The ESA/UPC GNSS-Lab Tool (gLAB)

An advanced multipurpose package for GNSS data processing

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Abstract—**Satellite Navigation has become a keystone for the development of Europe and its citizens. It is then essential to provide adequate educational programmes so to ensure a prepared workforce for the GNSS sector in Europe. In this context, ESA has launched a complete Satellite Navigation Educational program, called EDUNAV, aiming at providing up-to-date GNSS based educational material and educational tools. The GNSS-Lab (gLAB) Educational Software Tool is part of this ESA EDUNAV initiative.**

gLAB, developed under ESA Contract by the research group of Astronomy and Geomatics (gAGE) from the Universitat Politecnica de Catalunya (UPC), is an interactive educational multipurpose package to process and analyse GNSS data. gLAB performs precise modeling of GNSS observables (pseudorange and carrier phase) at the centimetre level, allowing both standalone GPS positioning and PPP. Every single error contributor may be assessed independently, which, in turn, provides a major educational benefit. gLAB is adapted to a variety of standard formats like RINEX-3.00, SP3, ANTEX and SINEX files, among others. Moreover, functionality is also included for GPS, Galileo and GLONASS, allowing performing some data analysis with real multi-constellation data.

The gLAB software tool is quite flexible, able to run under Linux and Windows operating systems and is provided free of charge by ESA to universities and GNSS professionals.

GNSS software tool; formation PPP; gLAB; open source; Galileo; GNSS data processing; GPSTk

I. INTRODUCTION

Nowadays, GNSS systems are a crucial component of the global information infrastructure enabling broad new market capabilities and facilitating innovation in efficiency, safety, environmental, science and public security.

The development of Galileo and EGNOS infrastructures will then have a major influence in the creation and development of new GNSS related applications and services, having a major impact on the growing Europe GNSS market and related job opportunities.

In this context, ESA has launched a complete Satellite Navigation Educational program, called EDUNAV, aiming at providing up-to-date GNSS based educational material and educational tools. The GNSS-Lab (gLAB) Educational Software Tool is part of this ESA EDUNAV initiative.

The objective of this educational initiative is supporting university students to have a comprehensive knowledge of GNSS. As outputs expected from this activity are the following:

- An educational GNSS Software Tool that gives students the capability to be taught both in the theoretical and practical points of view of the GNSS systems (e.g. GPS, EGNOS and future Galileo).
- Software routines of GNSS processing concepts to support the learning process of the students and provide practical exercises.
- Educational material /manual that support the learning process of the students and provide practical exercises ranging from the basics to more complex concepts of GNSS processing.

The requested Educational GNSS Software Tool constitutes a step forward in the ESA-Education Office aim at fostering the transfer of knowledge in GNSS through the provision of GNSS-based educational utilities. The good consecution of this objective will help to enhance the GNSS knowledge of European students and professionals.

In this context, the research group of Astronomy and Geomatics (gAGE) from the Universitat Politecnica de Catalunya (UPC) has developed the GNSS-Lab (gLAB) tool suite, which is an interactive educational multipurpose package to process and analyse GNSS data.

This software package is targeting the following groups of users:

- Education professionals aiming to teach GNSS from both a theoretical and practical points of view.
- Standalone students and professionals with basic knowledge on GNSS as a self-learning tool.
- Professionals with more in deep knowledge on GNSS who want an easy and user-friendly tool with precise positioning capability.

The gLAB tool is distributed within a learning material package containing the following components:

- Software: A set of binary files able to read GPS RINEX data, process it and show the results in the form of data files and graphics. The processing options are fully parametrizable through a GUI that eases to understand the tool and its different options.
- Tutorial: A book containing the GNSS fundamentals and several practical exercises covering from the basics of data processing, such as reading standard RINEX format, to more complex processes like positioning a rover and analysing the results.
- Data: The data sets files used in the exercises.

Further details about the software set of tools follows.

II. GENERAL SOFTWARE CHARACTERISTICS

This tool performs a precise modelling of the GNSS observables (pseudorange and carrier phase) at the centimetre level, allowing both standalone GPS positioning and PPP. The first release of this software package implements full processing capabilities for GPS data and is prepared to incorporate future module updates, such as an expansion to Galileo and GLONASS systems, EGNOS and differential processing.

The gLAB software is capable of reading a variety of standard formats like RINEX-3.00, SP3, ANTEX and SINEX files, among others. Moreover, functionality is also included for GPS, Galileo and GLONASS, allowing performing some data analysis with real multi-constellation data.

