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RESEARCH ARTICLE

Investigation of Doppler Collision Effects in Kinematic Conditions and its Mitigation for NavIC System

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ABSTRACT

NavIC (Navigation with Indian Constellation) constellation consists of four geosynchronous and three geostationary satellites and it is developed by ISRO, India. It provides position, velocity and timing services. Doppler Collision (DC) is a phenomenon where tracking errors are introduced in the measurements due to cross-correlation between the satellites. If relative doppler between satellites is less than the code loop bandwidth, then DC occurs. In this paper, to analyze DC impact on NavIC, the Doppler shift of each GEO satellite is calculated, the most effected GEO satellite pair is identified. In high dynamic applications like missile launches the effect of DC is very significant. In order to investigate DC in high dynamic conditions a simulation of trajectory path of the receiver is considered. For the precise position estimation, the contribution of DC error will be high, so it needs to be minimized. An efficient algorithm is developed to mitigate the DC using narrow correlator design of the receiver. Using the proposed algorithm, the DC duration for 1C-1G satellite pair has been reduced from 50min 21sec to 2sec in static conditions. Whereas in dynamic conditions from 4h20min 28sec to 5sec with DLL bandwidth of 4Hz and 0.1 chip spacing of receiver design.

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Introduction

GPS is the universally used navigation system that covers the whole globe which was developed by the USA. Russia (GLONASS), Europe (Galileo) and China (BeiDou) have also developed their own navigation systems which cover the whole Earth. Countries like India (NavIC) and Japan (QZSS) have developed their own regional navigation systems which cover their country and some regions around. India is developing IRNSS which has an operational name NavIC. The system presently consists of a constellation of seven active satellites [15][17]. As of now nine satellites have been launched as a part of developing the system. The first satellite was launched in 2013 and in the span of 5 years the next 8 satellites were launched. The seven satellites are a mix of both geosynchronous and geostationary. Presently there are 4 geosynchronous and 3 geostationary satellites.

The GEO satellites will have no or very less angle of inclination but the GSO satellites will have higher angle of inclinations [4]. NavIC provides its services to the entire Indian subcontinent and extends up to 1500km around it. NavIC provides two levels of service on two bands of frequency, L5 (1176.45 MHz) and S1 band (2492.08 MHz). It provides both RINEX v3.03 and NMEA data files. The four important functions of the IGS receiver are acquisition, tracking, decoding and position solution. The block diagram og the IGS receiver is shown in Figure 1.

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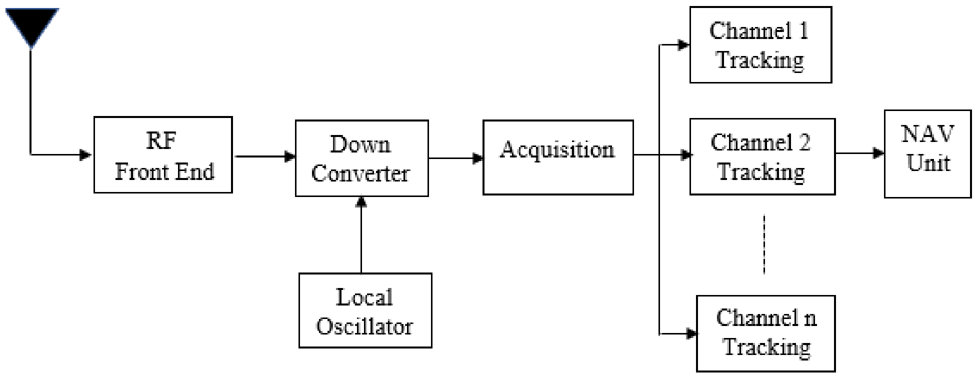

Figure 1. IRNSS-GPS-SBAS (IGS) receiver block diagram

Doppler Collision is a phenomenon observed in code division multiple access (CDMA) systems. Occurrence of DC leads to cross correlation effects between two or more satellites as a result code measurement error are developed in GNSS. The study of forces and their effect on objects is known as kinematics [2]. In kinematics three conditions of an object are defined namely static, low dynamic and high dynamic conditions. In static conditions the object is at rest and the position of the receiver can be calculated precisely. In low dynamic conditions the acceleration is less than 10g while in high dynamics it is considered to be around 100g [6][7]. In both dynamic conditions the receiver experiences a shift in Doppler values received from the satellites [3][5]. As doppler shift values increase relative doppler between the satellites change accordingly resulting in Doppler collision occurrence. The DC error envelope is similar to multipath error envelope and the mitigation techniques used for multipath can also be used for DC [8][9]. One of them is narrow correlator which mainly focuses on the chip spacing of the Delay locked loop (DLL) [1][11]. Chip spacing is the space between the early and late signals generated in the correlator of the receiver. The standard correlator uses 1 chip spacing and narrow correlator uses 0.1 chip spacing. By reducing the chip spacing Doppler Collision occurrence can be minimized.

