Tutorial 6
Kinematic orbit estimation of a LEO satellite

Professors Dr. Jaume Sanz Subirana, Dr. J. M. Juan Zornoza
and **Dr. Adrià Rovira Garcia**

Research group of Astronomy & Geomatics (gAGE)
Universitat Politècnica de Catalunya (UPC)
Barcelona, Spain

gAGE/UPC
Research group of Astronomy & Geomatics
Technical University of Catalonia

Authorship statement

This material authorship and Intellectual Property Rights are owned by Jaume Sanz Subirana, José Miguel Juan Zornoza and Adrià Rovira Garcia.

These slides can be obtained either from the server `http://www.gage.upc.edu`, or `jaume.sanz@upc.edu`. Any partial reproduction should be previously authorized by the authors, clearly indicating the slides reference.
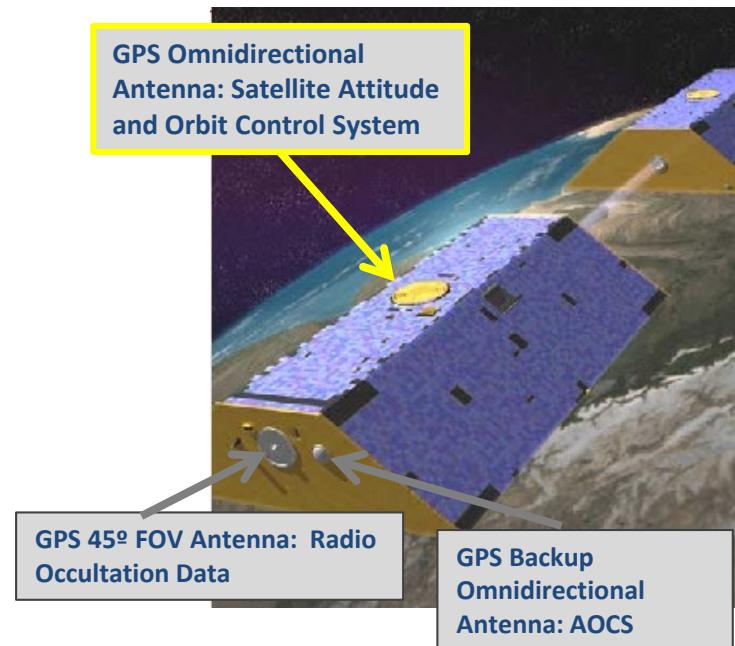
This authorship statement must be keep untouched at all times.

August 2022

2

Kinematic positioning of a LEO satellite

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

GRACE SATELLITES (A & B)

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

GPS Omnidirectional Antenna: Satellite Attitude and Orbit Control System

GPS 45º FOV Antenna: Radio Occultation Data

GPS Backup Omnidirectional Antenna: AOCS
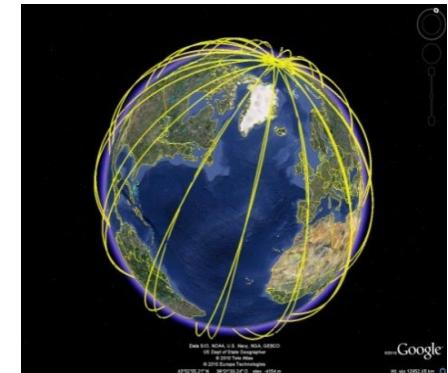
More details at: `http://op.gfz-potsdam.de/grace/index_GRACE.html`

gAGE/UPC
Research group of Astronomy & Geomatics
Technical University of Catalonia

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?
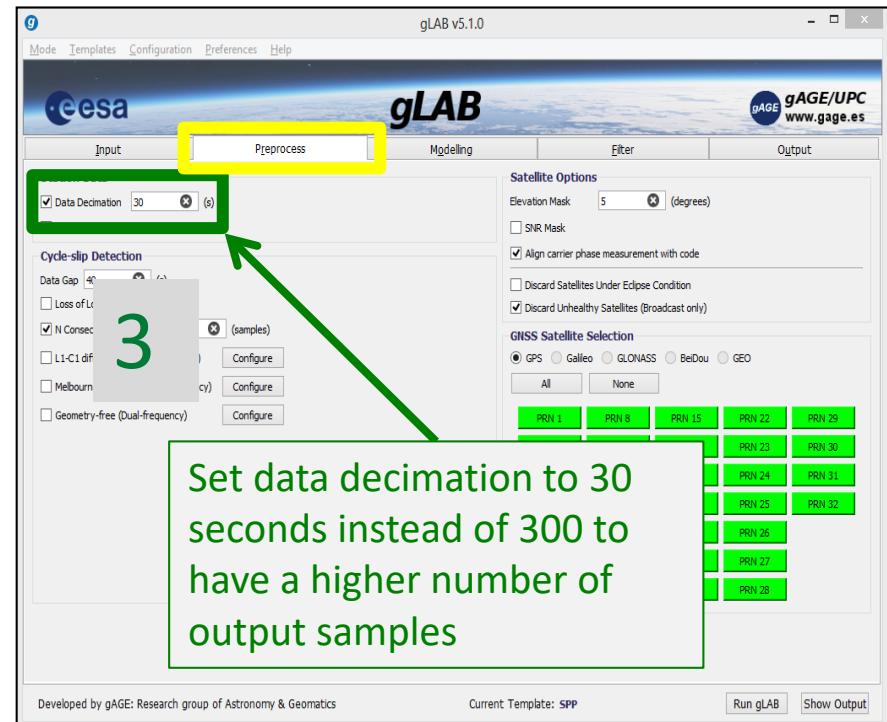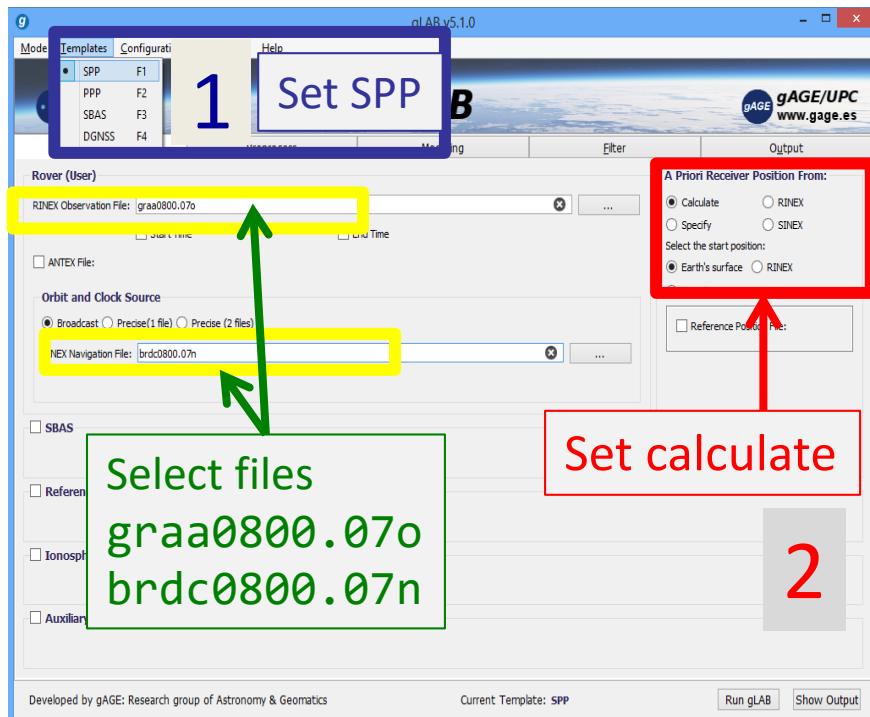
Kinematic positioning of a LEO satellite

⤷ **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`

Mode1: Single frequency C1 code with broadcast orbits & clocks

Example of computation with gLAB:

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

Set SPP

Select files
graa0800.07o
brdc0800.07n

Set calculate

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

gAGE/UPC
Research group of Astronomy & Geomatics
Technical University of Catalonia

Mode1: Single frequency C1 code with broadcast orbits & clocks

Example of computation with gLAB:

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


From SPP template disable:
- Ionospheric
- Tropospheric

Set output SP3 file as
gLAB.sp3

Disable all messages except:
- Print INFO Messages
- Print OUTPUT Messages
  to avoid big output files

Run gLAB
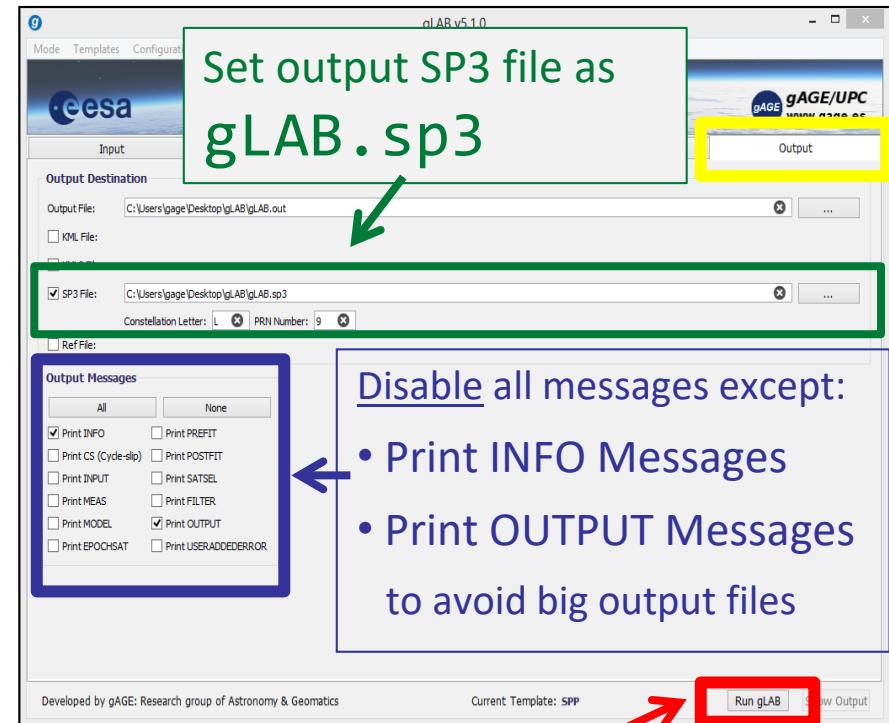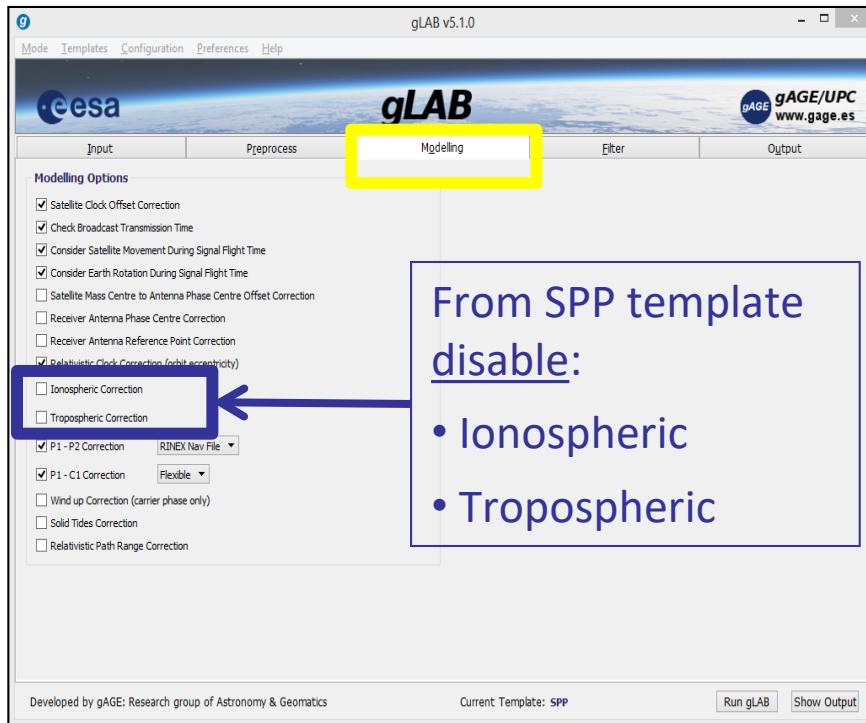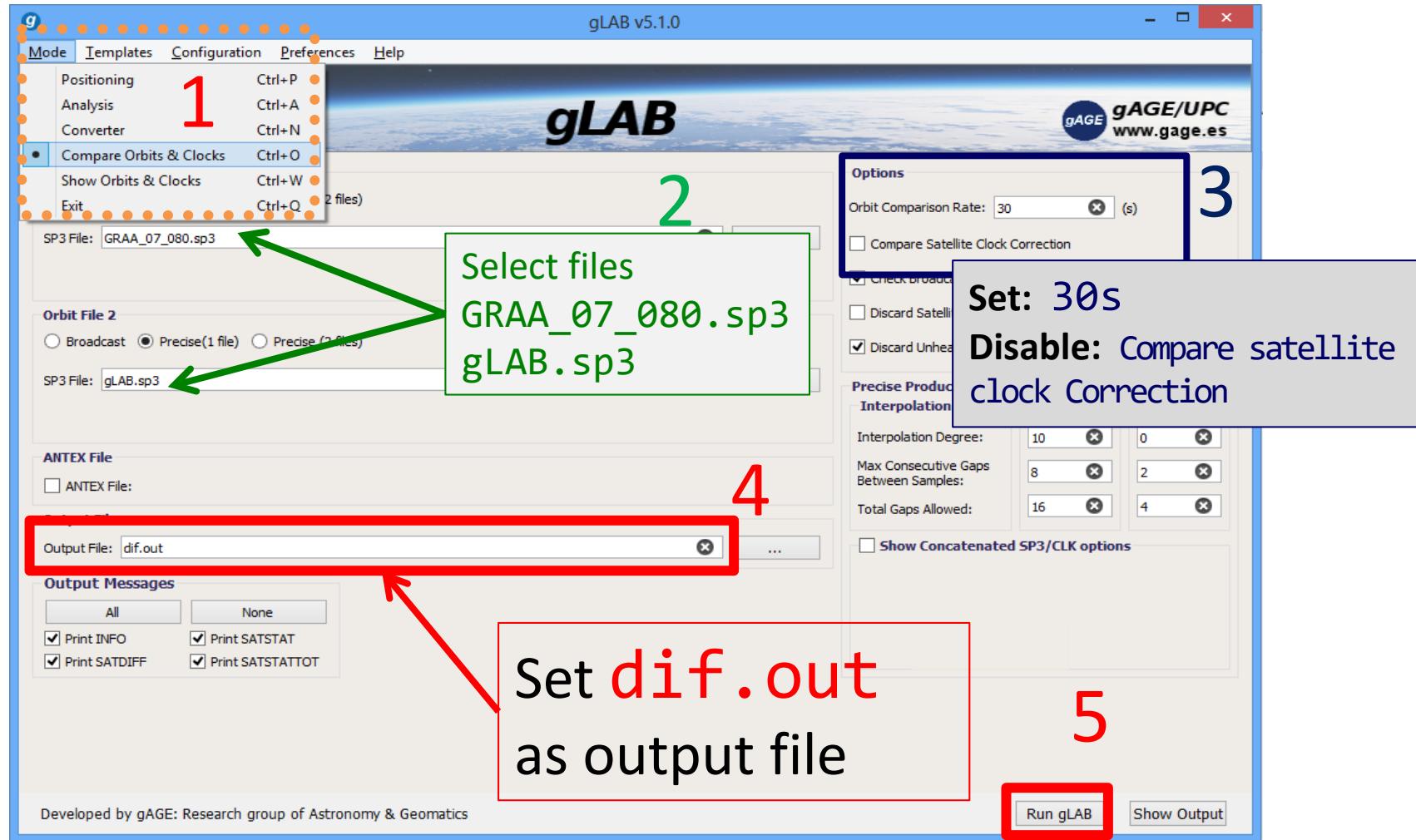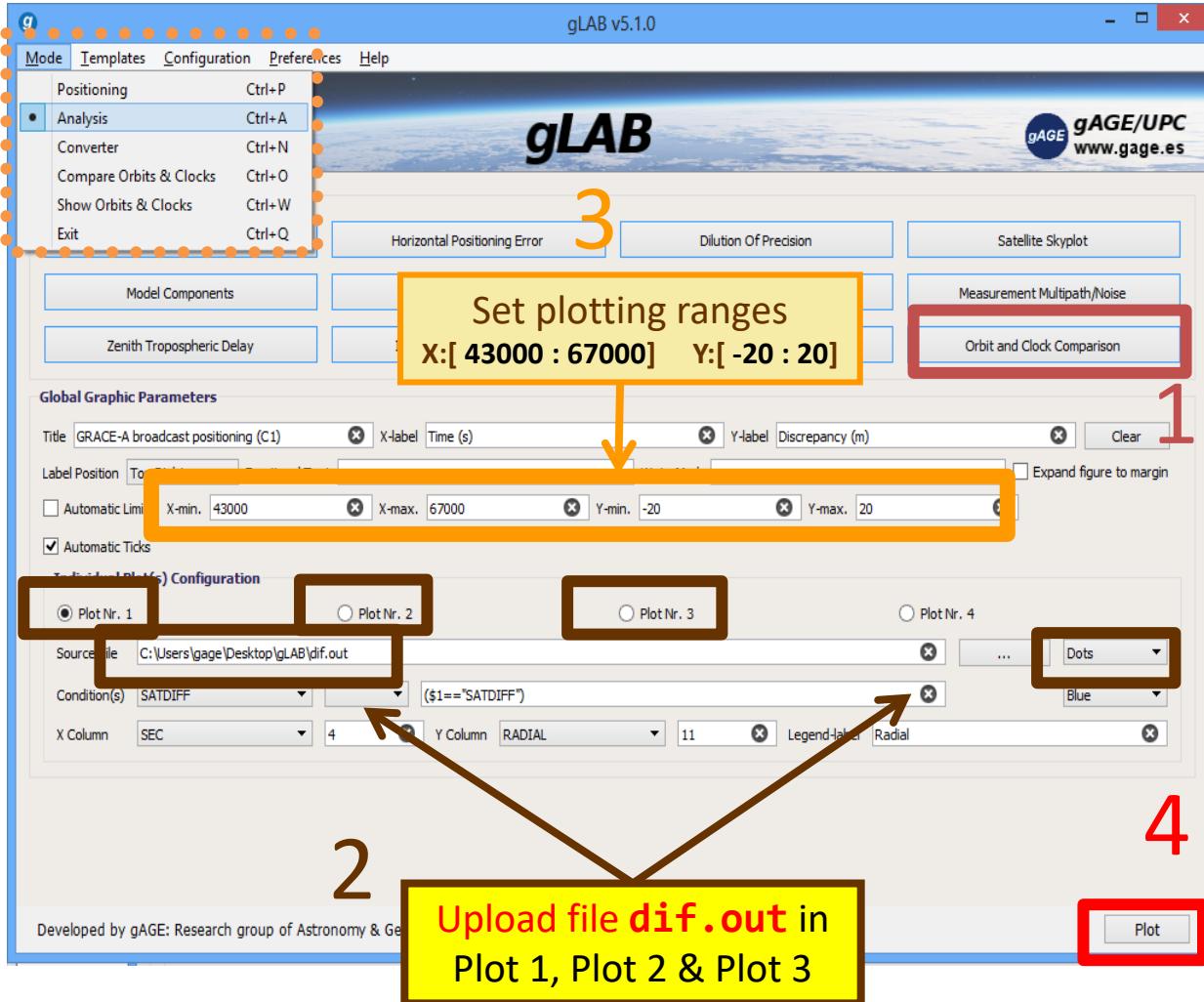
Mode1: Single frequency C1 code with broadcast orbits & clocks
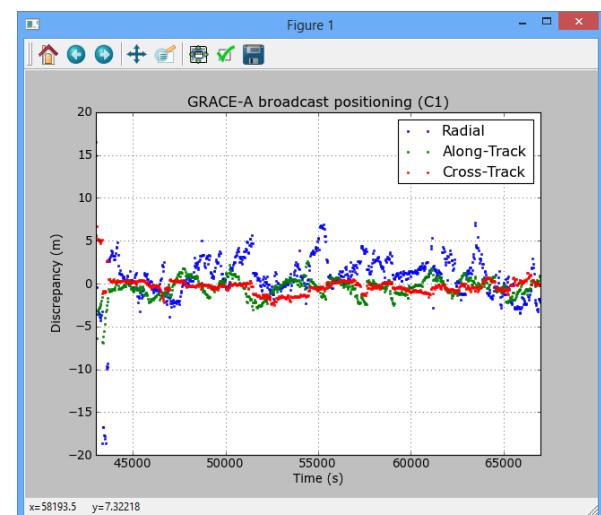
- Accuracy assessment of the computed solution (from **gLAB.sp3** file) with the reference coordinates of file **GRAA_07_080.sp3**:

Select files
GRAA_07_080.sp3
gLAB.sp3

Set: 30s
Disable: Compare satellite clock Correction

Set dif.out as output file
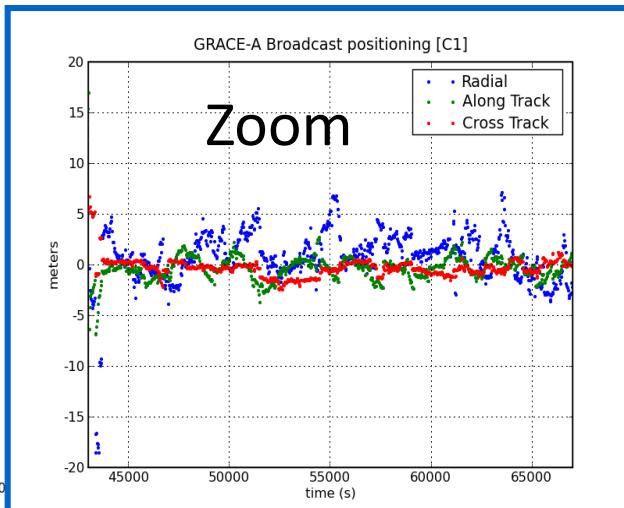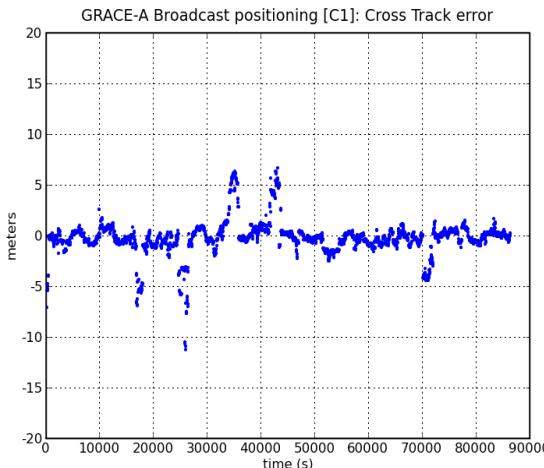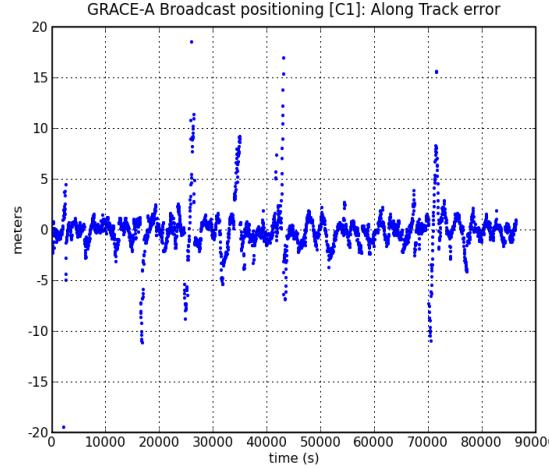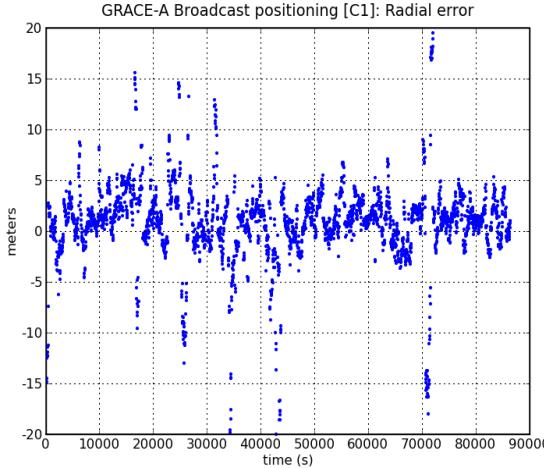
Mode1: Single frequency C1 code with broadcast orbits & clocks

Plotting **dif.out** with the GUI

Research group of Astronomy & Geomatics
Technical University of Catalonia

Mode1: Single frequency C1 code with broadcast orbits & clocks

GRACE-A Broadcast positioning [C1]: Radial error

GRACE-A Broadcast positioning [C1]: Along Track error

GRACE-A Broadcast positioning [C1]: Cross Track error

Zoom
GRACE-A Broadcast positioning [C1]
Radial · Along Track · Cross Track

Questions

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

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

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

Mode1: Single frequency C1 code with broadcast orbits & clocks

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

– Troposphere:

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

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

– Ionosphere:

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

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

⬥ **Homework:**

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

Mode1: Single frequency C1 code with broadcast orbits & clocks

⚐ **Answer to Question 2:**
In this approach, is it necessary to introduce an additional model term to account for the relativity effect on LEO satellite?

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

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

⚐ **Answer to Question 3:**
What could be the reason for the large error peaks seen in the plots?

- The large error peaks are associated to bad GPS-LEO satellite geometries and mismodelling. Notice that the satellite is moving at about 8 km/s and therefore the geometry changes quickly *(see HW2)*. Also, the geometry is particularly poor when GRACE-A satellite is over poles.
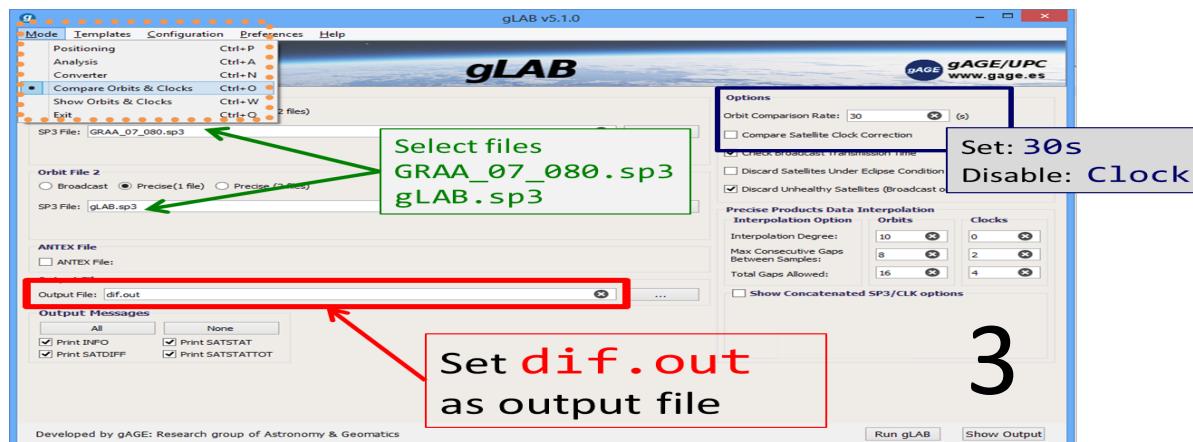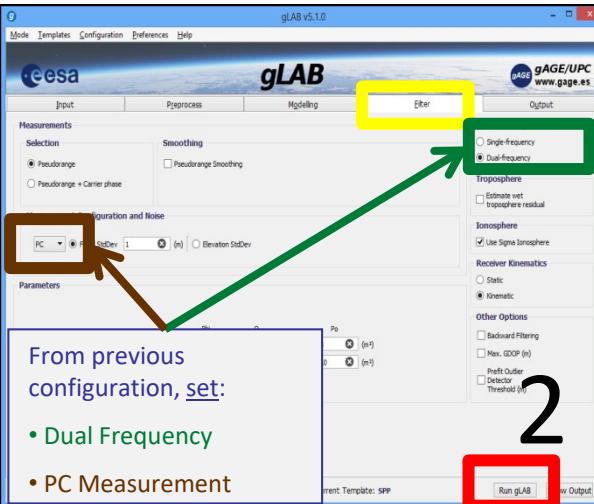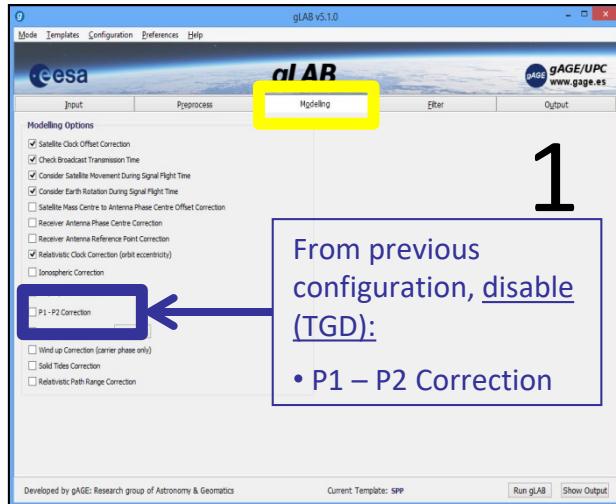
⚐ **Homework:**
- ⚐ **HW2:** Plot in the same graph the "True 3D error", the "Formal 3D error" (i.e, the 3D-sigma) and the number of satellites used. Analyze the evolution of the error.

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

Example of computation with gLAB:
Code positioning + broadcast orbits: Dual frequency: PC code combination.

