Mitigation of short duration satellite outages for Advanced RAIM and other integrity systems based on GNSS

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ABSTRACT

In most systems providing GNSS integrity to aircraft, like Satellite-based Augmentation Systems (SBAS), Ground-based Augmentation Systems (GBAS), Receiver Autonomous Integrity Monitoring (RAIM), or the proposed Advanced RAIM, the user position is computed using only the measurements of the current epoch (albeit carrier-smoothed). This snapshot approach is well suited for integrity, because it does not require a complex characterization of the ranging errors. In particular, except for multipath, no assumptions need to be made on the time correlation of the ranging errors. Also, the snapshot solution has been proven to be sufficient for SBAS and RAIM, and availability simulations suggest that it will be sufficient for Advanced RAIM.

However, these availability simulations typically assume that as long as a satellite is above a given mask angle, it will be tracked. That is, they do not take into account that measurement outages above the mask angle can occur. Among other reasons, these outages can be due to aircraft banking, interference (either intentional or not), or ionospheric scintillation -this latter cause is especially relevant as both dual frequency SBAS and Advanced RAIM are intended to provide service in low latitude regions, where GNSS signals are frequently affected by scintillation. The temporary loss of measurements will degrade the user geometry, which could result in the loss of service. In Advanced RAIM, the Protection Level is very dependent on the worse subset geometry (out of the set of subsets that contains a fault free solution with high probability). As a consequence, ARAIM is potentially more sensitive to the loss of measurements.

In this paper we describe, develop, and test an algorithm designed to mitigate the effect of short duration outages. The proposed technique exploits the temporal correlation of the pseudorange errors, which is not currently exploited. This correlation is routinely exploited in Real Time Kinematic and Precise Point Positioning techniques to fix the carrier phase ambiguities, and has been proposed to improve Advanced RAIM performance by exploiting the geometry diversity provided by satellite motion. However, these techniques rely on temporal error models that, while realistic, might not be sufficiently conservative for integrity purposes. The algorithm proposed here exploits the temporal correlation of the errors in a simple way and with a low computational load.

INTRODUCTION

In GNSS integrity systems for aircraft, like Satellite-based Augmentation Systems (SBAS), Ground-based Augmentation Systems (GBAS), Receiver Autonomous Integrity Monitoring (RAIM) [1], or the proposed Advanced RAIM [2], the user position is computed using only the measurements of the current epoch (albeit carrier-smoothed). This snapshot approach is simple and therefore well suited for integrity, because it does not require a complex characterization of the ranging errors, and allows a relatively straightforward application of overbounding principles [7]. In particular, except for multipath, no assumptions need to be made on the time correlation of the ranging errors.

So far, the snapshot solution has appeared to be sufficient for SBAS and RAIM. Availability simulations suggest that it will be sufficient for Advanced RAIM [2]. However, SBAS and GBAS systems are being deployed in areas that might be more susceptible to pseudorange disruptions (mostly due to scintillation). Also, as the domain of GNSS applications increases, it is natural to expect that more challenging conditions will be encountered –for example, approaches with turns. The availability simulations used to evaluate both RAIM and ARAIM typically assume that as long as a satellite is above a given mask angle, it will be tracked. That is, they do not take into account that measurement outages above the mask angle can occur.

Causes of outages

There are at least two main causes of short outages in airborne receivers: aircraft banking and ionospheric scintillation. The aircraft attitude affects the reception of the signal, because the antenna pattern is such that signals coming from underneath the plane of the aircraft suffer a significant loss of power. This loss of power can be sufficient to disrupt the tracking of GNSS signals [3]. For aircraft holding purposes, ICAO requires that the bank angle should not exceed 25 degrees. This bank angle usually corresponds to a rate turn of less than 3 degrees per second [4], which means that an outage due to banking will last on the order of tens of seconds.

Outages can also be due to ionospheric scintillation, especially in low latitude regions, which are affected by the equatorial anomaly. In certain occurrences of high scintillation, average time between fades as low as 12 s have been recorded [5]. These statistics however do not factor in possible improvements in signal tracking and may be very conservative. The outages due to scintillation last less than a second, but they cause the smoothing filters to restart [6].