Analysis of a Receiver in Kinematic Conditions

Launching of missiles or rockets, movement of aircraft etc., are few examples of high dynamic motions. As stated earlier in high dynamic conditions the rate of change of velocity of the body with respect to time is very high [18]. With change in position, velocity and acceleration for every second these applications are always in immense need of perfect positioning systems, to ensure smooth functioning [12]. If the calculation in position of these applications is not accurate, the controlling actions become harder and can lead to crashes. As velocities and position parameters are involved, anybody moving in high dynamic conditions is susceptible to Doppler Collision effect [17][18]. For observing the effect of Doppler Collision in high dynamics few parameters like position, velocity, elevation, trajectory path etc. are to be known beforehand [10]. For this purpose, a receiver travelling in an aircraft between two cities has been considered, the below are the steps involved in the analysis of DC in high dynamics;

1) Observation of receiver velocity and acceleration on the runway and during takeoff.
2) Simulation of trajectory path of the receiver with help of data containing latitude, longitude and altitude of 18 places between Hyderabad and Bangalore.
3) Calculation of Doppler Shift for the geostationary IRNSS satellites.
4) Determination of relative doppler and DC occurrence for the effected IRNSS satellite pair.

Variation of Acceleration of the Receiver

In the beginning the receiver starts from rest in static condition and slowly accelerates into low dynamics and finally reach the high dynamic conditions. During the initial 3 to 4 seconds the receiver will be in low dynamics with acceleration up to 15m/s^2. By the end of 8 to 10 seconds the receiver enters high dynamics as shown in Figure 2. The acceleration of the receiver does not increase sharply at any given point of time. The acceleration remains constant for a couple of seconds after the receiver has changed into a new kinematic condition.

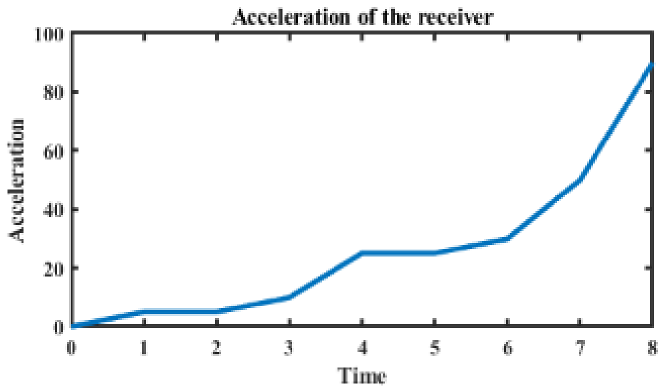

Figure 2. Acceleration variation of the receiver

Simulation of Trajectory Path of the Receiver

A receiver travelling from one place to another in an aircraft will be having a combination of all the kinematic conditions during its flight, hence it would be the best real-world consideration for analysing DC effect in various kinematic conditions [13][14]. For this work as no practical data is available for an IRNSS receiver in flight, the data has been considered with appropriate assumptions from good sources [15].

Figure 3 shows the trajectory path of the receiver with the assumed data. The trajectory path is plotted as the variation of the altitude of the receiver with respect to time during its flight. Within 5minutes from the flight take off of the receiver will reach its maximum altitude. Once the receiver reaches the maximum height, which is 10km in this case, there will be no significant increase in the altitude of the receiver.

