A Novel Device for Autonomous Real-Time Precise Positioning with Global Coverage

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ABSTRACT

Precise Point Positioning (PPP) is a relatively new positioning technique providing centimeter-level error. PPP processes dual-frequency pseudorange and carrier-phase measurements from a single user receiver, using detailed physical models and corrections, and precise GNSS orbit and clock products calculated beforehand (for example products from IGS, the International GNSS Service). PPP is different from other precise-positioning approaches like RTK in that no reference stations are needed in the vicinity of the user receiver. The only observation data that must be processed are measurements from the user receiver. Another advantage of PPP is that since the GNSS orbit and clock products are by nature global, the PPP solutions are also global, i.e., the PPP approach works for a receiver located anywhere on or above the Earth surface, and the resulting position is referred to a well-known terrestrial reference frame (normally ITRF). PPP can be applied at post-processing level and also in real-time applications, provided that real-time input orbits and clocks are available. One disadvantage of standard PPP however is its relatively slow convergence time, which is of the order of an hour for decimetric accuracy, as compared to nearly instantaneous convergence with centimetric accuracy in short-baseline RTK.

In 2008 GMV introduced *magicGNSS*, a web application for high-accuracy GNSS data processing. *magicGNSS* is available online at http://magicgnss.gmv.com. A free account can be requested online for a one-month trial period. A PPP software module is available in *magicGNSS*, allowing the user the post-processing of dual-frequency static and kinematic RINEX measurement files. The PPP module supports GPS and GLONASS data. Satellite orbits and clock products are calculated internally in a transparent way for the user. GMV has developed an infrastructure for the generation of precise GPS and GLONASS orbits and clocks with very low latency in a first step, and in real time in a second step. The products generated this way are contributed to the IGS Real Time Pilot Project, and are also used to feed the PPP service, part of the web application *magicGNSS*.

The product generation is based on an Orbit Determination and Time Synchronisation (ODTS) process, which runs typically every 15 minutes. This process receives as input dual-frequency code and phase measurements collected in real time from a world-wide network of IGS stations, using the NTRIP protocol. Then, they are pre-processed also in real time by a Pre-Processing and Validation module (PPV) and made available to the different algorithms. In parallel to the ODTS, another process estimates the clocks in real time

taking as input the observations and the outputs from the last ODTS execution. There is a small latency in the delivery of the clock estimation, which is associated to the time that the algorithm waits for the arrival of the measurements from the station through the Internet, typically one or two seconds.

The GPS and GLONASS satellites are processed together, in order to ensure a consistent solution. It is necessary to estimate an inter-channel bias when processing GLONASS data. This must be done in order to compensate for the different internal delays in the pseudorange measurements through the GLONASS receiver, associated to the different frequencies used by the different satellites. The real-time orbits and clocks are available as a data stream to real-time processing algorithms (such as real-time PPP), and stored in standard formats (SP3, clock RINEX) for offline use. In the near future the products will contain also additional clock biases to allow the resolution of integer carrier-phase ambiguities in PPP, for improved positioning accuracy and shorter convergence time.

In parallel to the PPP product generation, GMV is developing a novel user terminal prototype for PPP, that can be connected to any GNSS receiver providing real-time raw measurements and navigation messages through a serial or USB port (in RTCM format), and can receive PPP orbit+clock corrections via GSM/GPRS (internet through mobile phone network) and also via Iridium (satellite based, with global coverage). This device is a self-contained, DC-powered case, containing mainly a Single Board Computer (SBC board) running Linux for the PPP client software, an additional board hosting the new Iridium 9602 modem, plus a LCD touch display for terminal control and visualization of results. The major advantage of this design is that the PPP user terminal can be connected to virtually any professional GNSS receiver in the market, since practically all of them are able to generate raw output in RTCM format via a serial or USB port.

For remote locations without GSM/GPRS coverage, satellite communications via Iridium shall be used. The Iridium SBD service has a low, uniform global latency reported to be of the order of half a minute. PPP service via Iridium is based on clock corrections sent at a rate of one minute; this is believed to be a reasonable compromise between positioning performances and communications costs.

