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Ionospheric Delay Estimation during Ionospheric Depletion Events for Single Frequency Users of IRNSS

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Abstract

The IRNSS (Indian Regional Navigation System) navigation users estimate their position by using a receiver which receives the navigation signal from the IRNSS satellites which will be operating on L5 (1176.45MHz) and S (2492.028MHz) frequencies. There are 3 types of IRNSS users: 1) Dual frequency (L5 and S), 2) Single frequency (L5) and 3) Single frequency (S). The signal from the satellites before reaching the user receiver passes through the ionospheric layer of the atmosphere and suffers a delay. The delay in the signal introduces error in the position computed by the user. The dual frequency users of IRNSS correct the ionospheric error by taking advantage of the dispersive nature of ionosphere. On the other hand, single frequency user requisite an algorithm for computing the ionospheric delay along his line of sight. In IRNSS, the ionospheric error corrections for single frequency (L5 or S) users will be provided by two ways: 1) Grid based and 2) Coefficient based. These corrections may not be valid when an abnormal behavior of ionosphere occurs due to geomagnetic storm, solar coronal mass ejections or any other disturbances in the earth's magnetic field. The abnormal behavior may result in increase or decrease of the TEC (Total Electron Content) in the ionosphere. Ionospheric depletion event is one such, where there is a sudden drop in TEC forming plasma bubbles travelling through the ionosphere. A user, whose line-of-sight when crosses such a TEC depleted area of ionosphere suffers from an extra error due to depletion. The amount of error is proportional to the depth of depletion. This error in the range ultimately results in the user position accuracy degradation. In this paper a novel algorithm has been designed and developed which will estimate the ionospheric delay, thereby providing ionospheric corrections even at times of depletions. The developed technique in turn provides achievable position accuracy during times of ionospheric depletions. The developed technique has been tested with GAGAN (GPS Aided GEO Augmented Navigation) INRES (Indian Reference Stations) data and IRNSS IRIMS (IRNSS Range and Integrity Monitoring Stations) data having deep ionospheric depletions. The fully tested and validated ionospheric delay estimation algorithm is proposed to be implemented in IRNSS single frequency (L5/S) receivers.

Keywords: IRNSS Single Frequency User, Ionospheric Error, Ionospheric Depletion, Ionospheric Delay Estimation, Kalman Filter

1. Introduction

Indian Regional Navigational Satellite System (IRNSS) envisages establishment of regional navigational satellite system using a combination of GEO and GSO Spacecrafts. The IRNSS system provides navigation solution all time, all weather, anywhere within India and a region extending about 1500 km around India, expected to provide position accuracy better than 20m(95%). The IRNSS system (as in SIS ICD) mainly consists of three segments namely: 1) Space Segment, 2) Ground Segment and 3) User Segment. The IRNSS space segment consists of 7 satellites (3 GEO and 4 GSO). The three GEOs will be located at 32.5° E, 83°E and 131.5° E and the four GSOs have their longitude crossings 55° E and 111.75° E (two in each plane). IRNSS satellites have two types of payload, Navigation and Ranging payload. The Navigation Payload of IRNSS is a broadcasting type of payload which will transmit the ranging codes being generated onboard with the navigation data up linked from the ground using TTC transponder. The ground Segment is responsible for maintenance and operation of the IRNSS constellation. The Ground segment comprises of: 1) IRNSS TTC Stations (IRTTC), 2) IRNSS Spacecraft Control Facility (IRSCF), 3) IRNSS Navigation Centre (INC), 4) IRNSS Range and Integrity Monitoring Stations (IRIMS), 5) IRNSS NetWork Time Centre (IRNWT), 6) IRNSS CDMA Ranging Stations (IRCDR), 7) IRNSS Laser Ranging Station (IRLRS) and 8) IRNSS Data Communication Network (IRDCN). The User segment mainly consists of: 1) Single frequency IRNSS receiver capable of receiving SPS signal at L5 or S band frequency and 2) A dual frequency IRNSS receiver capable of receiving both frequencies (RS/SPS).