The tool is able to run under Linux and Windows operating systems (OS). It is programmed in C and Python languages and is divided in three main software modules:

1. The Data Processing Core (DPC),
2. The Data Analysis Tool (DAT), and
3. The Graphic User Interface (GUI).

The DPC implements all the data processing algorithms and can be executed in command line. The DAT provides a plotting tool for the data analysis. The GUI consists in different graphic panels for a user friendly managing of both the DPC and DAT. Both the DPC and DAT modules may be used independently of the GUI, including them in batch files to automatically process GNSS data.

A. Main software features

The gLAB tool features a wide range of characteristics only available in advanced GNSS data processing software. The main features are mentioned here, and a more detailed list may be found in the provided Annex:

- Graphical User Interface allowing high customization and processing of a wide range of options.

- Capable of reading the following formats: Observation RINEX 2.11 and 3.00, RINEX ephemeris and clocks, SP3, IONEX, ANTEX and SINEX, among others.
- Able to process both pseudorange and carrier phase.
- Detection of cycle-slips in carrier phase observations.
- Pseudorange jump checking according to receiver.
- Orbit/Clock comparison mode.
- It implements standard GPS SPS modelling plus satellite and receiver phase centre corrections, wind-up, Differential Code Biases (DCB), solid tides, gravitational delays, etc.
- Full Precise Point Positioning (PPP) implementation according to [1].
- Reconfigurable Extended Kalman Filter (EKF).

B. Minimum hardware requirements

The gLAB requires the following relatively modest computer minimum hardware requirements in order to be properly executed:

- 256 MB of memory.
- CPU with at least 1GHz.
- 200MB of hard disk free space.
- Screen resolution of at least 1024x768 is recommended. In order to cope with potential users using small screens, scrollbars can be displayed in the preferences button. This requirement may be waived when just the DPC and DAT modules are used.

C. gLAB validation

The validation of results is a very important aspect of a tool as gLAB. In this regard, both the modelling and positioning results were carried out using as reference de "GPS Toolkit" (GPSTk). The GPSTk [2] is very active open source international project initiated and maintained by the Applied Research Laboratories of the University of Texas (ARL:UT), having several collaborators around the world. This project aims to provide a GNSS library computing suite to the satellite navigation community, consisting in a core library, accessory libraries, and some applications.

The gAGE/UPC research group is actively involved in GPSTk development, and the results obtained with the provided PPP modules compare with the best PPP tools available [3]. Validation studies done during gLAB development for ESA have confirmed that this tool keeps at least the same level of accuracy as of the GPSTk [4].

III. GLAB GRAPHIC USER INTERFACE (GUI)

The GUI is an interface between the other two components (DPC and DAT). It allows the user to change the parameters, and execute the other two programs with the proper arguments. The initial screen of the GUI can be seen in Fig. 1.

Figure 1. gLAB GUI initial screen

In this screen, two main tabs may be found:

- **Positioning**: This tabs interfaces with the DPC tool, and allows selecting the different processing options.

- **Analysis**: This tabs interfaces with the DAT tool, and allows selecting the plotting options.

A. Positioning tab

The positioning tab is split into 5 different sections, which correspond to 5 different modules inside the DPC:

- INPUT: It is like a "driver" between the input data and the rest of the program. This module implements all the input reading capabilities and stores data in appropriate internal structures.

- PREPROCESS: This module process the data before the MODEL. It checks for cycle-slips, pseudorange-carrier phase inconsistencies and decimates the data (if required).

- MODEL: This module has all the functions to fully model the receiver measurements. As said, it implements several kind of models, which can be enabled or disabled at will. Fig. 2 shows the screen corresponding to the MODEL module.

- FILTER: This module implements a fully configurable Extended Kalman Filter (EKF), and obtains the estimations of the required parameters.

- OUTPUT: This module outputs the data obtained from the FILTER.

It is very important to notice that the GUI provides to the novice user a couple of "data processing templates", shown as buttons in the lower centre part of the interface with labels "SPP Template" and "PPP Template".

Figure 2. gLAB MODEL module

Those "templates" automatically configure the appropriate options to carry out the desired data processing strategy. In the case of the "SPP Template", the configuration corresponds to the Standard Positioning Service defined for the GPS system, while the "PPP Template" configures gLAB to carry out the Precise Point Positioning strategy as defined by [1].