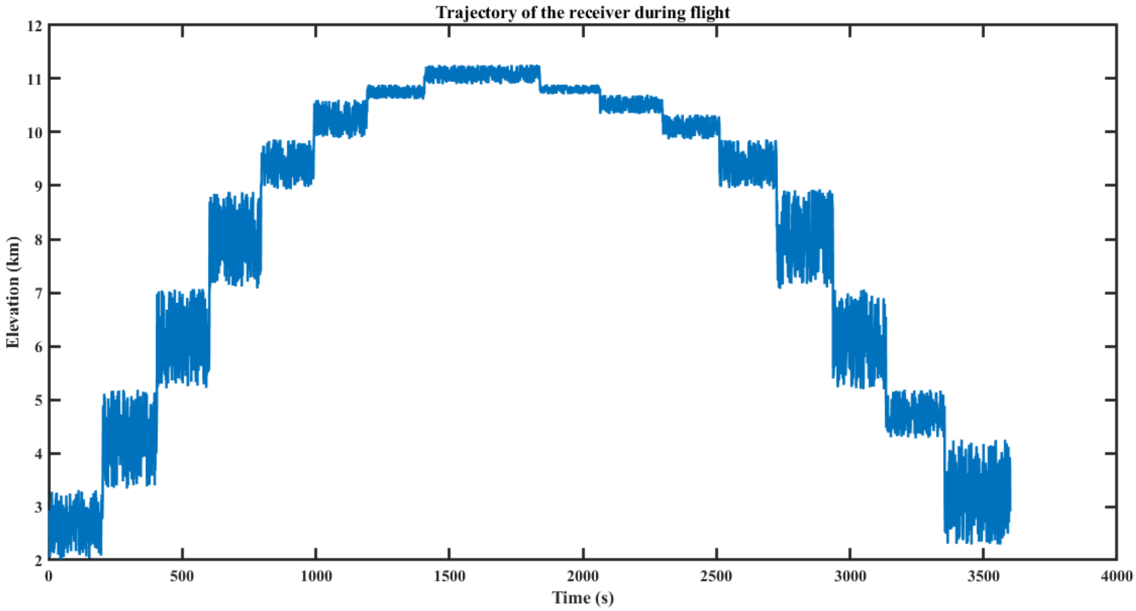

Figure 3. Trajectory path of the receiver

During ascending and descending, the receiver never increases its altitude manifold. The major change in the altitude of the receiver is seen only during its takeoff and landing. Tracking the altitude for each second leads to the trajectory path as shown. The trajectory path of the receiver is observed to be in parabolic shape.

Estimation of Doppler Shift of the Receiver and GEO Satellites

As there will be a change in position and velocity of the receiver and satellite for every second doppler shift exists between them. The doppler shift of each satellite is computed using the formulae from equation 1 and 2. Figure 4 shows the Doppler shift of each satellite calculated with respect to the receiver. The Doppler Shift shows larger variations when there is a large variation in the altitude of the receiver during its flight. The doppler shift values range between ±2000Hz.

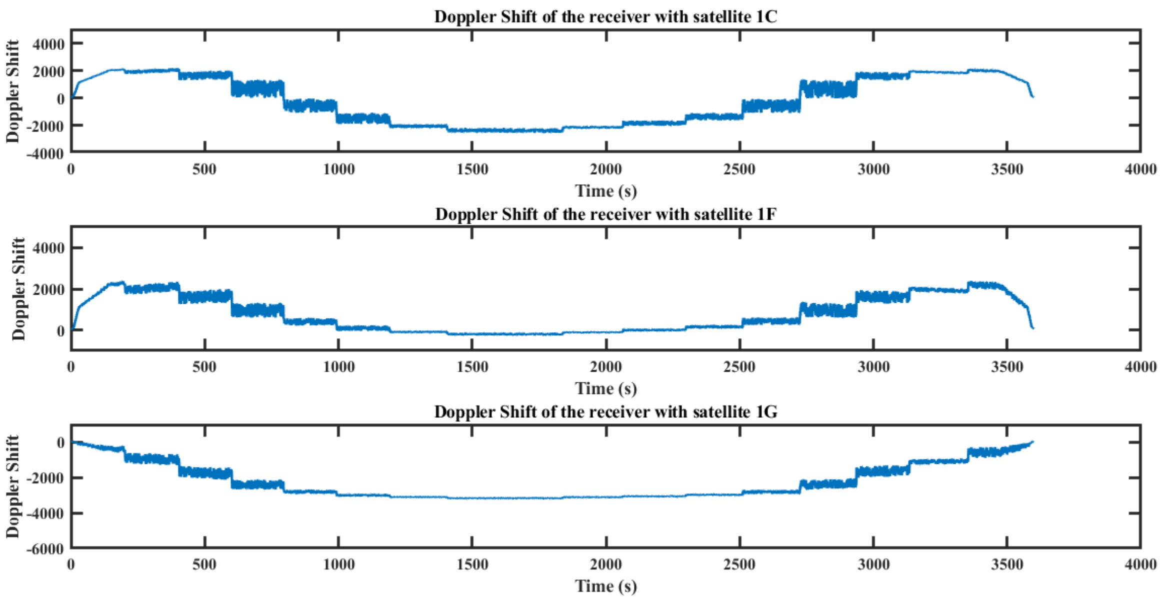

Figure 4. Doppler Shift of the receiver with (a) 1C (b) 1F and (c) 1G

Computation of Relative Doppler between GEO Satellites

From the estimated Doppler shift between the receiver and the satellites, relative Doppler is calculated. Using the relative doppler calculation, the necessary condition is checked for observing the DC duration. Figure 5 shows the relative Doppler between the three pairs of satellites. The range of the relative Doppler values varies in each case depending on the Doppler shift values of the respective satellites. For this simulation DC has occurred only in the case of 1C and 1F as the Doppler shift plot of these two satellites is similar. It may be incurred that during the interval of the flight of the receiver satellites 1C and 1F are orbiting in the same direction hence the chance of DC occurrence is more for this pair. These results can be used as reference for any future experimentations of such kind.

