Filling in the gaps of RTK with Regional PPP

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ABSTRACT

A growing number of GNSS users are demanding highly-accurate positioning services with minimal latency and maximal availability.

Within the existing techniques which allow real time positioning, Real Time Kinematic (RTK) and Precise Point Positioning (PPP) may be the most widely spread ones.

Although both positioning techniques use dual-frequency pseudorange and carrier-phase measurements, PPP differs from RTK in that no observation data from reference stations, with precise known coordinates, are needed in the proximity of the user receiver. The only observation data that must be processed are measurements from the user receiver. It also removes the need of having simultaneous observations on both target receiver and base station receiver.

Although the PPP concept is commonly understood as a global technique, it is possible to develop a regional PPP service by using a relatively sparse regional network of base stations to compute the reference orbit and clock products. This new approach is a very attractive complement to the existing RTK networks, as it allows providing precise positioning services far away from the existing base stations without the need for deploying additional sites. One example would be a relatively large region (> 500 km wide) with RTK coverage on two or three distant areas.

This paper presents in more detail the concept of regional PPP, and addresses the performances achievable in regions of different sizes. The required density of reference stations is analyzed, and the performances are evaluated versus PPP with global products and versus RTK.

REAL TIME KINEMATIC

RTK (Real Time Kinematic) is a differential positioning method, developed in the early 1990's, based on the use of dual-frequency carrier phase measurements of the GNSS (GPS, GLONASS, QZSS, COMPASS, etc) signals where a base station receiver at a well known, calibrated location transmits signal corrections in real time to one or several rover receivers.

RTK corrections compensate atmospheric delay, orbital and clock errors, etc, increasing positioning accuracy up to the centimeter level.

RTK is a technique employed in applications where precision is mandatory; it is not only used as a precision positioning tool, but also in automatic machine guidance activities such as precision farming.

The positioning determination process begins with a preliminary ambiguity resolution. This is a crucial aspect of any kinematic system, particularly in real-time where the velocity of a rover receiver should not degrade either the achievable performance or the system's overall reliability.

The correction data is typically sent via UHF or spread spectrum radios that are built specifically for wireless data transfer. The corrections from the base station receiver can be sent to an unlimited number of rovers.

One of the main limiting factors of RTK is the maximum distance, in terms of acceptable performances, between the base station and the rover, so it implies having a rather large density of base stations to ensure a proper coverage in large areas. The variability of both the troposphere and the ionosphere introduces systematic errors which limit this maximum allowable distance for obtaining precise positioning to 10 or 20 km.

In order to tackle this distance problem, the concept of Virtual Reference Station (VRS) was introduced in the year 2000 [1]. VRS allows performing RTK positioning in reference station networks with distances of up to 40 km. The idea is to generate Virtual Reference Stations which simulate a local base station close to the user receiver. Thus, the errors cancel out better than by using a more distant base station. However, even 40 km distance between base stations may still imply a rather large station density for big areas.

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:

$$l_P = \rho + c(b_{Rx} - b_{Sat}) + Tr + \varepsilon_P \tag{1}$$

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

Where:

l_P is the ionosphere-free combination of L1 and L2 pseudoranges

$l\phi$ 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 ε_ϕ 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:

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

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* [2] 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.

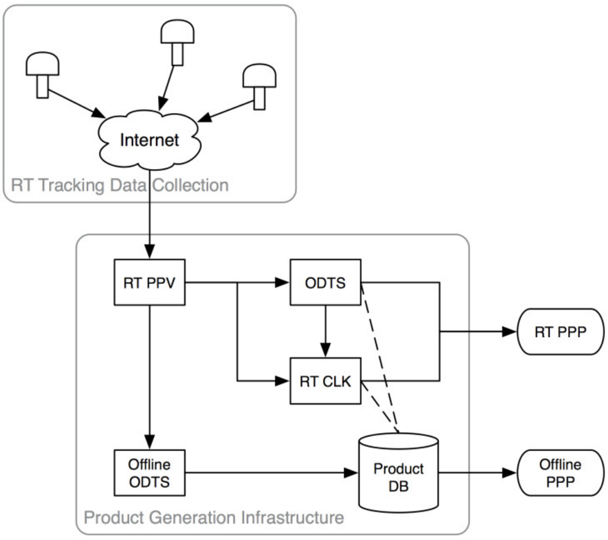

Figure 1 Product Generation Infrastructure High-level Layout

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 estimate, 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 estimate 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* [3].