The IRNSS users estimate their position by using a receiver which receives the navigation signal from the IRNSS satellites which will be operating on L5 (1176.45MHz) and S (2492.028MHz) frequencies. There are 3 types of IRNSS users: 1) Dual frequency (L5 and S), 2) Single frequency (L5) and 3) Single frequency (S). The signal from the satellites before reaching the user receiver passes through the ionospheric layer of the atmosphere and suffers a delay as shown in Figure 1. The delay in the signal introduces error in the position computed by the user. The dual frequency users of IRNSS correct the ionospheric error by taking advantage of the dispersive nature of ionosphere. On the other hand, single frequency user requisite an algorithm for computing the ionospheric delay along his line of sight. In IRNSS, the ionospheric error corrections for single frequency (L5 or S) users will be provided by two ways: 1) Grid based as defined in IRNSS SIS ICD and 2) Coefficient based as defined in Rethika et al. In grid based method, the ionospheric error corrections will be provided at the pre defined $5^o \times 5^o$ grid points identified over the Indian Region. The IRNSS user coming under any of the four grid points will compute the ionospheric error along his line-of-sight using interpolation. In coefficient based method, the ionospheric error corrections are provided in the form of 8 coefficients.

These corrections may not be valid when an abnormal behavior of ionosphere occurs due to geomagnetic storm, solar coronal mass ejections or any other disturbances in the earth's magnetic field. The abnormal behavior may result in increase or decrease of the TEC in the ionosphere. Ionospheric depletion event is one such, where there is a sudden drop in TEC forming plasma bubbles travelling through the ionosphere. A user, whose line-of-sight when crosses such a TEC depleted area of ionosphere suffers from an extra error due to depletion. The amount of error is proportional to the depth of depletion. This error in the range ultimately results in the user position accuracy degradation. Hence it is required to provide the actual ionospheric corrections to the IRNSS single frequency users to achieve good position accuracy even at times of disturbed ionospheric conditions. In this regard, Ionospheric characteristics over Indian region (N. Dashora et al, P. T. Jayachandran et al, K. Patel et al, H. S. S. Sinha et al) and already available Ionospheric depletion related algorithms (Bakry El-Arini et al and Cueto et al) has been studied. Keeping the perspective of detecting the depletions and providing the actual ionospheric corrections in real time, a novel technique has been designed and developed in this paper. The developed technique has been validated and verified with GAGAN INRES data as well as IRNSS IRIMS data affected by deep ionospheric depletions over Indian region.

2. Effect of Ionospheric Depletion on IRNSS

In IRNSS, ionospheric error correction is accomplished in two ways namely 1) Grid based iono corrections over Indian land mass. 2) Coefficient based iono corrections (Rethika et al) over IRNSS service region. But these ionospheric corrections are not valid when there are unexpected and strong disturbances in the ionosphere. One of such event is ionospheric depletion which is identified by a sudden drop in the iono delay value against the background correction values. As India is in the equatorial region, depletion events are more frequent and its effect has to be eliminated to obtain better user position accuracy. This can be done by developing an algorithm which could be built into the user receivers to protect the users by estimating the ionospheric delay at times of depletion. Figures 2 & 3 illustrate ionospheric depletion phenomena: (time along x-axis and ionospheric delay along the y-axis).

From figure 3, we see that, ionospheric delay (red color line) has undergone a depletion event. The dotted line represents the normal behavior of the ionospheric delay over a day when no depletion events occur. Since IRNSS single frequency users operate on L5, It is required to provide corrections to the IRNSS users at times of these depletion events so as to make the ionospheric corrections provided to users valid.

2.1 Characteristics of Ionospheric Depletion

The following characteristics are predominantly observed whenever an ionospheric depletion is observed:

1) ***Time of Occurrence:*** Usually the ionospheric depletions occur during the post-sunset hours (predominantly between 20:00 and 00:30 hrs of LT).
2) Depletion events are more at times of equinox and places of equatorial anomaly. Equatorial anomaly region refers to the region lying with 15^0-20^0 north and south of the equator.
3) ***Duration:*** Depletion events may last from minimum duration of 30 min to a maximum duration of 2 hours.
4) ***Depletion depth:*** The depth of depletion varies from 4m to 14m (on L1).

2.2 Effects of Ionospheric Depletion

The following are the effects of ionospheric depletions:

1) Ionospheric depletions are more severe with radio signals of low frequency. Hence L5 signals are more prone to depletions than S frequency signals.
2) Severe depletions may also lead to sudden and irregular fluctuations in the amplitude and phase of the signals. This effect is referred to as ionospheric Scintillation.
3) The ionospheric scintillation events can result in the loss of lock of signals.
4) The ionospheric corrections for the navigation service users are computed taking into account the overall behavior of ionosphere over India. Depletions in the user's line-of-sight make these broadcasted ionospheric corrections invalid.