1

From previous configuration, disable (TGD):
• P1 – P2 Correction

2

From previous configuration, set:
• Dual Frequency
• PC Measurement

3

Select files
GRAA_07_080.sp3
gLAB.sp3

Set: 30s
Disable: Clock

Set dif.out as output file

---
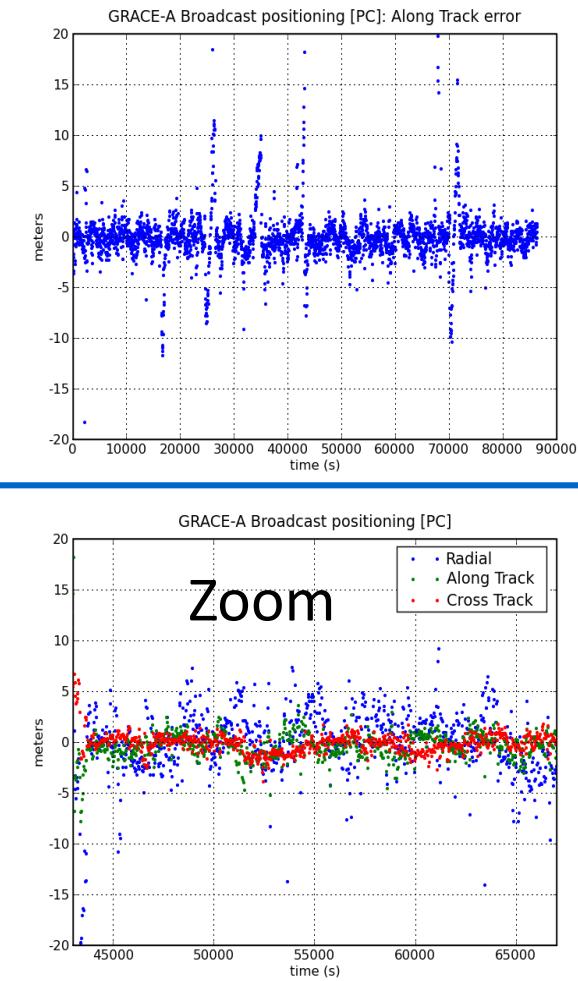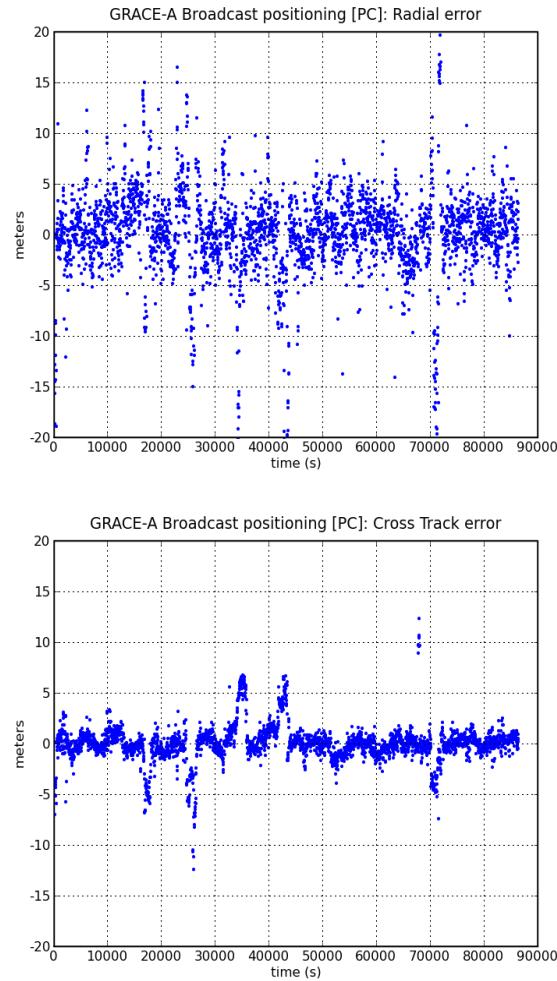
Complete the steps (from previous configuration):

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

---

gAGE/UPC
Research group of Astronomy & Geomatics
Technical University of Catalonia

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

GRACE-A Broadcast positioning [PC]: Radial error

GRACE-A Broadcast positioning [PC]: Along Track error

GRACE-A Broadcast positioning [PC]: Cross Track error

GRACE-A Broadcast positioning [PC]

Zoom

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

GRACE-A Broadcast positioning [PC]: Radial error

GRACE-A Broadcast positioning [PC]: Along Track error

GRACE-A Broadcast positioning [PC]: Cross Track error

GRACE-A Broadcast positioning [PC]

Zoom

Plotting

- Make the same plots as in the previous case.

Questions

4. Why is the solution noisier than the previous one with C1 code?

5. Discuss the pros and cons of the ionosphere-free combination of codes (PC), compared with C1 code.

6. How could the performance be improved?

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

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

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

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

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

- **Answer to Question 6:**
  How could the performance be improved?
  - Smoothing the code with the carrier and/or using precise orbits and clock products as well.
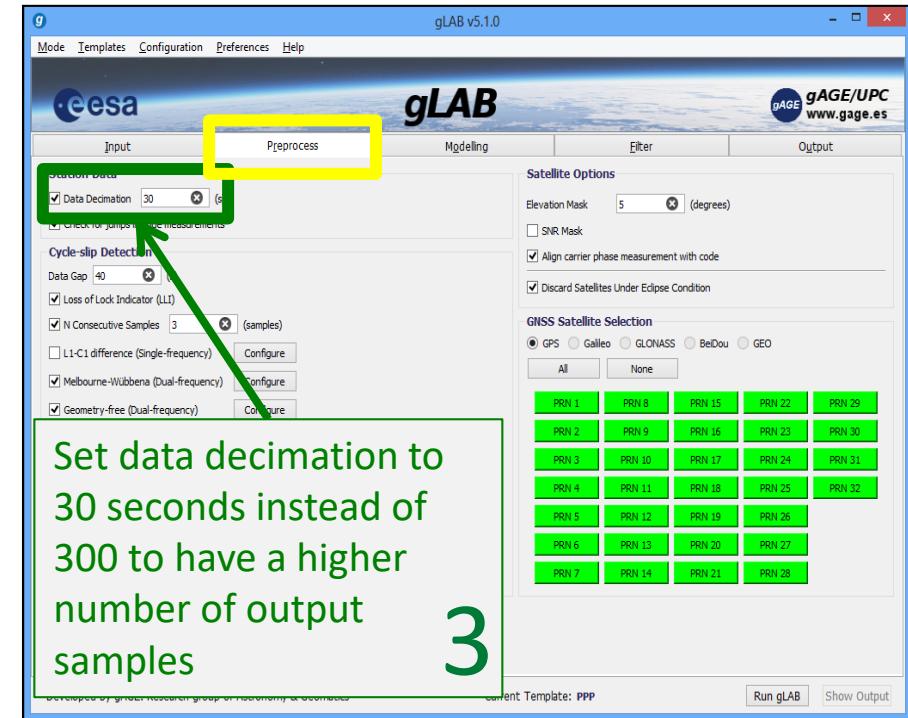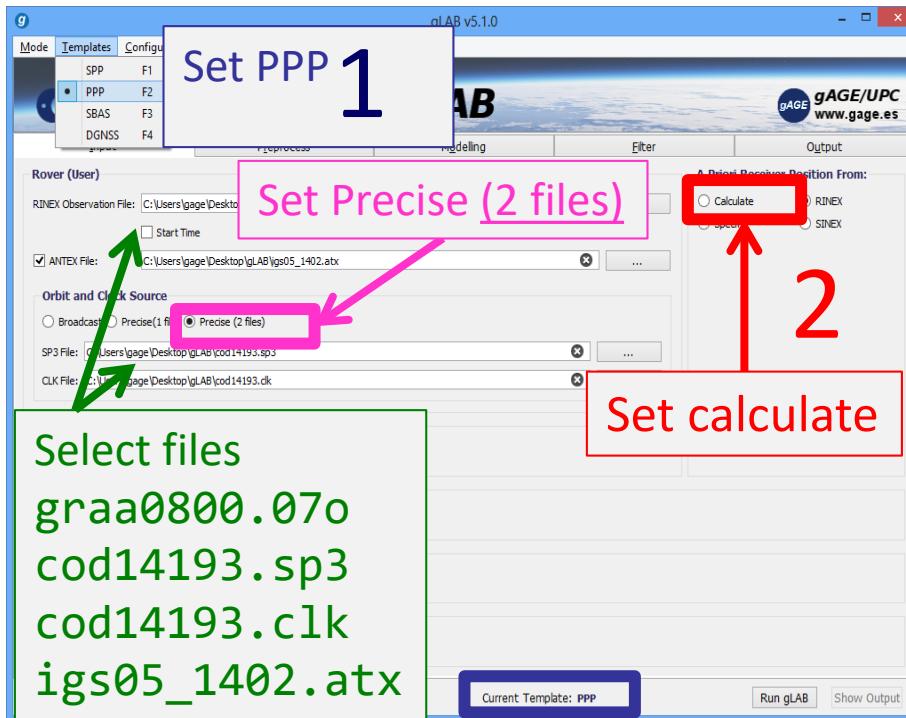
- **Homework:**
  - **HW3:** Assess the measurement noise on the C1, P1, P2 and PC code measurements.

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

Example of computation with gLAB:
Code & Carrier + precise orbits & clocks: Dual frequency (LC, PC)

Set PPP **1**

Set Precise (2 files)

2

Set calculate

Select files
graa0800.07o
cod14193.sp3
cod14193.clk
igs05_1402.atx

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

3

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

gAGE/UPC
Research group of Astronomy & Geomatics
Technical University of Catalonia

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**

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 **dif.out** as output file

Set: 30s
Disable: Clock

2

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

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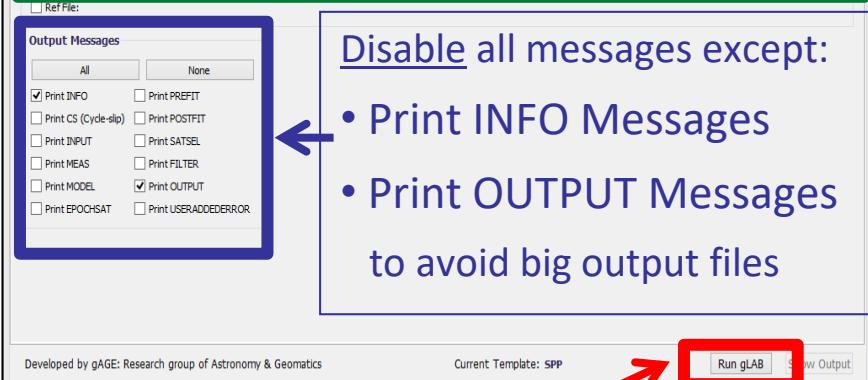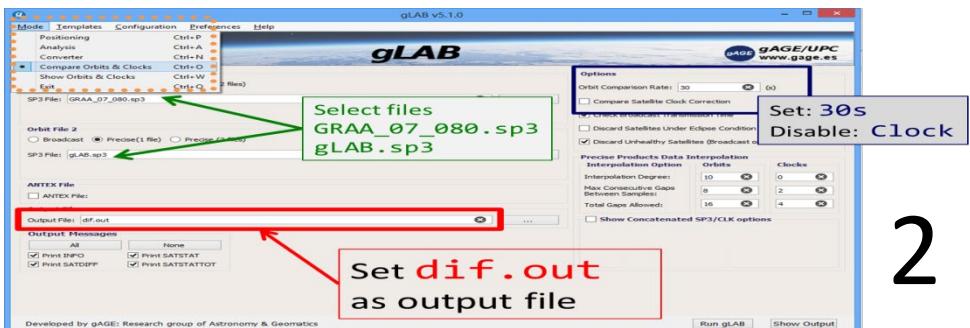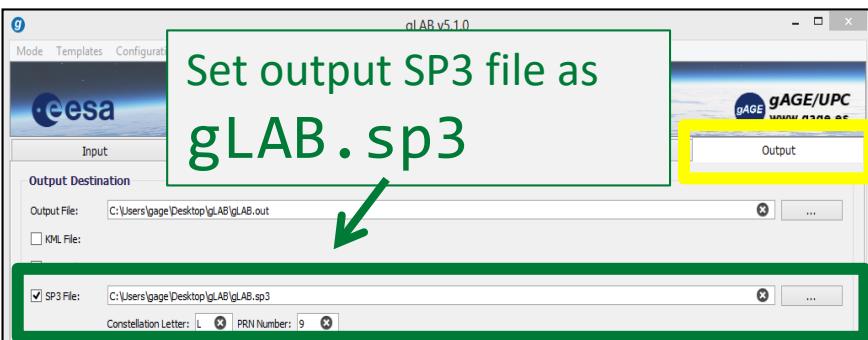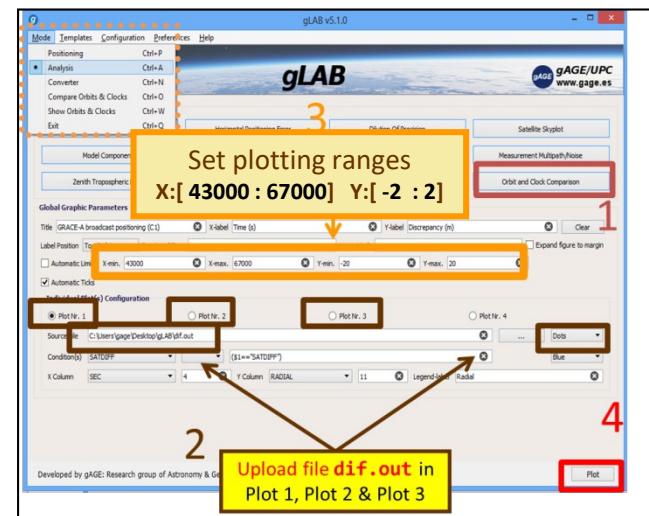
1. Run gLAB

2. Generate dif.out file

3. Make plots as before

gAGE/UPC
Research group of Astronomy & Geomatics
Technical University of Catalonia

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

GRACE-A Broadcast positioning [LCPC]: Radial error

GRACE-A Broadcast positioning [LCPC]: Along Track error

GRACE-A Broadcast positioning [LCPC]: Cross Track error

Zoom

Orbits and Clock Comparison

- Radial
- Along-Track
- Cross-Track

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.

• <u>Homework:</u>

⋏ **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).

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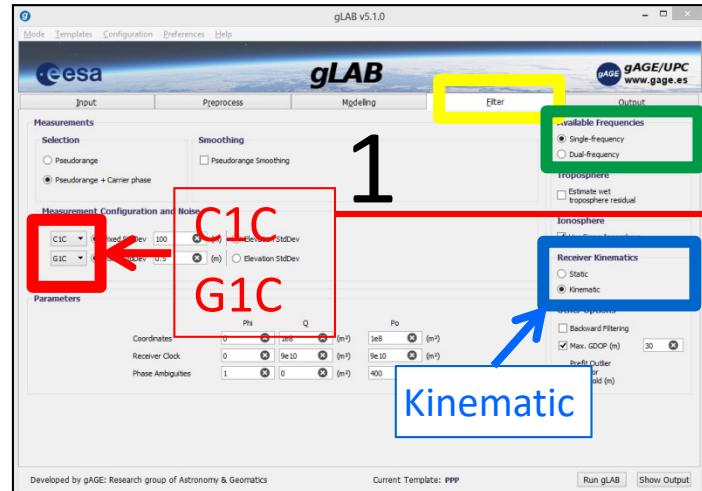
✠ **Answer to Question 11:**
Why do wind-up and GPS satellite antenna phase center offset corrections have to be applied? What about the solid tides correction?