Loss of performance due to outages

The temporary loss of measurements degrades the user geometry. Although this degradation does not necessarily result in large positioning errors, it can often result in the degradation of the error covariance. This results in larger protection levels (the integrity error bounds) which could result in loss of service. In RAIM and Advanced RAIM, the effect is likely to be worse than in SBAS or GBAS, as the Protection Level is very dependent on the worst subset geometry (out of the set of subsets that contains a fault free solution with high probability) [2]. As a consequence, RAIM and ARAIM are potentially more sensitive to the loss of measurements. In all cases, the effect of the outage will typically last longer than the outage itself, as the smoothing filter will only start again when the signal is re-acquired, and the pseudorange accuracy of the signal is 3 to 10 times worse when it is not smoothed.

Mitigations against outages

The effect of satellite outages can be mitigated using several techniques. One of the most common ones is using a Kalman filter for the position estimation. The performance of the Kalman filter will be greatly improved with the use of additional sensors, in particular by integrating measurements from an inertial measurement unit (IMU) [8]. Such Kalman filter implementations require a dynamic model of the platform and an IMU.

In this work, we seek a solution that is contained in the GNSS receiver. One way to improve the positioning performance is by exploiting the temporal structure of the pseudorange measurements. This correlation is routinely exploited in Real Time Kinematic and Precise Point Positioning techniques [9] to fix the carrier phase ambiguities. It was also exploited in [10] to use carrier phase coasting in RAIM. More recently, it has been proposed to improve Advanced RAIM performance by exploiting both the geometry diversity provided by satellite motion and the temporal behavior of the pseudorange errors [11].

The goal of the present paper is to develop and test a technique to exploit the temporal characteristics of the pseudorange error that is as simple as possible, and that does not require a complex model of the temporal correlation of the error. Temporal evolution models are difficult to verify, and the burden of proof in integrity systems is very high. Also, we seek a technique that does not require a large increase in computational load.

The first part will describe the approach, which consists on using one epoch of previous data in addition to the present one. The second part is a preliminary study on the magnitude of the covariance as a function of the difference in time for the main error sources. Finally we will apply the algorithm to real GNSS measurements under rea; amd simulated outage conditions. The performance of the technique will be assessed by examining the position solution error and the protection level statistics.

EXPLOITING TEMPORAL CORRELATION OF THE RANGING ERRORS

Let us first consider the measurement equation at the time of interest (time t_0):

$$y_0 = G_0 x_0 + \varepsilon_0 \tag{1}$$

where:

y_0 are the linearized carrier smoothed pseudorange measurements

G_0 is the geometry matrix at time t_0

ε_0 is the vector of errors at time t_0

The errors ε_0 are assumed to be overbounded by $N(0, C_0)$, where C_0 is assumed to be diagonal. The least squares solution is given by:

$$\hat{x}_0 = \left(G_0^T W_0 G_0\right)^{-1} G_0^T W_0 y_0 \tag{2}$$

where**:**

$$W_0 = \left(C_0\right)^{-1} \tag{3}$$

Now, let us consider the measurements at a previous time t_p:

$$y_p = G_p x_p + \varepsilon_p \tag{4}$$

where:

$$\varepsilon_p \sim N\left(0, C_p\right) \tag{5}$$

We now write the measurement equation for times t_0 and t_p jointly:

$$\begin{bmatrix} y_0 \\ y_p \end{bmatrix} = H \begin{bmatrix} x_0 \\ x_p \end{bmatrix} + \begin{bmatrix} \varepsilon_0 \\ \varepsilon_p \end{bmatrix} \tag{6}$$

where:

$$H = \begin{bmatrix} G_0 & 0 \\ 0 & G_p \end{bmatrix} \tag{7}$$

To compute the least squares solution of the joint system we need to consider the covariance of the joint vector of errors. We note:

$$\begin{bmatrix} \varepsilon_0 \\ \varepsilon_p \end{bmatrix} \sim N\left(0, C\right) \tag{8}$$

where C is given by:

$$C = \begin{bmatrix} C_0 & C_{0,p} \\ C_{0,p}^T & C_p \end{bmatrix} \tag{9}$$

The matrix $C_{0,p}$ characterizes the covariance between the errors at time t_0 and at time t_p.

