Applying differential corrections to PVT estimates to reduce positioning error

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ABSTRACT

Solutions and applications based on Global Navigation Satellite Systems (GNSS) have experienced a boost in the recent years, despite being already active for more than 30 years. This boost is mainly due to the myriad of mobile devices (smartphones, Unmanned Aerial Vehicles, vehicles, Internet-of-things devices...) equipped with a low cost GNSS chipset. In this context, the European GNSS Agency (GSA) reports that Location Based Services and road applications based on those devices represent alone more than 90% of the total positioning market (source: GSA market report, March 2015). Most of these devices, however, are systems based on closed hardware that deliver only filtered PVT (Position Velocity Time) estimates, with no access to raw measurements. This does not allow the application of classical Differential GNSS techniques such as Real Time Kinematic (RTK) in order to obtain more accurate baseline estimation (and absolute position if the coordinates of the reference receiver are precisely known). This work shows the preliminary results achieved with an algorithm that directly combines PVT estimates (rather than raw measurements) with I-UERE (Ionosphere - User Equivalent Range Error) corrections provided by a nearby GNSS reference receiver. These range error corrections are projected into position domain and applied to the PVT solution in a Least Mean Square (LMS). The improvement of this technique can amount to a reduction in bias of 0.5m to 1m in each position component in conditions where the ionospheric delay is high (low latitudes, local noon, ionospheric storms).

Keywords: GNSS, RTK, differential techniques, mass-market receivers

INTRODUCTION

As it is known, the real-time high-precision positioning market is dominated by differential techniques such as Real Time Kinematics (RTK) that mostly use double-frequency geodetic grade receivers. The accuracy of such techniques (as well as other differential techniques) is on the order of centimeters, but the applicability of such differential techniques is limited to short (<20km) baselines. Such baseline can be partially extended by using techniques such as Virtual Reference Stations (VRS, [1]) or Wide Area RTK (WARTK, see [2]). Alternatively, high-precision can be achieved with Precise Point Positioning (PPP, [3]), which can be used in cases where there are no reference receivers, but requires the provision of precise GNSS orbits and clocks. In PPP, similar performances (error of centimeters) can be obtained using also geodetic grade receivers.

In mass-market applications, devices (smartphones, car navigators, position sensors in drones or automobiles) usually make use of a low cost GNSS chipset that is usually a single-frequency receiver. Even though some efforts have been made to make accessible the raw GNSS measurements in mass-market devices such as smartphones ([4]), the carrier phase measurement is not usually available in such devices ([5]) due to critical constraints in battery life, that force the implementation of duty-cycling that trigger a cycle-slip at each sample ([6]), rendering the carrier-phase observable useless. In general, such mass-market devices have to be considered a black box that delivers only the position directly through a data stream in e.g. NMEA format ([7]). In some cases, this chipset is able to receive and process data from Satellite Based Augmentation System (SBAS) which might reduce to some extent the ionospheric delay due to the use of a ionospheric model based on a grid, rather than using the Klobuchar model ([8]). In those cases, sub-meter accuracies can be achieved in best conditions scenarios.

For other low cost devices, where neither the ranges are available nor the SBAS corrections can be used, there are still other possibilities to improve accuracy. Several patents (see for instance [9]) describe Central Processing Facilities (CPF) that receive locations from rover devices and refine them using a set of state corrections that consist mainly on ionospheric corrections, but may be extended in the future to include orbits and clocks and/or tropospheric corrections. Alternatively, as shown in this work, one could apply differential techniques to improve the PVT estimates ([10]). Such differential techniques might be used to reduce one of the most critical error sources of the GNSS signal: the ionosphere. The main difference of the proposed technique relative to classic DGNSS is that this technique does not need the pseudoranges, it generates corrections in the position domain that can be then applied locally (in the device) to refine the position estimates. This paper describes this technique and provides the preliminary estimated improvement based on a set of tests done using a prototype implementation.