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.

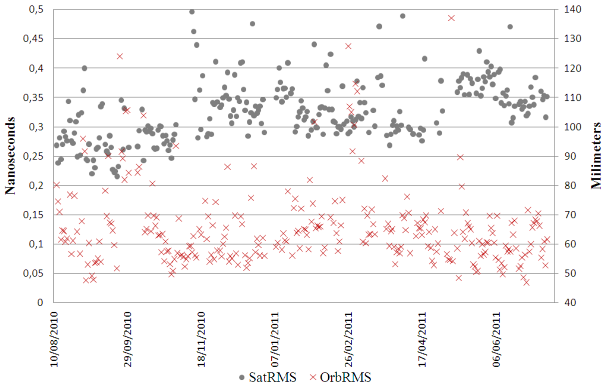

Figure 2 GMV's Real Time products VS IGS

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.

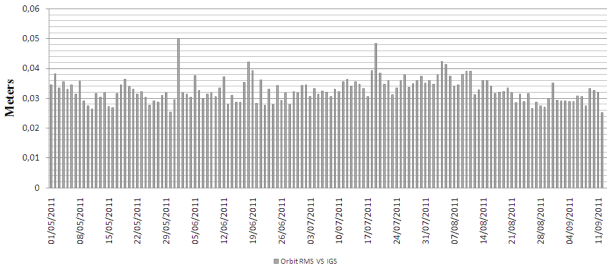

Figure 3 Orbit comparison between IGS products and off-line GPS products for 2011.

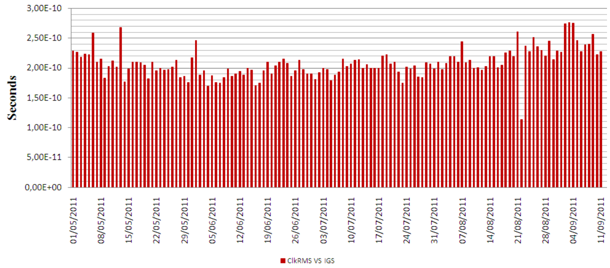

Figure 4 Clock comparison between IGS products and off-line GPS products for 2011.

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 0.2ns.

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.

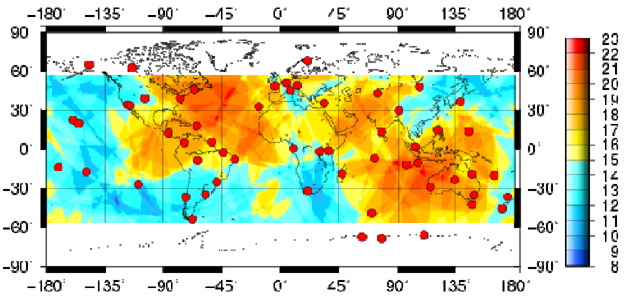

Figure 5 NTRIP Tracking Station Network

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.

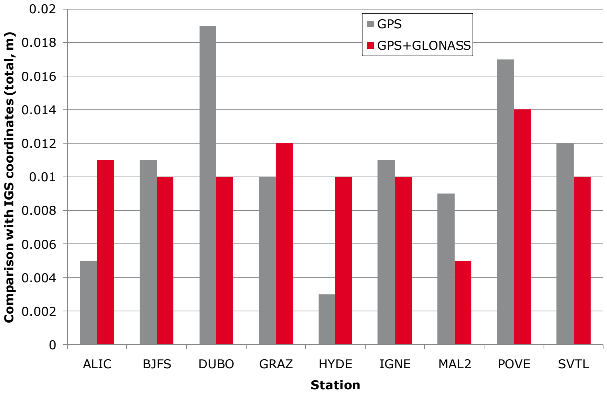

Figure 6 Static PPP Performances VS IGS coordinates (24-hours)

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.