This feature must not be underestimated, because it provides the novice user with a quick and friendly way to setup the processing, reducing the learning curve slope. Once the basics are mastered, the user may easily explore the effects of modifying some aspects of the original provided strategies.

Figure 3. gLAB Analysis tab

B. Anaysis tab

The analysis tab allows configuring all the visualization options for the DAT, as Fig. 3 shows.

The Analysis tab also uses the templates concept for ease of use. The templates are a set of preconfigured plotting options for the *Graphic Details* section. Clicking on any button will

load the options in that section, allowing modifying or plotting them directly. The available templates are:

- NEU position error: The NEU position error template sets the options to print the three components (North, East and Up) of the error of the receiver positioning obtained by the filter. This error is computed by the difference between the direct filter estimation and the Apriori Receiver Position in the Input section. Thence, in order to obtain a reliable error estimation this apriori position should be precise.

- North-East dispersion: The North-East dispersion template sets the options to print the North vs. East position error components. This provides an insight of the horizontal dispersion and biases of the errors.

- Model components: The Model components template sets the options to print a component of the model as a function of time. By default, it selects the Relativity effect, but it can easily be chosen which model to print, by selecting it in the Y Column option.

- Ionospheric combinations: The Ionospheric combinations template sets the options to print the two ionospheric (geometric-free) combinations: P_I (P2-P1) [pseudorange] and L_I (L1-L2) [carrier phase].

- Zenith Tropospheric Delay: The Zenith Tropospheric Delay template sets the options to print the tropospheric estimations as a function of time. It includes the nominal part corrected in the modelling and the estimated part computed in the filter.

- Postfit residuals: The Postfit residuals template sets the options to print the filter residuals (postfits) as a function of the satellite elevation. It prints both pseudorange and carrier phase postfits. This plot allows observing the dependence of residuals from elevation. In general, carrier phase residuals will be quite independent from elevation, while pseudorange residuals can have a large dependence on it.

- Satellite skyplot: The Satellite skyplot template sets the options to print the elevation/azimuth of the satellites in a skyplot, being the center of the plot the zenith of the receiver and the extremes are the lower elevations.

- Carrier phase ambiguities: The Carrier phase ambiguities template sets the options to print the estimation of carrier phase measurements in the filter. This is only possible in a processing with the *Pseudorange + carrier phase* measurements (in the Filter section).

On the other hand, the "Global Graphic Parameters" section below the templates allows the user to fine tune different options of the plots, providing full flexibility.

IV.   GLAB DATA PROCESSING CORE (DPC)

The DPC is the processing tool of gLAB, and it has been programmed in C with special care for the following objectives:

- Easy to use for an advanced user.

- Modularized, in order to incorporate future updates.

- Optimized for CPU and memory usage.

The options of the DPC are basically the same as the options of the GUI, with some exceptions that provide further flexibility. The DPC can be executed with the '-help' argument, which will provide detailed information of the different arguments that can be used. Currently almost one hundred options are available.

It is also worth mentioning that the DPC also can read the processing options from a configuration file, allowing easy repeatability of results as well as automatic batch processing.

A.   Work modes

gLAB can work in four different modes:

- *Positioning Mode*: 'Standard' mode, where all the processing is done and the position solution for a receiver is provided as OUTPUT messages. The minimum parameters required for this mode are an input observation file ('-input:obs') and orbit and clock products ('-input:nav', '-input:SP3' or '-input:orb'/'-input:clk'). Using precise products will also require the use of an ANTEX file ('-input:ant').

- *Show Input Mode*: This mode only reads an input RINEX observation file and prints its measurements. The parameter required for this mode is '-input:obs', and specifically, no orbit nor clock products should be provided (if provided, gLAB will switch to Positioning Mode).

- *Product Comparison Mode*: This mode reads and compares two different sources of orbit and clock products. In order to use this mode, '-input:obs' must be avoided, and two different orbit and clock products should be provided. This mode outputs the SATDIFF, SATSTAT and STASTATTOT messages.

- *Show Product Mode*: This mode reads a single source of orbit and clock products. In order to use this mode, '-input:obs' must be avoided, and a single orbit and clock product should be provided. This mode output SAT messages.