The least squares solution of the joint system is given by:

$$\begin{bmatrix} \hat{x}_0 \\ \hat{x}_p \end{bmatrix} = \left(H^T W H\right)^{-1} H^T W \begin{bmatrix} y_0 \\ y_p \end{bmatrix} \tag{10}$$

This estimate of $\hat{x}_0$ accounts for the measurements at time t_0 ant time t_p. It is straightforward to verify that if $C_{0,p} = 0$, no information is gained by adding the measurements, in the sense that the estimate coincides with the snapshot estimate.

In the next section, we examine the formation of the cross covariance matrix $C_{0,p}$.

CHARACTERIZATION OF THE TIME CORRELATION OF RANGING ERRORS FOR INTEGRITY PURPOSES

Each entry in the i,j in the matrix $C_{0,p}$ corresponds to the covariance of the error i at time t_0 with the error j at time t_p. As in the snapshot case, we will assume that the covariance between measurements from different satellites is zero. We therefore only need to characterize the covariance of the error i at time t_0 with the error j at time t_p if i and j refer to the same satellite.

The starting point for the error characterization is [12]. There are three contributors to the error:

$$\varepsilon(t) = \varepsilon_{URA}(t) + \varepsilon_{tropo}(t) + \varepsilon_{user}(t) \tag{11}$$

where:

ε_{URA} is the clock and ephemeris error

ε_{tropo} is the residual tropospheric delay

ε_{user} is the code noise and multipath error of the ionospheric free carrier smoothed dual frequency combination

Formulas for the variance of these three terms (σ_{URA}, σ_{tropo}, and σ_{user}) are given in [12]. What follows is a preliminary estimate of the covariance based on previous research.

Clock and ephemeris correlation

A preliminary bound on the worst case bound on the correlation can be derived from the GPS SPS [13]. Although there is currently no commitment on the worst case error growth, it is indicated that "a high probability (6-sigma) upper bound on the SPS SIS instantaneous

URRE which is typically used for design purposes is 0.02 m/sec over any 3-second interval during normal operations at any AOD". We can therefore write:

$$\operatorname{var}\left(\varepsilon_{URA}(t_0)-\varepsilon_{URA}(t_p)\right)\le\sigma_{URRE}^2\left(t_p-t_0\right)^2 \quad (12)$$

with $\sigma_{URRE}=0.02/6=0.0033\ \text{m.s}^{-1}$

As a consequence:

$$\operatorname{cov}\left(\varepsilon_{URA}(t_0),\varepsilon_{URA}(t_p)\right)=\frac{\sigma_{URA}(t_0)^2+\sigma_{URA}(t_p)^2-\sigma_{URRE}^2\left(t_p-t_0\right)^2}{2} \quad (13)$$

Unfortunately, this formula does not automatically lead to an overbounding covariance (indeed, it could result in a covariance matrix that is not positive definite). Instead, we will define the matrix:

$$C_{URA}=\begin{bmatrix} C_{URA,0} & C_{URA,0,p} \\ C_{URA,0,p}^T & C_{URA,p}\end{bmatrix}$$

where:

$$C_{URA,0}=\sigma_{URA}(t_0)^2$$

$$C_{URA,0,p}=\sigma_{URA}(t_0)^2$$

$$C_{URA,p}=\max\left(\sigma_{URA}(t_0)^2+\sigma_{URRE}^2\left(t_p-t_0\right)^2,\sigma_{URA}(t_p)^2\right)$$

This definition guarantees that the overbounding properties in any of the terms $\sigma_{URA}(t_0)^2,\sigma_{URRE}^2\left(t_p-t_0\right)^2,\sigma_{URA}(t_p)^2$ translate to the covariance matrix.