The content of this paper focuses on the regional PPP concept, and therefore, the GPS plus GLONASS reference products for *magicGNSS* PPP have not been used in the analyzed cases due to their worldwide coverage. However, GMV's product generation infrastructure has been used to generate the regional reference products used throughout this paper, and it will be explained in the following section.

GLOBAL VS REGIONAL PPP

The accuracy of the satellite clocks and orbits is probably one of the most important factors affecting the quality of the PPP solution. This does not necessarily mean that the accuracy of these reference products has to be global, it is only necessary to ensure their quality in the proximity of the target receiver.

This fact makes it therefore feasible for a regional PPP service provider to obtain highly accurate reference products with local applicability based on GNSS observations from a reduced set of local stations, without having to rely on the availability of global reference products coming from external providers, nor investing a large budget on a global tracking network infrastructure.

In this section *magicGNSS* has been used to generate 2 sets of local reference products for Australia and Brazil, and to compare PPP performances in both countries when using as reference products, precise clock and orbits coming from the regional solution and IGS final products.

The first scenario compares the coordinates of ALIC, XMIS and PIMO stations obtained by means of 2 PPP, one using IGS final products and the second one using as reference products the orbit and clock outputs obtained from an ODTS process based on the observations coming from a regional network (5 IGS stations, the yellow station is the master station which determines the time reference).

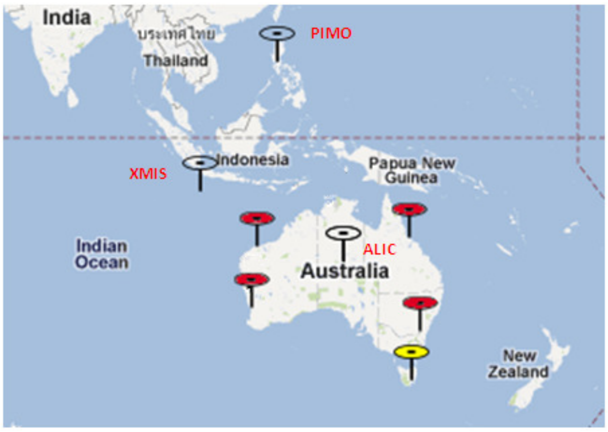

Figure 7 Australian Regional Tracking Station Network.

The coordinate comparison statistics in Figure 8 shows how, as the receiver lies further from the local network, the regional PPP performance degrade versus PPP using IGS final products.

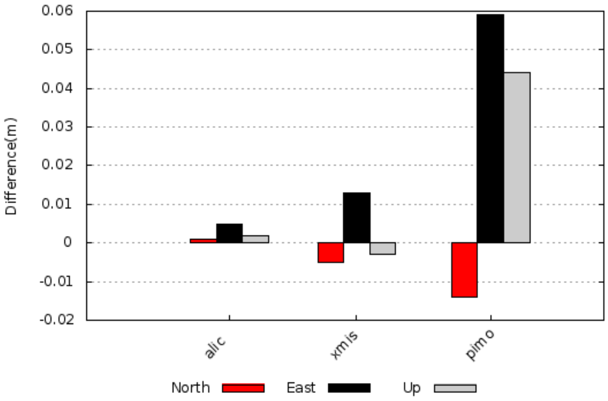

Figure 8 Coordinate comparison in Australia

The second scenario compares the coordinates of BRAZ, CONZ and ISPA stations obtained by means of 2 PPP, one using IGS final products and the second one using as reference products the orbit and clock outputs obtained from an ODTS process based on the observations coming from a regional network (5 IGS stations, the yellow station is the master station which determines the time reference).

