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Analysis of the Impact of Seasonal Variations on the Vertical Accuracy of Sentinel-1 DEM in Federal University of Technology, Akure (FUTA) Main Campus

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ABSTRACT

Digital Elevation Models (DEMs) derived from Sentinel-1 Synthetic Aperture Radar (SAR) data are widely used for terrain analysis, environmental monitoring, and disaster management; however, their accuracy is influenced by seasonal and environmental conditions. This study investigates the impact of seasonal variation on the vertical accuracy of Sentinel-1 DEM over the Federal University of Technology, Akure (FUTA) main campus to determine the most suitable season for reliable elevation modelling. Sentinel-1 SAR datasets representing wet and dry seasons were obtained from the Copernicus platform, while meteorological data were sourced from the European Centre for Medium-Range Weather Forecasts (ECMWF). A total of 256 Ground Control Points (GCPs) collected through GNSS surveys were used as reference data for validating the DEMs. Seasonal analysis considered January, July, and October as representative months of the hydrological cycle. October recorded the highest average temperature (25.40 °C) and precipitation (223.561 mm), July exhibited the highest relative humidity (88.29%), while January showed the lowest values across temperature (23.56 °C), precipitation (1.606 mm), and humidity (71.78%), reflecting dry-season conditions. Correlation analysis between DEM error and climatic variables showed weak relationships ($|r| < 0.13$), indicating no strong linear dependence. Accuracy assessment revealed that the dry-season DEM performed best, with the lowest Root Mean Square Error (RMSE = 2.711 m) and Mean Absolute Error (MAE = 0.583 m), compared with higher RMSE values of 2.842 m (October) and 2.878 m (July). The study concludes that seasonality significantly affects Sentinel-1 DEM accuracy, with dry-season data providing more reliable elevation estimates due to reduced moisture, vegetation density, and atmospheric interference.

Keywords: Digital Elevation Models (DEMs); GNSS; Seasonal Variations; Sentinel-1 Synthetic Aperture Radar (SAR); Vertical Accuracy

1.0. Introduction

Digital Elevation Models (DEMs) serve as foundational data layers for geospatial applications, providing information about the Earth's surface elevation at various spatial scales (Purinton and Bookhagen, 2017). Traditional methods for DEM generation, such as LiDAR (Light Detection and Ranging), can be costly and limited by factors such as weather conditions and vegetation cover (Chai, 2022). In recent years, Synthetic Aperture Radar (SAR) data, particularly from satellites like Sentinel-1, has emerged as a viable alternative for DEM creation due to its all-weather imaging capabilities, frequent revisit times, and global coverage (Ayub, 2018).Accurate representation of terrain is key for a wide range of geospatial applications, spanning from urban planning and infrastructure development to natural hazard assessment and environmental monitoring (Elsonbaty *et al.,* 2023; Azim, 2020).

The Sentinel-1 mission, operated by the European Space Agency (ESA), comprises a constellation of twin radar satellites equipped with C-band SAR sensors (Borlaf-Mena *et al.,* 2020). These satellites acquire high-resolution SAR data with a revisit time of up to six days, making them suitable for monitoring dynamic environmental processes and terrain changes (Ayub, 2018). SAR interferometry (InSAR) techniques leverage the phase difference between SAR images acquired from slightly different viewing angles to generate DEMs with vertical accuracy comparable to traditional methods (Polat *et al.,* 2020).

However, despite the advantages of SAR-based DEMs, their accuracy can be affected by various factors, including terrain characteristics, acquisition parameters, and environmental conditions (Ghannadi *et al.,* 2020). One significant factor influencing DEM accuracy is seasonal variations in environmental and climatic parameters such as vegetation dynamics, soil moisture content, temperature, humidity and surface roughness (Dabboor *et al.,* 2019). For instance, vegetation growth and phenology can introduce temporal changes in radar backscatter, leading to variations in the penetration of SAR signals into the vegetation canopy and affecting the accuracy of elevation estimation. Similarly, variations in soil moisture can alter the dielectric properties of the Earth's surface, impacting SAR signal propagation and the resulting DEM accuracy.

