RADFXSAT (FOX-1B) CubeSat Tracking and Link Budget Analysis

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1. Introduction

The RADFXSAT (FOX-1B) CubeSat will be observed and analyzed from December 10 to December 24, 2022, to study its orbital characteristics, visibility periods, and the effectiveness of the communication link with ground stations. The primary aim of this research is to evaluate the downlink performance to ensure a reliable connection between the satellite and the receiving station on Earth.

This study focuses on precise calculations of orbits, predictions of visibility, and analysis of link budgets, using simulations with the Skyfield module to identify important orbital parameters. The analysis also looks at Doppler shifts, which lead to changes in frequency because of the satellite's movement relative to the observer, and evaluates elevation angles that affect how high the satellite seems from the observer's viewpoint. Furthermore, the effectiveness of the ground station antenna in receiving signals is examined to guarantee optimal communication.

The RADFXSAT (FOX-1B) CubeSat will be continually followed in orbit during the project, enabling a thorough assessment of its real-time communication capability. The analysis's conclusions will advance knowledge of the satellite's behaviour and dependability in communicating with the ground station.

2. Orbit Calculation and Satellite Tracking

2.1 Two-Line Element (TLE) Data for RADFXSAT (FOX-1B)

To accurately track the satellite, the latest TLE parameters were extracted:

```
1. 43017U 17073F 23313.35485710 .00001552 00000+0 10234-3 0 9995

2. 43017 97.6646 47.6582 0226447 98.2282 263.6763 14.85276338329245
```

Ground Station: At 2022-12-10T00:00:00Z**,** the location was Latitude: 45.67, Longitude: -123.45, and at 2022-12-10T00:01:00Z**,** it was Latitude: 46.01, Longitude: -122.88**.** First, we identify the time intervals when the satellite is visible, as detailed in the next section.

2.2 Satellite Passes over Bremen

The visibility of the satellite above **30° elevation** was determined using orbital simulations. Key sighting times:

Sightings in Bremen:

2024-11-17T11:29:00Z rise above 30°

2024-11-17T11:31:30+00:00 culminate

2024-11-17T11:34:00Z set below 30°

2024-11-17T22:28:00Z rise above 30°

2024-11-17T22:30:00+00:00 culminate

2.3 Ground Track Analysis

Plotting the latitude and longitude coordinates for the satellite onto a world map every minute of the day shows its path. Figure 1 shows wide geographic trajectory for December 10. We used Cartopy to plot the satellite extent changes in terms of latitude and longitude over time, revealing the path across the globe.

