Integrity measures in direct-positioning

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BIOGRAPHY

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Dr. Juan Blanch is a senior research engineer at Stanford University, where he works on integrity algorithms for Space-based Augmentation Systems and on Receiver Autonomous Integrity Monitoring. He proposed and developed the central ionospheric estimation algorithm currently implemented in the Wide Area Augmentation System. Dr. Blanch developed an Advanced RAIM algorithm that has become a reference for the aviation integrity community. A graduate of Ecole Polytechnique in France, he holds an MS in Electrical Engineering and a Ph.D. in Aeronautics and Astronautics from Stanford University. He received the 2004 Parkinson Award for his doctoral dissertation and the 2010 Early Achievement Award from the Institute of Navigation.

ABSTRACT

Direct Position Estimation (DPE) is a promising solution to enhance sensitivity and robustness of GNSS receivers. At a glance, it involves directly solving for the position, velocity, and time (PVT) without the intermediate steps of computing observables. This was seen, both theoretically and experimentally, to be outperform two-steps positioning in many challenging situations. On the other hand, signal integrity is a major concern in safety-critical applications and there is a need to investigate how integrity of DPE solution can be measured. This article discusses a possibility, leveraging on existing integrity algorithms for two-steps.

INTRODUCTION

Global Navigation Satellite System (GNSS) is the general concept used to identify those systems that allow user positioning based on a constellation of satellites. The term therefore includes GPS, Galileo, GLONASS, or Beidou systems. These systems rely on the same principle: the user computes its position by means of measured distances between the receiver and a set of visible satellites. These distances are calculated estimating the propagation time that transmitted signals take from each satellite to the receiver. Then, these distances are used to obtain user position by means of a procedure referred to as multilateration. Despite its known vulnerabilities [1], GNSS is the technology of choice in most of the applications requiring positioning information.

The proposal of new techniques for GNSS receiver design is blooming due to the advances in digital signal processing devices, which allow increased computational complexity at faster rates [2]. Recently, fundamental modifications to the conventional receiver architecture were proposed. Here we refer to those approaches that not only substitute certain parts of the receiver by more sophisticated algorithms, but those which entail an essential modification of the receiver's operation. A promising architecture integrates code/carrier tracking loops and Navigation Solution in a single step. This is the basis of the so-called Direct Position Estimation (DPE) concept introduced in [3]. Initialization of a DPE-enabled receiver involves an rough initial PVT (position-velocity-time) solution, which can be extracted from already implemented two-steps modules. Then, DPE involves the optimization of a cost function over the PVT space, with this cost function taking baseband samples instead of pseudorange observables. These samples can be either at pre- or post- correlation stage. In this context, there are several contributions in the literature aiming at efficiently implementing the optimization problem. Certainly, the area is gaining momentum, showing the potential of such approach.

This paper leverages on DPE results to investigate and analyze the potential of the architecture in terms of integrity monitoring. Inclusion of Receiver Autonomous Integrity Monitoring (RAIM) in DPEs framework has never been explored and we provide here some discussion and way forwards. In safety-of-life applications, the integrity of the estimates becomes critical [4]. RAIM algorithms check the consistency of the navigation solution by inspecting the residuals of the PVT algorithm. That is, the residual errors in the range observations are computed upon subtracting an estimation of the ranges to the observed ranges. Note that this is straightforward in the context of a Least Squares based conventional receiver (likewise for Kalman filter based PVT solutions), but should be carefully thought within DPE since no observables are computed. Conversely, DPE seems a natural way of implementing RAIM since it already operates in the position-domain. In this paper we explore integrity monitoring by exploring alternatives in the use of position-domain techniques. We investigate how to provide integrity using and exploiting the DPE architecture. We will start by reviewing the basics of a DPE receiver. Then, we will discuss a RAIM algorithm, popular in the context of two-steps receivers. Leveraging on it, we will propose a method to assess integrity in a DPE scheme. This method, although based on popular integrity techniques, need to be specifically redesigned for the DPE architecture. We carry out a simulation study showing integrity results to detect faulty satellites and compare it to two-steps solutions. This paper aims at providing a seminal look into this promising area.

