Mathematical Model Development for Navigation with Indian Constellation (NavIC) L-Band Geo Synchronous Satellite’s Direct Signal and Multipath Signals

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Accepted: 29 May 2022 / Published online: 31 August 2022
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Abstract
NavIC L-band satellite signal that travels from the satellite to the receiver undergoes mainly shadowing and multipath effects. In this research paper, NavIC satellites were observing and analyzing signal efficiency for both the direct signal and multipath signal over the Dehradun area. Two open space data series (direct signal and multipath signal) for Dehradun were obtained in this analysis by the satellite receiver. The methodology includes evaluation, testing, and analysis of data in both cases. Based on collected data, a general mathematical model has been developed, describing the signal intensity in the open space context. The both NavIC Mathematical model was validated with the experimental data. The average R² and RMSE values developed for the direct signal mathematical model were 0.89 and 1.08% respectively which show a good prediction of NavIC C/N₀ value with the developed model. For the multipath mathematical model, four cases have been evaluated. Comparing the graphical view of all four cases for C/N₀ multipath signal concerning raw NavIC C/N₀ multipath signal has been done to select the best mathematical model.

Keywords Mathematical model · NavIC · Direct signal · Multipath signal · Regression model

1 Introduction
This research aims at developing a mathematical model that can predict the NavIC Geosynchronous satellite’s direct signal and multipath signals. The signal distortion or maximum signal blocking of NavIC satellite signals are due to urban obstruction. One of the major sources of signal loss is multipath. When the signals are received from more than one path, the NavIC Multipath signal provides a positional error. The accuracy of the obtained signal is influenced by many factors such as temperature, the multipath [1–6], and satellite Geometry, Ionospheric effect [7], etc. Signals are also influenced by the electrical properties of the roof and the wall. Therefore, the diffraction coefficients are also used in

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mathematical model of direct signal. Most of the work carried out in this domain belongs to Global Positioning System (GPS). Deep et al. [1] derived the regression model correlating GPS signal SNR and satellite elevation angle in an open environment. Third order polynomial has been used to develop the relationship between SNR and elevation angle. Another regression model which is given by Pai et al. [2] represents the overall signal performance in open space in Polynomial of order 4. Both models were used to predicted the SNR of GPS signal only.

Han et al. [3] proposed a curve-fitting semi-empirical model to predict SNR (signal-to-noise ratio) data collected by a GNSS receiver. The objective of this model is to reestablish the direct and reflected signals from SNR data and to extract frequency and phase information affected by soil moisture as proposed by Larson [4]. Zavorotny et al. [5] proposed a GPS multipath physical model for assessing soil moisture around the recipient. Authors have developed an electro-dynamic model that connects bare soil to power obtained by the GPS receiver. This electro-dynamic model facilitates the determination of reflection coefficients at different polarization. Reflection coefficient is a function of soil dielectric and dielectric property of soil varies with the change in moisture content of the soil. One of the drawbacks of such a model is the idea of out-of-soil water that was used to forecast soil dielectric properties and frequency scattering. The findings were confined to one place (Marshall, CO) therefore to determine the reliability of model it should be tested to other locations also.

Semi-empirical and physical models that have been established are complex and depend on numerous parameters. Consequently, there is a need for a less complex mathematical model. In this study, mathematical model for both direct and multipath signals have been developed to determine the relationship between NavIC signal intensity and angle of elevation. These mathematical models can be used in a variety of applications, including soil moisture estimation [8–14]. The measurement of soil moisture content is important in the fields of agriculture, climate monitoring, climate change, soil erosion, etc. [15–23]. Other applications of GNSS are snow depth estimation, climate model, weather monitoring, soil erosion, soil moisture modeling and integrated sensing of soil moisture, and etc. [24–31].

The paper is divided into five sections. Section 1 introduces and discusses the direct signal and multipath signal obtained from the receivers. Section 2 contains information on the experimental setup for receiving NavIC data along with difference and comparison of the NavIC data received at two different locations. Section 3 discusses the methodology for developing mathematical models to predict the direct signal and multipath signal. The results have been discussed in Sect. 4. Finally, in Sect. 5, conclusions have been made.

2 Experimental Setup for Receiving NavIC Data

Two experimental setups to predict NavIC Direct $C/N_0$ and multipath $C/N_0$ have been used in this research. The first experimental configuration consists of two modules, the first being external and the second internal. The external module comprises receiver antenna mounted on the top of the building as shown in Fig. 1. The internal module is composed of the IGS receiver [30], desktop, and energy supply as shown in Fig. 2.