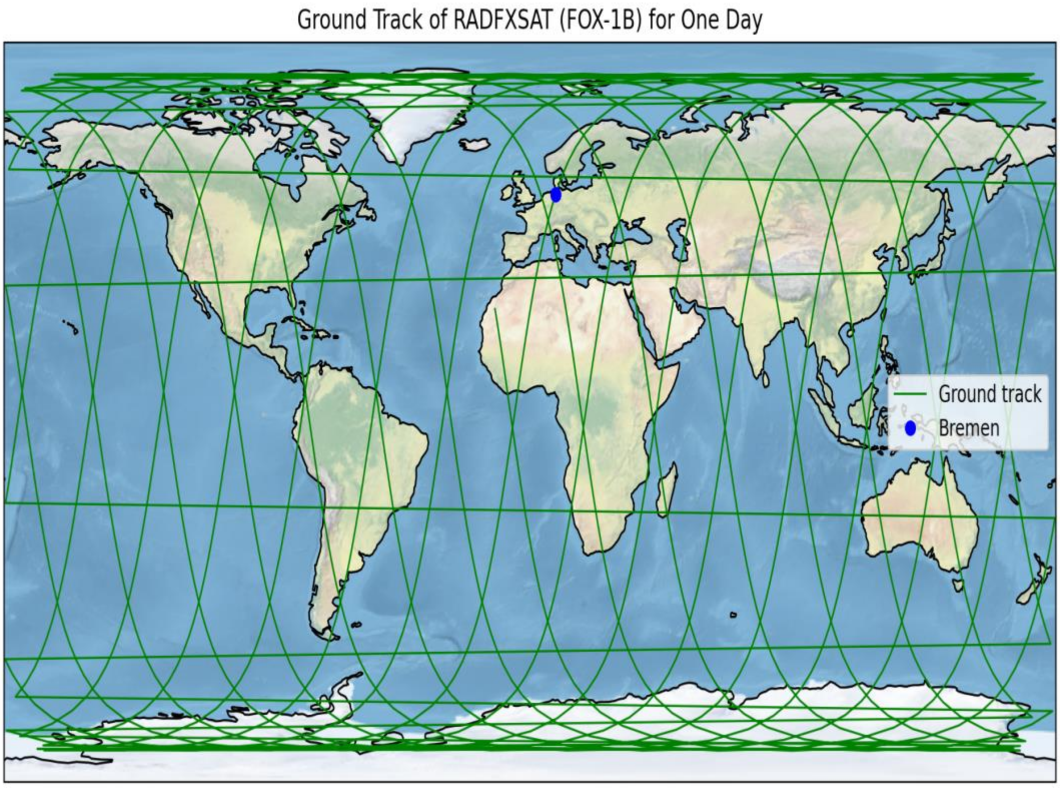

Figure 1: Ground Tracking for one day

Figure 2 illustrates the time when the satellite is visible and within communication range from the Bremen, Germany, ground station by displaying the ground track of a satellite passing over a particular area. 2022-12-10T12:37:00Z and 2022-12-10T12:43:00Z are when the connection

takes place. The red dot indicates the position of the ground station in Bremen, and the blue line shows the satellite's estimated journey around the surface of the Earth during this period. The connection track shows the area where a stable communication link is ensured by the satellite maintaining at least a 10° elevation angle. Effective communication session planning, pass duration prediction, and satellite visibility comprehension are all aided by this visualisation.

The satellite's movement in relation to the ground station can be analysed using key features like azimuth, elevation angles, and distance over time. The azimuth angle indicates the spacecraft's orientation with regard to true north, while the elevation angle indicates how high the satellite appears in the sky from the observer's perspective. Furthermore, the distance between the satellite and the ground station is always shifting due to its orbital motion. These variations over time provide crucial details regarding the satellite's visibility and communication feasibility. The accompanying figure illustrates these relationships by displaying the changes in azimuth, elevation, and distance throughout the observation.

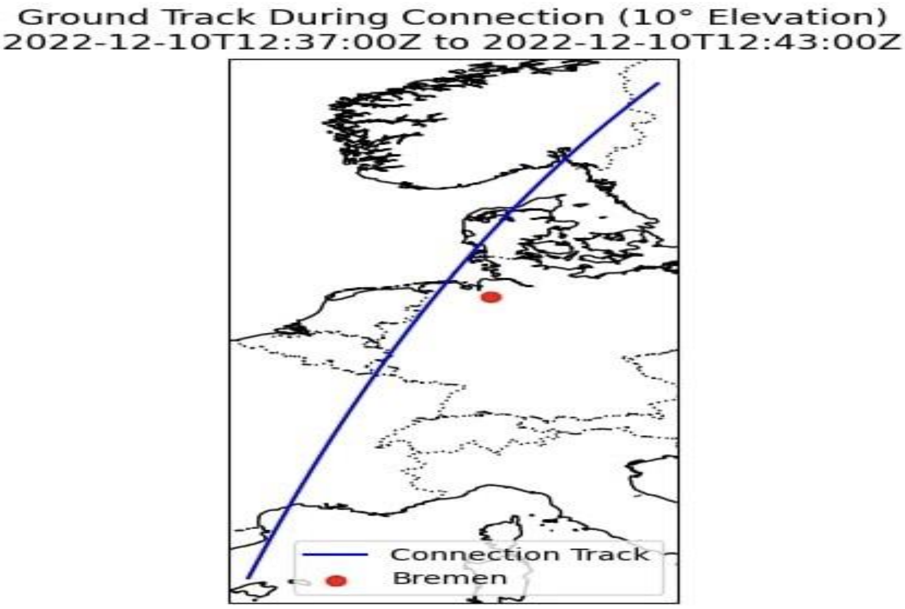

Figure 2 : Ground Track Bremen

Figure 3 depict Two graphs that show a satellite's **elevation and azimuth** from the ground station throughout the period 022-12-10T12:37:18 UTC to 2022-12-10T12:43:42 UTC are included in the image.