B.   DPC processing example

The following example gives an overview of a simple processing using the gLAB DPC component. The example carries out Precise Point Positioning in static mode to obtain the precise coordinates of a given station (ROAP). Those coordinates are then compared against the IGS-provided solution in the corresponding SINEX file and the corresponding differences in the "North", "East" and "Up" directions are plot.

Opening a command line window in the gLAB directory (in Windows this can be directly done by the option "Command line in directory" in the program group installed in the Start menu), it is enough to type the following command:

```
$ gLAB -input:obs roap1810.09o

  -input:ant igs05_1525.atx

  -input:SP3 igs15382.SP3

  -input:snx igs09P1538.snx

  -output gLAB_DPC.out
```

In about a second, the file "gLAB_DPC.out" will be generated with the all the output details. When plotting the results, Fig. 4 is obtained.
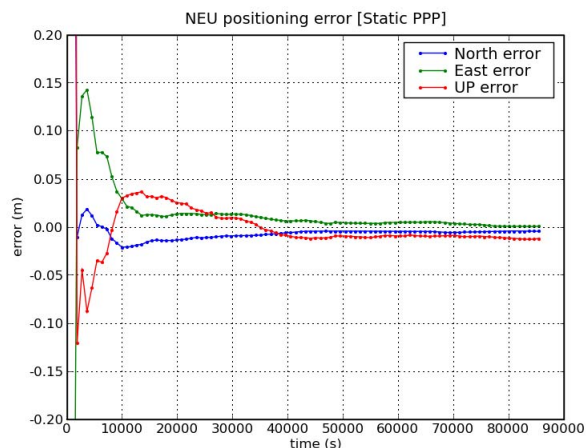

Figure 4.   Static PPP results

Please note that the positioning errors are below 1 cm, with convergence time (errors below 10 cm) of about 1 h. This performance is comparable with the best PPP processing suites currently available.

V.   GLAB DATA ANALYSIS TOOL (DAT)

The DAT is an advanced plotting utility prepared to graph different combinations of columns taking into account several user-defined conditions. The DAT, as the DPC, is highly configurable with multiple options available to set scale, titles, ranges, styles, colours, plotting conditions, etc.

An important additional feature of DAT module is the capability to output multiple image formats, including png, jpeg, pdf, eps, svg, among others.

VI.   DATA PROCESSING EXAMPLES

As an example of a non-trivial GNSS data processing exercise, the LEO satellite GRACE-A will be kinematically positioned using the GRAPHIC combination [5]. The positioning errors are plot in the radial, along track and cross track directions, using the GRACE-A Precise Reference Orbit results from the JPL Propulsion Laboratory as reference.

Starting the processing with the INPUT module, the procedure to follow is:

- Use the SPP template.

- Select the input files: Observation file: graa0800.07o, Precise ephemeris files: cod14193.sp3, cod14193.clk, Antenna phase centres file: igs05_1402.atx.

- Set "Calculate" to refresh the a priori position.

- In the PREPROCESS module set the data decimation to 30 s instead of the default 300s.

- Given that the GRAPHIC combination eliminates the ionospheric effects, the ionosphere correction must be disabled in the MODELING module. The tropospheric correction must also be disabled because GRACE-A is orbiting at a height of about 450 km.

- In the FILTER module, the "Single Frequency" option must be enabled, but the observables to be used must be changed to C1C (standard C/A observable) and G1C (GRAPHIC combination).

- The C1C steers the solution only during the first few epochs, so it is assigned a large sigma (100 m) in the filter. On the other hand, the G1C combination will drive the final solution (after carrier phase ambiguity is estimated), and has smaller noise than C1C. Therefore its filter assigned sigma is relatively small (0.5 m).

- Finally, press the "Run gLAB" button to start the DPC and use the "Analysis" tab to plot the results.

Fig. 5 plots the comparison of gLAB results with respect to the reference GRACE-A trajectory.
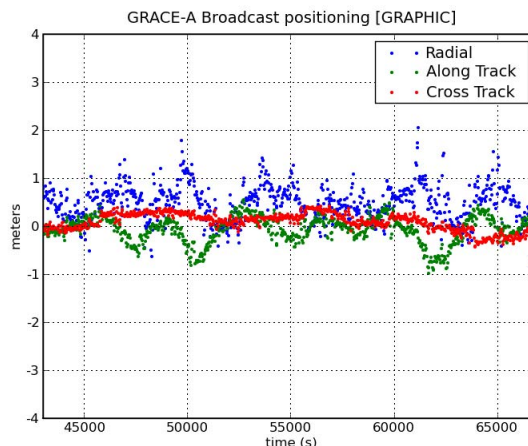

Figure 5.   GRACE-A positioning using GRAPHIC combination

As shown, a very sophisticated processing with very good results can be achieved with gLAB following a simple procedure.

