellite [longitude, latitude, height] coordinates of message OUTPUT in the gLAB.out file. Generate a file with these coordinates (comma-separated).

```
grep OUTPUT gLAB.out |gawk ‘BEGIN{OFS=“,“} {print $16,$15,$17}’ > track.tmp
```

2. Add the header (**`Prefix.kml`**) and the tail (**`Postfix.kml`**) files to the previous **`track.tmp`** data file:

```
cat Prefix.kml  >  grace_track.kml
cat track.tmp   >> grace_track.kml
cat Postfix.kml >> grace_track.kml
```

3. View the file with: Google earth



Thanks for your attention

Acknowledgements

- The ESA/UPC GNSS-Lab Tool suit (gLAB) has been developed under the ESA Education Office contract N. P1081434.
- The data set of GRACE-A LEO satellite was obtained from the NASA Physical Oceanography Distributed Active Archive Center at the Jet Propulsion Laboratory, California Institute of Technology.
- The other data files used in this study were acquired as part of NASA's Earth Science Data Systems and archived and distributed by the Crustal Dynamics Data Information System (CDDIS).
- To Pere Ramos-Bosch for his fully and generous disposition to perform gLAB updates in his afterhours.
- To Adrià Rovira-Garcia for his contribution to the edition of this material and gLAB updating.
- To Dagoberto Salazar for the English reviewing and integrating this learning material into the GLUE.