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Comparative Analysis of NavIC Multipath Observables for Soil Moisture over Different Field Conditions

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Abstract—Studies of soil moisture with Global Navigation Satellite System (GNSS) have gained the attention of several researchers. Multipath amplitude, multipath phase, and multipath frequency are multipath observables that are utilized in the study of soil moisture. However, an inter-comparison of the performance of these parameters for soil moisture under different roughness and vegetation conditions is very much required to have a better insight so that more robust inversion algorithm for soil moisture retrieval with multipath observables can be designed. Therefore, this paper analyses the performance of these multipath observables for soil moisture over bare smooth soil, rough surface, and vegetated soil. Two different fields have been investigated to include the location variability. Navigation with Indian constellation (NavIC) multipath signal has been used in this study. Statistical parameters such as correlation coefficient (R), Root Mean Square Error (RMSE), and sensitivity have been determined to study the performance of multipath observable for soil moisture under different surface roughness and vegetation conditions.

1. INTRODUCTION

The sensitivity of L-band microwave signals for soil moisture investigation has been demonstrated in several studies [1–5]. The vertical profile of soil moisture is the least significant at L-band in comparison to C and X-band [6]. Further, L-band can also penetrate the vegetation cover to reach the soil surface which makes it ideal for soil moisture analysis [3, 7]. Navigation satellites also operate in L-band; therefore, they are very much suitable for the investigation of soil moisture. The sensitivity of navigation signals for soil moisture has been demonstrated in several research works [6, 8–11]. There are two methods for using the Global Navigation Satellite System (GNSS) signal to investigate soil moisture. The first method is called GNSS-IR (Interferometric Reflectometry), and the second method is called GNSS-R (Reflectometry) [12]. This paper utilizes GNSS-IR technique to study soil moisture. In GNSS-IR, multipath signals are collected using a single geodetic near-surface ground-based antenna. The interference pattern generated using multipath signals is investigated for soil moisture analysis [1, 10]. On the other hand, in GNSS-R technique, separate antennas are used to receive the direct and reflected signal [12].

GNSS-IR technique provides low spatial resolution because multipath signals are received from the Fresnel zone using a low-height ground-based antenna. The height of antenna, as stated in various studies, is close to 2 m from the soil surface [2, 3, 6, 11, 13]. GNSS-IR has the advantage of cancelling out all the atmospheric disturbances as it works on path delay between the direct and reflected signal. The amplitude, phase, and frequency of generated sinusoidal interference at lower elevation angles are the observables that are analyzed in the study of soil moisture and termed as multipath amplitude,

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multipath phase, and multipath frequency, respectively [1, 3, 6, 13, 14]. Signals originated from GPS, GLONASS, and BDS have been mostly analyzed in the study of soil moisture over bare and vegetated soil [3, 11, 15]. Studies in the case of vegetated soil are limited to sparse vegetation, and the condition of sparse vegetation has been obtained from normalized multipath amplitude (A_{norm}) whose value should be greater than 0.78 [2, 16].

Three different multipath parameters, i.e., multipath amplitude, multipath phase, and multipath frequency, utilize different phenomena to analyze the soil moisture. Multipath phase and multipath frequency are related to the penetration depth of the signal whereas multipath amplitude is related to the contrast between the mediums (air, vegetation, and soil surface). The study of soil moisture with multipath amplitude is related to the scattering from soil surface which is dependent on the moisture condition and roughness of soil in the case of bare soil. However, in the case of vegetated surface, the scattering of multipath signal is also affected by the vegetation, and the study of moisture with multipath amplitude becomes a cumbersome task. Therefore, most of the soil moisture studies utilize multipath amplitude for bare soil only [1, 13]. However, in some of the studies, multipath amplitude has been utilized as a measure of sparse or dense vegetation [10, 17]. Multipath phase is the most utilized multipath observable in soil moisture studies with GNSS over bare as well as vegetated soil. The change in multipath phase with soil moisture is related to the change in penetration depth of the signal which changes the path difference between the direct and reflected signals [1, 6, 18]. It has been observed that multipath phase is less affected by the presence of vegetation if it is sparse vegetation. However, the retrieval of soil moisture in the presence of dense vegetation provides less accurate results [6]. To date, the retrieval of soil moisture with GNSS signal in the presence of vegetation is a challenging task with multipath amplitude and multipath phase. The third multiple observable, i.e., multipath frequency, is least utilized parameter in the study of soil moisture. However, it has been shown that multipath frequency also depends on soil moisture [3, 8, 15]. The retrieval of multipath amplitude and multipath phase is carried out with Least Square Estimation (LSE) whereas Lomb Scargle Periodogram (LSP) is utilized to determine multipath frequency component from the multipath GNSS signal. Multipath frequency is also related to the penetration depth of signal which results from the change in effective height of the antenna from the soil surface. The presence of vegetation will create multipath frequency component at the receiver, and a careful investigation of LSP spectrum will provide the frequency component related to the soil moisture. This paper provides a careful analysis of these three multipath observables for two different locations in which one location provides the study in the presence of vegetation. The surface roughness conditions of these two locations are also different. Therefore, the study in this paper provides the variability in vegetation condition along with surface roughness and analyses their effect on multipath variables. Geosynchronous satellite of Navigation with Indian constellation (NavIC) L5-band (Central Frequency: 1147.45 MHz, bandwidth: 24 MHz) has been used in this study. This study will be very useful in developing an inversion model for retrieval of soil moisture by utilizing all multipath observables.