An even better solution may be obtained with gLAB using dual-frequency Pc, Lc combinations (ionosphere-free) with precise orbits and clocks in PPP kinematic mode. The procedure is very similar to the former, but with small differences:

- Use the PPP template instead of the SPP one.

- In the MODELING mode, the solid tides corrections must be disable, besides ionosphere and troposphere.

- In the FILTER module the two-frequency measurement configuration is PC/LC, the residual tropospheric estimation is disabled, and the EKF is set to kinematic mode.

The rest of the procedure is basically the same as before, and the obtained results are shown in Fig. 6.
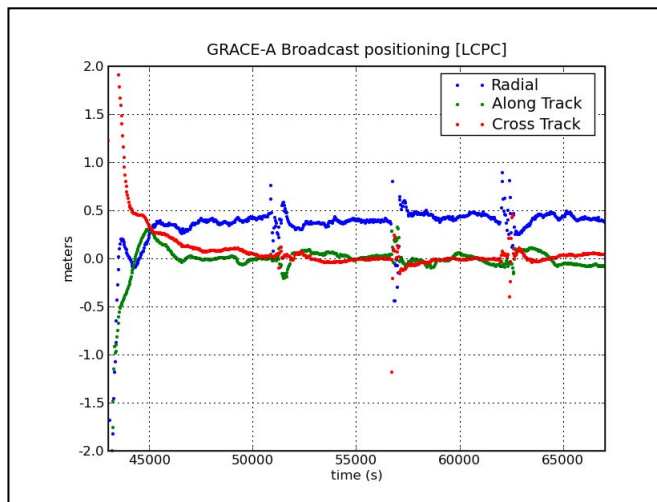

Figure 6.   GRACE-A positioning using kinematic PPP.

It is interesting to note that the bias in the Radial direction corresponds to GRACE-A antenna phase centre position with respect to satellite's centre of mass (0.414 m), confirming the accuracy of the gLAB-based solution.

Using the Google Earth® tool to plot the results obtained with gLAB for several GRACE-A ground tracks, Fig. 7 is obtained.
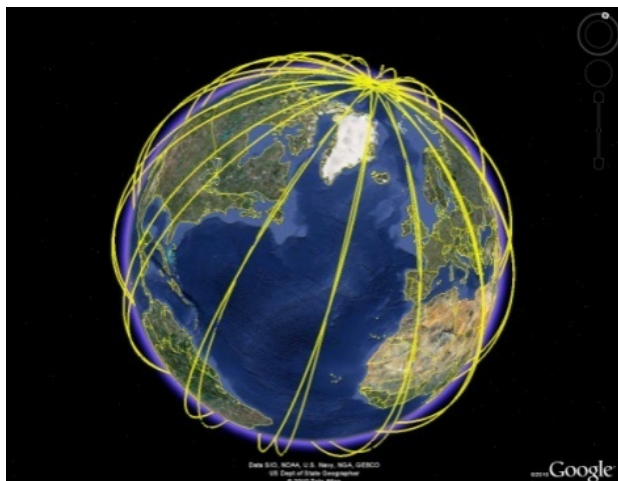

Figure 7.   GRACE-A ground tracks obtained with gLAB.

VII.   SUMMARY

The GNSS-Lab Tool suite (gLAB) is an advanced interactive educational multipurpose package to process and analyse GNSS data. The first release of this software package allows full processing capability of GPS data, and partial handling of Galileo and GLONASS data. In addition, the tool is prepared to incorporate future module updates, such as complete expansion for Galileo and GLONASS systems, as well as EGNOS.

From an operative point view, this tool is conceived as a software package to support a practical GNSS course, where the fundamentals introduced in the theory are experimented through guided exercises. In this way, the tool is conceived for being used:

- as part of a GNSS course with practical exercises integrated following a manual, or

- experimenting around with contextual help with hyperlinks for more information, or

- to process RINEX data and obtain both GPS Standard Positioning Service or Precise Point Positioning (PPP) solutions for specific research or GNSS applications development.

The GNSS-Lab Tool suite (gLAB), developed through contract with ESA Education Office, is intended to fill an educational gap supporting European university students and professionals to have a comprehensive knowledge of GNSS data processing.

