



Study and Analysis of GNSS Signals using In-house Developed Interference Tool

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ABSTRACT

Interference analysis of navigation signals belonging to the same group and with the signals of the satellites belonging to other groups is an important parameter that must be considered while designing a GNSS receiver and for introducing a new signal for any GNSS satellite. Troposphere and ionosphere are the layers of the atmosphere which affect the GNSS signals by creating delays and scintillations. Multipath is one of the major cause which creates maximum error budget at the receiver side of the GNSS system. The error budget differs with the type of correlator that is used. The number of navigations satellites and the services provided by them are increasing fast increasing the interference with other signals. So for this reason analysis of the interference of the signal using C/N0 degradation measurement [ITU recommendation M.1831] and the effect of troposphere, ionosphere and multipath on various signals is necessary.

In this paper, an attempt has been made to develop a tool for interference analysis of the various GNSS signals, using this tool this paper analyses the degradation of the IRNSS signals due to troposphere, ionosphere and multipath effects of the GNSS signals.

Keywords

PSD, GNSS, C/N0, IRNSS, GPS, RMS

1. INTRODUCTION

Global Navigation Satellite System includes network of earth orbiting satellites that broadcast signals used in positioning, navigation and timing services, anywhere on the surface of earth. Today two core global navigation satellite systems (GNSS) namely, United States' Global Positioning System (GPS) and the Russian Global Navigation satellite System (GLONASS) are fully operational and the European navigation satellite system GALILEO and Beidou (China) are currently under development. Many regional navigation satellite systems such as IRNSS (India) and QZSS (Japan) are in the process of development. In addition to these, there also exists many satellite based augmentation systems like GAGAN from India, WAAS from United States of America and EGNOS by European Space Agency.

With the increase in number of navigation signals day by day, the performance assessment of existing and planned GNSS signals becomes necessary from compatibility and interoperability [1] point of view.

Interference analysis is being carried out by various GNSS service provider. F. Soualle et al [2] and S. Wallner et al [3]

presented the interference analysis between GPS and Galileo signals. Similarly RAN Yi-hang et al [4] presented the details interference analysis between Galileo and Compass navigation systems. There is various other literatures also, where a detailed interference analysis between various GNSS systems is presented [5]. Wei Liu et al. in [5] and Stefan Wallner et al. in [14] present a methodology to determine the C/N0 degradation of a desired signal by the inter and intra system interference. The effective carrier- power-to-noise-density ratio denoted as effective C/N0 is used to indicate the effect of the interference on the signal-to-noise-plus-interference ratio of both coherent and non coherent outputs. ITU recommendation M.1831 et al. [17] gives the formula for total degradation of a signal in dB.

Troposphere causes delay in the signals of GNSS according to Hofmann-Wellenhof and Lichtenegger and Wasle [1] are attenuated and delayed due to refraction and the troposphere (troposphere and stratosphere together) acts as a non dispersive medium for GNSS bands. It is also mentioned that the ionosphere (ionized layer) gives scintillation and delay in the signal of GNSS.

Hofmann-Wellenhof and Lichtenegger and Wasle [1] have given a basic model for the phase and amplitude change for any signal for one reflection and have also given a method for deriving the multipath error envelope for narrow correlator.

2. INTERFERENCE SOFTWARE

2.1 Parameters under consideration:-

2.1.1 Carrier Power to noise density ratio:-

According to Wei Liu et al. in [5] and Stefan Wallner et al. in [14] the formula used to assess the C/N0 for a signal interfering with other is given by

$$\left(\frac{C}{N0}\right) = \frac{C \int_{-\frac{B_r}{2}}^{\frac{B_r}{2}} G_s(f) df}{N0 \int_{-\frac{B_r}{2}}^{\frac{B_r}{2}} G_s(f) df + C_I \int_{-\frac{B_r}{2}}^{\frac{B_r}{2}} G_s(f) G_I(f) df} \quad (1)$$

Where $G_s(f)$ is the normalized power spectral density. C is the received power of the useful signal. $N0$ is the power spectral density of the thermal noise. $G_I(f)$ is the normalized spectral density of the interfering signal. C_I is the received power of the interfering signal. B_r is the receiver front end bandwidth.

The above equation is modified when inter system and intra system interference exists as

$$\left(\frac{C}{N_0}\right) = \frac{C}{N_0 + \sum_{i=1}^M \sum_{j=1}^{K_i} C_{i,j}} \quad \text{----- (2)}$$

$C_{i,j}$ is the received power of the j^{th} interfering signal by the i^{th} satellite .

