

# GNSS Data Processing Laboratory Exercises

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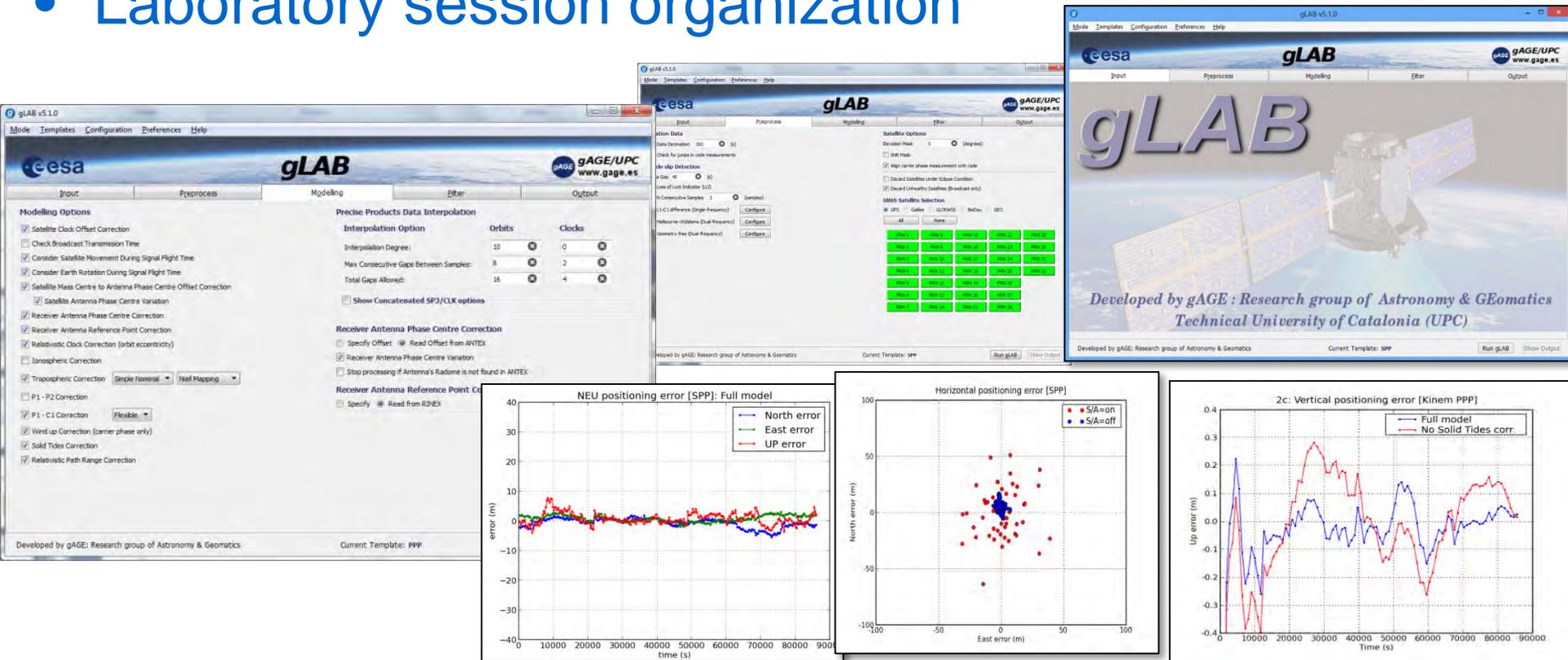
*gAGE/UPC*

*Research group of Astronomy & Geomatics*  
Technical University of Catalonia

# OVERVIEW



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



# 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.

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- Introduction
- The gLAB tool suite
- Examples of GNSS Positioning using gLAB
- gLAB software installation



# 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 contracts N. P1081434 and C4000113054.

## ★ 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 screenshot displays the gLAB v5.1.0 software interface with an error dialog box open. The dialog box, titled "Errors found", contains the following text:

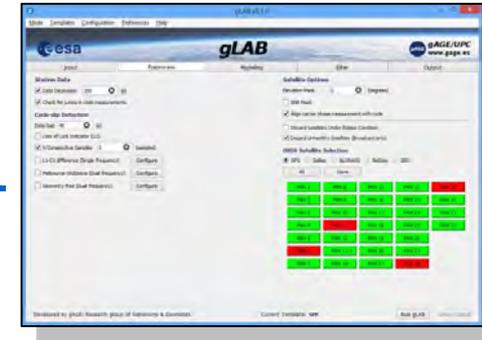
gLAB has found the following errors, please correct them before executing processing again:

- INPUT: RINEX Observation file is a required input.
- INPUT: RINEX Broadcast navigation file is a required input if 'Broadcast' orbit and clock source is specified.

The background interface shows the "Modelling Options" and "Station Data" tabs. The "Modelling Options" tab includes checkboxes for "Satellite Clock Offset Correction", "Check Broadcast Transmission Time", "Consider Satellite Movement During Signal Flight Time", "Consider Earth Rotation During Signal Flight Time", "Satellite Mass Centre to Antenna Phase Centre Offset Correction", "Receiver Antenna Phase Centre", "Relativistic", "Ionospheric", "Tropospheric", "P1 - P2 Correction", "Wind up Correction", "Solid Tides Correction", and "Relativistic Path Range Correction". The "Station Data" tab includes fields for "Data Decimation", "Check for jumps in code measurements", "Cycle-slip Detection", "Data Gap", "Loss of Lock Indicator (LLI)", "N Consecutive Samples", "Reference (Single-frequency)", "Wübbena (Dual-frequency)", and "Free (Dual-frequency)". The "Satellite Options" tab includes "Elevation Mask", "SNR Mask", "Align carrier phase measurement with code", "Discard Satellites Under Eclipse Condition", "Discard Unhealthy Satellites (Broadcast only)", and "GNSS Satellite Selection". A red box highlights the "Current Template: PPP" label at the bottom of the interface.

# 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**.



```
File Edit View Terminal Help
g4:~/workspace/edunav> ./gLAB_linux -input:obs test/madr2000.06o -input:sp3 test/igs13843.sp
3 -input:ant test/igs05.atx
```

# The gLAB Tool suite

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



- The package contains:
  - Windows binaries (with an installable file).
  - Linux .tgz file.
  - Mac installable .dmg file.
  - Source code (to compile it in both Linux, Windows and Mac OS) under an Apache 2.0 and LGPL v3. licenses.
  - 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.
- SBAS files: EMS, RINEX-B
- RTCM-v2x and RTCM-x3x

## 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 center correction.
- Receiver phase center correction. (frequency dependent).
- Relativistic clock correction.
- Relativistic path range correction.
- Ionospheric correction (Klobuchar, NeQuick, IONEX).
- Tropospheric correction
  - Simple and Niell mappings.
  - Simple and UNB-3 nominals.
- Differential Code Bias corrections.
- Wind up correction.
- Solid tides correction (up to 2<sup>nd</sup> degree).
- SBAS Messages.
- RTCM messages.

# 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/PO 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:

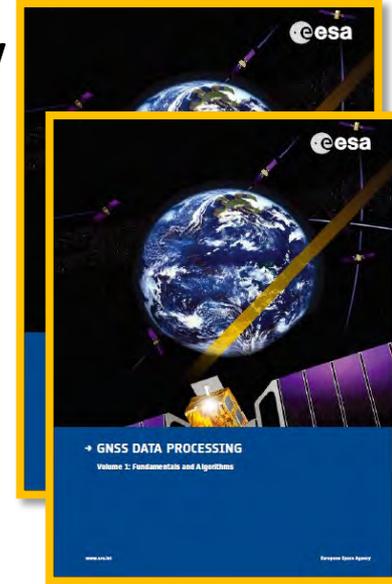
- Computation of satellite coordinates and clocks from RINEX and SP3 files.
- Satellite coordinates comparison mode. For instance RINEX navigation vs. SP3, or SP3 vs. SP3 (along-track, cross-track and radial orbit errors, clock errors, SISRE).
- Show input mode. No processing, only parsing RINEX observation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



# OVERVIEW



- Introduction
- The gLAB tool suite
- Examples of GNSS Positioning using gLAB
- gLAB software installation

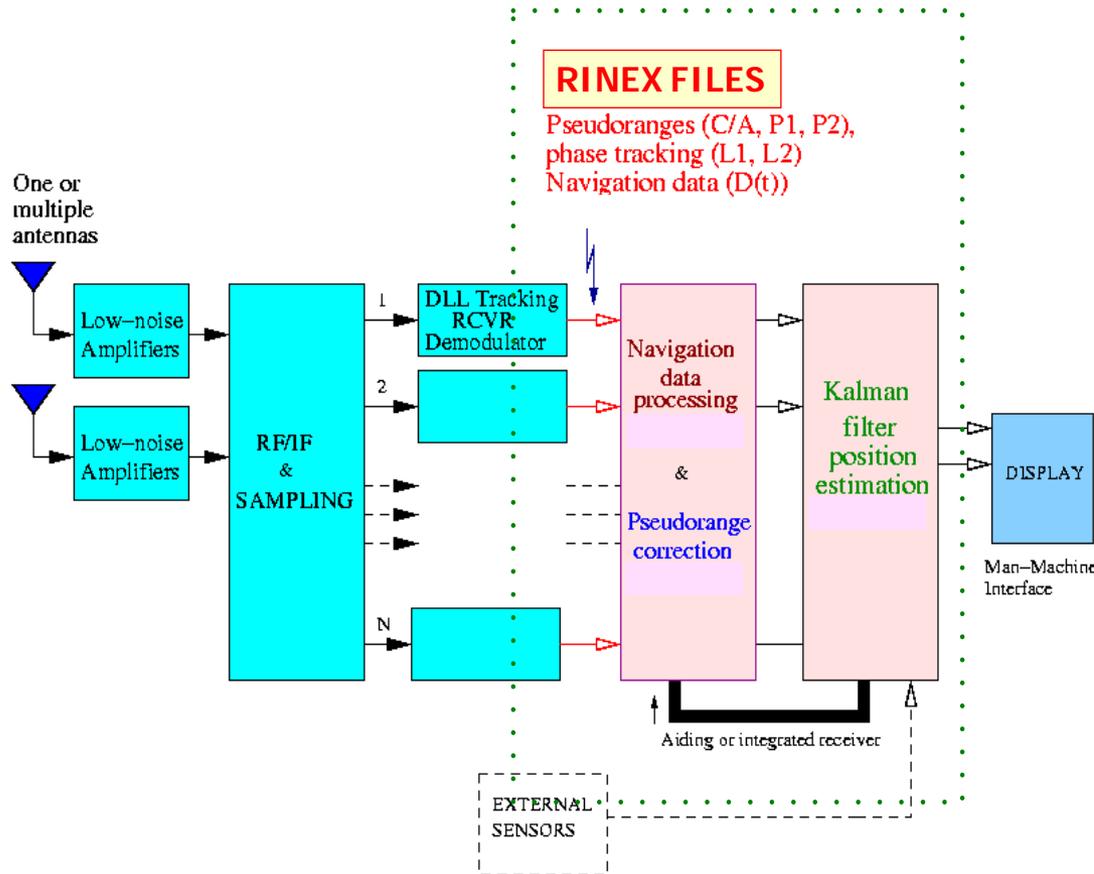


# Basic: Introductory Lab. Exercises

- 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 assess the positioning error.

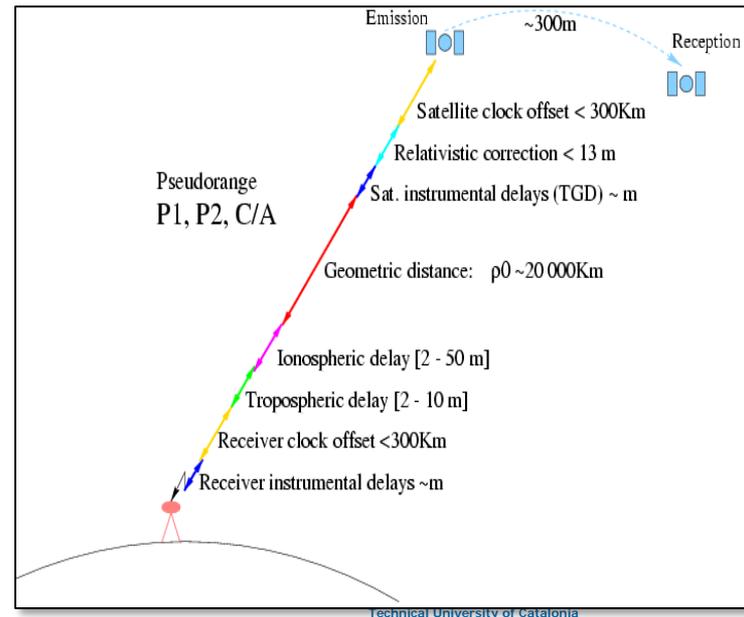
*Note: the receiver coordinates were kept fixed during the data collection.*

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



```

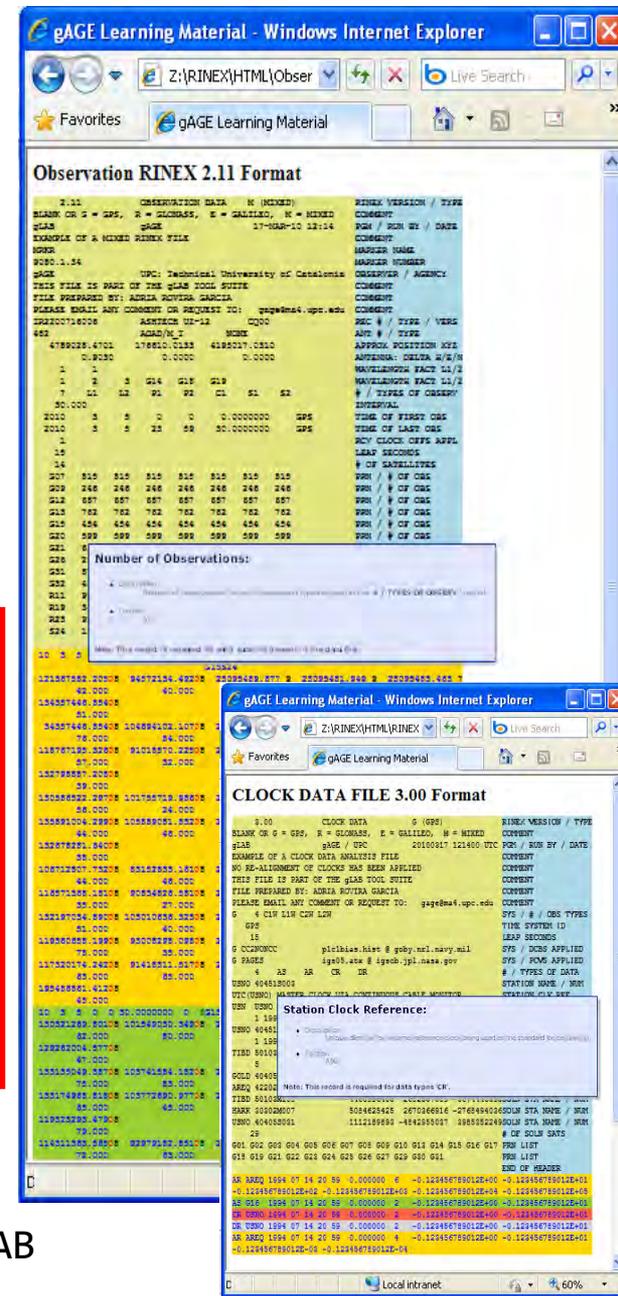
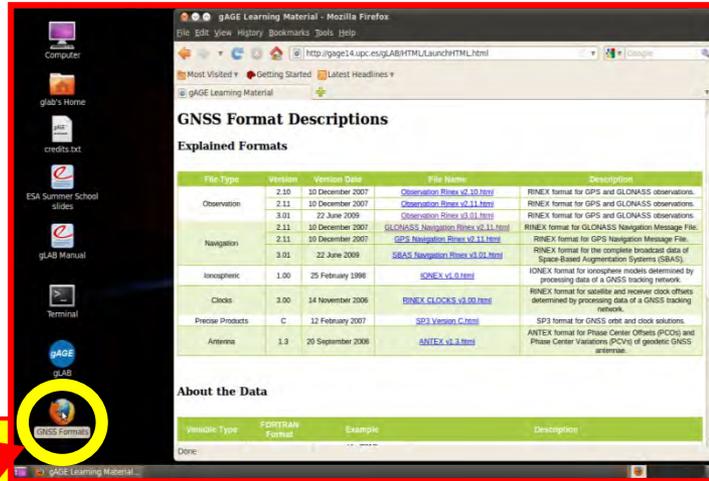
RINEX: observables
2          OBSERVATION DATA      G (GPS)          RINEX VERSION / TYPE
RGRINEXD V2.4.1 UX  AUSLIG        10-JAN-97 10:19  PGM / RUN BY / DATE
Australian Regional GPS Network (ARGN) - COCOS ISLAND COMMENT
BIT 2 OF LLI (+4) FLAGS DATA COLLECTED UNDER "AS" CONDITION COMMENT
-0.00000000103          HARDWARE CALIBRATION (S) COMMENT
-0.000000054663          CLOCK OFFSET (S)          COMMENT
COCO
AU18
mrh
auslig
ROGUE SNR-8100          93.06.25 / 2.8.33.2 REC # / TYPE / VERS
DORNE MARGOLIN T
ANT # / TYPE
-741950.3241 6190961.9624 -1337789.9813 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          30.00000000 TIME OF FIRST OBS
1997          1          9          23          59          30.00000000 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 -19063282.892 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

2

3

Run gLAB

1. Select the **SPP** Template

2. Upload the **RINEX** files:

- Measurement: roap1810.09o

- Navigation: brdc1810.09n

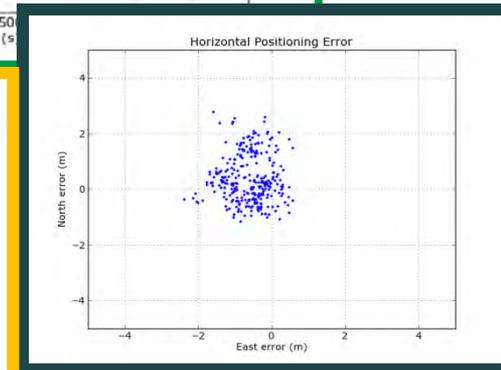
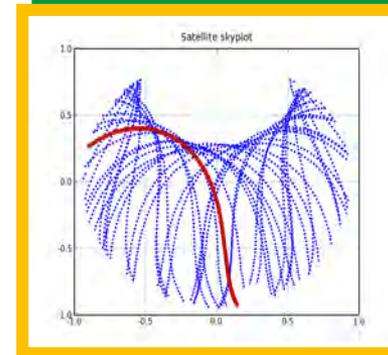
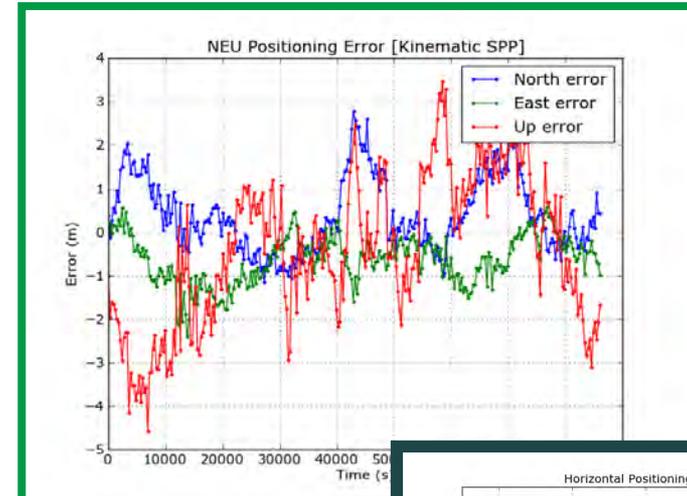
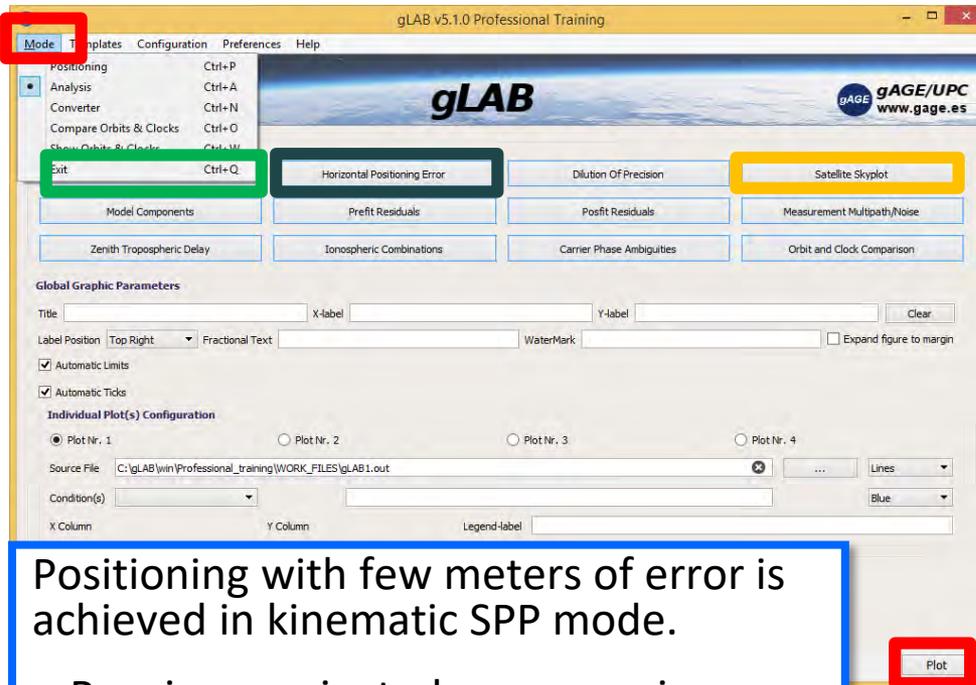
3. **RUN** gLAB

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**

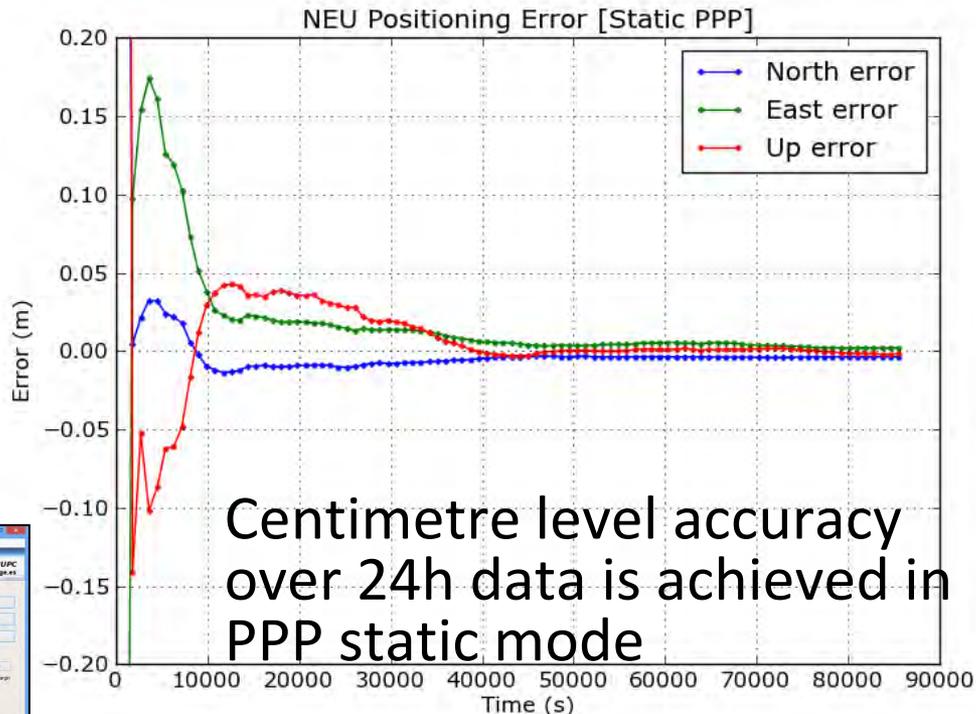
↓

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.



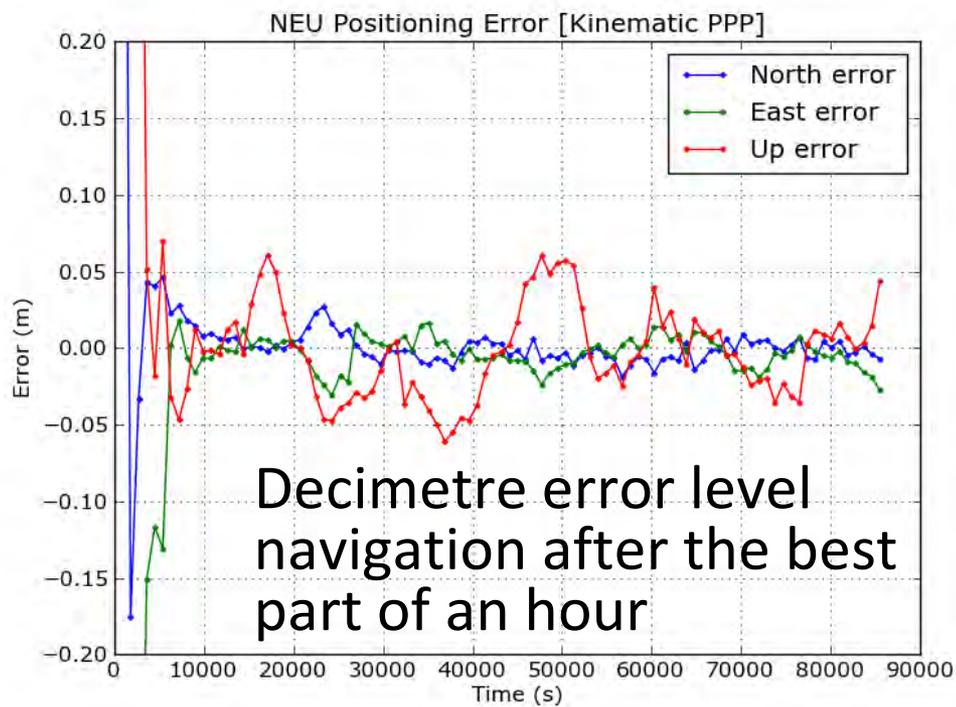
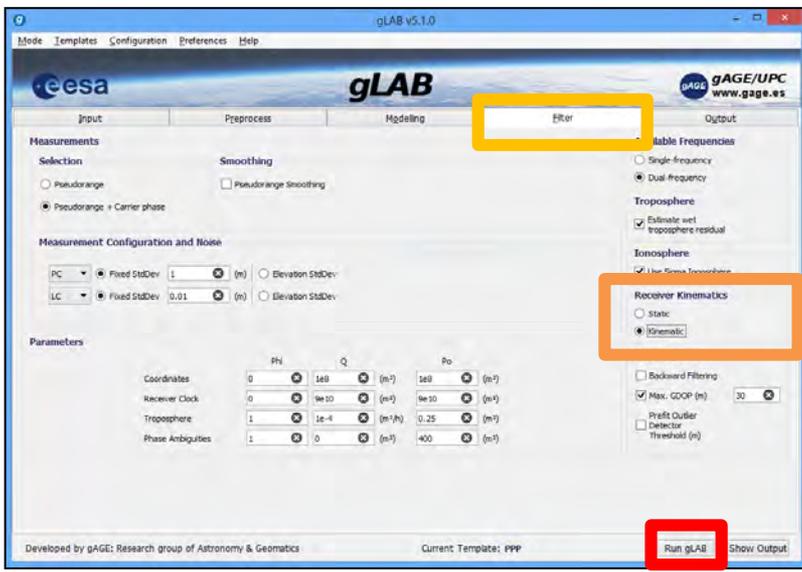
Centimetre level accuracy over 24h data is achieved in PPP static mode



# 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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- **gLAB software installation**



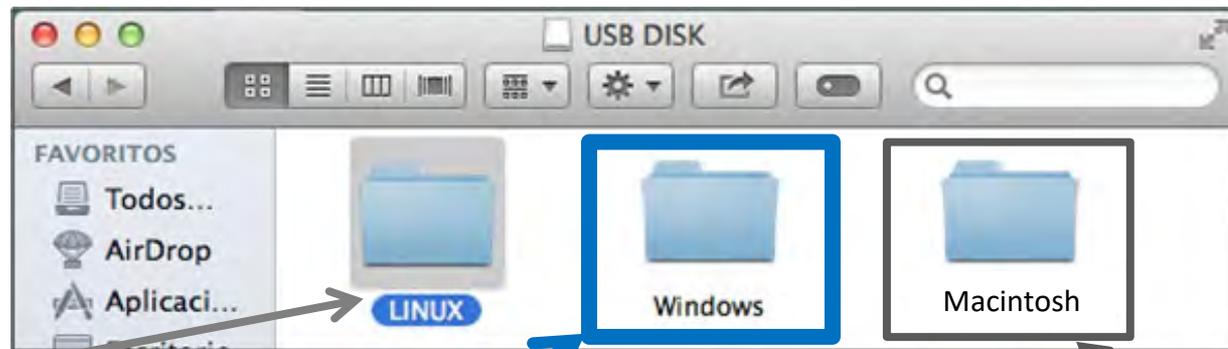


# Installing the software



This tutorial has been designed to be executed under **UNIX (Linux) Operative System (OS)**, which is a very powerful and robust environment.

Nevertheless, the necessary tools are provided for **Windows or Macintosh** users to install this software and to emulate a UNIX command line shell over Windows.

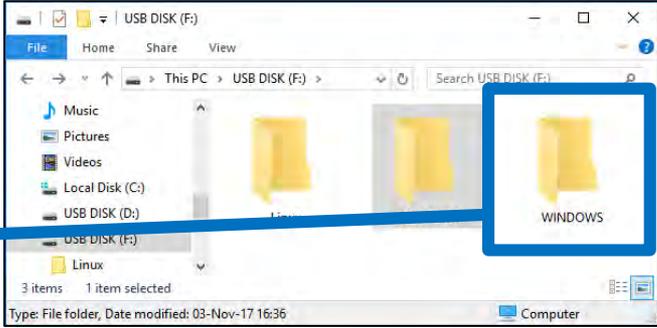
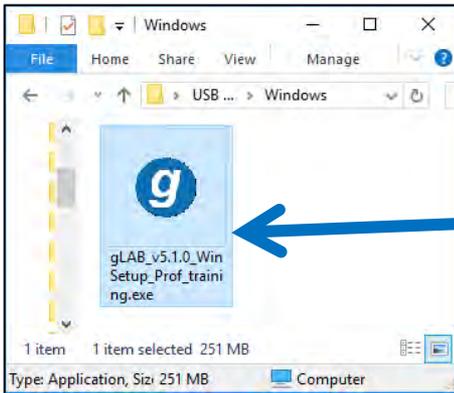


 **Linux** users can install the **native version** of the software

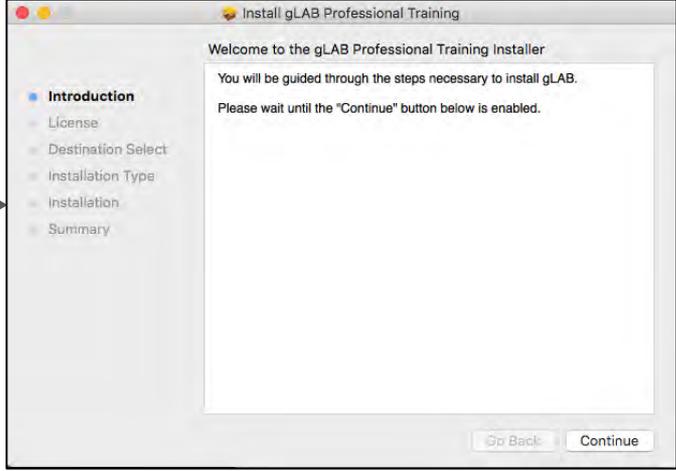
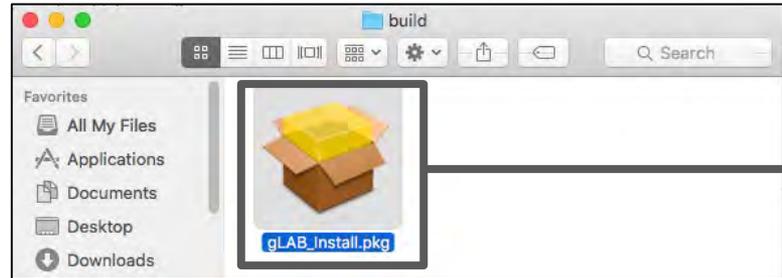
 **Windows** users can install the windows version of **gLAB** and the **Cygwin** emulator of a Linux command shell.

 **Macintosh** users can install the software with the “gLAB\_Install.pkg” file.

Inside the “**Windows**” folder, there is the installable *gLAB program*. Follow the instructions of Software Installation file.



Inside the “**Macintosh**” folder, there is the dmg file. Double click on the “gLAB\_Install.pkg” file, and follow the instructions.





# Installing the software

## Windows users



The Medium and Advanced exercises of this tutorial have been designed to be executed under **UNIX (Linux) Operative System (OS)**. Which is a very powerful and robust environment.

Nevertheless, **Windows OS** users can do the laboratory session by using **Cygwin**, which is a tool that allows to emulate a UNIX command line shell over Windows.

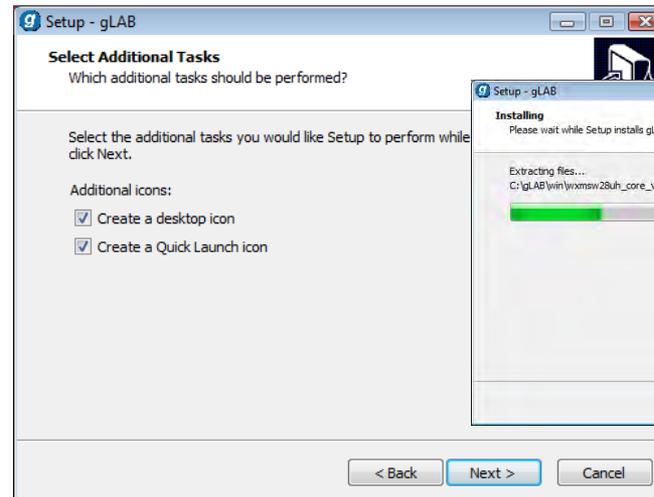
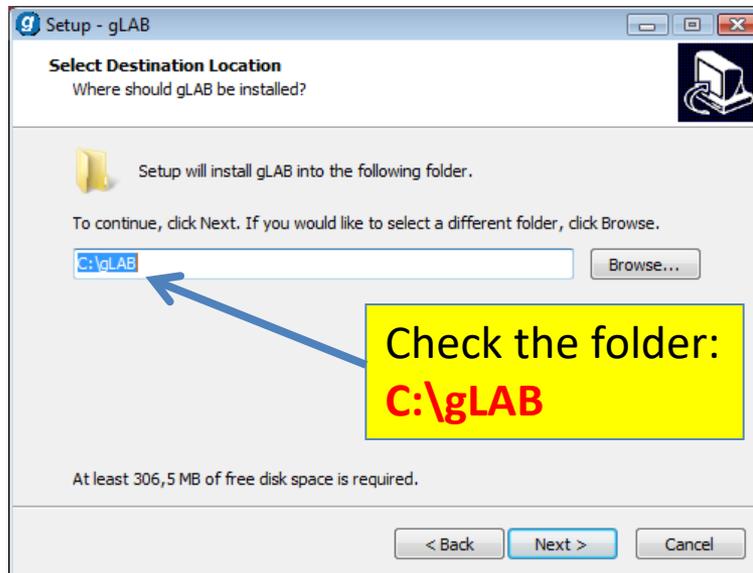
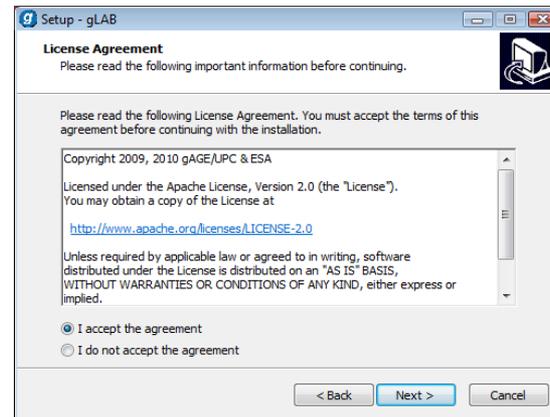
Indeed, after installing **Cygwin**, users can develop the laboratory session as if they were working on a UNIX system (as this tutorial was designed).



# Installing gLAB + Cygwin

1.- First step: Click over the icon

 gLAB\_v5.1.0\_WinSetup\_Prof\_training.exe



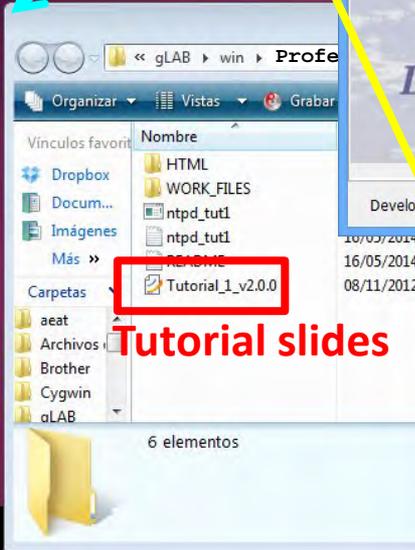


## 2.- Second Step: Completing the gLAB Setup Wizard

The image shows two overlapping windows from a Windows operating system. The top window is titled "Setup - gLAB" and is in the "Completing the gLAB Setup Wizard" stage. It contains the following text: "Setup has finished installing gLAB on your computer. The application may be launched by selecting the installed icons. Click Finish to exit Setup." Below this text are two checked checkboxes: "Launch Cygwin installation" and "Launch gLAB". A blue box highlights these checkboxes, with a blue arrow pointing from a yellow callout box to them. The callout box contains the text: "Cygwin and gLAB installation must be selected." The bottom window is titled "0% - Cygwin Setup" and shows a progress bar for the installation of "base-files-4.2-2". The progress bar is partially filled with green. Below the progress bar are fields for "Total:" and "Disk:" with corresponding progress indicators. At the bottom of the window are buttons for "Atrás", "Siguiente", and "Cancelar".



Once the installation finish, the icons of **gLAB**, **Cygwin Terminal** and the **Professional training folder** will appear.



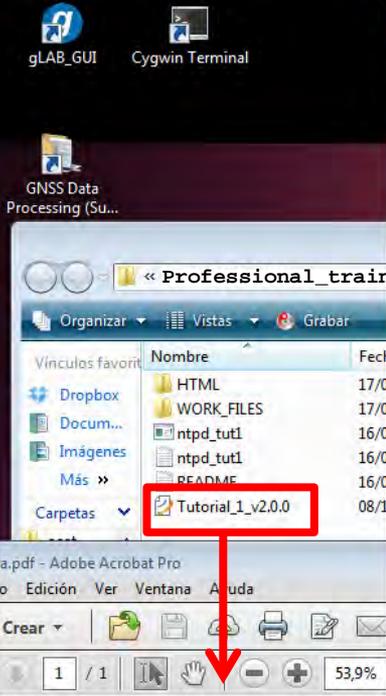
**Tutorial slides**



