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Comparative Studies on Methods to Overcome the Ionospheric Effects on GNSS Signals

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Abstract: Global Navigation Satellite System (GNSS) signals are relatively weak in nature and are more difficult to detect under impaired visibility conditions. For an effective position solution accuracy measurement of pseudorange solving for three unknown positions (latitude, longitude, and altitude) using at least three satellites are possible. One more satellite is required as time is considered as another unknown for solving the receiver clock bias. Ionospheric delay can cause error in pseudorange measurements. This is caused due to free ions which interfere with the Global Navigation Satellite System (GNSS) signal. These free ions in the atmosphere are created by solar and cosmic radiation. The ionospheric delay/ phase advance depends on weather, geographic location, solar, geomagnetic activities etc. Therefore, ionospheric delay is unpredictable. Ionospheric delay is considered a significant source of error in measuring the position solution determined by the GNSS signals. This paper proposes two main ideas for overcoming the ionospheric effects. One idea establishes that the inclusion of more satellites or Multi-GNSS scheme could be useful for overcoming the ionospheric effects. The other idea is to deliberately choose ionofree data for obtaining a better solution accuracy. This paper shows the usability of two aforesaid processes in different scenarios. The paper identified the sources of error mentioned by the previous research groups. From this background study the motivation for this research had been identified. Then the paper is organized with research methodology, obtained results, their discussions. In the conclusion section the gaps and future scopes for study have been discussed.

Keywords: Pseudorange, Ionospheric, GNSS, Multi-GNSS

1. Introduction

Many factors influence weak GNSS signals. Those electromagnetic signals are vulnerable to space weather scintillation effects. Ionospheric and tropospheric errors adversely affect the GNSS signals. This leads to an ambiguity in position solution. It is seen that ionospheric effects cause more error in position than that of a tropospheric error [12]. Ionosphere lies from 50kms and spreads about 1000kms above ground. This is a part of the earth's atmosphere where the gases are in ionized form. Solar Extreme Ultraviolet Radiation, cosmic rays, solar winds are the several causes of ionization of the neutral gas in the earth's atmosphere. The variable refractive index of the ionosphere causes propagation delay/ phase advance of GNSS signals [13]. Ionosphere is a dispersive medium with respect to the Radiowave [14]. Therefore, the magnitude of ionospheric error depends on the signal frequency [14]. The errors caused by the ionosphere can be eliminated with the use of dual- frequencies. But this approach and method needs modification for the higher order errors caused by bending in signal, inhomogeneity in plasma distribution and anisotropy [14]. In past years these higher order errors are the field of interest for further study. Several researchers proposed their unique methods for eliminating higher order ionospheric effects. But after a long study it was seen hat the contribution of higher order errors due to ionosphere are less than 1% of the 1st order errors in GNSS signals [14]. Researchers found millimeter level shift in receiver position error cause by 2nd pr 3rd order ionospheric errors [10]. Some other research group reported the same error to be at the order of a few centimeters [6]. For a very accurate position solution requirement this higher order ionospheric correction terms need consideration. But for civilian users' higher order correction terms are not always required. A cm level accuracy can be achieved by operating the receiver in dual frequency mode. These 1st order ionospheric effects on GNSS signals are the points of interest of this paper. This paper identifies the gaps and disadvantages of using dual- frequency receivers. Researchers in the past considered higher order ionospheric effects for their studies [1-11, 14-18]. But an appropriate study for identifying the gaps of using a dual-frequency receiver had never been explored before. This paper tries to identify the real time and real-life scenarios following the linear approach of using combination of dual frequency mode for GNSS position solutions.

2. Method

A 216-Channel, Multi-GNSS receiver capable of operating in dual frequency mode is selected for data collection. This receiver can receive data with 0.2 mm GLONASS dynamic correction. Data is collected in NMEA format. Manufacturer supplied software is used for operating the receiver in different modes. The receiver is capable of operating in GPS, GLONASS, Galileo and Multi-GNSS modes. The GrAnt antenna used for this study is capable of tracking data of GPS, GLONASS, GALILEO, COMPASS, WAAS, EGNOS, MSAS, GAGAN and QZSS signals. The three modes GPS, GLONASS and GPS+ GLONASS are chosen for this study. These modes are selected for study because of the following reasons:

1. GPS and GLONASS are compatible and interoperable with each other.
2. Both systems are operating on the same frequency bands (L1 and L2).

GPS+ Galileo is discarded because of the following reasons:

1. GPS and Galileo are using a different third frequency band.
2. The receiver is capable of using finer and corrected version of GLONASS signals, no such advantages are provided for using the Galileo system.