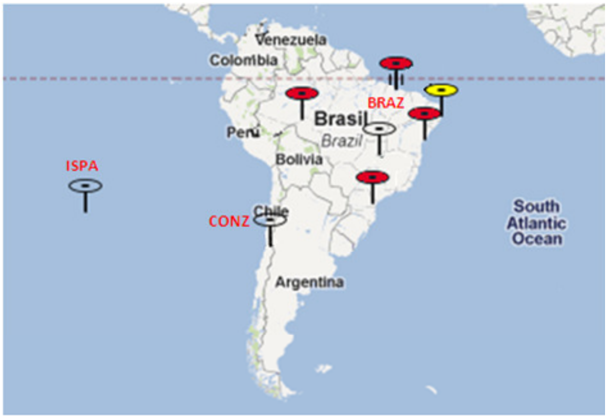

Figure 9 Brazilian Regional Tracking Station Network

The coordinate comparison statistics in Figure 10 show how, as the receiver lies further from the local network, the regional PPP performance degrade versus PPP using IGS final products.

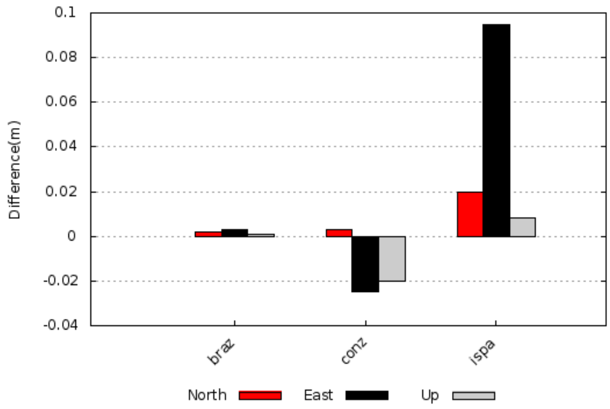

Figure 10 Coordinate comparison in Brazil

Only 5 stations have been necessary to ensure comparable performances between regional and global PPP for rather large areas (5th and 6th largest countries in the world).

This results show that when trying to obtain high precision performances in a local region, regional PPP technique is a good choice in order to avoid external product data dependence or large investments on global infrastructures, as only a few stations are needed to obtain the desired performances.

Nevertheless, it seems also clear the tradeoff between the regional network coverage and the validity of the PPP solution as the distance from the network increases.

The advantage of not having to ensure global accuracy for the reference products used in regional PPP, allows a regional PPP service provider to take a further step towards its independence from possible external providers, not only for obtaining the reference products (coming from IGS, for instance), but also for the dependency of GNSS constellations.

As an alternative to GNSS constellations (global navigation satellite systems such as GPS, GLONASS, GALILEO or COMPASS), regional satellite navigation systems, such as LCNSS (Low Cost Navigation Satellite System [4]), can be designed for optimizing positioning performances over a certain regional area while minimizing space and ground segment costs. This can be achieved by using geosynchronous orbits and optimizing the constellation parameters (inclination, eccentricity, number of planes, phasing between planes and satellites within each plane) to provide the required performances over the required coverage area.

Unfortunately, the only currently planned autonomous (the Quasi-Zenith Satellite System (QZSS) is an enhancement for GPS, not a fully autonomous satellite navigation system) regional satellite navigation system; IRNSS (the Indian regional Navigational Satellite System), is not yet operational. The first satellite of IRNSS is expected to be launched in last quarter of 2011 according to ISRO (Indian Space Research Organization, www.irnssindia.com), and therefore, no regional PPP results based on regional satellite navigation system could be presented on this paper.

RTK VS PPP IN POST-PROCESSING

Once the performances of regional PPP strategy have been tested against global PPP, it will now be compared with RTK both in post-processing and in real time modes using kinematic data.

The post-processing scenario consists of an open field terrestrial trajectory of around 2.5 km, without obstacles that may reduce the visibility, of around 30 minute of duration. A Topcon Hyper Plus receiver was mounted on the roof of a van and taken on a circular tour near GMV’s headquarters in Madrid.