```
gAGE@gage-PC: /cygdrive/c/gLAB/win/Professional_training/WORK_FILES |
```

UNIX (Linux) console to execute "command line" sentences

Suggested desk configuration to start working



gLAB v5.1.0

Mode Templates Configuration Preferences Help

eesa gLAB gAGE/UPC www.gage.es

Input Preprocess Modelling Filter Output

**Station Data**

- Data Decimation 300 (s)
- Check for jumps in code measurements

**Cycle-slip Detection**

- Data Gap 40 (s)
- Loss of Lock Indicator (LLI)
- N Consecutive Samples 3 (samples)
- L1-C1 difference (Single-frequency)
- Melbourne-Wübbena (Dual-frequency)
- Geometry-free (Dual-frequency)

**Satellite Options**

- Elevation Mask 5 (degrees)
- SNR Mask
- Align carrier phase measurement with code
- Discard Satellites Under Eclipse Condition
- Discard Unhealthy Satellites (Broadcast only)

**GNSS Satellite Selection**

- GPS  Galileo  GLONASS  BeiDou  GEO
- 

PRN 1	PRN 8	PRN 15	PRN 22	PRN 29
PRN 2	PRN 9	PRN 16	PRN 23	PRN 30
PRN 3	PRN 10	PRN 17	PRN 24	PRN 31
PRN 4	PRN 11	PRN 18	PRN 25	PRN 32
PRN 5	PRN 12	PRN 19	PRN 26	
PRN 6	PRN 13	PRN 20	PRN 27	
PRN 7	PRN 14	PRN 21	PRN 28	

Current Template: SPP

error (m)

time (s)

North error  
East error  
Up error

x=3.1e+04, y=39

**Tutorial 1**  
**GNSS Data Processing Lab Exercises**

Prof. Dr. Jaume Sanz Subirana and Prof. Dr. J. M. Juan Zornoza  
assisted by Dr. Adrià Rovira Garcia

Research group of Astronomy & Geomatics (gAGE)  
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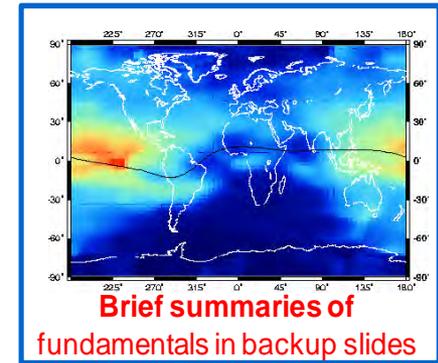
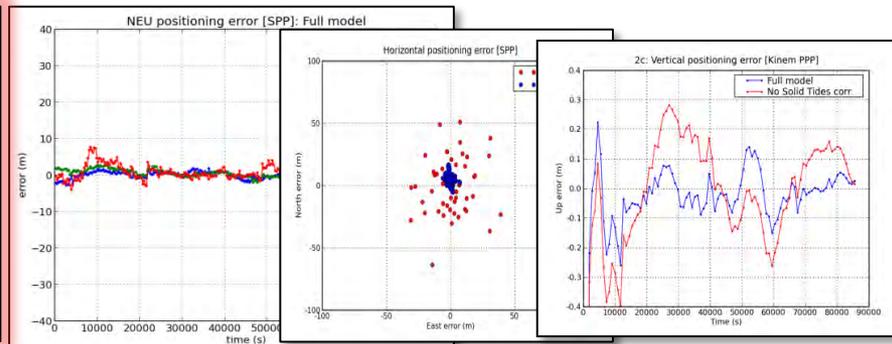
©gAGE/UPC <http://www.gage.upc.edu>

# Model Components Analysis

## Exercises 1 and 2.

They consist of 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**

# Model Components Analysis

## 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.

# Exercise 1: SPP Model components analysis

## 1. Compute SPP using files: `chpi0010.04o`, `brdc0010.04n`

Cachoeira Paulista station (in the south of Brazil:  $\lambda=-22.7^\circ$ ,  $\phi=-45.0^\circ$ ). January 1<sup>st</sup> 2004.

The image shows the gLAB v5.1.0 software interface with several steps highlighted by numbered annotations:

- 1**: The 'Templates' menu is open, and 'SPP' is selected.
- 2**: The 'RINEX Observation File' and 'RINEX Navigation File' fields are highlighted with green boxes.
- 3**: A file selection dialog box is open, showing the file `rosp1810.09o` selected.
- 4**: The 'NEU Positioning Error' plot configuration window is open, and the 'Source File' is set to `gLAB.out`.
- 5**: The 'Global Graphic Parameters' section is highlighted, showing the 'Y-min' and 'Y-max' values set to -40 and 40 respectively.
- 6**: The 'Plot' button is highlighted in red.

The main interface shows the 'SPP' model selected, with the 'Run gLAB' button at the bottom. The plot window displays the 'NEU Positioning Error' graph, showing North error, East error, and Up error over time.

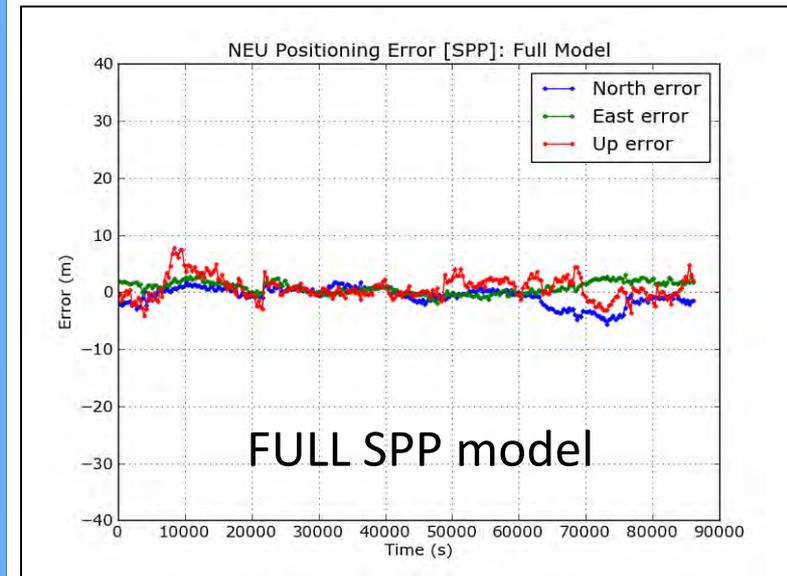
# NEU Position Error plot from gLAB.out

The screenshot shows the gLAB v5.1.0 software interface. A large brown box labeled "NEU plot template configuration" is positioned over the top part of the window. Below it, the "Global Graph Parameters" section is visible. The "Title" field is set to "NEU Positioning Error". The "X-label" is "Time (s)" and the "Y-label" is "Error (m)". The "Y-min" is set to -40 and the "Y-max" is set to 40. In the "Plot Configuration" section, three radio buttons are visible: "Plot Nr. 1" (selected), "Plot Nr. 2", and "Plot Nr. 3". Each radio button is enclosed in a colored box: blue for Plot Nr. 1, green for Plot Nr. 2, and red for Plot Nr. 3. Arrows point from these boxes to the plot configuration fields below. The "Condition(s)" field is set to "OUTPUT". The "X Column" is "SEC" and the "Y Column" is "DSTAN". The "Legend-label" is "North error".

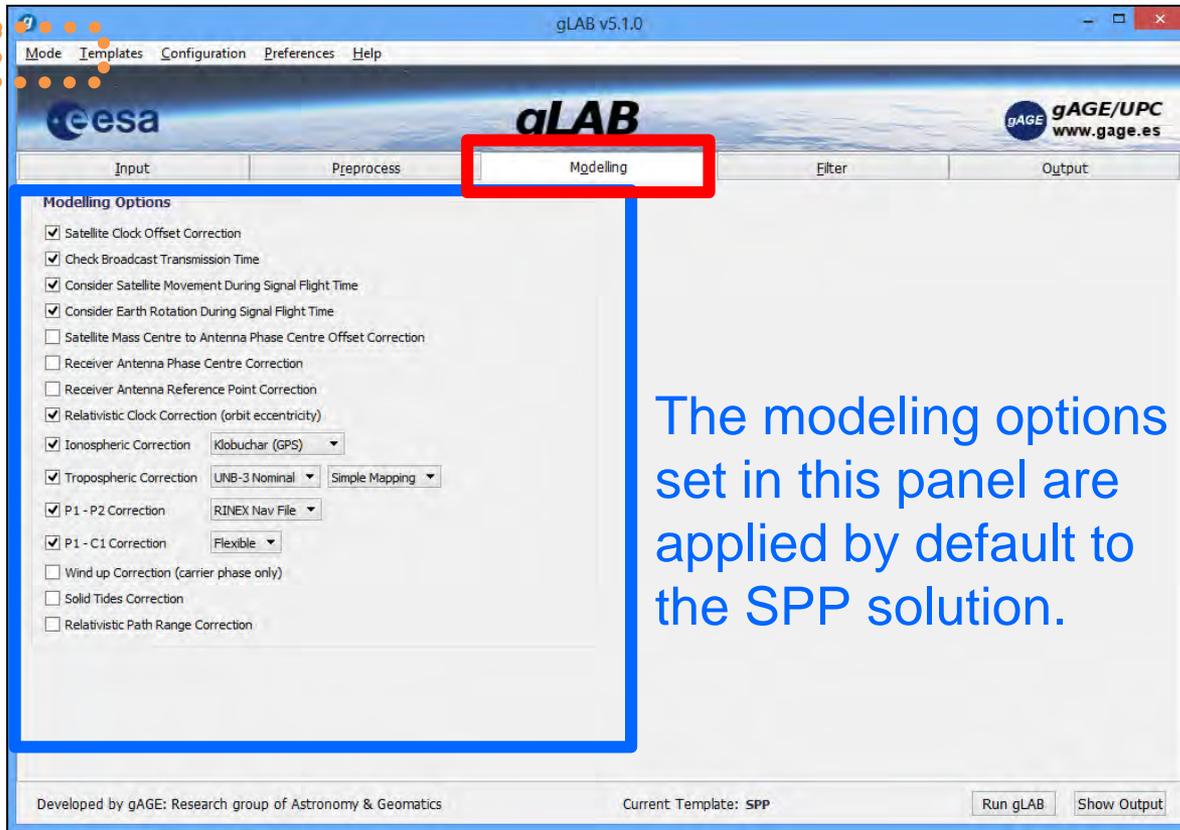
North

East

Up



# Exercise 1: SPP Model components analysis



The modeling options set in this panel are applied by default to the SPP solution.

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.

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.

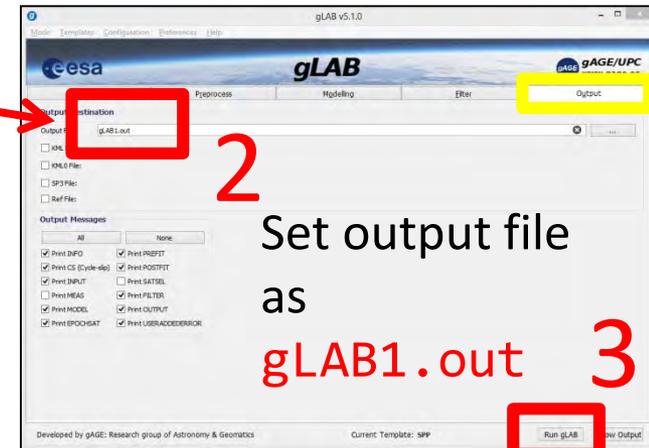
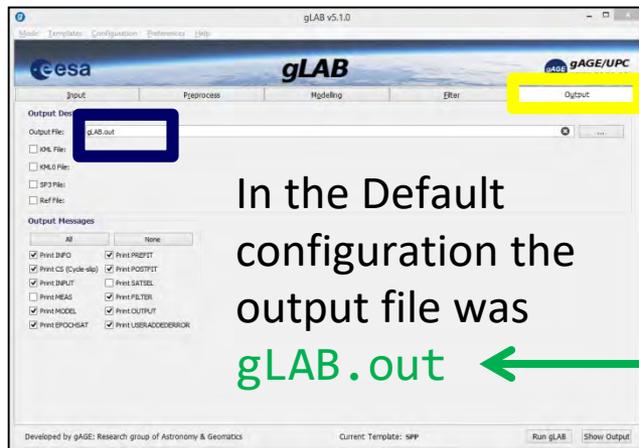
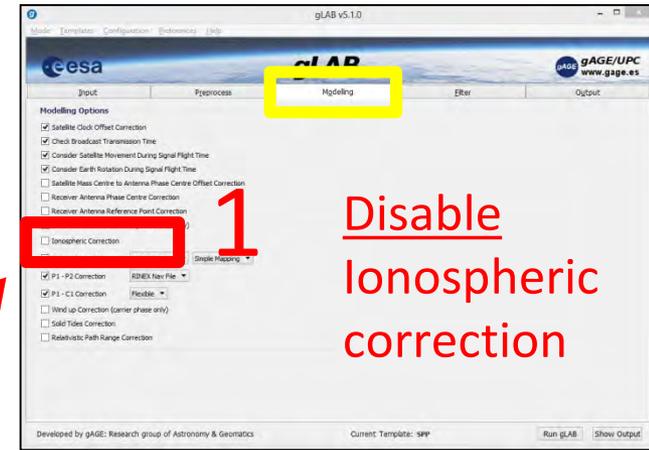
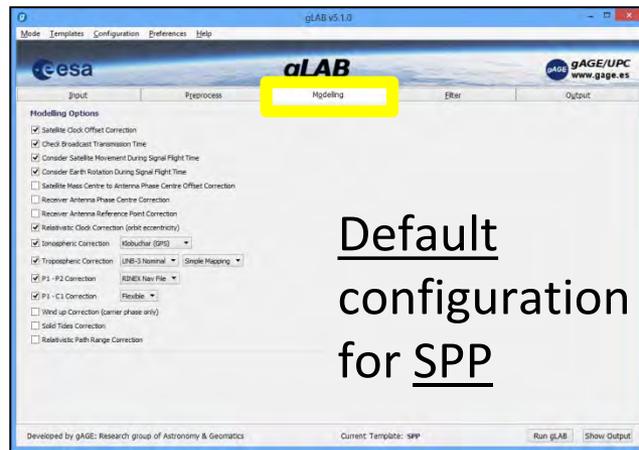
Notice that the gLAB.out file contains the processing results with the FULL model, as it was set in the default configuration.

Default  
configuration  
for SPP

In the Default configuration the output file was gLAB.out

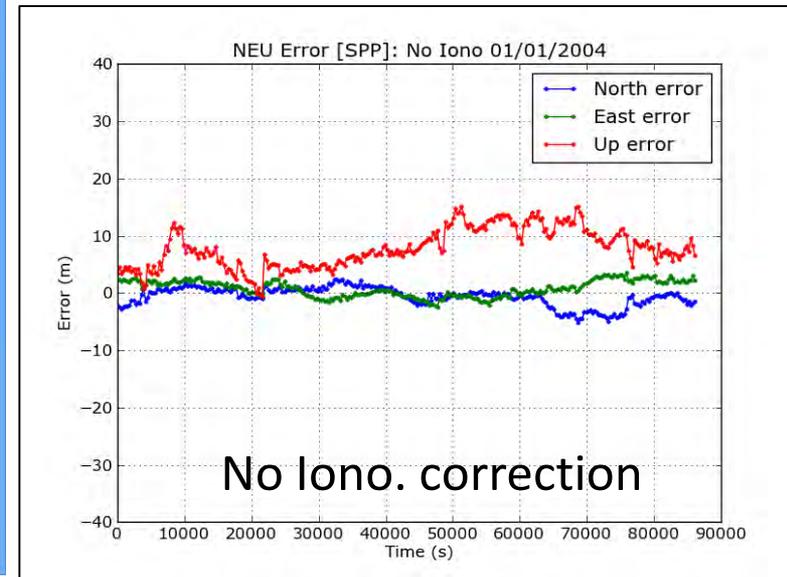
Disable  
Ionospheric  
correction

Set output file  
as  
gLAB1.out



# NEU Position Error plot from gLAB1.out

The screenshot shows the gLAB v5.1.0 software interface. A large box labeled "NEU plot template configuration" highlights the "NEU Positioning Error" button. Below it, the "Global Graphic Parameters" section is visible, showing the title "NEU[Error[SPP]: No Iono 01/01/2004", X-axis label "Time (s)", and Y-axis label "Error (m)". The "Configuration" section shows "Plot Nr. 1" selected, with "Source File" set to "gLAB1.out", "X Column" set to "SE", and "Y Column" set to "DSTAN".



North

East

Up

gLAB1.out

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

**1** Click Clear to restart plots

**2** Y-min, Y-max

**3** gLAB.out

**2** gLAB1.out

**3** gLAB.out

**OUTPUT**

**Time (sec): 4**

**Vertical: DSTAU: 20**

Vertical Positioning Error (m)

Error (m)

Time (s)

Legend: No Ionosphere, Full Model

gLAB v5.1.0

Mode Templates Configuration Preferences Help

Global Graphic Parameters

Title: Vertical Positioning Error (m)

X-label: Time (s)

Y-label: Error (m)

Label Position: Top Right

Y-min: -40

Y-max: 40

Plot(s) Configuration

Plot Nr. 1: gLAB.out

Plot Nr. 2: gLAB.out

Condition(s): OUTPUT

X Column: SEC, 4

Y Column: DSTAU, 20

Legend-label: Full Model

Plot

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

**1** Click Clear to restart plots

**2**

**3**

X-min, Y-min, Y-max

gLAB1.out

gLAB.out

East: 19

North: 18

East: DSTAE: 19

North: DSTAN: 18

# Ionospheric model component plot: gLAB.out

gLAB v5.1.0

Mode Templates Configuration Preferences Help

eesa gLAB gAGE/UPC www.gage.es