The **elevation angle(blue line)** in the upper plot indicates the satellite's apparent altitude in the sky. The elevation climbs with the satellite's ascent, peaks, and then falls with its descent. The 10° elevation threshold, the lowest elevation necessary for a reliable communication link, is shown by a red dashed line.

The **azimuth angle (green line),** which shows the satellite's orientation with respect to true north, is shown in the lower plot. It also shows how the satellite's distance from the ground station changed during the course of the observation.

When the satellite is above the necessary elevation threshold, these graphs assist in analysing its movement, determining its visibility window, and determining the best time for contact.

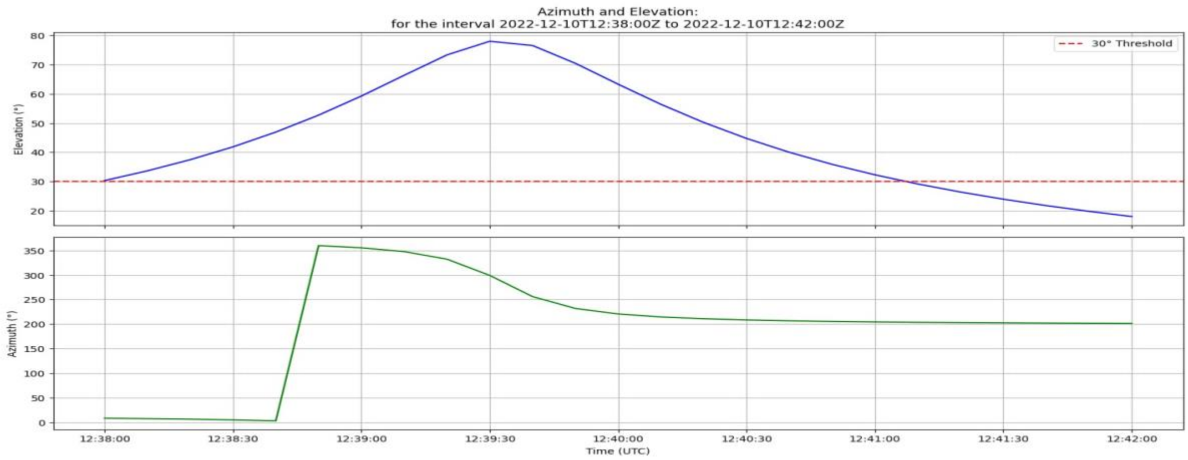

Figure 3 : Elevation (top) & Azimuth (buttom) angel of Sat tracking vs time

Figure 4 displays the RADFXSAT (FOX-1B) CubeSat's distance from Bremen over time. The x-axis shows the time in UTC, while the y-axis shows the distance in km. The plot's periodic pattern shows how the satellite goes through its orbit, with the distance between it and the base station changing as it does so. The troughs show when the satellite is closest to the ground station (perigee), and the peaks show when it is furthest away from Bremen(apogee).

Since the satellite is more accessible for signal transmission when it is closer to the ground station, this information is crucial for identifying the best communication windows. The satellite's low Earth orbit (LEO) features, where it makes several passes over the ground station in a single day, are also reflected in the regular fluctuations.