Summing up, DPE provides enhanced positioning capabilities. These features were analyzed both theoretically and experimentally in the literature. The main research question we aim at addressing here is whether integrity monitoring can benefit from this enhanced architecture. We believe the research in this paper can lead to innovative avenues and open some room for further research.

DIRECT POSITION ESTIMATION

To contextualize the contribution of this article, we briefly comment on the operation of standard (two-steps) receivers and DPE schemes. The baseband operation of legacy GNSS receivers is depicted in Fig. 1. First, the receiver needs to detect which are the visible satellites and obtain a rough estimate of the time-delay and Doppler-shifts of those satellites [5]. This initial operation is referred to as *acquisition*, and it can also be seen as an open-loop processing of the data. Once the rough estimates are obtained, the receiver can start operating in *tracking* mode. The goal is then to obtain fine measurements of the time-delay, Doppler-shifts, and carrier-phases of the satellite signals (typically implemented in a closed-loop architecture) for the sake of more accurate estimates of the user's position. Standard GNSS receivers typically compute the user position from the time-delay estimates. Although other position related parameters can yield position estimates, for instance carrier phase measurements that yield to more precise position estimates. The most widely adopted positioning technique is in fact a two-step approach. In a first step, the time-delay or time of arrival (TOA) of the signal transmitted by each in view satellite is estimated. This process is typically performed by correlating the received signal with a locally generated replica. In a second step, the position of the receiver is computed upon taking into account the geometrical relation between the set of estimated TOAs and the user position. The resulting trilateration problem is typically solved by a Least Squares algorithm. Note that in this process the receiver also needs to estimate the receiver clock bias that represents the offset between the receiver time and the GNSS time. Two-steps positioning has established itself as the *de facto* technique for GNSS receivers. This is due to its modularity, re-use of well-known receiver blocks, and, importantly, notable performance over the years. The two-steps technique will be referred to as the conventional approach in the sequel.

On the other hand, we find DPE, a receiver architecture in which PVT is computed directly from the sampled signal, avoiding the intermediate calculation of observables (refer to Fig. 2). Intuitively, one can see the DPE approach as the inverse process of the conventional approach in what concerns the relation between the user position and the time-delays. Consider some observations with the carrier wiped off. On the one hand, the conventional approach estimates the different time-delays from the maximum of the correlations of the satellites in view, in a individual way. On the other hand, DPE defines a set of candidate positions, determines the associated time-delays with the positions, and computes the energy found at the different correlation signals, in a joint manner. Then the tentative position that maximizes the global energy is selected through optimization of a cost function. DPE was seen to provide advantageous features, compared to two-steps. Receivers based on this approach are able to enhance tracking of satellites and deliver PVT under challenging scenarios such as multipath propagation or weak signal and fading conditions. Contrary to two-steps architectures, DPE approach has the ability to use (and extract useful information from) weak signals, cope with signal blockages, allowing fast recovery and even operate with low satellite coverage [6]. It was shown that direct-positioning improves estimation lower bounds [7, 8], turning out that under certain scenarios there is an increase in sensitivity for DPE in the order of $10\log(\mathrm{M})$ dB, M being the total number of used satellites.

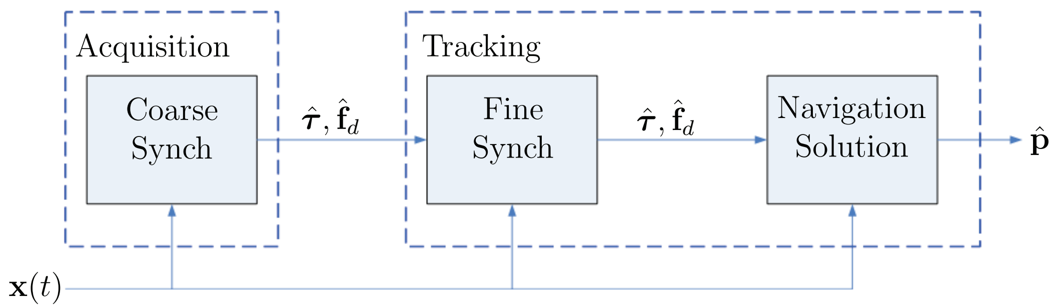

Fig. 1. Receiver flowgraph for standard two-steps GNSS receiver.