Residual tropospheric delay

The growth of the tropospheric delay is nominally very small [14]. However, differences in tropospheric delay of up to 30 cm have been observed for baselines of 5 km [15]. Assuming that this value corresponds to a 2-sigma value in the decorrelation magnitude, and that an aircraft will cover 5 km in 60 s we can write that:

$$\operatorname{var}\left(\varepsilon_{tropo}(t_0)-\varepsilon_{tropo}(t_p)\right)=\sigma_{tropo,decorr}^2\left(t_p-t_0\right)^2 \quad (14)$$

with:

$$\sigma_{tropo,decorr}=\frac{0.30}{2*60}=2.5\cdot10^{-3}\text{m.s}^{-1} \quad (15)$$

As with the URA, we define:

$$C_{tropo}=\begin{bmatrix} C_{tropo,0} & C_{tropo,0,p} \\ C_{tropo,0,p}^T & C_{tropo,p}\end{bmatrix}$$

where:

$$C_{tropo,0}=\sigma_{tropo}(t_0)^2$$

$$C_{tropo,0,p}=\sigma_{tropo}(t_0)^2$$

$$C_{\text{tropo},p}=\max\left(\sigma_{tropo}(t_0)^2+\sigma_{tropo,decorr}^2\left(t_p-t_0\right)^2,\sigma_{tropo}(t_p)^2\right)$$

Code noise and multipath

The error bound provided in [12] assumes that the code has been carrier smoothed for at least 100 s. For this reason, the estimate of the carrier phase bias will have decorrelation time on the order of 100 s. Also, we will assume that the carrier phase multipath is completely decorrelated from epoch to epoch, and that the noise from the carrier phase multipath is assumed to be 1 cm [9], which is very conservative. Taking this into account, we will assume that the covariance term is given by:

$$\operatorname{cov}\left(\varepsilon_{user}(t_0),\varepsilon_{user}(t_p)\right)=e^{-\frac{t_0-t_p}{T_C}}\sigma_{user}(t_0)\sigma_{user}(t_p) \quad (16)$$

where T_C is the correlation time (we will assume T_C = 100 s).

This analysis is very preliminary. It will need to be expanded, and extended to other sources of error as: signal deformation, antenna bias, and second order ionospheric delay.

Overbounding conditions

One of the difficulties in exploiting the temporal correlation of pseudorange errors is the fact that there is not a straightforward notion of overbounding. Remaining within the Gaussian assumption, in the snapshot case it is sufficient to have:

$$\sigma_{true}^2(t_0)\le\sigma^2(t_0) \quad (17)$$

where $\sigma_{true}^2(t_0)$ refers to an hypothetical true standard deviation. For the case where two epochs are used, it can be verified that we now need a matrix inequality:

$$\begin{bmatrix} \sigma_{true}^2(t_0) & \Sigma_{true}(t_0,t_p) \\ \Sigma_{true}(t_0,t_p) & \sigma_{true}^2(t_p) \end{bmatrix} \le \begin{bmatrix} \sigma^2(t_0) & \Sigma(t_0,t_p) \\ \Sigma(t_0,t_p) & \sigma^2(t_p) \end{bmatrix} \quad (18)$$

where: $\Sigma(t_0,t_p) = \mathrm{cov}(\varepsilon(t_0),\varepsilon(t_p))$

As a consequence, in addition to the overbounding of each variance, we have the condition:

$$\begin{vmatrix} \sigma^2(t_0)-\sigma_{true}^2(t_0) & \Sigma(t_0,t_p)-\Sigma_{true}(t_0,t_p) \\ \Sigma(t_0,t_p)-\Sigma_{true}(t_0,t_p) & \sigma^2(t_p)-\sigma_{true}^2(t_p) \end{vmatrix} = \\ (\sigma^2(t_0)-\sigma_{true}^2(t_0))(\sigma^2(t_p)-\sigma_{true}^2(t_p)) \\ -(\Sigma(t_0,t_p)-\Sigma_{true}(t_0,t_p))^2 \ge 0 \quad (19)$$

For both the URA and the residual tropospheric delay, condition (19) is verified.