The accuracy of SAR-based DEMs (which are seasonal in nature) are affected by environmental and climatic factor. Existing literature (Braun, 2021; Ayub 2018; Ayub 2020) predominantly focuses on the technical aspects of SAR data processing and DEM generation algorithms, often overlooking or inadequately addressing the temporal variability introduced by seasonal changes in environmental conditions. While it is widely acknowledged that climatic factors such as vegetation growth, soil moisture content, and snow cover can impact SAR signal characteristics and, consequently, DEM accuracy, there is a lack of comprehensive studies systematically analyzing the effects of seasonal variations on Sentinel-1 DEMs. Understanding how seasonal variations impact the vertical accuracy of Sentinel-1 DEMs provides crucial insights for improving the precision and reliability of elevation data in dynamic tropical environments like the Federal University of Technology Akure (FUTA) campus area.

The aim of this research is to analyze the impact of seasonal variations on the vertical accuracy of Sentinel-1 DEM in FUTA Campus with a view to ascertain the most suitable season and to also identify the climatic factors that impact accuracy of DEM along with their effect, observe the variation in the climatic factors identified and evaluate the vertical accuracy of DEM derived from sentinel satellite mission at various seasons of the year over the study area.

2.0 Methodology

2.1 The Study Area

The study area is the Federal University of Technology, Akure campus which is situated on the northwestern flank of Akure, and it occupies an area of about 5km^2 (Adekunle, 2017). It is geographically referenced on coordinate lines of latitude 7° 17' 42.617" N to 7° 18' 55.15" N and longitude 5° 07' 01.57" E to 5° 08' 30.486" E of the WGS84 Zone 31N coordinate system on the Eastern flank of meridians (Olaoluwa & Samuel, 2018). The University is one of the Federal Universities of Technology established by the Federal Government of Nigeria in 1981 in a quest for technological development. The elevation range is between 356m to 395m.

Climatically, FUTA falls under humid tropical climate of the West African Monsoonal type with distinct wet and dry seasons. Annual rainfall reaches mean value of about 1350mm coupled with high temperatures reaching a peak of about 32°C around February and a threshold of about 21°C around August (Balogun, & Ishola, 2017). Relative humidity ranges from about 70% to 90% (January to July). Vegetation in the study area is however of regrowth rainforest type with evident spread of grasses and scattered trees, however, most areas have been modified with human activities such as civil engineering structures such as buildings, roads and land cultivation needed for the growth of the varsity. The study area is a fast-growing Federal University of Technology which at present had only built up 45% of her land area.

The topography is undulating with the presence of depressions at the Southern part and fairly level plain at the Northern part of the study area. The study area is well-drained and the streams draining the area flow southward. Most of the stream channels shows a meandering pattern while some flow in a straight pattern of about 300m which can be suggested as fracture-controlled drainage system (Balogun *et al.,* 2023).

