

SIMULATING IRS NAVIGATION SYSTEM USING GPS RECEIVER

A S Ganeshan^{*}, S C Rathnakara^{**}, R Gupta^{**}, C Shekhar[#], S Banerjee^{##}

* Head, Navigation Systems, FDD, ISAC, Bangalore, India
(FAX : +91-80-5263626, E-Mail : asganesh@isac.ernet.in)

** Engineer, Flight Dynamics Division, ISAC, Bangalore

Engineer, Aeronautical Development Agency, Bangalore

Engineer, Eicher India Limited, Faridabad, India

ABSTRACT. IRS is an Indian remote sensing spacecraft placed in 817 km orbit. It was planned to put a six channel C/A code GPS receiver on-board IRS to provide the instantaneous state vector of the spacecraft. The state vector is computed from the pseudo range and deltarange measurements with respect to visible GPS satellites. The state vector and the measurements are transmitted in Real Time (RT) mode of spacecraft telemetry to the ground. Since, the telemetry does not contain GPS ephemeris, a GPS receiver on ground yields the GPS positions of common visibility to the ground and on-board receiver. The measurement data and the GPS positions are used to estimate the IRS position on ground as well. For assessing the achievable accuracies of IRS state estimation on ground, the measurement data simulation is necessary. It involves the creation of range and deltarange measurements between IRS and the visible GPS satellites. Subsequently, noise are added to the measurements using the Gauss-Markov process to simulate the realistic data. The noise patterns applicable at IRS altitude are assumed to be owing to selective availability (SA), receiver noise and constant receiver error. The errors stemming from ionosphere, troposphere and multipath are assumed negligible for the IRS satellite. However, the same are taken to be present for the ground receiver. In the ground processing, the state vector estimates of IRS are improved further by assessing and removing SA errors from the measurement data of IRS. The paper mainly discusses the simulation algorithm and the results. The navigation aspects are explained briefly.

1.INTRODUCTION

The Indian remote sensing spacecrafts of IRS series have multi-payload configuration. A GPS receiver was to be one of the piggy back payloads on-board IRS spacecraft. The receiver has six channels and provides the instantaneous state vector of IRS in Real Time (RT) mode by processing C/A code measurements. The state vector of IRS is computed using the pseudo range and pseudo deltarange measurements from a minimum of four GPS satellites visible to IRS. The GPS satellites are selected by the on-board receiver according to minimum GDOP criteria. The measurement data alongwith the GPS ID's are telemetered to the ground during ground visibility periods. The ground processing involves telemetry data handling and processing of ground GPS receiver data. The ground GPS receiver, located at a pre-surveyed landmark, provides the GPS ephemeris and the ground measurements in P-code for a maximum of 8 GPS satellites. The ground simulation & estimation of IRS state is therefore a unique process of blending the on-board receiver data with the ground receiver data. The on-board data does not provide GPS ephemeris, which is extracted from ground receiver data based on GPS time and GPS ID's.

In order to assess the achievable accuracies of IRS state estimation, it is mandatory to simulate the measurements of on-board receiver. The main objective of this paper, is the simulation of the measurement data and modeling of the uncertainties which represent the data to the navigation system process. The simulation process involves the creation of true range and deltarange measurements between the IRS spacecraft to visible GPS satellites. Further, Gauss-Markov noise is

introduced over these true measurements for simulating realistic data. The noise patterns applicable at IRS altitude (typically 817 km) are assumed to be owing to selective availability (SA), receiver noise and constant receiver error. Noise contributions stemming from ionosphere, troposphere and multipath are assumed negligible for the on-board receiver. However, the same are assumed to be present for the ground GPS receiver. The noisy data (pseudo ranges and delta pseudo ranges) is then converted to RT stream format of on-board receiver. The data thus generated forms the test bed on which various test cases are conducted.

The present paper describes the simulation and modeling of measurement data of GPS receiver on-board IRS spacecraft. The various aspects of simulation including the error sources modeling and measurement uncertainties are dealt with. The navigation process has been explained briefly and the simulation results are discussed.

2.MODELING OF UNCERTAINTIES

The uncertainties in pseudorange measurement could be due to systematic errors or biases and random noise. The error sources can be classified into three groups, namely satellite related errors, propagation medium related errors and receiver related errors [1]. Systematic errors can be eliminated to a high degree by double differencing. That is, differencing between receivers eliminates satellite specific biases and differencing between satellites eliminates receiver specific biases.

The user position errors are determined by pseudorange errors and satellite geometry. Pseudorange errors are caused by the combined satellite errors, atmospheric errors, and receiver errors. Individual components of the pseudorange error are modeled as either a Gauss-Markov process or as a white noise. Some of the pseudorange errors are receiver specific. The satellite geometry is determined by simulation. The effects from switching satellites and varying number of visible GPS satellites are also obtained from the simulation based on minimum GDOP.