- **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)
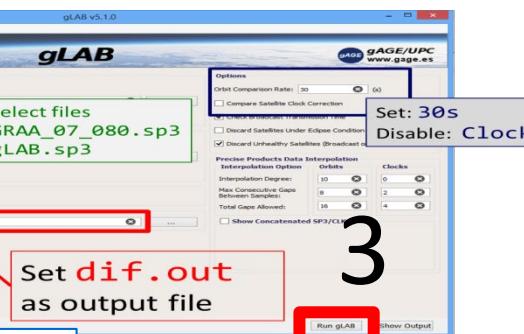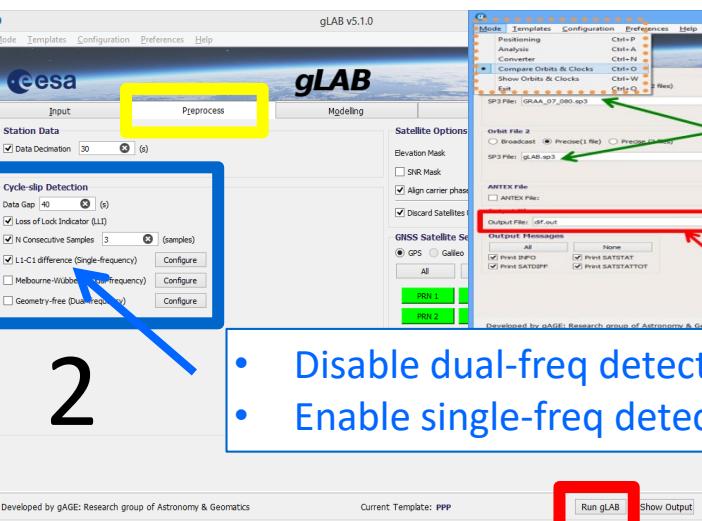
Single frequency

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

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

C1C
G1C

Kinematic

1

Disable dual-freq detectors
Enable single-freq detector

2

Select files
GRAA_07_080.sp3
gLAB.sp3

Set dif.out as output file

Set: 30s
Disable: Clock

3

http://www.gage.upc.edu
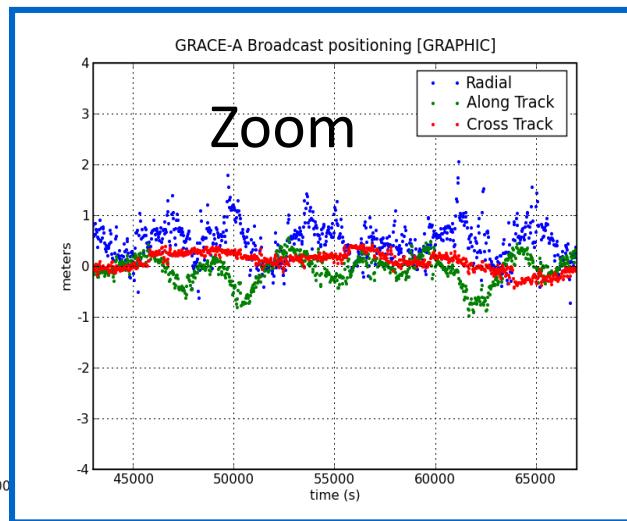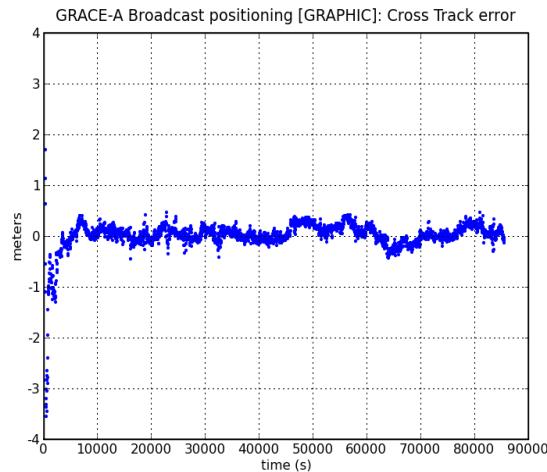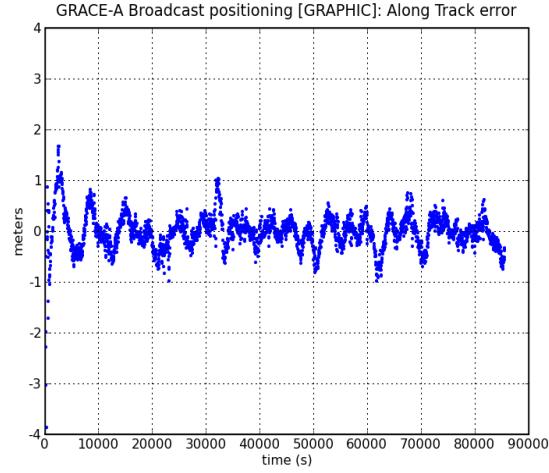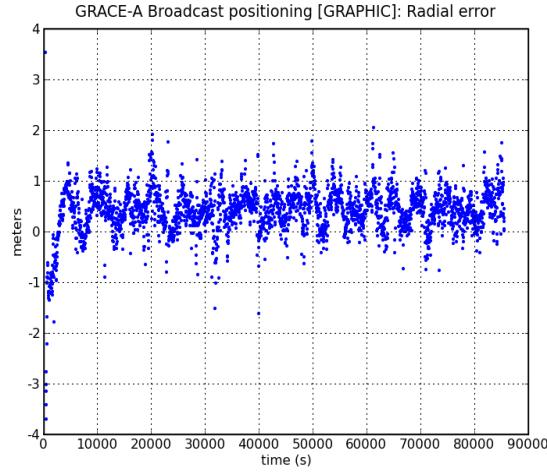
Complete the steps
(from PPP configuration mode):

1. [Filter]:
   - Single Frequency
   - C1C (C1 code [*])
   - G1C (GRAPHIC)
   - Set Kinematic Mode

2. [Model]:
   - Disable P1 – P2 Corr.

3. [Output]:
   - Set gLAB.sp3 format file.

4. [Preprocess]:
   - Unable MW, GF detectors
   - Enable L1-C1 detector

5. Run gLAB

6. <u>In Compare Orbits & Clocks</u>:
   - Compute differences with ref. file GRAA_07_080.sp3

<u>Make plots</u> as before.

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

GRACE-A Broadcast positioning [GRAPHIC]: Radial error

GRACE-A Broadcast positioning [GRAPHIC]: Along Track error

GRACE-A Broadcast positioning [GRAPHIC]: Cross Track error

GRACE-A Broadcast positioning [GRAPHIC]

Zoom

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: $G = \dfrac{1}{2}\left(P_1 + L_1\right)$

– Thence, since the ionospheric refraction has opposite sign in code P_1 and carrier L_1, GRAPHIC removes the ionospheric error.
– On the other hand the code noise is reduced by a factor 2 (i.e., $\sigma_G = 1/2\,\sigma$).
– However, this is an ambiguous measurement due to the unknown carrier phase bias.
– Note: Due to the gLAB filter design, a code measurement must also be provided to the filter along with the GRAPHIC one. Nevertheless, a large sigma noise is set to this code in order to downweight this measurement in the filter (in this way the solution will be driven by the GRAPHIC combination).

⅄ **Answer to Question 13:**
Why is the solution noisier than the previous one with LC, PC?

– Unlike the previous case (where carrier phase data with few millimetres of error were provided), now the most accurate measure provided to the filter is the GRAPHIC combination with tens of centimetres of error.

⅄ **Answer to Question 14:** Let's see the next two exercises.
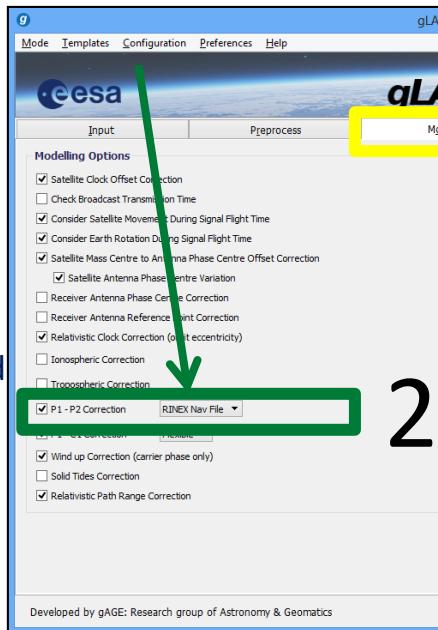
Mode 5. Single freq. L1, C1 carrier and code with precise orbits & clocks

Example of computation with gLAB:

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

From previous configuration, complete the following steps:
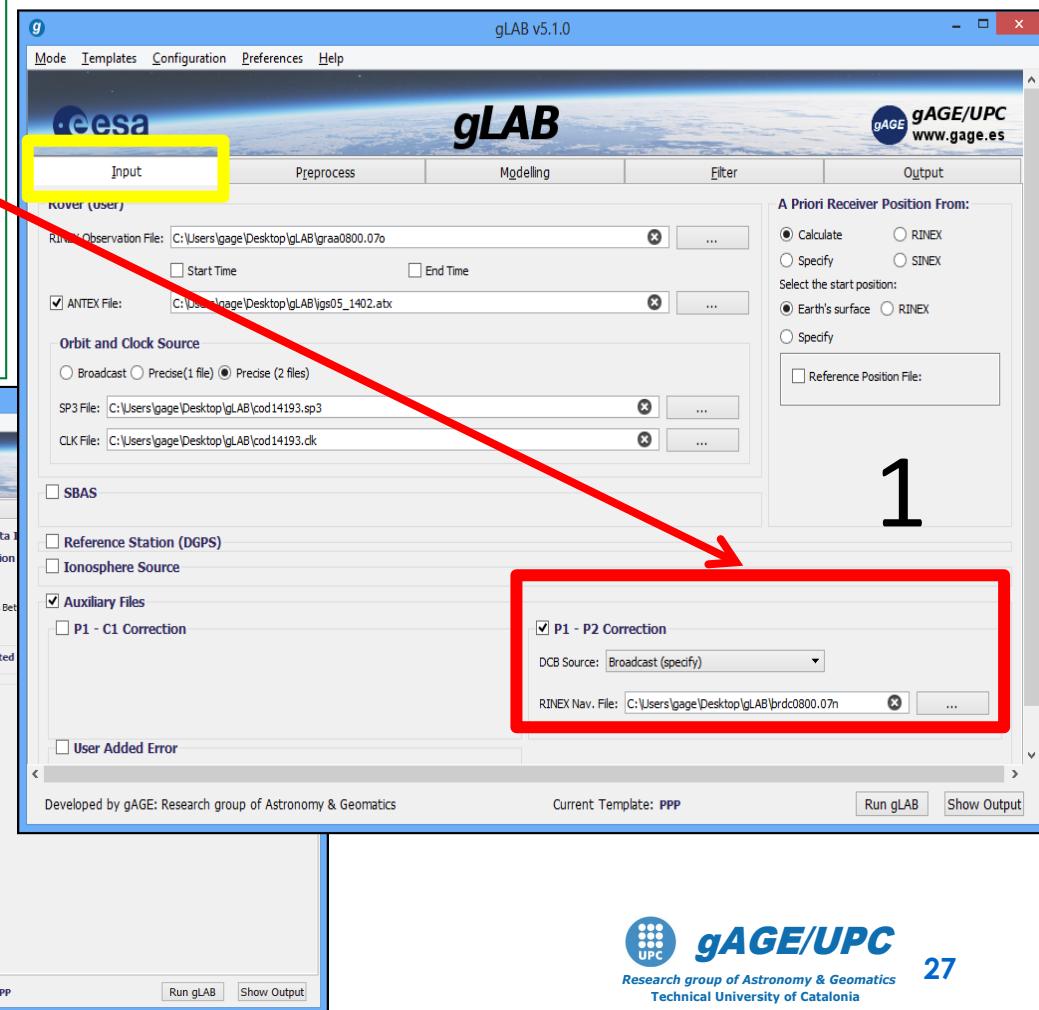
1. **[Input]**: Upload the `brdc0800.07n` file in the P1-P2 correction.

   Select DCB source: Broadcast (specify)

2. **[Model]**: Set **P1-P2 correction**, select RINEX Navigation as **DCB File**.

Note:

TGDs (i.e, P1-P2 DCBs) are needed for single-frequency positioning.
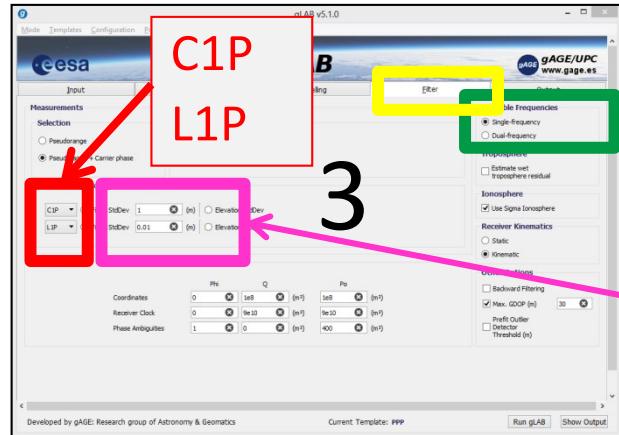
Research group of Astronomy & Geomatics
Technical University of Catalonia

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)