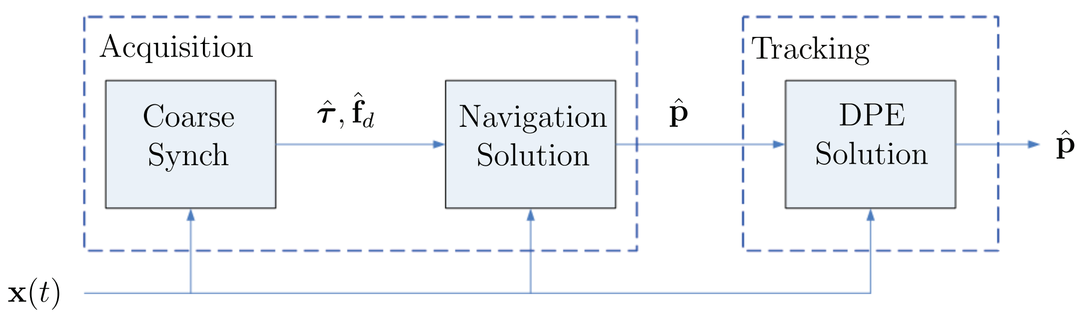

Fig. 2. Receiver flowgraph for a DPE GNSS receiver.

INTEGRITY REQUIREMENT AND MEASURES

This section discusses a particular integrity monitoring solution within two-steps receivers and then proposes a methodology to extend the technique to DPE-enabled receivers.

The objective of an integrity monitor is to make sure that the probability that the position error exceeds a certain limit (the Vertical Alert Limit (VAL) for the vertical coordinate and the Horizontal Alert Limit (HAL) for the horizontal coordinates) and there is no alert is below the allowed Probability of Hazardously Misleading Information (P_{HMI}). The design of the RAIM algorithm consists in deciding two elements: which position fix to choose, and when to declare an alert as a function of the measurements. Deciding when to declare an alert is equivalent to the determination of a region where the measurements are deemed to be consistent. This is referred to as the *integrity requirement*.

In addition to the integrity requirement, there is the *continuity requirement*, we must make sure that the probability that the monitor declares an alert is bounded. In this paper, we will only limit the alert probability under nominal conditions ($\mathcal{H}_0$). This requirement ensures that a given service will be available with a certain probability, and also that once the operation has started, that it will not be interrupted during the operation.

The protection level is a measure of the integrity that allows the receiver to operate without knowing the Alert Limit (AL). Ideally, it is defined as the Alert Limit for which the integrity risk is exactly P_{HMI}. In practice, only an upper bound is achieved, which is conservative. In any case, if VPL $<$ VAL and the consistency check passes, the operation (an approach for example) is said to be available.

In the two-step process, the measurements $\mathbf{y}$ are the pseudorange measurements resulting from the tracking process. In most cases, they are also carrier smoothed. In this paper, we will limit ourselves to the pseudorange measurements based on the code, for the sake of simplicity. The position solution is then obtained using the usual least squares iteration. In most RAIM algorithms, the analysis is performed assuming that $\mathbf{y}$ are the pseudorange measurements linearized around a neighboring location. The position solution is then given by the least squares position solution as defined in [4]

$$\hat{\mathbf{x}} = \left(\mathbf{G}^\top \mathbf{W} \mathbf{G}\right)^{-1} \mathbf{G}^\top \mathbf{W} \mathbf{y} \tag{1}$$

where $\mathbf{G}$ is the geometry matrix, and $\mathbf{W}$ is the diagonal matrix whose entries are the inverse of the variance of the nominal errors

The threat model in RAIM can be defined as a set of hypothesis $\mathcal{H}_i$ that form a partition: the error model follows one of the hypotheses $\mathcal{H}_i$ and only one. Each hypothesis $\mathcal{H}_i$ has a certain probability p_i and can be modeled with the addition of a new unknown state, as described in [4], in addition to the position coordinates and the receiver clock. For example, single faults are characterized by the addition of an unknown bias in the pseudorange of the affected satellite. In this paper, we will limit ourselves to scenarios with single faults only.