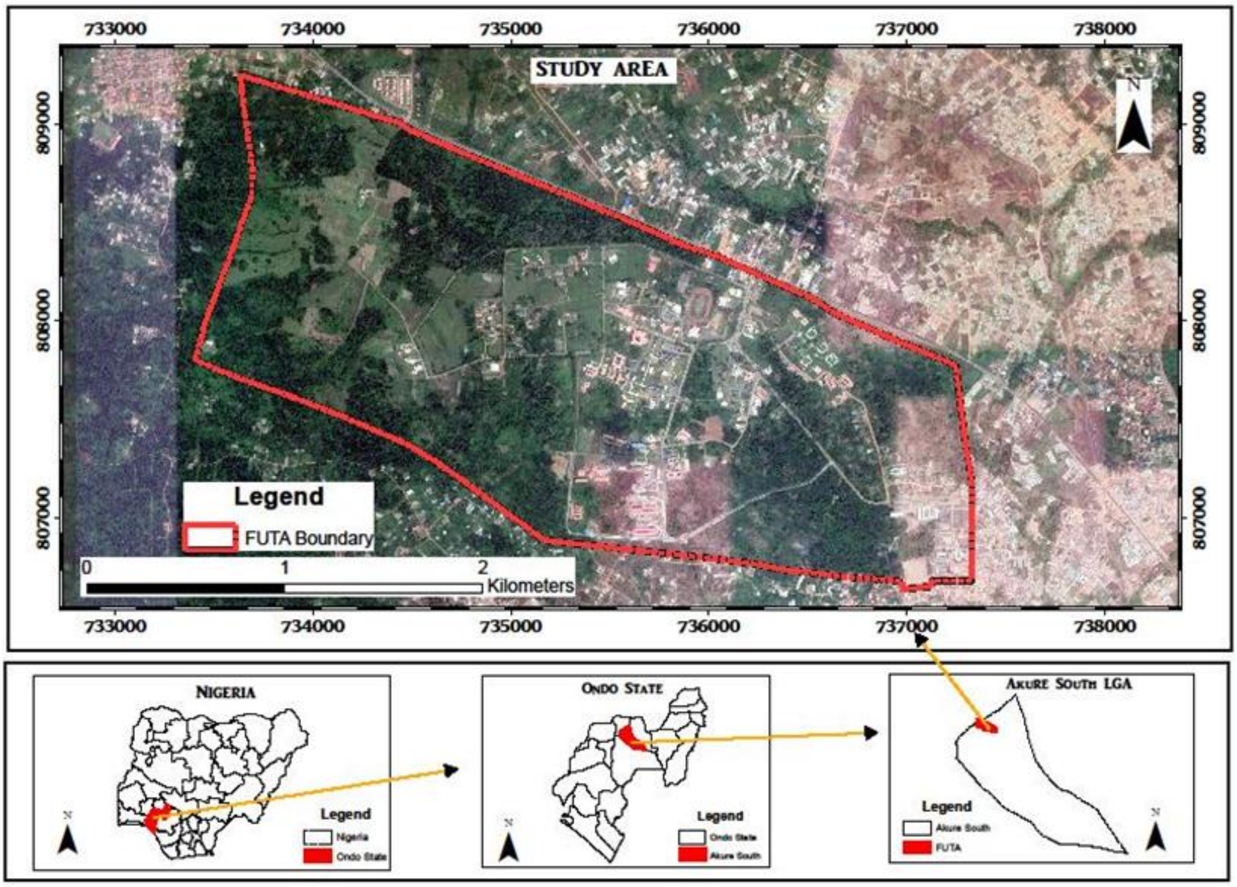

Figure 1: Map showing the study area. Source: Tata and Raufu, 2018.

2.2. Materials

In this research, Sentinel-1 SAR data covering multiple seasons over the study area was gathered from Copernicus website. Meteorological data (precipitation, temperature and relative humidity) was obtained from European Centre for Medium-Range Weather Forecasts (ECMWF) website to correlate climatic conditions with DEM accuracy. Table 1 shows the summary of materials used in this work.

Global Navigation Satellite System (GNSS) surveys were done using Tersus David differential GNSS to obtain the coordinates of 256 controls in the study area which were used to validate the accuracy of the Sentinel-1 DEMs. The control station used in this research for GPS observation were selected at the study area. The coordinates of the control station and the existing rover stations used were collected from the Department of Surveying and Geoinformatics, FUTA and presented in Table 2.

The existing controls were checked for their stability before extending controls from it thereafter, framework was created for the job. The instruments used in acquiring the data in this research were tested and ensured to be in good order so as to give an accurate result. GNSS receiver tests was done to the differential GPS. Comparison was made between the known coordinates of the control points and the processed coordinates to check for difference in these coordinates.

Table 1: Data, Source, Resolution, their application in the study

S/N	Datasets	Data Description	Source	Resolution (m) / Scale	Period of Data Collection (Primary/Secondary)	Application in the study
1	Control Point Coordinate	Easting, Northing and Height Minna Datum WGS 84 / Zone 31N	Department of Surveying and Geoinformatics, FUTA	N/A	2024	Reference point for GPS observation
2	GNSS observation.	Easting, Northing and Height of 256 points Minna Datum WGS 84 / Zone 31N	Field Survey Tersus David GPS (Dual Frequency)	N/A	2024	To validate the accuracy of the Sentinel-1 DEMs
3	Sentinel-1 SAR data (IW SLC format)		Copernicus website http://dataspace.copernicus.eu	3m x 3m	15th/27th July, 7th/19th October, 17th/29th January 2024	For extraction of DEM.
4	Meteorological data	Temperature, Precipitation and relative humidity data	European Centre for Medium-Range Weather Forecasts (ECMWF) website http://www.ecmwf.int	N/A	July, October, January 2024	To correlate climatic conditions with DEM accuracy

Table 2: Control Points Coordinates

Std. ID	Northing	Easting	Height
G1303	807177.166	735839.050	375.108
G1306	807944.115	735547.970	375.881
G1307	807850.546	735783.830	385.379

