# GPS aided INS system performance under slowly varying GPS error conditions: A flight simulation case study

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*Abstract*—**GPS aided INS navigation systems depend on the complimentary accuracy properties of GPS and INS to produce superior performance. Wild input rejection feature typically incorporated in such systems protects the complimentary filter internal states from corruption by noisy GPS signal samples. This paper presents a case where a progressively degrading GPS output compromises such protection features and results in aided output errors. Such uncharacteristic behavior can occur in a launch vehicle flight GPS receiver when there is a troposphere effect on the signal from a negative elevation GPS satellite resulting in unintentional occultation. The effect of this GPS error on the aided system outputs are brought out in this paper. The troposphere induced error on GPS range and range rate measurements are simulated using a model based approach assuming ionosphere free measurements to establish the observations. An altitude based elevation cut off scheme for avoiding such occulted measurements is presented.**

*Keywords—Occultation-Negative Elevation-GPS aided INS*

## I. INTRODUCTION

Launch vehicle navigation systems were traditionally inertial navigation systems (INS), which depended on standalone inertial sensors; however with the advent of Global Positioning System (GPS), external aid from GPS applied to the resident inertial system have been demonstrated to bring in tremendous improvement in the navigation accuracy. GPS aided INS navigation systems depend on the complimentary accuracy properties of GPS and INS to produce superior performance. The INS errors are slowly varying and unbounded, which can be attributed to sensor drifts, biases and the inherent multiple integration process. Whereas comparatively, GPS errors due to satellite clock and ephemeris parameters, atmospheric propagation, receiver noise and multipath, are all fast varying and bounded generally. The efficacy of the integrated system, based on a complementary filter configuration using an optimal filter such as a Kalman filter, lies in the bounding of the error growth of an INS based system using GPS.

This paper presents a specific case where the GPS receiver in flight exhibits a slowly varying position and velocity error due to troposphere effect on the signal from a negative elevation GPS satellite resulting in unintentional occultation. The usual protection features in the aiding scheme cannot reject such slowly varying erroneous measurements from the receiver before they significantly affect the states of the filter, resulting in degraded filter performance. The GPS receiver navigation error and the corresponding errors in the aided outputs are studied.

An altitude based elevation cut off scheme for avoiding such occulted GPS measurements is also described in the paper. In this scheme, the earth obscuration angle considering troposphere height is continuously computed by the GPS receiver as the launch vehicle moves along the trajectory. When the elevation of a tracked satellite falls within a margin of this angle, the measurements are masked from usage in the navigation solution, even though the signal is still tracked with sufficient strength. This avoids erroneous measurements affecting the navigation solution. Another computationally less intensive scheme involving a fixed cut-off angle is also evaluated against the former scheme using nominal trajectories of several launch vehicle missions, and error mitigation performances are evaluated.

## II. A TYPICAL GPS AIDED INS SCHEME

For the purposes of this study a typical uncoupled GPS aided INS scheme is considered as shown in Figure 1.

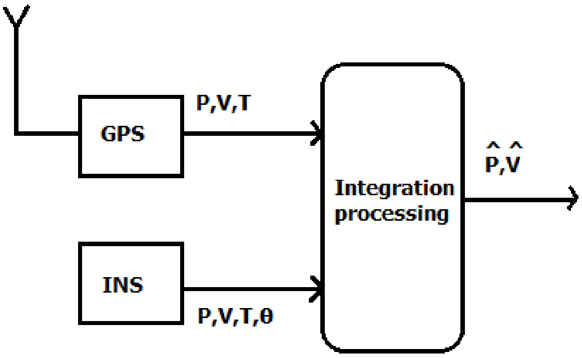

Figure 1. Uncoupled GPS aided INS scheme

In this scheme, the functional outputs of the GPS system and the INS system are processed by an integration filter, such as Kalman filter to generate aided outputs [1]. The term ‘uncoupled’ indicates that there is no feedback. With such an aided scheme used for preliminary orbit determination of the injected satellite, accuracy improvements of 5 to 6 km in apogee are usually attained compared to the standalone INS system as seen in Table 1.

| Orbit | Perigee (km) | Apogee (km) | Inclination (deg) |
|---|---|---|---|
| INS | 721.16 | 730.30 | 98.299 |
| GPS aided INS | 720.64 | 723.89 | 98.332 |
| Reference | 720.62 | 723.99 | 98.335 |

Table 1. Orbit performance improvement with GPS aided INS

As the INS is a self contained system whereas GPS depends on external radio frequency signals, well designed aiding schemes include protection features to avoid possible corruption of the internal filter states from wild GPS samples. Typically multiple GPS sample consistency validation, absolute value bound check, Position Dilution Of Precision (PDOP) check etc are used to screen out bad GPS data. The fundamental premise behind these methods is that GPS errors have only high frequency noise characteristics.