Ultimately, the accuracy of user position computed using the broadcasted ionospheric corrections is degraded.

2.3 Implications on Navigation Receivers

The following are the user-wise implications of ionospheric depletion events:

1) **IRIMS Rx**: Since IRIMS RX provide dual frequency measurements (on L5 and S), the iono free measurements are directly computed and hence remain unaffected by depletions, even if observed.
2) **User Rx (dual frequency):** The ionospheric error free measurements can be directly computed and hence remain unaffected by depletions, even if observed.
3) **User Rx (L5):** If these depletions are observed along the user line of sight then the user position accuracy will be degraded depending on the magnitude of the depletion. **Mitigation:** User depletion algorithm at the user Rx.
4) **User Rx (S):** Impact on S frequency will be much lesser than L5; however user depletion algorithm can be implemented at the user Rx.

3. Estimation of Single Frequency Ionospheric Delay during Ionospheric Depletion Events

The estimation module is designed to compute and remove the actual ionospheric delay from the single frequency measurements in the presence of depletions. It will take the code range and carrier phase measurements at every epoch as input. These inputs are provided to a Kalman Filter residing at the receiver level. The ionospheric delay along the user's line-of-sight is estimated at every epoch. Figure 4 provides the design for the ionospheric delay estimation module at the receiver end.

The methodology takes advantage of code carrier divergence property of ionosphere. A kalman filter is designed to estimate the ionospheric delay in near real time to get a better accurate ionospheric correction during times of ionospheric depletion. The kalman filter equations are:

Prediction

Predicted (a priori) state estimate $\hat{x}_{k|k-1} = F_k \hat{x}_{k-1|k-1} + B_k u_k$ (1)

Predicted (a priori) estimate covariance $P_{k|k-1} = F_k P_{k-1|k-1} F_k^T + Q_k$ (2)

Updation

Innovation or measurement residual $\tilde{y}_k = Z_k - H_k \hat{x}_{k|k-1}$ (3)

Innovation (or residual) covariance $S_k = H_k P_{k|k-1} H_k^T + R_k$ (4)

Optimal Kalman gain $K_k = P_{k|k-1} H_k^T S_k^{-1}$ (5)

Updated (a posteriori) state estimate $\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k \tilde{y}_k$ (6)

Updated (a posteriori) estimate covariance $P_{k|k} = (I - K_k H_k) P_{k|k-1}$ (7)

The developed technique has been tested with data having depletions for its efficient functioning at times of depletion. The results for the performance of the estimation module are provided in the next section.

4. Results with Developed Technique

4.1 Results with GPS data (on L1 Frequency)

Data Used: GAGAN INRES data

INRES (Indian Reference Station) refers to GAGAN (GPS Aided GEO Augmented Navigation) ground stations located across India which receives the **GPS L1/L2 data** for the generation of SBAS error corrections. There are about 15 INRES station across India. The input to the estimation module will be **GPS L1** code and carrier measurements along with the broadcast navigation messages.

The following are the results of the study wherein depletion occurred along the INRES's line-of-sight. The results are compared with true delay computed using dual frequency measurements of the INRES.

Date: 12/Oct/2011

INRES Station: Bhubaneswar

Figure 5 shows the ionospheric depletion observed in the line-of-sight of Bhubaneswar station for GPS PRN: 21. The red color line shows the estimated **iono delay on L1** at the time of depletion.

From figure 5, we see that, even at times of depletion, the ionospheric delay estimation module is able to provide corrections to the user. Table 1 provides the ionospheric error for the user with and without estimation module at the time of ionospheric depletion along the line of sight for Bhubaneswar on 12/Oct/2011.

From table 1, we observe the residual error due to ionospheric delay in **the L1 signal** is significantly reduced by the use of iono delay estimation module. Also, we observe that there is a significant improvement in the position accuracy at times of ionospheric depletions with the estimation module.

Date: 12/Oct/2011

INRES Station: Ahmedabad

Figure 6 shows the ionospheric depletion observed in the line-of-sight of Ahmedabad station for GPS PRN: 29. The red color line shows the estimated **ionospheric delay on L1** at the time of depletion.