All RAIM algorithms are to a certain extent equivalent [4]. The differences arise from the choice of test statistic, and the approximations and upper bounds used to compute the integrity risk or, equivalently, the protection level. Since the goal of this paper is to compare the two-step positioning and DPE with regard to integrity, it was decided to choose and algorithm that would be easily adapted to DPE. This is the case of the RAIM algorithms based on solution separation. Solution separation algorithms are easier to apply in situations where errors are non-Gaussian, have optimality properties, and the generalization to multiple faults is straightforward and transparent. The idea in solution separation is to compare the all-in-view solution $\mathbf{x}_0$ with the subset solutions $\mathbf{x}_i$ that are fault tolerant to the faults included in the threat model (and cannot be neglected). If all tests pass, the measurements are deemed consistent and a PL is computed. $\mathbf{x}_0$ and $\mathbf{x}_i$ refer to the PVT solution for the all-in-view case and when the i-th satellite is excluded, respectively.

In order to apply a solution separation algorithm we need the distribution of the difference between the all-in-view position and a subset position solution, and the distribution of the position error for the all-in-view position solution and each subset position solution. These distributions only need to be characterized or bounded under nominal conditions, not under faulted conditions.

For this paper, we will use a very simple version of the solution separation algorithm based on [ref], both for the two-step positioning and DPE. The description is given for one coordinate only (for example the vertical). Here are the main steps of the algorithm:

1. For each hypothesized fault i, compute the position solution $\mathbf{x}_i$ that is fault tolerant to fault i. This includes the fault free which is indexed by 0.
2. Compute $\mathbf{x}_0 - \mathbf{x}_i$ and, for each coordinate (East, North, Up), compare to a pre-defined threshold T_i
3. If all tests pass, compute the PL using the formula:

$$\mathrm{PL} = \max_i \{T_i + K_{\mathrm{HMI}}\sigma_i\} \tag{2}$$

where σ_i is the standard deviation of $\mathbf{x}_0 - \mathbf{x}_i$ and K_{HMI} is determined by the integrity allocation to fault mode i, as shown in [4]. The threshold Ti is given by:

$$T_i = K_{fa_i}\sigma_{ss_i} \tag{3}$$

where σ_{ss_i} is the standard deviation of the difference $\mathbf{x}_0 - \mathbf{x}_i$ under nominal conditions K_{fa_i} is determined by the false alert requirement [4]. In case one of the tests fail, exclusion can be attempted. The exclusion function consists in finding a subset of the measurements for which the consistency checks do pass.

As mentioned above, the RAIM approach adopted in this article is the solution separation algorithm. This approach is based on the comparison of the all-in-view solution $\mathbf{x}_0$ and the subset solutions $\mathbf{x}_i$. Therefore, the algorithm can be applied in a similar way to DPE approach, the main difference being that the solutions $\mathbf{x}_0$ and $\mathbf{x}_i$ are obtained with DPE algorithm rather than the conventional Least Squares solution in (1).

COMPUTER SIMULATIONS

Computer simulations are performed in order to assess the performance of two-steps positioning and DPE with RAIM algorithms. The simulations are performed for Galileo OS E1 signals. We consider the presence of 7 satellites in view. All the satellite signals are received with a carrier-to-noise-ratio of $C/N_0 = 60$ dB-Hz.

The two-steps and DPE receivers operate in open-loop configuration, meaning that the signal is processed in a snap-shot. The received signals are coherently integrated during 10 ms. The front-end filter bandwidth is of 4 MHz. The sampling frequency is set to $f_s = 50$ MHz. However, in order to obtain fine time measurements, the received signal has been interpolated with a factor 10 in order to obtain a a time resolution of $c/(f_s * 10) = 0.6$ meters.

As explained above, we consider scenarios with single faults scenario. For this purpose, we introduce a fault in the range of one of the satellites. The range error introduced spans from 0 to 400 meters.