## III. A CASE OF SLOWLY VARYING GPS ERROR

A typical case of slowly varying GPS error due to occultation of a tracked negative elevation satellite is generated using Spirent SimGen® simulator software. The simulated trajectory is along an arbitrary path at an altitude of nearly 800km, which is a portion of flight path typically seen during controlled thrusting phase in launch vehicles. As the vehicle advances through the simulated trajectory segment, the negative elevation angle of SVID 26 varies from nearly 22 to 29 degrees, resulting in the satellite being progressively occulted by the earth. Figure 2 shows the case of occultation where a GPS receiver in a flight path tracks a bent signal through the troposphere [2].

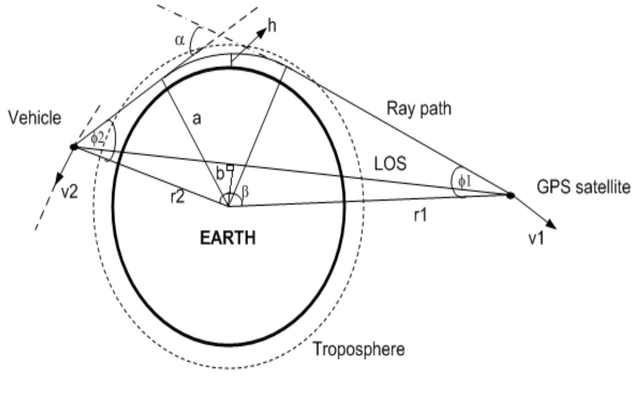

Figure 2. GPS receiver in a flight path tracking bent signal

Considering an eight channel receiver to be used in the vehicle, range and range rate data from eight visible satellites as well as satellite position velocity information logged from the simulator are used for processing. We consider all the error sources as zero, and utilize true range and range rate from the simulator to feed into the position-velocity computation algorithm. This allows a clear assessment of the error contributed by the specific situation under consideration. In practice, with Selective Availability (SA) off, the major source of measurement error is ionosphere, and our assumption of zero ionospheric error is justified to the first order by assuming that the receiver under consideration is a dual frequency GPS receiver that operates on ionosphere free pseudoranges. For the occulted GPS satellite, the tropospheric refraction effect is modeled in Matlab®, and the excess phase and excess doppler are obtained analytically. These values are added to the true (line of sight) range and range rates for the occulted satellite to form the occulted measurements of interest. The receiver measurements and satellite position-velocities are fed into a standard receiver position-velocity computation module based on the Least Square Error (LSE) algorithm.

Comparison of the position-velocity solutions including and excluding the occulted measurements reveals the extent of navigation error introduced [2]. The position and velocity errors are determined to be up to 750m and 38m/s in the root mean squared (RMS) sense due the use of the occulted satellite. The plot of the position and velocity error is shown in Fig 3 and Fig 4 respectively. However, in practice, the receiver may not continue to track the signal as the height of tangency point reaches very low values because of low signal power. Further, other factors, for example signal acceleration due to high refractivity gradient, or physical jerk events on the thrusting vehicle also may result in early tracking loss. In that case, it turns out to be beneficial for the navigation receiver if it were tracking the occulted satellite., as the position-velocity error will be lower. Based on link budget calculations, a practical PLL loop based receiver with a sensitivity of -145dBm operating under the conditions of this case will track the satellite with a carrier to noise ratio of 30dBHz up to nearly 55 seconds, beyond which it may lose lock, limiting the position error to around 150m and velocity error to 14m/s in the RMS sense.