From figure 6, we see that, even at times of depletion, the ionospheric delay estimation module is able to provide corrections to the user. Table 2 provides the ionospheric error for the user with and without the estimation module at the time of ionospheric depletion along the line of sight for Ahmedabad INRES on 12/Oct/2011.

From table 2, we observe the residual error due to ionospheric delay in **the L1 signal** is significantly reduced by the use of ionospheric delay estimation module. Also, we observe that there is a significant improvement in the position accuracy at times of ionospheric depletions with the estimation module.

4.2 Results with IRIMS (IRNSS) data (on L5 frequency)

IRIMS (IRNSS Range and Integrity Monitoring Station) refers to IRNSS ground stations located across India which receives the **IRNSS L5/S data** for the generation of orbit, ionospheric and clock error corrections for IRNSS broadcast to the navigation users. There are about 9 IRIMS station operationalized across India as of June 2014. The input to the estimation module will be **IRNSS L5** code and carrier measurements along with the broadcast navigation messages.

The following are the results of the study wherein depletion occurred along the IRIMS's line-of-sight. The results are compared with true delay computed using dual frequency measurements of the IRIMS and the delay computed using IRNSS grid ionospheric corrections.

Data Used: Bangalore IRIMS data

Date: 3/Nov/2013

Figure 7 shows the ionospheric depletion observed in the line-of-sight of Bangalore station for IRNSS-1A. The red color line shows the estimated **ionospheric delay on L5** at the time of depletion.

From figure 7, we see that, even at times of depletion, ionospheric delay estimation module is able to provide corrections to the user which ultimately improves the position accuracy of the IRNSS users. Table 3 provides the ionospheric error for the user with and without the estimation module at the time of ionospheric depletion along the line of sight for Bangalore IRIMS on 3/Nov/2013.

From table 3, we observe the residual error due to ionospheric delay in **the L5 signal** is significantly reduced by the use of iono delay estimation module. Also, we observe that there is a significant improvement in the position accuracy at times of ionospheric depletions with the ionospheric delay estimation module.

Date: 15/Nov/2013

Figure 8 shows the ionospheric depletion observed in the line-of-sight of Bangalore station for IRNSS-1A. The red color line shows the estimated **ionospheric delay on L5** at the time of depletion.

From figure 8, we see that, even at times of depletion, the ionospheric delay estimation module is able to provide corrections to the user which ultimately improves the position accuracy of the IRNSS users. Table 4 provides the ionospheric error for the user with and without the estimation module at the time of ionospheric depletion along the line of sight for Bangalore IRIMS on 15/Nov/2013.

From table 4, we observe the residual error due to ionospheric delay in **the L5 signal** is significantly reduced by the use of estimation module. Also, we observe that there is a significant improvement in the position accuracy at times of ionospheric depletions with the ionospheric delay estimation module.

5. Conclusion

In this paper, a methodology for ionospheric delay estimation during depletion for single frequency users of IRNSS has been designed and developed. The developed single frequency ionospheric delay estimation module has been tested with GAGAN INRES L1 data with deep ionospheric depletions. It successfully tracks and corrects the L1 ionospheric delay at times of depletion. It is also tested with IRNSS L5 data with ionospheric depletions. It works well in tracking and correcting the L5 ionospheric delay at times of ionospheric depletion events and provides achievable position accuracy for IRNSS single frequency users.

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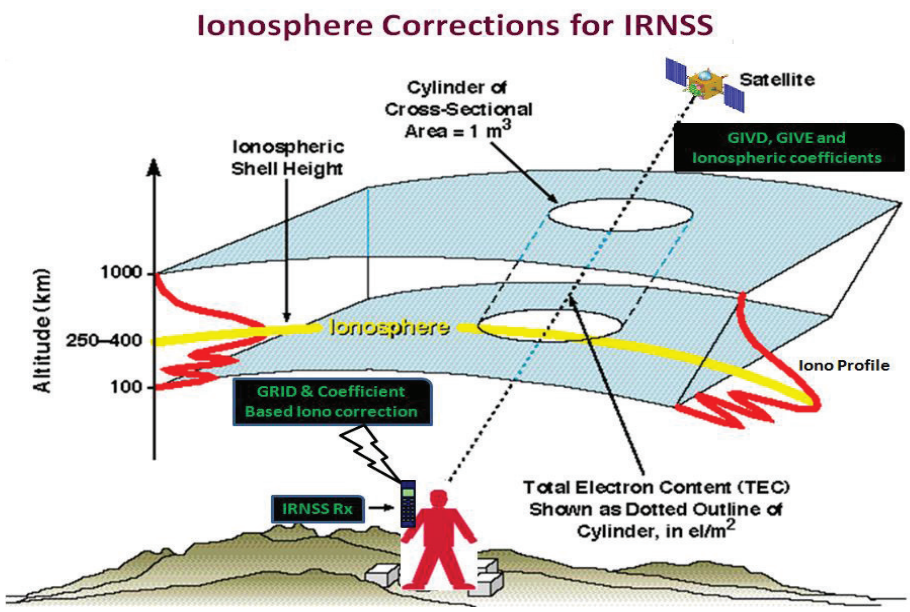