ALGORITHM

Since the raw measurements are not available, the classic differential techniques cannot be conventionally applied in this case. To do so, an alternative method based on projecting the STEC into the position domain is proposed.

The basic assumption of the proposed algorithm is that the main source of error in single frequency GNSS receivers, after the orbits and clocks errors (i.e. broadcast orbits and clocks), is the ionospheric delay. Furthermore, an additional assumption (inherited from differential techniques) is that this ionospheric delay (caused by the Slant Total Electron Content or STEC) is similar to the one experienced by a nearby (<10km) reference receiver.

Also, since the algorithm assumes that no raw measurements are available, the correction has to be made in the position domain. Therefore, the core of the algorithm is to obtain the STECs seen by nearby reference receiver(s) and project each of these STECs (one per line-of-sight) into a state correction vector. The rover device determines its position, ***r'***, by computing and applying a correction vector, $\Delta \boldsymbol{r}$, to the initial position estimate, ***r***:

$$\boldsymbol{r}' = \boldsymbol{r} - \Delta \boldsymbol{r} \tag{1}$$

The components of this correction vector, $\Delta \boldsymbol{r}$, are defined as

$$\Delta \boldsymbol{r} = (\Delta x, \Delta y, \Delta z) \tag{2}$$

The correction vector ($\Delta \boldsymbol{r}$) is then obtained by solving the following linear system:

$$\begin{pmatrix} \Delta x \\ \Delta y \\ \Delta z \end{pmatrix} = (A^T \cdot \mathrm{W} \cdot \mathrm{A})^{-1} A^T \cdot W \cdot \begin{pmatrix} IUERE_1 \\ IUERE_2 \\ \vdots \\ IUERE_N \end{pmatrix} \tag{3}$$

where:

$$A = \begin{pmatrix} p_{1,x} & p_{1,y} & p_{1,z} \\ p_{2,x} & p_{2,y} & p_{2,z} \\ & \vdots & \\ p_{N,x} & p_{N,y} & p_{N,z} \end{pmatrix} \quad (4)$$

and:

$$W = \begin{pmatrix} w_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & w_N \end{pmatrix} \quad (5)$$

In this linear system, the matrix $\boldsymbol{A}$ is constituted by $p_{j,x}$, $p_{j\ y}$ and $p_{j,z}$, the *range partials*, which determine the displacement of each Cartesian component $(\Delta x, \Delta y, \Delta z)$ for a given range error (I-*UERE*). The system also includes a weighting matrix W, used to weight each observation. This weight will be usually dependent on the elevation (el_j) of the observation. A typical weighting approach is to use $w_j = 1 / sin(el_j)$. In other words, this step is the projection from the error in range to an error in each of the three Cartesian components. For convenience, the partials for a measurement will be expressed in vector form as follows:

$$\boldsymbol{p}_j = (p_{j,x}, p_{j,y}, p_{j,z}) \quad (6)$$

These partials are computed from the azimuth and elevation of each range measurement, as follows:

$$\begin{aligned} \boldsymbol{p_j} &= E(\lambda, \phi) \cdot \vec{u}(az_j, el_j) \\ &= \begin{pmatrix} -\sin\lambda & -\cos\lambda \cdot \sin\phi & \cos\lambda \cdot \cos\phi \\ \cos\lambda & -\sin\lambda \cdot \sin\phi & \sin\lambda \cdot \cos\phi \\ 0 & \cos\phi & \sin\phi \end{pmatrix} \cdot \begin{pmatrix} \cos el_j \cdot \sin az_j \\ \cos el_j \cdot \cos az_j \\ \sin el_j \end{pmatrix} \end{aligned} \quad (7)$$

where:

- $\vec{u}(az_j, el_j)$ is the unitary direction vector of the line-of-sight between the j-th transmitter and reference receiver, which depends exclusively on the azimuth and elevation (az_j and el_j respectively). This is expressed in local geodetic frame East, North and Up (ENU) components.
- $E(\lambda, \phi)$ is the matrix that transforms from ENU components to XYZ Cartesian coordinates and it depends on the longitude (λ) and latitude (ϕ) of the rover receiver, therefore it is common to all transmitters in view.