As per ITU Recommendation M.1831 [17], the total signal to noise degradation experienced by user in the presence of another interfering signal is given by:-

$$\Delta_{dB} = \left[1 + \frac{I_0}{N_0 + P_0}\right]_{dB} \quad \text{----- (3)}$$

Where N_0 is the thermal noise floor, P_0 is intra system interference, and I_0 is the external interference. The external interference level is calculated as

$$I_0[dB/Hz] = G_{agg}[dB] + P_{max}[dBW] + SSC[dB/Hz] + L_x[dB] \quad \text{----- (4)}$$

G_{agg} is the aggregate gain taking into account the interference introduced by all the satellites of one system in view. P_{max} is the maximum user receive power, SSC is spectral separation coefficient between interfering and the desired signals. L_x is the processing loss.

2.1.2 Tropospheric refraction:-

The effect of troposphere and stratosphere (collectively called as troposphere by GNSS community or as non ionized part) is denoted by the Tropospheric path delay due to the refraction. The neutral atmosphere is a non dispersive medium up to 30 GHz according to [1]. The tropospheric path delay is given by [1] as

$$\Delta T_{Trop} = \int (n - 1) ds \quad \text{----- (5)}$$

Where n is the refractive index of troposphere. Taking $N = 10^6(n-1)$. According to Hopfield HS [7] the Tropospheric refractive index and the delay can be divided into two components N_{dry} and N_{wet} due to the dry and wet components of the atmosphere respectively. The method for finding zenith delay due to dry and wet components is given by [7] as

$$K_{dry} = 155208 \times 10^{-4} \times P_{amb} \times \frac{(40136 + 148.72 \times T_{amb})}{(T_{amb} + 273.14)} \quad \text{----- (6)}$$

and

$$K_{wet} = -0.287 \times \frac{P_{vap}}{(T_{amb} + 273.16)} + \frac{8307.2 \times P_{vap}}{(T_{amb} + 273.16)^2} \quad \text{----- (7)}$$

K_{dry} and K_{wet} are the zenith dry and wet delays. P_{amb} is the ambient pressure, T_{amb} is the ambient temperature and P_{vap} is the vapor pressure. The total delay is given by the formula

$$\Delta_{trop} = \frac{K_{dry}}{\sin^2(\sqrt{E l^2 + 1.904 \times 10^{-3}})} + \frac{K_{wet}}{\sin^2(\sqrt{E l^2 + 1.904 \times 10^{-3}})} \quad \text{----- (8)}$$

El is the elevation angle of the satellite in radians.

According to Saastamoinean J [8] taking into consideration all the gas laws and considering many approximations the Tropospheric delay can be derived as

$$\Delta_{trop} = \frac{0.002277}{\cos z} \times \left[p + \left(\frac{1255}{T} + 0.05 \right) e - B (\tan z)^2 \right] \quad \text{----- (9)}$$

2.1.3 Friis Transmission Formula:-

The loss through the atmosphere follows the Friis transmission formula, which is given by

$$L_0 = \left(\frac{c}{2\pi\rho f}\right)^2 \text{ and } L_{atm} = kL_0 \quad \text{----- (10)}$$

Where ρ is the distance from satellite to receiver and k varies from 0 to 1 depending on the condition of atmosphere.

2.1.4 Ionospheric Refraction

The ionosphere is the electrically charged component of the higher atmosphere. It consists of variety of charged, free and neutral particles in it. This layer is subdivided into many layers. The ionosphere refraction is modeled as a function of the total electron content (TEC) of the atmosphere.

The phase refractive index of the GNSS signals as

$$n_{ph} = 1 + \frac{c_2}{f^2} + \frac{c_3}{f^3} + \dots$$

The quantities c_2, c_3, \dots do not depend on frequencies but on the number of electrons per cubic meter. The approximation is done till the quadratic term only.