In Figure (3) we show the impact of a faulty satellite in the position error for the all-in-view solution x_0. The position error of the conventional approach, in blue dashed line, increases linearly with the introduced error, as expected from the LS algorithm. The position error for the DPE approach however, in green solid line, behaves in a different way. The position error is equal for both approaches until a fault magnitude of 75 meters takes place. After 75 meters, the position error of DPE decreases slowly until roughly 140 meters, increases with a peak again at 175, and vanishes permanently after 225 meters. This behavior can be explained after observing the autocorrelation function of the Galileo BOC(1,1) signal, in Figure (4). The first minimum of the position error, at 140 meters, coincides with the range of the secondary lobes of the BOC(1,1) signal.

From the figure we can appreciate that DPE is naturally more robust to faults than the two-steps approach. For low magnitude faults, the DPE position error starts decreasing as soon as the autocorrelation function of the faulty satellites separates from the global maximum of the cost function. Once the fault magnitude is high enough, the faulty signal does not impact the solution and DPE becomes virtually unaltered by the faulty satellite.

We check now the RAIM algorithm in the scenario with one faulty satellite described above. Figure (5) illustrates the position error and the fault detection probability with respect to the fault magnitude. The position error is represented on the left of the y-axis and the fault detection probability on the right of the y-axis. For a fault magnitude of 10 meters the faulty

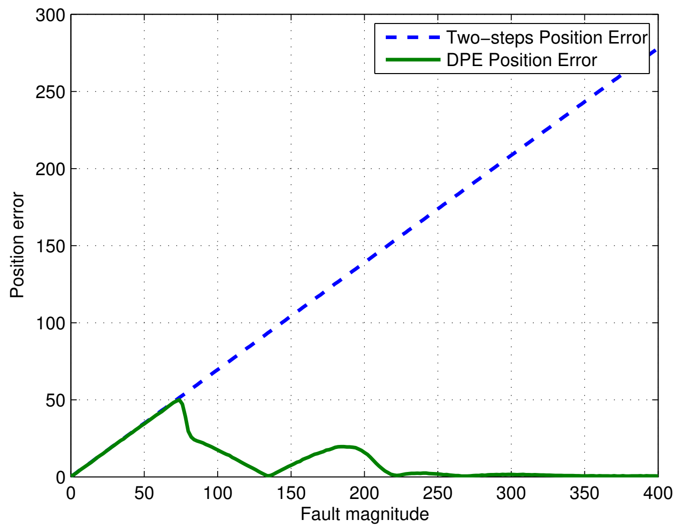

Fig. 3. Position error for Galileo E1 with respect to the fault magnitude

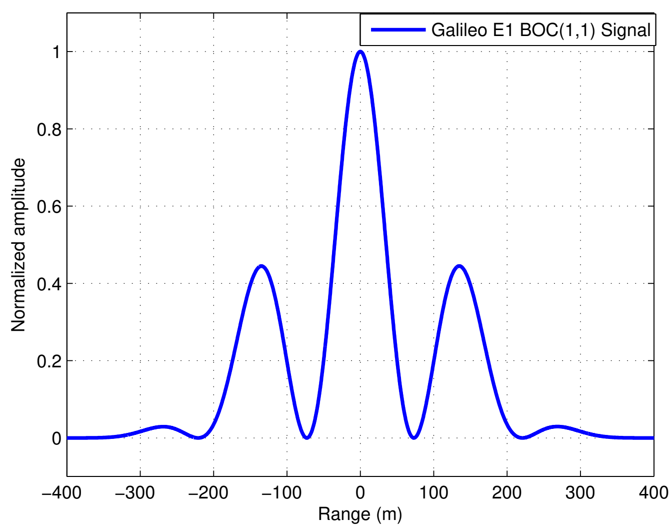

Fig. 4. Normalized, filtered Galileo E1 signal autocorrelation

satellite is detected with both approaches in the same way. For the two-steps approach, the detection probability stays for the remaining values of fault magnitude. For the DPE approach, however, no faults are detected around 140 meters and from 250 meters onwards. This values are in line with range errors where the position error is low in the all-in-view solution, as observed in Figure (3).

