A UHF half-wave dipole antenna for the AcubeSAT mission

AcubeSAT-COM-G-025

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Contents

Appendices

Changelog

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Reviewed and approved for public release by the Systems Engineering Team.

Acronyms

EIRP Effective Isotropic Radiated Power

FR-4 Flame Retardant 4

HPBW Half-Power Beamwidth

UHF Ultra High Frequency

VNA Vector Network Analyzer

References

[1] Mavrikakis Parmenion. *UHF Turnstile Antenna*. Version 1. Dec. 2019. URL: https://drive.google.com/file/d/1fxwMFnYej4NiXjo2gp6ElKLWf7mIqRFU/view?usp=sharing.

1 Abstract

The antenna used in nanosatellite systems for the reception of telecommands and the transmission of telemetry data plays a crucial role in assuring the reliability of the essential link between the mission operator and the spacecraft. In this work, the design of the on-board UHF half-wave dipole antenna for the AcubeSAT satellite mission is presented. This document includes the derived antenna requirements, as well as all the theoretical analysis and simulations that went into the design of this antenna.

2 Requirements

2.1 Mission Requirements

During the design phase of the antenna, the main aspects that have been taken into consideration include:

- **Size**: Due to the constraints imposed by nanosatellite structures like AcubeSAT, a compact deployable antenna is vital.
- **Power availability**: Since the link budget of the transmission of telemetry data to ground is limited by the spacecraft's EIRP, the antenna shall have sufficient gain to compensate for the limited input power of 30 dBm.
- **Nadir pointing deviation**: An antenna of high directivity implies a link budget prone to spacecraft pointing losses, depending on the attitude control/nadir-pointing accuracy, as well as the beamwidth of the antenna. For this reason, it is of great importance to have a wide HPBW, in order for an extended mean communication window to be feasible.
- **Path loss**: Due to the significant free-space path loss (FSPL) imposed by the satellite's high altitude given by

$$\mathrm{FSPL_{dB}} = 10\log_{10}\left[\left(\frac{4\pi d}{\lambda}\right)^2\right] \overset{\lambda=\frac{c}{f}}{=\!=\!=} 20\log_{10}\left(\frac{4\pi d f_c}{c}\right), \tag{1}$$

where d is the slant range, λ is the wavelength, f_c is the center frequency and c is the speed of light, 436 MHz has been selected to be the uplink/downlink frequency for the transmission of telecommands and telemetry data respectively.

The low data rate of 20 kbps imposes no strict requirement concerning the bandwidth of the antenna.

2.2 Antenna Requirements

Based on the aforementioned factors, AcubeSAT's on-board UHF antenna shall fulfill the following requirements:

- **Reflection coefficient (bandwidth)**: $\mathrm{S}_{11}(f) < -10$ dB, $\forall f \in [433\ \mathrm{MHz}, 438\ \mathrm{MHz}]$;
- **Gain**: $G(\theta = 0°, \phi = 0°) \geq 2$ dBi;
- **Beamwidth**: HPBW $> 70°$.

Following the finalization of the requirements of the antenna, the design procedure is discussed.

3 Design

3.1 Theoretical Analysis

3.1.1 Antenna Resonance

The scattering parameter S_{11} of an antenna is determined by the complex impedance of the feedline Z_0 and the impedance of the antenna:

$$Z_{\text{in}} = R_r + jX_r, \tag{2}$$

where R_r is the resistance and X_r is the reactance of the antenna.

Since the impedance of the transmission line connecting the on-board COMMS board to the antenna is equal to

$$Z_0 = 50 + j0\ \Omega, \tag{3}$$

in order to minimize the impedance mismatch between Z_{in} and Z_0, the antenna shall be purely resistive[1]:

$$X_r = \Im(Z_{\text{in}}) = 0\ \Omega. \tag{4}$$

An ideal $\lambda/2$ dipole has a complex impedance of

$$Z_{\text{in}} \approx 73 + j42.5\ \Omega. \tag{5}$$

Because Equation 5 does not consist of a resistance equal to $50\ \Omega$, the reflection coefficient Γ will be suboptimal. Additionally, the imaginary part $X_r \neq 0\ \Omega$ further degrades Γ. Thus, the dimensions and geometry of the proposed UHF dipole antenna shall be adjusted to have an appropriate impedance, matching the real and imaginary parts of the transmission line and COMMS board (Equation 3).