The group refractive index of the ionosphere is given by

$$n_{gr} = 1 - \frac{c_2}{f^2} \text{ where } c_2 = -40.3N_e$$

By using the Fermat's Principle we get the for delay is calculated as

$$\Delta_{ph}^{iono} = -\frac{40.3}{f^2} \int N_e ds_0 \quad \text{and} \quad \Delta_{gr}^{iono} = \frac{40.3}{f^2} \int N_e ds_0 \quad \text{----- (11)}$$

According to Klobuchar [9] the delay through the ionosphere can be calculated without directly calculating the TEC by using a simple algorithm as shown below

$$\psi = 0.0137 / (E + .11) - 0.022$$

E is the elevation angle and ψ is the earth center angle.

$$\varphi_l = \varphi_u + \psi \cos A$$

$$\lambda_l = \lambda_u + \psi \frac{\sin A}{\cos \varphi_l}$$

φ_l, λ_l are the sub ionospheric latitude and longitude, A is the azimuth angle, φ_u, λ_u are the latitude and longitude of the receiver.

$$t = 4.32 \times 10^4 \lambda_l + time$$

If $t > 86400$ then $t = t - 86400$ if $t < 0$ $t = t + 86400$. The slant factor F is given by

$$F = 1 + 16(.53 - E)^3$$

$$\phi_m = \varphi_l + 0.064 \times \cos((\lambda_l - 1.617) \times \pi)$$

$$PER = \sum_{n=0}^3 \beta_n \phi_m^n$$

If $PER < 72000$ then $PER = 72000$

$$X = \frac{2\pi(t - 50400)}{PER}$$

$$AMP = \alpha_1 + \alpha_2 \cdot \phi_m + \alpha_3 \phi_m^2 + \alpha_4 \phi_m^3$$

$$T_{iono} = F \times 5 \times 10^{-9} \times AMP$$

$$T_{iono} = F \times 5 \times 10^{-9} \times AMP \times \left(1 - \frac{X^2}{2} + \frac{X^4}{4}\right)$$

According to [16] the Global Ionospheric Scintillation Model (GISM) is a model accepted by the International Telecommunication Union (ITU).

The TEC ionospheric maps are available online and it can be used to get the electron content in any point on the world at any particular time. So this data can be obtained and can be used to get the delay profile of the signals in various bands.

$$\Delta_{ph}^{iono} = -\frac{40.3}{f^2} \cdot TEC \quad \text{----- (12)}$$

2.1.5 Multipath Analysis

The multipath is a phenomenon where by a radio signal arrives at a receiver via two or more possible paths. Even though these signals have a common time origin at the transmitter they reach the receiver with different phases and different amplitudes.

Some methods suggested for removing the multipath effects are

- Model the multipath understand its pattern and correct the error.
- Design an antenna which has smaller side lobe.

The multipath performance of a navigation signal is to be considered while proposing a new GNSS signal. This is because multipath cannot be easily modeled and it differs largely from one place to another. A multipath error envelope is used to evaluate the multipath performance of a signal this gives the graph of the correlator versus the path delay. The various factors which affect the multipath error are:

- Signal type, modulation scheme of the signal and the chipping rate of the code.
- Band width of receiver and the type of filter that is used.
- Number of multipath signals and the signal attenuation due to the reflection.
- Chip spacing using between the correlator used for tracking.
- The delay of multipath signals with respect to line of sight signals and type of correlator used.

According to Hofmann-Wellenhof, Lichtenegger and Wasle [1] the method to find the multipath error envelope is described below

$$s_r(t) = s_d(t) + \beta s_m(t + \tau_m) \quad \text{----- (13)}$$

$s_d(t)$ is the direct line of sight signal and $s_m(t)$ is the delayed multipath signal.

$$R_r(\tau) = \int_0^T s_d(t) s_l(t + \tau) dt + \int_0^T \beta s_m(t + \tau_m) s_l(t + \tau) dt$$

$$= R_d(\tau) + R_m(\tau)$$

$s_r(t)$ is correlated with the locally generated signal $s_l(t)$. The resultant autocorrelation function is the sum of autocorrelation function of the line of sight signal and the reflected signal. The narrow correlation spacing is one method to decrease the

multipath influence. Other methods are double –delta correlation, early late slow correlator etc.