Several sources of errors are associated with the measurement process. However, the errors of primary concern are the ones which can be eliminated or significantly reduced being common to both on-board and reference ground receivers. Fundamentally, these errors are composed of the satellite's clock error, error in the satellite's broadcast ephemeris data, and signal propagation delays that are not accounted for by the receiver's measurements or modeling i.e ionosphere, troposphere delays [2]. Other error sources not correlated between two receivers are the receiver interchannel biases, receiver noise and quantization errors, and local multipath effects.

One major source of receiver position error is the selective availability (SA), which limits C/A code users to around 250-m accuracy in the absolute navigation mode. While the details of SA are classified, it is known that SA can involve a combination of signal dithering and ephemeris data manipulation. In the first case, SA introduces a slowly varying (but unknown) delay into the time of satellite signal transmission. The gross features of this dithering can be approximated by a second order Markov process. If signal dithering alone is used, then the pseudorange error would be about 30 meters. Additionally, the signal dithering causes a differential correction to suffer from temporal decorrelation, which would amount to about 2 meters of pseudorange error after about 30 seconds. In the second case, SA introduces a bias error into the satellite ephemeris data. This results in no temporal decorrelation, but spatial decorrelation does result [3].

Since the ground receiver performs P-code measurements, the ionospheric delay is determined by dual frequency measurements. For the on-board receiver, it is assumed that the ionospheric delays are negligible. The tropospheric delay is related with atmospheric refraction index. The index of refraction of the lower atmosphere is not quite unity (typically 1.0003), and thus can result in a delay at very low satellite elevation angles (i.e below about 10 degrees). A simple troposphere model for ground GPS receiver predicts most of this effect, but the unmodeled error can reach 2 to 3 meters

at about 5 degree elevation [4]. While the signal ray paths to user and station can traverse quite different terrain, the differential tropospheric error is usually less than a meter, and varies very slowly. There is a small random component as well, but it is very small.

As regards inter channel bias errors, these errors are typically less than 1 meter, but random errors also exist. These errors are usually reduced by a navigation filter, which acts later in the signal processing. A potentially significant error source is multipath, particularly of the stationary sort produced by reflections from surfaces near the antenna. In the extreme, measurement errors of tens of meters on the P signal and hundreds of meters on the C/A signal can arise from such reflections. However, in the simulations of the measurement, the errors due to multipath are considered to be small.

The simulation involves the noise addition to the ranges and delta ranges from GPS satellites to IRS. The noise thus introduces errors into the true range/delta range. The ground receiver measurements modeling includes the errors due to ionosphere, troposphere, multipath, selective availability and the receiver noise. However, for simulating the on-board receiver measurements, the following noises are modeled,

- (i) Selective Availability of the GPS satellites, indicating the presence of errors stemming from clock dithering and GPS ephemeris
- (ii) The receiver error due to clock bias of IRS with respect to the GPS satellites.

The pseudorange measurements, r and dr/dt , can be taken as noisy estimates of the range and range rate, R and dR/dT . The model for pseudorange measurements is [5],

$$r = R + d(\text{eph}) + d(\text{iono}) + d(\text{trop}) + d(\text{SA}) - cT + d(\text{mp}) + v_{\text{rcvr}} \quad (1)$$

The error parameters and corresponding values of standard deviation and time constant are [6],

| Error Parameter | Std Dev (m) | Time Constant (sec) | On-board (O)/Ground (G) Receiver |
|-------------------------------|-------------|---------------------|----------------------------------|
| Ephemeris, $d(\text{eph})$ | 3.0 | 1800 | O and G |
| Ionosphere, $d(\text{iono})$ | 5.0 | 1800 | G |
| Troposphere, $d(\text{trop})$ | 2.0 | 3600 | G |
| SA, $d(\text{SA})$ | 30.0 | 80 | O and G |
| Multipath, $d(\text{mp})$ | 5.0 | 600 | O and G |
| Rcvr Noise, v_{rcvr} | 3.0 | - | O |
| L1 Carrier | 0.0019 | - | O |

where, c is the speed of light and T is receiver clock error.