Single frequency

C1P
L1P

3

Set

σ_{C1P}=1 meter

σ_{L1P}=0.01 meters

4

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

5

Set **dif.out**
as output file

Select files
GRAA_07_080.sp3
gLAB.sp3

Set: **30s**
Disable: **Clock**

http://www.gage.upc.edu
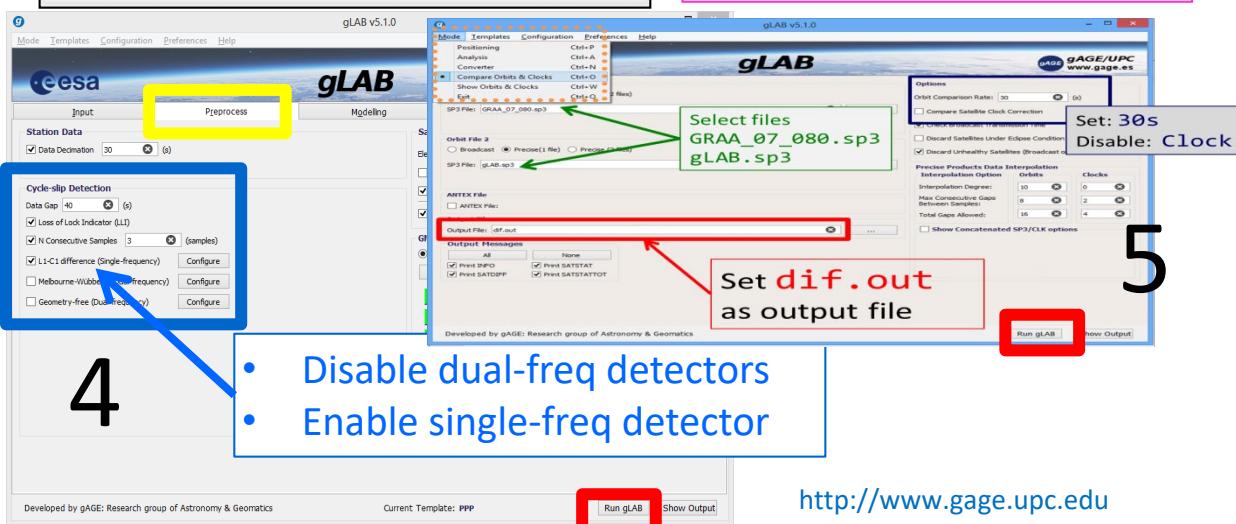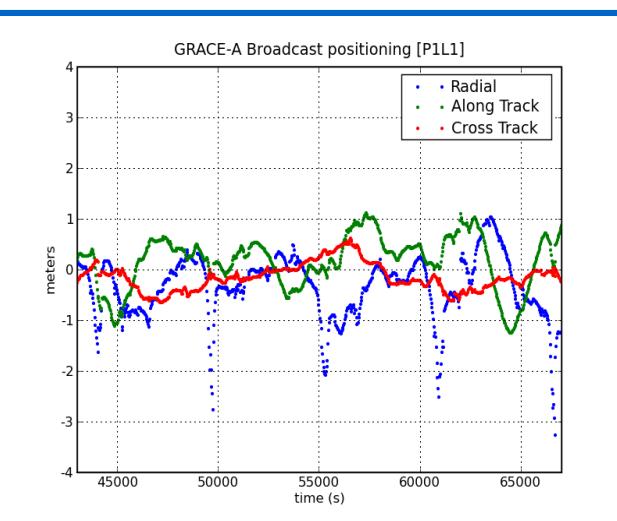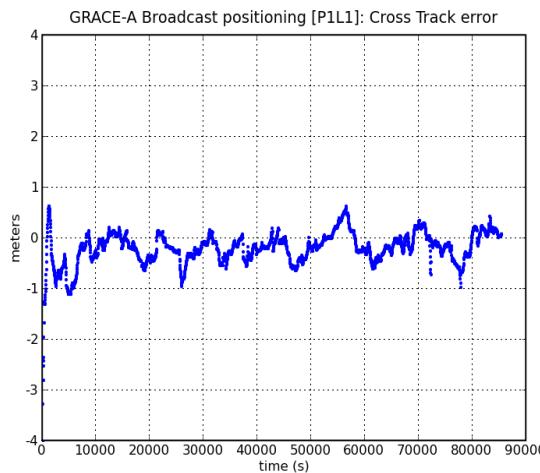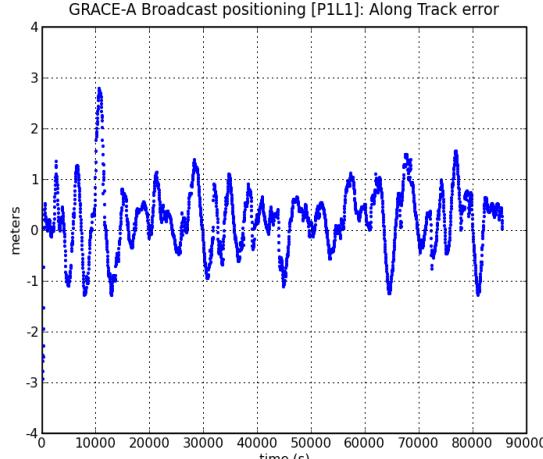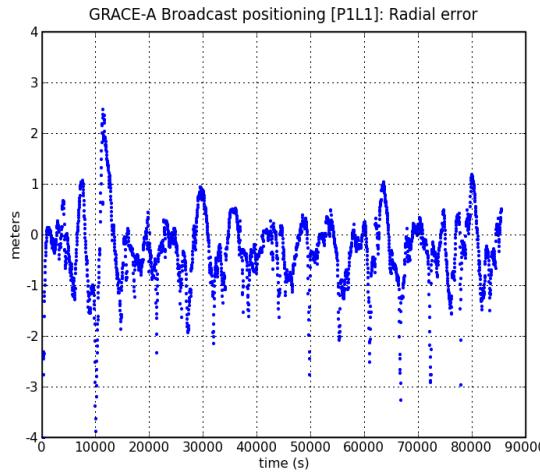
Complete the steps

3. [Filter]:
   • Single Frequency measurements
   • L1P (L1 carrier)
   • C1P (P1 code)
4. [Output]:
   • Set gLAB.sp3 format file.
5. [Preprocess]:
   • Unable MW, GF detectors
   • Enable L1-C1 detector
6. 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

GRACE-A Broadcast positioning [P1L1]: Radial error

GRACE-A Broadcast positioning [P1L1]: Along Track error

GRACE-A Broadcast positioning [P1L1]: Cross Track error

GRACE-A Broadcast positioning [P1L1]

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?

gAGE/UPC

Research group of Astronomy & Geomatics
Technical University of Catalonia

⚓ **Answer to Question 15:**
Explain why the solution has a more defined pattern, with large oscillations.

– This effect is due to the error introduced by the ionosphere and the broadcast differential code biases inaccuracy.

⚓ **Answer to Question 16:**
No ionospheric corrections have been applied in this run. What would happen if the Klobuchar model is applied?

– In general, the performance will degrade. As commented before, the correction from Klobuchar model is tuned for ground receivers, only removes about the 50% of ionospheric delay, and its usage can produce more harm than benefit. *(see HW6)*.

⚓ **Homework:**

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

Google earth

Homework help and answers

gAGE/UPC
Research group of Astronomy & Geomatics
Technical University of Catalonia
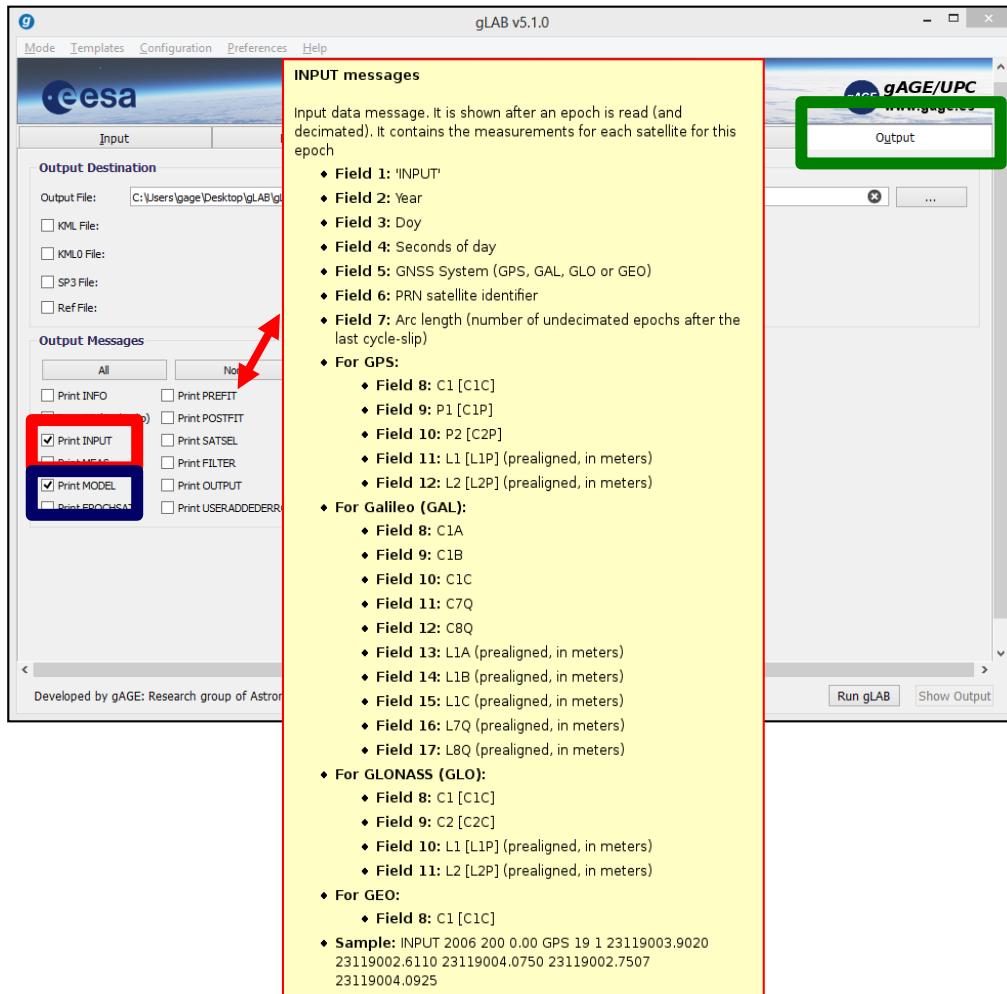
Proposed Homework exercises

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

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

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

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

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

Proposed Homework exercises

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

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

HW1: Assessing the ionospheric delay on the GRACE-A satellite
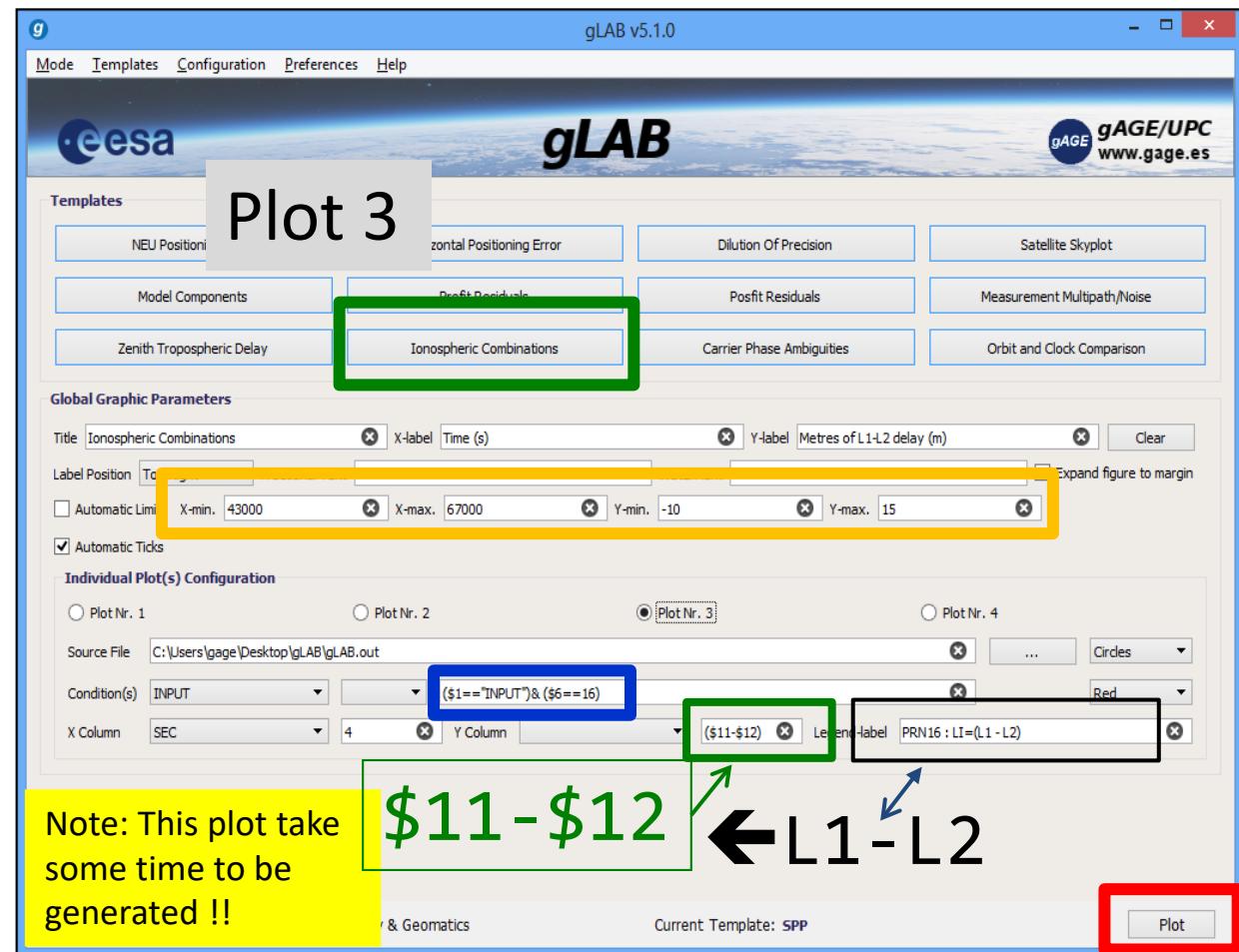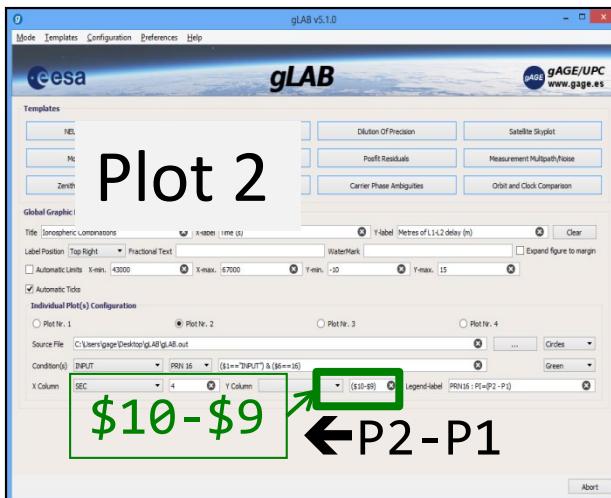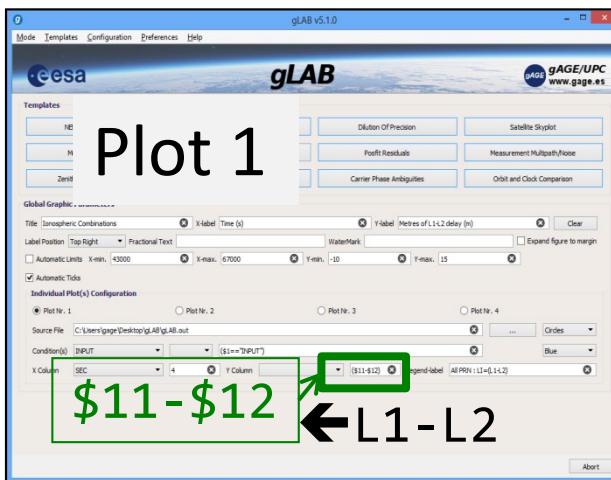
Configure gLAB as in <u>Mode 1</u> and complete the following steps:

1. [Output]: set
    • Print INPUT Message
    • Print MODEL Message
    (see message content in the Tooltips)

2. <u>Run</u> gLAB.