Figure 1. Ionospheric error corrections for Single Frequency users of IRNSS

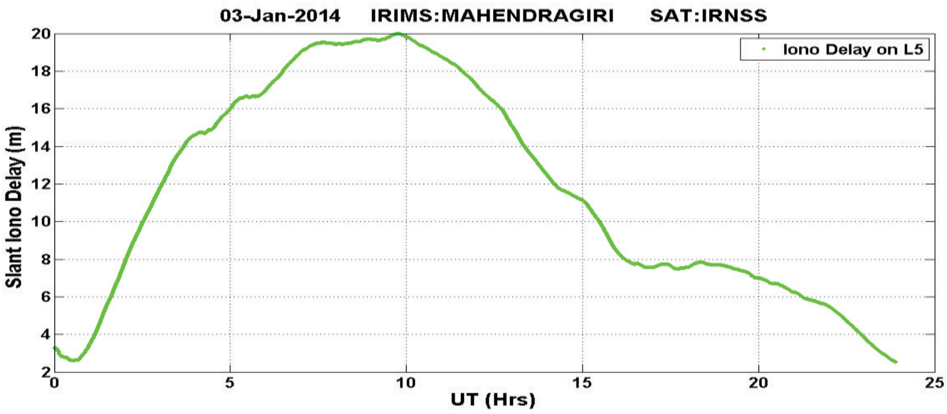

Figure 2. Nominal ionospheric behavior

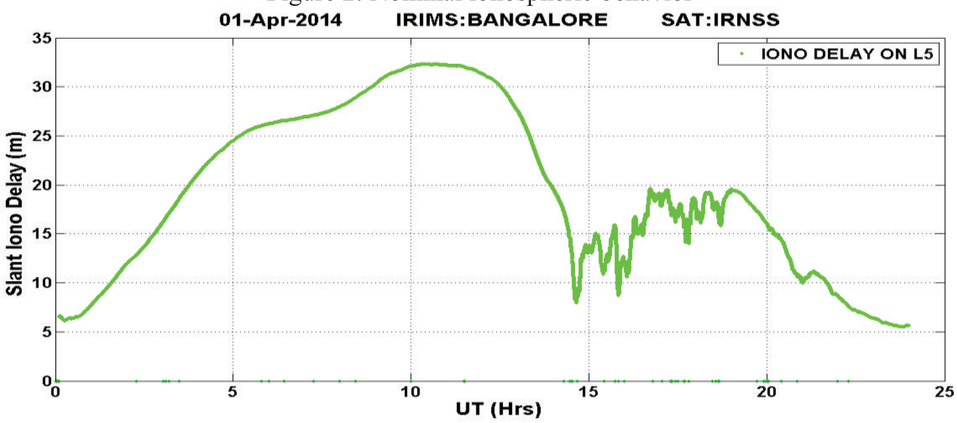

Figure 3. Ionospheric behavior in the presence of depletions

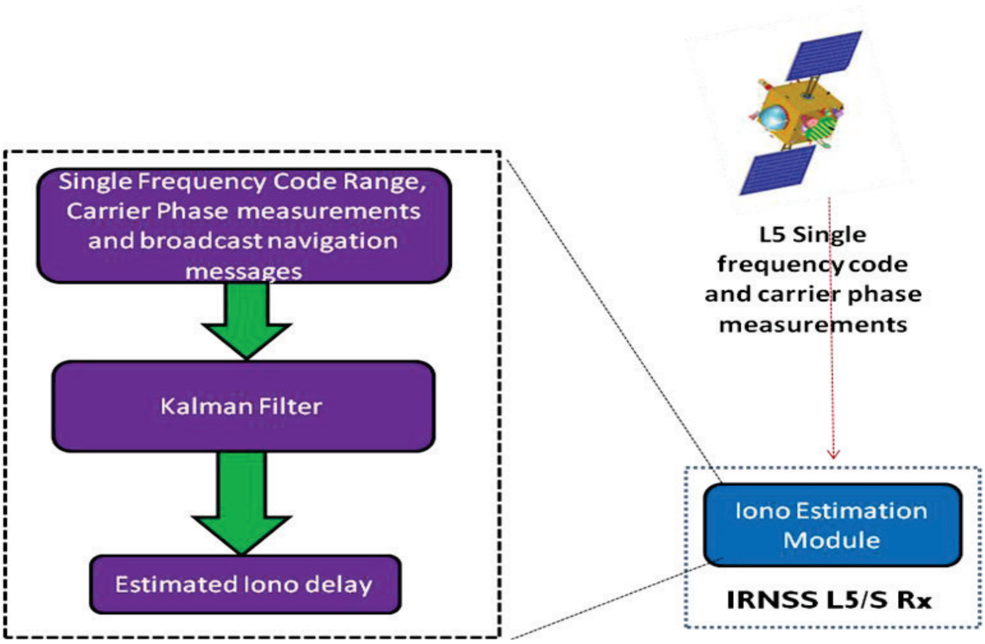