This paper describes the implementation of GMV´s infrastructure for real-time PPP products and their usage in the new user terminal.

PRECISE POINT POSITIONING

PPP is a position location process which performs precise position determination using ionosphere-free measurements, obtained from the combination of undifferenced, dual-frequency observations coming from a single GNSS receiver, together with detailed physical models and corrections, and precise GNSS orbit and clock products calculated beforehand (for example products from IGS, the International GNSS Service). The quality of the reference orbits and clocks used in PPP is critical, as they are both two important error sources in GNSS positioning.

Apart from observations and precise reference products, PPP algorithm also needs several additional corrections which mitigate systematic effects which lead to centimeter variations in the undifferenced code and phase observations, for example phase wind-up corrections, satellite antenna offsets, station displacements due to tides (earth and oceanic), etc.

At a given epoch, and for a given satellite, the simplified observation equations are presented next:

$$l_P = \rho + c(b_{Rx} - b_{Sat}) + Tr + \varepsilon_P \qquad (1)$$
$$l_\emptyset = \rho + c(b_{Rx} - b_{Sat}) + Tr + N\lambda + \varepsilon_\emptyset \qquad (2)$$

Where:
  l_P is the ionosphere-free combination of L1 and L2 pseudoranges
  l_ϕ is the ionosphere-free combination of L1 and L2 carrier phases
  b_{Rx} is the receiver clock offset from the reference (GPS) time
  b_{Sat} is the satellite clock offset from the reference (GPS) time
  c is the vacuum speed of light
  Tr is the signal path delay due to the troposphere
  λ is the carrier combination wavelength
  N is the ambiguity of the carrier-phase ionosphere-free combination (it is not an integer number)
  ε_P and $\varepsilon_\circ$ are the measurement noise components, including multipath and other effects
  ρ is the geometrical range between the satellite and the receiver, computed as a function of the satellite (x_{Sat}, y_{Sat}, z_{Sat}) and receiver (x_{Rx}, y_{Rx}, z_{Rx}) coordinates as:

$$\rho = \sqrt{(x_{Sat} - x_{Rx})^2 + (y_{Sat} - y_{Rx})^2 + (z_{Sat} - z_{Rx})^2} \ (3)$$

The observations coming from all the satellites are processed together in a process that solves for the different unknowns; the receiver coordinates, phase ambiguity terms, the receiver clock offset and the zenith tropospheric delay.

Most implementations of PPP algorithms use a sequential filter in which the process noise for the coordinates is adjusted depending on the receiver dynamics, the time

evolution of the clock is more or less unconstrained (white noise with a high sigma), and the process noise for the tropospheric delay is adjusted to standard tropospheric activity. In the case of phase ambiguities, they are considered as a constant per pass.

Other implementations feature a batch algorithm instead, and therefore no process noise has to be modeled. In this case, the receiver clock offset is estimated at every measurement epoch, the coordinates are adjusted for all the observation interval (static mode) or per epoch (kinematic mode), the troposphere is estimated at regular fixed intervals and the ambiguities are also estimated per pass.

Given that PPP is not a differential technique, it cannot resolve integer carrier phase ambiguities (at least, without new enhancements). Hence, it cannot converge to a precise solution in a short time, as other techniques do (RTK, for instance), and requires longer observation times for static positioning.

PPP has been normally conceived as a global service, taking into account that the orbit and clock products are themselves global. This assumption can only be considered valid as long as the tracking network used for the computation of the precise products has worldwide coverage.

Under the previous assumption, good visibility of the satellites along all their orbits can be expected, and the accuracy of the orbit and clock estimations does not depend on the receiver location. This approach may lead to some limitations as there are mainly two options in order to fulfill the global coverage:

1. To deploy a global stations tracking network. This may be complex for political and logistic reasons for example, and possibly too expensive to operate for a regional service provider, whose target may not necessarily be to guarantee a global positioning service.