EVALUATION OF THE PROPOSED ALGORITHM

Data

Two data sets were used. Both data sets include GPS L1 CA, and GPS L2 semi-codeless. The position estimation used a carrier smoothed ionospheric free combination. The first data set was collected at 1 Hz for 8 hours at a Stanford University rooftop by a multi-frequency multi-constellation receiver (Trimble NetR9). The second data set was collected during a flight test and is described in [16]. It contains several real outages (most likely due to the combination of banking and lower power in the L2 semi-codeless signal).

Outage simulation

The receiver location is relatively free of obstructions, so there are no natural outages. For this reason, outages were simulated. The simulation was meant to reflect an environment with some ionospheric scintillation. For this purpose, we provoked outages in all satellite tracks every 30 minutes. The first outage in each series was randomized in the first hour of the simulation. The outages were made to last 30 seconds.

Effect on position error

In this first implementation of the algorithm, we used a fixed value of the lag t_p-t_0 of 60 s. The covariance was calculated as shown above. Figure 1 shows the vertical position error when the snapshot solution is used. Each of the spikes corresponds to the outages. Figure 2 shows the vertical position error when the proposed algorithm is used: most of the spikes are gone, and the accuracy has significantly improved during the outages. Figure 3 shows a detail of the two traces: one can see that the error growth is sharply decreased when using data from a minute before.

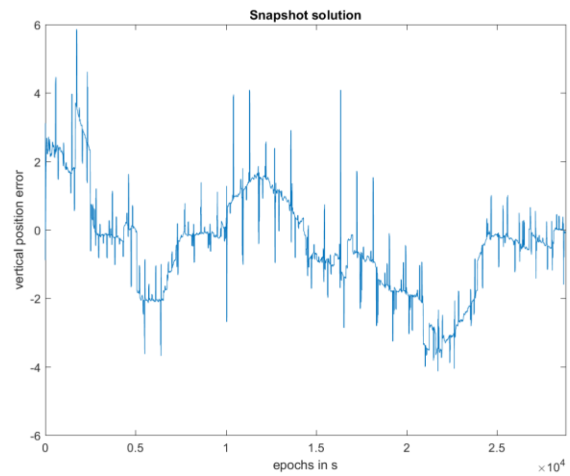

Figure 1. Vertical position error using the snapshot solution.

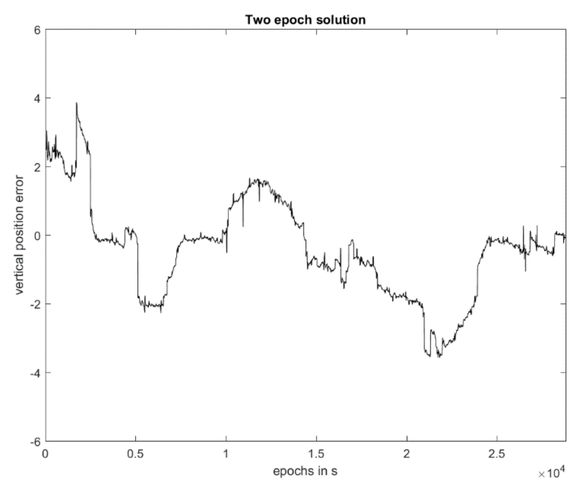

Figure 2. Vertical position error using proposed two epoch solution.

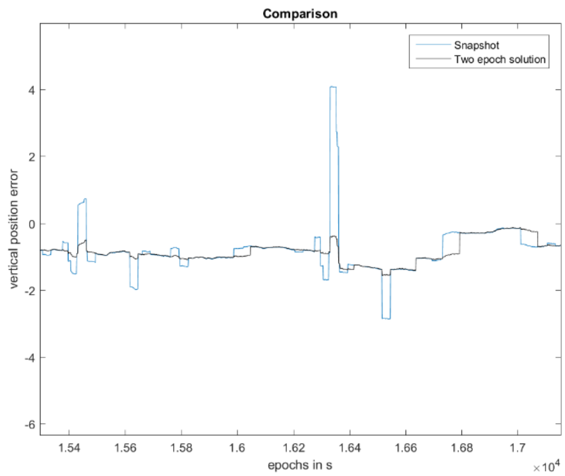

Figure 3. Detail of vertical position error for both algorithms.