Section 1 provides the basic introduction and advantages of the NavIC-IR technique. In Section 2, the experimental setup is demonstrated. Section 3 deals with the conceptualization of the NavIC-IR observables and methodology. Further, detailed results are discussed in Section 4, and Section 5 provides the conclusion of the research work carried out in this paper.

2. EXPERIMENTAL SETUP

Experiments were carried out in Dehradun, Uttarakhand, India. The latitude and longitude of the first observation field were 30.2880°N and 78.0881°E, and second observation field was 30.2683°N and 77.9945°E. The first observation field was a flat surface as shown in Fig. 1(a), whereas the second observations were made in an agricultural field as shown in Fig. 1(b). The first and second observation fields are designated as field-1 and field-2, respectively. Dehradun is a valley region with a subtropical temperate zone. Observations were carried out from Aug. 20, 2020 to Oct. 15, 2020 over field-1 and Dec. 09, 2019 to Jan. 15, 2020 over field-2. The mean surface roughness, during the entire observation period for field-2, was 0.79 cm. The vegetation investigated in this paper was wheat crop, and the total investigation time is one month. Observations started from the date of sowing till the crop height reached at 25 cm, and vegetation water content reached near about 0.4 kg m^{-2}.

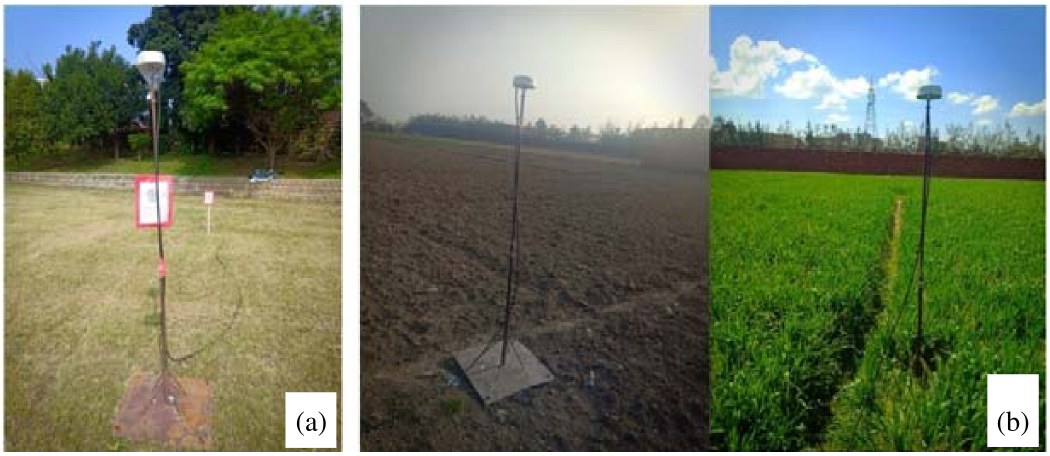

Figure 1. Antenna placement over two different land covers, (a) flat bare land and (b) agricultural land (with and without vegetation).

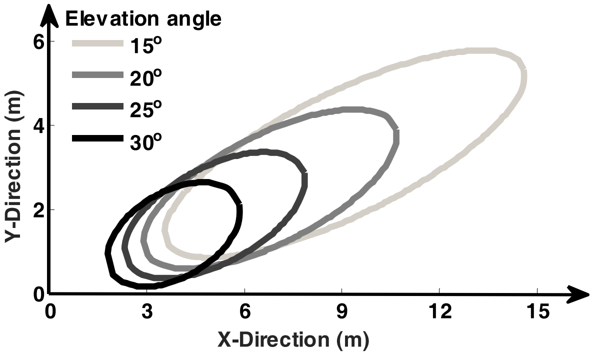

Figure 2. Fresnel zone for different elevation angle when antenna height is 2.1 m above the surface.