2. To relay on an external precise orbit and clock product provider. This may limit accuracy, real time capabilities and multisystem approaches. For instance, the IGS products (ultra-rapid, rapid, or final) are widely used due to their known high accuracy, however the IGS does not currently provide GLONASS clocks. Furthermore, oficial IGS products (IGS Real Time Pilot Project, http://www.rtigs.net/, provide precise ephemeris corrections with few seconds latency) have a latency of several hours, which makes them not valid for real-time PPP.

In the frame of this paper, and taking advantage of *magicGNSS* [1] tool, GMV has tackled the previously mentioned limitations by using their own precise GPS and GLONASS orbits and clocks products based on local tracking networks composed of IGS stations.

REFERENCE PRODUCTS FOR PPP

PPP positioning performances are directly related to the accuracy of the reference GNSS orbit and clock products. Therefore, prior to the performance comparison between PPP and RTK, the process followed for the generation of the precise satellite orbits and clocks used in regional PPP will be explained. A complex process as it implies facing the challenge of generating products for a real time PPP service.

For the past years, GMV has been developing an infrastructure for the generation of precise GPS and GLONASS orbits and clocks with very low latency in a first step, and in real time in a second step. A high-level layout of the infrastructure is shown in Figure 1.
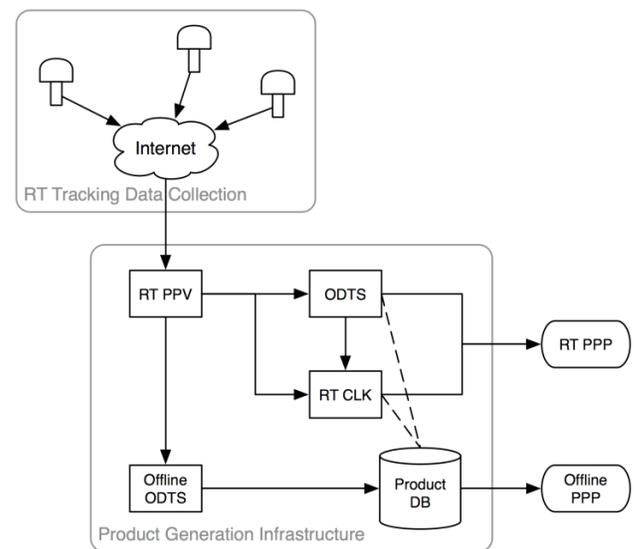
Figure 1 Product Generation Infrastructure High-level Layout

This process retrieves, from a worldwide station network, via Networked Transport of RTCM via Internet Protocol (NTRIP) (http://igs.bkg.bund.de/ntrip/ntriphomepage), dual-frequency code and phase measurements in real time.

Once collected, they are pre-processed also in real time by a Pre-Processing and Validation module (PPV), which then makes iono-free and geometry-free measurements available to the different algorithms.

The reference product generation is based on an Orbit Determination and Time Synchronisation (ODTS) process, which runs every 15 minutes. The ODTS processes 2-days

of data in every execution, and provides updated satellite orbits and other estimated parameters (such as phase ambiguities, station tropospheric zenith delays and Earth orientation parameters).

In parallel to the ODTS, another process called RT_CLK estimates the satellite clocks in real time taking as input the pre-processed observations coming from PPV and the outputs from the last ODTS execution. There is a small latency in the delivery of the clock estimation, which is associated to the time that the algorithm waits for the arrival of the measurements from the station through the Internet; typically one or two seconds.

Both GPS and GLONASS satellites are processed together, in order to ensure a consistent solution. It is necessary to estimate an *inter-channel bias* when processing GLONASS data. This must be done in order to compensate for the different internal delays in the pseudorange measurements through the GLONASS receiver, associated to the different frequencies used by the different satellites. Otherwise the station clock estimation would not be coherent with the pseudoranges. It has been observed that in GPS data this effect is much smaller and therefore negligible; normally it is not necessary to estimate such an inter-channel bias for GPS data.