The dataset was recorded on June 23rd 2010. Figure 11 shows both the rover trajectory and GAP1 base RTK station, located at GMV’s roof.

Figure 11 Rover trajectory and GAP1 station

In this case, the regional sensor station network chosen for the regional PPP reference product generation had European coverage and can be seen in Figure 12.

The network is composed of 8 IGS stations in Europe, where WTZR (Wettzell / Germany www.bkg.bund.de) station was used as ODTS time reference for the reference product generation.

Figure 12 European Regional Tracking Station Network.

The rover trajectory was estimated both by means of a regional PPP and RTK using GAP1 as base station. The comparison through time for both RTK and regional PPP trajectories is depicted in Figure 13.

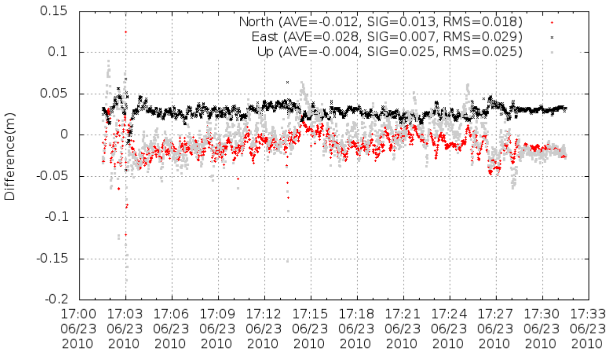

Figure 13 RTK vs Regional PPP trajectory comparison

From Figure 13 it is clear that the performances of the two positioning techniques are comparable (RMS position error in all 3 components is below 3cm), proving that reliable trajectories of a moving receiver can be calculated by means of PPP, using reference clocks and orbits obtained with a regional station network.

The main RTK limitation, which was the principal motivation for this paper, is that in order to ensure high positioning precision, the receiver/rover has to be in the proximity (within a few kilometers distance) of the base station, whereas in the regional PPP strategy, a small set of stations can provide accurate positioning for rather large areas (as shown in the previous section for Australia and Brazil).

In this paper it has been analyzed the RTK performance degradation as the distance between the rover and the base station increases. In order to do so, 5 RTK processes were performed to determine the rover trajectory using as base stations 5 different stations (MADR, EBRE, 3CAN, PENA and VILL). The station positions can be seen in Figure 14.

Figure 14 RTK base stations, Spain and Madrid

Table 1 show the comparison between the trajectory obtained via RTK using GAP1 station (about 1 kilometer from the rover) as base station and the ones obtained when using the other 5 stations as base stations in the RTK process.

	Distance to GAP1 (m)	RMS North (cm)	RMS East (cm)	RMS Up (cm)
PPP	-	1,8	2,9	2,5
3CAN	2,5	0,7	0,8	1,4
VILL	25	3,0	2,9	3,7
MADR	50	4,2	5,4	5,5
PENA	116	10,7	6,0	14,7
EBRE	360	21,7	14,1	27,3

Table 1 Trajectory comparison w.r.t. RTK with GAP1

It seems quite clear from the obtained results that in a scenario where no base station is available within less that 25 km from the rover/receiver, choosing a regional PPP approach instead of performing an RTK process for obtaining accurate positioning may me a better choice.

RTK VS PPP IN REAL TIME

The results of the previous section seems to be valid for post-processing applications, but the regional PPP performances vs RTK in a real time scenario are still to be tested, where the convergence time for both methods, differ.

that PPP is not a differential technique, it cannot resolve integer carrier phase ambiguities (at least, without new enhancements). This fact makes the convergence period longer than in RTK.

In order to compare RTK and PPP performances in real time, data coming from GAP1 receiver via NTRIP was processed for around 46 minutes.

For RTK, rtklib tool (www.rtklib.com) was configured to retrieve data from GAP1 and IGNE stations via NTRIP protocol. IGNE was used as base station.