Templates

- NEU Positioning Error
- Horizontal Positioning Error
- Dilution Of Precision
- Satellite Skyplot
- Model Components**
- Profit Residuals
- Posfit Residuals
- Measurement Multipath/Noise
- Zenith Tropospheric Delay
- Ionospheric Combinations
- Carrier Phase Ambiguities
- Orbit and Clock Comparison

Global Graphic Parameters

Title: Model Components X-label: Time (s) Y-label: Model (m) Clear

Label Position: Top Right Fractional Text: WaterMark: Expand figure to margin

Automatic Limits

Automatic Ticks

Individual Plot(s) Configuration

Plot Nr. 1 Plot Nr. 2 Plot Nr. 3 Plot Nr. 4

Source File: gLAB.out Dots

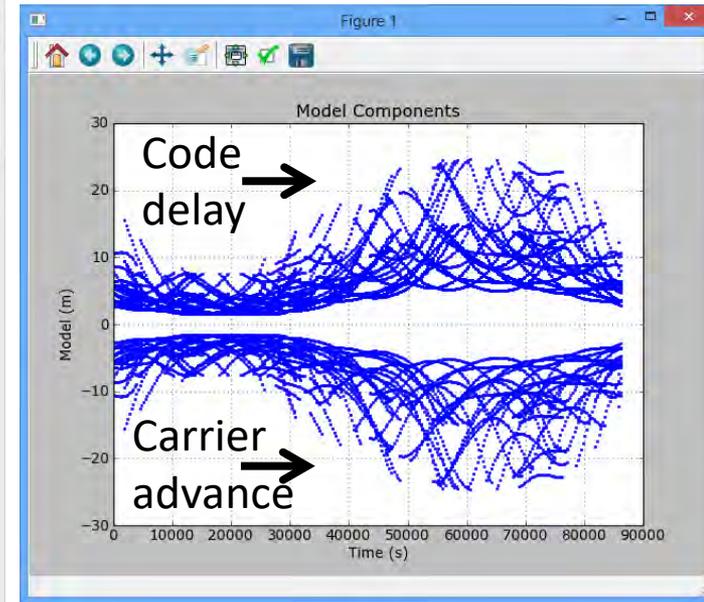
Condition(s): MODEL (\$1=="MODEL")

X Column: SEC 4 Y Column: IONO Legend-label

Developed by gAGE: Research group of Astronomy & Geomatics Current Template: SPP Plot

Select IONO

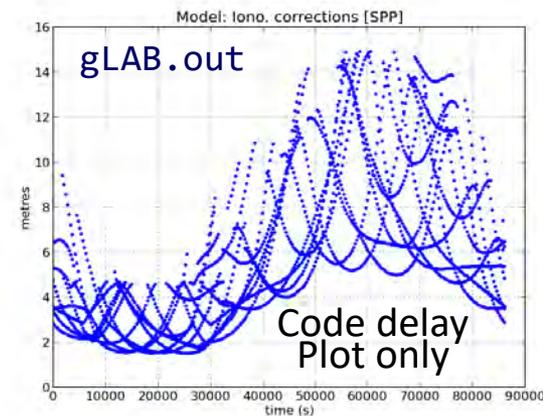
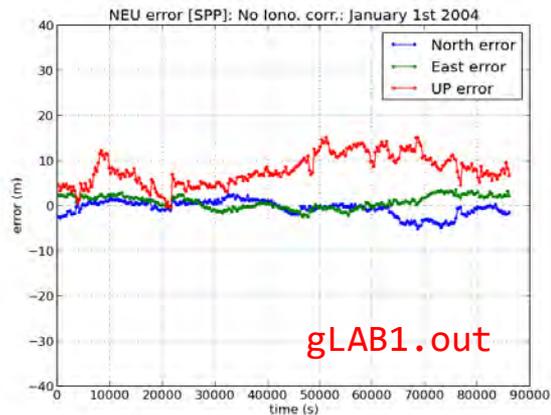
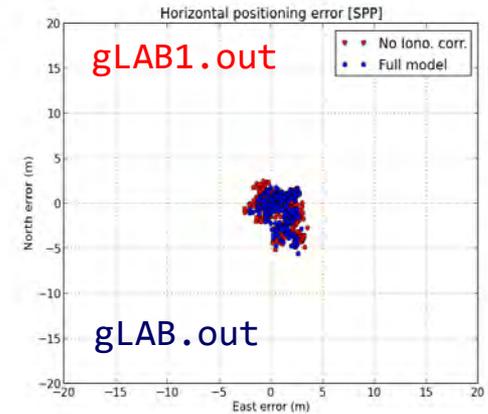
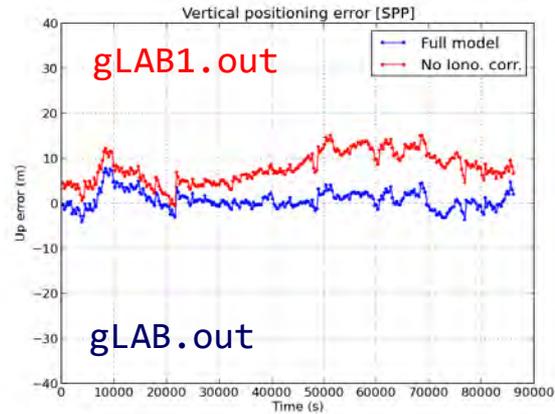
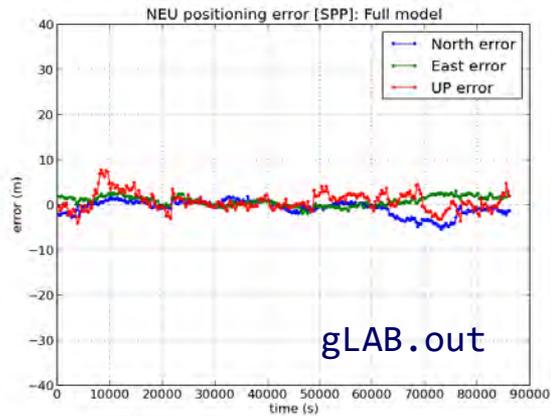
gLAB.out



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



**Ionospheric correction**  
(broadcast Klobuchar)

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

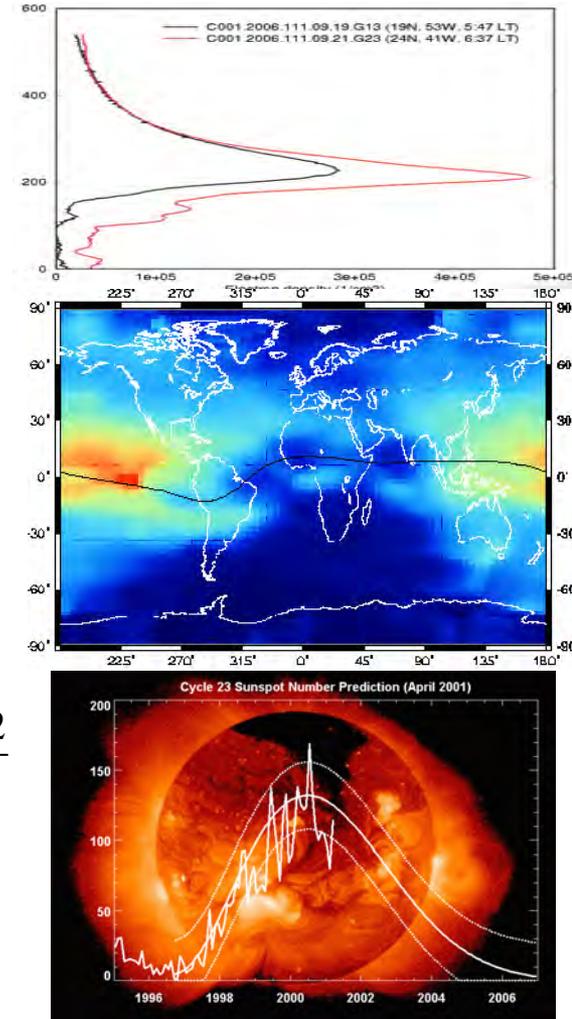
Large positioning errors (mainly in vertical) appear when neglecting iono. corr.

# Exercise 1: SPP Model components analysis

## Ionospheric delay

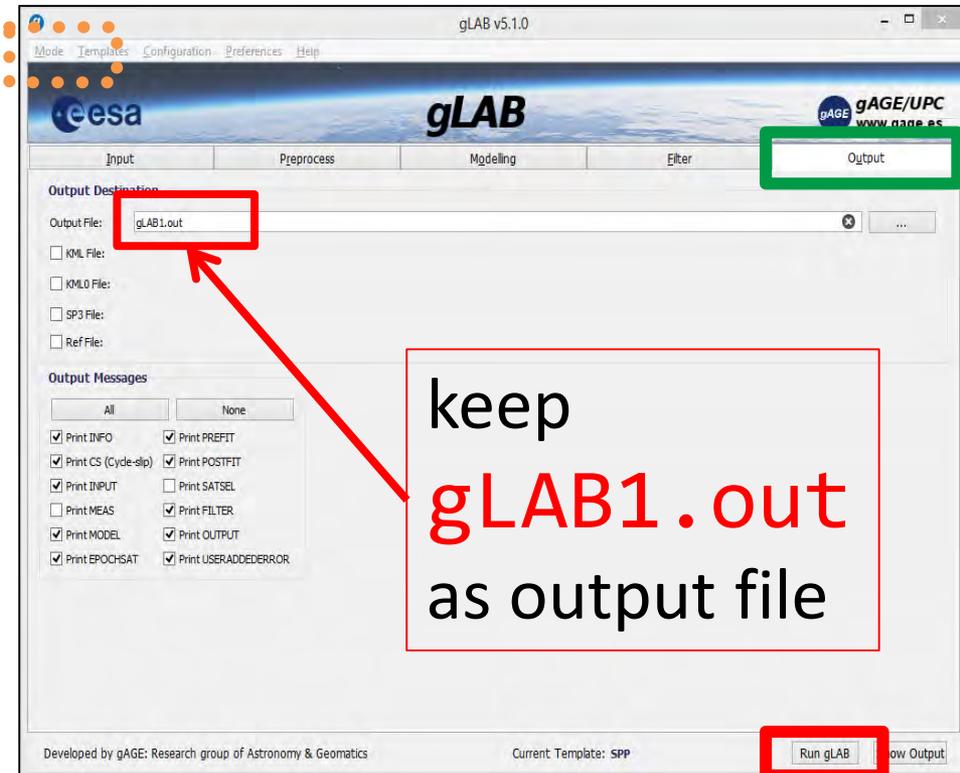
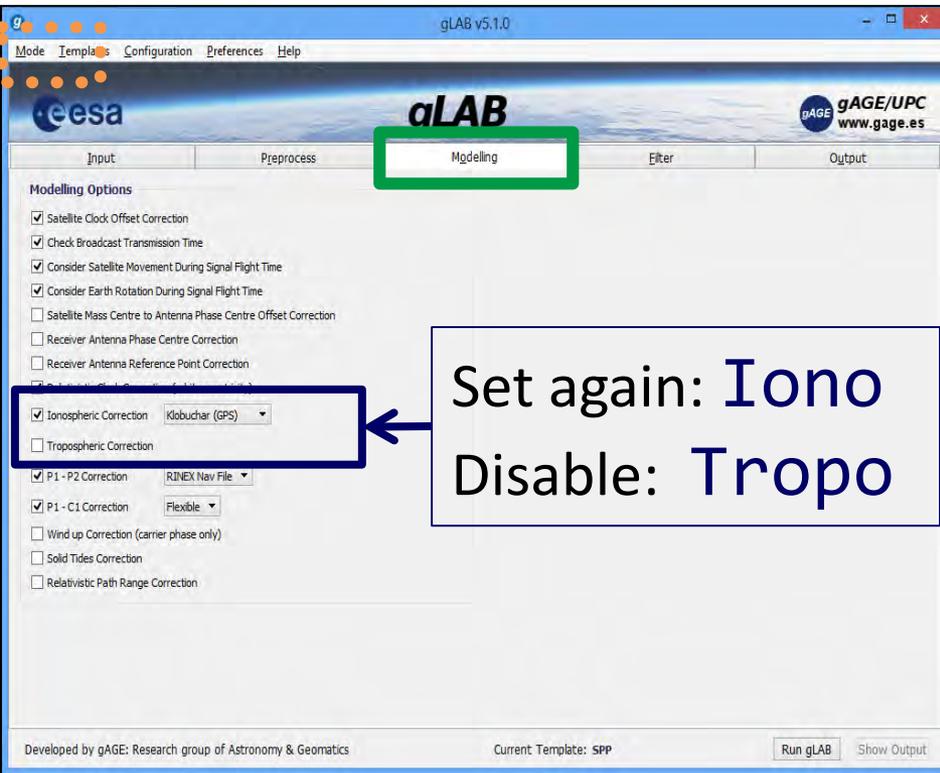
The ionosphere extends from about 60 km over the Earth surface until more than 2000 km, with a sharp electron density maximum at around 350 km. The ionospheric refraction depends, among other things, of the location, local time and solar cycle (11 years).

- First order (~99.9%) ionospheric delay  $\delta_{ion}$  depends on the inverse of squared frequency:  
where  $I$  is the number of electrons per area unit along ray path (STEC: Slant Total Electron Content).  
$$\delta_{ion} = \frac{40.3}{f^2} I$$
$$I = \int N_e ds$$
- 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.



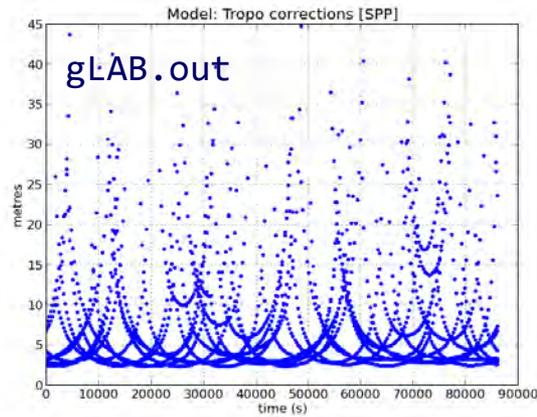
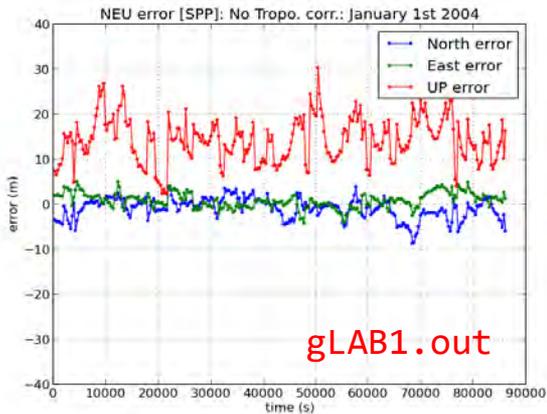
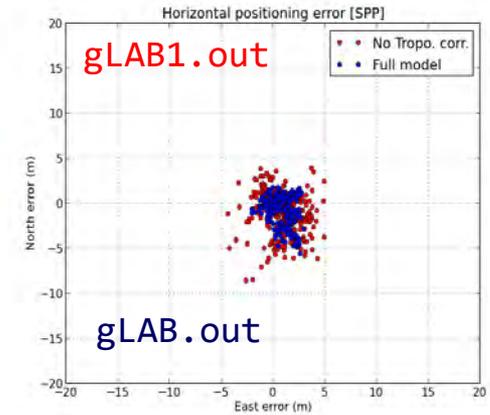
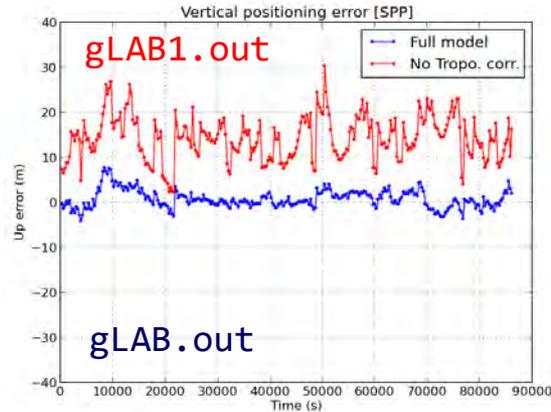
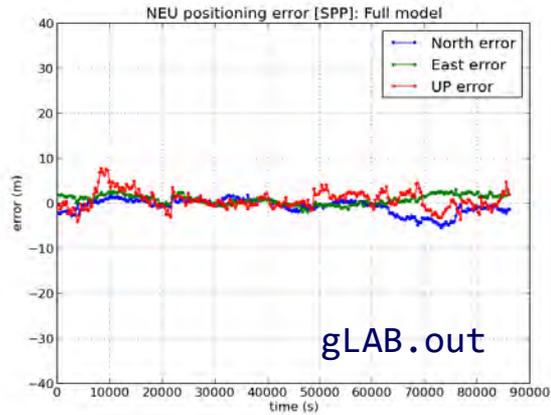
# Example of model component analysis: TROPO.

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



## Tropospheric correction (blind model)

Tropospheric and vertical error are highly correlated. A displacement of vertical component appears when neglecting tropospheric corrections.

# Exercise 1: SPP Model components analysis

## Tropospheric delay

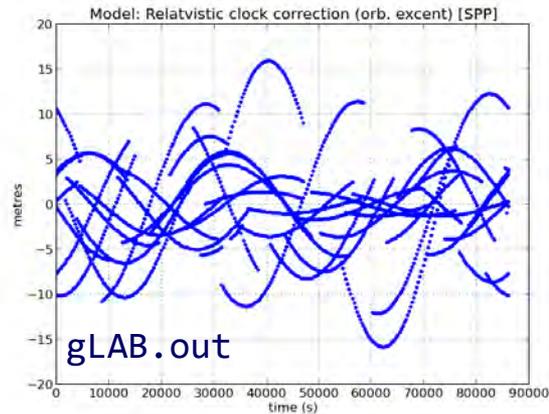
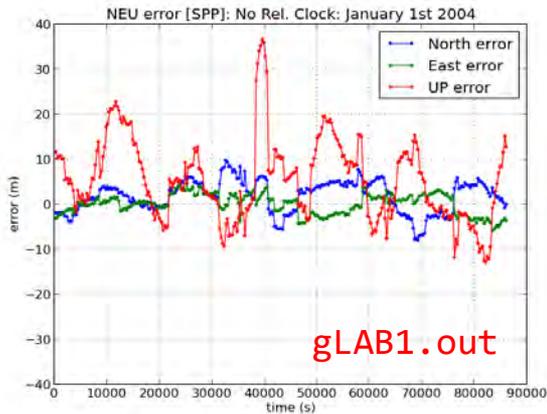
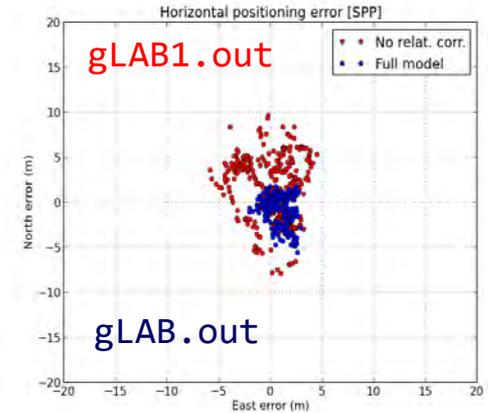
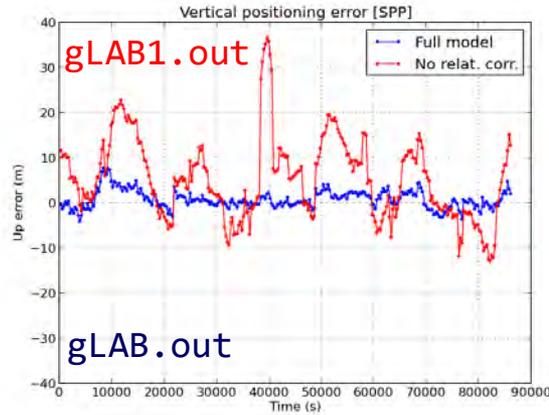
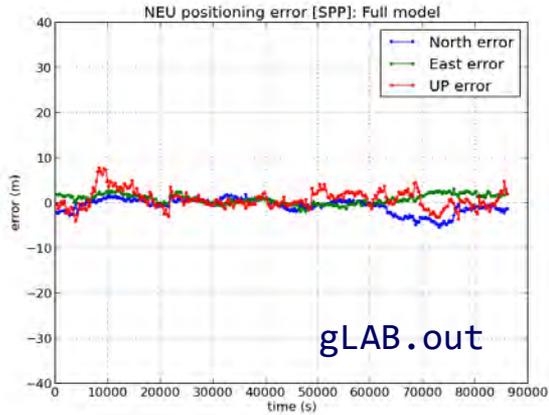
The troposphere is the atmospheric layer placed between Earth's surface and an altitude of about 60 km.

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



**Relativistic correction**  
on satellite clock due to  
orbit eccentricity.

This is an additional  
correction to apply at the  
receiver level. The satellite  
clock oscillator is modified  
on factory to compensate  
the main effect ( $\sim 40\mu\text{s}/\text{day}$ ).

# 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:

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

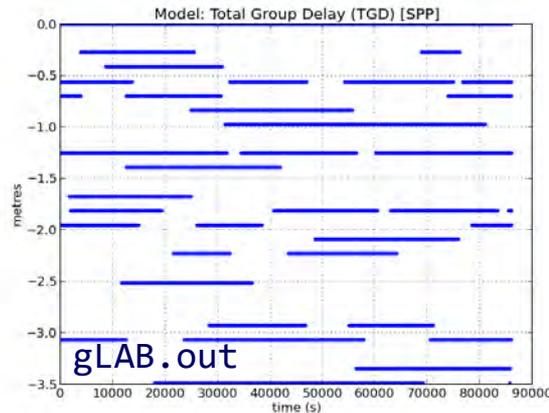
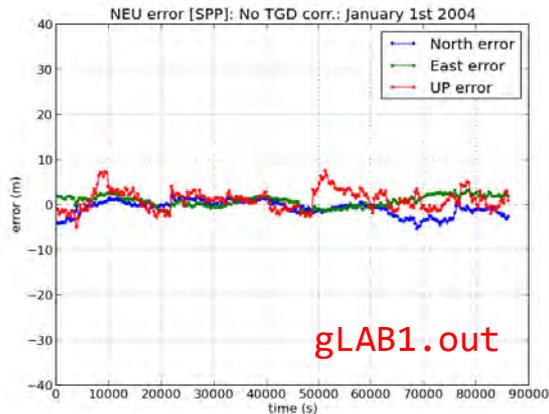
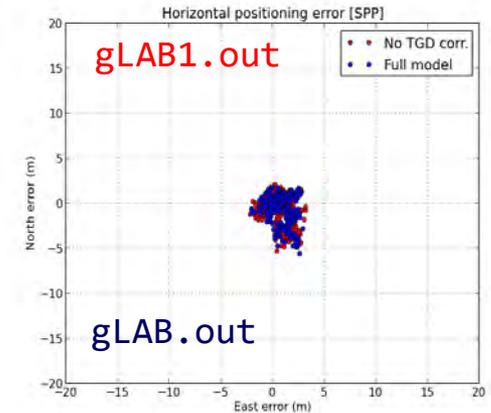
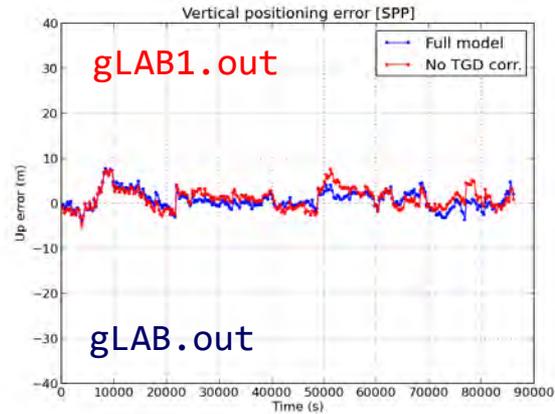
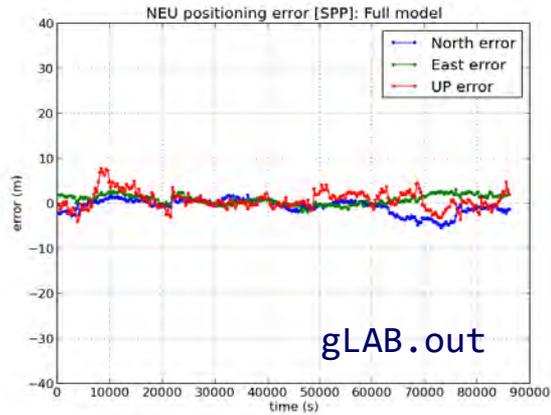
being  $f_0 = 10.23 \text{ MHz}$ , we have  $\Delta f = 4.464 \cdot 10^{-10} f_0 = 4.57 \cdot 10^{-3} \text{ Hz}$ . So, satellite should use  $f_0' = 10.22999999543 \text{ MHz}$ .

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

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

Being  $\mu = G M_E = 3.986005 \cdot 10^{14} \text{ (m}^3/\text{s}^2)$  the gravitational constant,  $c = 299792458 \text{ (m/s)}$  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



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.

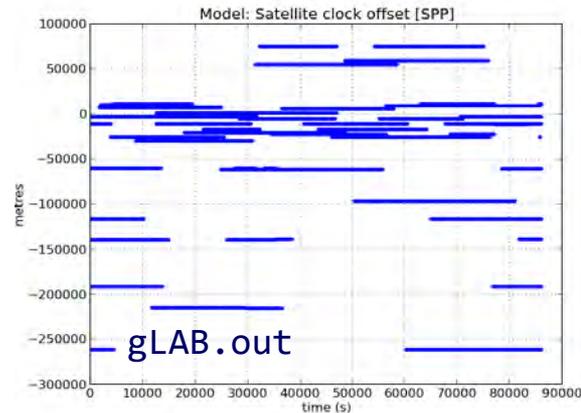
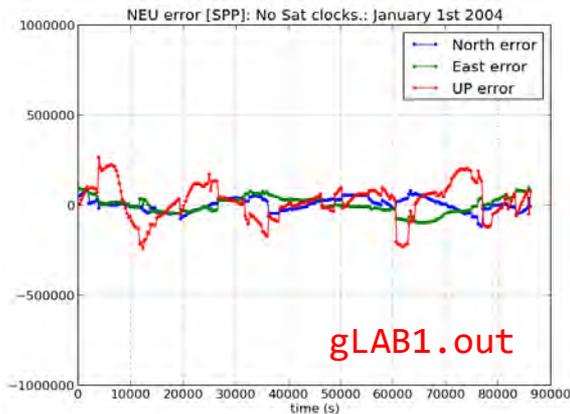
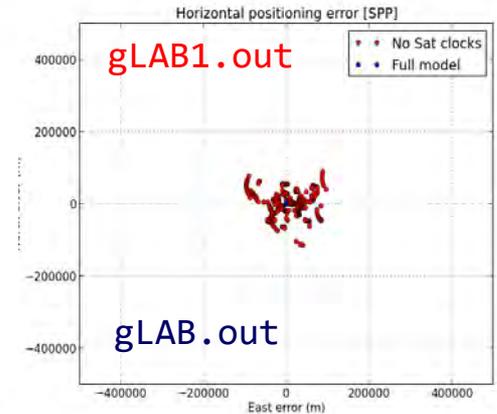
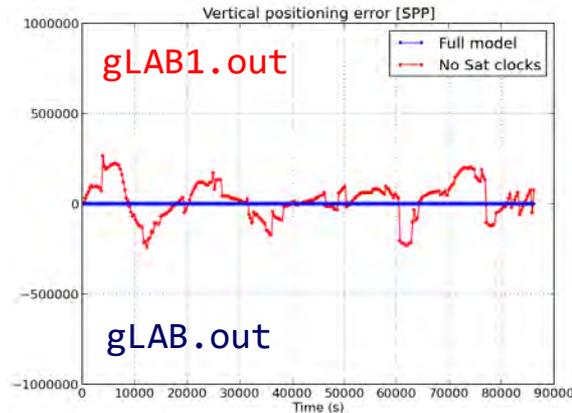
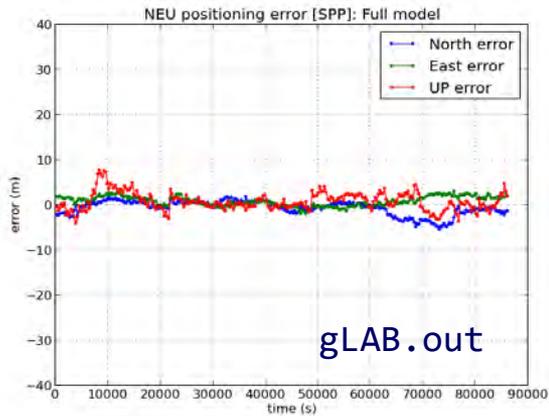
# Exercise 1: SPP Model components analysis

## 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



## Satellite clock offsets

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

# Exercise 1: SPP Model components analysis

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

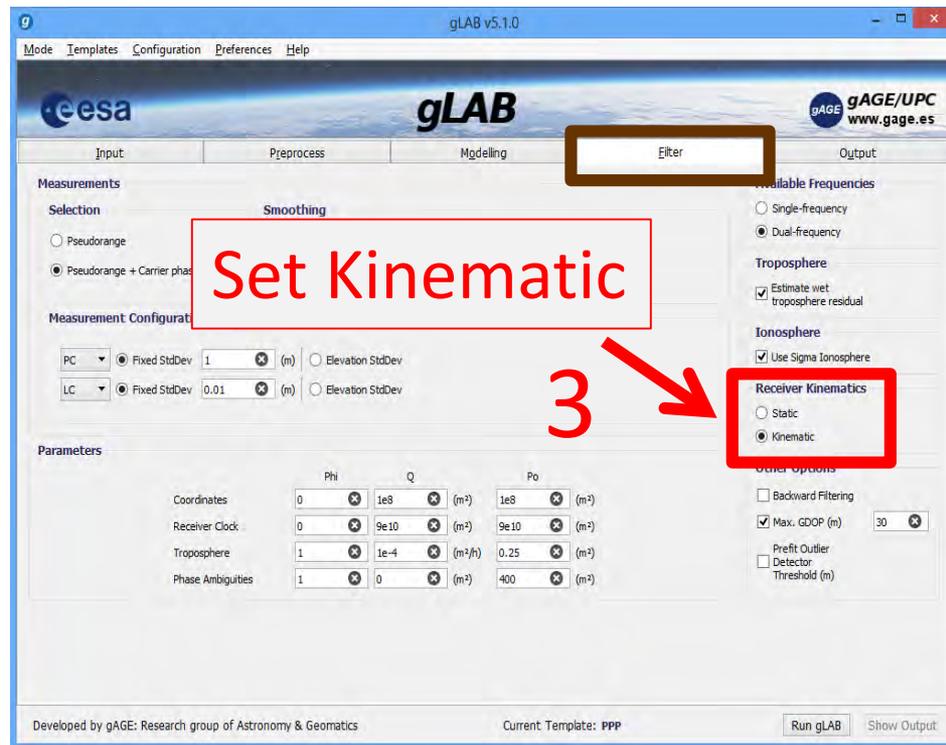
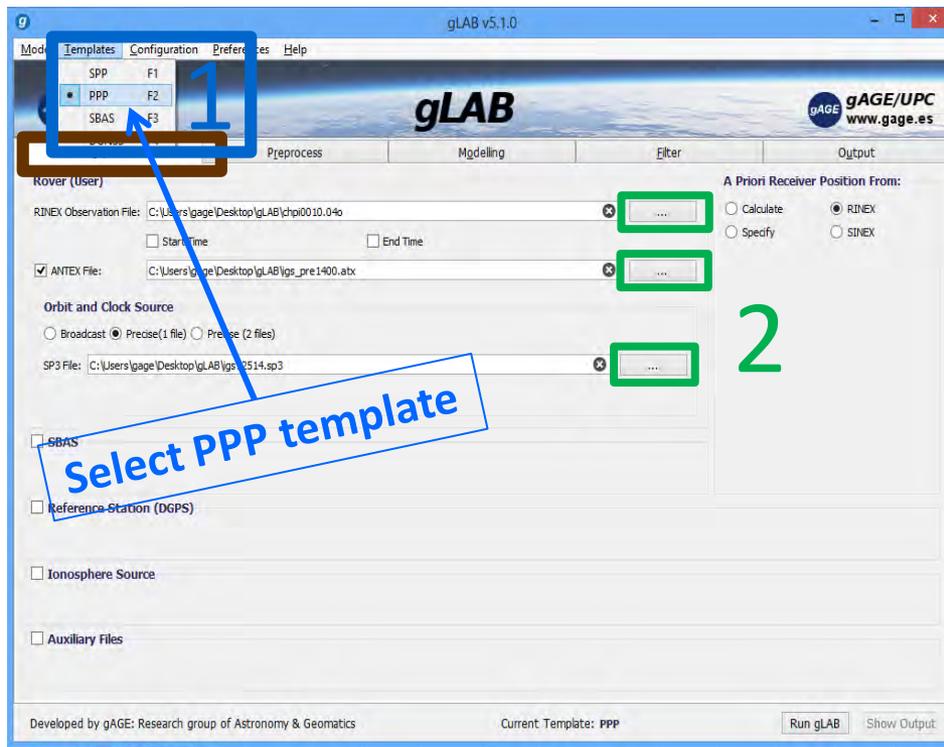
# Basic: Introductory laboratory exercises

## Exercise 2: Model components analysis for PPP

- This exercise is devoted to analyse 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.

# Exercise 2: PPP Model components analysis

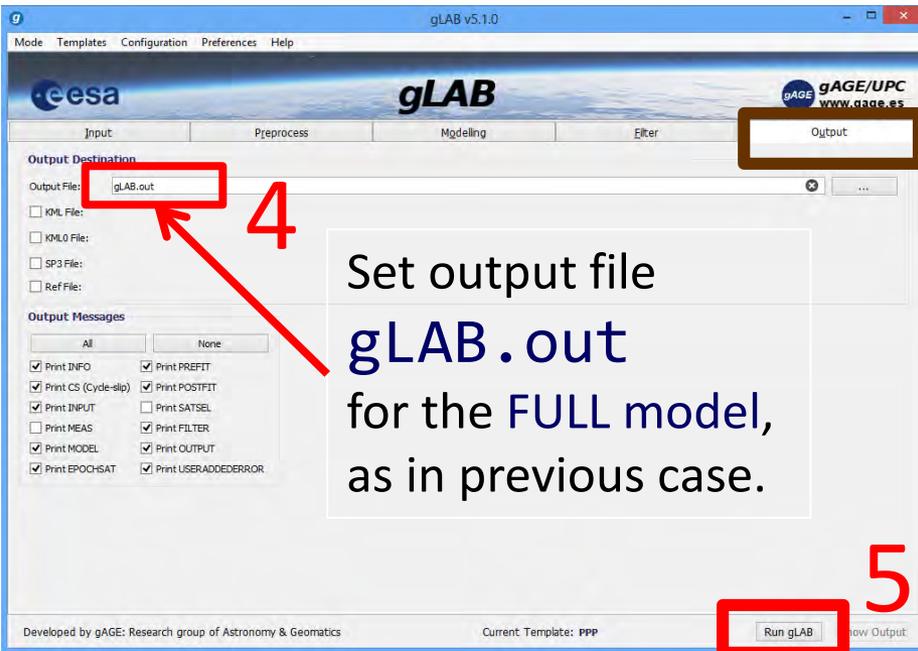
- Compute the **kinematic** PPP solution using files:  
`chpi0010.04o`, `igs_pre1400.atx`, `igs12514.sp3`



*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 `chpi0010.04o`,  
`igs_pre1400.atx`, `igs12514.sp3`



Mode Templates Configuration Preferences Help

eesa **gLAB** gAGE/UPC www.gage.es

Input Preprocess Modelling Filter **Output**

Output Destination

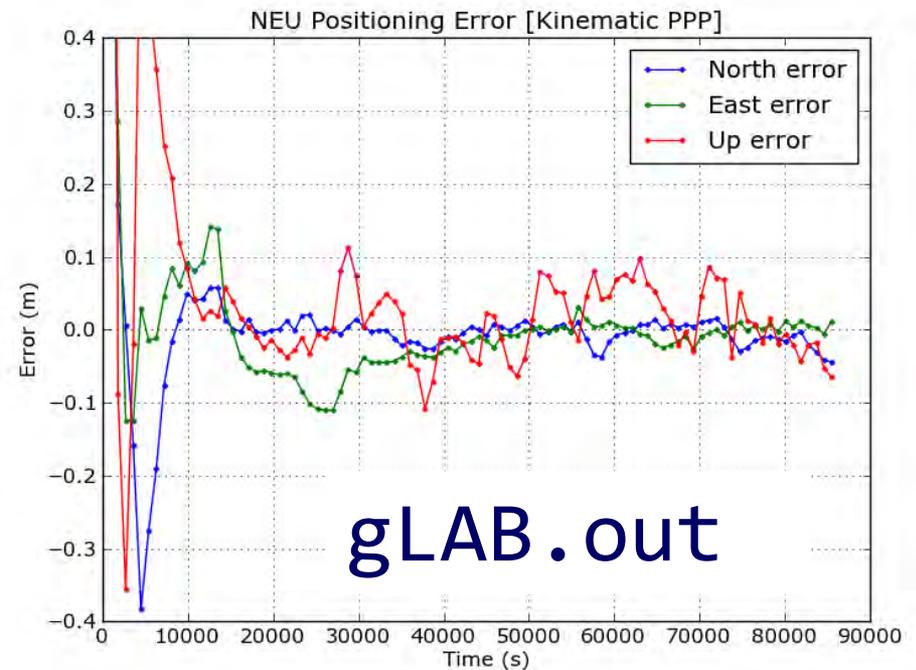
Output File: **gLAB.out**

KML File:  
 KML0 File:  
 SP3 File:  
 Ref File:

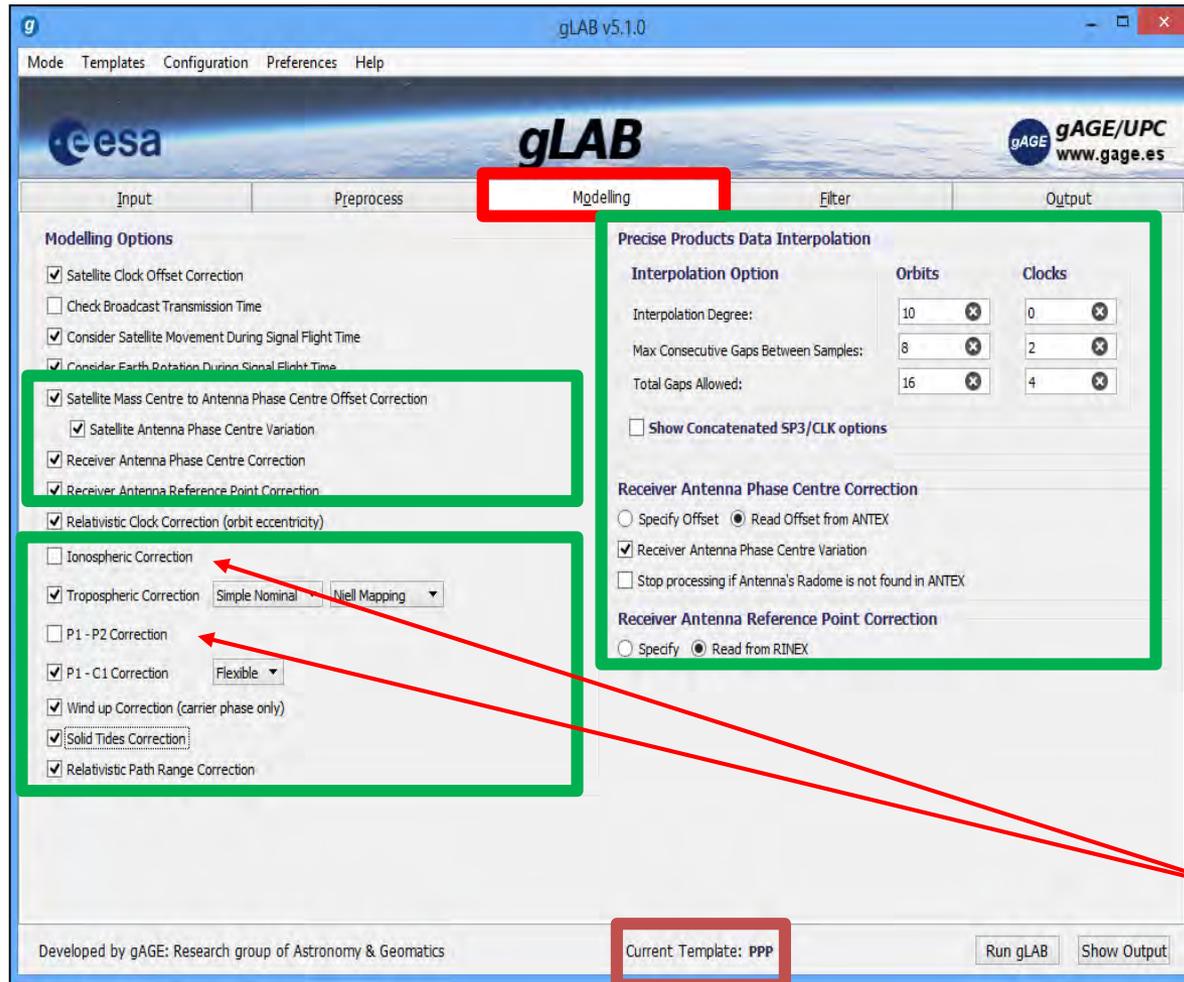
Output Messages

<input checked="" type="checkbox"/> Print INFO	<input checked="" type="checkbox"/> Print PREFIT
<input checked="" type="checkbox"/> Print CS (Cycle-slip)	<input checked="" type="checkbox"/> Print POSTFIT
<input checked="" type="checkbox"/> Print INPUT	<input type="checkbox"/> Print SATSEL
<input type="checkbox"/> Print MEAS	<input checked="" type="checkbox"/> Print FILTER
<input checked="" type="checkbox"/> Print MODEL	<input checked="" type="checkbox"/> Print OUTPUT
<input checked="" type="checkbox"/> Print EPOCHSAT	<input checked="" type="checkbox"/> Print USERADDEDERROR

Developed by gAGE: Research group of Astronomy & Geomatics Current Template: PPP **Run gLAB** Show Output