The second experimental setup also consists of a receiver antenna and an IGS receiver. NavIC antenna has been mounted in the playground of Graphic Era Deemed to be University (Latitude 30.2681°N and Longitude 77.9944°E), Dehradun. This NavIC antenna was used to collect the multipath signal data from the bare land as shown in Fig. 3.
2.1 Difference Between Receiver Setup Between Rooftop and Ground

To receive the NavIC signal we have two receiver antennas, one receiver antenna is mounted on the rooftop of the building and the other one mounted in the playground. The receiver antenna also receives GPS and GAGAN signals. The antenna mounted on the rooftop is expected to receive only a direct signal and not the multipath. With the elevation angle, the received signal intensity increases. Signal power is improved with the increase in elevation angle and reached its highest value when the satellite is just above the antenna, in the case of a GPS whereas in case of a NavIC, the signal strength is maximum at 58° for NavIC—4, and NavIC—5 and 68° for NavIC—1, NavIC—2 and NavIC—9.

The antenna mounted at the height of 2-m from the ground is expected to receive direct as well as the reflected signal from the ground (in our case it is soil surface). The selection of receiver height is another important aspect of the work. The height of the receiver directly affects the multipath fluctuation of NavIC data. Several researchers have preferred to keep the receiver at a height of 2 m, 2.5 m, or 3 m in soil moisture studies [3–5, 13–15, 23–31]. In this work, we kept our receiver antenna at a height of 2 m from the soil surface to collect the multipath data. Figure 4 shows the radial distance of reflection point from the receiver base with elevation angle. It can be observed from the figure that increasing the height of receiver will also increase the coverage area of reflected signal. As the elevation angle increases, reflections received at the receiver are from a very near point. For large elevation angles, the reflection points are much far away.

2.2 Comparison of NavIC Data Received at Two Different Locations

Figures 5, 6, 7 and 8 show the comparison of data received from two different locations. The signal receives from the rooftop receiver is almost the same on all 4 days. There is a marginal
change in the $C/N_0$ or the contribution multipath to the $C/N_0$ is so little. However, when we compare GEU ground receiver data we observe that the multipath contribution in the signal is more than the receiver at the rooftop. Changes in $C/N_0$ with the soil moisture can be observed at a lower elevation angles. Table 1 shows the value of soil moisture for respective dates.

3 Methodology for Developing Mathematical Model

3.1 Regression Model to Predict NavIC Direct Signal

To predict the direct signal of NavIC constellation, we have developed a general mathematical model. Figure 9a–d illustrates the outcome of NavIC regression model derived for the NavIC satellite data to link the $C/N_0$ data to the satellite elevation angle. Chamoli et al. has proposed an empirical relationship, given by Eq. 1, to predict the NavIC $C/N_0$ [31].
3.2 Theoretical Retrieval of Multipath C/N0 Data for NavIC: Mathematical Model

The multipath data received by the NavIC receiver is composed by direct and reflected signal. Therefore C/N0 can be written as

\[ C/N_0 = (3.199 \times 10^{-5} \times (\theta)^3 - 0.00051 \times (\theta)^2 + 0.44 \times (\theta) + 3 \times 10^{-8}) + Bandwidth_{NavIC \_L5} \]  

(1)

3.2 Theoretical Retrieval of Multipath C/N0 Data for NavIC: Mathematical Model

The multipath data received by the NavIC receiver is composed by direct and reflected signal. Therefore C/N0 can be written as

\[ C/N_0 = A [G_d \cos \alpha + \Gamma G_r \cos(\alpha + \psi)] \]  

(2)

where \( A \) is amplitude, \( \alpha \) is the initial phase, \( G_d \) and \( G_r \) are the direct signal gain of antenna and reflected signal gain of antenna, \( \Gamma \) is reflection coefficient, \( f \) represents the frequency and \( \psi \) is the phase difference of multipath signal. The phase difference due to multipath is given as
Fig. 4 Ground reflection distance of from the receiver at different elevation angle and at different antenna height

Fig. 5 Raw C/N₀ data for NavIC—4 on date 04/Sep/2017 a receiver installed on rooftop b receiver on ground

Fig. 6 Raw C/N₀ data for NavIC—4 on date 05/Sep/2017 a receiver installed on rooftop b receiver on ground
where \( h \) is the height of the receiver from the ground and \( \lambda \) is the wavelength of the transmitted signal.