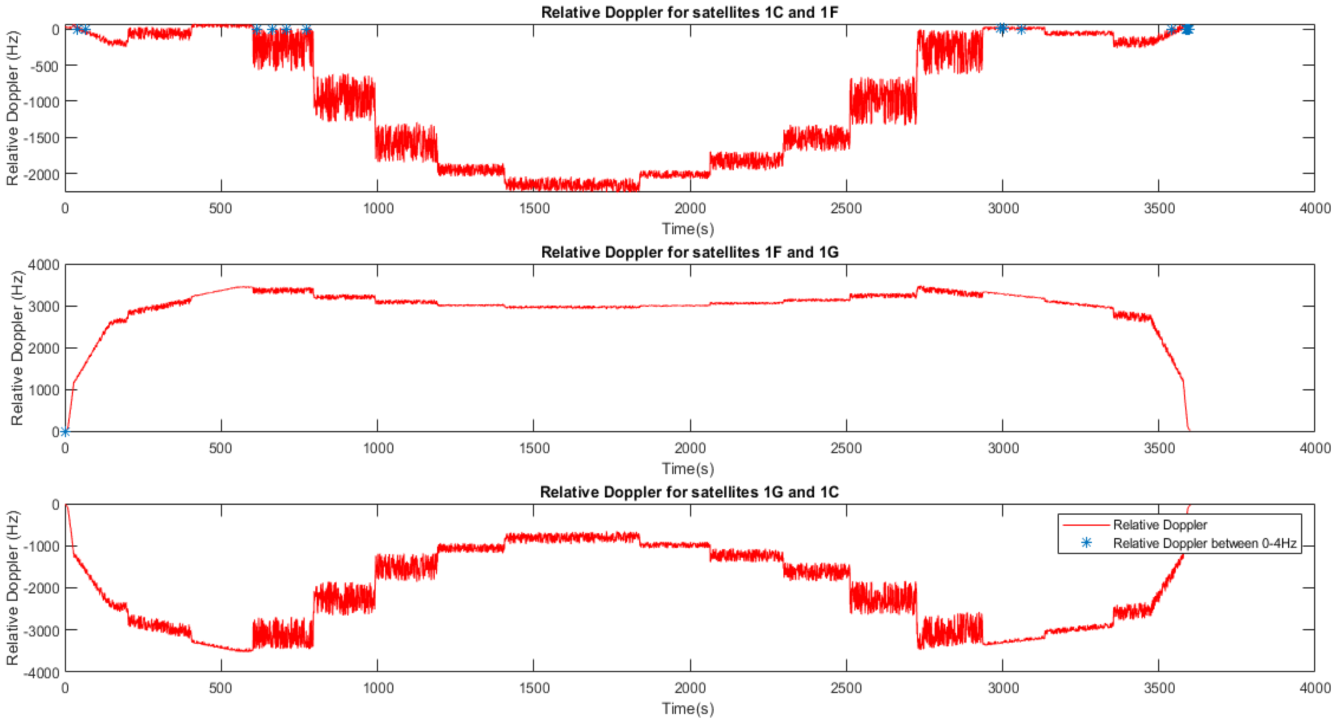

Figure 5. Relative Doppler of the satellites (a) 1C and 1F (b) 1F and 1G and (c) 1C and 1G

Mitigation of Doppler Collision

As DC leads to tracking errors and results in inaccurate position estimation it must be mitigated. Controlling the doppler of a satellite and using even length Gold codes in place of regular C/A codes are very effective methods to reduce the impact of DC but these methods are fruitful only when the system is still in planning phase. As the satellites have been deployed already these methods are not useful for reducing the effect of Doppler Collison. Alternate technique to reduce the DC is using multipath mitigation methods as both have similar error envelop. The narrow correlator design in the receiver is a broadly accepted method to mitigate multipath effects, hence the same can be applied for the mitigation of doppler collision. The exceptional feature of the narrow correlator is the use of lesser chip spacing. The chip spacing in narrow correlator is 10 times lesser compared to that of a standard correlator.