The ephemeris, ionosphere, troposphere, selective availability and multipath errors are modeled as Gauss-Markov processes, i.e. having exponential autocorrelation function with variance and time constant, $1/B$. The equation for SA modeling is,

$$x_{k+1} = e^{*(-BdT)} x_k + w_k \quad (2)$$

where, x_k is the SA being modeled, $1/B$ is the time constant, dT is the sample time and w_k is the white gaussian noise. The corresponding discrete time model is given by,

$$\begin{aligned} [xR]_{i+1} &= [P11.xR + P12.xDR + U11.w1 + U12.w2]_i \\ [xDR]_{i+1} &= [P21.xR + P22.xDR + U21.w1 + U22.w2]_i \end{aligned} \quad (3)$$

The initial xR and xDR are the Gaussian random variables for position and velocity respectively. The $w1$ and $w2$ are the Gaussian white noise processes. The matrix P and U are the standard matrices

of dimension 2x2 with numerical values as their elements. During simulation the first state of the Gauss-Markov process is used to corrupt the true range with noise, and the second state is used to corrupt the delta range.

The errors specific to the on-board receiver are modeled as white gaussian processes. A variance of 3.0 m^2 and constant receiver error of 2.5 m is used for modeling the noise in range measurements. While for noise modeling in delta range measurement, a variance of $.0004 \text{ m}^2$ is used.

The GPS receiver on-board IRS measures signal travel time from four to six satellites. In the absence of measurement errors, the equation for pseudorange is,

$$t_k * c = r_k + c * (b - b_k) + c * d_k = \rho_k \quad (4)$$

In equation (4), t_k is the receiver measured travel time of the signal from the k th satellite to IRS, c is the speed of light and cd is the on-board receiver clock drift rate. The parameter b is the IRS receiver clock bias, and b_k is the clock bias of the k th satellite. The product, $t_k * c$, is called the pseudorange (ρ_k) and differs from the true range (r_k) because of two main reasons. Firstly, the IRS receiver clock is not perfectly synchronized with the GPS clock. Secondly, the signal is slowed due to ionospheric Total Electron Content (TEC). This ionospheric error at IRS altitude to GPS altitude are not modeled due to non-availability of a good ionospheric model in the region between IRS and GPS altitudes.

3. NAVIGATION PROCESS

The navigation process involves the ground data processing and estimation of IRS state from the on-board measurements and ground receiver measurements. The ground GPS receiver yields the range measurements and GPS states for the set of GPS satellites visible to the ground. The GPS positions of common visibility are extracted from ground receiver data based on the visible GPS PRN's provided by on-board receiver. Moreover, IRS state vector (obtained in RT stream) is improved further by assessing SA errors from ground measurements and removing these from the on-board measurement data alongwith receiver specific errors in the DGPS mode of navigation. The pseudorange from IRS to a typical GPS satellite can be computed in terms of the IRS position (x, y, z) and the GPS satellite position (x_k, y_k, z_k) ,

$$\rho_k = [(x - x_k)^2 + (y - y_k)^2 + (z - z_k)^2]^{1/2} + c * (b - b_k) + c * d_k \quad (5)$$

In equation (5), the position of each IRS visible GPS satellite (x_k, y_k, z_k) and the satellite clock offset (b_k) at the time of signal transmission are known. The user clock offset (b) along with unknown position (x, y, z) of IRS can be computed from the pseudoranges. The delta pseudo ranges derived from pseudoranges are used in computing IRS velocity components. The accuracy of the position and time estimates is a function of the pseudorange errors, and the geometry of GPS satellites.

The geometry of continuously changing GPS satellites is an important factor in achieving accurate navigation solution especially for a highly dynamic platform like IRS. The geometry changes with time due to relative motion of GPS satellites with respect to IRS. A measure for the geometry is the dilution of precision (DOP), usually represented by GDOP. Since more than 4 GPS satellites will be visible to IRS at different times, there will be many combinations of GPS satellites. The best one is to be selected by minimum GDOP criterion for all the combinations. The GDOP is computed at every instant logically and exhaustively to identify the best GPS satellite combination out of the many. Towards this, GPS positions and IRS position are propagated by employing the simple two-body model and the GDOP variation is obtained.

The position of IRS is improved further in the DGPS mode. This is achieved mainly by removing the SA errors. The SA errors present in the on-board measurements with respect to visible GPS are

removed by estimating the SA of corresponding GPS from ground receiver data. This is done by predicting the true range between the ground receiver and the GPS satellites of common visibility to the ground receiver. The pseudo ranges from the ground receiver are treated for the atmospheric and receiver specific errors. The SA component of a GPS PRN is then the difference between the true range and the corrected pseudorange. The computation is made from the GPS satellite positions (based on broadcast ephemeris) and the known ground station antenna location. Differences between the predicted and observed pseudoranges are filtered to remove receiver-unique errors, and then corrections are applied to the pseudoranges measured by the on-board GPS receiver. The modified measurements are then subjected to the estimation process to improve the state vector of IRS.