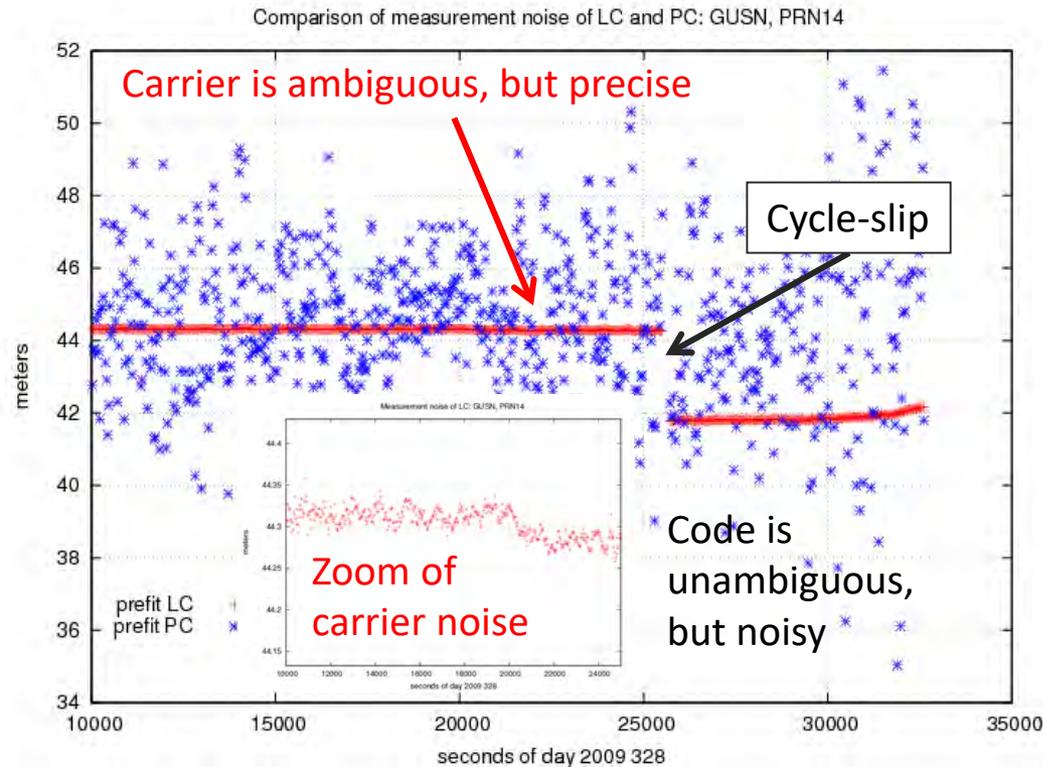
# Exercise 2: PPP Model components analysis



- 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 Measurement noise

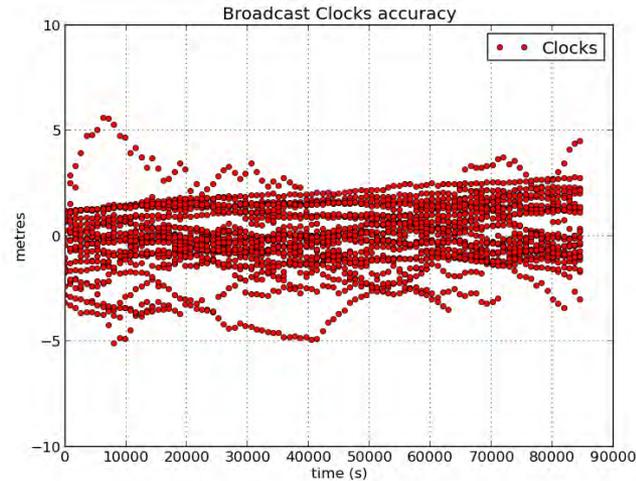
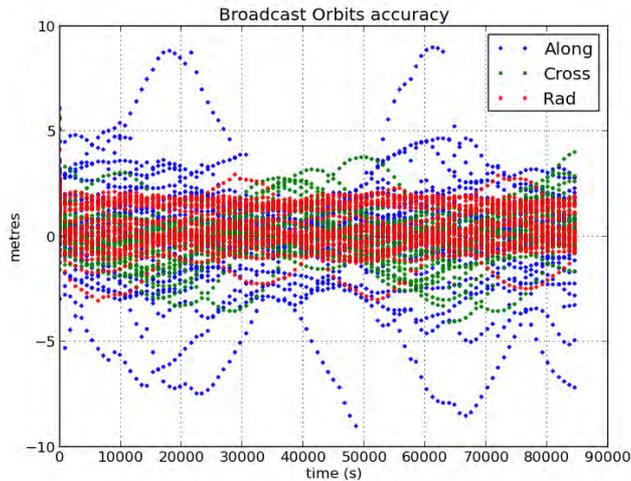


- Code measurements are unambiguous but noisy (meter level measurement noise).
- **Carrier measurements are precise but ambiguous**, meaning that they have some millimetres of noise, but also have unknown biases that could reach thousands of km.
- Carrier phase biases are estimated in the navigation 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.

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

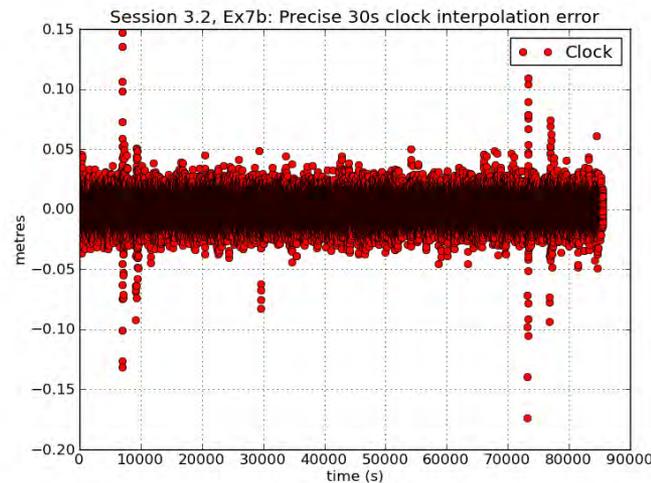
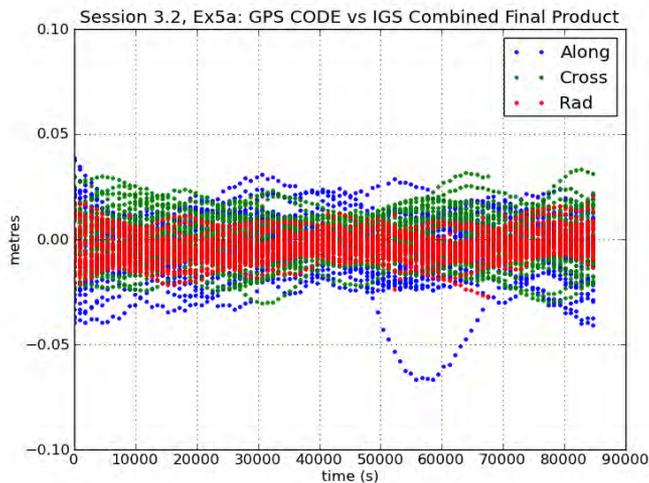
# Exercise 2: PPP Model components analysis

## Orbits & clocks accuracies



### Broadcast:

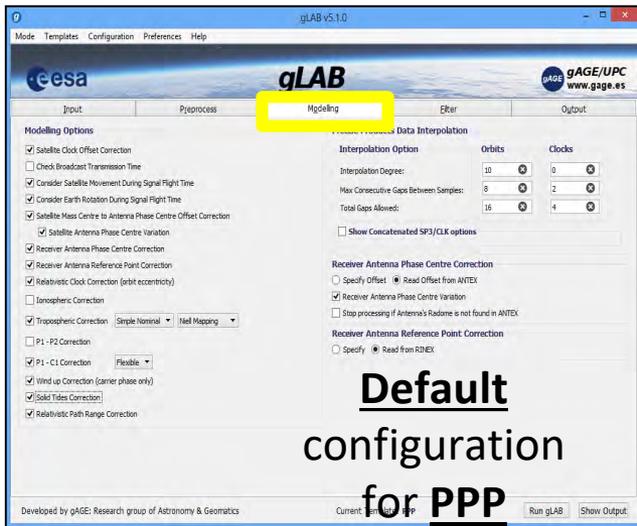
- Few metres of accuracy for broadcast orbits and clocks



### Precise:

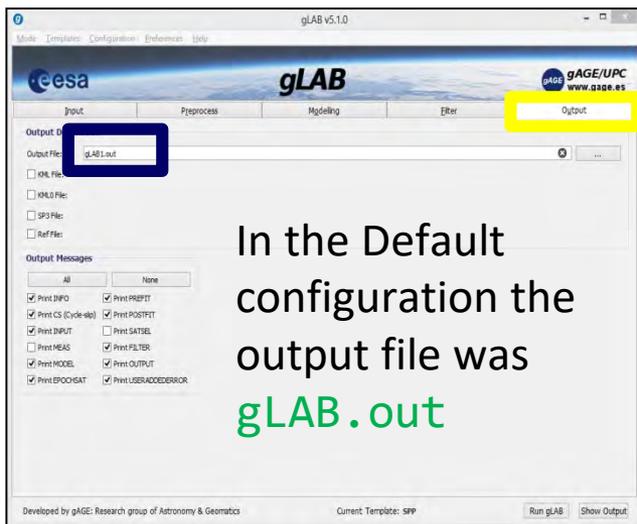
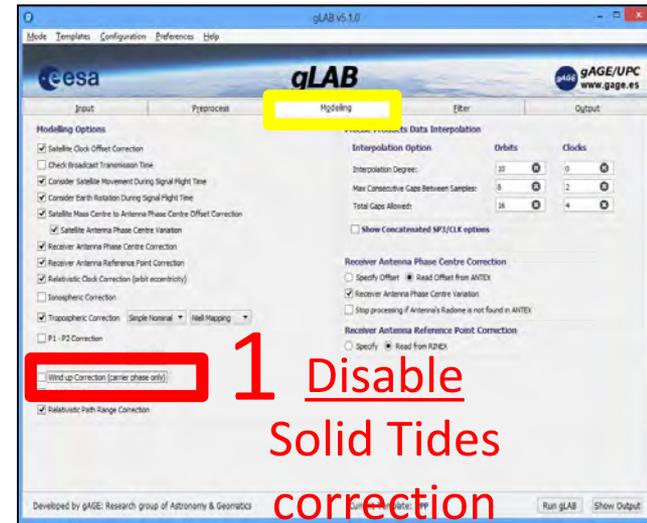
- Few centimetres of accuracy for broadcast orbits and clocks

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



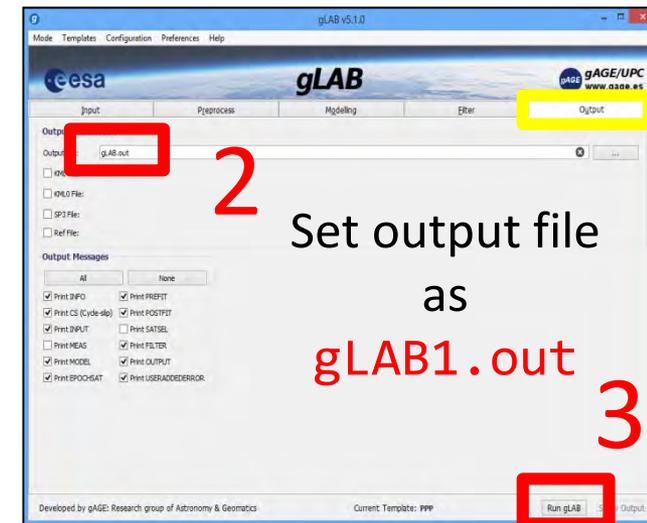
Proceed as in the previous exercise:

1. In **Modeling** panel, disable 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 38-40).



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

1 Click Clear to restart plots

2

3

Y-min, Y-max

OUTPUT

gLAB1.out

gLAB.out

Time (sec)

Vertical

Time (sec): 4

Vertical: DSTAU: 20

Vertical Positioning Error [Kinematic PPP]

Time (s)

Error (m)

Y-min: -0.4 Y-max: 0.4

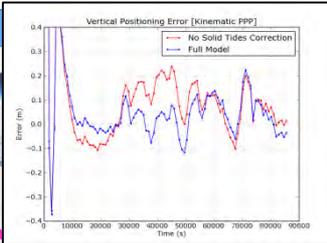
Source File: gLAB.out

Condition(s): OUTPUT (\$1=="OUTPUT")

X Column: SEC 4 Y Column: DSTAU 20

Legend-label: Full Model

Plot



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

gLAB v5.1.0

Mode Templates Configuration Preferences Help

eesa gLAB

Templates

NEU Positioning Error Horizontal Positioning Error Dilution Of Precision

Model Components Prefit Residuals Posfit Residuals

7-tropospheric Tropospheric Delay Ionospheric Combinations Carrier Phase

2

Horizontal Positioning Error [Kinematic PPP] X-label East Error (m) Y-label North Error (m)

X-min. -0.4 X-max. 0.4 Y-min. -0.4 Y-max. 0.4

Individual Plot(s) Configuration

Plot Nr. 1

Source File gLAB1.out

Condition OUTPUT (\$1=="OUTPUT")

X Column DSTAE 19 Y Column DSTAN 18

gLAB1.out

East: DSTAE: 19

North: DSTAN: 18

OUTPUT

gLAB v5.1.0

Mode Templates Configuration Preferences Help

eesa gLAB

Templates

NEU Positioning Error Horizontal Positioning Error Dilution Of Precision

Model Components Prefit Residuals Posfit Residuals

7-tropospheric Tropospheric Delay Ionospheric Combinations Carrier Phase

1 Click Clear to restart plots

X-min, Y-min, Y-max

Horizontal Positioning Error [Kinematic PPP] X-label East Error (m) Y-label North Error (m)

X-min. -0.4 X-max. 0.4 Y-min. -0.4 Y-max. 0.4

Individual Plot(s) Configuration

Plot Nr. 2

Source File gLAB.out

Condition OUTPUT (\$1=="OUTPUT")

X Column DSTAE 19 Y Column DSTAN 18

Legend-label Full Model

Clear

Horizontal Positioning Error [Kinematic PPP]

Measurement Multipath/Noise

Light and Clock Comparison

gLAB.out

East: 19

North: 18

3

# Solid Tides model component plot: gLAB.out

gLAB v5.1.0

Mode Templates Configuration Preferences Help

eesa gLAB gAGE/UPC www.gage.es

Templates

- NEU Positioning Error
- Horizontal Positioning Error
- Dilution Of Precision
- Satellite Skyplot
- Model Components**
- Profit Residuals
- Posfit Residuals
- Measurement Multipath/Noise
- Zenith Tropospheric Delay
- Ionospheric Combinations
- Carrier Phase Ambiguities
- Orbit and Clock Comparison

Global Graphic Parameters

Title: Solid Time Model [Kinematic PPP] X-label: Time (s) Y-label: Model (m)

Label Position: Top Right Fractional Text: WaterMark: Expand figure to margin

Automatic Limits  Automatic Ticks

Individual Plot(s) Configuration

Plot Nr. 1 Plot Nr. 2 Plot Nr. 3 Plot Nr. 4

Source File: gLAB.out

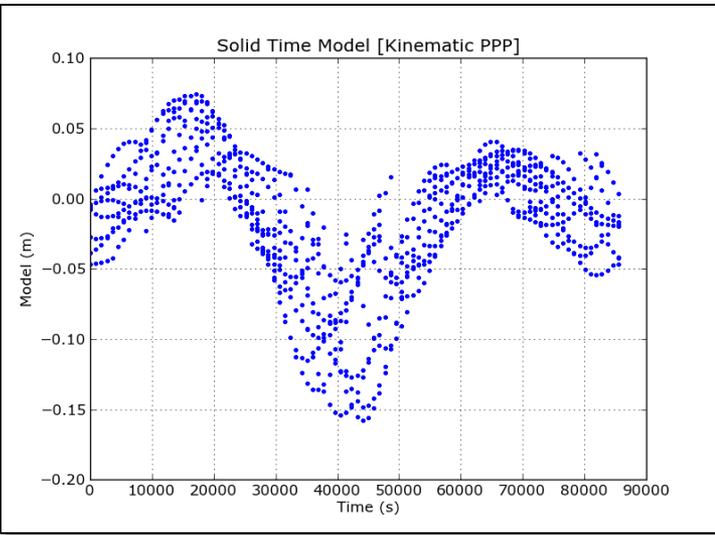
Component(s): MODEL (\$1=="MODEL")

X Column: SEC 4 Column: SOLIDTIDES 28 Legend-label:

Developed by gAGE: Research group of Astronomy & Geomatics Current Template: PPP Plot

**gLAB.out**

Select SOLIDTIDES



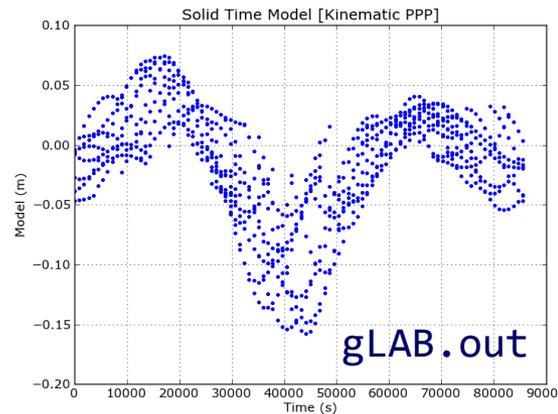
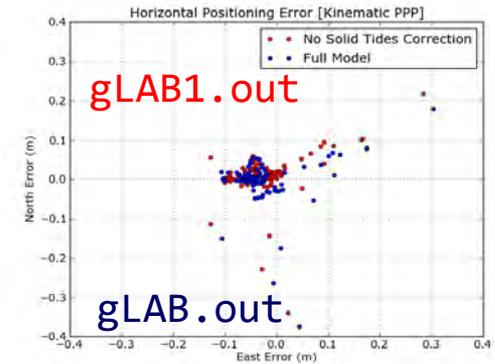
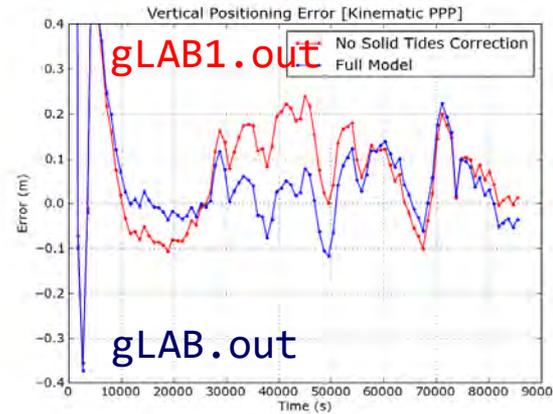
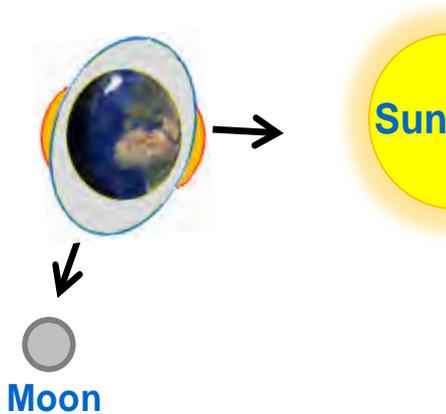
Solid Tides plot

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

# 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.

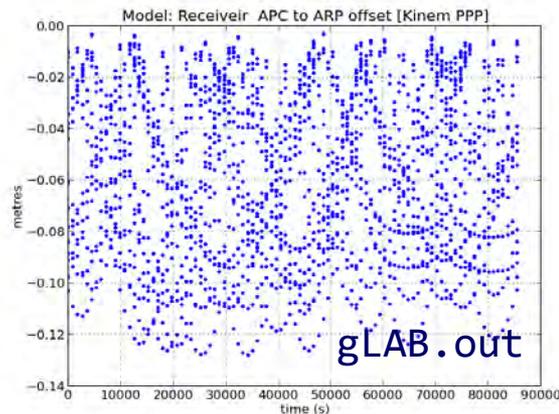
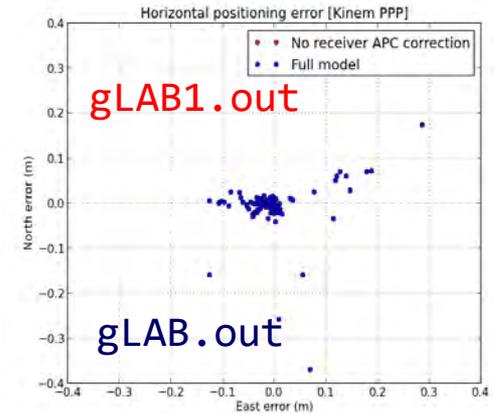
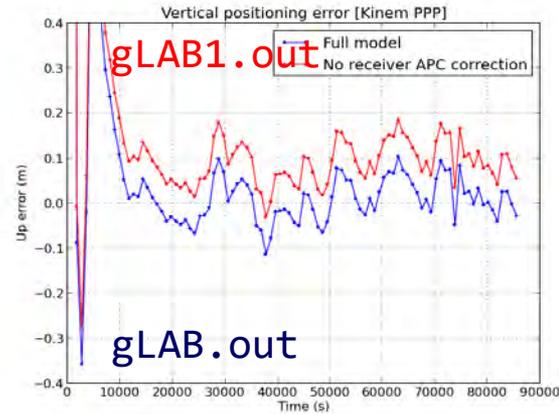
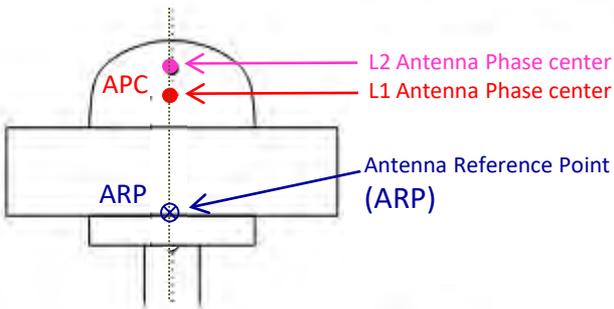


## Solid Tides:

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.

# Exercise 2: PPP Model components analysis

## Receiver Antenna Phase center (APC)



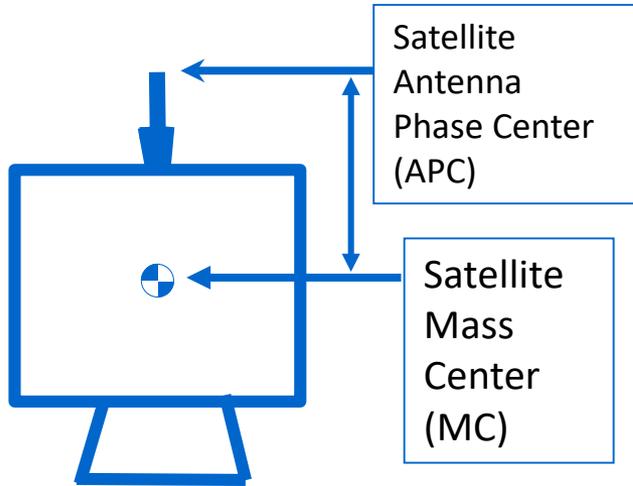
## Receiver APC:

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

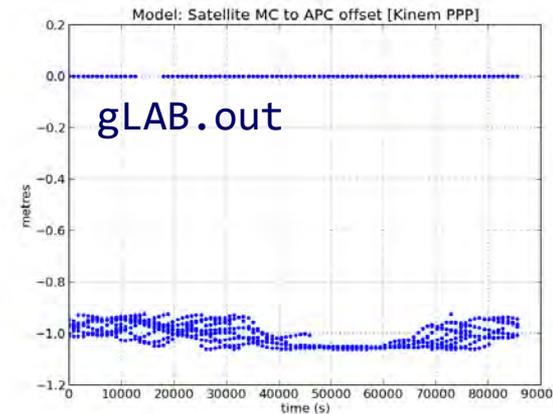
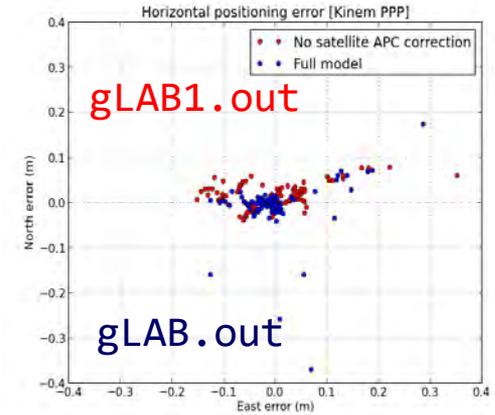
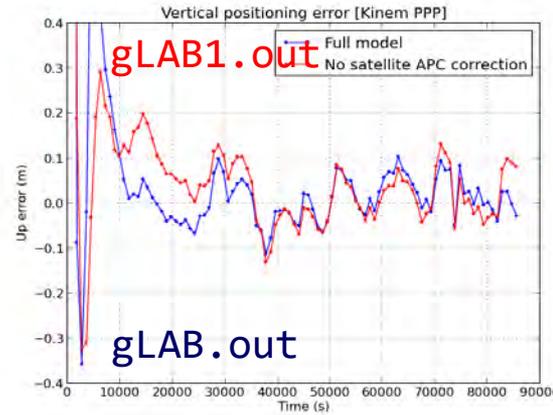
Thence, neglecting this correction, an error on the vertical component occurs, but not in the horizontal one.

# Exercise 2: PPP Model components analysis

## 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.



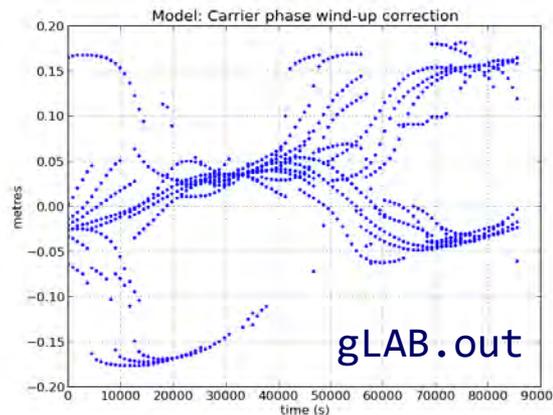
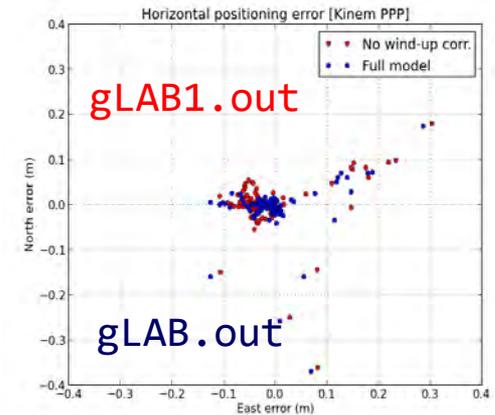
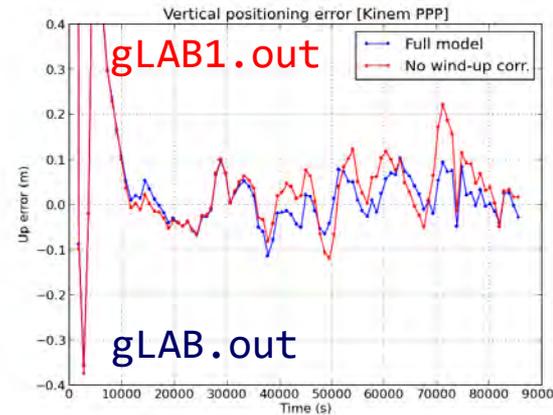
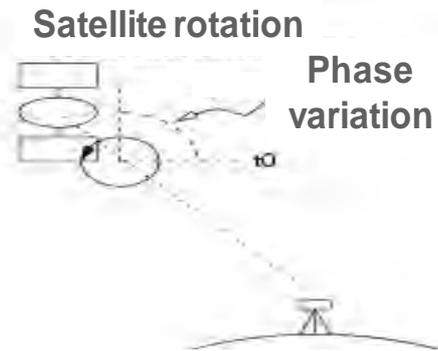
## Satellite MC to APC:

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

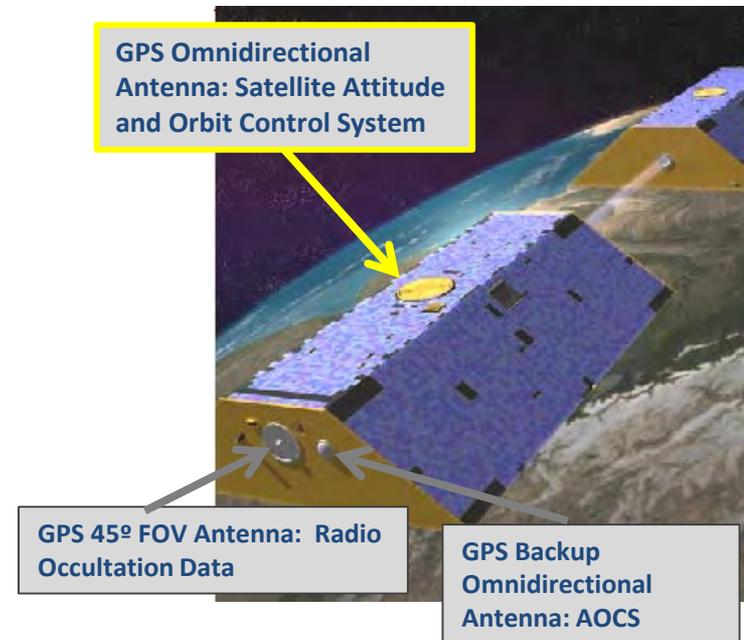
Wind-up changes smoothly along continuous carrier phase arcs.

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

# Exercise 3: Kinematic positioning of a LEO

- 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.

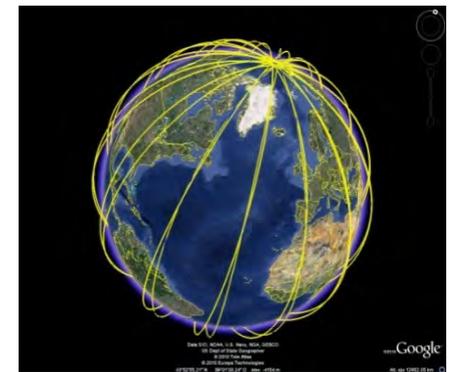
GRACE SATELLITES (A & B)	
Nominal altitude:	460 km
Orbital period:	1.5 h (aprox.)
Mass:	432 kg
Launch date:	May 17 <sup>th</sup> , 2002
Space Agency:	NASA/GFZ
Designed life-time:	5 years
<hr/>	
Receiver pseudorange noise:	40 cm
Receiver carrier-phase noise:	8 mm
Receiver GRAPHIC noise:	12 cm