Atmospheric scintillation effects are more during dusk or early night hours. Therefore, data have been collected just after sunset. In a first experiment the receiver is operated in GPS, GLONASS and MIX (GPS+GLONASS) modes. With these experimental results the favorable mode of operation for determining position solution accurately is identified first. Then the data are collected by operating the receiver in single and dual frequency modes for verifying the fact of eliminating ionospheric effects in dual frequency mode. The block diagram of the experimental set- up is shown in Figure 1.

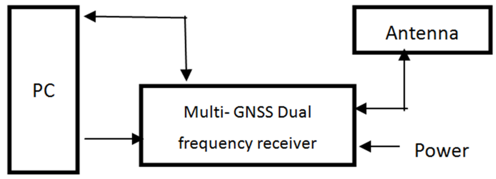

Figure 1. *Experimental set up.*

Data are recorded from the following location.

Table 1. *Location for study.*

Data Monitoring Station	Approximate Location ($L\_(a\_0)$, $L\_(t\_0), h\_0$)
GNSS Laboratory, Department of Physics, The University of Burdwan, India	23°15.27' N 87°50.81' E 49.55m

3. Results

Data is taken in GPS, GLONASS and MIX modes consecutively by operating the receiver in dual frequency mode. Data are taken for 15 minutes in each of the mode to avoid solution accuracy ambiguities arising due to change in satellite geometries. 2- dimensional and 3- dimensional position solutions are calculated using the standard formula.

$$Error_{2d} = \sqrt{\left(1852.\Delta L_t.\cos L_{a_0}\right)^2 + (1852.\Delta L_a)^2} \quad (1)$$

$$Error_{3d} = \sqrt{\Delta h^2 + \left(1852.\Delta L_t.cos\, L_{a_0}\right)^2 + (1852.\Delta L_a)^2} \quad (2)$$

Where,

$Error_{2d}$= Error in 2-dimension (horizontal error) for the instantaneous solution w.r.t. the reference.

$Error_{3d}$ = Error in 3-dimension of the instantaneous solution w.r.t. the reference.

Δh = Difference of the instantaneous height from the reference height, meter.

ΔL_t = Difference of the instantaneous and reference longitude values, minute of arc.

ΔL_a = Difference of the instantaneous and reference latitude values, minute of arcand 1 minute of arc of curvature of Earth is equivalent to 1852m.

Data is logged and collected as an NMEA data stream. Then data is analyzed and sorted using software developed in- house. Data is logged and analyzed by operating the same receiver in single frequency for GPS and GLONASS modes. From those results it was already observed that dual frequency operations provide improved results over the single frequency mode. So, those discussions are beyond the scope of further analysis for the sake of requirement of this paper. We have chosen the dual frequency scenarios for discussion in GPS and GLONASS modes of operations. Errors in 2- dimension and 3- dimension are calculated in GPS, GLONASS and MIX modes. Results are shown in

Table 2 and Table 3 respectively.

Table 2. *2-dimensional errors for GPS, GLONASS and MIXED in dual frequency modes.*

Approx Time	Avg. Error (m)			Stdev of Error (m)			Peak to Peak Error (m)		
Duration (min)	GPS	GLO	MIX	GPS	GLO	MIX	GPS	GLO	MIX
15	4.11	1.58	3.37	0.60	0.16	0.14	2.19	0.71	0.58
15	3.36	1.51	3.36	0.09	0.87	0.15	0.47	11.0	0.58
15	0.54	1.49	3.37	0.14	0.58	0.16	0.43	0.83	0.59

Table 3. *3-dimensional errors for GPS, GLONASS and MIXED in dual frequency modes.*

Approx Time	Avg. Error (m)			Stdev of Error (m)			Peak to Peak Error (m)		
Duration (min)	GPS	GLO	MIX	GPS	GLO	MIX	GPS	GLO	MIX
15	4.62	7.40	3.68	0.64	0.62	0.21	2.62	3.26	0.76
15	5.08	6.91	3.69	0.63	1.65	0.23	2.39	19.2	0.79
15	0.93	6.63	4.01	0.37	0.95	0.21	1.27	3.96	0.78

From the above results it can be interpreted that the errors in 2- dimension and 3- dimension are much lower when the receiver is operated in MIXED mode than that of any individual mode of operation.

Therefore, the receiver is chosen to be operated both in single and dual frequency modes. Now, the same dual frequency receiver is operated in single and dual frequency modes respectively to see whether ionospheric effects can be disrupted in a dual frequency mode. Data is taken for 15 minutes and 30 minutes duration respectively. Those switch overs can be made manually using the external hardware and inbuilt software provided with the receiver. As per the receiver control software, choosing "ca" mode switches the receiver to operate in single frequency (L1 only) operation, while choosing "ionofree" mode switches the operation to multifrequency (L1, L2 together) operations using ionospheric corrections. Where, L1 = 1575.42 MHZ and L2 = 1227.6 MHZ. Results are shown in Table 4 followed by their representations in Figures.