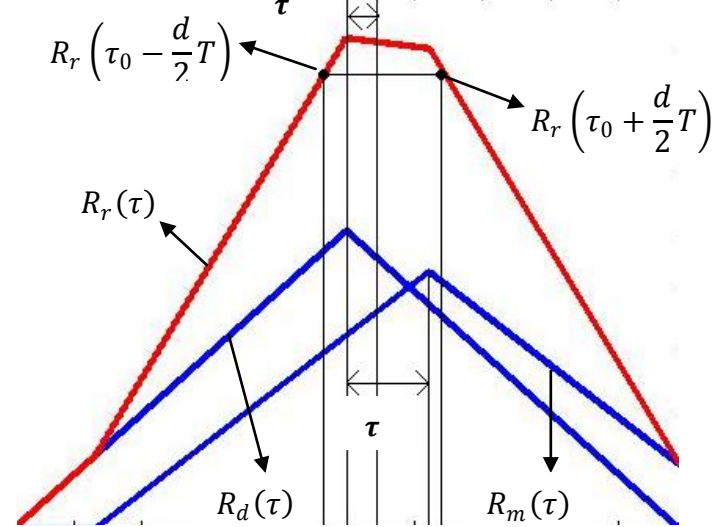


Figure 1 – Autocorrelation function of direct, reflected and the total signal

The multipath error envelope has some limitations which are it takes into consideration only one reflected signal. It does not take the channel into consideration. The error envelope varies with the type of the correlator used. The weighted multipath error envelope gives a more realistic view on the multipath performance, a statistical channel model is used to scale. Here the consideration that the short delay multipath occurs more frequently than the long delay ones.

$$\rho(\tau) = \frac{1}{\tau_0} e^{-\tau/\tau_0} \quad \text{----- (14)}$$

$$A(\tau) = a_0 e^{-\tau/2\tau_0} \quad \text{----- (15)}$$

$\rho(\tau)$ models the multipath delays and $A(\tau)$ models the multipath amplitudes. Combining these two we get the equation as

$$E'(\tau) = E(\tau) \cdot e^{-3\tau/2\tau_0} \quad \text{----- (16)}$$

$E(\tau)$ is the multipath error envelope got by using any correlator. τ_0 is the code tracking error, τ is the path delay and a_0 is normalized amplitude.

As mentioned in [1], we can model the multipath by considering the most simple case of single reflection from the ground as shown in figure 2.

So direct signal can be represented as

$$\text{Sig}_{\text{direct}} = a \cdot \sin \varphi$$

and reflected signal can be represented as

$$\text{Sig}_{\text{reflected}} = \beta \cdot a \cdot \sin(\varphi + \Delta\varphi)$$

Using superposition of the signals, we are getting

$$\tan(\Delta\varphi_m) = \frac{\beta \sin \Delta\varphi}{1 + \cos \Delta\varphi} \quad \text{----- (17)}$$

$$\beta_m = \sqrt{1 + \beta^2 + 2\beta \cos \Delta\varphi} \quad \text{----- (18)}$$

Where $\Delta\varphi$ is the phase shift due to path delay, β is the damping factor and β_m is the factor by which the resultant

amplitude is increased or decreased. This is the simplest model of the multipath

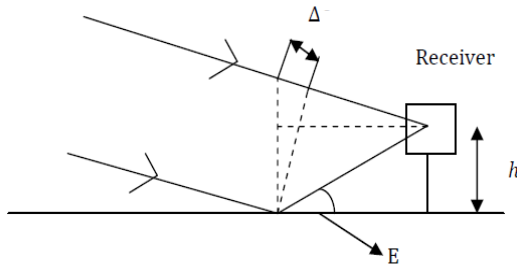


Figure-2 The geometry of multipath

3. OBSERVATIONS

3.1 Results on tropospheric delay

Byalalu is the place in Karnataka, India where the ISRO Navigation Center is present and this is the center which sets all the navigation parameter and acts as the nerve center for the IRNSS ground segment.

The climatic conditions in Byalalu is like

Temperature average = 30⁰C

Pressure average = 1016 hPa

Dew point at the place = 15⁰C

The IRNSS space segment consists of a constellation of seven satellites: three (Geostationary Orbit) GEOs located at 34° E, 83° E and 131.5° E and four (Inclined Geosynchronous Orbit) IGSOs at an inclination angle of 29° placed two each at with equator crossing at 55° and 111° East. The vapor pressure got from dew point is 17.06hPa.

The latitude and longitude of Byalalu is 12.5971° N, 77.3418° E. The elevation angle for each satellite is calculated approximately as follows

34° E satellite - 0.6429 rad

83° E satellite – 1.2880rad

131.5° E satellite – 0.47324 rad

When the GSO satellites cross the equator

55°E satellite – 1.0507 rad

111°E satellite – 0.84795 rad

Table 1 showing the longitude of IRNSS satellites at Byalalu near the equator and their elevation angles from INC

Satellite type	Longitude closing at the equator(°E)	Elevation angle (rad)
Geostationary(GEO)	32.5	0.6429
	83	1.288
	131.5	0.4724
Geosynchronous(IGSO)	55	1.0507
	111	0.84795