A Right Handed Circularly Polarized (RHCP) geodetic antenna is placed parallel to the reflecting surface at a height of 2.11 m as shown in Fig. 1, and it remained untouched for the entire observation period. Fresnel zone, which is important to determine the locations of *in-situ* measurements, is shown in Fig. 2 for 2.11 m antenna height. The raw multipath signals from the research area were collected using NGS (NavIC/GPS/SBAS) receiver which was developed by Accord Pvt. Ltd. The *in-situ* soil moisture was collected using MPM 160-B soil moisture probe developed by ICT International Pvt. Ltd. as shown in Fig. 3. Total of 20 samples from Fresnel zone were collected, and their average has been considered as *in-situ* soil moisture for that day.

3. METHODOLOGY

3.1. NavIC Signal Preprocessing

The received NavIC multipath signal, which is an interference pattern formed due to the direct and reflected signals, contains high frequency noise and trend of the direct signal. This received raw multipath signal has to go through some preprocessing steps as shown in Fig. 4, which are elevation angle range selection, filtering, and detrending, before the estimation of multipath observables, i.e., multipath amplitude, multipath phase, and multipath frequency. The useful range of elevation angles for soil moisture studies with NavIC-IR technique is 15° to 30° [13, 18]. Therefore, elevation angle range selection is required to obtain the appropriate elevation angle range from the available elevation angle range that is 13.6° to 58°. Filtering is required to remove the high frequency noise from the NavIC

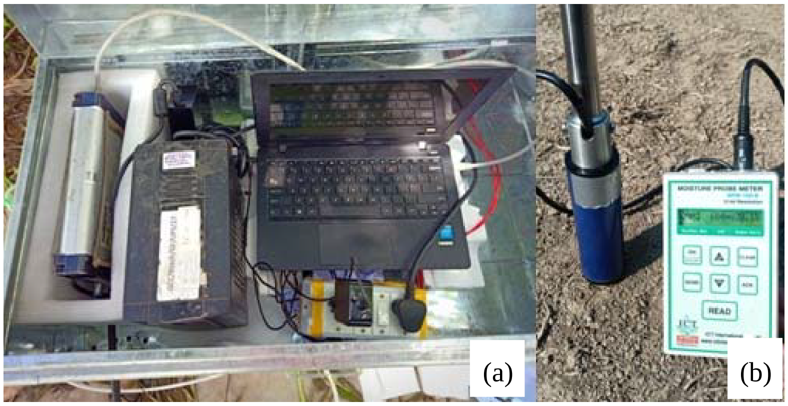

Figure 3. Experimental setup (a) NGS receiver and (b) soil moisture probe.

