IONOSPHERE ERROR ESTIMATION IN GAGAN: AN END-TO-END APPROACH

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ABSTRACT

The primary objective of GAGAN (**G**ps **A**ided **G**eo **A**ugmented **N**avigation) is to provide vertical accuracy and integrity during aircraft landing. The accuracy is largely governed by accurate estimation of ionosphere error and its confidence in real time. The paper highlights the algorithms for decoupling of ionosphere error from raw measurements and estimation of smooth ionosphere error (with biases), separation of slant delays and biases. Finally, the ionosphere delay computation at ionosphere grid points (IGPs) using Planar and Kriging methods are presented and verified with SBAS messages. This paper establishes an end-to-end approach for real time ionosphere delay estimation in GAGAN.

1.0 INTRODUCTION

The ionosphere characterization for SBAS application has been a very active area of interest in the recent past by the researchers' world over. In this regard, the work done at Stanford University [1-4] has been of great importance and use in establishing a software architecture for ionosphere error estimation in GAGAN. Here, it is important to note that even though, a number of approaches and methods have been discussed in literature; but an end-to-end approach has not been discussed. This paper provides a comprehensive approach (Fig. 1) for estimating grid ionosphere vertical delay (GIVD) & grid ionosphere vertical error (GIVE) at IGPs using GPS dual frequency raw measurements of code and carrier phase

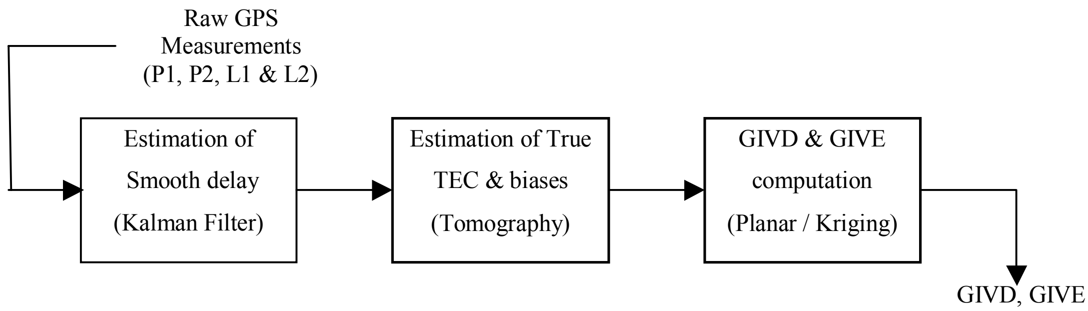

Fig.1. Ionosphere software architecture

at 1 Hz rate. This computation involves a four step procedure to provide an end-to-end solution. The first step is the Kalman filter based estimation of code-carrier smoothed and lumped ionosphere delay. In the second step, the TEC (Total Electron Content) is estimated, by separating the total group delay due to two frequencies at satellite and the receiver. The estimated TEC is at the ionosphere pierce point (IPP) in the line-of-sight from ground station to the satellite. Subsequently, in the third step, GIVD and GIVE are computed at the IGPs, using planar model. Further, these delays at IGP are improved in the forth and final step, using Kriging technique. At IPP, the error estimates of Planar and Kriging are verified through statistical analysis. However, the ionosphere delays at IGP are verified through corresponding values from a standard source.

2.0 ESTIMATION OF TRUE IONOSPHERE DELAY

The estimation of true ionosphere delay involves two steps; firstly the dual frequency ionosphere delay is smoothed using code and carrier measurements through a Kalman filter. This is followed by separating the TEC from satellite and receiver biases using Tomography approach.

2.1 Ionosphere Smoothening Using Code & Carrier

The ionosphere computation using dual frequency raw code measurements is very noisy, which can not be used for the precise applications like GAGAN. In the same way, the ionosphere computation using dual frequency carrier phase is difficult, since the carrier measurements suffer from inherent integer ambiguity problem. Therefore, it becomes necessary to combine dual frequency code and carrier measurements, to obtain a smooth estimate of the ionosphere.