3. Make plots:
    [Analysis] section:
    • <u>Click</u> on the preconfigured Ionospheric combinations option.
    • <u>Complete</u> the [Plot1, Plot2, Plot3] panels configuration as indicated in the next slide.
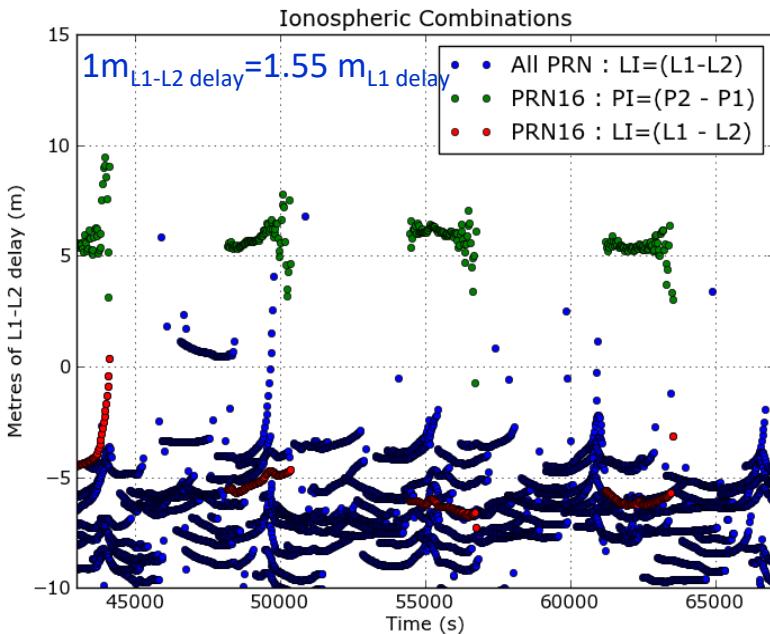
<u>Note</u>: This configuration will provide:
Plot 1: L1-L2 as a function of time for ALL sat.
Plot 2: L1-L2 as a function of time for PRN16.
Plot 3: P2-P1 as a function of time for PRN16

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

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

Execute:

```
gLAB_linux -input:cfg meas.cfg -input:obs graa0800.07o > meas.txt
```
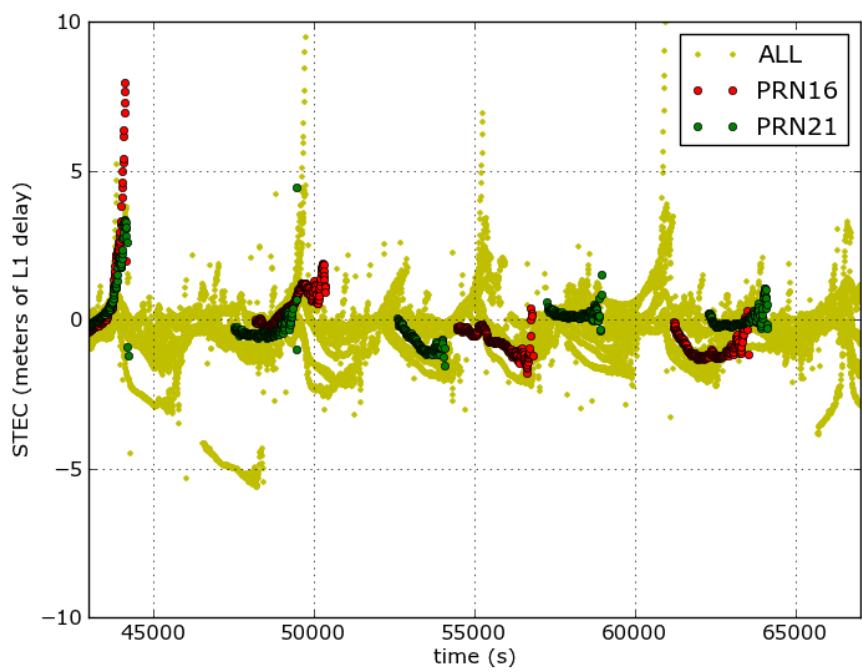
2. From file `meas.txt`, compute the ionospheric delay as $I_1 = \frac{1}{2}(C1 - L1) + bias$

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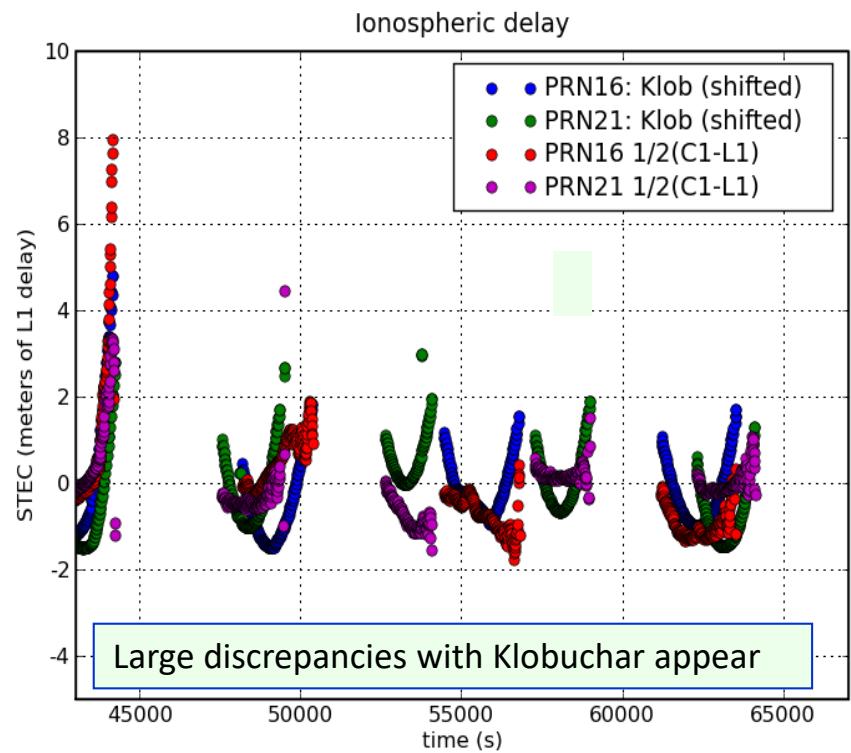
```
graph.py -f I1.txt -x2 -y3 -s. --cl y -l "ALL"
         -f I1.txt -c '($1==16)' -x2 -y3 -so --cl r -l "PRN16"
         -f I1.txt -c '($1==21)' -x2 -y3 -so --cl g -l "PRN21"
         --xn 43000 --xx 67000 --yn -10 --yx 10
         --xl "time (s)" --yl "STEC (meters of L1 delay)"
```