The NavIC signal is a right-hand circular polarization (RHCP). This implies that a helix from a right-hand screw in the propagation path is shown by the electric field vector. Horizontal and vertical polarization elements are circular polarization. The vertical component gets inverted if the incident angle is less than Brewster Angle. The vertical component of signal remains unchanged after reflection if incidence angle is higher than Brewster Angle. Figure 10 shows the graph of Brewster angle calculation considering dielectric constant from 3 to 30. For NavIC satellite data the range of Brewster angle is 59°–79° when dielectric constant changes from 3 to 30.

\[
\psi = \frac{4\pi h}{\lambda} \sin \theta
\]  

(3)
The polarization of a signal will then shift from RHCP to LHCP and vice versa, depending on the surface reflection and incidence angle \[32\]. The reflected signal can be seen as the sum of two circularly polarized signals, one which maintains the co-polarizing \(\tau_o\) (original RHCP) and a cross-polarizing \(\tau_x\) (component opposite LHCP).

\[
\tau_o = \frac{\tau_h + \tau_v}{2}
\]  \hspace{1cm} (4)

Fig. 9 A modified regression model to predict C/N\(_0\) with the satellite data. a 05/September/2017 b 05/October/2018 c 20/March/2019 d 24 April 2020
where $h$ is horizontal polarization, $v$ is vertical polarization and $\theta$ is satellite elevation angle.

The relative dielectric constant ($\varepsilon$) can be evaluated by Eq. (8) with given value of soil moisture ($m$) [33].

$$e = 3.03 + 9.3m + 146m^2 - 76.7m^3$$  \hspace{1cm} (8)

The reflection coefficient ($\Gamma$) may be both RHCP and LHCP. Literature shows that theoretically if GNSS signal are RHCP and it’s reflected from the planer surface its changes its polarization and convert it in LHCP [32]. But practically the soil surface is not a perfect planner surface and soil dielectric also affects it, so that all RHCP polarization will not convert to LHCP polarization. Therefore following four cases have been considered to estimate the $C/N_0$ in this research.

(a) LHCP × Reflected gain
(b) LHCP × Direct gain
(c) RHCP × Reflected gain
(d) $(n \times $LHCP $+ n \times $RHCP$)$ Direct/Reflected gain; ($n=0–1$).
4 Result and Discussion

4.1 Regression Model to Predict NavIC Direct Signal

To access fitness, the Ordinary Least Squares (OLS) have been used. In OLS analysis, R-squared (Coefficient of determination) and Root Mean Square Error (RMSE) are used to determine the efficiency of the operation. RMSE and R-squared value for the randomly selected data for the years 2017, 2018, 2019, and 2020 have been analyzed. $R^2$ varies from 0.86 to 0.92 and RMSE values varies from 0.88 and 1.53%. The mean value of $R^2$ is therefore 0.89 and RMSE 1.08%. This model has an $R^2$ value of 0.89 which shows that 89% of $C/N_0$ variance can be represented in this regression model. For the model, RMSE is 1.08, showing the goodness of fitted regression model.

4.2 Theoretical Retrieval of Multipath $C/N_0$ Data for NavIC

CASE 1 When LHCP $\times$ Reflected gain has been considered as reflection coefficient. Equation 9 gives the value of multipath $C/N_0$.

\[ C/N_0 = A \left[ G_d \cos \alpha + (LHCP \times G_r) \cos (\alpha + \psi) \right] \]  

Figures 11 and 12 show the graph of $C/N_0$ with respect to elevation angle ranging from 13°–30° to 13°–70°, respectively. It can be observed from both the graphs that as the dielectric value of soil moisture increase the value of $C/N_0$ amplitude also increase whereas, after 50° we get approximately direct signal component only.

CASE 2 When LHCP $\times$ Direct gain have been considered as reflection coefficient. Equation 10 gives the value of multipath $C/N_0$.

\[ C/N_0 = A \left[ G_d \cos \alpha + (LHCP \times G_d) \cos (\alpha + \psi) \right] \]
Figures 13 and 14 show the graph of $\frac{C}{N_0}$ with respect to elevation angle ranging from 13°–30° and 13°–70°, respectively. It can be observed from both the graphs that as the dielectric value of soil moisture increase the value of $\frac{C}{N_0}$ amplitude also increase whereas, after 70° we get approximately direct signal component only reflected signal amplitude get amplified.