Effect of Chip Spacing on Doppler Shift

From the equations 1 and 2, for static conditions $\bar{v}_u = 0$

Therefore $\Delta v = \bar{v}_s \dfrac{\bar{p}_s - \bar{p}_u}{\|\bar{p}_s - \bar{p}_u\|}$ (1)

$$\Delta f = \frac{f_t}{c}\left[\bar{v}_s \frac{\bar{p}_s - \bar{p}_u}{\|\bar{p}_s - \bar{p}_u\|}\right] \quad (2)$$

Let us assume that for two calculations of Doppler Shift we got the values as x and y

Relative Doppler (RD) = x - y

Multiplying the Doppler Shift formula with $\frac{1}{k}$ factor where k is the chip spacing $\Delta f' = \frac{1}{k}\left(\frac{f_t}{c}\left[\bar{v}_s \frac{\bar{p}_s - \bar{p}_u}{\|\bar{p}_s - \bar{p}_u\|}\right]\right)$

When chip spacing=1 k =1 (3)

$$\Delta f' = \frac{f_t}{c} \cdot \left[\bar{v}_s \frac{\bar{p}_s - \bar{p}_u}{\|\bar{p}_s - \bar{p}_u\|}\right] \quad (4)$$

For two calculations of Doppler Shift the values obtained will be x and y only

$$RD_1 = x - y$$

(i) When chip spacing=0.5 k =0.5

$$\Delta f' = \frac{1}{0.5} \cdot \frac{f_t}{c} \cdot \left[\bar{v}_s \frac{\bar{p}_s - \bar{p}_u}{\|\bar{p}_s - \bar{p}_u\|} \right] \quad (5)$$

For the two calculations of Doppler Shift the values obtained will be $2x$ and $2y$

$$RD_2 = 2x - 2y = 2(x - y)$$

(ii) When chip spacing=0.1 k =0.1

$$\Delta f' = \frac{1}{0.1} \cdot \frac{f_t}{c} \cdot \left[\bar{v}_s \frac{\bar{p}_s - \bar{p}_u}{\|\bar{p}_s - \bar{p}_u\|} \right] \quad (6)$$

For the two calculations of Doppler Shift the values obtained will be $10x$ and $10y$

$$RD_3 = 10x - 10y = 10(x - y)$$

It is observed that

$$RD_3 > RD_2 > RD_1$$

Also, the values of Doppler Shift are increasing when the chip spacing is decreased.

Hence

$$\text{Doppler Shift } (DS) \propto \frac{1}{chip \quad spacing}$$

Therefore there will be a greater chance of RD_1 being less than DLL bandwidth (1Hz in case of static) when compared with RD_2 and RD_3. And with decrease in chip spacing the chance of occurrence of Doppler Collision will decrease. So narrow correlator with 0.1 chip spacing can be used for mitigation of DC.

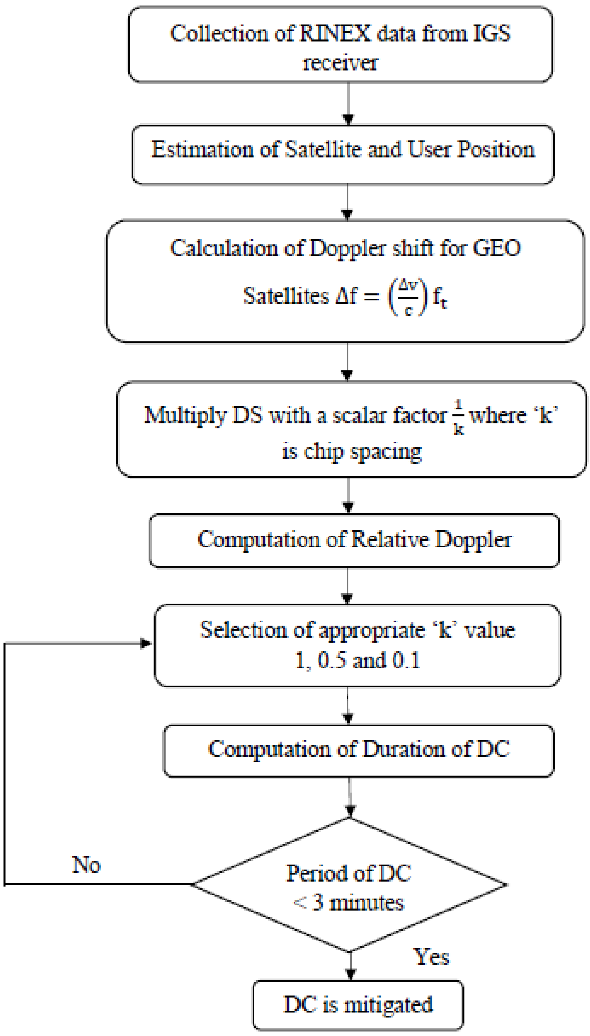

Figure 6. Steps for the mitigation of DC using chip spacing

Mitigation in Static Conditions

Figure 6 shows the relative doppler plots for the receiver in static conditions with 1 chip spacing and 1Hz DLL bandwidth. The plots for 0.5 and 0.1 chip spacing and 1Hz DLL bandwidth are as shown in Figure 7 and 8. The range of doppler shift of the satellites has increased hugely. The range of the DS has increased the maximum for 1G satellite compared to the other two, hence the chance of occurrence of DC with satellite 1G decreases. There is still a chance of occurrence of DC between 1C and 1F but for very less duration.