Once a fault is detected, the procedure is to exclude a satellite until a subset of satellites that satisfy the integrity test is found. In Figure (6) we present the position error after applying the fault detection and exclusion algorithm. It appears from the Figure that the detection of faulty satellites is successful for both algorithms and that the position error remains below 5 meters. However, for the cases where the DPE algorithm is a slightly impacted by the faulty satellite, the corresponding position error is not large enough to be detected. This is the case of fault magnitude values equal to 140, 250 and 300 meters. Nevertheless, the position error remains below the protection level.

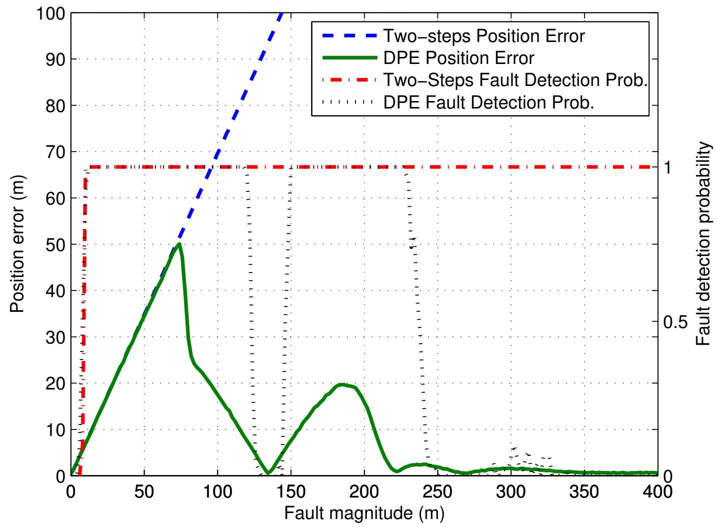

Fig. 5. Fault detection for Galileo E1 with respect to the fault magnitude

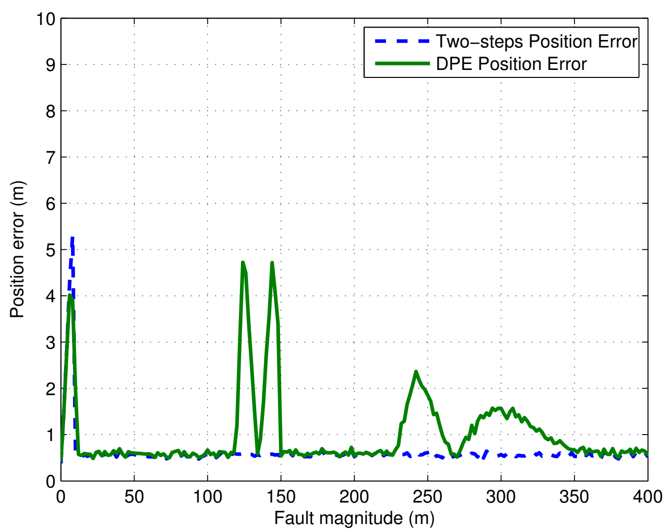

Fig. 6. Fault detection and exclusion for Galileo E1 with respect to the fault magnitude

CONCLUSIONS

This paper compares the solution separation RAIM algorithm for DPE with the conventional two-steps solution for an open-loop receiver structure. The DPE RAIM algorithm is based on the two-steps approach, being the position estimator the only difference. A single fault scenario has been considered. For the all-in-view solution, the DPE approach is more robust to faulty satellites and becomes virtually unaffected when the fault magnitude is larger than half the autocorrelation function width. The fault detection is successful for both approaches. However, the natural robustness to range errors of DPE makes it difficult to detect faulty satellites when the position error is small. For large fault magnitudes, the DPE performs in the same way as the least-squares approach.

The RAIM algorithm for DPE discussed here is based on an existing one for two-steps. The results show that improved RAIM DPE algorithms can be designed. The design of such algorithm could be based on the consistency of the DPE cost function in the presence of faulty satellites.

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