Table 4. *A comparative study between single frequency and dual frequency modes of operation for MIXED mode.*

Approx Time Duration	Avg. Error (m)		Stdev of Error (m)		Peak to Peak Error (m)	
	Single frequency (ca)	Dual frequency (iono)	Single frequency (ca)	Dual frequency (iono)	Single frequency (ca)	Dual frequency (iono)
2- dimensional error						
15	2.07	3.37	0.09	0.14	0.41	0.58
15	3.42	3.37	0.17	0.14	0.88	0.58
15	2.58	3.37	0.12	0.14	0.55	0.58
30	3.50	3.09	0.31	0.20	1.13	0.84
30	2.87	3.09	0.67	0.20	1.76	0.84
30	2.94	3.09	0.44	0.20	1.34	0.84
3- dimensional error						
15	7.81	3.68	0.68	0.21	2.02	0.77
15	7.82	3.68	0.39	0.21	4.81	0.77
15	5.88	3.68	0.90	0.21	2.73	0.77
30	6.86	3.83	0.96	0.79	3.62	3.62
30	7.82	3.83	0.53	0.79	5.31	3.62
30	6.72	3.83	1.20	0.79	4.81	3.62

A clear advantage of using dual frequency satellite signals is found for 3- dimensional errors but no such advantage is seen for the 2- dimensional position solutions. As the errors obtained using GNSS are more likely to lie within small values, so for selection of class widths of errors a practical approach is adopted. Error class width of 1m is taken for errors up to 6m, then class width of 2m is taken for error values of 6-10m; above errors of 10m, class widths of 5m and 10m are taken for error values of 10-20m and greater than 20m respectively. Numbers of samples falling in each error class for a month are added up and using the total number of samples for the month, percentage of occurrence of error values in each "error value class" is obtained. Then, cumulative percentage of error in a class is calculated by adding percentage of occurrences in the same and higher error classes together. In other words,

$$Percentage\ of\ occurance = (Total\ number\ of\ samples\ lies\ within\ a\ particular\ range)/(Total\ number\ of\ saples) * 100 \tag{3}$$

$$Cumulative\ percentage\ of\ occurance = Percentage\ of\ occurance\ of\ a\ particular\ errorrange\ bin + Percentage\ of\ occurance\ above\ that\ particular\ range\ bin \tag{4}$$

These cumulative percentage of occurrences are plotted for 2- dimensional and 3- dimensional errors in meters. Those results are shown in Figures 2 to 5 respectively.