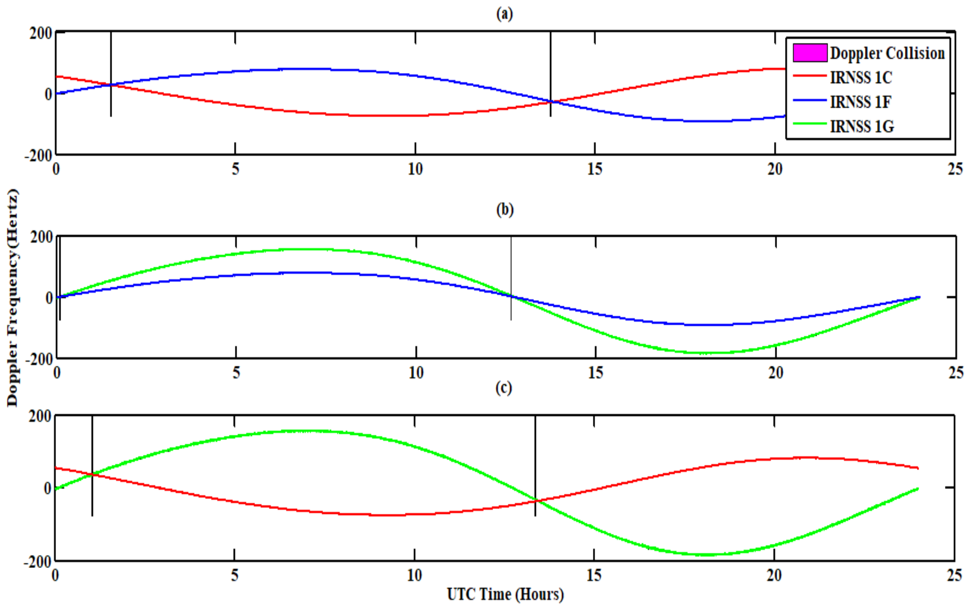

Figure 7. Relative Doppler between (a) 1C and 1F (b) 1F and 1G and (c) 1C and 1G for 0.5 chip spacing

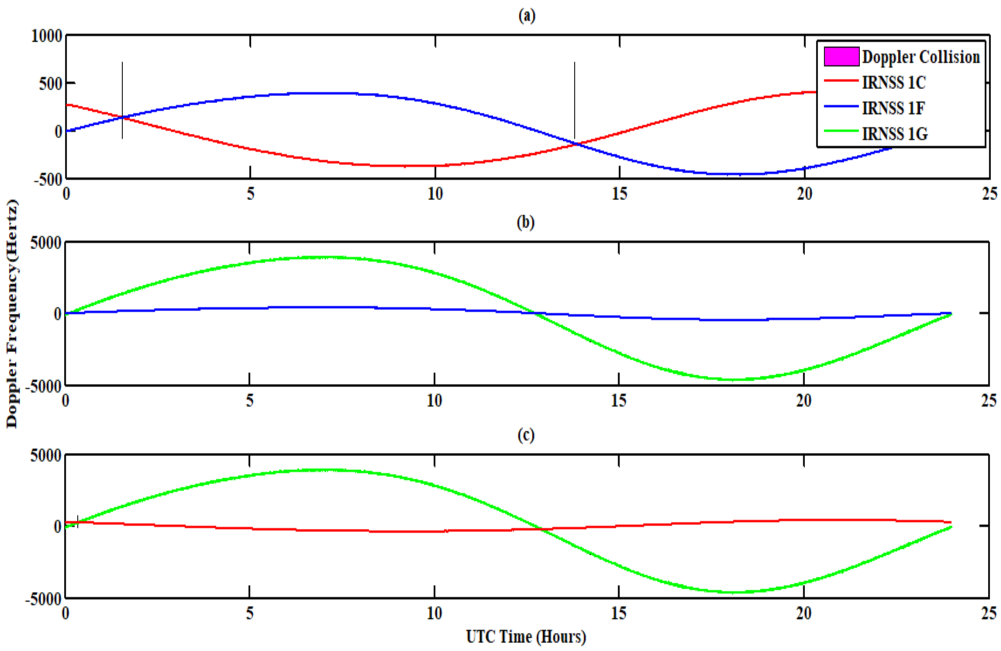

Figure 8. Relative Doppler between (a) 1C and 1F (b) 1F and 1G and (c) 1C and 1G for 0.1 chip spacing

Table 1 shows the Doppler Collision occurrence durations for the three GEO satellites. The duration has decreased as the chip spacing has been decreased.