3.1.2 Radiation Pattern

The electromagnetic fields formed as a result of antenna excitation for a dipole are shown in Figure 1. From the visualization of the fields, it is easy to deduce the radiation pattern of a $\lambda/2$ dipole to be omnidirectional (see Figure 2), suggesting the gain is merely a function of altitude θ, as the azimuth ϕ does not influence the directivity of the antenna:

$$G(\theta, \phi) = G(\theta). \tag{6}$$

[1] Ideally, the resistance of the antenna should also be matched to the resistance of the transmission line, i.e. $\Re(Z_{\text{in}}) = \Re(Z_0) = 50\ \Omega$. However, this can generally be dealt with the use of impedance transformers.

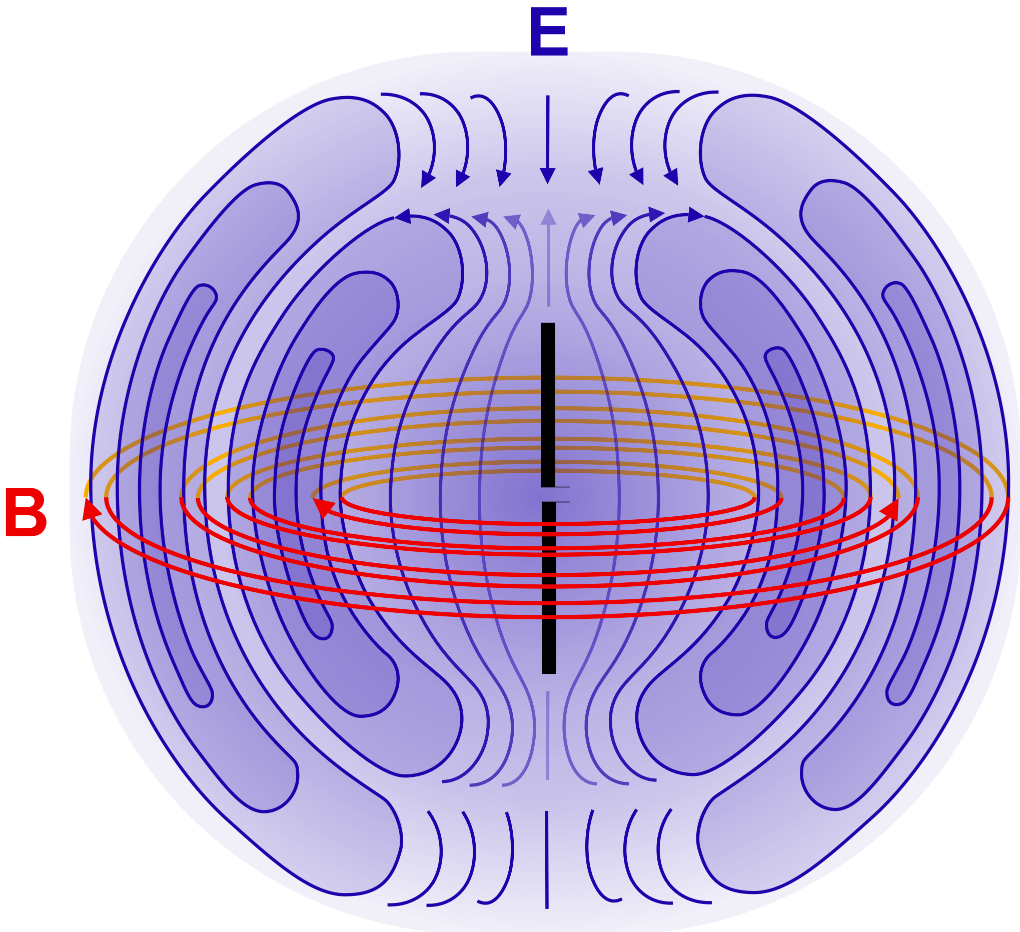

Figure 1: Near-field visualization of the formation of the electric and magnetic field for a half-wave dipole.

For nanosatellite systems, the radiating nature of omnidirectional antennas is considered a powerful benefit, as it enables communication links to take place despite potential limitations and failures concerning the spacecraft's attitude determination and control system.