Table 2 showing the delay measured due to troposphere for the IRNSS satellites, in the order as given in table 1, at INC

Delay measured (meters)		
Hopfield	Saastamoinen	Chao's mapping function
3.9681	3.9658	3.3297
8.1849	8.2914	6.97
5.1849	5.2146	4.3846
2.7772	2.7438	2.3
3.1961	3.1736	2.6652

3.2 Results of Ionospheric delay.

Table 3 showing the longitude IRNSS satellites near the equator, their elevation and azimuthal angles from INC calculated

satellite type	longitude at the equator(°E)	elevation angle (rad)	Azimuthal angle(rad)
Geostationary (GEO)	32.5	0.6429	4.4968
	83	1.288	2.7148
	131.5	0.4724	1.728
Geosynchronous (IGSO)	55	1.0507	4.22495
	111	0.84795	1.88692

Table 4 showing the delay measured due to ionosphere for the IRNSS satellites, in the order as given in table 3, at INC by using TEC maps calculated by GUI

delay measured (meters)			
L1	L2	L5	S
10.1	24	26	5.8
8.2	13.5	14.5	3.27
10.9	17.8	19.5	4.33
9.8	16.3	17.6	3.96
8.6	14.3	15.5	3.47

3.3 Results of C/N0 degradation

The degradation in C/N0 is basically a degraded C/N0 value at which receiver will work away from theoretical value. In order to calculate C/No degradation of IRNSS signal due to other GNSS signal, table 5 shows the major parameter of existing GNSS signals taken for calculation.

Table 6 shows the degradation of IRNSS existing and proposed signals due to other GNSS signals. The front end receiver bandwidth is taken 30 Mhz in L1 band, 24 Mhz in L5 band and 16.5 Mhz in S band.

Table 5 Parameter taken into the GUI to calculate the C/N0 degradation

	inputs taken(all are in dB or dB/Hz)			
	Gagg	Pmax	Noise	processing loss
GPS	-11	-136	-201	40
Galileo	-11	-136		
Compass	-11	-136		
QZSS	-11	-136		
Glomass	-11	-136		

Table 6 – table showing the total C/N0 value from the GUI for all IRNSS signals in dB/Hz

	Signal of IRNSS	C/N0 DEGRADATION in dB/Hz			
		GPS	COMPASS	GALILEO	QZSS
L1	*MBOC(6,1,11)	5.6	3.0	-	-
	*BOC(12,2)	.45	.35	-	-
	*BOCcos(12,2)	.26	.39	-	-
L5	BOC(5,2)	1.02	.59	.52	1.05
	BPSK(1)	.61	.79	.28	.62
S	BOC(5,2)	-	4.15	-	-
	BPSK(1)	-	4.16	-	-

*Proposed candidate in L1 Band

3.4 The results of multipath effects

The multipath error envelope obtained by using the method as described above is displayed here.

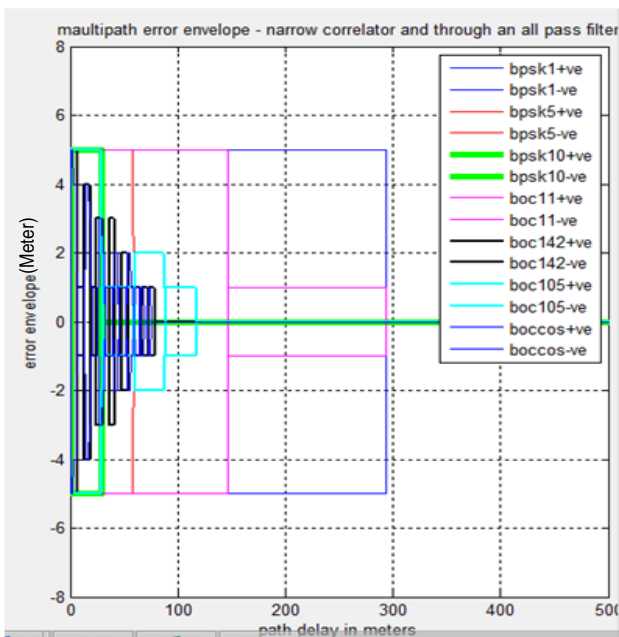


Figure-3 The multipath error envelope [in meters] versus the path delay in meters

4. NEW SIGNAL EXPLORATION

4.1 New signal in L1 Band

MBOC modulation can be considered as an ideal candidate for new IRNSS signal in L1 band. The reason behind selection of MBOC modulation scheme is as follows:-