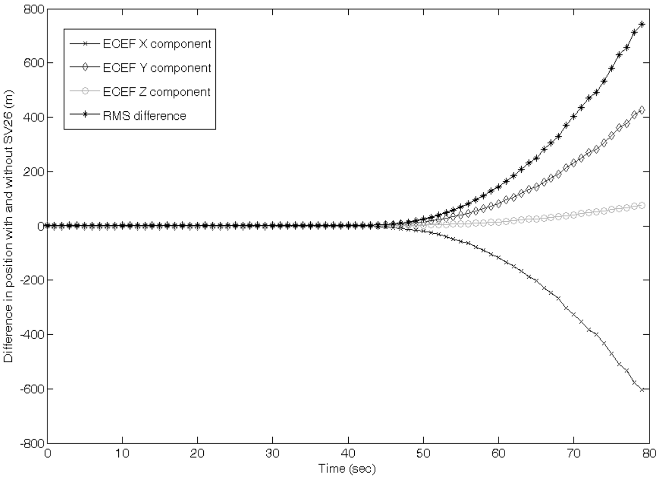

Figure 3. Position error due to occultation of SV26

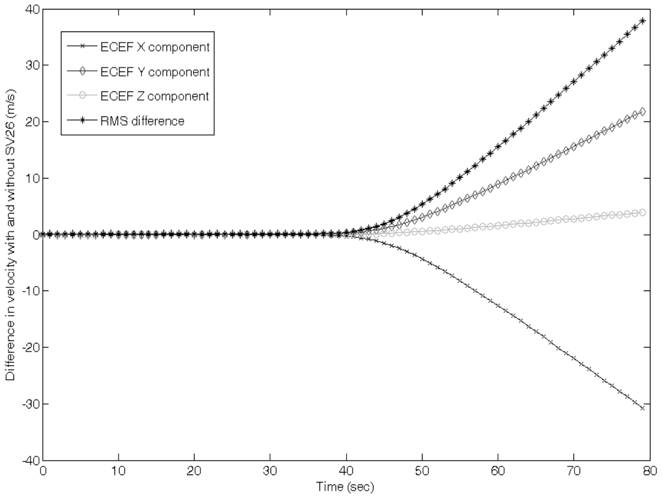

Figure 4. Velocity error due to occultation of SV26

## IV. EFFECT ON AIDED OUTPUTS

It can be seen that the errors described in Section III are slowly varying, uncharacteristic of normal GPS errors, and hence these errors will creep into the aided output despite the usual protection features implemented. Fig 5 shows the variation of INS-GPS input velocity to the filter showing the same trend as the raw GPS velocity error shown in Fig 4.

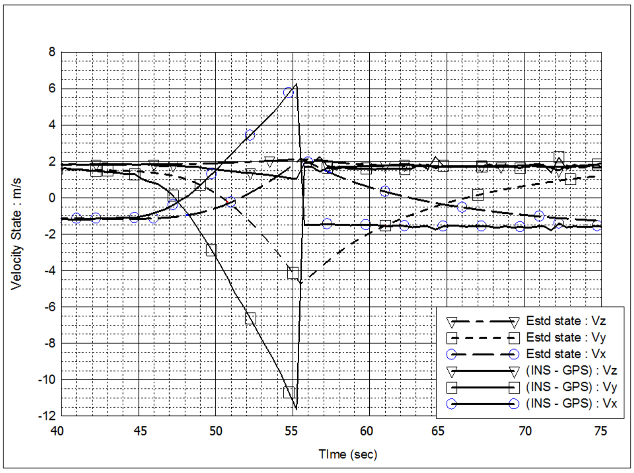

Figure 5. Aided output error due to slowly varying GPS error

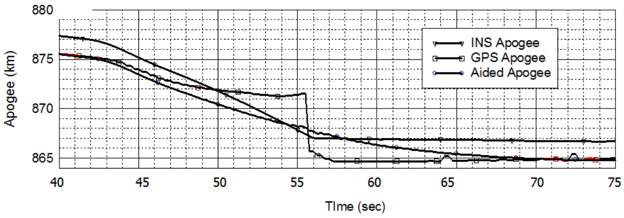

Figure 6. Aided apogee error due to slowly varying GPS error

The resultant corruption of filter is evident from the deviation of estimated states as shown by dotted lines in Fig 5. The plots in Fig5 correspond to the practical case where the GPS signal tracking is lost at 55 seconds due to low signal strength. This has limited the GPS velocity error to 14m/s which has resulted in an aided velocity error up to 5 m/s. Correspondingly the GPS position error of 150m resulted in aided position error of 100m.

## V. ERROR MITIGATION STRATEGY

The case presented shows that position and velocity errors are progressively introduced in the receiver navigation solution as one of the GPS satellites used in computation sets below the earth horizon. Therefore it follows logically that the errors can be avoided by forcibly removing that particular satellite from navigation computations from the onset of occultation. Though the actual onset of occultation can be easily identified from the post-processed profiles of excess doppler or excess phase versus time, it cannot be accurately determined from the measurements in real time as the excess quantities are extremely small in comparison to their absolute values. However with the knowledge of the vehicle altitude, using a spherical earth approximation, the half angle that the earth plus the atmosphere subtends at the vehicle location can be determined. From this angle, a corresponding elevation limit angle can be computed. As the actual elevation of the negative elevation satellite goes beyond this limit value, it can be considered as the onset of occultation, from which point that satellite must be dropped from usage in navigation computations.