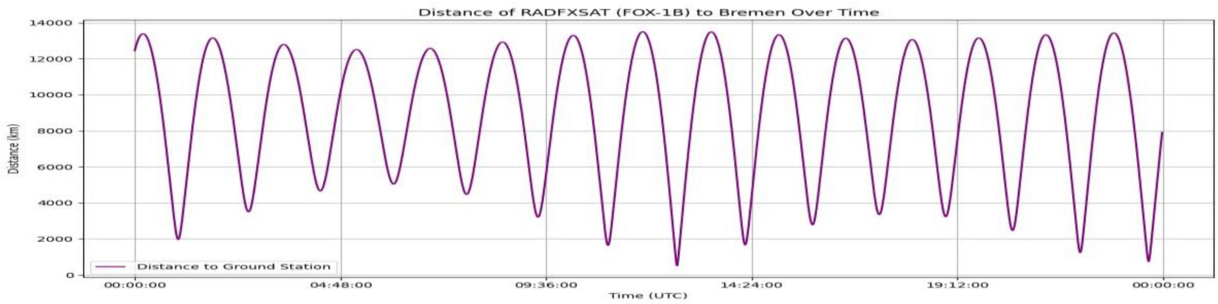

Figure 4 : Distance to Bremen over Time

The elevation angle of the satellite fluctuates with time, peaking at 63.31° and falling to a minimum of -88.36°. Maximum elevation is the highest point the satellite reaches in the sky during its transit, while minimum elevation shows that the satellite is below the horizon at specific times and cannot be seen from the ground station.

3. Link Budget Analysis

3.1 System Parameters

- **Frequency**: 145.8 MHz
- **Bandwidth**: 1.0 MHz
- **EIRP (Satellite)**: 2 W (3 dBW)
- **Ground Station Antenna Gain**: 18 dBi
- **Noise Figure**: 3 dB
- **Data Rate**: 200 bps
- **Minimum Elevation Angle**: 10°

3.2 Received Noise Calculation

The noise power at the antenna is calculated using the formula:

$$N_i = k \times T \times B$$

$$\mathbf{= -143.97\ dBW}$$

Where , k = 1.38×10^{-23} J/K (Boltzmann constant), T = 290 K (system noise temperature),

B = 1.0 MHz = 10^6Hz (bandwidth).

The receiver noise figure (F) is 3 dB.

Converting to linear scale:

$$F = 10^{\frac{3}{10}}$$

The output noise power is:

$$N_o = F \times N_i$$

$$\mathbf{= -140.9\ dBW.}$$

Required Signal Power (So) and Required Input Signal Power (Si) :For FM systems, the minimum SNR is typically 10 dB. converting to linear scale:

$$\mathbf{SNR = 10.}$$

The required signal power at the receiver is:

$$s_o = SNR \times N_o$$

= -130.97 dBW

The path loss is calculated as:

$$\boldsymbol{L_{p = 20\,log \times \frac{4\times\pi\times 2000km}{\lambda}}}$$

=141.74 dB

Where , r = 2000 km = 2.0 × 10^6 m, f = 145.8 MHz = 145.8× 10^6 Hz.

The input signal power at the antenna is:

$$s_i = \; = s_o \; + \mathrm{Gr} - L_p$$

= -254.7 dBW

Link Budget Table is shown in Table 1 in a structured format**:**

Category	**Parameter**		**Value**
General	Frequency	f	145,800,000 Hz
	Wavelength	λ	2.057 m
	Boltzmann Constant	K	1.38 × 10^{-23} J/K
Transmitter	Tx Power	Pt	3 dBW
	Antenna Gain	Gt	3 dBi
	Effective Isotropic Radiated Power	EIRP	3 dBW
Path	Path Distance	r	2000 km
	Path Loss	Lp	141.75 dB
	Power Flux Density at Ground	s	3.98 × 10^{-11} W/m²
Receiver	Antenna Diameter	D	6.71 m
	Physical Area	A_{phy}	35.43 m²
	Antenna Efficiency	ηant	60%
	Antenna Gain	Gr	18 dBi
	G/T	Pr=Si	-254.7 dBW
	Receiver Gain	G	18 dBi
	Signal Output	S_o	-130.97 dBW
Noise	Antenna Noise Temperature	T_a	288.62 K
	Noise Input	N_i	-143.97 dBW

Category	Parameter		Value
	SNR Input	SNR_i	10 dB
	Noise Figure	F	3 dB
	Equivalent Noise Temperature	Te	290 K
	Noise Output	N_o	-140.97 dBW
	SNR Output	SNR_o	10 dB
Digital Modulation	Bits per Symbol	m	1
	Bit Rate	Rb	200 bps
	Roll-Off Factor	α	9.9
	Bit Error Ratio	BER	3.87×10^{-6}

4. Doppler Shift Analysis

The Doppler shift effect was analyzed for frequency variations due to relative velocity:

For a velocity of 7.5 km/s, the calculated shift was **3820.69 Hz**.A circular plot was generated to visualize frequency shifts over time.