The real-time orbits and clocks are available as a data stream to real-time processing algorithms (such as real-time PPP), and stored in standard formats (SP3, clock RINEX) to be used as GPS plus GLONASS reference products for *magicGNSS* PPP service.

The products generated this way contribute to the IGS Real Time Pilot Project since 2010, and are also used to feed GMV's PPP service, part of the web application *magicGNSS* [2].

The real time orbit and clock reference products performances versus IGS rapid products can be seen in Figure 2. It covers the period since mid 2010 till July 2011.
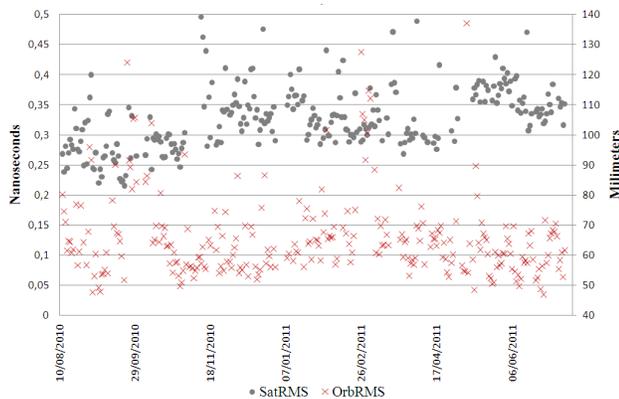
Figure 2 GMV's Real Time products VS IGS

The clock RMS stays around 0.3 ns and the 15 minute prediction orbit error stays around 6 cm.

As it is also represented in Figure 1, there is also an offline ODTS process running in off-line post-processing mode with a latency of 2 days and specific setup, which allows the generation of more precise products than the real time ones. When available, such products are then used for off-line PPP in replacement of the ones generated previously in real time.
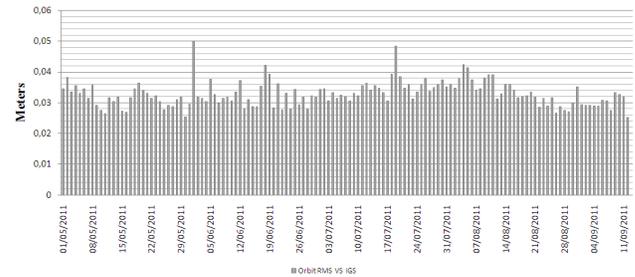
Figure 3 Orbit comparison between IGS products and off-line GPS products for 2011.
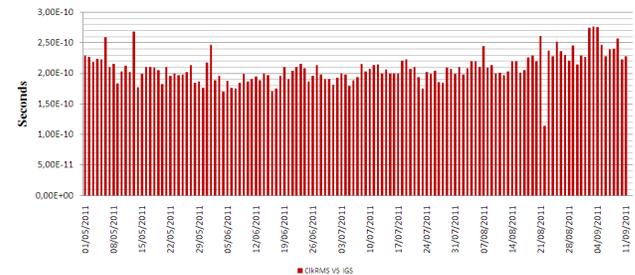
Figure 4 Clock comparison between IGS products and off-line GPS products for 2011.

The comparison of the off-line products with the IGS for a typical day is shown in Figure 3 for orbit and in Figure 4 for clocks. In this case the typical orbit performances are around 3cm, and clock accuracy is around 0.2 ns.