Source: Department of Surveying and Geoinformatics, FUTA

2.3 Methods

Sentinel-1 SAR Data was acquired from Copernicus for January (Dry season), July (Wet season) and October (Wet season) 2024. Meteorological data (e.g., precipitation, temperature and relative humidity) was obtained from European Centre for Medium-Range Weather Forecasts (ECMWF) website to correlate climatic conditions with DEM accuracy. Meteorological data was analyzed to observe seasonal variations in climatic factors such as precipitation, temperature, and humidity over the study area. A temporal analysis was conducted to examine the seasonal dynamics of climatic factors over the study period. Sentinel-1 SAR data acquired during different seasons was processed using interferometric SAR (InSAR) techniques to generate DEMs with high spatial resolution. Ground control points (GCPs) were collected using Global Navigation Satellite System (GNSS) surveys to validate the accuracy of the Sentinel-1 DEMs. The metadata of the Sentinel-1 data used in this study is presented in Table 3.

Table 3: Metadata of Sentinel-1 SAR Data

S/n	Mission	Sentinel-1A
1.	Acquisition Mode	Interferometric Wide Swath (IW)
2.	Polarization	VV + VH
3.	Resolution	3m x 3m (Single Look Complex)
4.	Orbit Direction	Ascending/Descending
5.	Revisit Time	12 days
6.	Processing Level	Level-1 Single Look Complex (SLC)
7.	Projection	WGS 84 / UTM Zone 31N
8	Elevation Reference	Ellipsoidal

The acquired SAR data undergo some pre-processing steps to correct for geometric distortions, radiometric calibration, and terrain-induced effects to ensure accurate elevation extraction. This preprocessing operation was done using Sentinel Application Platform (SNAP) software. SNAP is an open-source software developed by ESA for processing and analyzing SAR data. The Sentinel-1 Single Look Complex (SLC) data was acquired which contains both amplitude and phase information required for interferometry. The final DEM was exported in a standard GIS-compatible format. The Sentinel-1 SAR data was used to generate DEM which gives the topographic information of the study area. However, since the Sentinel-1 DEM referenced to the ellipsoidal surface, while the GNSS elevation data used for validation is orthometric (based on EGM96), there was need to comute orthometric heights H for the Sentinel-1 DEM using Equation 1.

$$H = h - N \qquad 1$$

Where h is the ellipsoidal height N is the geoidal height derived from EGM96 geoid.

Correlation analysis was performed to calculate correlation coefficients between climatic factors and DEM accuracy metrics. Pearson product Moment correlation coefficient method in Equation 2 was used to compute the correlation coefficients between climatic factors and DEM accuracy. This analysis helps to identify any linear relationships between the extracted Sentinel-1 DEM and climatic factors obtained at different seasons of the year. Positive or negative correlations indicate the strength and direction of the relationship.

$$\boldsymbol{r} = \frac{\sum_{i=1}^{n}(x_i-\bar{X})(y_i-\bar{Y})}{n \; S_x S_y} \qquad 2$$

$x_i = \text{extracted Sentinel} - 1 \text{ DEM}$
$y_i = Climatic\ factors\ like\ temperature, precipitation\ and\ humidity$
$\bar{X} = mean\ of\ x$
$\bar{Y} = mean\ of\ x$
$S_x = Standard\ deviations\ of\ x$
$S_y = Standard\ deviations\ of\ y$
$r = \text{Pearson's Product} - \text{Moment Correlation Coefficient}$
$S_x$and S_y are calculated as follows:

$$\boldsymbol{S_x} = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{X})^2}{N}} \qquad 3$$

$$\boldsymbol{S_y} = \sqrt{\frac{\sum_{i=1}^{n}(y_i-\bar{Y})^2}{N}} \qquad 4$$

N = number of observations

Statistical analyses, including Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Normalized Median Absolute Deviation (NMAD), were computed using Equations 5 - 7 respectively in order to quantify the vertical accuracy of the DEMs and the accuracy of DEMs obtained during different seasons was compared to evaluate seasonal variations in DEM performance. The accuracy of DEMs generated during different seasons was compared in order to evaluate seasonal variations in DEM performance.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - x_i)}{n}} \quad 5$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}(y_i - x_i) \quad 6$$

$$\text{NMAD} = 1.4826 \times \text{median}(|\text{error} - \text{median}(\text{error})|) \quad 7$$

Where

y_i = DEM-derived elevations

x_i = Observed elevations.