Showing how the frequency change of the satellite signal varies with regard to direction, the graphic shows a circular representation of the Doppler shift against azimuth. The Doppler shift is shown by the radial axis; the azimuth angle indicates the satellite's position relative to the ground station.

The Doppler shift change as the satellite travels across the sky is indicated by the curve's form. At its maximum altitude, the Doppler shift is negligible, but it is most pronounced when the satellite is moving towards or away from the ground station. Using this information is crucial for modifying receiver frequencies in order to preserve precise signal tracking while communicating via satellite.

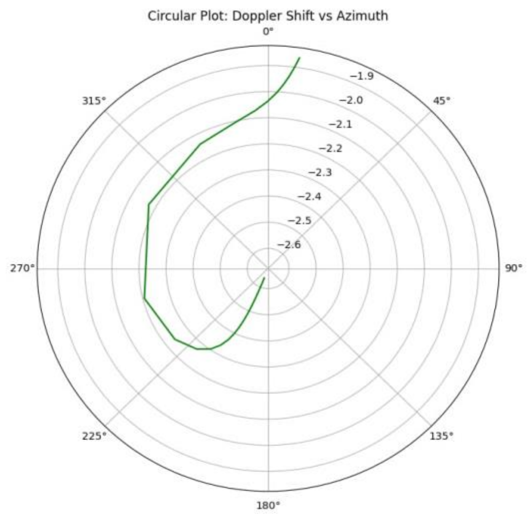

Figure 5 : Doppler shift vs Azimuth angle

5. Practical Satellite Tracking with Gpredict

Using the HSB ground station and software tools like GPredict and Gqrx, the lab's goal was to follow satellites and evaluate their signals. Two-Line Element (TLE) data was used to identify satellites, rotators were used to configure antenna alignment and listening to communications in the 70 cm amateur radio band (435–438 MHz) in real time. Nevertheless, the weather on the day of the lab—which included rain and dense clouds—made it more difficult to acquire and monitor satellites.

5.1 Experimental Setup

The HSB ground station, which has modern satellite communication equipment, was used for the experiment. These were the main elements:

- **Antennas**: an omnidirectional antenna for tracking in both directions and a Yagi antenna forincreased reception of the signal.
- **Rotator System:** To stay in alignment with satellites in orbit, the SPID rotator, which was controlled by GPredict, changed the Yagi antenna's azimuth and elevation.
- **Software GPredict:** Open-source program for controlling antenna rotators, calculating Doppler shift, and tracking satellites in real time. Gqrx is a software-defined radio (SDR) tool for frequency tuning, signal demodulation, and spectrum analysis.

Using TLE data from sources such as Celes Trak, satellites operating in the 70 cm band were located. These satellites were tracked by GPredict, and Gqrx made it easier to receive and examine the signals they sent.

Procedure:

The lab started by configuring GPredict to track satellites transmitting in the 70 cm band.It was developed a new module and imported TLE data to fill the list of satellites.GPredict had shown the orbital paths and coverage footprints, which helped in of satellites for tracking purposes. A more detailed investigation was carried out on satellites such as SO-50 and AO-7 observation.

The rain and thick cloud cover hampered the tracking operation. There the signal would attenuate and satellites would have limited visibility, making it hard to establish and maintain connections. In its current configuration the rotator system had been driven by the GPredict interface, which outputs real-time azimuth and elevation data. The SPID rotator was used to orient the Yagi antenna according to the satellite position.