The network used, which is represented in Figure 5, provides global coverage and some redundancy to cover the relatively frequent (especially from some stations) outages of the real-time data streams. The different colours indicate the number of stations (also called Depth-of-Coverage or DOC) that are tracking a satellite when it is flying over a particular location.
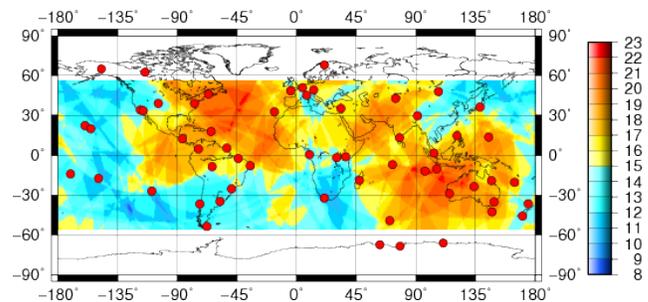
Together with the comparison of the off-line reference products with IGS rapid products, their quality is also assured by performing PPP for several IGS stations of known coordinates, over 1 day observation period.
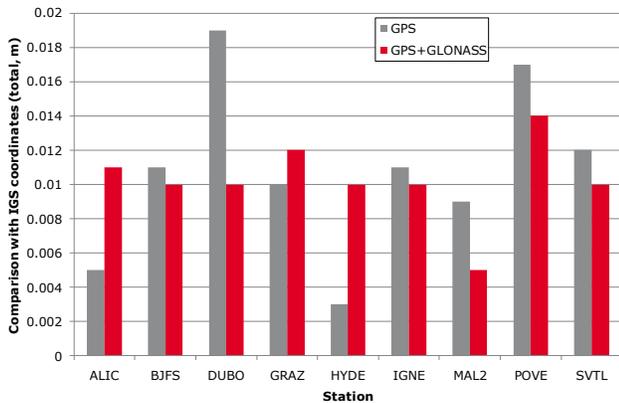
Figure 6 Static PPP Performances VS IGS coordinates (24-hours)

Figure 6 shows the positioning performances for 9 IGS stations with respect to the published IGS coordinates. It can be seen that the accuracy of the PPP solution is around 1 cm, both for GPS and GPS+GLONASS. This result illustrates the good quality of the reference products (both for GPS and for GLONASS) as well as the level of performances of the PPP algorithm.

CARRIER-PHASE AMBIGUITY RESOLUTION IN PPP

The biggest limitation of the PPP algorithm is that it takes at least one hour to achieve an accuracy of a few centimeters. In contrast, RTK needs only a few seconds. The main clue is that RTK is able to fix the carrier-phase ambiguities to their integer values, in a short period of time. On the other hand, PPP relies on a standard floating estimation, which requires a big amount of observation time to converge. And, in fact, ambiguities are the driver of the positioning performance.

There is an explanation for the absence of ambiguity fixing methods in most PPP algorithms. The carrier-phase observations contain station and satellite biases that cannot be separated from the ambiguity estimation. Thus, individual ambiguities cannot be fixed to integers. A well-known solution is to fix double-differenced combinations, which requires at least two stations (e.g. RTK). However, PPP processes data from only one receiver, and the mentioned strategy is not valid. Note that the above is only valid for GPS or Galileo: for GLONASS satellites, the receivers show satellite dependent biases (due to FDMA) and double-differences of ambiguities are still not integer.

There exists a different approach that is indeed valid for PPP. It requires the knowledge of the satellite fractional biases contained in the carrier-phase observations (also known as *uncalibrated phase delays* or UPDs). This approach requires an enhancement on both sides of the system:

- Server side: A process computes the UPDs using the data from the tracking station network. This amounts to fixing (a part of) the integer ambiguities after the estimation of the orbit and clock products, or as a dedicated algorithm. This is a setup where the ambiguity fixing problem is known to have a solution.
- Receiver side: The UPDs are transmitted to the receiver in the same way as other products (orbits and clock corrections). Then, the single differences with pairs of satellites can be fixed to integers, by using one of the existent methods.

The use of UPDs for PPP has been analyzed in other references (e.g. see [3, 4]). It has been observed that the phase delays are quite stable and that the whole concept works well in practice. The question remains open whether it can converge as fast as RTK, given that it cannot take advantage of the cancelation of terms that is characteristic of the latter. As an example, the due estimation of the tropospheric delay in PPP may put some limits, since it is not accurate for short observation periods. A possible mitigation is the combination of GPS and GLONASS satellites in PPP, even if only the former can be used for the integer ambiguity fixing. Note that for a dense reference network PPP should perform at the same level as RTK, but the greatest interest is in making it work with a small number of reference stations.