$\bar{x}$= Mean of Observed elevations

n = Number of observations

3.0. Results and Discussions

The result of this study provides information on the impact of seasonal variations on the vertical accuracy of Sentinel-1 DEM in FUTA Campus with a view to ascertain the most suitable season for acquiring the Sentinel DEM. The findings from this study is in line with discoveries from (Wen et al., 2024; Zumo, & Hashim 2020). Among the month considered in this study, October has the highest average temperature of 25.40ºC with January having the least average temperature of 23.56 ºC. October has the highest average monthly precipitation of 223.561mm among the month considered in this study, while January has the least average monthly precipitation of 1.606 mm. July has the highest relative humidity of 88.29%, which dropped to 85.36% in October and January has a least relative humidity of 71.78%.

Figure 2 shows the DEM map for the month of July. The elevation ranges between 427.136m and 370.694m. June falls within the wet season, which means the area likely experiences higher rainfall, increased water flow in rivers, and potential flooding or erosion. Lower elevations might show signs of sediment deposition or erosion due to increased water flow. Areas with lower elevations (closer to 370.694m) might be more prone to flooding during the wet season. Temporary water bodies (e.g., ponds or wetlands) might form in low-lying areas, which could slightly alter the elevation readings. The high elevation (427.136m) likely represents stable, elevated terrain that is less affected by seasonal changes.

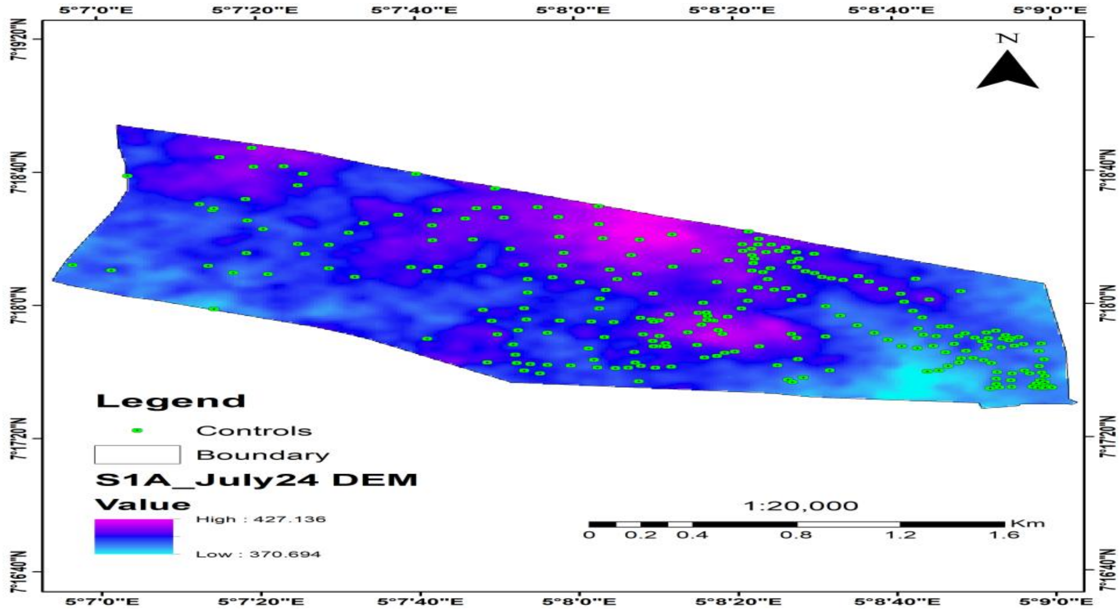

Figure 2: DEM Map of the Study Area for July

Figure 3 shows the DEM map for the month of January. The elevation ranges between 425.233m and 372.369m.The elevation data in January is consistent with the dry season, showing little variation from

January's data. The high elevation of 425.233m and low elevation of 372.369m values are close to those in January, indicating that the topography remains relatively unchanged during the dry season.