The computation of Ionosphere error using dual frequency code ranges P1 and P2 is computed and is termed as measurement for the Kalman filter. Further, the computation of Ionosphere error using dual frequency carrier phase measurements L1 and L2 is obtained and this is the state for the filter. Further, the Kalman Filter is initiated with the measurement and state, to obtain smoothed value of ionosphere and its variance.

2.2 Tomography to Estimate TEC & Satellite and Receiver Biases

In order to obtain Ionosphere delay in the line of sight, termed as truth data, hardware biases must be removed from code carrier smoothed ionosphere delay. Earlier approaches are based on 2-D and 3-D models of ionosphere; however basic assumption of a single thin ionosphere shell with a fixed altitude between 250 and 450 km above the earth's surface has been used in 2-d models. This is not necessarily in agreement to real physical conditions of ionosphere. The variation of ionosphere vertical profile is reflected only at the altitude in accordance with the height of single layer (2-D) model. These shortcomings of 2-D models led to development of 3-D model. The model based on tomography technique has been used by many researchers earlier to get truth in the LOS. The coefficients and inter –frequency biases were determined using a batch process with 60 hours data as indicated in [1]. This processing method would require extensive computational resources and large amount of GPS data and very long processing time. So, it is not feasible to use this processing method in real time ionosphere modeling. Here 3-D modeling of ionosphere is used only for separation of hardware biases,

$$TEC = \int_{R}^{S} N_e(r) dl(r) \tag{1}$$

This problem is inverse problem i.e. given TEC values to obtain electron density Ne(r).This problem is reduced to a linear problem by approximation of integral operator through matrix A, which involves application of Riesz representation theorem and Domain decomposition theorem,

$$AX = TEC \tag{2}$$

Where, X consists of electron density and hardware biases,

$$A_{ij} = \int_{LOS_j} \psi_i(r) dl \tag{3}$$

Where LOSj indicates the line of sight for TEC_j, ψ_i is the linear coefficient corresponding to the i^{th} basis function, representing the ionosphere's electron density distribution. Basis functions are integrated in LOS (in solar magnetic frame) to form the elements of matrix A. TEC values are the values of smooth ionosphere delay in LOS obtained in the previous step . Minimum variance followed by Kalman filter is being used for estimation of electron density and hardware biases.

3.0 ESTIMATION OF GRID IONOSPHERE DELAY & CONFIDENCE

The ionosphere corrections for GAGAN require the delay (GIVD) and confidence (GIVE) to be available at pre-defined grid points (IGPs). These can be computed using either a planar model or a Kriging Technique, which are described further.

3.1 Planar Model at Grid Points

This model requires the vertical ionosphere delays at the INRES IPPs, $I_{v,IPP}$, the measurement variances, $^{2}_{I,IPP}$, the confidences on the estimated IFB, τ_{gd}, ($_{bias}$) and $_{decor}$, the decor relation of the ionosphere over the plane, which is constant number arrived using the post-processed data. Output will be the GIVDs, GIVEs at the predefined grid locations. Given a set of measurements ($I_{v,IPP}$), this method uses a planar fit to interpolate the delay at any desired location within the fit radius. The fit radius and the number of measurements used in the fit ('N') can be varied. It was observed that for CONUS region a fit radius of 2000 km with N = 20 can provide good estimate of the GIVDs.