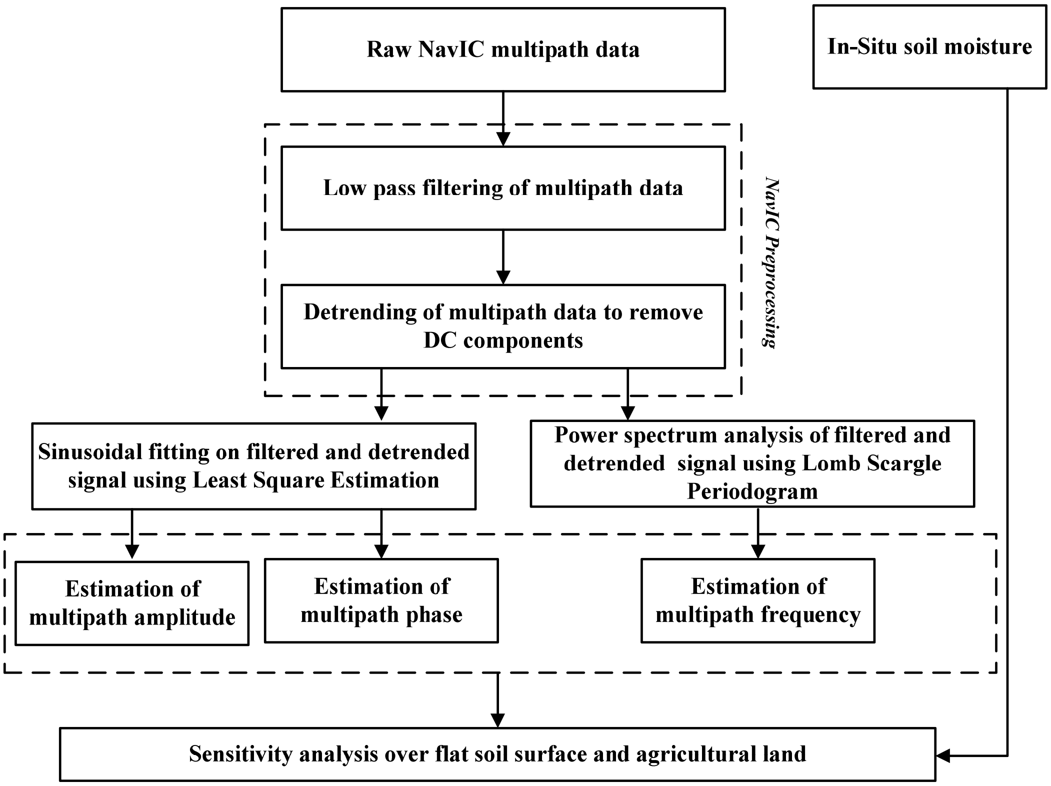

Figure 4. Flowchart for performing the comparative analysis of the NavIC-IR observables for soil moisture investigation.

multipath signal. A Low pass filter has been used to remove the high frequency noise [6, 10]. Further, detrending of signal is required to remove the DC component present in the signal. Therefore, the signal has been detrended to zero level, and this signal is referred as reflected signal [1]. Now the elevation angle range selected, filtered and detrended signal can be used to determine multipath observables.

3.2. Determination of Multipath Observables

The direct and reflected signals oscillate in and out of phase as the satellite signal is traced, resulting in both constructive and destructive interference. This interference pattern of sine wave is affected by the effective height of the antenna above the reflecting surface, frequency of the signal, and the elevation angle (θ). Assuming the horizontal terrain surface, the extra distance (δ) traveled by the signal can be given as [1, 13],

$$\delta = 2h \sin\theta \tag{1}$$

where θ and h are elevation angle and the height of the receiver antenna from the surface, respectively. The path difference between direct and multipath signals results in a phase difference which can be expressed as,

$$\psi = \frac{2\pi}{\lambda} \times \delta = \frac{4\pi h}{\lambda} \sin\theta \tag{2}$$

where λ is the wavelength of incoming satellite signal. Now, the angular frequency (ω) of the multipath signal can be expressed in terms of antenna height (h), rate of epoch (dt), wavelength (λ), and satellite elevation angle (θ) as [1, 8, 15, 16],

$$\omega = \frac{d\psi}{dt} = \frac{4\pi h}{\lambda} \cos\theta \frac{d\theta}{dt} \tag{3}$$

Equation (3) reveals that the multipath angular frequency (ω) will effectively be the function of antenna height (h) because the wavelength of observed GNSS signal (λ) and the range of elevation angle (θ) will be a constant parameter on all observation days. The height of the antenna will depend on the penetration depth of the signal; therefore, its value will depend on moisture content in soil and correspondingly will reflect in multipath frequency. Therefore, in effect, multipath frequency will represent the moisture content in soil. Lomb Scargle Periodogram (LSP) can be utilized to determine the power spectrum of multipath signal which will provide the multipath frequency that will be the function of soil moisture. The working principle of LSP is similar to the Fourier transform. It is used to estimate the power of the frequency spectrums mainly the one with the sinusoidal characteristics. Out of all frequency components the one with maximum power will be considered as the multipath frequency in this study. At high soil moisture, most of the signal gets reflected from the top layer of the soil, whereas at lower moisture values the signal penetrates more deeply. This causes the change in antenna height which reflects in angular frequency. The total change in the antenna height can be understood with two conditions. The effective antenna height will be maximum when the soil surface is completely dried out. Further, the effective height will be minimum in the highest wet condition. The net difference can be understood as the change in the antenna height which is the factor of soil moisture.

Now, if we consider $\sin\theta$ instead of rate of epoch as a variable then the multipath frequency can be written as [2, 16, 17],

$$\omega = \frac{d\psi}{d(\sin\theta)} = \frac{4\pi h}{\lambda} \tag{4}$$

The multipath frequency given by Equation (4) can be considered as constant if we consider the height of antenna from the physical soil surface as it will be a constant value. In this case, the effect of penetration depth will appear in multipath phase of the carrier to noise (C/N_o) signal as expressed by Equation (5).

$$C/N_o = A \cos\left(\frac{4\pi h}{\lambda} \sin\theta + \phi\right) \tag{5}$$

Therefore, elevation angle range selected, filtered and detrended signal is first represented in terms of sine of elevation angle, and then LSE is used to determine the multipath phase and multipath amplitude as per Equation (5) [1, 2, 10, 11, 13, 19].