- From Compatibility and interoperability point of view as GPS, GALILEO and COMPASS is already using MBOC modulation.
- Flexibility as MBOC modulation is combination of BOC (1, 1) and BOC(6,1) ,so in case of large interference more power will be given to BOC(6,1) modulation scheme for more reliable tracking.
- Flexibility in receiver design as simplest receiver can use only BOC(1,1) for tracking purpose, while complex receiver use both BOC(6,1) and BOC(1,1) for tracking purpose.
- Since MBOC is already transmitted by GPS, GALILEO and COMPASS, this signal has a larger C/N0 degradation than other signals.
- MBOC can be implemented using other power sharing like MBOC(6,1,2/11) or
- MBOC(6,1,3/11) instead of MBOC(6,1,1/11), so their C/N0 degradations are seen by using the GUI.

The result can be seen in the table shown below for a 30 MHz front end receiver bandwidth.

Table 9 – Table showing the total C/N0 value from the GUI for various MBOC modulations in dB/Hz for L1 band.

Signal	C/N0 degradation
MBOC(6,1,1/11)	5.4
MBOC(6,1,2/11)	5.5
MBOC(6,1,3/11)	5.52
MBOC(6,1,4/11)	5.6
MBOC(6,1,5/11)	5.6

4.2 New signal in L5 Band

AltBOC (15, 10) is considered to be a one of the prominent candidate for future IRNSS signal in L5 band. AltBOC modulation, similar to BOC modulation provides high spectral isolation between the two upper main lobes and the two lower main lobes (considering the I and Q phases separately). This is accomplished by using different codes for each main lobe. The reason behind the selection of AltBOC modulation for

IRNSS in future L5 band is as follows:

- From Compatibility and interoperability point of view as GALILEO and COMPASS is already using AltBOC (15, 10) modulation.
- Two different types of services can be clubbed together in single AltBOC modulation. Hence, it will be an effective utilization of spectrum.



- Since AltBOC is already transmitted by GALILEO and COMPASS this signal has a larger C/N0 degradation than other signals.
- AltBOC can be implemented using other power sharing like AltBOC (5,2) or AltBOC(5,1) so their C/N0 degradations are seen using the GUI.

The result can be seen in the table shown below for a 30MHz front end receiver bandwidth.

Table 10 – table showing the total C/N0 value from the GUI for various AltBOC modulations in dB/Hz for L5 band.

signal	C/N0 degradation
AltBOC(15,10)	3.38
AltBOC(5,2)	1.59
AltBOC(5,1)	1.04
AltBOC(1,1)	3.66

5. CONCLUSION

The troposphere is a non-dispersive medium for the GNSS signals and it causes delay due to refraction and attenuation. Several models were proposed and various modifications are also done to them. The original Hopfield and Saastamoinen models are still fairly good methods to find the delay and their values are very close to each other. This delay can also be found using several mapping functions with certain limitations on the elevation angle and result of one such function is shown here. Ionosphere is a dispersive medium for GNSS signals. The Klobuchar method used to find ionospheric delay in GPS is used to calculate the delay over India (by using the GUI) and it is concluded that this method is not accurate over the Indian region. Hence by taking in the live TEC values delay due to ionosphere is calculated over India. It gives a fairly accurate value of delay due to ionosphere for the IRNSS signals.

Multipath error envelope obtained is not accurate as it is not filtered but it gives a rough idea about the multipath performance as the BOC (m,n) signals give a better multipath resistance as the value of m and n increases and this can be seen from the diagram. The MBOC signal, which is expected to be transmitted from IRNSS in L1 band, which uses the combination of both BOC(6,1) and BOC(1,1) has better multipath resistance than the others signals. This is also the case with AltBOC(15,10) which is expected to be transmitted in L5 from IRNSS. In case of BPSK signals as the chip length decreases the multipath performance improve. The MBOC is the expected signal in L1 band it has lot of advantages like compatibility and usage of multiple modulation schemes in a signal (BOC (1, 1) and BOC (6, 1)) but this has a major disadvantage of larger C/N0 degradation as this signal is transmitted by other systems also, found by using both GUI and experiments. So a highly sensitive receiver with Pmax nearly -100 dBW and much lower processing loss must be used for improving the C/N0 performance. The same is the case with AltBOC (15,10) in the L5 band. Other modulations of AltBOC like AltBOC(5,2) or AltBOC(1,1) can be used as they have better C/N0 degradation.

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