3.1.3 Near-field Electromagnetic Interaction

Assuming the center frequency is $f_0 = 436$ MHz, the wavelength of interest is equal to $\lambda = c/f_0 \approx 68.76$ cm. The reactive near-field region of an antenna is given by

$$R_1 < 0.62\sqrt{\frac{D^3}{\lambda}}, \tag{7}$$

where D is the largest dimension of the antenna (i.e. $\lambda/2$ for a half-wave dipole). The radiating near-field (Fresnel) region is given by

$$R_2 < \frac{2D^2}{\lambda}, \tag{8}$$

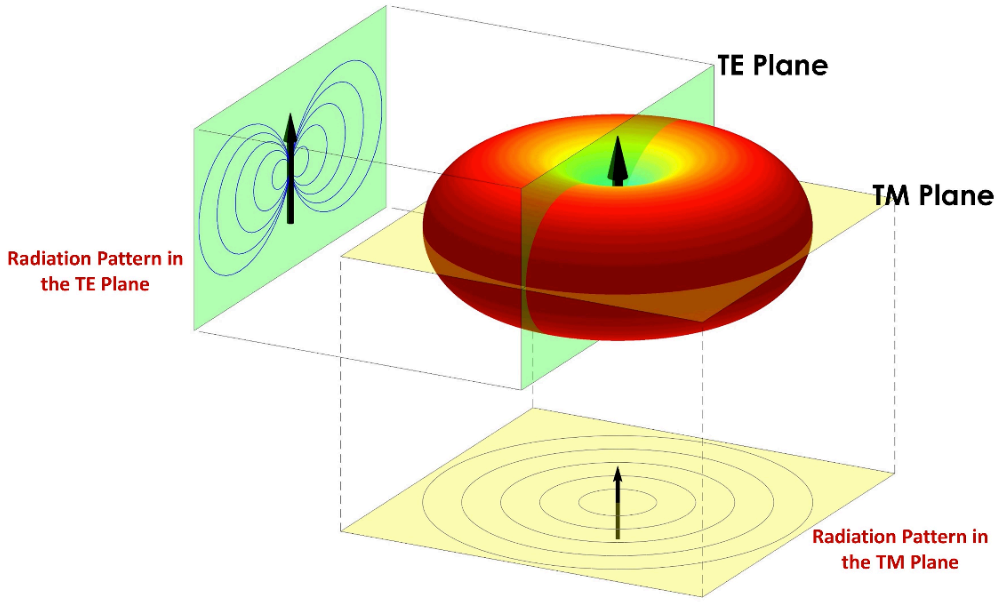

Figure 2: Typical radiation pattern of a dipole antenna.

with the far-field (Fraunhofer) region appearing beyond R_2. From (7) and (8), we summarize the position of each region:

$$0 < R_1 < 0.62\sqrt{\frac{D^3}{\lambda}} < R_2 < \frac{2D^2}{\lambda} < \infty. \tag{9}$$

Equation 9 is critical, because conductive materials and insulators in the R_1 and R_2 regions may have a significant influence on the radiating characteristics of the antenna. In particular, the directivity, gain and S_{11} may be observed to degrade with the presence of the deployment mechanism and the structure of the spacecraft.

For a half-wave dipole ($D = \lambda/2$), (9) becomes

$$0 < R_1 < \frac{0.62\lambda}{2\sqrt{2}} < R_2 < \frac{\lambda}{2} < \infty, \tag{10}$$

giving radius limits of 15.1 cm and 34.4 cm for the reactive and radiating near-field region respectively. These radii signify potential electromagnetic interaction effects of the deployment mechanism ($r = R_1$) and the CubeSat structure ($r = R_2$) on the radiating properties of the antenna. It is therefore of great importance for electromagnetic simulations to be conducted, in order to take all of these structural factors into consideration and obtain more accurate and realistic results concerning the radiating characteristics of the antenna.

3.1.4 Polarization

In satellite communications, the polarization of transmitted and received electromagnetic waves is affected by Faraday rotation[2]. This effect introduces polarization mismatch losses to the link, which can be mitigated with the use of circularly-polarized antennas on both ends (ground segment and spacecraft). Although a circularly-polarized[3] turnstile antenna has been among the first considerations for the mission [1], the deployment mechanism posed a risk regarding the unfolding of each dipole shown in Figure 3.