3.3. Response of Multipath Parameter for Soil Moisture

The performance assessment of multipath observables for soil moisture in the presence of vegetation and different surface roughness conditions has been carried out using different statistical measures namely: Pearson correlation coefficient (R), Root Mean Square error (RMSE), and slope of the observed relationship. R is mostly used for the linear regression analysis to measure the relationship between two variables. The range of R lies between -1 to 1, where both extremes indicate strong relationship.

The relationship between in-situ soil moisture and multipath observables can be demonstrated with R. Further, RMSE is the measure of absolute error between the obtained regression model and observed points [20]. Slope of the fit has been used as the measure of the sensitivity of GNSS observables for soil moisture. Basically, it tells the change in the value of the GNSS parameter for each unit change in VSM.

4. RESULT AND DISCUSSION

Figure 5(a) shows the raw multipath signal, and Fig. 5(b) shows the preprocessed, i.e., filtered and detrended multipath signal. Preprocessed multipath data shown in Fig. 5(b) has been used to determine multipath observables. As explained in methodology section, multipath amplitude and multipath phase have been evaluated by first observing the C/N_o as a function of sine of elevation angle and then applying LSE as shown in Fig. 6(a). The retrieval of multipath frequency has been carried out by applying LSP on preprocessed data as shown in Fig. 6(b). Similar process has also been adopted by other researchers to determine multipath observables for other GNSS systems [2, 6, 10]. These procedures have been applied on all the data sets available from both the fields to determine multipath amplitude, multipath phase, and multipath frequency. Fig. 7 and Fig. 8 show the behavior of multipath observables for *in-situ* measured soil moisture for field-1 and field-2, respectively. A linear trend between NavIC multipath observables and soil moisture can be observed for bare soil condition as well as soil covered with vegetation. As discussed in Section 1 that most of the soil moisture studies with GNSS system have been carried out with GPS constellation and linear behavior of multipath amplitude and multipath phase for soil moisture has been shown by the researchers [3, 7, 9, 11, 16]. However, very few studies have been carried out to determine the sensitivity of multipath frequency for soil moisture [15]. Our study shows a linear relationship between multipath frequency and soil moisture. Studies with GPS constellation

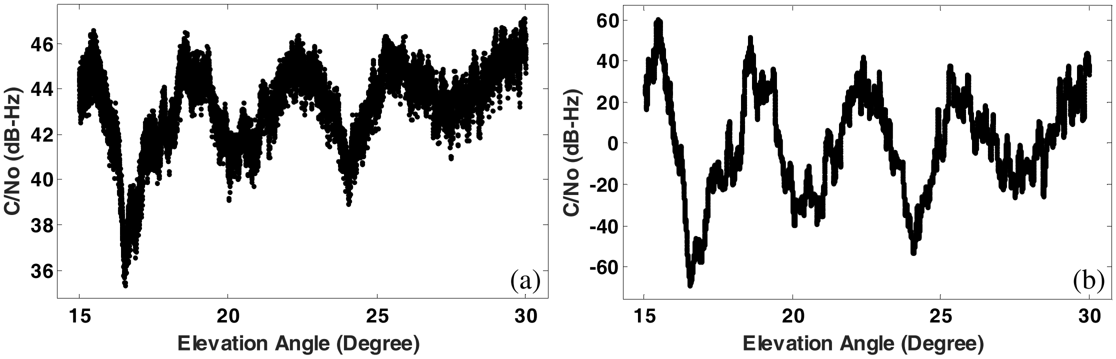

Figure 5. (a) Received NavIC multipath raw data, and (b) detrended and filtered NavIC multipath signal.

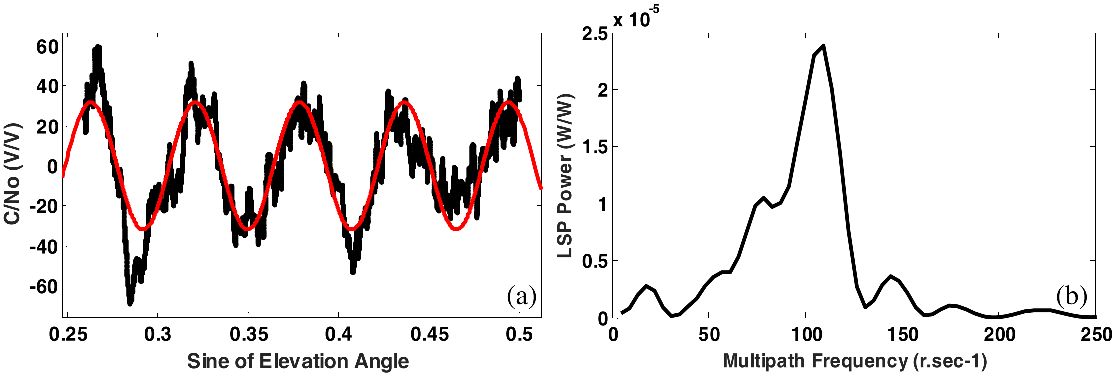

Figure 6. (a) Sine fitted plot using LSE for the estimation of multipath amplitude and multipath phase, (b) power spectrum analysis for the estimation of multipath frequency.