Antenna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



More details at: [http://op.gfz-potsdam.de/grace/index\\_GRACE.html](http://op.gfz-potsdam.de/grace/index_GRACE.html)

# 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?



# 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`

# Mode 1: Single frequency C1 code with broadcast orbits & clocks

## Example of computation with gLAB:

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

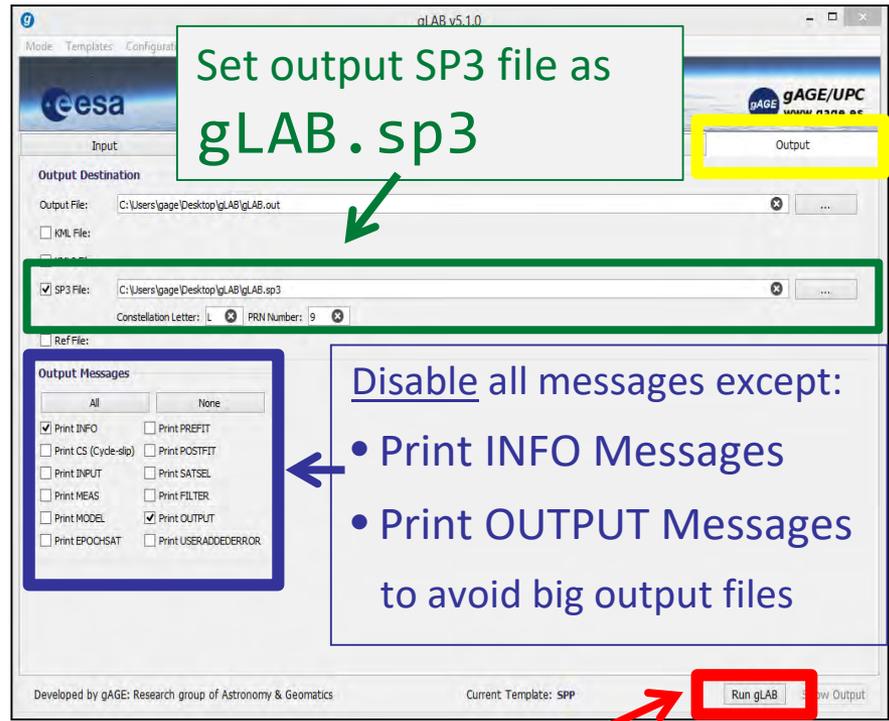
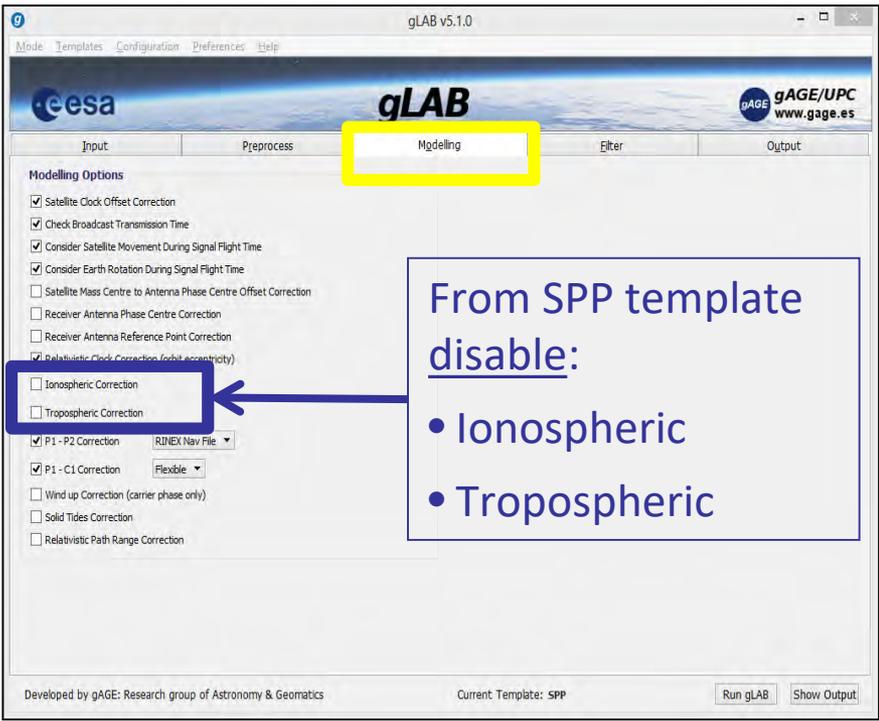
The screenshot shows the gLAB v5.1.0 interface. A blue box labeled '1' highlights the 'SPP' mode selection in the 'Mode' menu. A yellow box highlights the 'RINEX Observation File' field containing 'graa0800.07o' and the 'RINEX Navigation File' field containing 'brdc0800.07n'. A red box labeled '2' highlights the 'A Priori Receiver Position From:' section, where the 'Calculate' radio button is selected. A green box contains the text 'Select files graa0800.07o brdc0800.07n' with arrows pointing to the file input fields.

The screenshot shows the gLAB v5.1.0 interface with the 'Preprocess' tab selected. A yellow box highlights the 'Preprocess' tab. A green box labeled '3' highlights the 'Data Decimation' field set to '30 (s)'. A green box contains the text 'Set data decimation to 30 seconds instead of 300 to have a higher number of output samples' with an arrow pointing to the 'Data Decimation' field.

# Mode 1: Single frequency C1 code with broadcast orbits & clocks

## Example of computation with gLAB:

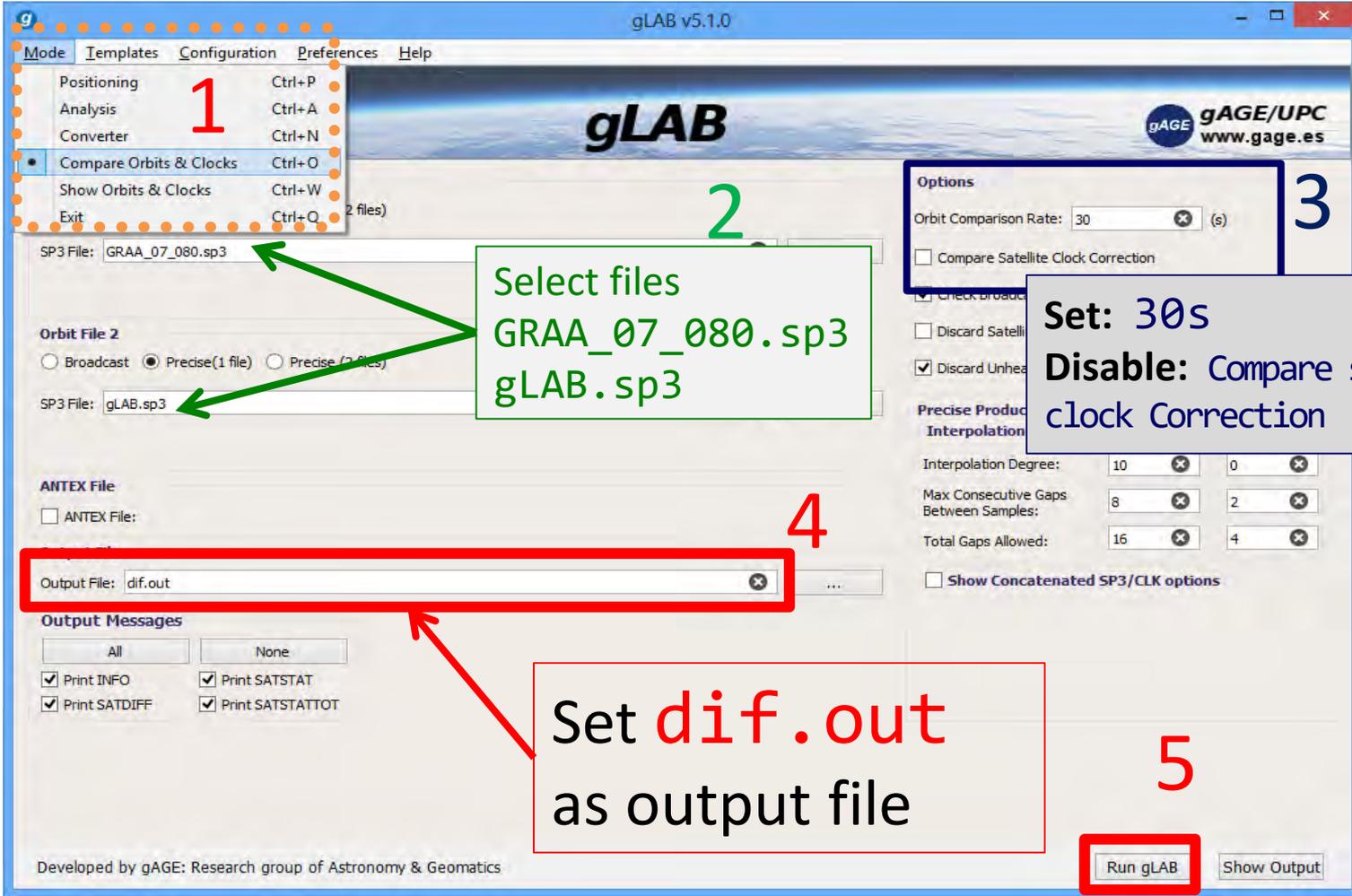
Code positioning + broadcast orbits: Single frequency: C1 code.



Run gLAB

# Mode 1: Single frequency C1 code with broadcast orbits & clocks

- Accuracy assessment of the computed solution (from **gLAB.sp3** file) with the reference coordinates of file **GRAA\_07\_080.sp3**:



Select files  
GRAA\_07\_080.sp3  
gLAB.sp3

Set: 30s  
Disable: Compare satellite clock Correction

Set dif.out as output file

# Mode 1: Single frequency C1 code with broadcast orbits & clocks

3  
Set plotting ranges  
X:[ 43000 : 67000] Y:[ -20 : 20]

1  
Orbit and Clock Comparison

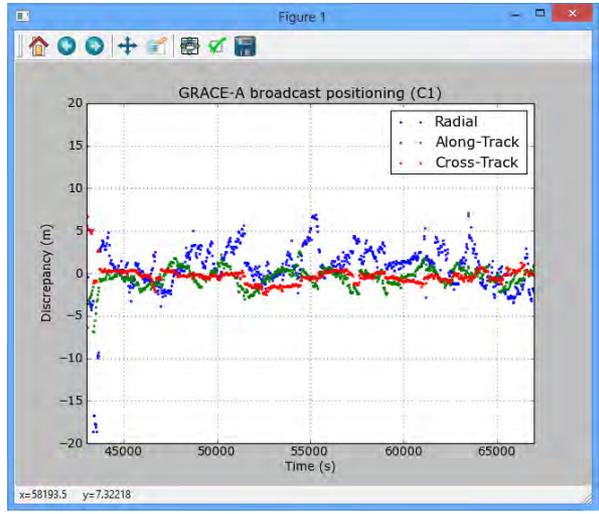
2  
Upload file dif.out in Plot 1, Plot 2 & Plot 3

4  
Plot

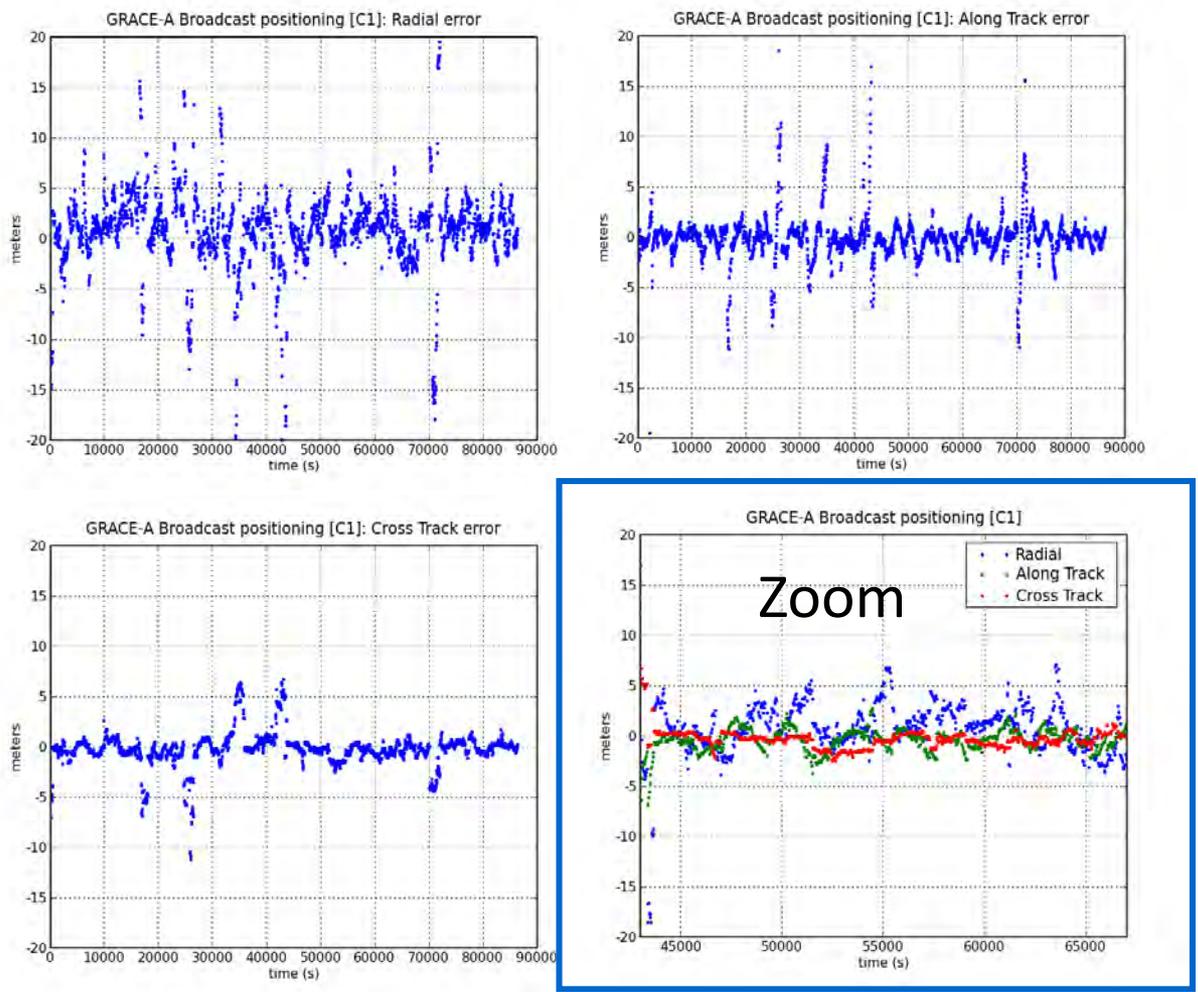
Global Graphic Parameters  
Title: GRACE-A broadcast positioning (C1) X-label: Time (s) Y-label: Discrepancy (m)  
X-min: 43000 X-max: 67000 Y-min: -20 Y-max: 20

Plot Configuration  
Plot Nr. 1 Plot Nr. 2 Plot Nr. 3 Plot Nr. 4  
Source file: C:\Users\gage\Desktop\gLAB\dif.out  
Condition(s): SATDIFF (\$1=="SATDIFF")  
X Column: SEC 4 Y Column: RADIAL 11 Legend-label: Radial

Plotting  
dif.out  
with the GUI



# Mode 1: Single frequency C1 code with broadcast orbits & clocks



- ## Questions
1. Is it reasonable to disable 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?

# Mode 1: 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.

# Mode 1: 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

From previous configuration, disable (TGD):

- P1 - P2 Correction

2

From previous configuration, set:

- Dual Frequency
- PC Measurement

Complete the steps (from previous configuration):

1. [Modeling]:
  - Disable P1-P2 correction
2. [Filter]:
  - Dual Frequency
  - PC measurement
3. Run gLAB
4. In Compare Orbits & Clocks mode:
  - Compute differences with reference file GRAA\_07\_080.sp3

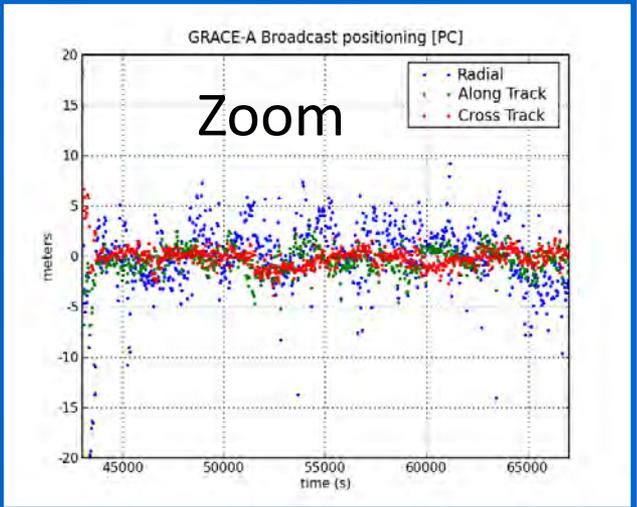
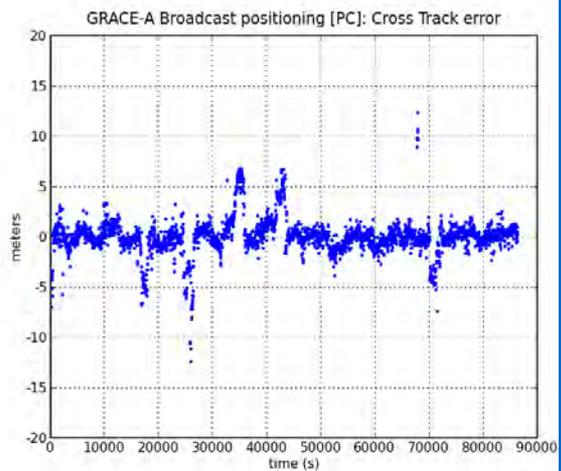
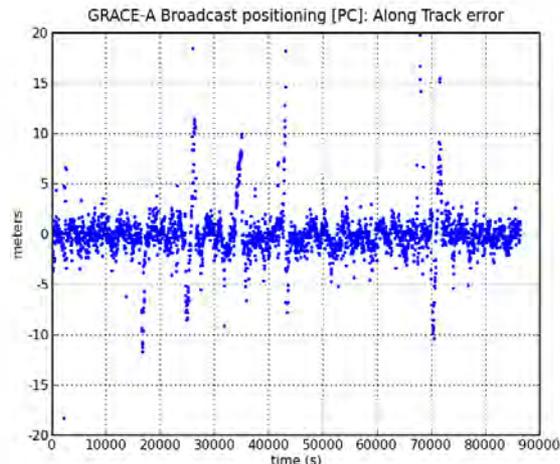
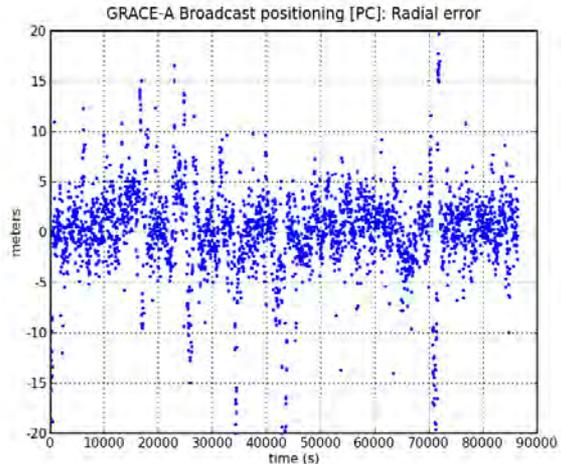
3

Select files GRAA\_07\_080.sp3, gLAB.sp3

Set: 30s, Disable: Clock

Set dif.out as output file

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

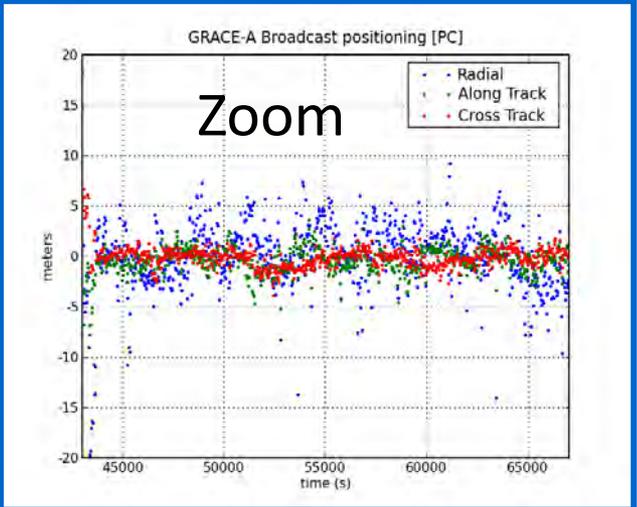
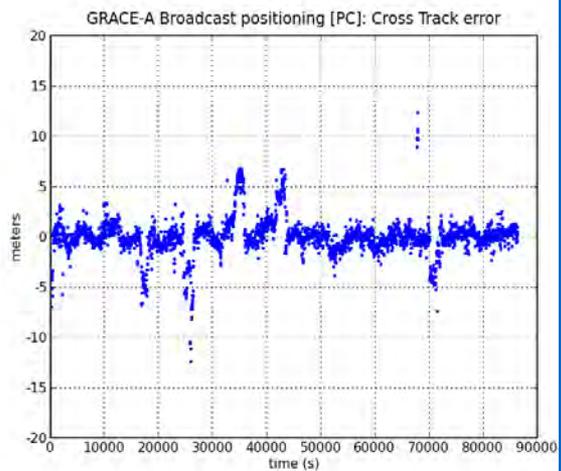
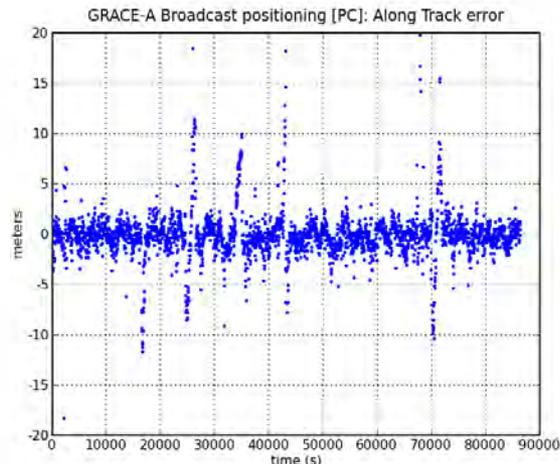
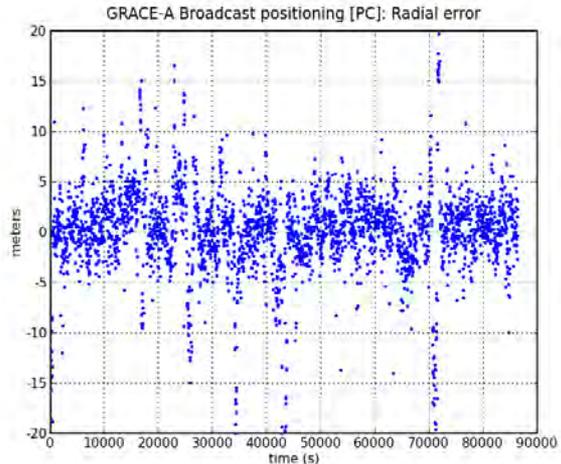


## Plotting

- 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



### 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  $P_1$  and  $P_2$  is computed as: 
$$P_C = \frac{f_1^2 P_1 - f_2^2 P_2}{f_1^2 - f_2^2} = \frac{\gamma P_1 - P_2}{\gamma - 1} \quad \gamma = \left(\frac{77}{60}\right)^2$$

Thence, assuming uncorrelated  $P_1$ ,  $P_2$  measurements with equal noise  $\sigma$ , it follows: 
$$\sigma_{P_C} = 3 \sigma$$

## 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)

**Set PPP 1**

**Set Precise (2 files)**

**2**

**Set calculate**

Select files  
graa0800.07o  
cod14193.sp3  
cod14193.clk  
igs05\_1402.atx

Current Template: PPP

Run gLAB Show Output

**Preprocess**

**3**

Set data decimation to 30 seconds instead of 300 to have a higher number of output samples

Current Template: PPP

Run gLAB Show Output

# 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)

**From PPP configuration, disable:**

- Receiver Antenna Phase Center
- Receiver Antenna Ref. Point
- Ionospheric (already disabled)
- P1 – P2 (already disabled)
- Tropospheric
- Solid Tides correction

**Disable Estimate Troposphere**

**Switch to Kinematic**

# 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)

**Set output SP3 file as gLAB.sp3**

**Output**

Output File: C:\Users\gage\Desktop\gLAB\gLAB.out

SP3 File: C:\Users\gage\Desktop\gLAB\gLAB.sp3

Constellation Letter: L PRN Number: 9

**Output Messages**

All	None
<input checked="" type="checkbox"/> Print INFO	<input type="checkbox"/> Print PREFIT
<input type="checkbox"/> Print CS (Cycle-slip)	<input type="checkbox"/> Print POSTFIT
<input type="checkbox"/> Print INPUT	<input type="checkbox"/> Print SATSEL
<input type="checkbox"/> Print MEAS	<input type="checkbox"/> Print FILTER
<input type="checkbox"/> Print MODEL	<input checked="" type="checkbox"/> Print OUTPUT
<input type="checkbox"/> Print EPOCHSAT	<input type="checkbox"/> Print USERADDEDEERROR

Developed by gAGE: Research group of Astronomy & Geomatics

Current Template: SPP

**Run gLAB**

**Disable all messages except:**

- Print INFO Messages
- Print OUTPUT Messages to avoid big output files

**Run gLAB**

**Select files GRAA\_07\_080.sp3 gLAB.sp3**

**Set: 30s Disable: Clock**

**Set dif.out as output file**

Options: Orbit Comparison Rate: 30 (s)