Figure 4. Block diagram for Iono Delay Estimation Module designed for IRNSS

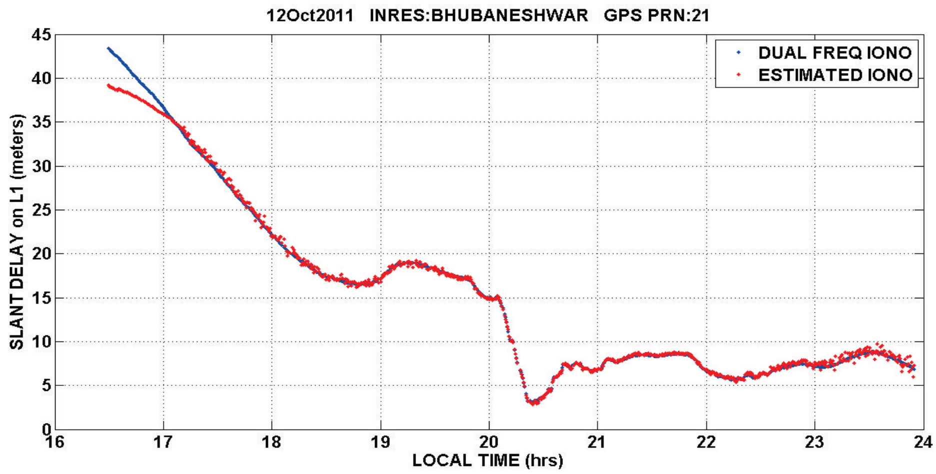

Figure 5. Single frequency L1 ionospheric delay estimation at times of depletion for Bhubaneswar

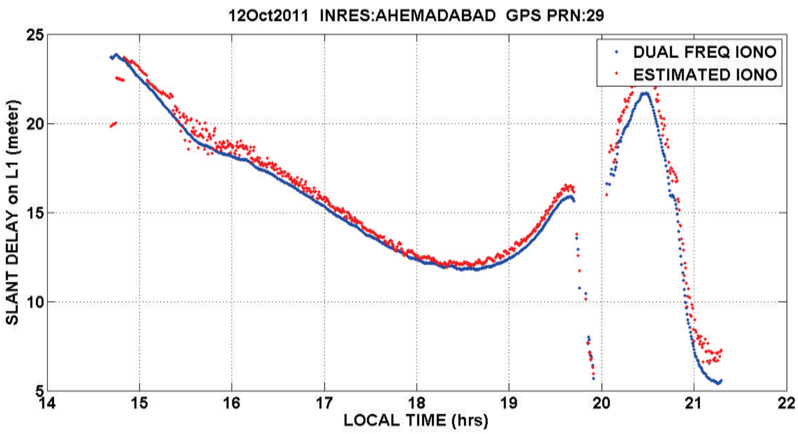

Figure 6. Single frequency L1 ionospheric delay estimation at times of depletion for Ahmedabad