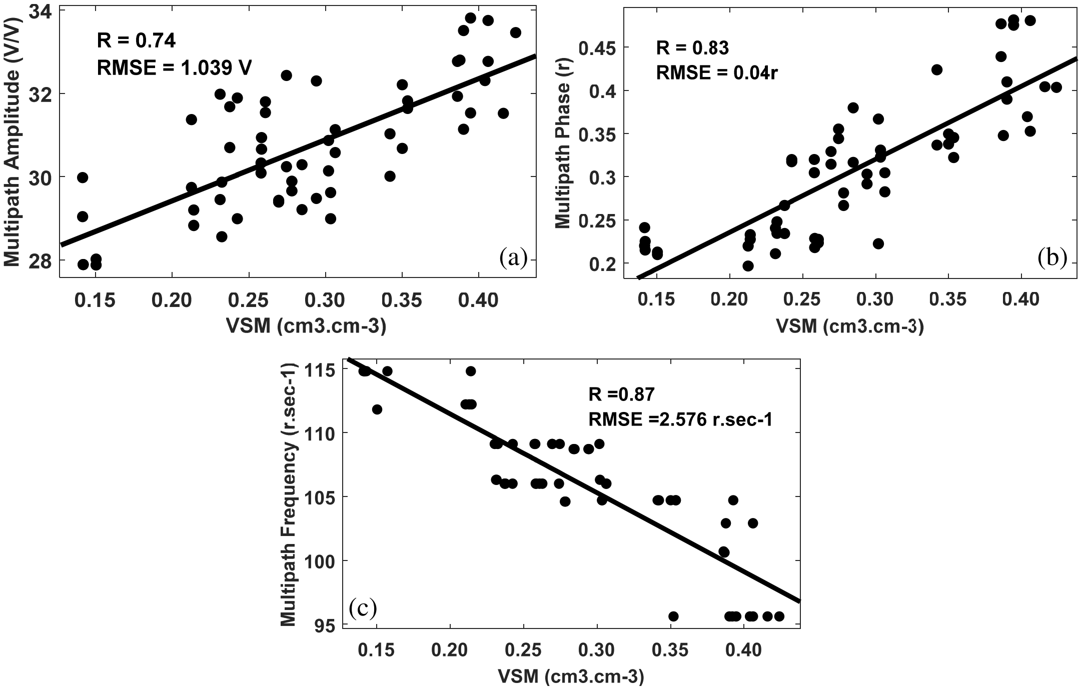

Figure 7. Linear regression performed between (a) multipath amplitude and soil moisture with correlation coefficient of 0.74, (b) multipath phase and soil moisture over with correlation coefficient of 0.83 and (c) multipath frequency and soil moisture with correlation coefficient of 0.87 over flat bare land.