4.RESULTS AND DISCUSSIONS

The simulation results are obtained for a typical pass of IRS over Bangalore Station, the prime station at which the data is to be received. The orbital parameters of IRS and the almanac data of GPS satellites (downloaded from the ground station receiver) form the inputs to the simulation algorithm. Since the selection of GPS satellites for on-board receiver is based upon the GDOP criteria, the simulation model accounts for GDOP computation in the choice of GPS satellites. In fact, a total of 8-9 GPS satellites are visible to IRS, but the selection of GPS satellites for the state vector estimation of IRS is done based on minimum GDOP. The simulation results provide time-varying effects of noise components simulated for the ground GPS receiver. Moreover, the effect of these noises in corrupting the true ranges from IRS to GPS manifest in terms of pseudorange, pseudorange rate and the GDOP. The noise components consist of the effects due to ionosphere, troposphere and selective availability (SA) for the ground GPS receiver.

The typical iono and tropo errors for a ground receiver are shown in fig 1. The tropospheric error varies nearly linear with time because of the time constant used. While the typical value of tropo error for the selected GPS is of the order of 3 to 4 meters, the error due to ionosphere effects varies from -2 to 0.5 meters, as shown in fig 1. The major contribution of errors in measurement is due to SA (selective availability) shown in fig 2. The SA component for GPS ID 1 varies from -20 m to 20 m, while it goes as high as 40 m to 100 m for the case of a different GPS (ID 20). The combined effect of these three major error sources (SA+iono+tropo) is displayed in fig 3. The error contribution also includes the IRS receiver clock bias, which has been assumed as 500 m for this simulation. It is evident that the combined errors vary from 470 to 530 m for different GPS satellites. The simulated pseudorange and pseudorange rate from IRS to a typical GPS are plotted in fig 4 and fig 5 respectively. These pseudo parameters are generated by considering the effect of all the noise components (SA + iono + tropo) and are the representative of the actual measurements from IRS to GPS. The GDOP variation over a complete pass is provided in fig 6. It clearly shows that the GDOP falls from an initial value of 4.5 to 2.5.

The simulation results represent the typical values of on-board measurements for the IRS satellite pass over Bangalore station. However, the measurement parameters will be different, depending upon the geometry of GPS satellite constellation visibility to the ground station and IRS. The measurements generated for the 4 best GPS PRN's are used for obtaining the state vector of IRS. The state is improved further in the DGPS mode of navigation solution.

5.CONCLUSIONS

The paper presented an algorithm for simulating the IRS navigation system using GPS measurements in terms of pseudorange and pseudorange rate. The pseudo measurements were

simulated by adding the noise to true measurements using the Gauss-Markov process. The measurement errors were modeled in terms of selective availability (SA), receiver noise and constant receiver error for the on-board receiver. The ground receiver measurement modeling included the errors due to ionosphere, troposphere and multipath, which were assumed negligible for IRS. The salient results obtained through simulation were discussed. The measurement data so simulated formed the test-bed equivalent to the data expected from the on-board receiver, which is used for ground processing and state vector estimation of IRS.

6.ACKNOWLEDGEMENTS

The authors express their sincere gratitude to Shri P S Goel, Associate Director, ISRO Satellite Centre, Bangalore for providing this challenging opportunity of working in the field of GPS based navigation. The necessary guidance and encouragement of Shri Y N Bhushan, Group Director, Mission Development Group has been of immense importance during the course of the work. The authors are grateful to Shri N S Gopinath, Head, Flight Dynamics Division for the keen interest shown throughout.

7.REFERENCES

- [1] Martin E.H., 'GPS User Equipment Error Models', Navigation : Journal of the Institute of Navigation, Vol 25, No 2, Summer, 1978.
- [2] Mertikas S.P., 'Error Distributions and Accuracy Measures in Navigation : An Overview', Department of Surveying Engineering, Technical Report No 113, University of New Brunswick, Fredericton, N.B., 1995
- [3] Enge P.K., 'Differential Operation of the Global Positioning System', IEEE Communications Magazine, Vol 26, No 7, July 1988
- [4] B.Hoffmann-Wellenhoff, H.Lichtenegger, Collins J., 'Global Positioning System - Theory and Practice', March 1993
- [5] Van Dierendonck, Russel, Kopitzke E.R., Birnbaum M., 'The GPS Navigation Message', Navigation : Journal of the Institute of Navigation, Vol 25, No 2, Summer 1978.
- [6] Cannon M.E. and La Chapelle G., 'Analysis of a High Performance C/A-code GPS Receiver in Kinematic Mode', Navigation : Journal of the Institute of Navigation, Vol 39, No 3, Fall 1992.