Table 1. Doppler Collision durations for geostationary satellites after mitigation

S.no	GEO Satellite Pair	1 Chip Spacing		0.5 Chip Spacing		0.1 Chip Spacing	
		1st DC duration	2nd DC duration	1st DC duration	2nd DC duration	1st DC duration	2nd DC duration
1.	1C and 1F	230s	259s	205s	114s	35s	9sec
2.	1G and 1F	316s	277s	71s	20s	-	-
3.	1C and 1G	1399s	1622s	18s	44s	2s	-

Mitigation in Dynamic Conditions

To adapt with the change in the kinematic condition the DLL bandwidth of the receiver is designed to be 4Hz. Figure 9 shows the plot of DC for 1chip spacing and 4Hz DLL bandwidth. When the chip spacing is reduced to 0.5 and 0.1 for this case the DC duration decreases as shown in Figure 10 and 11. There is a chance of occurrence of DC between 1C and 1F, 1C and 1G, 1F and 1G but for very less duration.

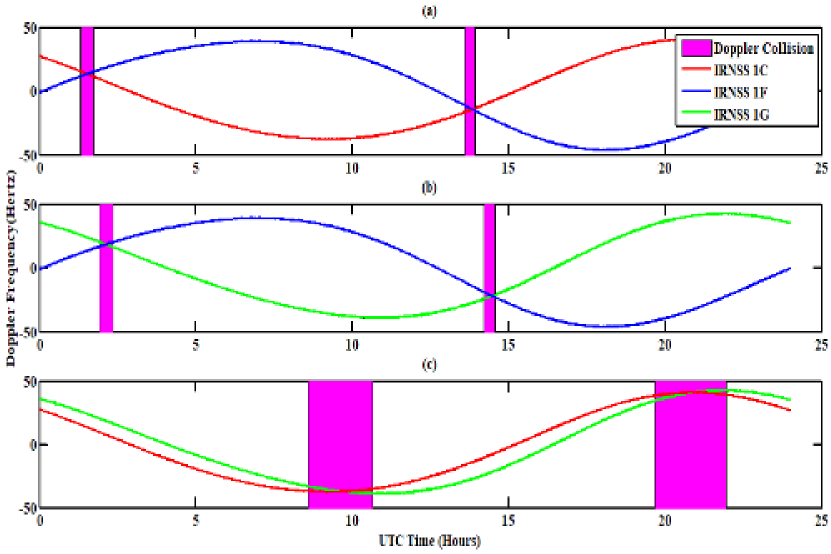

Figure 9. Relative Doppler between (a) 1C and 1F (b) 1F and 1G and (c) 1C and 1G for 1 chip spacing for DLL bandwidth 4Hz

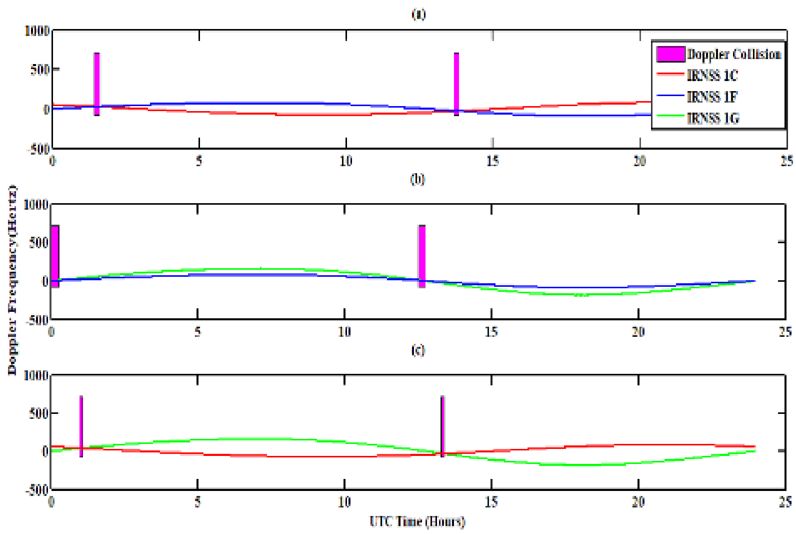

Figure 10. Relative Doppler between (a) 1C and 1F (b) 1F and 1G and (c) 1C and 1G for 0.5 chip spacing for DLL bandwidth 4Hz

