GNSS Data Processing Laboratory Exercises

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OVERVIEW

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

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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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- Examples of GNSS Positioning using gLAB
- gLAB software installation

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The gLAB Tool suite

The GNSS-Lab Tool suite (gLAB) is an interactive multipurpose educational and professional package for GNSS Data Processing and Analysis.

• gLAB has been developed under the ESA 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 gLAB Tool suite

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

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

• In order to 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.
  – HTML files describing the standard formats.

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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^{nd} degree).
- SBAS Messages.
- RTCM messages.

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The gLAB Tool suite

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

Output module:
- Cartesian / NEU coordinates.
- Configurable message output.

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

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

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

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

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

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Basic: Introductory Lab. Exercises

• Standard and Precise Point Positioning
  – To Illustrate how easy to process GNSS data using gLAB, a GPS receiver will be positioned in the next examples using:
    • Example 1: **Broadcast** orbits and clocks (**SPP**, **kinematic**).
    • Example 2: **Precise** Orbits and clocks (**PPP**, **static**).
    • Example 3: **Precise** Orbits and clocks (**PPP**, **kinematic**).
  – Solutions will be compared with an accurate reference value of receiver coordinates to assess the positioning error.

*Note: the receiver coordinates were keep fixed during the data collection.*
We will work after the correlator: Our input data are code and carrier measurements and satellite orbits and clocks.

**RINEX: observables**

Pseudoranges (C/A, P1, P2), phase tracking (L1, L2)

Navigation data (D(t))

**RINEX FILES**

One or multiple antennas

Low-noise Amplifiers

RF/IF & SAMPLING

DLL Tracking RCVR & Demodulator

Navigation data processing & Pseudorange correction

Kalman filter position estimation

DISPLAY

Man-Machine Interface

Aiding or integrated receiver

EXTERNAL SENSORS

~300km

Satellite clock offset < 300Km

Relativistic correction < 13 m

Geometric distance: \( p_0 \approx 20000 \text{Km} \)

Ionoospheric delay [2 - 50 m]

Tropospheric delay [2 - 10 m]

Receiver clock offset < 300Km

Receiver instrumental delays ~m

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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

More details at: http://www.gage.es/gLAB
Example 1: Standard Point Positioning (SPP)

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

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

Default output file: gLAB.out

Note: Reference coordinates are from RINEX
Example 1: Standard Point Positioning (SPP)

- Plotting Results

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

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

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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.

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Example 3: Kinematic Precise Point Positioning

From default configuration of [PPP Template],

• Select **kinematics** in the [Filter] panel. Run **gLAB** and plot results.

Decimetre error level navigation after the best part of an hour

Receiver navigated as a rover in a pure **kinematic** mode.
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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.
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.
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`

Check the folder: `C:\gLAB`

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2.- Second Step: Completing the gLAB Setup Wizard

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

UNIX (Linux) console to execute “command line” sentences.
Suggested desk configuration to start working

Tutorial 1
GNSS Data Processing Lab Exercises

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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.
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 1st 2004.

Set vertical range: -40, 40

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NEU Position Error plot from gLAB.out

NEU plot template configuration

FULL SPP model

North

East

Up

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Exercise 1: SPP Model components analysis

The different model components will be analyzed with gLAB:

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

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

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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.
NEU Position Error plot from gLAB1.out

NEU plot template configuration

No Iono. correction
Vertical Position Error plot from gLAB.out, gLAB1.out

1. Click Clear to restart plots
2. Y-min, Y-max
3. gLAB1.out
   - Time (sec): 4
4. gLAB.out
   - Vertical: DSTAU: 20

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Horizontal Position Error plot: `gLAB.out`, `gLAB1.out`
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 $\delta_{ion} = \frac{40.3}{f^2}I$ on the inverse of squared frequency:
  
  where $I$ is the number of electrons per area unit along ray path (STEC: Slant Total Electron Content).

  $I = \int N_e ds$

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

  $LC = \frac{f_1^2L_1 - f_2^2L_2}{f_1^2 - f_2^2}$

• 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!):

- **Set again:** Ionosphere
- **Disable:** Troposphere
- **Keep:** *gLAB1.out* as output file

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

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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 (~40µs/day).
Exercise 1: SPP Model components analysis

Relativistic clock correction

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

\[
\frac{f'_0 - f_0}{f_0} = \frac{1}{2} \left( \frac{v}{c} \right)^2 + \frac{\Delta U}{c^2} = -4.464 \cdot 10^{-10}
\]

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:

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

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.
Satellite clock offsets

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

The receiver clock offset is estimated together with receiver coordinates.