Note that, in low cost GNSS receivers, that usually deliver NMEA streams with the solutions, the longitude and latitude values are published in the RMC or GGA messages while the azimuth and elevation of each satellite are usually also available the e.g. GSV message of the NMEA stream (see [7]).

So far, the only external information that is required is the IUERE for each satellite in view. As stated before, the main assumption is that the main source of error is due to the ionosphere, more specifically, the residual non-corrected ionospheric error due to the delay difference between the internal ionospheric model (usually Klobuchar) and the actual delay due to the ionosphere. In general terms:

$$IUERE_j = \frac{40.3}{f_1^2} \cdot STEC_j \qquad (8)$$

Where f_1 is the frequency of the L1 GPS carrier (1.57542GHz, which is the frequency tracked by most of the low cost GNSS receivers), and STECj is the slant total electron content (integral of the ionospheric electron density along the line of sight) between the j-th transmitter and the reference receiver.

The STEC is the data that has to be provided by the reference receiver. To be able to estimate such STEC, a dual-frequency geodetic grade receiver that is able to track code and phase is required. In this case, the code-aligned phase (in offline processing) or phase-aided smoothed code (in real time operations) at both frequencies are subtracted to form the ionospheric combination (LI_j):

$$LI_j = L1_j - L2_j = \left(\frac{40.3}{f_2^2} - \frac{40.3}{f_1^2}\right) \cdot STEC_j + DCB_j + DCB_{ref} \qquad (9)$$

where $L1_j$ and $L2_j$ are the raw measurements at the two GNSS frequencies (f_1 and f_2) and DCB are the Differential Code Biases (e.g. bias between the codes at the two frequencies, see [11]). Therefore, these biases have to be removed so that the rover receiver can use a set of unbiased STEC measurements. Fortunately enough these DCB are slowly varying in time and can be calculated regularly in post-process. While the satellite DCB (DCB_j) can be obtained from analysis centers such as CODE, the reference receiver DCB has to be estimated. The receiver DCB is obtained by averaging the residuals between the observed ionospheric combination of all satellites (LI) and the modelled ones ($\widetilde{LI}$), like so:

$$DCB_{ref} = \langle LI - \widetilde{LI} \rangle \qquad (10)$$

The ionospheric combination (for the j-th satellite) can be modeled using the following expression:

$$\widetilde{LI_j} = m(el) \cdot \left(\frac{40.3}{f_2^2} - \frac{40.3}{f_1^2}\right) \cdot VTEC_j(\lambda_{IP}, \phi_{IP}) + DCB_j \qquad (11)$$

where:

- $m(el)$ is the geometric mapping function that translates from vertical to slant direction.
- $VTEC_j(\lambda_{IP}, \phi_{IP})$ is the Vertical Total Electron Content (VTEC) at the location of the ionospheric pierce point (IP). The IP point is the intersection of the line-of-sight and an imaginary layer of infinitesimal width that contains all the electron content of the ionosphere. The height of this layer is usually located at 450km above the Earth surface. The VTEC can be obtained from Global Ionospheric Maps (GIM) in e.g. IONEX format delivered by the International GNSS Service (IGS). More details on both the mapping function and the means to compute and interpolate the VTEC from IONEX maps can be found in [12] .

In order to properly apply the corrections, several assumptions on the processing done inside the GNSS chipset have to be done:

- The mobile device uses the Klobuchar to correct for the ionosphere. Therefore, the delay computed with this method has to be discounted from the I-UERE.

- In general, there will be a weighting of the measurements that depends on the elevation. This weighting criteria, which will usually depend on the chipset, has to be the same thatn the one used to refine the solution.
- Only the corrections for the satellites used in the estimation (usually indicated in the NMEA message), or a subset of those satellites, have to be applied. In principle this assumption is verified because the same satellites are usually observed by the reference and rover receivers (excepting those affected by an elevation mask).