Compare Satellite Clock Connection

Discard Unhealthy Satellites (Broadcast)

Print:  Print INFO  Print SATSTAT  Print SATSTATTOT

Developed by gAGE: Research group of Astronomy & Geomatics

**2**

**Set plotting ranges X: [ 43000 : 67000] Y: [ -2 : 2]**

**Upload file dif.out in Plot 1, Plot 2 & Plot 3**

Global Graphic Parameters

Plot Nr. 1 Plot Nr. 2 Plot Nr. 3 Plot Nr. 4

Source: C:\Users\gage\Desktop\gLAB\gLAB.out

Conditions: (SPP) (SPP) (SPP) (SPP)

X Column: SEC Y Column: RADIAL Legend: Blue

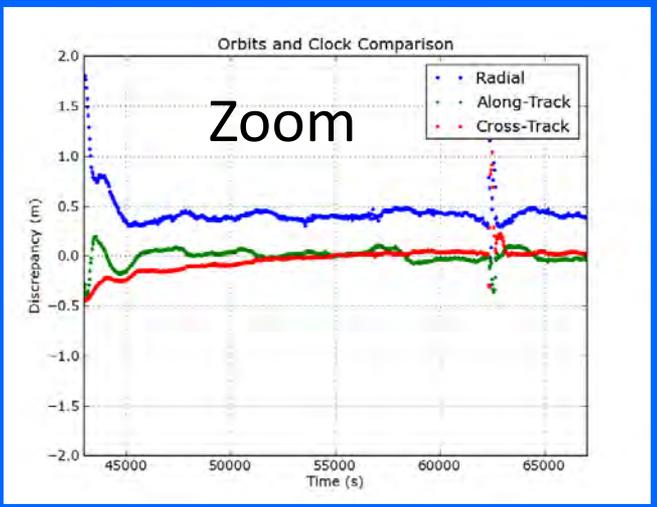
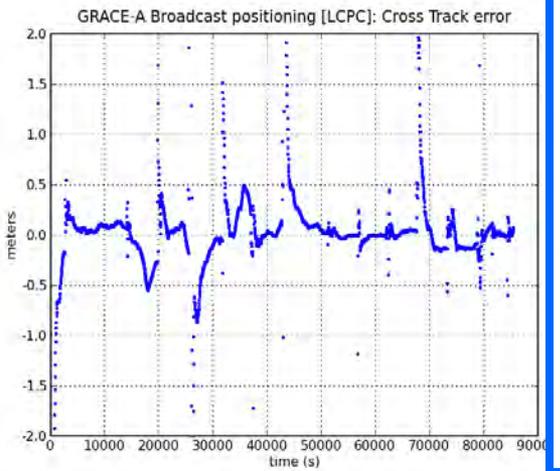
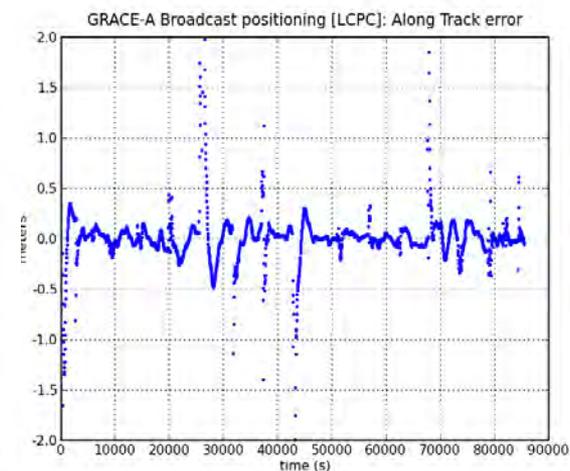
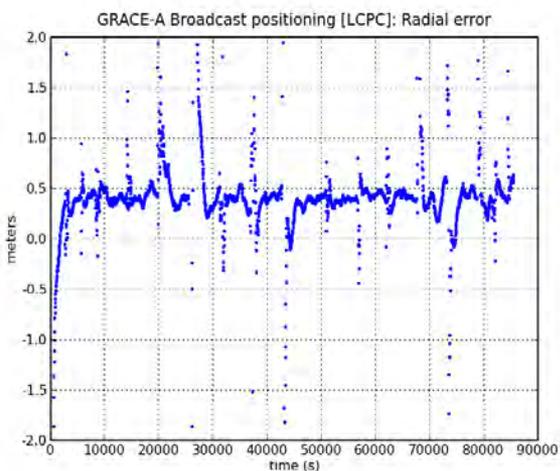
**Plot**

**3**

**4**

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

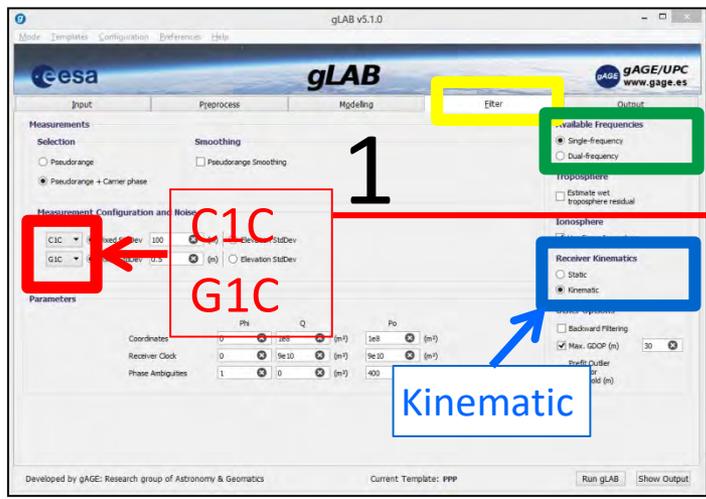
## ⤴ Answer to Question 11:

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 satellite movement relative to a receiver with fixed coordinates. 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

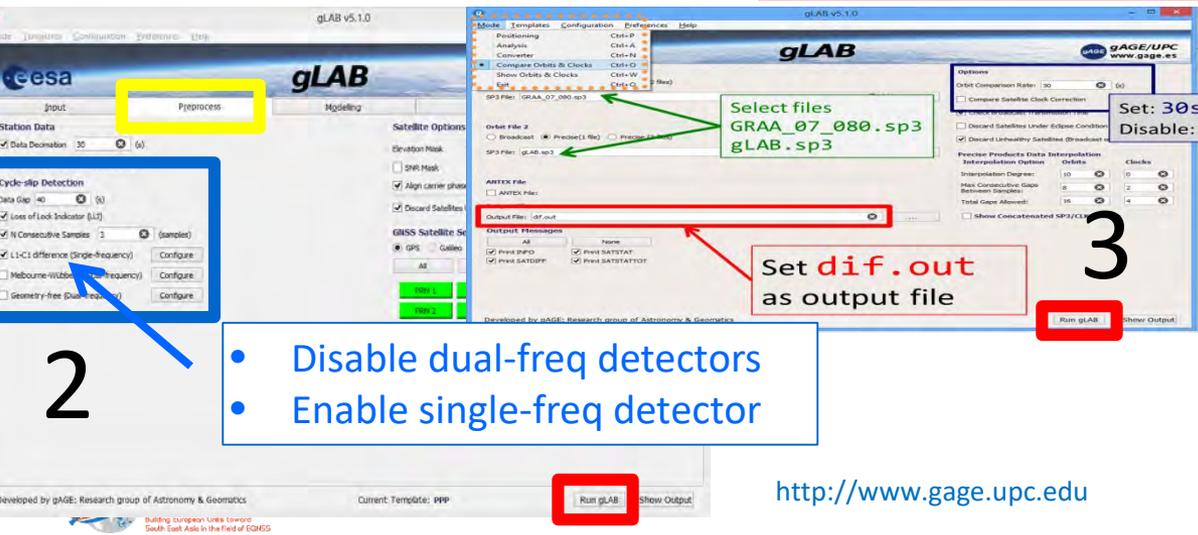
## Example of computation with gLAB: Code and Carrier + precise orbits & clocks: Single frequency (GRAPHIC)



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.

$\sigma_{C1} = 100$  meters  
 $\sigma_{G1} = 0.5$  meters



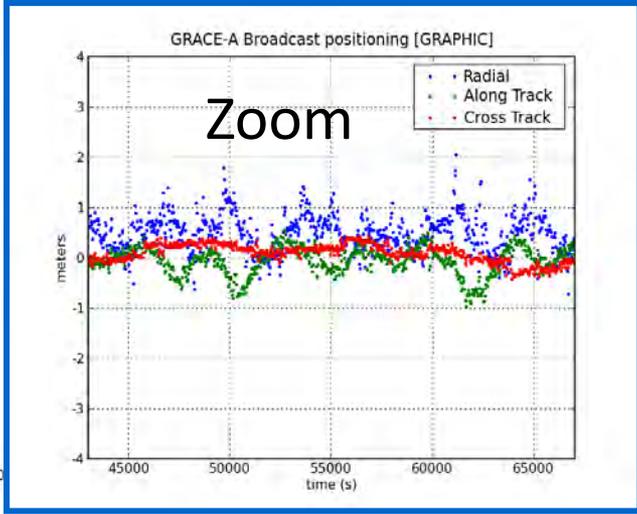
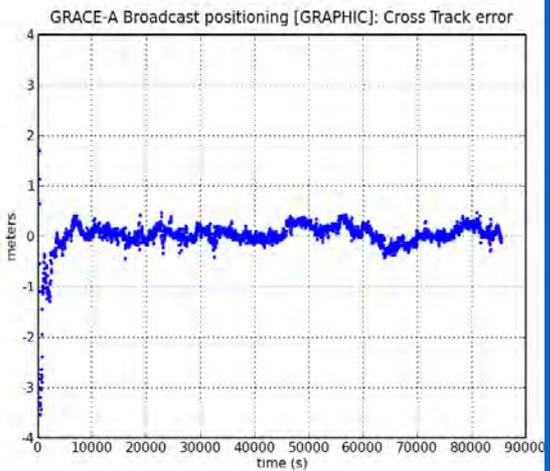
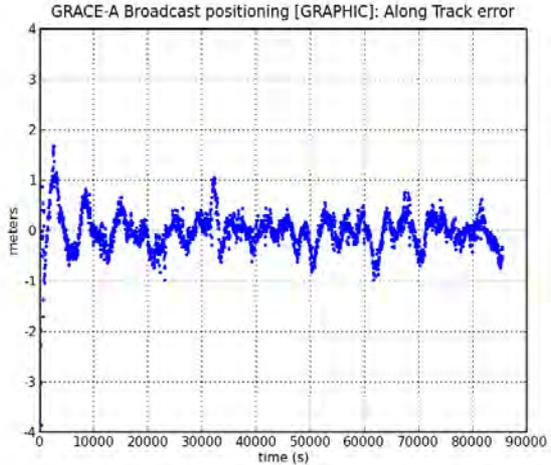
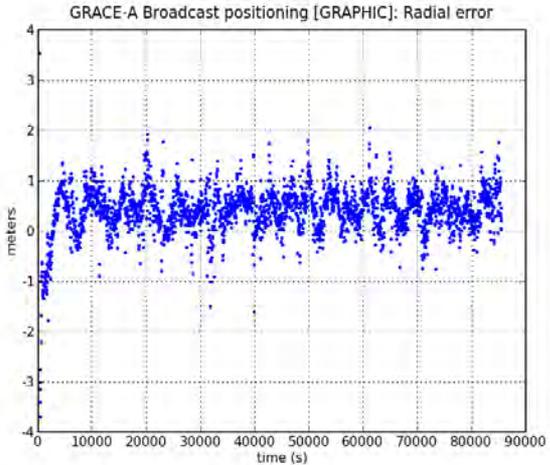
2

- Disable dual-freq detectors
- Enable single-freq detector

Complete the steps (from PPP configuration mode):

- [Filter]:
    - Single Frequency
    - C1C (C1 code [\*])
    - G1C (GRAPHIC)
    - Set Kinematic Mode
  - [Mode]:
    - Disable P1 – P2 Corr.
  - [Output]:
    - Set gLAB.sp3 format file.
  - [Preprocess]:
    - Unable MW, LI detectors
  - Run gLAB
  - In Compare Orbits & Clocks:
    - 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:  $G = \frac{1}{2}(P_1 + L_1)$
- 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.

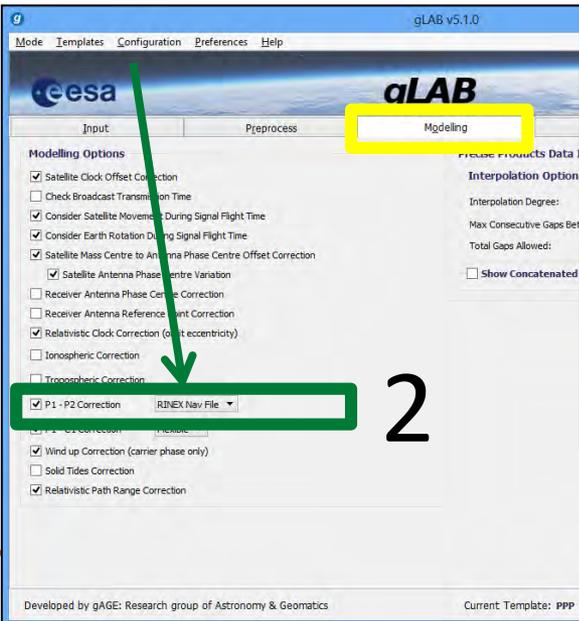
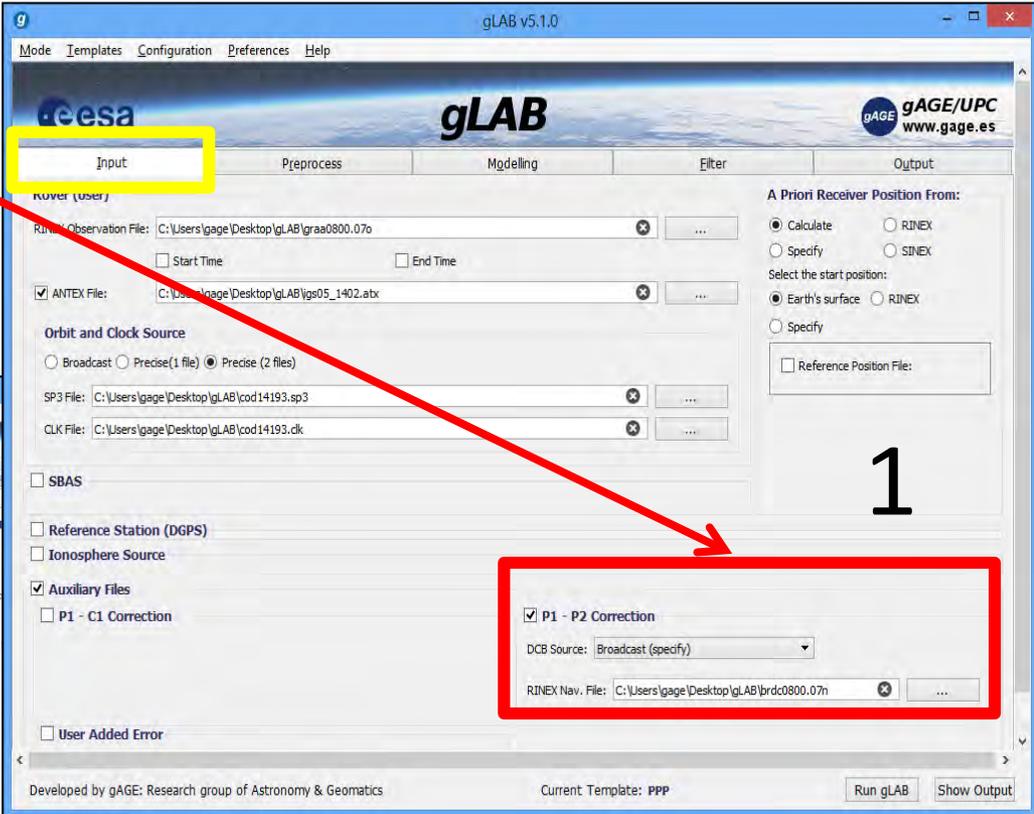
# Mode 5. Single freq. L1, C1 carrier and code with precise orbits & clocks

## 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. Select DCB source: **Broadcast (specify)**
- 2. [Mode]: Set **P1-P2 correction**, select RINEX Navigation as **DCB File**.



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

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

Example of computation with gLAB:

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

**3**

Single frequency

Set  $\sigma_{C1P}=1$  meter  
 $\sigma_{L1P}=0.01$  meters

**4**

- Disable dual-freq detectors
- Enable single-freq detector

**5**

Select files GRAA\_07\_080.sp3 gLAB.sp3

Set dif.out as output file

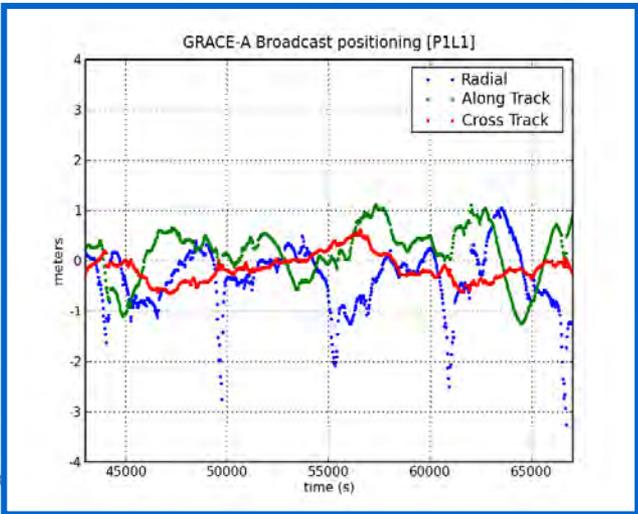
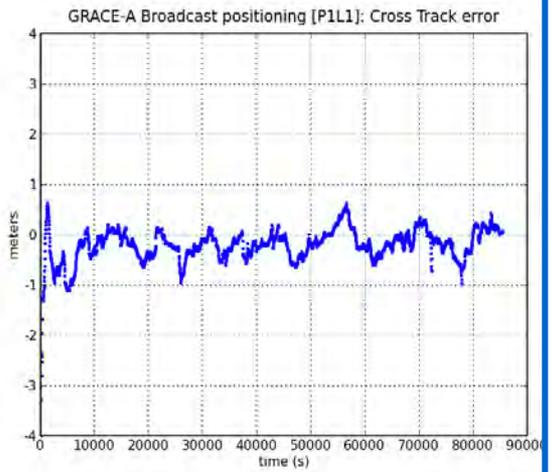
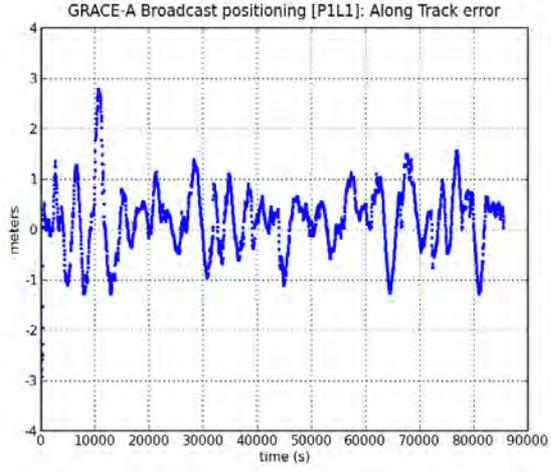
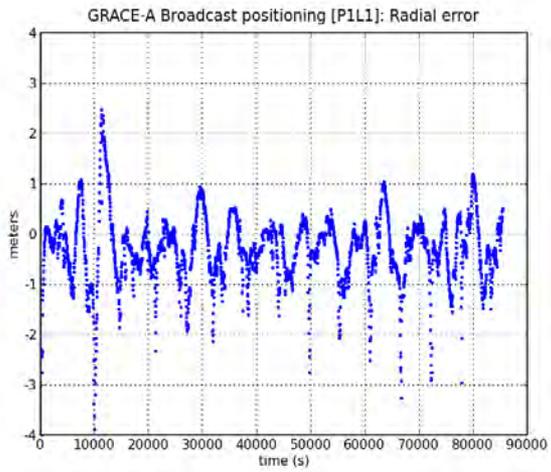
Set: 30s  
Disable: Clock

Run gLAB Show Output

Complete the steps

- [Filter]:
    - Single Frequency measurements
    - L1P (L1 carrier)
    - C1P (P1 code)
  - [Output]:
    - Set gLAB.sp3 format file.
  - [Preprocess]:
    - Unable MW, LI detectors
  - Run gLAB
- In Compare Orbits & Clocks:
- 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?

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

## ✦ 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



# Backup slides

Homework help and answers

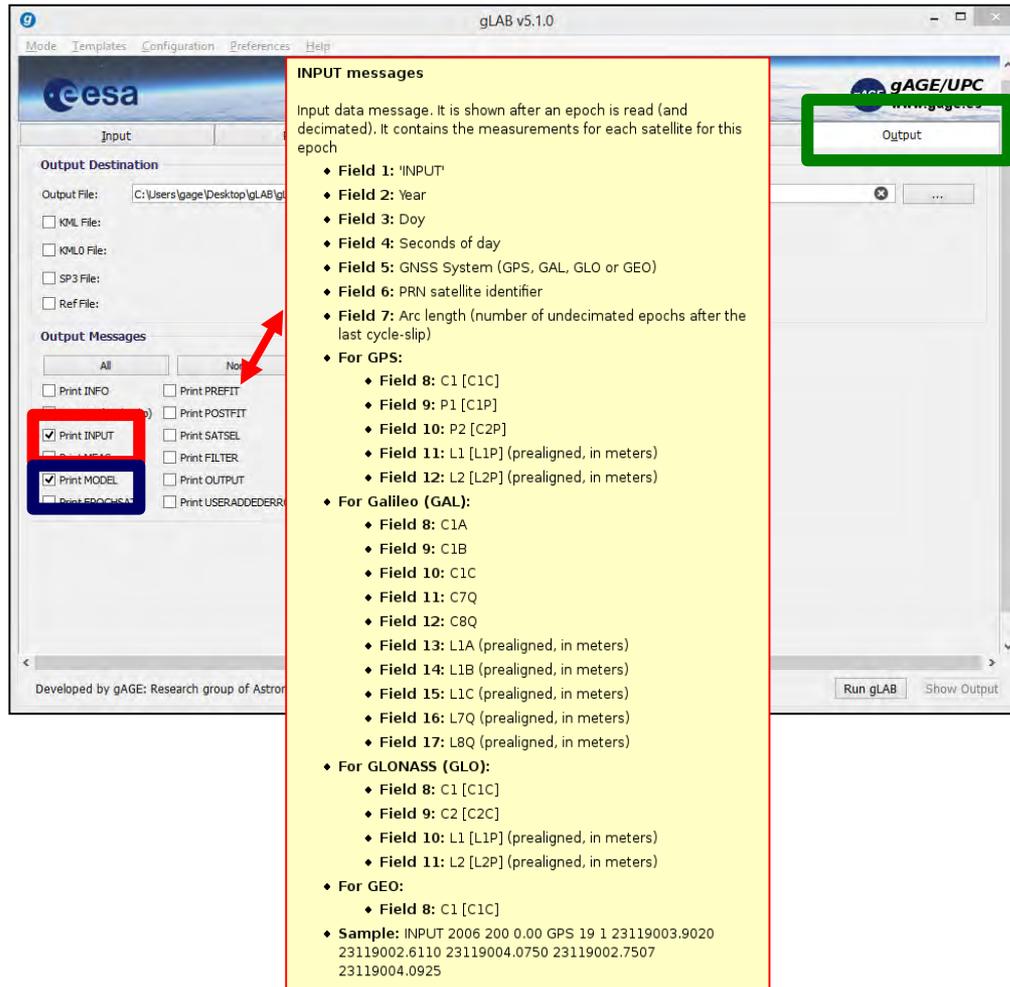
# Proposed Homework exercises

- ▶ 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 

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



The screenshot shows the gLAB v5.1.0 software interface. On the left, the 'Output Messages' section is visible, with checkboxes for 'Print INPUT' and 'Print MODEL' selected. A red arrow points from this section to a yellow box on the right. The yellow box contains the following text:

**INPUT messages**  
Input data message. It is shown after an epoch is read (and decimated). It contains the measurements for each satellite for this epoch

- **Field 1:** 'INPUT'
- **Field 2:** Year
- **Field 3:** Day
- **Field 4:** Seconds of day
- **Field 5:** GNSS System (GPS, GAL, GLO or GEO)
- **Field 6:** PRN satellite identifier
- **Field 7:** Arc length (number of undecimated epochs after the last cycle-slip)
- **For GPS:**
  - **Field 8:** C1 [C1C]
  - **Field 9:** P1 [C1P]
  - **Field 10:** P2 [C2P]
  - **Field 11:** L1 [L1P] (prealigned, in meters)
  - **Field 12:** L2 [L2P] (prealigned, in meters)
- **For Galileo (GAL):**
  - **Field 8:** C1A
  - **Field 9:** C1B
  - **Field 10:** C1C
  - **Field 11:** C7Q
  - **Field 12:** C8Q
  - **Field 13:** L1A (prealigned, in meters)
  - **Field 14:** L1B (prealigned, in meters)
  - **Field 15:** L1C (prealigned, in meters)
  - **Field 16:** L7Q (prealigned, in meters)
  - **Field 17:** L8Q (prealigned, in meters)
- **For GLONASS (GLO):**
  - **Field 8:** C1 [C1C]
  - **Field 9:** C2 [C2C]
  - **Field 10:** L1 [L1P] (prealigned, in meters)
  - **Field 11:** L2 [L2P] (prealigned, in meters)
- **For GEO:**
  - **Field 8:** C1 [C1C]
- **Sample:** INPUT 2006 200 0.00 GPS 19 1 23119003.9020  
23119002.6110 23119004.0750 23119002.7507  
23119004.0925

On the right side of the screenshot, the 'Output' window is visible, with a green box highlighting the 'Output' label.

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

Plot 1

Global Graphic Parameters

Title: Ionospheric Combinations

X-label: Time (s)

Y-label: Metres of L1-L2 delay (m)

Condition(s): INPUT

Legend-label: PRN 16 : LI=(L1 - L2)

$\$11-\$12 \leftarrow L1-L2$

Plot 2

Global Graphic Parameters

Title: Ionospheric Combinations

X-label: Time (s)

Y-label: Metres of L1-L2 delay (m)

Condition(s): INPUT

Legend-label: PRN 16 : PI=(P2 - P1)

$\$10-\$9 \leftarrow P2-P1$

Plot 3

Global Graphic Parameters

Title: Ionospheric Combinations

X-label: Time (s)

Y-label: Metres of L1-L2 delay (m)

Condition(s): INPUT

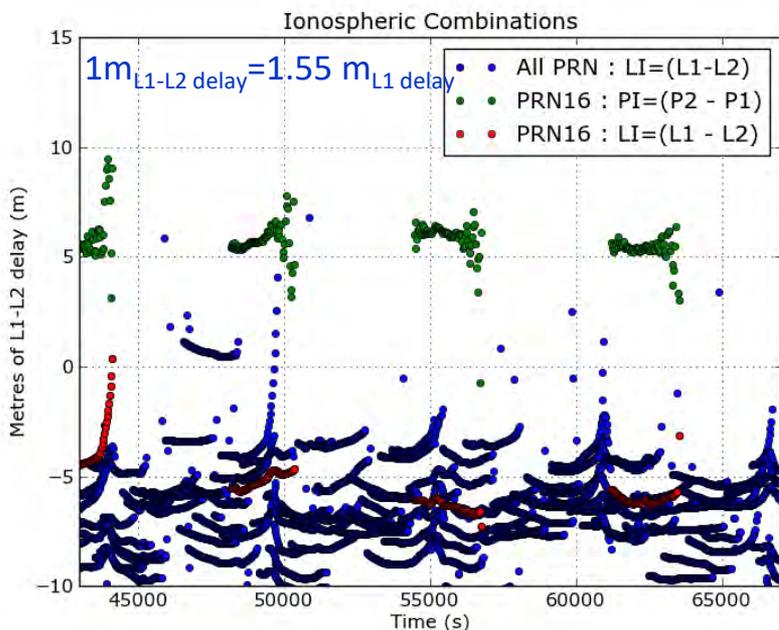
Legend-label: PRN 16 : LI=(L1 - L2)

$\$11-\$12 \leftarrow L1-L2$

Note: This plot take some time to be generated !!

Plot

# 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
```