The downlink frequency of a satellite was set in Gqrx after its position was aligned. For example, AO-7 and SO-50 were observed at 436.785 MHz and 436.795 MHz, respectively. The signal's intensity, modulation, and frequency fluctuations over time were displayed with the Gqrx spectrum analyser and waterfall display. Nevertheless, atmospheric influence resulted in weak or erratic signal strength in some situations

SO-50 Satellite Tracking:

- Using GPredict, the satellite was successfully tracked, and precise positional information was shown.
- The rotator system effectively followed the calculated azimuth (214.00°) and elevation (39.00°)
- The downlink frequency of 436.795 MHz was detected with stable signal strength.
- The Doppler shift effect was evident, necessitating ongoing frequency adjustments
- The Gqrx SDR displayed a distinct signal peak at the expected frequency, confirming successful reception.

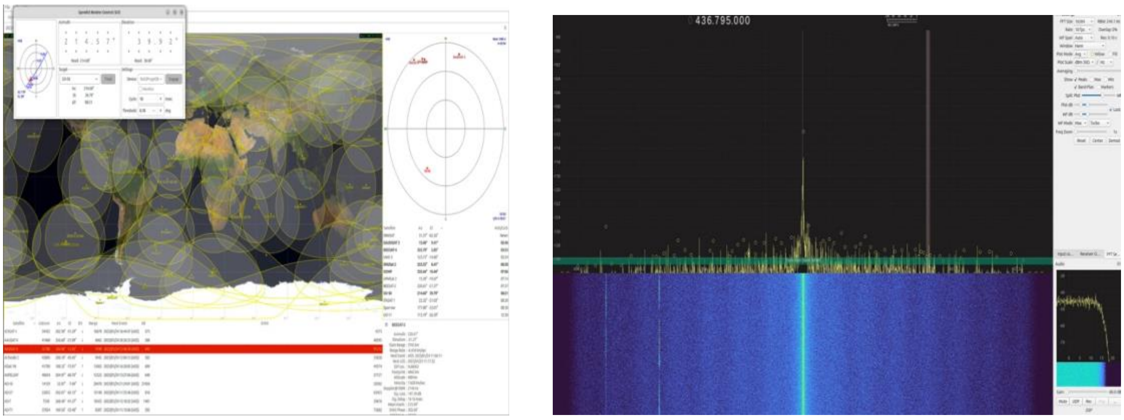

Figure 6 : SO-50 Ground station Setup

AO-7 Satellite Tracking:

- GPredict accurately tracked the satellite's path, noting an azimuth of 267.6° and an elevation of 32.53°.
- The downlink frequency was recorded at 436.785 MHz, exhibiting moderate signal clarity.
- Although the telemetry signals occasionally weakened, they remained recognizable within the anticipated frequency range.
- The SDR spectrum analysis revealed a clear signal signature, confirming successful tracking.

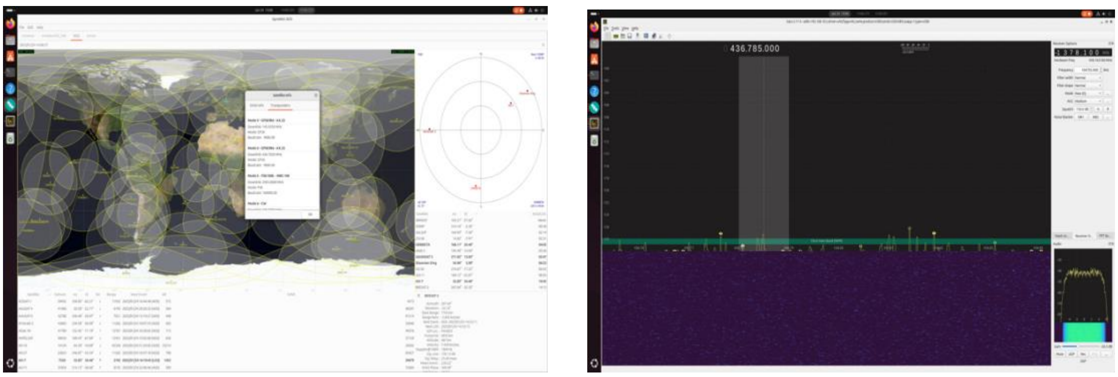

Figure 7 : AO-7 Ground station Setup

5.2 Observations

The experiment showcased both achievements and obstacles faced during poor weather conditions:

- **Satellite Tracking**: The real-time updates on azimuth and elevation from GPredict allowed for accurate adjustments to the rotator system. Nevertheless, cloud cover and rain made it challenging to maintain consistent tracking.
- **Signal Reception**:Signals received from satellites like SO-50 were weaker than anticipated because of atmospheric interference. The Doppler shift effect was noticeable, with the signal frequency changing as the satellite passed by.
- **Environmental Impact**: The rain and cloud cover led to signal loss and higher noise levels in the spectrum. This underscored the difficulties of satellite communication in less-than-ideal conditions**.**

6. Conclusion

The RADFXSAT (FOX-1B) CubeSat was successfully followed and analysed in this research to assess its orbit, visibility, and ground station communication link performance. The study calculated the satellite's trajectory, elevation angles, and Doppler shift effects all essential for precise tracking and signal reception using simulations with the Skyfield module. Taking into account variables including path loss, noise power, and necessary signal strength, the link budget analysis verified that the satellite's transmission power and antenna gain are adequate for sustaining a steady downlink connection..

The findings show that the satellite has a dependable orbital trajectory that passes over the ground station several times, enabling sporadic opportunities for communication. Frequency adjustments are crucial for preserving signal integrity, as demonstrated by the Doppler shift fluctuations seen in the study. Optimising signal reception and minimising losses also heavily depends on the ground station's antenna effectiveness.

Overall, This study offers an extensive understanding of the possibility of satellite tracking and communication . In order to increase communication dependability, future developments can include real-time tracking optimisations, improved signal processing methods, and higher gain antennas. The effective design and execution of upcoming satellite missions is supported by these discoveries, which offer insightful information about interactions between satellites and ground stations.

References

1. Gerard Maral and Michel Bousquet. *Satellite Communications Systems*. Wiley-Blackwell, 2020.
2. S. Peik. *Satellite Communication Lecture Notes ASC*. Hochschule Bremen, 2013.
3. ITU. *ITU Handbook on Satellite Communications*. Wiley-Interscience, 2002.