In the region about the IGP the ionosphere is estimated by,

$$I_{V,IGP}(x,y) = a_0 + a_1.x + a_2.y \tag{4}$$

Where, x,y are the distances from the IGP along the East and north directions in a local Cartesian frame with IGP as origin. The planar coefficients can be solved as,

$$[a_0, a_1, a_2] = [(GWG^T)^{-1}\ G\ W\ I_{v,IPP}] \tag{5}$$

and the error on the estimate

$$^{2}_{I,IGP} = [(GWG^T)^{-1}]_{1,1} \tag{6}$$

Here, 'G' denotes the observation matrix, 'W' is the weight matrix (accounting for error variances) and $I_{v,IPP}$, the vertical delays at the IPPs. Since the ionosphere is not always nominal, the entire user IPPs should be protected. This is done using a χ^2 test and irregularity parameters, which are derived from the χ^2 test. The GIVD estimated using a planar fit for a typical IGP over the Indian region is shown on figure no.:

3.2 Kriging Technique for GIVD, GIVE

The Kriging technique is a well-known method in geo-statistics, which has been used extensively in SBAS applications. This is based on a type of minimum mean square estimator. There are 3 major components of this technique, which have been adapted to generate GIVD and GIVE at the IGP's. The first step is to identify the IPP's around the chosen IGP, which is similar to the planar method. The next step in this technique is the **computation of experimental variogram, followed by the computation of model variogram coefficients. Further, usage of these coefficients in the Kriging equations [4] provides the GIVD and GIVE at the IGP.**

4.0 RESULTS AND DISCUSSIONS

The input data source for this paper is dual frequency 1-Hz GPS measurements from 24 stations of NSTB and WAAS. This was processed by various algorithms discussed previously and the typical results are discussed here. The duration of the data is considered almost a day (~ 22 hours) to visualize the peak ionosphere activity, occurring at 1400 hour local time. For a selected line of sight, the variation of raw ionosphere and smoothed ionosphere is displayed in Fig 2. This ionosphere includes the hardware biases of the satellite and the receiver. Thereafter, after removal of satellite and receiver biases through tomography, the true ionosphere delay for this line of sight is shown in Fig 3.

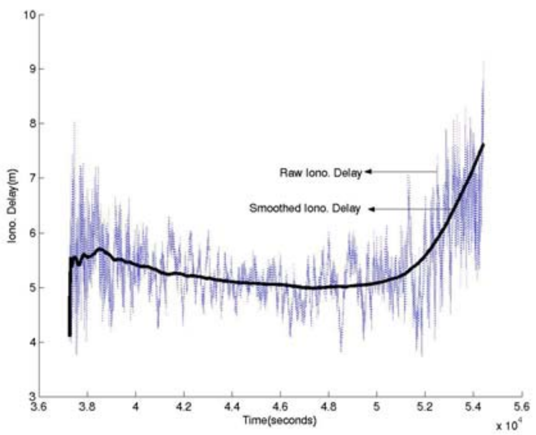

Fig 2: Code-carrier smoothed ionosphere

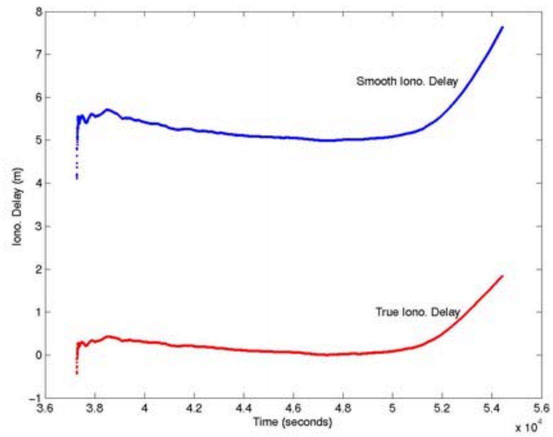

Fig 3: Ionosphere delays - smooth (biased) & true

Using the true ionosphere computed previously, the delay at a typical IGP was obtained for both the methods i.e. Planar and Kriging. The corresponding delays for the IGP were obtained from the NSTB message. The GIVD results for Planar & Kriging are displayed in Fig 4 and Fig 5 respectively for a chosen IGP. This comparison was repeated for all the IGPs and the values were verified.