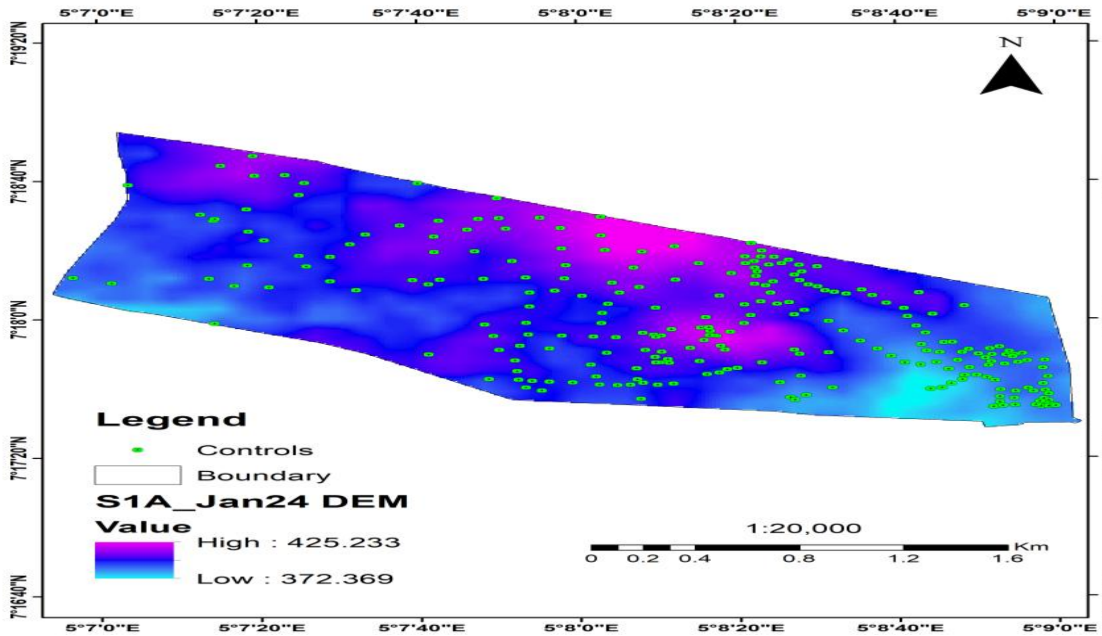

Figure 3: DEM Map of the Study Area for January

Figure 4 shows the DEM map for the month of October. The elevation ranges between 427.315m and 370.437m.The elevation data in October likely represents the "baseline" topography of the area, with minimal influence from water flow or erosion. The high elevation of 427.315m and low elevation of 370.437m values are relatively stable, reflecting the natural terrain without the effects of heavy rainfall.

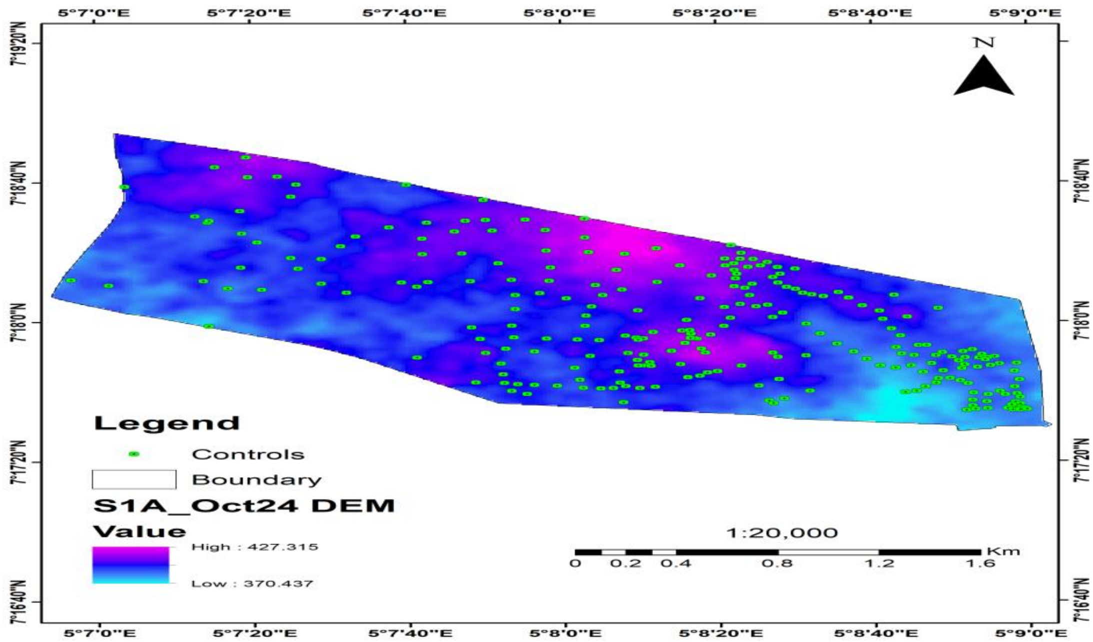

Figure 4: DEM map of the study area for October

The elevation ranges in July and October are close to each other while the elevation ranges is in the month of January is slightly far from July and October. This could be due to the July and October being a wet season and January a dry season.