The strategy sketched above is the basis of the integer ambiguity resolution in the PPP service. It does not depend on the details of the ambiguity fixing techniques that are finally implemented. As mentioned, it requires a new message to transmit the satellite biases (UPDs) to the users. It is important to note that the iono-free ambiguities obtained from a PPP are not suitable for ambiguity fixing. The combinations used for that purpose are the wide and narrow lanes. Typically, the former is obtained in a dedicated estimation and the latter from the wide-lane and iono-free values. So, the messages should in principle contain the wide-lane and iono-free (or narrow-lane) combinations. However, if the iono-free UPDs are applied to the clock corrections, it is only necessary to transmit the wide-lane biases.

STATE-SPACE REPRESENTATION (SSR) FOR REAL-TIME PPP

As opposed to differential techniques such as RTK, absolute GNSS positioning relies on the precise knowledge of each of the individual measurement error

components for pseudorage and carrier-phase observations. Satellite-dependent errors are independent of the user receiver and can be broadcast to aid user precise positioning. Such errors include orbit and clock corrections, as well as "clock biases" needed for carrier-phase ambiguity resolution.

Orbit and clock corrections refer to broadcast orbit and clocks (satellite navigation messages) in order to reduce the amount of information and hence needed bandwidth. Navigation messages are readily available from any professional receiver that supports the latest version (3.1) of the RTCM standard (messages 1019 and 1020 for GPS and GLONASS, respectively), therefore this information does not need to be provided by the PPP service, only the corrections themselves are required.

RTCM SC-104 is a standard that defines the data structure for differential correction information for a variety of differential correction applications, in particular RTK. It was developed by the Radio Technical Commission for Maritime services (RTCM) and has become an industry standard for communication of correction information. Latest RTCM official version is 3.1.

A draft RTCM specification supports already real-time corrections for PPP in the so-called "state-space representation" [5] or SSR. RTCM-SSR consists of additional messages to the SC-104 standard. GPS orbit and clock corrections can be inserted in the new 1057 and 1058 messages, respectively, or in the "combined orbit + clock" 1060 message. For GLONASS, such messages are numbered 1063, 1064, and 1066, respectively.

Additional messages are needed for broadcasting wide-lane and narrow-lane biases used in PPP for carrier-phase ambiguity resolution. Unfortunately the current RTCM-SSR draft specification does not specifically accommodate for such biases, since ambiguity resolution in PPP is a very recent advance. A possible work-around is to re-utilize some of the existing messages, like for example message 1059 for GPS code bias (1065 for GLONASS). This option has been selected by the CNES team in their PPP-Wizard project [6]. Another possibility is to slightly adapt the RTCM-SSR standard to accommodate for proprietary messages. This is the solution adopted by GMV. The final implementation has not yet been decided.

RTCM messages are suitable to be sent over the radio or the internet. The NTRIP standard has been specifically developed to develop RTCM corrections over the internet. "Networked Transport of RTCM via Internet Protocol" (NTRIP) stands for an application-level protocol streaming GNSS data over the Internet. NTRIP is a generic, stateless protocol based on the Hypertext Transfer Protocol HTTP/1.1. The HTTP objects are enhanced to GNSS data streams. NTRIP is an RTCM standard designed for disseminating differential correction data (e.g., in the RTCM-104 format) or other kinds of GNSS streaming data to stationary or mobile users over the Internet, allowing simultaneous PC, Laptop, PDA, or receiver connections to a broadcasting host. NTRIP supports wireless Internet access through Mobile IP Networks like GSM, GPRS, EDGE, or UMTS.

The rate of PPP corrections sent via RTCM/NTRIP is 15 min for orbits, 1 min for clocks, and 1 min for ambiguity-fixing biases.