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

## ★ 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 e1 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
```

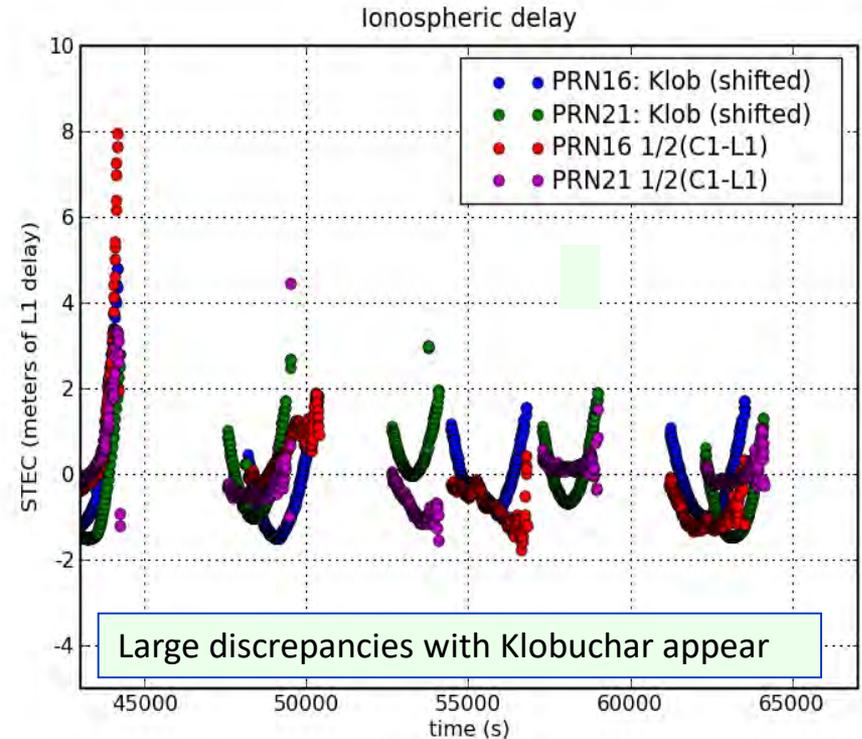
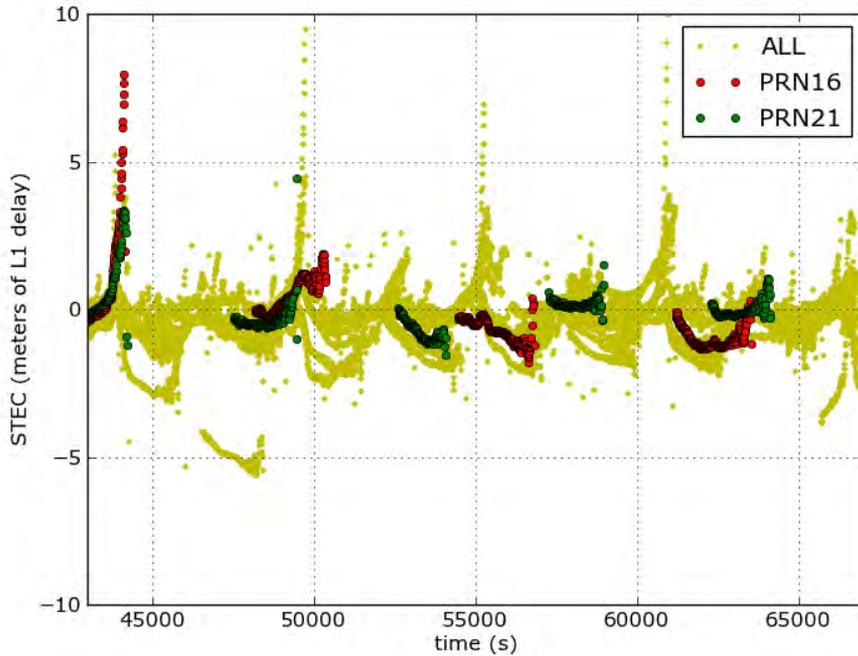
2. From file `meas.txt`, compute the ionospheric delay as  $I_1 = \frac{1}{2}(C1 - L1) + bias$

```
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. --c1 y -l "ALL"
-f I1.txt -c '($1==16)' -x2 -y3 -so --c1 r -l "PRN16"
-f I1.txt -c '($1==21)' -x2 -y3 -so --c1 g -l "PRN21"
--xn 43000 --xx 67000 --yn -10 --yx 10
--x1 "time (s)" --y1 "STEC (meters of L1 delay)"
```

# 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

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

## 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:

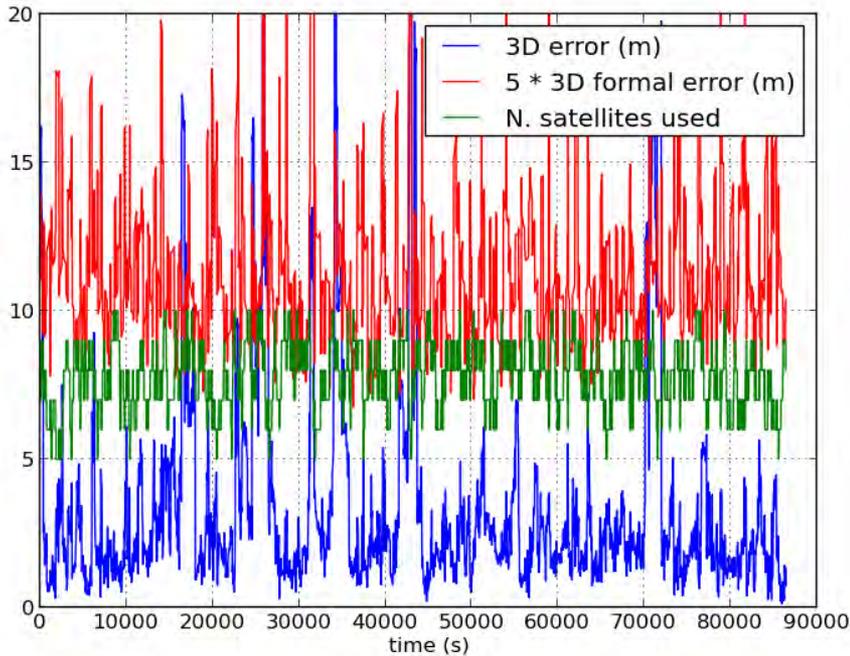
In the same graph, plot the “3D error” [from file `dif.out`], the formal error (the 3-D sigma) and the number of satellites used in the computation [from file `gLAB.out`].

```
graph.py -f dif.out -x4 -y9 -s- -l "3D error" -c '($1=="SATDIFF")'  
-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:**  $3D\text{-sigma} \approx \sigma PDOP$

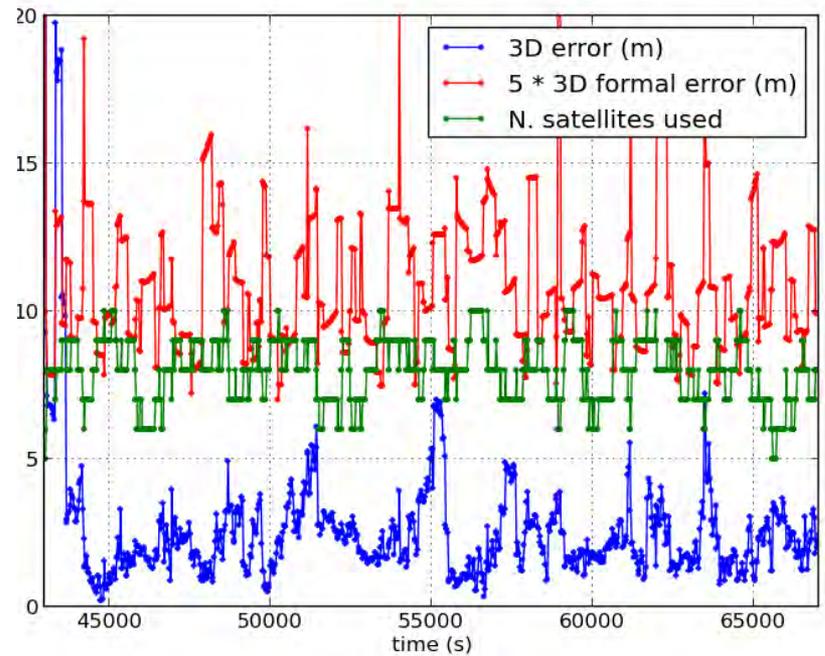
In the previous plot, the 3-D sigma is multiplied by 5 to enlarge the image.

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 e1 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: 
$$M_{C1} = C1 - L1 - \frac{2}{\gamma - 1} (L1 - L2) \quad \gamma = \left(\frac{77}{60}\right)^2$$

```
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. --c1 y --l "ALL"
-f C1.txt -c '($1==16)' -x2 -y3 -so --c1 r --l "PRN16"
-f C1.txt -c '($1==21)' -x2 -y3 -so --c1 g --l "PRN21"
--xn 43000 --xx 67000 --yn 8 --yx 28
```

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

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 e1 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:  $M_{P1} = P1 - L1 - \frac{2}{\gamma - 1}(L1 - L2)$   $\gamma = \left(\frac{77}{60}\right)^2$

```
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. --c1 y --l "ALL"  
-f P1.txt -c '($1==16)' -x2 -y3 -so --c1 r --l "PRN16"  
-f P1.txt -c '($1==21)' -x2 -y3 -so --c1 g --l "PRN21"  
--xn 43000 --xx 67000 --yn 8 --yx 28
```

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

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 e1 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. --c1 y --l "ALL"
-f P2.txt -c '($1==16)' -x2 -y3 -so --c1 r --l "PRN16"
-f P2.txt -c '($1==21)' -x2 -y3 -so --c1 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 e1 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:

$$M_{pc} = Pc - Lc$$

$$\left\{ \begin{array}{l} Pc = \frac{f_1^2 P_1 - f_2^2 P_2}{f_1^2 - f_2^2} = \frac{\gamma P_1 - P_2}{\gamma - 1}; \\ Lc = \frac{f_1^2 L_1 - f_2^2 L_2}{f_1^2 - f_2^2} = \frac{\gamma L_1 - L_2}{\gamma - 1} \end{array} \right.$$

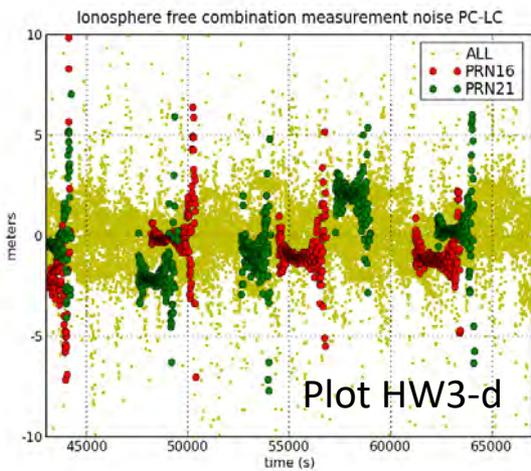
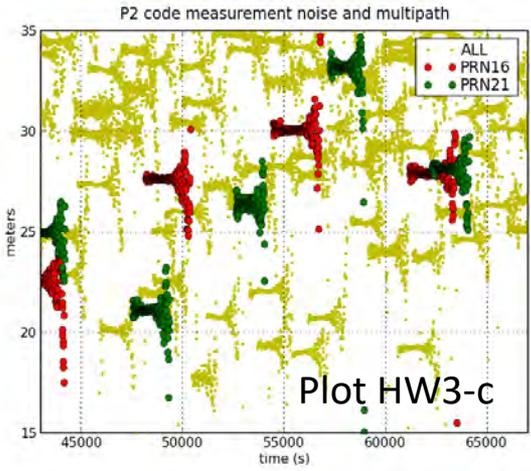
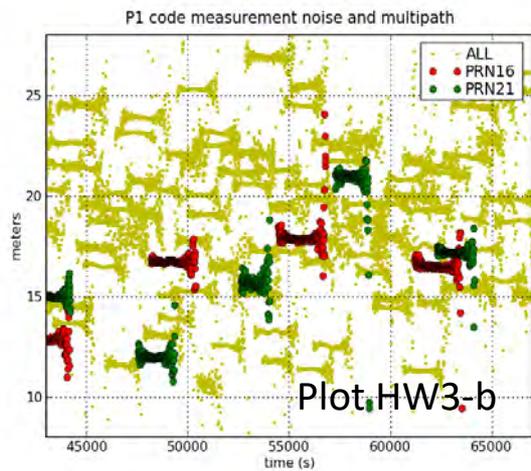
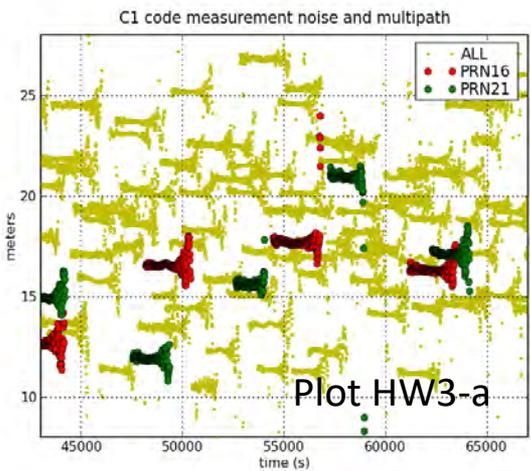
```
gawk 'BEGIN{g=(77/60)^2}{print $6, $4, (g*($13-$14)-($15-$16))/(g-1)}' meas.txt > PC.txt
```

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)

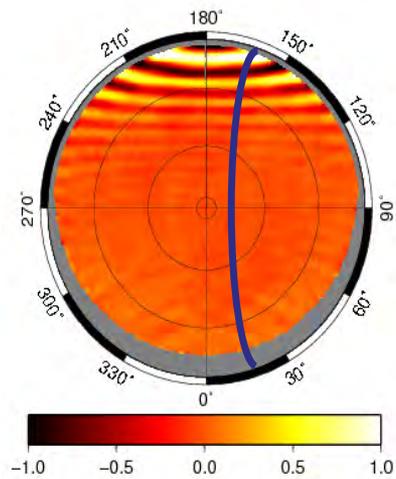
```
graph.py -f PC.txt -x2 -y3 -s. --c1 y --l "ALL"
-f PC.txt -c '($1==16)' -x2 -y3 -so --c1 r --l "PRN16"
-f PC.txt -c '($1==21)' -x2 -y3 -so --c1 g --l "PRN21"
--xn 43000 --xx 67000 --yn 8 --yx 28
```

# 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.



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`).