Satellite clock offset values are provided:
- In real-time, within the broadcast navigation message with a few meters of error
- 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.

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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`

Set output file `gLAB.out` for the FULL model, as in previous case.

4. Set output file `gLAB.out` for the FULL model, as in previous case.

5. Run `gLAB`.

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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 pre-fit-residuals, which are the input data for navigation equations.

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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. gLAB1.out
3. gLAB.out

Time (sec): 4
Vertical: DSTAU: 20

Y-min, Y-max

Developed by gAGE: Research group of Astronomy & Geomatics
Horizontal Position Error plot: gLAB.out, gLAB1.out

1. Click Clear to restart plots
2. X-min, Y-min, Y-max
3. gLAB1.out
   East: DSTAE: 19
   North: DStan: 18

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Solid Tides model component plot: `gLAB.out`

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.

These effects do not affect the GNSS signals, but if they were not considered, the station coordinates would oscillate with relation to a mean value. They produce vertical (mainly) and horizontal displacements.

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Exercise 2: PPP Model components analysis

Receiver Antenna Phase center (APC)

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

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

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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).
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.

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

More details at: 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.

- 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

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Mode 1: 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

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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:

1. Select files GRAA_07_080.sp3, gLAB.sp3
2. Set: 30s
3. Disable: Compare satellite clock Correction
4. Set dif.out as output file
5. Run gLAB
Mode 1: Single frequency C1 code with broadcast orbits & clocks

Plotting `dif.out` with the GUI

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

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

3. Mode: 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?
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.
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.

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

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

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?
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:
\[ P_c = \frac{f_1^2 P_1 - f_2^2 P_2}{f_1^2 - f_2^2} = \frac{\gamma P_1 - P_2}{\gamma - 1} \]
\[ \gamma = \left( \frac{77}{60} \right)^2 \]
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

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

Set Precise (2 files)

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

Set calculate
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

Switch to Kinematic

Disable Estimate Troposphere
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)

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

Set output SP3 file as gLAB_sp3

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

Run gLAB

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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.
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)

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, LI detectors

5. Run gLAB

6. In Compare Orbits & Clocks:
   - Compute differences with reference file GRAA_07_080.sp3
   - Make plots as before.

[Notes]
[*] 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

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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)?
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. **[Model]**: 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)

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, LI detectors

6. Run gLAB
   In Compare Orbits & Clocks:
   - Compute differences with reference file SHAAR_07_080 . sp3
   - Make plots as before.

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

Questions

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

16. No ionospheric corrections have been applied in this run. What would happen if the Klobuchar model is applied?
Answer to Question 15:
Explain why the solution has a more defined pattern, with large oscillations.
- This effect is due to the error introduced by the ionosphere and the broadcast differential code biases inaccuracy.

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

Homework:
- HW6: Apply the Klobuchar model and discuss the results.
- HW7: Generate a file with the satellite track (in a Earth-Fixed Earth-Centered reference frame) to be viewed with Google Earth.
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 Google Earth.
Configure gLAB as in Mode 1 and complete the following steps:

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

2. **Run gLAB.**

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

**Note: This configuration will provide:**
- Plot 1: L1-L2 as a function of time for ALL sat.
- Plot 2: L1-L2 as a function of time for PRN16.
- Plot 3: P2-P1 as a function of time for PRN16
HW1: Assessing the ionospheric delay on the GRACE-A satellite

Note: This plot takes some time to be generated!!
HW1: Assessing the ionospheric delay on the GRACE-A satellite

Plot HW1-a Comments:

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

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

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

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

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

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

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

   ```
   [Id YY Doy sec GPS PRN el Az N. list C1C L1C C1P L1P C2P L2P]
   1 2 3 4 5 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.
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 Mode 1 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-sigma ≈ σ PDOP
In the previous plot, the 3-D sigma is multiplied by 5 to enlarge the image.
HW2: Plot in the same graph the “True 3D error”, the “Formal 3D error” and the number of satellites used. Analyze the result.

Plot HW2-a
Periodic error peaks appear, mostly associated with losing a satellite and/or with bad geometries.

Plot HW2-b: Zoom of Plot HW2-a.
Along the peaks associated to bad geometries, mismodelling is also producing some error trends.
HW3: Code measurements noise assessment: C1, P1, P2 and PC

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

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

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

Execute:

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

2. From `meas.txt` file,

Compute C1 code noise and multipath as:

```
M_{C1} = C1 - L1 - \frac{2}{\gamma} \ln (L1 - L2)
```

```
\gamma = \left(\frac{77}{60}\right)^2
```

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

3. From `C1.txt` file,

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

```
graph.py -f C1.txt -x2 -y3 -s. --cl y --l "ALL"
-f C1.txt -c '($1==16)' -x2 -y3 -so --cl r --l "PRN16"
-f C1.txt -c '($1==21)' -x2 -y3 -so --cl g --l "PRN21"
--xn 43000 --xx 67000 --yn 8 --yx 28
```
B) The next commands compute the P1 code noise and multipath:

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

   \[
   \begin{array}{cccccccccccc}
   \text{Id} & \text{YY} & \text{Doy} & \text{sec} & \text{GPS} & \text{PRN} & \text{el} & \text{Az} & \text{N. list} & \text{C1C} & \text{L1C} & \text{C1P} & \text{L1P} & \text{C2P} & \text{L2P} \\
   1 & 2 & 3 & 4 & 5 & 6 & x & x & 9 & 10 & 11 & xx & 13 & 14 & 15 & 16
   \end{array}
   \]

   Compute P1 code noise and multipath as:
   
   \[
   M_{P1} = P1 - L1 - \frac{2}{\gamma-1} (L1 - L2) \quad \gamma = \left(\frac{77}{60}\right)^2
   \]

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

2. From previous *P1.txt* file,

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

   ```
   graph.py -f P1.txt -x2 -y3 -s. --cl y --l "ALL"
   -f P1.txt -c '($1==16)' -x2 -y3 -so --cl r --l "PRN16"
   -f P1.txt -c '($1==21)' -x2 -y3 -so --cl g --l "PRN21"
   --xn 43000 --xx 67000 --yn 8 --yx 28
   ```
C) The next commands compute the P2 code noise and multipath:

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

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

   Compute P2 code noise and multipath as:

   $$\gamma = \left(\frac{77}{60}\right)^2$$

   $$M_{p_2} = P2 - L2 - \frac{2\gamma}{\gamma-1}(L1 - L2)$$

   ```
   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
   ```
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]
```

Compute PC noise and multipath as:

\[
M_{PC} = P_C - L_C
\]

\[
P_C = \frac{f_1^2 P_1 - f_2^2 P_2}{f_1^2 - f_2^2} = \gamma \frac{P_1 - P_2}{\gamma - 1};
\]

\[
L_C = \frac{f_1^2 L_1 - f_2^2 L_2}{f_1^2 - f_2^2} = \gamma \frac{L_1 - L_2}{\gamma - 1};
\]

```
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

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.

This figure is from

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

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:** \( \text{SISRE} = \sqrt{(\Delta \text{Rad} - \Delta \text{Clk})^2 + \frac{1}{49}(\Delta \text{Alon}^2 + \Delta \text{Cross}^2)} \)
HW4: Broadcast orbits and clocks accuracy assessment using the IGS precise products as the accurate reference (i.e, the truth).

Comments

- Meter level errors are found on broadcast orbits and clocks.
- The bias seen in the radial component is due to the different APC’s used by the GPS ground segment (i.e, in broadcast orbits) and by IGS (precise products).
- This bias is compensated by a similar shift in clocks.
- For the Signal-In-Space-Range-Error (SISRE), please see the plot below.
HW4: Broadcast orbits and clocks accuracy assessment using the IGS precise products as the accurate reference (i.e., the truth).

Comments

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

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

- Notice that the biases in the radial component have disappeared.
HW5: Analyze the carrier phase biases convergence in the kinematic PPP positioning.

Complete the following steps

1. Configure gLAB as in Mode 2 for the Kinematic PPP positioning. Activate the “Print POSTFIT messages” in the OUTPUT 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).

```
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
```

Note: The GUI can be used instead of the “graph.py” command.
HW5: Analyze the carrier phase biases convergence in the kinematic PPP positioning.

Comments

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

- Carrier phase ambiguities converge quickly thanks to the rapid variation of geometry due to the LEO movement along its orbital path.
HW6: Single freq. L1, C1 carrier and code with precise orbits & clocks using Klobuchar ionospheric corrections

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

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

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

2. **[Model]:** set
   - P1 – P2 corr.
   - IONO corr.
HW6: Single freq. L1, C1 carrier and code with precise orbits & clocks using Klobuchar ionospheric corrections

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

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.

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

![Image of gLAB GUI](image)

**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
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