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, <u>activate the "Ionospheric Correction"</u> 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 <u>I1.txt</u> and <u>klob.txt</u> 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:
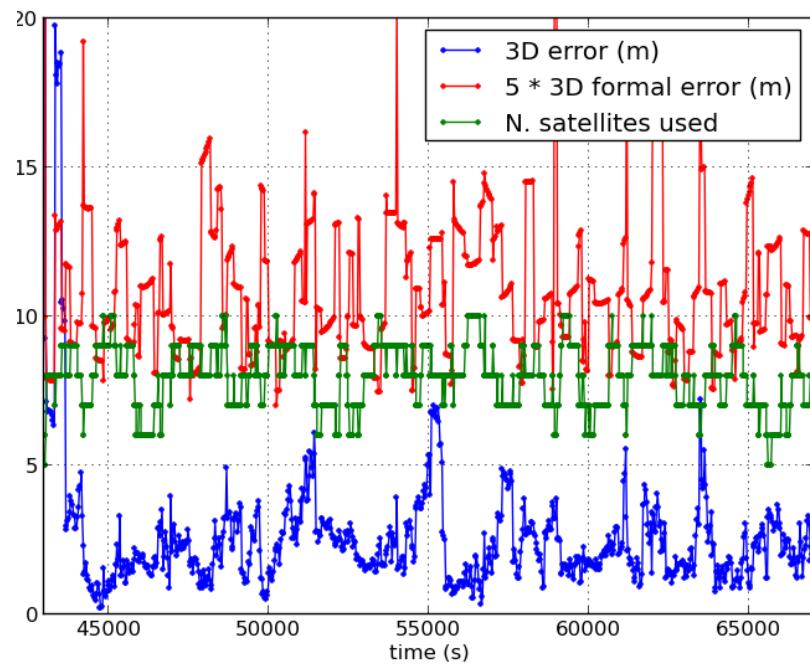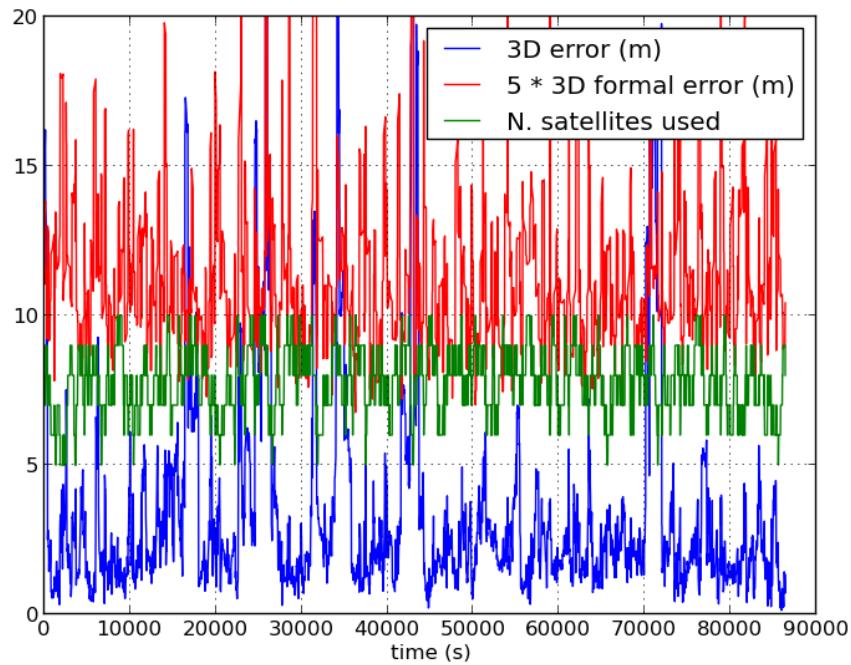
In the same graph, plot the "3D error" [from file `dif.out`], the formal error (the 3-D sigma) and the number of satellites used in the computation [from file `gLAB.out`].

```
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 <u>meas.cfg</u>, READ the RINEX and generate the MEAS message with data format:

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

Execute:

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

2. From `meas.txt` file,

Compute C1 code noise and multipath as:

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

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

3. From `C1.txt` file,

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

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

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

Compute P1 code noise and multipath as: $\boxed{M_{P1} = P1 - L1 - \dfrac{2}{\gamma - 1}(L1 - L2)}$ $\gamma = \left(\dfrac{77}{60}\right)^2$

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

2. From previous `P1.txt` file,

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

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

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

Compute P2 code noise and multipath as:

$$M_{P2} = P2 - L2 - \frac{2\gamma}{\gamma - 1}(L1 - L2) \qquad \gamma = \left(\frac{77}{60}\right)^2$$

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

2. From previous `P2.txt` file,

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

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

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

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

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

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

Compute PC noise and multipath as: $\boxed{M_{Pc} = Pc - Lc}$

$$Pc = \frac{f_1^2 P_1 - f_2^2 P_2}{f_1^2 - f_2^2} = \frac{\gamma P_1 - P_2}{\gamma - 1};$$

$$Lc = \frac{f_1^2 L_1 - f_2^2 L_2}{f_1^2 - f_2^2} = \frac{\gamma L_1 - L_2}{\gamma - 1}$$
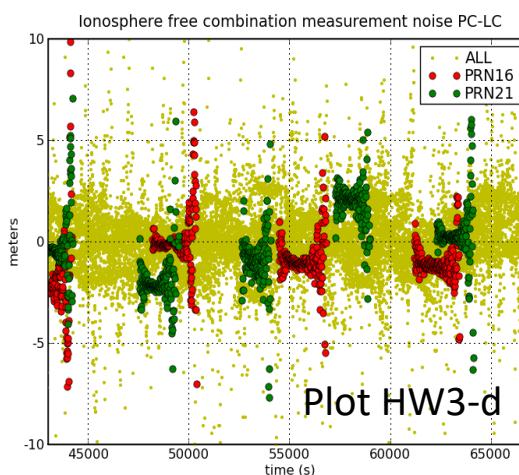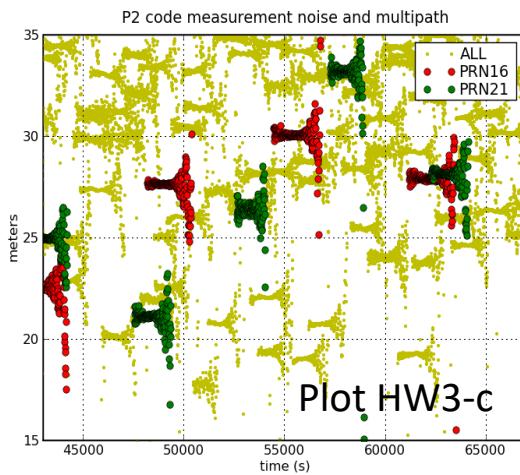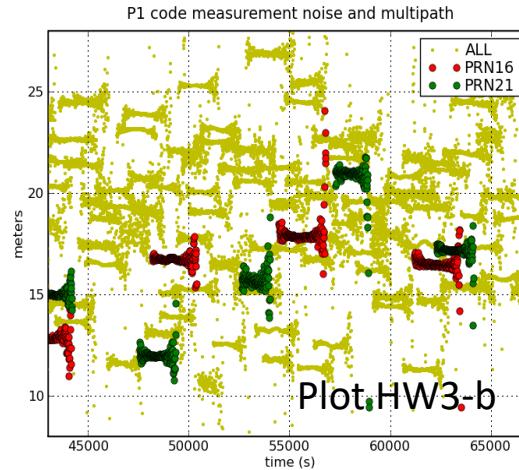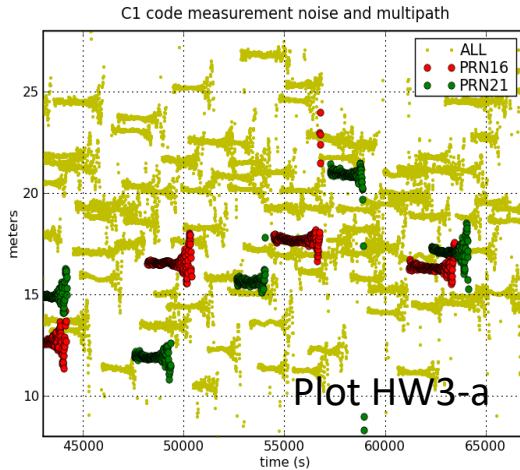
```
gawk 'BEGIN{g=(77/60)^2}{print $6, $4, (g*($13-$14)-($15-$16))/(g-1)}' meas.txt > PC.txt
```

2. From previous `PC.txt` file,

Plot the PC combination noise and multipath for time interval [43000:67000]. Show in the same graph: 1) ALL satellites, 2) PRN16 and 3) PRN21 (see Plot HW3-d)
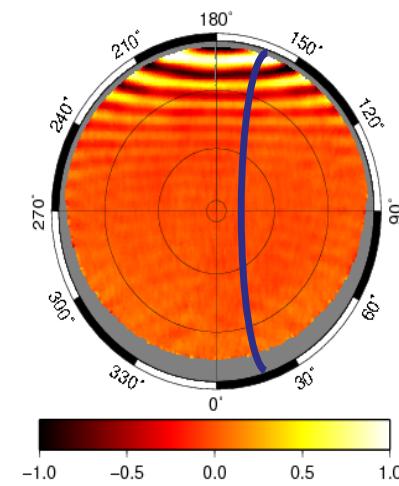
```
graph.py -f PC.txt -x2 -y3 -s. --cl y --l "ALL"
         -f PC.txt -c '($1==16)' -x2 -y3 -so --cl r --l "PRN16"
         -f PC.txt -c '($1==21)' -x2 -y3 -so --cl g --l "PRN21"
         --xn 43000 --xx 67000 --yn 8 --yx 28
```

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

Plot HW3-a — C1 code measurement noise and multipath

Plot HW3-b — P1 code measurement noise and multipath

Plot HW3-c — P2 code measurement noise and multipath

Plot HW3-d — Ionosphere free combination measurement noise PC-LC

Comments

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

C1 multipath map of sat. GRACE_A.

A GPS satellite track is shown in blue

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

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

Complete the following steps:

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

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

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

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

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

SATDIFF message content is shown in the table beside. *(see* `gLAB_linux –messages).`
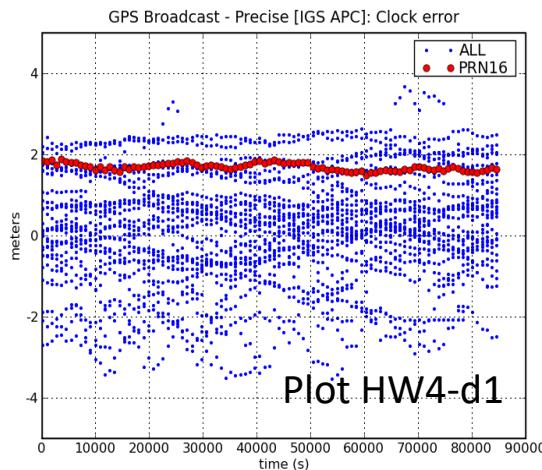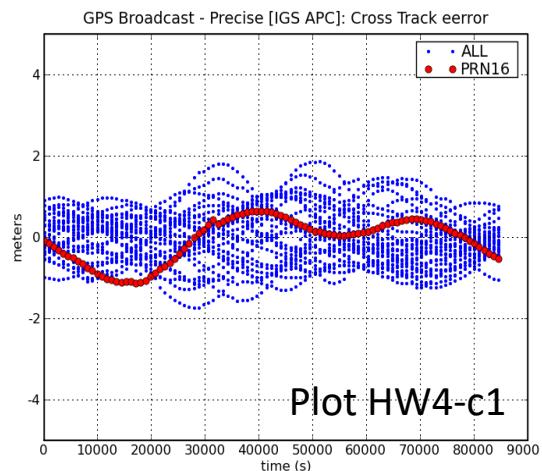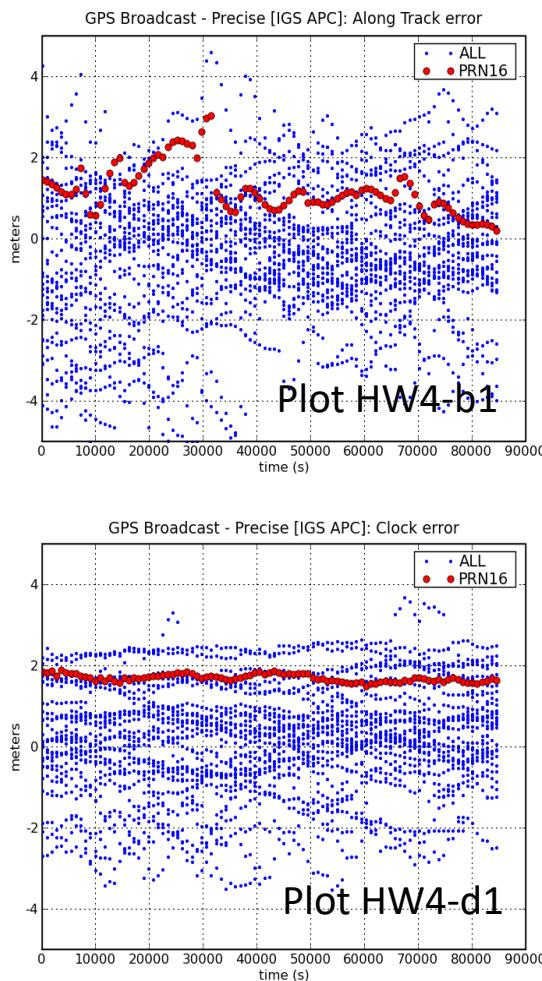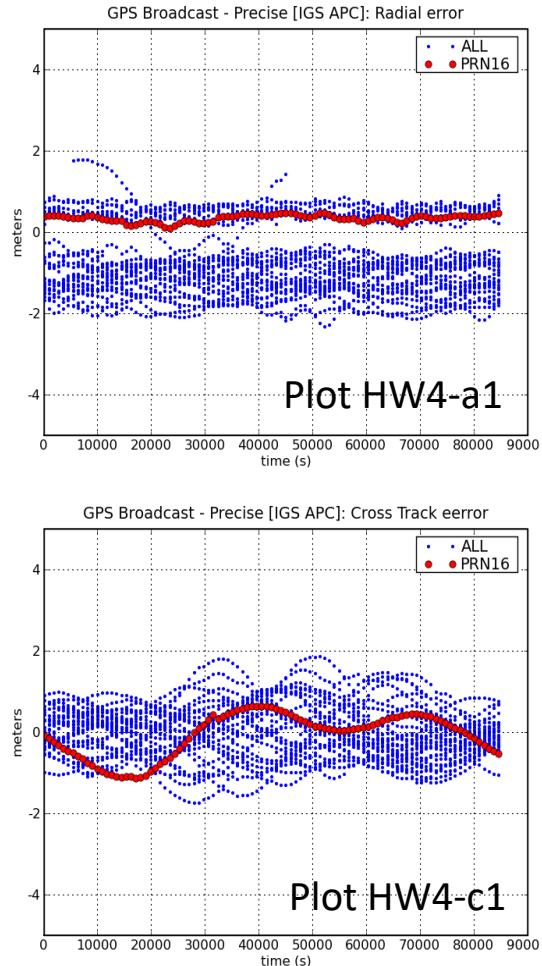
The IGS post-processed products are accurate at few cm level, thence they can be taken as the truth.

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

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

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

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

Plot HW4-a1 — GPS Broadcast - Precise [IGS APC]: Radial error

Plot HW4-b1 — GPS Broadcast - Precise [IGS APC]: Along Track error

Plot HW4-c1 — GPS Broadcast - Precise [IGS APC]: Cross Track error

Plot HW4-d1 — GPS Broadcast - Precise [IGS APC]: Clock error

Plot HW4-e1 — GPS Broadcast - Precise [IGS APC]: SISRE
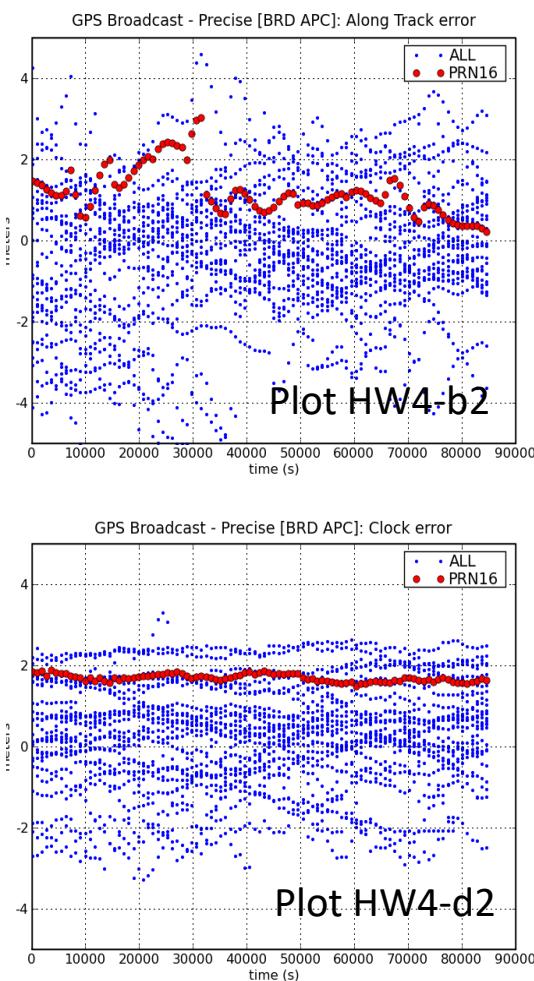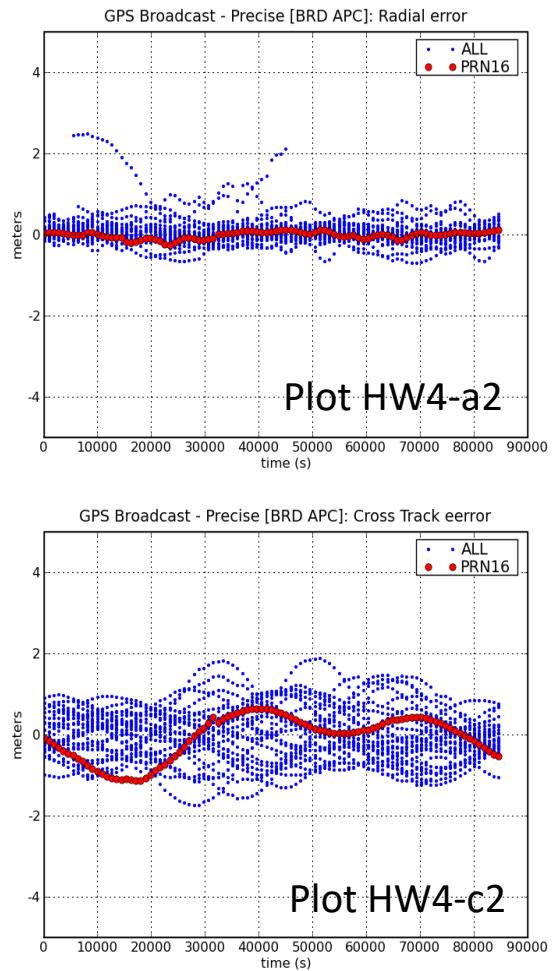
Comments

- 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).

Plot HW4-a2

Plot HW4-b2

Plot HW4-c2

Plot HW4-d2
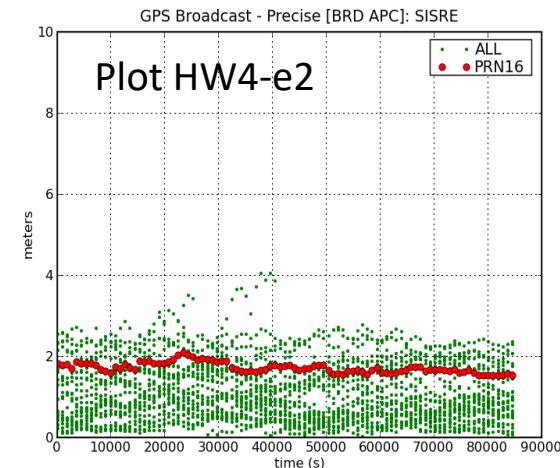
Comments

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.

Plot HW4-e2

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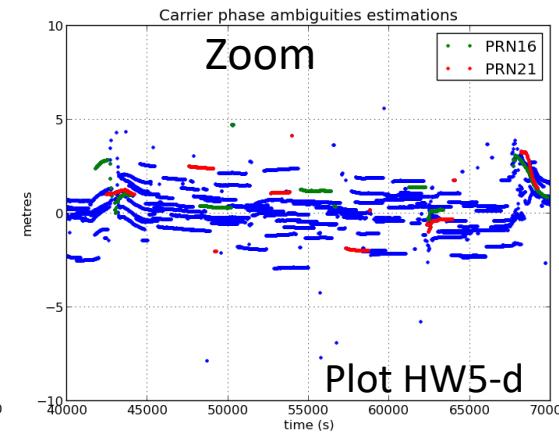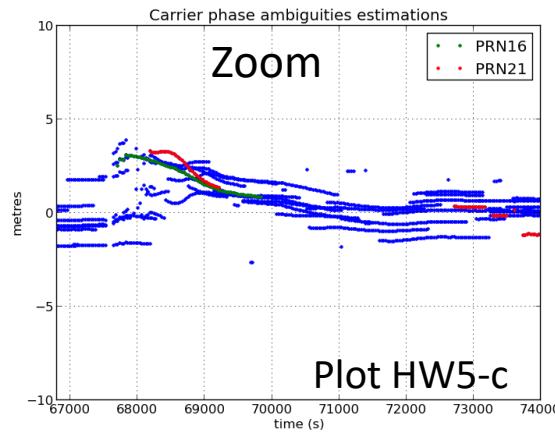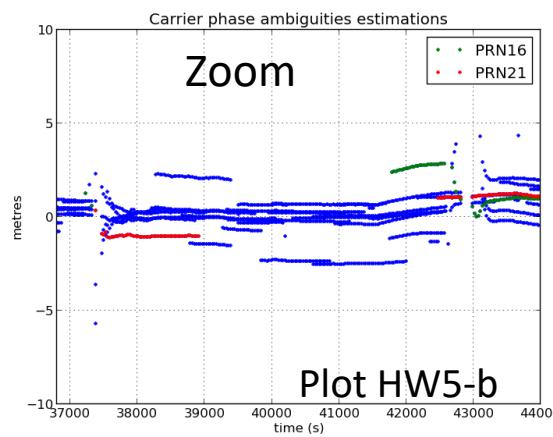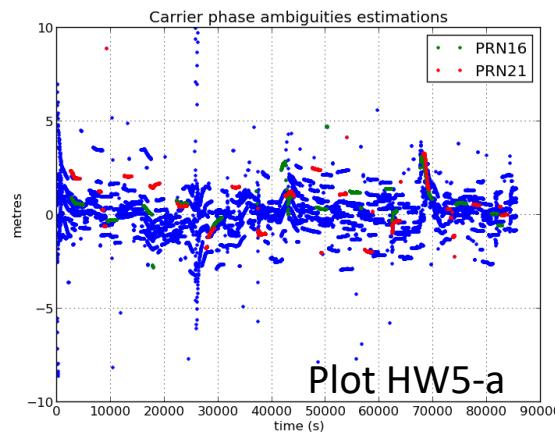
```
grep POSTFIT gLAB.out| gawk '{i=$6" "$4;a[i]=$13}END{for (i in a) print i,a[i]}' |sort -n > amb.out
```

   <u>Plot the results</u>: 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
```

gAGE/UPC
Research group of Astronomy & Geomatics
Technical University of Catalonia

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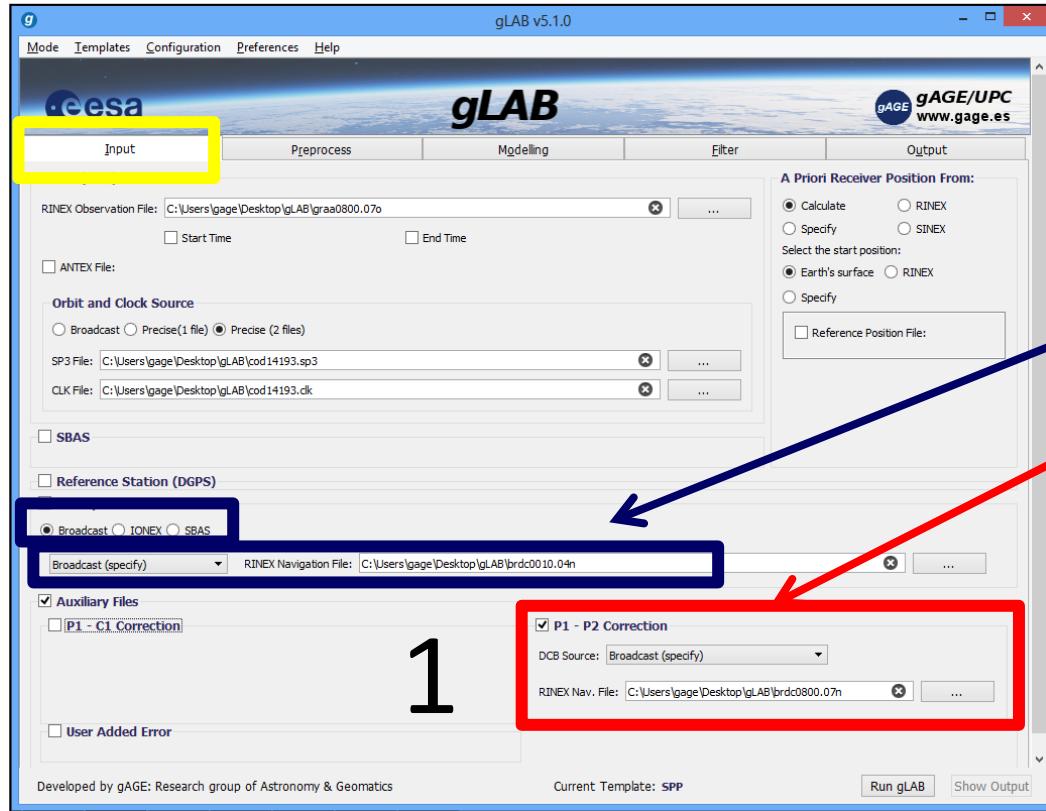
Comments

- Large peaks appear in the carrier phase biases due to massive cycle-slips:
  - Satellite tracking loses happen periodically after each revolution.
  - These satellite loses produce massive cycle slips which leads to a global reinitialization of carrier-phase biases in the navigation (Kalman) filter .
  - After such ambiguities reinitialization, the filter needs some time to converge.