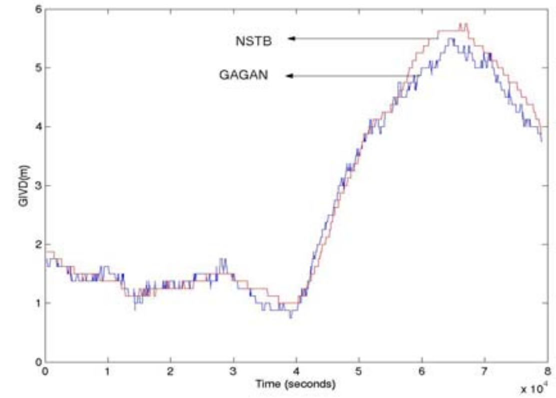

Fig 4: GIVD using Planar vis-à-vis NSTB

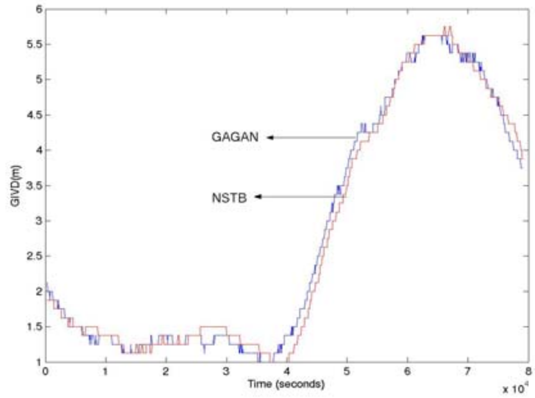

Fig 5: GIVD using Kriging vis-à-vis NSTB

Further, to verify the ionosphere computation, error distribution plots of Planar and Kriging are shown in Fig 6 and Fig 7. The variation captures the normal distribution characteristic of the modeled error.

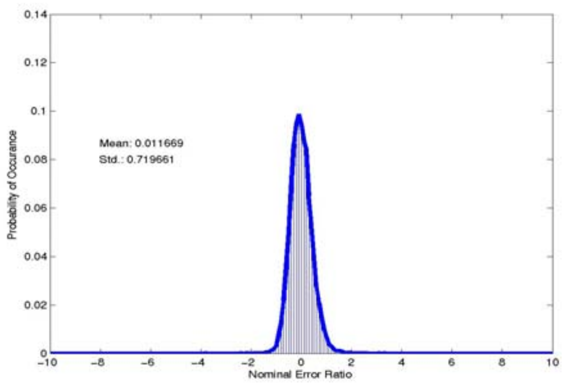

Fig 6: Planar Model Verification

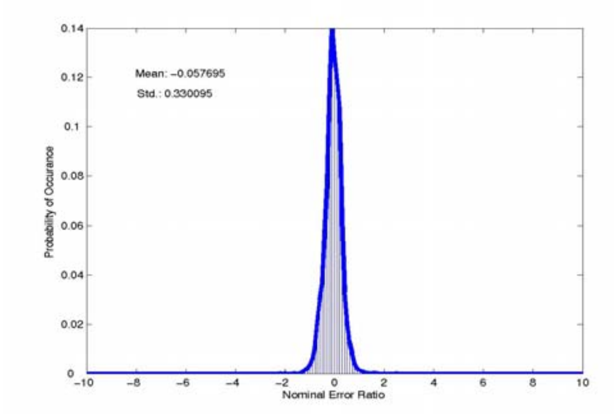

Fig 7: Kriging Technique Verification

5.0 CONCLUDING REMARKS

The primary objective of this paper was to establish an end-to-end approach for the ionosphere error estimation for GAGAN. The paper briefly describes the procedure of obtaining ionosphere delay at IGP, according to the MOPS (Minimum Operations and Performance Standards) structure. The paper essentially presented complete software architecture to achieve the desired goal. The procedure has been validated with 1 Hz real time measurements and the results were verified with the corresponding message.

6.0 REFERENCES

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