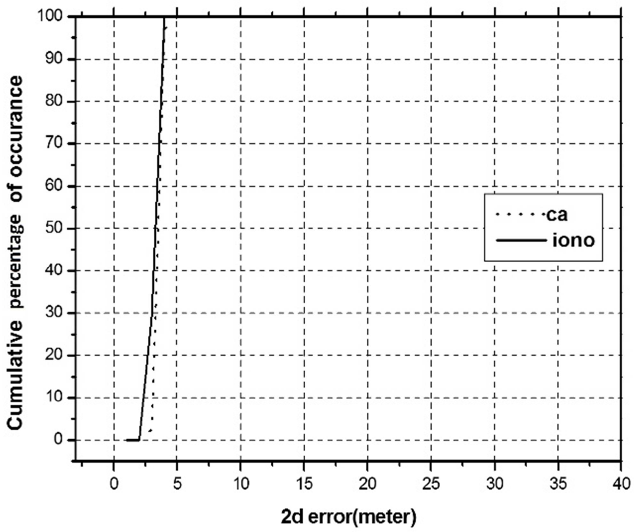

Figure 2. *2-dimemsional error (15 mins).*

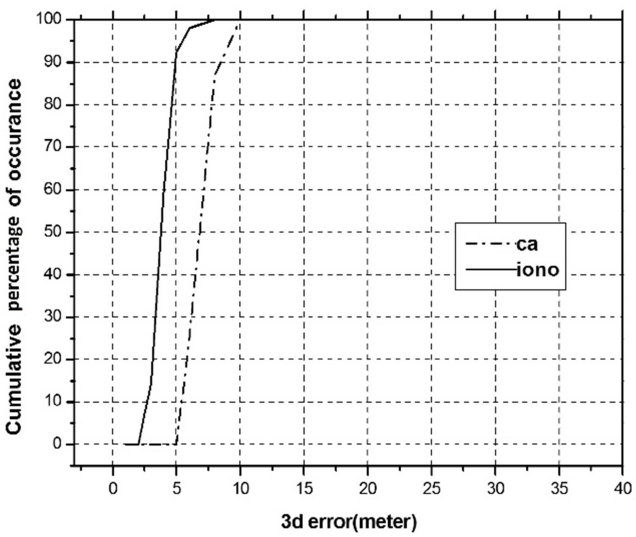

Figure 3. *3-dimensional error (15 mins).*

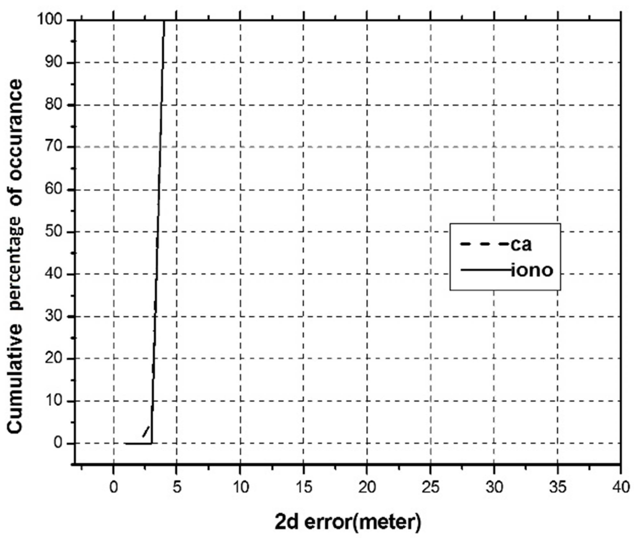

Figure 4. *2-dimansional error (30 mins).*

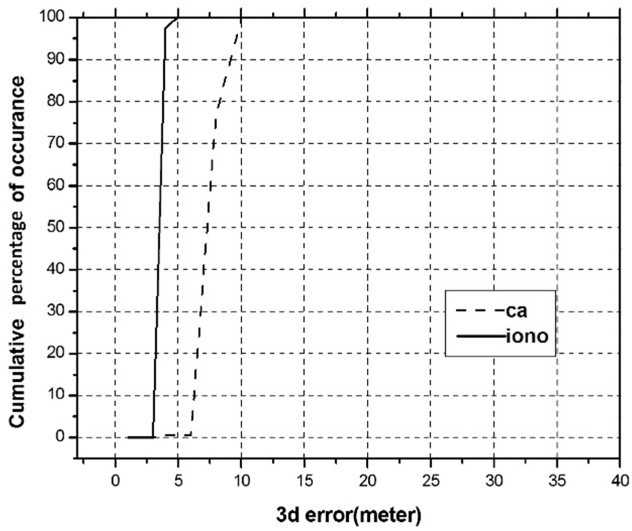

Figure 5. *3-dimensional error (30 mins).*

Dual frequency mode of operation does not always lead to elimination of errors caused by the ionospheric disturbances. From the results discussed above it is clear that MIX mode of operation where multi frequencies are available error values are lower than that of any single frequency mode of operation. But not much improvement is observed for 2-dimensional error calculations. Thus, for a 2- dimensional position solution, the impact of ionospheric disturbances can be treated as trivial as the position accuracies in MIXED mode lies within 5m for both single and dual frequency scenarios both with duration of 15 minutes and 30 minutes. While, for 3- dimensional errors, error values are within 5m when dual frequency mode of operations are considered. These values suddenly jump to 10m for single frequency operations. Therefore, for determination of 3- dimensional position solution accuracies using dual frequencies are an advantage over single frequency.

Another study of same kind had also been performed using a cost-effective receiver capable of operating only on a single frequency. The results are worse than the dual frequency receiver. Therefore, those results are not discussed in this paper. Also, as the studies of ionospheric effects on GNSS signals are the points of interest of this paper, therefore, a use of a single frequency cost- effective receiver is discarded for the discussion.

4. Conclusion

Ionospheric effects are surely among one of the most significant sources of position error determined using GNSS signals. This paper clearly states the idea of the advantages of using dual frequency over single frequency for eliminating errors arising due to the ionospheric disturbances. There are advantages of operating in dual frequency mode for a 3-dimensional position solution. But at the same time single frequency position solutions are fair enough whenever 2-dimensional solution is required. For this paper only the 1st order ionospheric effects are considered while higher order ionospheric effects are not. Furthermore, only GPS and GLONASS are considered for study. The other Global Navigation Satellite Systems are not considered for study. More than 100 satellites are available for use including 4 global and 2 regional satellite navigation systems. Combination of other GNSS signals should be taken into consideration for eliminating the 1st order ionospheric effects. Further studies can be explored using the available fully operational GNSS. With this study one can better understand the process of elimination of ionospheric errors using more signals together. This study needs further data with a spatial, temporal, and electronic variations.

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