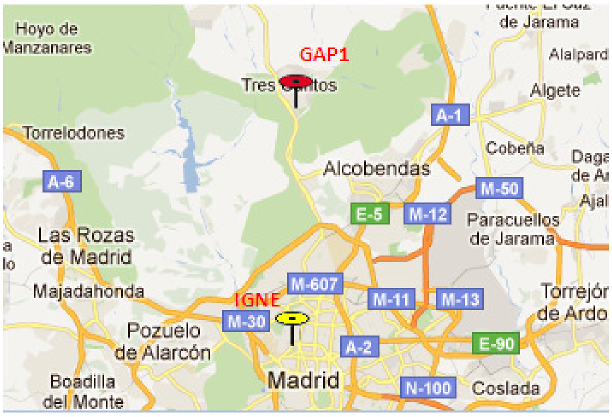

Figure 15 RTK real time scenario in Madrid

For real time PPP, GMV's core infrastructure described in Figure 1 was used to generate the real time reference products with which to perform the PPP. The set of stations used to generate the reference products come from an NTRIP European network as in the previous section.

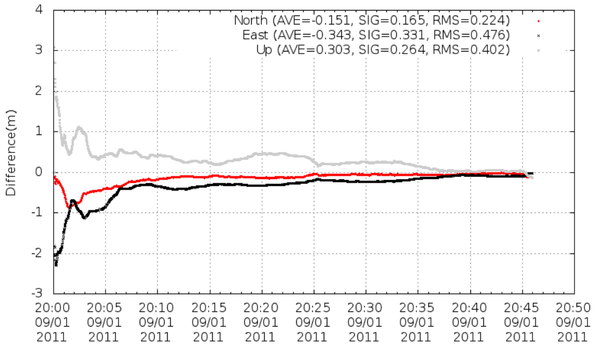

Figure 16 RTK vs Regional PPP in real time

Figure 16 compares the estimated coordinates for GAP1 station both with RTK and PPP in real time for the 46 minute observation period. It can be seen how the PPP real time technique require longer convergence time than RTK due to the ambiguity estimation problem.

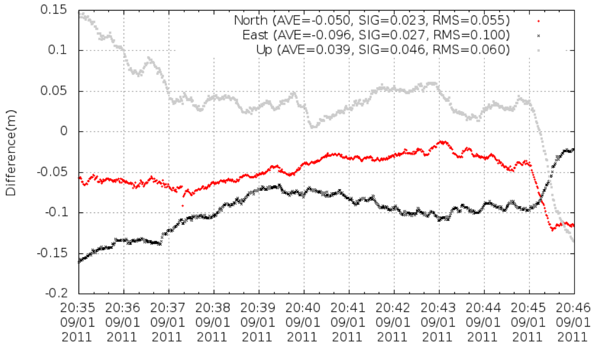

Figure 17 RTK vs Regional PPP after 35 min

Figure 17 shows how after 35 minutes, real time PPP and RTK have converged to the same position solution with comparable accuracy to the post-processing case.

CONCLUSIONS AND FUTURE WORK

Regional PPP has shown comparable positioning accuracy to PPP with global products and RTK, both with static and kinematic data.

Together with the obtained performances, regional PPP has shown to be a plausible solution for obtaining high position precision for local environments with minimal investment and external dependency compared to a global PPP service.

Regional PPP concept stands as an enhancement complement for RTK which sparse base station networks.

The convergence time needed by PPP in real time applications needs to be improved so that PPP can be accepted as a plausible alternative to RTK in scenarios where accurate position needs to be known after a few minutes or seconds. The best option is to implement integer ambiguity resolution as in RTK, using a scheme where fractional satellite biases are transmitted to the rover to avoid the need of double-differencing with respect to a reference station (as in RTK).

PPP and RTK performances in real time with a moving rover remain to be tested.

ACKNOWLEDGMENTS

RTK solution is calculated using RTKLIB developed by Tomoji Takasu (gpspp.sakura.ne.jp/rtklib/rtklib.htm).

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