EXPERIMENTAL RESULTS

In order to perform a preliminary validation of this approach, an experimental test has been carried out at Rokubun premises. A low cost receiver (single frequency UBLOX evaluation kit) has been connected to the same (static) antenna used by a dual-frequency code and phase RTK receiver (i.e. zero-baseline configuration), which provided the ground truth. As reference stations for the RTK processing, both a nearby RTK base station (RTKB, ca. 1.5m baseline) and a remote base station (GARR station, from the Cartographic Institute of Catalonia, ca. 6km baseline) have been used. The differences of the processing (with and without using the corrections) in East/North/Up components for both reference stations are shown in **Figure 1**. These differences, relative to the RTK-based position, are reduced especially during daytime, where the ionosphere delay is larger. The figure also includes the bias and standard deviation of each time series when using or not using the proposed technique (Poor Man's DGPS or PMDGPS).

It is noted that the improvement occurs mostly in the bias, which is reduced in all components (especially in the Up and North component). The East component is practically unaffected, which is reasonable considering that the corrections tend to be similar in the East/West direction. The standard deviation, on the other hand, is basically unaffected.

Provided that the code (C/A) is the only observable used to compute the position, the high standard deviation can be due to both multipath and the receiver tracking loop noise. Such errors cannot be mitigated with the proposed technique. However, a possible way to reduce this effect could be to include additional sources of information present in mobile devices such as accelerometers and/or gyroscopes. This is actually done in some mass-market devices and several dual frequency RTK systems that integrate Inertial Measurement Unit (IMU) sensors. Depending on the accuracy of those sensors the variance of the final solution might be further improved.

Regarding the dependency of the performance with the baseline, **Figure 1** shows that, for this study case (maximum distance of 6km), results using both reference stations give comparable results. This, however, will not likely hold if the baseline is extended to longest distances than the e.g. RTK limit (ca. 10km to 20km) or in situations where the ionosphere is very active (low latitude, high geomagnetic activity, …)