Figure 5 shows the comparison of GPS-measured heights and Digital Elevation Models (DEMs) derived from Sentinel-1 data for three different months (January, October, and July) across a number of stations or observation points. The graph shows that GPS Heights are consistently lower than the DEM values (for most of the locations), suggesting that sentinel-1 derived DEMs are reference on the ellipsoidal datum, while the GPS are on the geoid (EGM 96). However, for the purpose of computing the DEM evaluation metrics, the Sentinel DEM were trsformed using Equation 1 earlier stated. The July DEM (wet season) shows the highest elevation estimates overall. This is likely due to increased vegetation density and moisture in July, leading to more radar backscatter from higher surfaces (tree tops, wet leaves).The January DEM (dry season) shows slightly lower values compared to July and October, indicating less interference from vegetation. October DEM values lie between July and January in most locations.

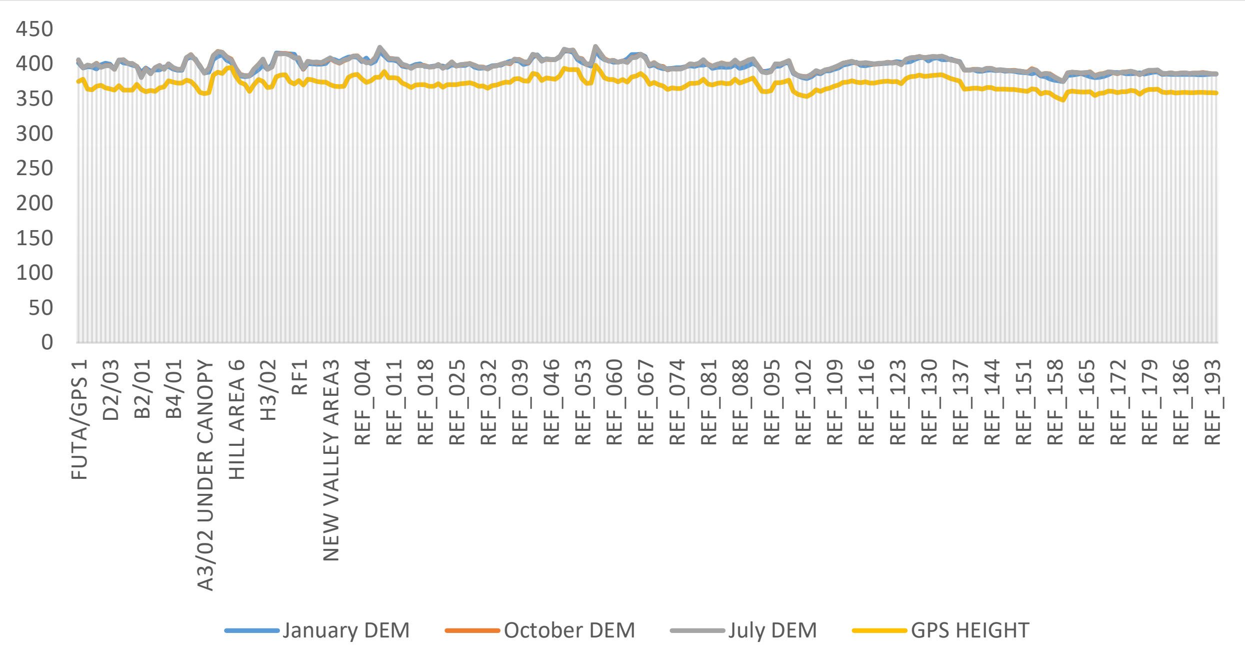

Figure 5: Comparison of GPS Height and Derived Sentinel -1 DEM

Table 4 presents the accuracy assessment metrics (RMSE, MAE, and NMAD) of the Sentinel-1 DEM across dry and wet seasonal conditions. The results indicate a clear seasonal influence on DEM accuracy in the study area. The dry season (January) shows the best performance, with the lowest RMSE (2.711 m), MAE (0.583 m), and NMAD (1.272 m). These low error values correspond with minimal precipitation, moderate temperature, and lower relative humidity, conditions that favor stable radar backscatter and improved interferometric coherence. This indicates that elevation estimates during the dry season may be reliable in and around the study area.