**CASE 3** When RHCP×Reflected gain has been considered as reflection coefficient. Equation 11 gives the value of multipath $\frac{C}{N_0}$.

$$\frac{C}{N_0} = A \left[G_d \cos \alpha + (RHCP \times G_r) \cos (\alpha + \psi)\right]$$ (11)

Figures 15 and 16 show the graph of $\frac{C}{N_0}$ with respect to elevation angle ranging from 13°–30° and 13°–70°, respectively. It can be observed from both the graphs that as the dielectric value of soil moisture increase the value of $\frac{C}{N_0}$ amplitude decrease whereas, after 40° we get approximately direct signal component only.

**CASE 4** Above three cases have been considered for LHCP and RHCP, separately. Now in the 4th case we have considered the following 3 sub-cases for both because during experimentally data collection both LHCP and RHCP reflection coefficient component may have been affected the signal:

**Case 4.1** Following Eq. 12 gives the value of multipath $\frac{C}{N_0}$.

$$\frac{C}{N_0} = A \left[G_d \cos \alpha + (0.3 \times LHCP) \times G_d + RHCP \times G_r \cos (\alpha + \psi)\right]$$ (12)

Figures 17 and 18 show the graph of $\frac{C}{N_0}$ with respect to Elevation angle ranging from 13°–30° and 13°–70°, respectively. It is clearly visible from both the graphs that the increase in dielectric value due to soil moisture increases the amplitude of $\frac{C}{N_0}$ data.

**Case 4.2** Eq. 13 gives the value of multipath $\frac{C}{N_0}$.

$$\frac{C}{N_0} = A \left[G_d \cos \alpha + 0.3 \times (LHCP \times G_r + RHCP \times G_r) \cos (\alpha + \psi)\right]$$ (13)
Figures 19 and 20 show the graph of $C/N_0$ with respect to elevation angle ranging from $13^\circ$–$30^\circ$ and $13^\circ$–$70^\circ$, respectively. It can be observed from both the graphs that as the dielectric value of soil moisture increase the value of $C/N_0$ amplitude decrease whereas, after $40^\circ$ we get approximately direct signal component only.

**Case 4.3** Eq. 14 gives the value of multipath $C/N_0$.

$$C/N_0 = A\left[G_d\cos\alpha + (0.7(LHCP) \ast G_r + RHCP \ast G_r)\cos(\alpha + \psi)\right]$$

Figures 21 and 22 show the graph of $C/N_0$ with respect to elevation angle ranging from $13^\circ$–$30^\circ$ and $13^\circ$–$70^\circ$, respectively. It can be observed from both the graphs that as the
dielectric value of soil moisture increase the value of C/N₀ amplitude increases whereas, after 40° we get approximately direct signal component only. Table 2 shows the summary of all four Cases with respect to increase in soil dielectric values.

4.2.1 Raw Multipath Data Received by a Receiver and Its Processing

The same soil moisture values and corresponding dielectric constant used in the above mathematical model have been taken in to account to draw a comparison of theoretical and experimental result. Figure 23 shows the raw C/N₀ data received on 12th September 2017,
7th June 2018 and 14th July 2018. The methodology used for determining the multipath amplitude has been taken from the Chamoli et al. [14].

Table 3 gives the Data set of multipath amplitude with respect to soil moisture and corresponding dielectric constant.

From the experimental data, it is clear that when the soil moisture increases the value of the amplitude also increases. Table 2 lists the soil moisture, its dielectric constant and corresponding amplitude obtained experimentally. Case 1, Case 2, Case 4.1, and Case 4.3 also exhibit the same trend, i.e., the value of amplitude increased with the increase in dielectric constant. Therefore, we have four mathematical equations to determine the $C/N_0$ of multipath signal. The $C/N_0$ data have been collected in August and September 2020. In these data sets, we have an elevation angle range of $13^\circ$–$70^\circ$ of NavIC $C/N_0$ data. So
that comparing the graphical view of Case 1, Case 2, Case 4.1 and Case 4.3, with the C/N₀ of multipath signal received on date 28th Aug 2020 and 7th Sep 2020 (Fig. 24) it is clear that only Case 4.3 gives the approximately same graphical view as compare to other cases. Therefore, Eq. 14 can be used as a mathematical model to determine the NavIC C/N₀ multipath signal.