Effect on Protection Level

We applied the proposed algorithm to the solution separation algorithm described in [3] to the second data set (collected during a flight test). The only change to the ARAIM algorithm is that the subset position solutions were computed using the proposed algorithm. It was also assumed that the nominal biases did not change signs between the two epochs used in the position solution. The algorithm uses the URA indices broadcast by GPS assumes the fault probabilities $P_{sat} = 10^{-5}$ and $P_{const} = 0$[1]. Figure 4 shows the trace of the HPL for the snapshot case and the real outages can be seen to cause large HPL spikes.

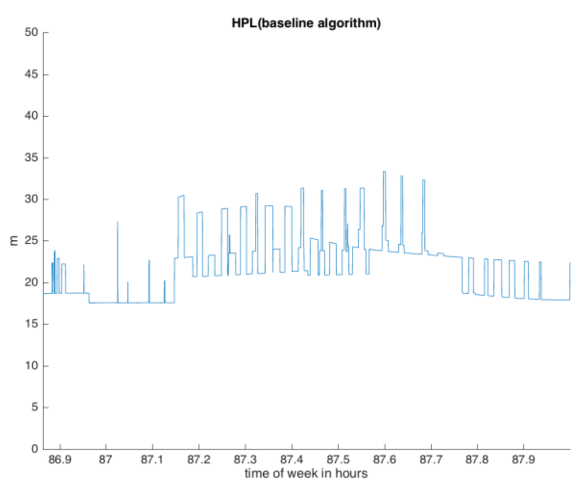

Figure 4. VPL trace for the snapshot algorithm under real outage conditions

We also induced simulated 20 s outages every 30 min in every line-of-sight. This scenario is intended to simulate the effect of mild scintillation [5]. The resulting HPL spikes can be seen in Figure 5.

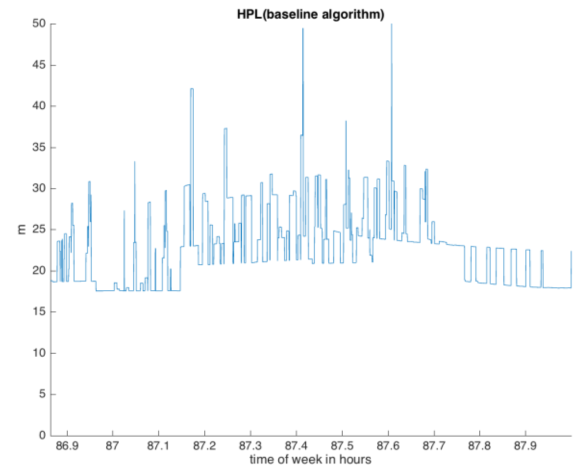

Figure 5. VPL trace for the snapshot algorithm under real and simulated outage conditions

Then we ran the proposed algorithm in these two scenarios (real outages and real+simulated outages). The HPL traces can be seen in Figures 6 and 8, and the corresponding histograms in Figures 7 and 9. Some HPL spikes do remain, but most have been mitigated.

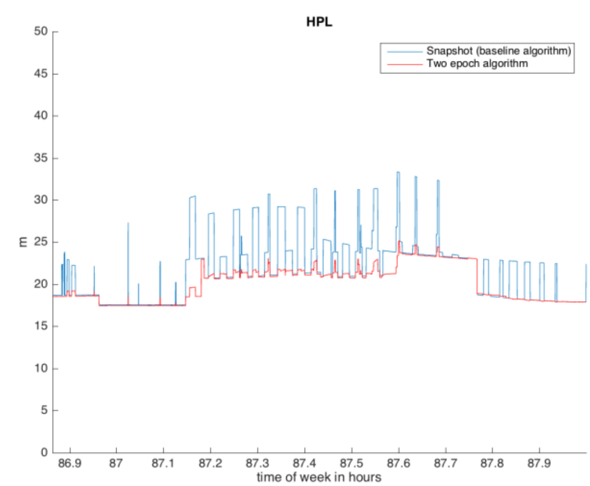

Figure 6. VPL trace for the proposed algorithm (red) and the baseline snapshot algorithm (blue) under real outage conditions