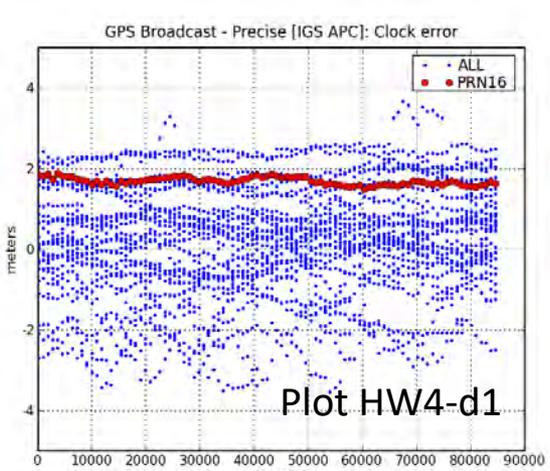
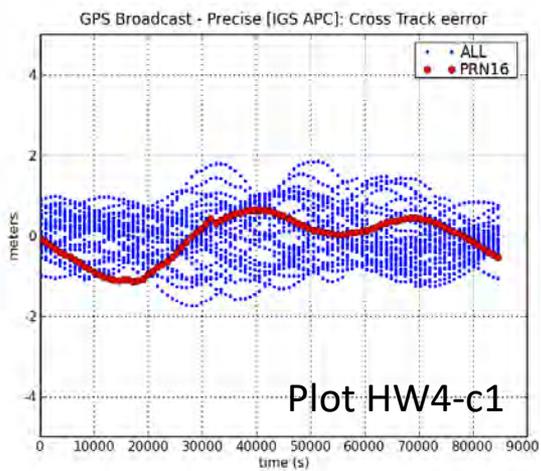
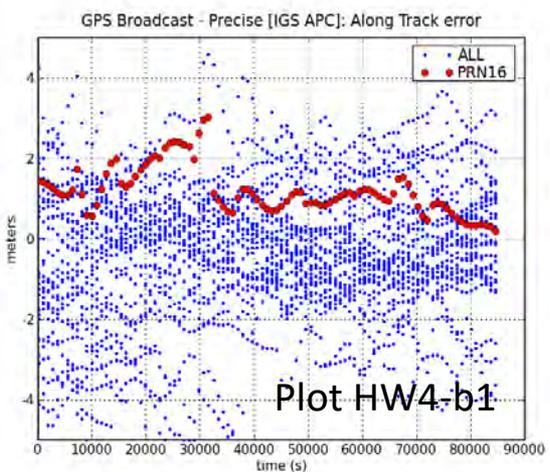
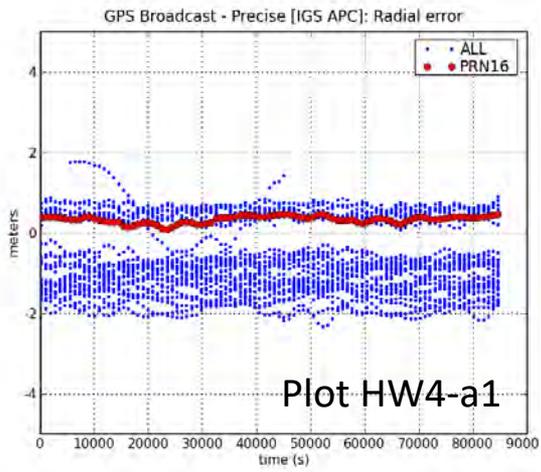
The IGS post-processed products are accurate at few cm level, thence they can be taken as the truth.

3. [Plot](#) `dif.out` file as in the first exercise.

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

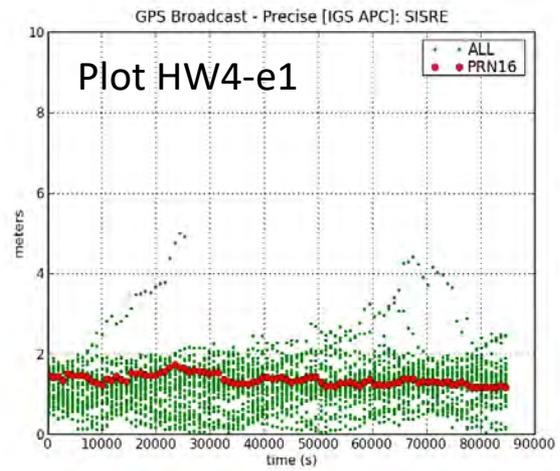
Field	Content
1	'SATDIFF'
2	Year
3	Doy (Days-of-Year)
4	Seconds of day (seconds)
5	GNSS System (GPS, GAL, GLO or GEO)
6	PRN satellite identifier
7	SISRE difference (meters)
8	SISRE orbit-only difference (meters)
9	3D orbit difference (meters)
10	<i>clkDiff</i> : Clock difference (meters)
11	<i>radDiff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

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

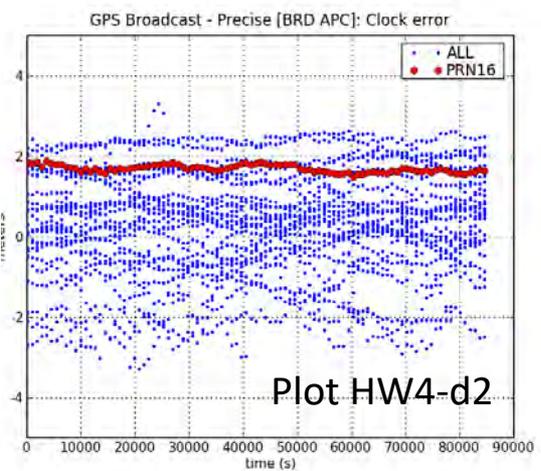
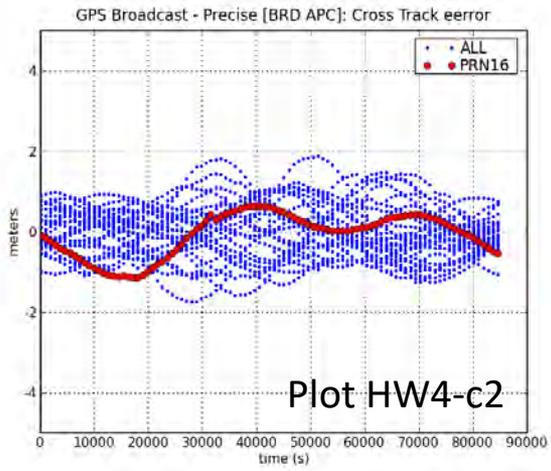
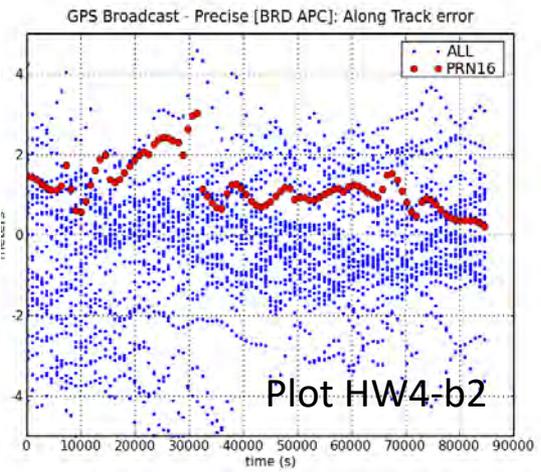
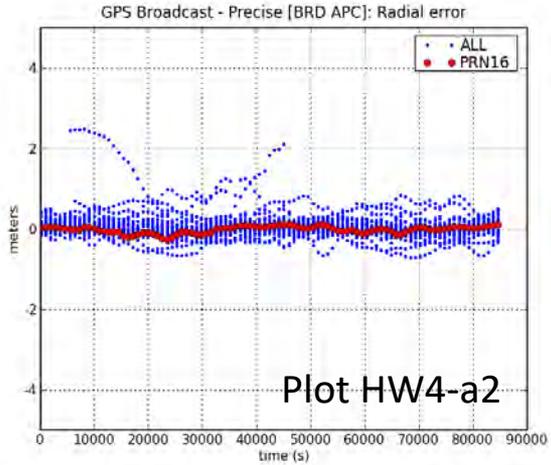


## Comments

- 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).

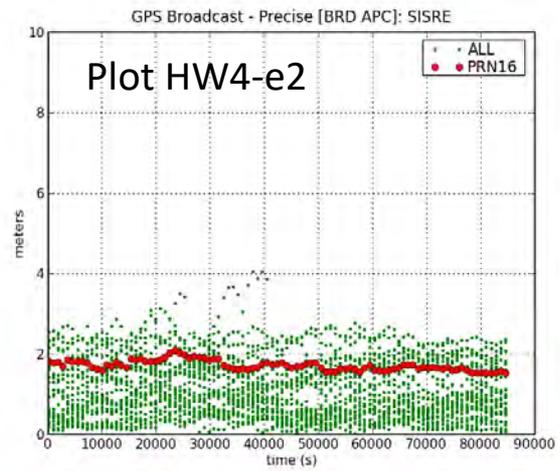


## Comments

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:

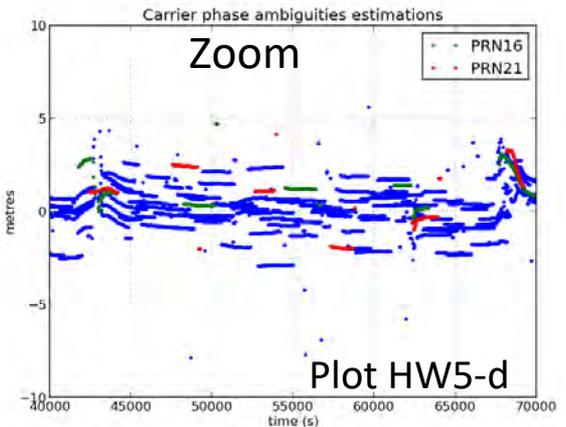
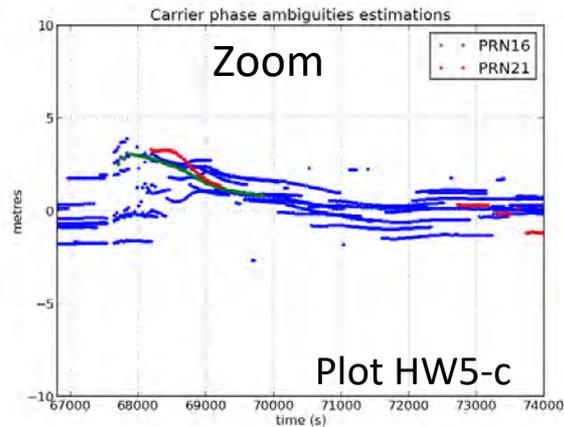
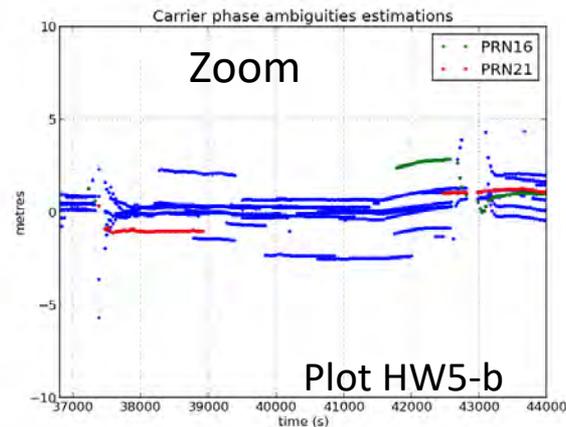
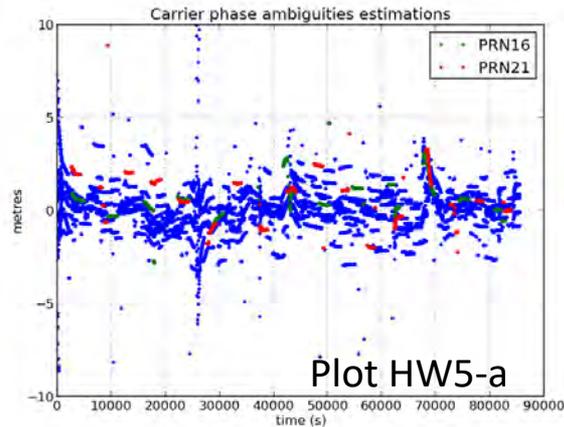
```
grep POSTFIT gLAB.out | gawk '{i=$6" "$4;a[i]=$13}END{for (i in a) print i,a[i]}' |sort -n > amb.out
```

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.

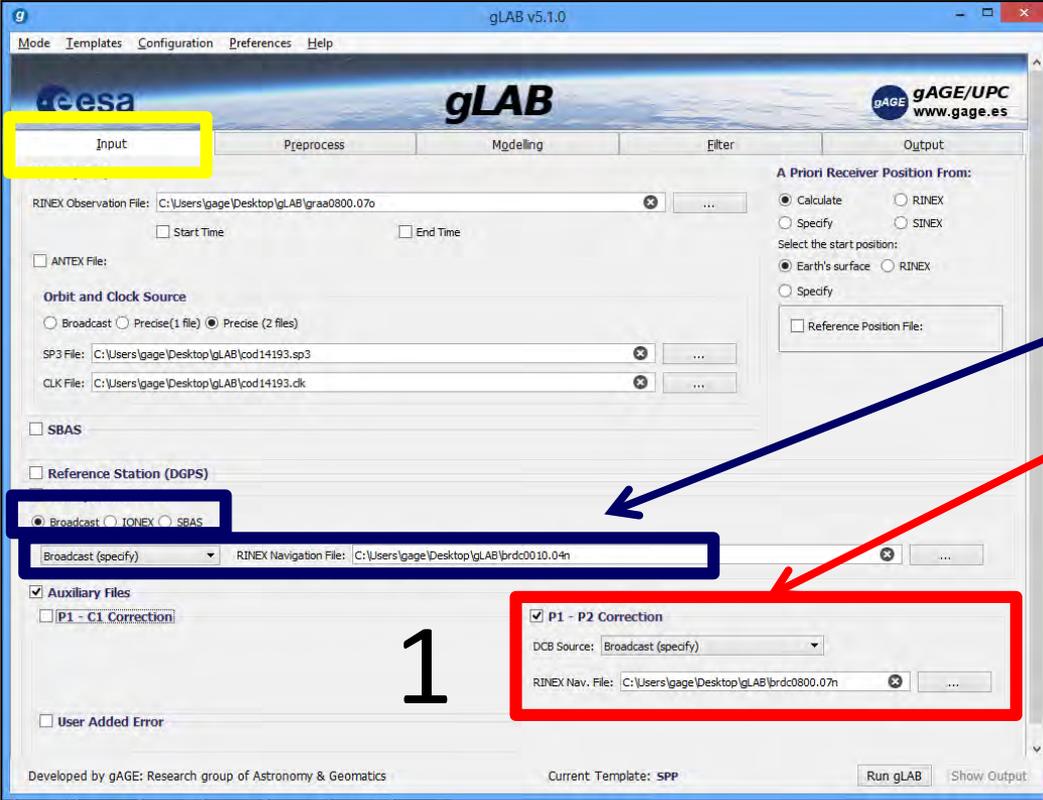


## Comments

- Large peaks appear in the carrier phase biases due to massive cycle-slips:
  - Satellite tracking losses happen periodically after each revolution.
  - These satellite losses 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.

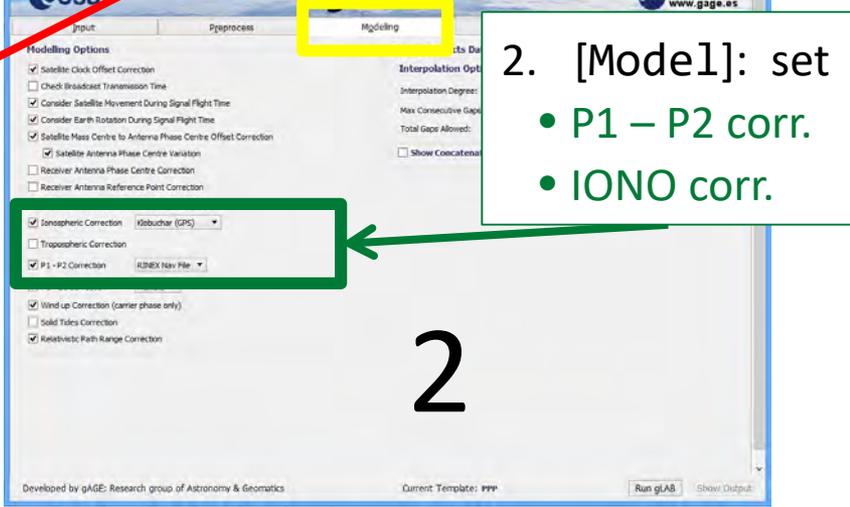
# HW6: Single freq. L1, C1 carrier and code with precise orbits & clocks using Klobuchar ionospheric corrections

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



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

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



- [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

**Single frequency**

**Set  $\sigma_{C1P}=1$  meter**  
**Set  $\sigma_{L1P}=0.01$  meters**

**Select files GRAA\_07\_080.sp3**  
**gLAB.sp3**

**Set dif.out as output file**

**Set plotting ranges [Xmin, Xmax] [Ymin, Ymax]**

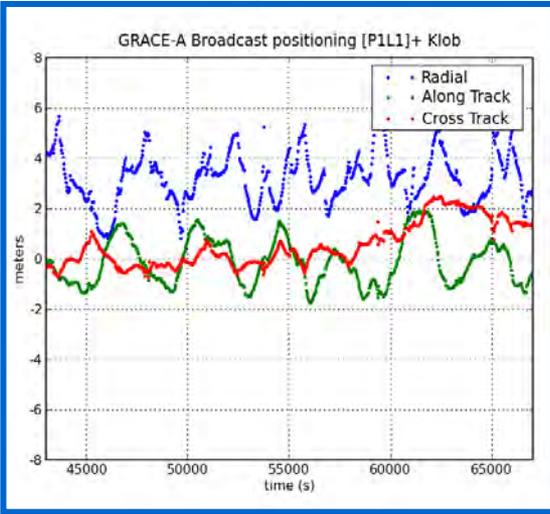
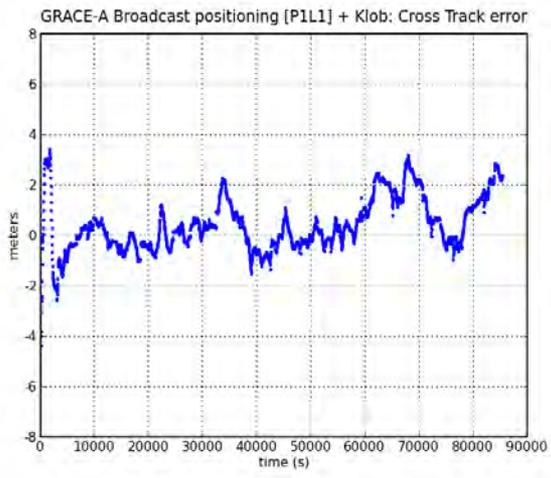
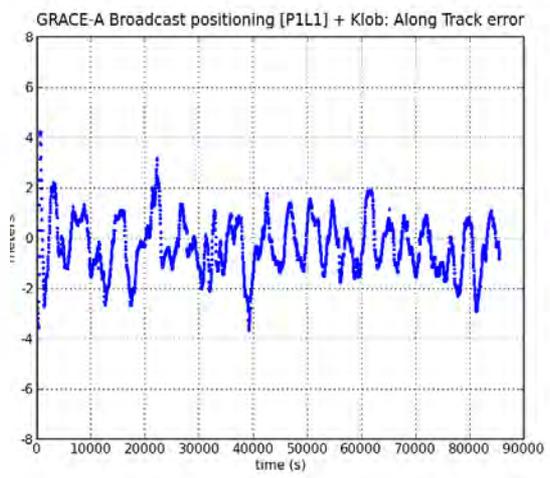
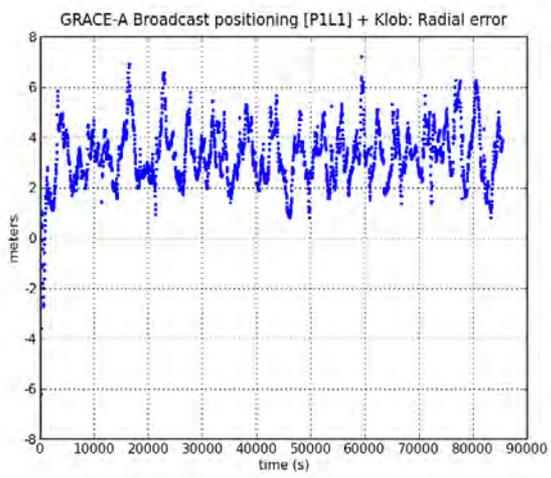
**Upload file dif.out in Plot 1, Plot 2 & Plot 3**

Annotations include: C1P, L1P, Run gLAB, and numbered steps 1-4.

- Complete the steps
3. [Filter]:
    - Single Frequency measurements:
    - L1P (L1 carrier)
    - C1P (P1 code)
  4. Compute differences with reference file GRAA\_07\_080.sp3

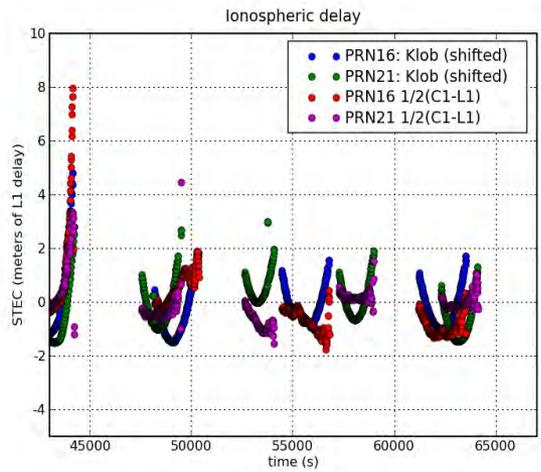
Make plots as before.

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



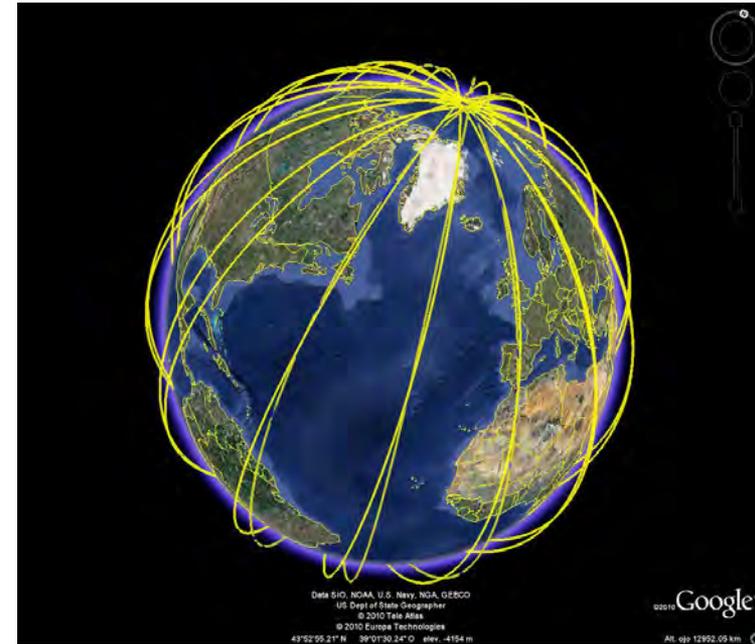
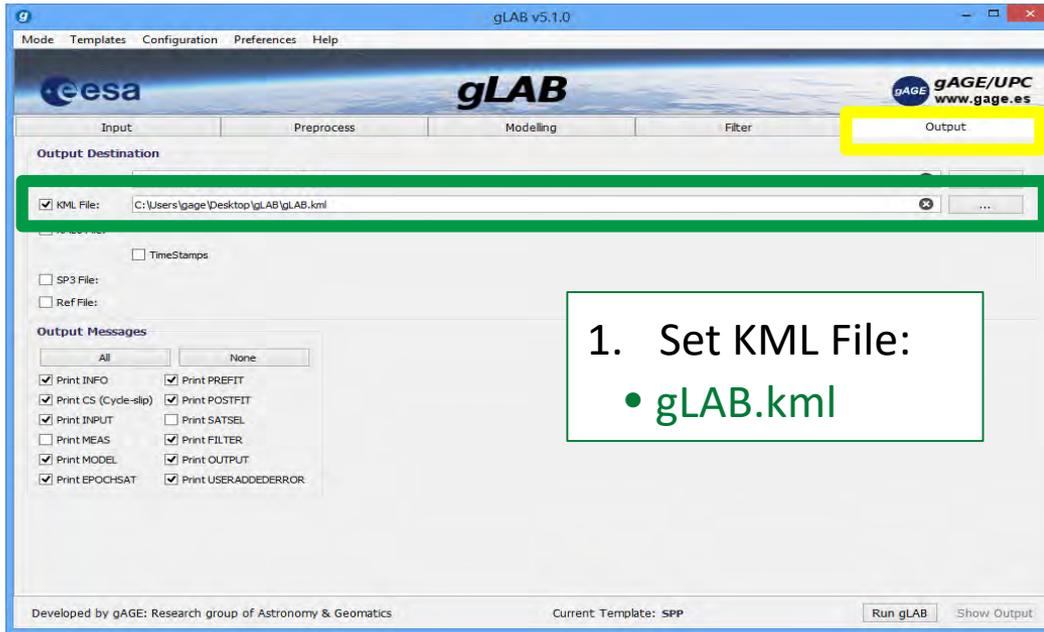
## Comments

- 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

## ★ Option A: GUI



## ★ Option B: Command Line

1. Add the header (Prefix.kml)
2. Select the satellite [longitude, latitude, height] coordinates of message OUTPUT in the gLAB.out file. Generate a file with these coordinates (comma-separated).
3. Add the tail (Postfix.kml) files to the previous track data file

```
cat Prefix.kml > grace_track.kml  
grep OUTPUT gLAB.out |gawk 'BEGIN{OFS=","} {print $16,$15,$17}' >> grace_track.kml  
cat Postfix.kml >> grace_track.kml
```

# Thanks for your attention

Other Tutorials are available at  
<http://www.gage.upc.edu>

The screenshot shows the website [www.gage.es/tutorials](http://www.gage.es/tutorials) in a browser window. The page is titled "GNSS Tutorials" and features a navigation menu on the left with categories like Personnel, Publications, Learning Material, Projects, and Patents. The main content area lists various tutorial resources, including "GNSS Course", "GNSS Data Processing: Theory Slides", "GNSS Data Processing: Laboratory Exercises", and "Associated Software and Data Files". To the right of the text, there are images of slide decks and CDROMs. On the far right, there is an "About us" section, "Shortcuts" (with "GNSS Course and associated Tutorials" highlighted in a red box), a "User login" form, and a "Who's online" status.

**GNSS Tutorials**

- GNSS Course (associated to the **GNSS Data Processing Book**)
  - About the course
  - GNSS Data Processing: Theory Slides (Full compendium)**
    - Lecture 0: Introduction
    - Lecture 1: GNSS measurements and their combinations
    - Lecture 2: Satellite orbits and clocks computation accuracy
    - Lecture 3: Position estimation with pseudorange
    - Lecture 4: Introduction to DGNSS
    - Lecture 5: Precise positioning with carrier phase (PPP)
    - Lecture 6: Differential positioning with code pseudorange
    - Lecture 7: Carrier based differential positioning, Ambiguity resolution techniques
  - GNSS Data Processing: Laboratory Exercises (Full compendium)**
    - Tutorial 0: UNIX environment, tools and skills. GNSS standard file formats [Format files description]
    - Tutorial 1: GNSS data processing laboratory exercises
    - Tutorial 2: Measurement analysis and error budget
    - Tutorial 3: Differential positioning with code measurements
    - Tutorial 4: Carrier ambiguity fixing
    - Tutorial 5: Analysis of propagation effects from GNSS observables based on laboratory exercises
    - Tutorial 6: Differential positioning and carrier ambiguity fixing
- Associated **Software and Data Files (Linux)**
  - CDROM zipped tar file. How to install the CDROM [Linux]
  - CDROM ISO. How to install the CDROM [Linux]
- Associated **Software and Data Files (Windows)**
  - Instalable Toolkit (gLAB + Cygwin)**
  - Data Files**
  - How to install the Software
- Bootable USB stick (Linux live)**
  - gAGE-GLUE** (to build-up a bootable USB stick). How to burn the gAGE-GLUE. **How to use the bootable USB stick.**
  - How to start-up the laboratory session.**
- Useful tools for Windows:** Windows users can install the next ports of Linux tools (instead of Cygwin) at [gnuwin32.sourceforge.net/packages.html](http://gnuwin32.sourceforge.net/packages.html):

# Acknowledgements

- The ESA/UPC GNSS-Lab Tool suit (gLAB) has been developed under the ESA Education Office contract N. P1081434.
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- 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).
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- To Deimos Ibáñez for his contribution to gLAB updating and making the Windows, Mac and LINUX installable versions for this tutorial.