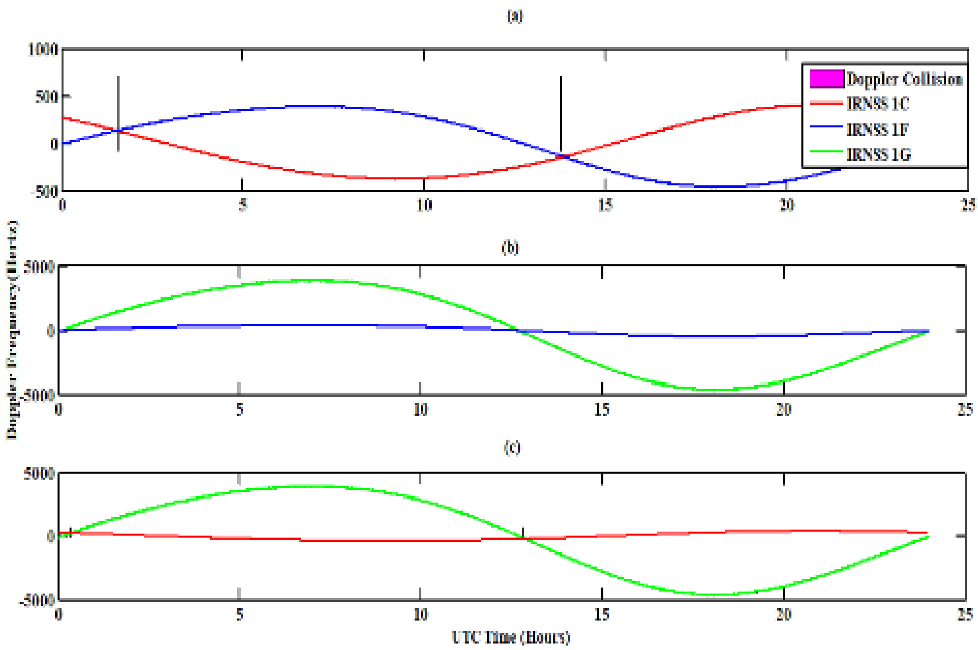

Figure 11. Relative Doppler between (a) 1C and 1F (b) 1F and 1G and (c) 1C and 1G for 0.1 chip spacing for DLL bandwidth 4Hz

Table 2 shows the Doppler Collision occurrence durations for the three GEO satellites for different chip spacing values in a 4Hz DLL bandwidth receiver. The duration has decreased as the chip spacing has been decreased.

Table 2. Doppler Collision durations in dynamic conditions for geostationary satellites after mitigation

S.no	GEO Satellite pair	1 Chip Spacing		0.5 Chip Spacing		0.1 Chip Spacing	
		1st DC duration	2nd DC duration	1st DC duration	2nd DC duration	1st DC duration	2nd DC duration
1.	1C and 1F	24 min 21 sec	20 min 17 sec	11 min 16 sec	9 min 25 sec	52 sec	1 min 18 sec
2.	1G and 1F	25 min 5 sec	20 min 48 sec	16 min	13 min 59 sec	2 sec	-
3.	1Cand 1G	2h 2min 36 sec	2h 17min 52 sec	6 min 6 sec	5 min 2 sec	2 sec	3 sec

Conclusion

Doppler Collision is a phenomenon which can occur in any navigational satellite systems resulting in errors during position estimation. It is predominant in satnav systems with GEO satellites because of their low angle of inclination with respect to the equator of the earth. Doppler Collision occurrence has been determined by examining the relative doppler parameter. The chance of occurrence of DC in a day for 1C and 1F satellite pair is 0.566%, for 1G and 1F pair it is 0.686% and for 1C and 1G pair it is 3.496% when the receiver is in static condition. If the same is observed for the receiver in dynamic conditions the chance of occurrence of DC is increased by a factor of 5 times for each pair and the highest is for 1C and 1G satellite pair at 18.088%. Therefore, the occurrence of Doppler Collison increases with increase in the dynamic condition of the receiver and it primarily effects 1C and 1G satellite pair as they orbit in the same direction. Simulation of the trajectory path of a receiver in high dynamic conditions and doppler shift of the GEO satellites in the same, result in better understanding the need to reduce DC effect. The mitigation of DC is done with the help of chip spacing variation in the receiver design. In this project the chip spacing has been changed from the standard, 1 to 0.5 to 0.1 for both static and dynamic conditions of the receiver. The range of the doppler shift values increase by 20 times and 100 times for 0.5 and 0.1 chip spacing respectively, when compared with the range using 1 chip spacing. Thus, chip spacing and doppler shift are inversely proportional. Using this relation, the DC duration has been reduced from 50min 21sec to 2sec in static conditions and from 4h 20min 28sec to 5sec in dynamic conditions for 1C and 1G satellite pair. Moreover, the lessening of chip spacing gives better accuracy during the correlating of satellite signal with the locally generated signal, thus giving exact position. Further the work done in this project, include analysis of DC on marine environmental conditions, design of SDR based IRNSS receiver to adjust the DLL bandwidth for the mitigation of DC. A real-life experiment of the receiver in high dynamic conditions is to be done for understanding the extent of the effect of DC in such applications.

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