In contrast, the wet season months (October and July) exhibit higher error magnitudes. October records increased RMSE (2.842 m), MAE (4.030 m), and NMAD (4.027 m), while July shows the highest errors, particularly MAE (4.885 m) and NMAD (5.371 m). These months are characterized by high precipitation and relative humidity, which are known to degrade radar signal coherence due to surface moisture, vegetation growth, and atmospheric effects.

The progressive increase in MAE and NMAD from October to July suggests that peak wet-season conditions exert a stronger negative impact on Sentinel-1 DEM accuracy than transitional wet periods. These findings indicates that Sentinel-1 DEM accuracy is season-dependent, with dry-season acquisitions providing more accurate elevation estimates than wet-season data.

Table 4: Accuracy assessment metrics of the seasonality on Sentinel-1 DEM

RMSE (m)	MAE (m)	NMAD (m)	Months/ Season	Average monthly Temperature (^{0}C)	Average monthly Precipitation (mm)	Average monthly Relative Humidity(%)
2.711	0.583	1.272	January (Dry)	23.56	1.606	71.78
2.842	4.030	4.027	October (Wet)	25.40	220.586	85.36
2.878	4.885	5.371	July (Wet)	24.69	223.561	88.29

Table 5 presents the Pearson correlation coefficients between climatic variables (temperature, precipitation and relative humidity) values and the DEM accuracy. All correlation coefficients are close to 0, ranging from about -0.098 to 0.124, which indicates that there is no strong or meaningful linear relationship between DEM error and any of the individual climatic variables within each month. Any observed variation in DEM accuracy within a single month is likely not directly explained by temperature, precipitation, or relative humidity alone. Precipitation in October shows the highest correlation (r = 0.124), which still represents a very weak positive correlation. This could suggest a slight increase in DEM error with increased precipitation in October perhaps due to vegetation or surface wetness, but the relationship is still too weak to be reliable. Relative Humidity shows slightly negative correlations in January and October, suggesting that as Relative Humidity, DEM error may slightly decrease, but again, this trend is negligible.

Table 5: Correlation Analysis between Climatic Variables and DEM accuracy

	Correlation coefficient (r)		
Months	Temperature	Precipitation	Relative Humidity
January	0.027013379	0.08926678	-0.081707231
October	-0.06972995	0.12428061	-0.059836434
July	-0.06710775	-0.09764716	-0.001533526

4.0 Conclusion

This study examined the influence of seasonal variations on the vertical accuracy of Sentinel-1 derived Digital Elevation Models (DEMs) over the FUTA Campus, with the objective of identifying the most suitable season for DEM acquisition. The findings demonstrate that Sentinel-1 DEM accuracy is clearly season-dependent, largely influenced by prevailing surface and atmospheric conditions associated with wet and dry seasons. Elevation comparisons across July, October, and January show that while the overall terrain structure remains stable, wet-season conditions introduce subtle elevation variations attributable to increased moisture, vegetation density, and surface water presence.

The dry season (January) consistently produced the highest DEM accuracy, as reflected by the lowest RMSE, MAE, and NMAD values. These results indicate improved interferometric coherence under conditions of low precipitation, reduced vegetation interference, and moderate atmospheric stability. In contrast, wet-season months (October and especially July) exhibited higher error magnitudes, with July showing the poorest performance. Peak wet-season conditions appear to amplify radar signal decorrelation due to surface wetness, dense vegetation, and atmospheric effects, leading to reduced DEM reliability.

Although correlation analysis revealed no strong linear relationship between individual climatic variables and DEM error within each month, the cumulative influence of wet-season conditions is evident in the overall degradation of DEM accuracy. This suggests that DEM error is better explained by combined seasonal surface dynamics rather than by single climatic parameters alone.

In conclusion, dry-season Sentinel-1 acquisitions are most suitable for reliable elevation modelling in the study area. These findings align with previous studies and provide practical guidance for researchers and practitioners using Sentinel-1 DEMs for terrain analysis, hydrological modelling, and geospatial applications in tropical environments.

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