PPP MESSAGES OVER IRIDIUM

Iridium is a constellation of 66 satellites (6 planes of 11) in polar orbit at a height of 780 km, used for worldwide voice and data communication from hand-held satellite phones and other transceiver units. The Iridium network is unique in that it covers the whole Earth, including poles, oceans and airways. Iridium operates in the 1610.0-1626.6 MHz frequency band.

For PPP we intend to use the Iridium Short Burst Data (SBD) service, which allows two-way communications to a mobile transceiver. Using the new Iridium 9602 modem, the SBD service allows Mobile Originated (MO) messages up to 340 bytes, and Mobile Terminated (MT) messages up to 270 bytes. The Iridium 9602 modem has been selected due to small size and low power consumption.

Remote Applications send MO-SBD data messages via an Iridium Transceiver. The application microcontroller or microprocessor communicates with the Transceiver using AT commands over an RS232 serial port. The application loads the data message into the Transceiver and instructs it to send the data message. The data message is transmitted across the Iridium satellite network to the Iridium Gateway. From there, the data message is transferred via e-mail or an IP Socket to GMV's host computer system. Here the message is stored in a database for further data processing.

Mobile Terminated SBD (MT-SBD) messages are sent to the Iridium Gateway via e-mail or IP Socket from GMV's host computer system. With appropriate configuration and provisioning, the Iridium Gateway will send a 'Ring Alert' to the Transceiver when a MT-SBD message has been queued. The Mobile Application will then decide whether to retrieve the MT-SBD data message at that time or later.

According to Iridium figures, global network transmit latency for delivery of messages ranges from approximately 5 seconds for short messages to

approximately 20 seconds for maximum length messages. This latency is the elapsed time before the Iridium SBD system sends the SBD message to its e-mail destination. Additional latency introduced by the Internet is not in Iridium's control. Experience shows that actual latency is between 20 and 30 seconds.

The rate of Iridium messages containing PPP corrections is the same as the rate via RTCM/NTRIP: 15 min for orbits, 1 min for clocks, and 1 min for ambiguity-fixing biases. No performance degradation expected due to this correction transmission method, taking into account the short message delay from the server to the user terminal (around half a minute).

USER TERMINAL OVERVIEW

GMV is developing a novel user terminal prototype for PPP. The terminal can be connected to any GNSS receiver providing real-time raw measurements and navigation messages through a serial or USB port (in RTCM format).

The terminal receives PPP orbit+clock corrections via GSM/GPRS (internet through mobile phone network) or, in remote location without mobile internet, via Iridium (satellite based, with global coverage). The device consists of a self-contained, DC-powered case, containing mainly a Single Board Computer (SBC board) running Linux for the PPP client software, an additional board hosting a GSM modem and the new Iridium 9602 modem, plus a LCD touch display for terminal control and visualization of results.

The major advantage of this design is that the PPP user terminal can be connected to virtually any professional GNSS receiver in the market, since practically all of them are able to generate raw output in RTCM format via a serial or USB port.

The device is DC-powered and can be plugged into a 12-volt car socket. The GSM swivel antenna is attached to the terminal. A 5-cm diameter Iridium magnetic antenna, can be attached to a car roof, normally close to the GNSS receiver antenna.

The LCD touchscreen gives access to a dedicated Graphical User Interface than can be used to start/stop the PPP application and visualize the resulting trajectory. For demonstration purposes, a RTK solution (based on RTKLIB) can be compared to PPP solution in real time on the device screen.

Computations are carried out in a Single Board Computer (SBC) running Debian Linux. The SBC is based on an inexpensive Intel Atom @ 1.1 GHz. Typically PPP and RTK processes take only around 5% of CPU each.

Figure 7 The PPP user terminal prototype

Figure 7 shows a photograph of the user terminal prototype. From upper left to lower right the following elements can be seen on the case side: LEDs for power on/off and Iridium coverage, Ethernet socket (for maintenance and debugging), power socket, on/off button, SMA connectors for GSM and Iridium antennas, and RS-232 serial port for GNSS receiver.

ACKNOWLEDGEMENTS

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