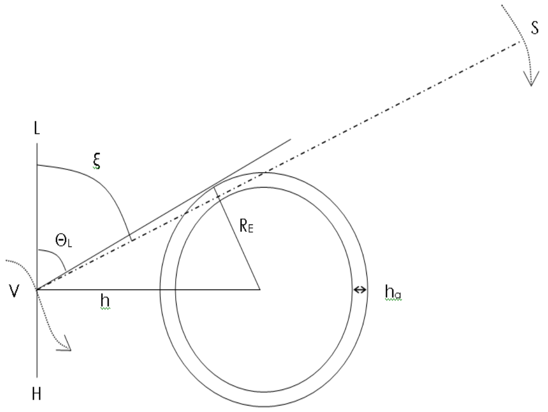

Figure 7. Geometry indicating actual elevation angle and limit angle of occulted satellite

The satellite receiver geometry for the situation is depicted in Fig 7. In Fig 7, ‘V’ indicates the vehicle position and ‘S’ indicates the occulted satellite position. The dotted lines with arrow head indicate the vehicle and satellite trajectories. ‘LH’ is the local horizontal at the vehicle location. $R_E$ represents the mean earth radius. ‘$h_a$’ is the assumed height of the atmosphere and ‘h’ is the actual altitude of the vehicle. ‘ξ’ and ‘$\Theta_L$’ indicate the actual elevation angle and the elevation limit angle respectively. This method of avoiding the measurements from a satellite using elevation cut-off criterion alleviates the possibility of navigation error due to occulted measurements, at the same time retaining the DOP advantage due to the negative elevation satellite till that point of time.

However this scheme is computationally intensive especially in software GPS receivers where the correlation processing as well as navigation computations are handled in the same processor. In such cases, mission dependant fixed elevation cutoffs is a viable alternative. For example in flights where the final orbit is around 700km altitude, the negative elevation cut-off can be fixed at -26 degrees allowing a margin for trajectory variations. Figure 8 shows the computed elevation cut-off, fixed elevation cutoff and the actual elevations of tracked satellites for a typical case. The tradeoff is that the former method allows usage of the satellite for a longer duration until the start of occultation compared to the latter.

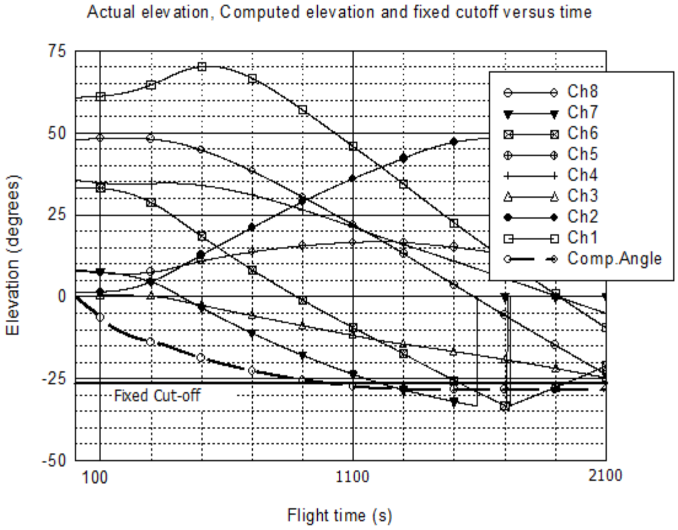

Figure 8. Actual satellite elevation, computed and fixed elevation cutoffs

As a further measure the protection feature in aiding scheme can also be strengthened. This can be implemented as a bound check operating on fixed number of previous samples of innovation. This will avoid the GPS error from affecting the filter states beyond those many samples.

## VI. CONCLUSIONS

In this paper, uncoupled GPS aided INS system behavior due to slowly varying GPS error conditions was investigated. A typical case of unintentional occultation of a tracked GPS satellite, which resulted in the introduction of such an error in the flight GPS receiver output was simulated. Results indicate GPS position errors may be as high as 750m and velocity errors up to 38m/s. In practice, the errors may be lesser depending on the atmospheric conditions, vehicle trajectory and the duration for which the receiver maintains lock on the signal from the occulted satellite. For a typical case studied, GPS position and velocity errors up to 150m and 14m/s were observed. The aided output error due to this was found to be up to 5m/s in velocity and 100m in position. An altitude based elevation cut off scheme for utilizing negative elevation satellites was also presented. Under this scheme, the negative elevation satellite is used for positioning until the elevation reaches a computed limit based on altitude, beyond which it is dropped.

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