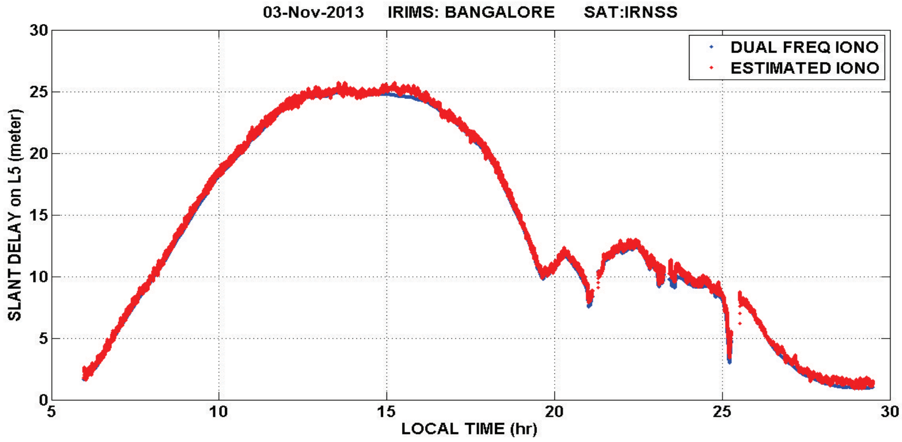

Figure 7. Single frequency L5 ionospheric delay estimation at times of depletion for 3/11/2013

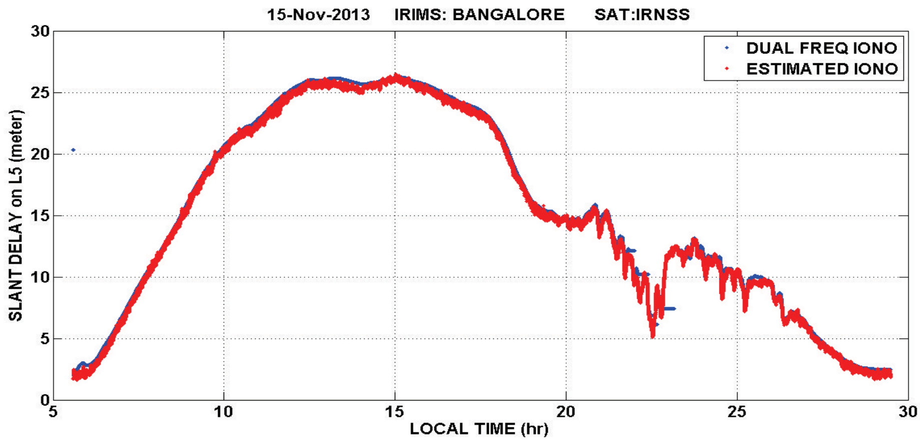

Figure 7. Single frequency L5 ionospheric delay estimation at times of depletion for 15/11/2013

Table 2. Ionospheric Error at time of depletion for Bhubaneswar

Depletion time	Mean Error (m) on the range	Std Error (m) on the range	Position error (2σ)(m)
With Broadcast Ionospheric corrections	3.6517	1.2811	19.5
With iono delay estimation module	0.0986	0.0710	9.2

Table 3. Ionospheric Error at time of depletion for Ahmedabad on 12/Oct/2011

	Mean Error on the range (m)	Std Error on the range(m)	Position error (2σ)(m)
With Broadcast Ionospheric corrections	5.0517	1.3973	29.9*
With iono delay estimation module	1.0783	0.4522	11.62

* Since the magnitude of the depletion is very high (~9m), the position accuracy degradation is more if it is not corrected for depletion.

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Table 4. Ionospheric Error at time of depletion for Bangalore on 3/Nov/2013

	Mean Error (m) on the range	**Std Error (m) on the range**	**Position error (2σ)(m)**
With Broadcast Ionospheric corrections	0.8227	0.9268	11
With iono delay estimation module	0.3919	0.2124	9.8

Table 5. Ionospheric Error at time of depletion for Bangalore for 15/Nov/2013

	Mean Error (m) on the range	**Std Error (m) on the range**	**Position error (2σ) (m)**
With Broadcast Ionospheric corrections	1.1035	0.8406	12
With iono delay estimation module	0.4165	0.5413	9.9