Fig. 19  Plot between C/N₀ and elevation angle (13°–30°)

Fig. 20  Plot between C/N₀ and elevation angle (13°–70°)
5 Conclusion

The current work has been done with the NavIC IGS receivers for open-space environments in the Dehradun area. In this research paper two mathematical models, i.e., mathematical model to predict direct signal of satellite and mathematical model for a multipath signal of a satellite have been developed. At any given time, NavIC direct signal can be predicted using a mathematical model (Eq. 1) in open environments. The predictive model could efficiently predict the availability of satellites and the quality of signals for
Table 2 show the summary of all four cases

| Case no | Case                                      | Amplitude | Remark                                                                 |
|---------|-------------------------------------------|-----------|------------------------------------------------------------------------|
| Case 1  | LHCP × Reflected gain                     | Increased | After 50° we get approximately direct signal component only            |
| Case 2  | LHCP × Direct gain                        | Increased | When signal reaches upto 70° elevations angle the direct signal and reflected signal amplitude get amplified |
| Case 3  | RHCP × Reflected gain                     | Decreased | After 40° we get approximately direct signal component only            |
| Case 4  | (n × LHCP + n × RHCP) direct/reflected gain; (n=0–1) |           |                                                                        |
| 4.1     | FOR 0.3 × (LHCP × DIRECT GAIN) + RHCP × REFLECTED GAIN | Increased | When signal reaches upto 70° elevations angle the direct signal and reflected signal amplitude get amplified but less than results of case 2 |
| 4.2     | FOR (0.3 × (LHCP) + RHCP) × REFLECTED GAIN | Decreased | After 40° we get approximately direct signal component only            |
| 4.3     | (0.7 × (LHCP) + RHCP) × REFLECTED GAIN    | Increase  | After 40° we get approximately direct signal component only            |
numerous geographic environments. To access fitness, the Ordinary Least Squares (OLS) are used. $R^2$ has varies from 0.86 to 0.92 and RMSE has varies from 0.88 and 1.53%. This model has an average $R^2$ value of 0.89 which shows that 89% $C/N_0$ variance can be represented in this regression model. For the model, average RMSE is 1.08%, showing the fitted regression model is very good. The results of this study can be used to assess the impact of various mobile satellite environments in order to improve the quality of service.

The multipath data received by the NavIC receiver is a combination of direct signal and reflected signal. For developing the mathematical model for multipath signal, we have considered four cases. The value of the amplitude is increased in Case 1, Case 2, Case 4.1, and Case 4.3. Therefore we have only four Mathematical equations out of six equation models to determine the NavIC $C/N_0$ multipath signal. Now comparing the graphical view of in Case 1, Case 2, Case 4.1, and Case 4.3, $C/N_0$ multipath signal with respect to raw NavIC $C/N_0$ multipath signal on date 28th Aug 2020 and 7th Sep 2020. It seems clear that only Case 4.3 gives the approximately same graphical view as compare to others. Therefore, the mathematical equations (Eq. 14) have been used to determine the NavIC $C/N_0$ multipath signal. These mathematical models can be used in a variety of applications, including soil moisture estimation, snow depth estimation, climate model, agriculture, climate monitoring, climate change, soil erosion controlling, and etc.

![Fig. 23](image_url)

Table 3  Data set of multipath amplitude with respect to soil moisture and corresponding dielectric constant

| Date       | Soil moisture (%) | Amplitude (V/V) | Dielectric constant (e) |
|------------|-------------------|-----------------|-------------------------|
| 12-Sep-2017 | 10.25             | 15.75           | 5.4346                  |
| 07-June-2018| 15.72             | 23.85           | 7.8019                  |
| 14-July-2018| 31.85             | 37.51           | 18.3245                 |
Author Contributions Not applicable.

Funding This work is supported by the Space Applications Center (SAC), Indian Space Research Organization (ISRO), Ahmedabad India under NavIC—GAGAN Utilization Program.

Availability of Data and Material According to the undertaking signed with SAC, this data is the property of SAC and hence cannot be shared.

Code Availability According to the undertaking signed with SAC, this data is the property of SAC and hence cannot be shared.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Fig. 24 Raw C/N₀ data received on a 28th Aug. 2020 and b 7th Sep. 2020
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