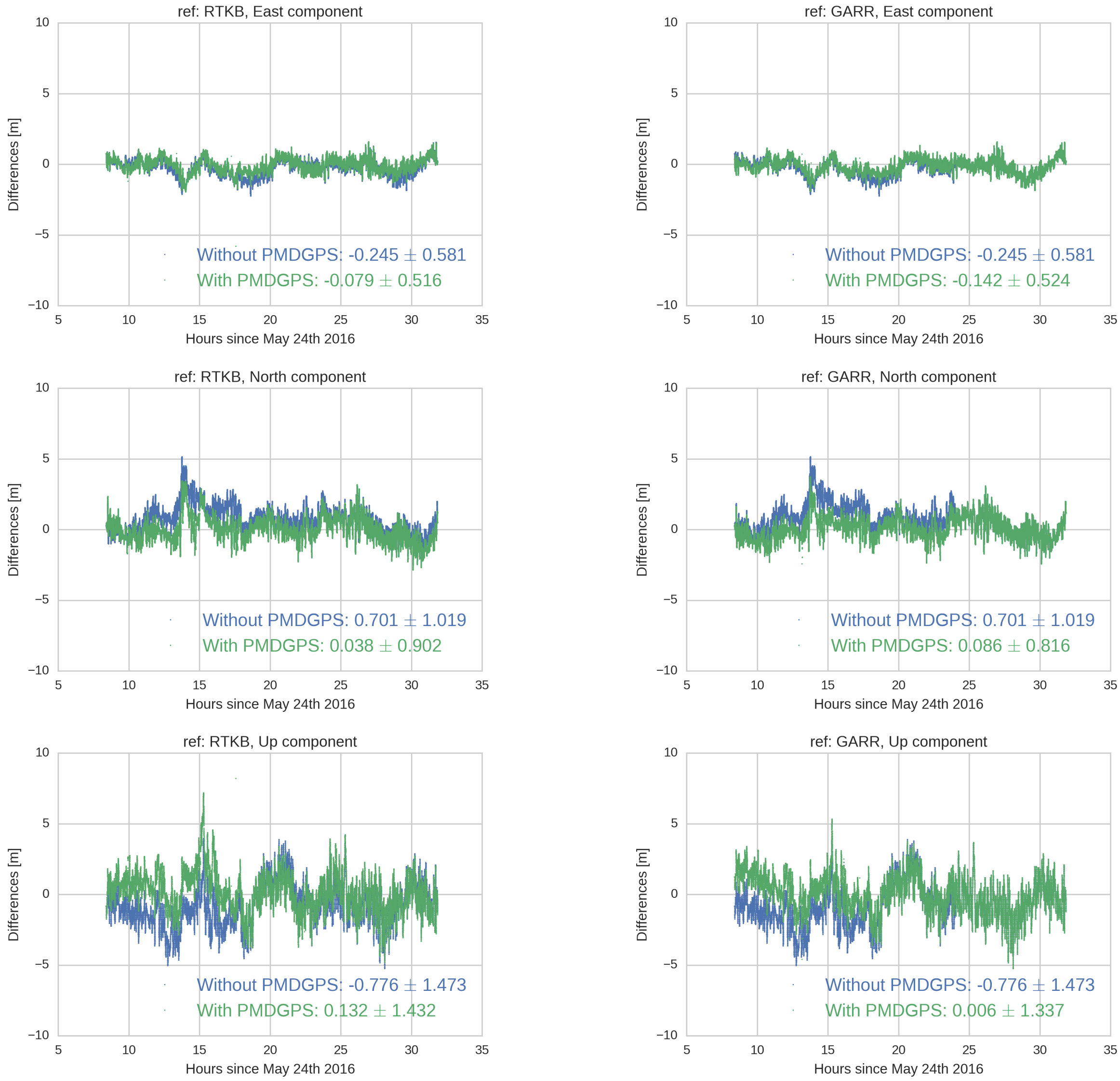

Figure 1 Differences in ENU components of single-frequency processing with and without PMDGPS relative to reference RTK solution (computed using dual-frequency code and phase receiver on a zero-baseline configuration)

CONCLUSIONS

The present paper introduces a technique that attempts to improve the PVT estimates of low cost receivers by means of differential techniques. As opposed to classical DGNSS, the proposed approach does not use the raw measurements (code and carrier phase), but the filtered PVT solutions directly. Even though the improvement is not drastic, a reduction of 0.5m to 1m in the bias of all position components can be obtained. This is especially true for the Up component, which accumulates most of the error due to the un-modeled ionosphere.

Even though the benefit of using this technique might be smaller when augmentation systems such as Satellite Based Augmentation System (SBAS) or accurate ionospheric models are being used, this technique may be of interest for those receivers that use a coarse ionospheric model (such as Klobuchar). Such receivers are in fact the majority of GNSS chipsets embedded in e.g. smartphones, tablets or cheap navigation sensors used by drones.

Regarding the standard deviation of the error (due to multipath and receiver noise), further improvement might be achieved in mobile devices (as already done in IMU+GNSS systems) by further filtering the solution using embedded accelerometer and gyroscope.

Due to the limited availability of raw measurements in typical GNSS chipsets of mobile devices and despite the assumptions that have to be done regarding the processing done in the mobile device, the proposed technique could of interest for those budget applications that require sub-meter (rather than centimetric) accuracies. Typical examples of those applications can be found in fields such as automotive, drones, automated logistics, precision farming... The platforms used in these applications already contain the connectivity needed to receive the corrections, additional inertial sensors such as accelerometers (that could help mitigating the multipath) and the processing capabilities to embed this algorithm simply by making a software (or firmware) update.

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