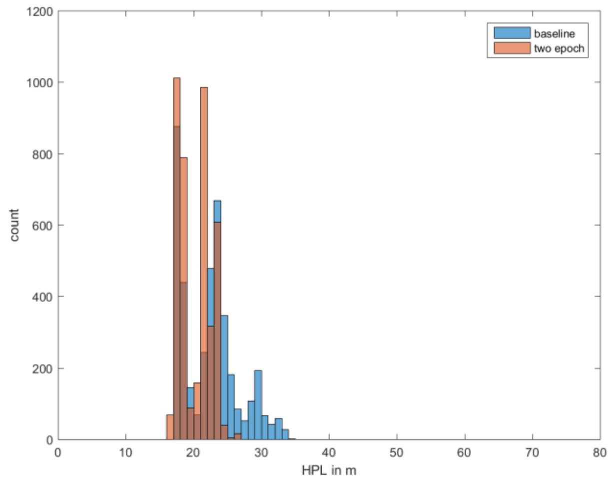

Figure 7. VPL histograms for the proposed algorithm (red) and the baseline snapshot algorithm (blue) under real outage conditions

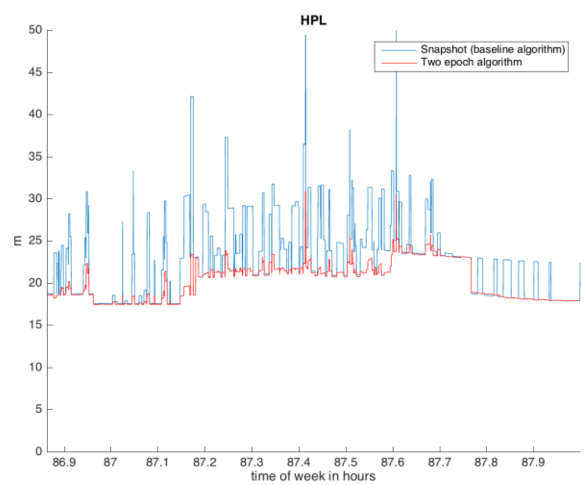

Figure 8. VPL trace for the proposed algorithm (red) and the baseline snapshot algorithm (blue) under real + simulated outage conditions

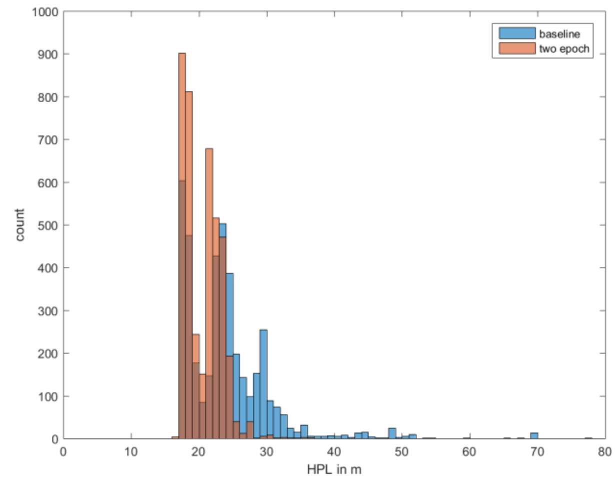

Figure 9. VPL histograms for the proposed algorithm (red) and the baseline snapshot algorithm (blue) under real + simulated outage conditions

SUMMARY

We have presented a position solution estimator that has the potential to mitigate the effect of short duration outages in both accuracy and error bounds. The approach consists in including measurements from one previous epoch in the estimate of the current position, and by taking into account the short term temporal correlation of the pseudorange errors. This effectively reduces the effect of the outage by taking into account the fact that the error growth will be limited. We tested the algorithm on GPS measurements collected from both a static receiver and from data collected during a flight test. The static data shows that accuracy can be greatly improved during outages, and the flight test data shows that the Protection Level spikes can be mitigated. This algorithm could prove useful in integrity applications, as the required temporal characterization of the errors is relatively simple, and can be made robust.

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