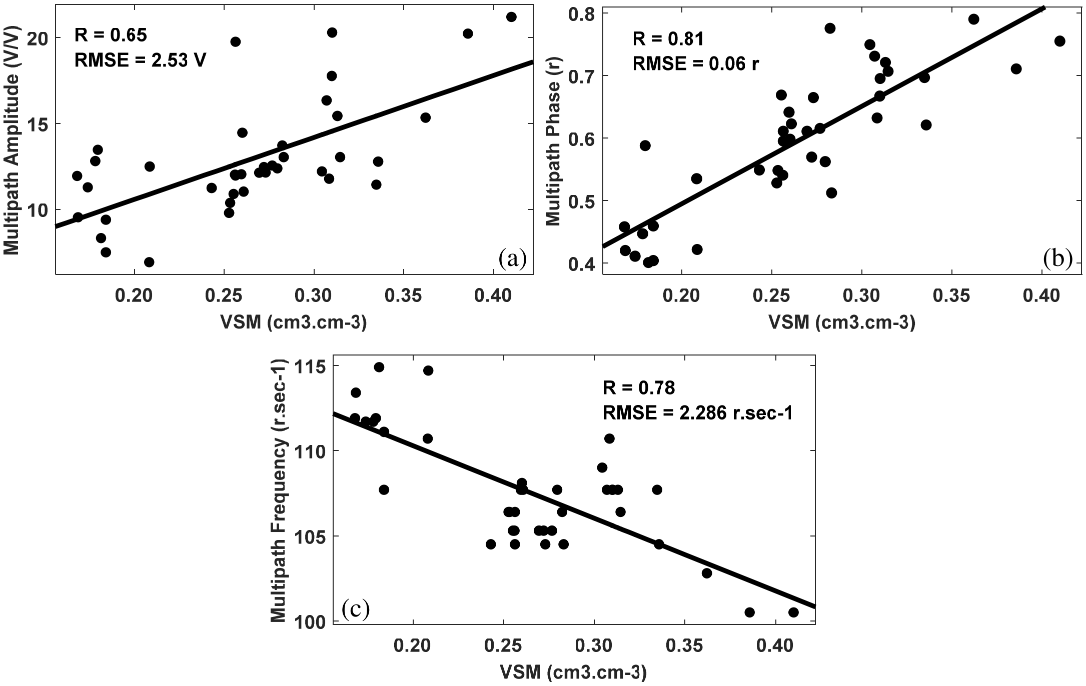

Figure 8. Linear regression performed between (a) multipath amplitude and soil moisture with correlation coefficient of 0.65, (b) multipath phase and soil moisture over with correlation coefficient of 0.81 and (c) multipath frequency and soil moisture with correlation coefficient of 0.78 over agricultural land.

utilize 5° to 30° elevation angles to evaluate multipath observables whereas in the case of NavIC, 15° to 30° elevation angles are utilized because NavIC geosynchronous satellite captures data from 13.8° to 58° elevation angles. The linear trend of NavIC multipath observables for soil moisture which is similar to the GPS multipath observations shows the potential of NavIC multipath data in predicting soil moisture by observing the elevation angles from 15° to 30°. Further, NavIC constellation works at L5 frequency which is lower than the widely utilized L1 frequency of GPS system. The advantage of lower frequency is the higher wavelength which is very much helpful when the objective is to analyze the soil moisture in crop covered field because the higher wavelength will provide better penetration. Therefore, NavIC system may be better utilized than the GPS system in studies of crop covered soil moisture.

The linear relationship between multipath observables and soil moisture depicted in Fig. 7 represents the behavior of multipath observable over bare soil whereas Fig. 8 represents their behavior for vegetation covered soil. The linear relationship between multipath observables and soil moisture for these two different field conditions can be analyzed based on linear regression. The correlation coefficient between multipath observables and soil moisture reveals that multipath phase and multipath frequency are better correlated with soil moisture than the multipath amplitude in both the observed fields. For field-1, the correlation coefficient of soil moisture with multipath amplitude, multipath phase, and multipath frequency is 0.74, 0.83, and 0.87, respectively, whereas in the case of field-2 its value is 0.65, 0.81, and 0.78, respectively. Further, if we compare the correlation coefficients of multipath observables and soil moisture at two different fields, it can be observed from Table 1 that very little change occurs in the case of multipath phase; however, a significant change can be observed for multipath amplitude and multipath frequency. Therefore, it can be inferred that multipath phase is least sensitive parameter if the observations are made at different fields. In this case, field-1 is a bare smooth field whereas field-2 is vegetated agriculture field with Root Mean Square (RMS) surface height 0.79 cm. Observations form Table 1 suggest less change in RMSE value of multipath phase and multipath frequency for field-1 and field-2. On the other hand, significant change in RMSE values can be observed in the case of multipath amplitude. The observation based on correlation coefficient and RMSE suggests that multipath phase provides consistent value in comparison to multipath amplitude and multipath frequency. The behavior of multipath amplitude is highly variable. The multipath amplitude varies from 27.88 V/V to 33.81 V/V in the case of bare smooth soil whereas its value significantly decreases and varies from 6.91 V/V to 21.21 V/V in the case of agricultural land with rough and vegetated surface. However, in the case of multipath phase and multipath frequency the ranges of values are approximately similar for field-1 and field-2.

The decrease in multipath amplitude of multipath signal in the presence of roughness and vegetation is the effect of surface and volume scattering. In the case of bare smooth soil, most of the signal reflecting from the soil surface reaches the receiver antenna whereas when the surface is rough, or there is vegetation, due to scattering a significant amount of signal is scattered in different directions, and less amount of signal is received by the receiver antenna. This decrease in multipath amplitude has been utilized as a measure of vegetation density by some of the researchers [2, 3, 10, 17]. In the case of multipath phase and multipath frequency, the phenomenon is related to the penetration depth of the signal; therefore, scattering has minimal effect on these parameters.