- Carrier phase ambiguities converge quickly thanks to the rapid variation of geometry due to the LEO movement along its orbital path.
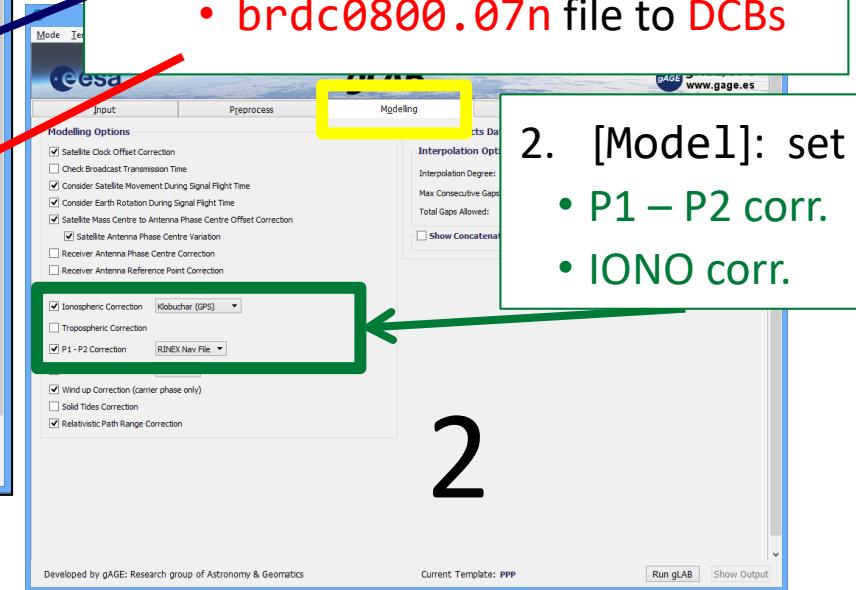
gAGE/UPC
Research group of Astronomy & Geomatics
Technical University of Catalonia

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 <u>Mode 5</u> and complete the following steps:
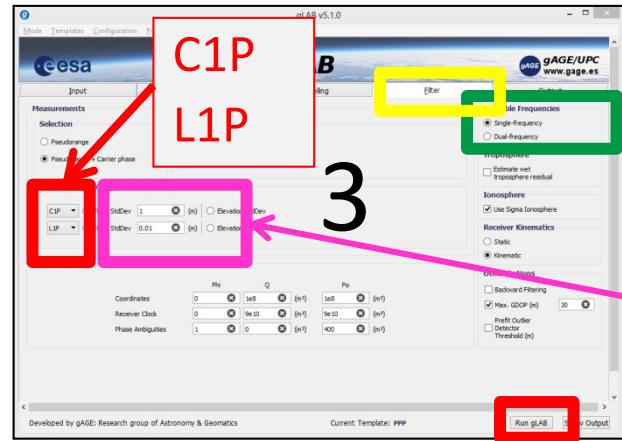
1. [Input]: Upload the
   - brdc0800.07n file to IONO
   - brdc0800.07n file to DCBs

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

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

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

C1P
L1P

3

Single frequency

Set
σ_{C1P}=1 meter
σ_{L1P}=0.01 meters

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
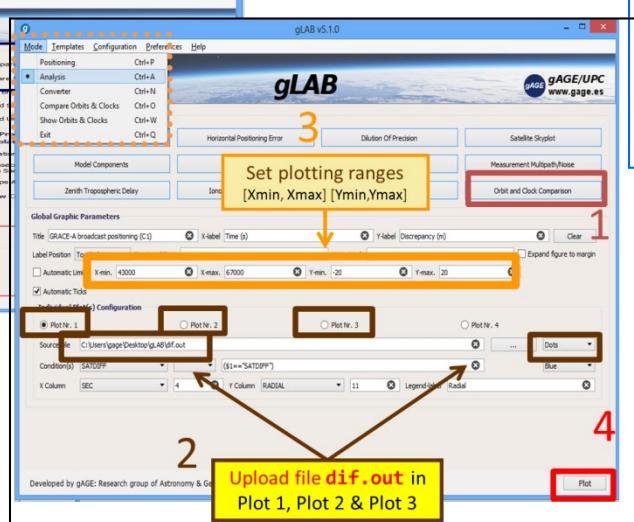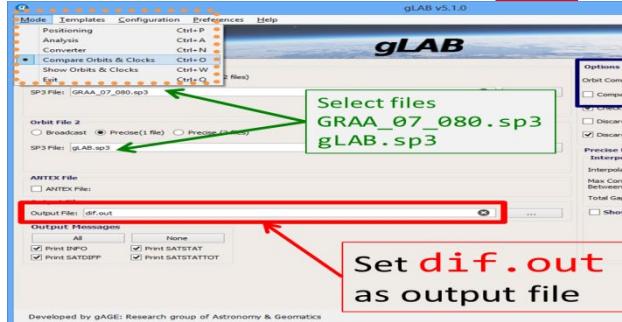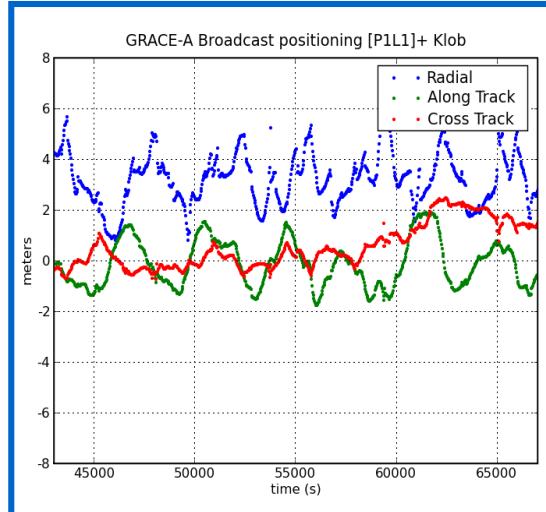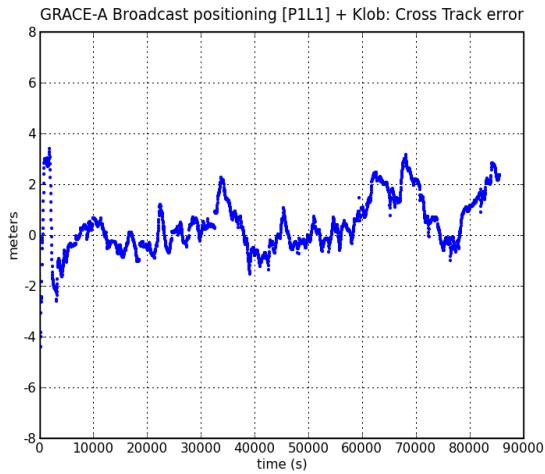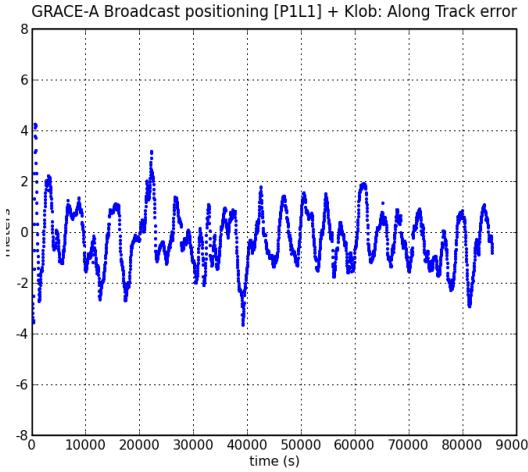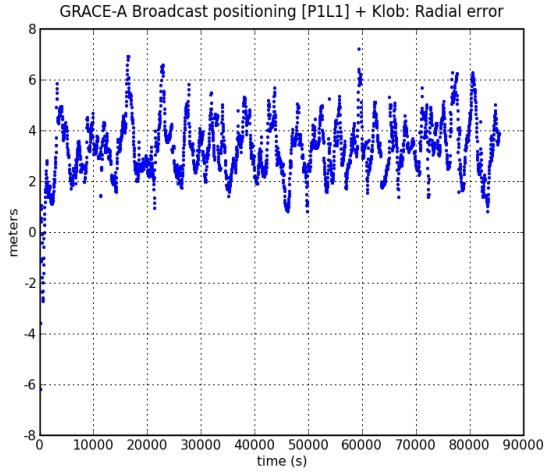
Complete the steps

3. [Filter]:
   • Single Frequency measurements:
   • L1P (L1 carrier)
   • C1P (P1 code)

4. Compute differences with reference file GRAA_07_080.sp3
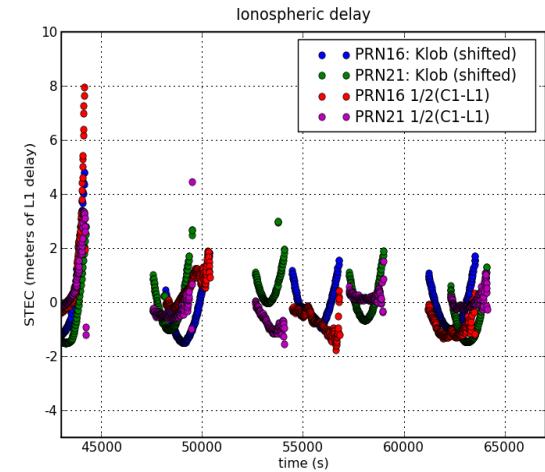
Make plots as before.

gAGE/UPC
Research group of Astronomy & Geomatics
Technical University of Catalonia

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

GRACE-A Broadcast positioning [P1L1] + Klob: Radial error

GRACE-A Broadcast positioning [P1L1] + Klob: Along Track error

GRACE-A Broadcast positioning [P1L1] + Klob: Cross Track error

GRACE-A Broadcast positioning [P1L1]+ Klob

Ionospheric delay
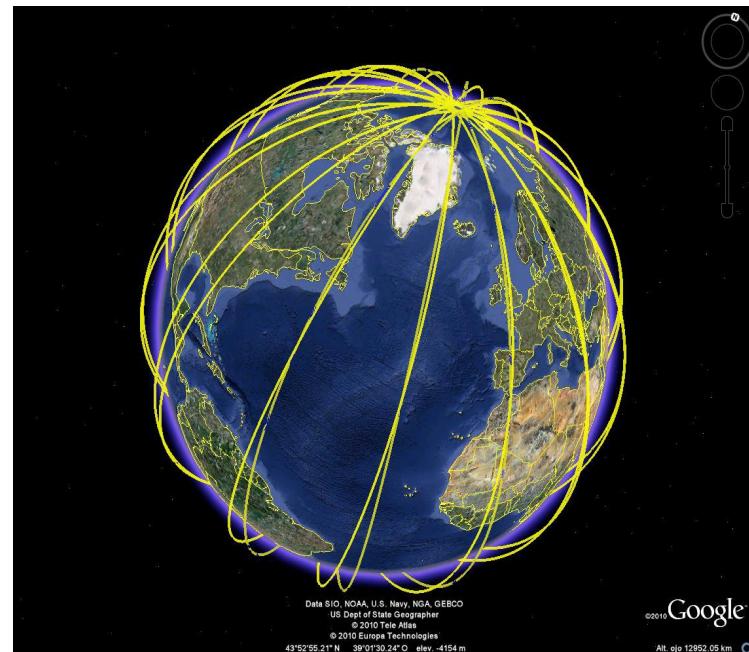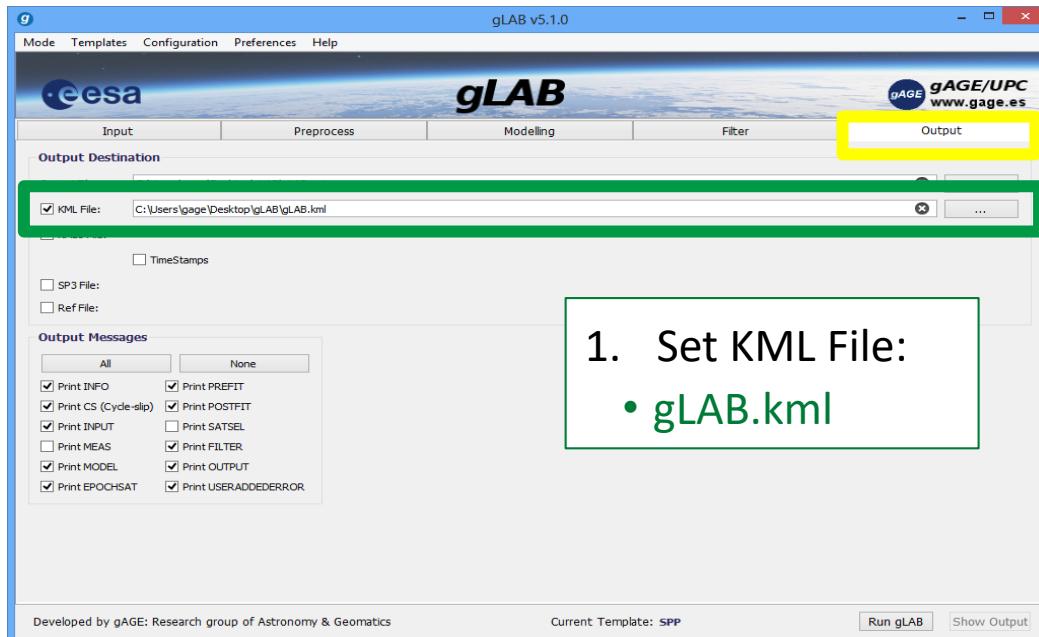
Comments

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

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

⌃ Option A: GUI

1. Set KML File:
   • gLAB.kml

⌃ 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

gAGE/UPC
Research group of Astronomy & Geomatics
Technical University of Catalonia

Acknowledgements