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Detailed software features:

The gLAB tool features a wide range of characteristics only available in advanced GNSS data processing software:

- Graphic User Interface (GUI) to ease the utilisation of the tool with most of the capabilities of the DPC. The GUI allows a high customisation interface to process a wide range of options.

- Tooltips in the GUI, which allow understanding and using the different options.

- Capable of reading:

  o Station measurements from observation RINEX standard 2.11 and 3.00 files.

  o Navigation RINEX standard files.

  o Satellite clocks from Clocks RINEX files.

  o Satellite orbits and clocks from SP3 files.

  o Ionospheric maps from IONEX standard.

  o Constellation status (with information between Satellite Vehicle Number (SVN) and PRN) of the satellite.

  o Antenna Phase Centre information from ANTEX standard.

  o Differential Code Biases from precise DCB files.

  o Receiver type information from GPS Receiver File Types,

- The DPC is able to work both with command-line parameters and a configuration file.

- Automatic detection of RINEX 2.11/3.00 formats.

- Fully capable to read Galileo (and other constellations) data from RINEX.

- Able to process both pseudorange and carrier phase.

- Detection of cycle-slips in carrier phase measurements for GPS with three different methods:

  o Geometric-free carrier phase combination.

  o Melbourne-Wübbena combination.

  o Code-Phase difference (for single-frequency receivers),

- Time handling routines (the native time format of the software is Modified Julian Day and seconds of day).

- Prealignment of carrier phase to pseudorange measurements to avoid large differences between both kinds of measurements, allowing a more direct comparison. Alignment is done keeping the integer part of the carrier phase.

- Pseudorange jump checking. Some receivers have an inconsistent set of pseudorange and carrier phase measurements when they adjust their own clocks (introducing one or more leap milliseconds). Their pseudorange measurements are consistent with this clock change but carrier phases are not, creating an inconsistency and a cycle-slip for all satellites if not handled properly. gLAB detects and corrects this.

- Decimation capabilities. gLAB can decimate the input RINEX to increase computation speed when a high sampling rate is not needed. Decimation comes after cycle-slip detection to profit from full input data rate.

- Able to individually select/deselect each satellite.

- Able to set an elevation mask to ignore low satellites.

- Able to specifically mark which frequencies are available (to simulate single-frequency receivers from dual-frequency RINEX data).

- Pseudorange smoothing option.

- Orbit interpolation of SP3 data.

- Broadcast message support (orbit estimation, clock correction, TGD correction).

- Orbit/Clock comparison mode (it can compare the orbit and clocks from 2 different sources, i.e. broadcast, SP3 and clocks files).

- Sun approximate positioning (for satellite orientation).

- Models implemented (all of them can be enabled or disabled at will):

  o Satellite clock error correction.

  o Transmission time computation.

  o Earth rotation during flight time of signal.

  o Satellite phase centre correction.

  o Receiver phase centre correction.

  o Receiver Antenna Reference Point (ARP) correction.

  o Relativistic correction.

  o Klobuchar ionospheric correction.

  o Tropospheric correction (one simple model and the more refined Niell mapping model).

  o P1 – P2 Differential Code Bias (DCB) correction.

  o P1 – C1 Differential Code Bias (DCB) correction.

  o Wind-up effect.

  o Solid tides correction.

- o Gravitational delay correction (an effect of general relativity due to the gravity field gradient between receiver and transmitter).

- Able to choose different measurements (1 or more) for the filter estimation (both carrier phase and pseudorange). It could even work with a set of different pseudorange measurements from different signals. This could be useful in the future Galileo scenario, where some processing with different measurements can be desired.

- Able to assign different weights for different measurements.

- Able to assign elevation-dependent weights.

- Able to translate from native Cartesian coordinates to geodetic coordinates.

- Orientation estimation of both satellites and receiver (and thence the azimuth/elevation of the receiver-satellite pair).

- Standalone processing using broadcast and C/A code (fully configurable to be able to used also carrier phase if required).

- Precise Point Positioning (PPP) with precise orbit and clocks, precise models and Pc/Lc measurements (ionospheric-free combinations). It is also fully configurable.

- Able to create different plots to visualise the data processed.

- Detection and warning of convergence problems.

It is important to emphasize that gLAB is still under development, and new characteristics are added to this extensive list on a monthly basis.