The performance of multipath phase is better than multipath frequency. In the case of multipath frequency, high frequency noise is associated with low multipath frequency, and it is difficult to determine this low frequency component. However, some other techniques such as wavelet can be adopted to separate low frequency component from high frequency component for better retrieval of multipath frequency. If we observe Fig. 7(c) and Fig. 8(c) a kind of saturation can be observed in multipath frequency with respect to soil moisture. Further, if we look for theoretical aspect of multipath frequency in the presence of vegetation, different peaks of reflected signal from top of the vegetation and soil surface can be obtained. However, due to the association of high frequency noise, the correlation of multipath frequency with soil moisture decreases significantly for rough vegetated soil. The sensitivity of multipath observables for soil moisture as provided in Table 1 reveals that the sensitivity of multipath amplitude, multipath phase, and multipath frequency decreases from field-1 to field-2. Finally, we may say that all the considered statistical parameters perform well in the case of multipath phase; however, their performance is also satisfactory in the case of multipath amplitude and multiple frequency. Therefore, all these observations can be used in one or other way in the retrieval of soil moisture for bare and vegetated fields.

Another important parameter that affects the multipath observables is the soil surface roughness. This study considers two fields with different surface roughness. Field-1 is a bare smooth filed (Fig. 1(a)); therefore, no roughness measurements were carried out in this field. However, field-2 is an agriculture field with surface roughness. Therefore, the surface roughness measurements were carried out throughout observation period, and the average value of RMS surface height has been reported in the paper (i.e., 0.79 cm). There was no activity to change the surface roughness in the agriculture field except the rain, and it was observed that the change in roughness during the observation period was very little; therefore in this study, we have considered the constant surface roughness for respective fields. The large decrease in multipath amplitude can also be attributed to the surface roughness along with the presence of vegetation. The smooth surface provides specular scattering whereas rough surface provides diffuse scattering; therefore, the antenna placed in specular direction will receive less amount of power in the case of rough surface. Multipath phase and multipath frequency observables are dependent on penetration depth of the signal; therefore, these observables are less affected by surface roughness. It can be observed form Table 1 that multipath phase is the least affected parameter when the observations are made at different fields. However, correlation coefficient of multipath frequency varies significantly from field-1 to field-2, but less change can be observed in RMSE values. To determine the effect of surface roughness on multipath observables, a comprehensive experimental work should be carried out by changing the roughness of field artificially for bare soil as well as crop covered field.

Table 1. Obtained goodness of fit between multipath signal parameters and soil moisture for both land covers.

Parameter Goodness of Fit		Multipath Amplitude	Multipath Phase	Multipath Frequency
1st Land Cover (Flat bare land cover)	RMSE	$1.039\,\mathrm{V/V}$	$0.04\,\mathrm{r}$	$2.576\,\mathrm{r{\cdot}sec^{-1}}$
	R	0.74	0.83	0.87
	Slope	$14.7\,\mathrm{v/cm^3{\cdot}cm^{-3}}$	$0.84\,\mathrm{r/cm^3{\cdot}cm^{-3}}$	$-61.7\,\mathrm{r{\cdot}sec^{-1}/cm^{-3}{\cdot}cm^3}$
2nd Land Cover (Agricultural Land)	RMSE	$2.53\,\mathrm{V/V}$	$0.06\,\mathrm{r}$	$2.286\,\mathrm{r{\cdot}sec^{-1}}$
	R	0.65	0.81	0.78
	Slope	$36.1\,\mathrm{v/cm^3{\cdot}cm^{-3}}$	$1.55\,\mathrm{r/cm^3{\cdot}cm^{-3}}$	$-32.8\,\mathrm{r{\cdot}sec^{-1}/cm^{-3}{\cdot}cm^3}$

5. CONCLUSION

This study shows significant correlation between multipath observables and soil moisture under different surface roughness and vegetation conditions. However, high correlation was observed for bare smooth soil, and its value decreases due to the presence of surface roughness and vegetation. Multipath phase shows the least effect whereas correlation coefficient of multipath amplitude and multipath frequency decreases significantly. Still the correlation coefficient value is sufficiently high, i.e., 0.65 and 0.78 for multipath amplitude and multiple frequency, and it can be considered as good correlation for observing the soil moisture for rough and vegetation covered soil surface. Further, good sensitivity has been observed for all the multipath observables for the change in soil moisture. Similar studies can also be carried out with GPS and Galileo which include the same frequency band, L5 and E5a, respectively. Further, not limited to GPS L5 and Galileo E5a, the results can also be explored for other L-band signals of GPS, GLONASS, Galileo, and BeiDou.

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