Appendix

```
import numpy as np
import matplotlib.pyplot as plt
from skyfield.api import Topos, load, EarthSatellite
from datetime import timedelta
import cartopy.crs as ccrs
import cartopy.feature as cfeature
import matplotlib.dates as mdates

# TLE Data for RADFXSAT (FOX-1B)
tle_lines = [
    "1 43016U 17073E   24323.25583792  .00000107  00000+0  36910-4 0  9992",
    "2 43016  97.7321 340.5206 0250187 104.1177 258.4146 14.80873291342894"
]

# Create Satellite Object
ts = load.timescale()
satellite = EarthSatellite(tle_lines[0], tle_lines[1], "RADFXSAT (FOX-1B)", ts)

# Observer's Location (Bremen, Germany)
bremen = Topos(latitude_degrees=53.0793, longitude_degrees=8.8017)

# Observation Period: Jan 12 - Jan 13, 2024
start_time = ts.utc(2024, 1, 12, 0, 0, 0)
end_time = ts.utc(2024, 1, 13, 0, 0, 0)
time_step = 10  # seconds

# Create Time Array
times = []
current_time = start_time
while current_time.utc_datetime() <= end_time.utc_datetime():
    times.append(current_time)
    current_time = ts.utc(current_time.utc_datetime() + timedelta(seconds=time_step))

# Initialize Data Arrays
elevation = []
azimuth = []
distance = []
ground_track_lat = []
ground_track_lon = []
visible_passes = []
culminations = []

# Process Data
for time in times:
    # Satellite position relative to observer
    difference = satellite - bremen
    topocentric = difference.at(time)
    el, az, dist = topocentric.altaz()
```

```
    elevation.append(el.degrees)
    azimuth.append(az.degrees)
    distance.append(dist.km)

    # Sub-satellite point (ground track)
    subpoint = satellite.at(time).subpoint()
    ground_track_lat.append(subpoint.latitude.degrees)
    ground_track_lon.append(subpoint.longitude.degrees)

    # Identify visible passes
    if el.degrees > 30:
        visible_passes.append((time.utc_datetime(), "rise above 30°" if len(visible_passes) == 0
else ""))
        if len(visible_passes) > 1 and elevation[-2] < el.degrees > elevation[-1]:  # Culmination
            culminations.append((time.utc_datetime(), el.degrees))
        if el.degrees < 30 and len(visible_passes) > 1:
            visible_passes.append((time.utc_datetime(), "set below 30°"))

# TLE and Sightings Output
print("TLE Data:")
print("\n".join(tle_lines))
print("\nSightings in Bremen:")
for time, event in visible_passes:
    print(f"{time}: {event}")

# Convert times to Matplotlib format
times_mpl = mdates.date2num([time.utc_datetime() for time in times])

# Global Ground Track Plot with Cartopy
fig = plt.figure(figsize=(12, 6))
ax = plt.axes(projection=ccrs.PlateCarree())
ax.add_feature(cfeature.LAND, edgecolor='black')
ax.add_feature(cfeature.COASTLINE)
ax.add_feature(cfeature.BORDERS, linestyle=':')
ax.add_feature(cfeature.RIVERS, alpha=0.5)
ax.add_feature(cfeature.LAKES, alpha=0.5)
ax.set_global()
ax.plot(ground_track_lon, ground_track_lat, color='red', transform=ccrs.Geodetic(),
label='Ground Track')
ax.scatter([8.8017], [53.0793], color='blue', transform=ccrs.PlateCarree(), label='Bremen')
ax.set_title("Global View: Ground Track of RADFXSAT")
ax.legend()
plt.show()

# Bremen Area Ground Track Plot with Cartopy
fig = plt.figure(figsize=(8, 6))
ax = plt.axes(projection=ccrs.PlateCarree())
ax.add_feature(cfeature.LAND, edgecolor='black')
ax.add_feature(cfeature.COASTLINE)
ax.set_extent([0, 30, 50, 60], crs=ccrs.PlateCarree())  # Zoomed into Bremen area
```

```
ax.plot(ground_track_lon, ground_track_lat, color='red', transform=ccrs.Geodetic(),
label='Ground Track')
ax.scatter([8.8017], [53.0793], color='blue', transform=ccrs.PlateCarree(), label='Bremen')
ax.set_title("Zoomed View: Ground Track Over Bremen")
ax.legend()
plt.show()

# Azimuth and Elevation Plots
plt.figure(figsize=(12, 6))
plt.subplot(2, 1, 1)
plt.plot(times_mpl, elevation, color="blue", label="Elevation")
plt.axhline(30, color="red", linestyle="--", label="30° Elevation Threshold")
plt.title("Elevation Over Bremen")
plt.ylabel("Elevation (°)")
plt.legend()
plt.gca().xaxis.set_major_formatter(mdates.DateFormatter('%H:%M:%S'))

plt.subplot(2, 1, 2)
plt.plot(times_mpl, azimuth, color="green", label="Azimuth")
plt.title("Azimuth Over Bremen")
plt.xlabel("Time (UTC)")
plt.ylabel("Azimuth (°)")
plt.legend()
plt.gca().xaxis.set_major_formatter(mdates.DateFormatter('%H:%M:%S'))
plt.tight_layout()
plt.show()

# Circular Doppler Shift Plot
plt.figure(figsize=(8, 8))
doppler_shift = [(satellite.at(time).velocity.km_per_s[2] / 299792.458) * 145.8e6 for time in
times]
ax = plt.subplot(111, polar=True)
azimuth_radians = np.radians(azimuth)
ax.plot(azimuth_radians, doppler_shift, label="Doppler Shift (Hz)", color="purple")
ax.set_theta_zero_location("N")
ax.set_theta_direction(-1)
ax.set_title("Circular Plot: Doppler Shift vs Azimuth", va="bottom")
plt.legend()
plt.show()
```