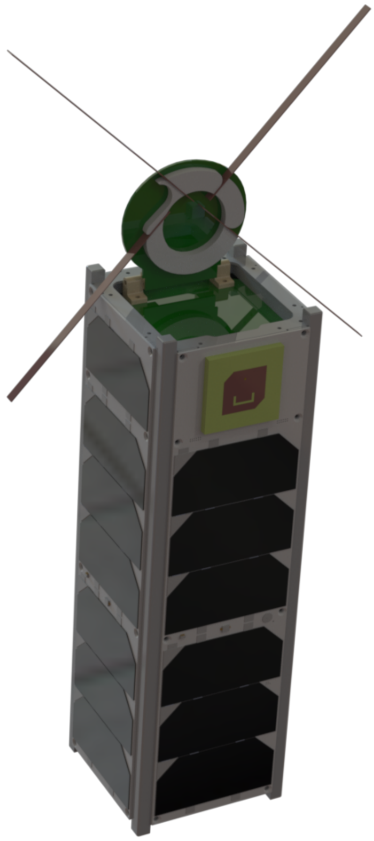

Figure 3: The AcubeSAT turnstile antenna (preliminary design).

Consequently, the selection of a single linearly-polarized half-wave dipole antenna in Figure 4 minimizes the risk of deployment issues, while reducing the complexity of the feeding circuit.

Since the ground segment consists of a UHF circularly-polarized helical antenna, the introduced link loss due to the mismatch between circular and linear polarization will be approximately equal to 3 dB. Assuming the on-board antenna is perfectly (purely) linearly-polarized and the axial ratio of the ground station antenna is 0 dB, this loss will be constant regardless of the orientation of the satellite. Despite this loss, link budget

[2] Faraday rotation takes place in the ionosphere, causing a rotation of the plane of polarization by an unpredictable amount.

[3] This would be achieved with the use of an appropriate feeding circuit that would excite the dipoles with a 90° phase shift to simulate circular polarization from two linearly-polarized dipoles.

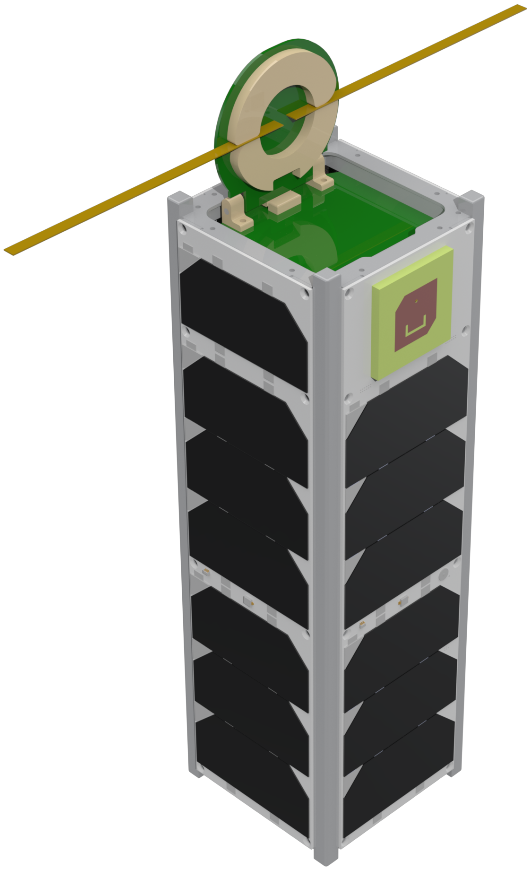

Figure 4: The finalized on-board dipole antenna of AcubeSAT.

analyses have shown that this mismatch is acceptable, meaning that the links for telemetry and telecommands appear achievable without problems.

3.2 Model Parameters

After several simulation iterations in CST STUDIO SUITE, the dimensions that give the optimal results found in section 4 are summarized in Table I.

Table I: Dimensions of the AcubeSAT UHF dipole antenna

Parameter	Description	Value	Unit
l	Length of each radiating element (pole)	154.4	mm
w	Width of each radiating element (pole)	6	mm
h	Strip height (conductor thickness)	0.5	mm
d	Separation distance between radiating elements (poles)	12.78	mm

The materials assigned to the dipole, its holders, the deployment plate and the structure of the spacecraft were **Brass (91%)**, **Preperm PEEK700**, **FR-4 (loss free)** and **Aluminum** respectively.

4 Simulations

The antenna, its deployment mechanism and the CubeSat structure were modeled in CST. Simulations took place to determine the most suitable dimensions for the AcubeSAT mission (see Table I) and the results are presented in the following subsections.

4.1 Reflection Coefficient

As shown in Figure 5, the magnitude of S_{11} is less than -10 dB in the frequency range 433-438 MHz. In particular, the magnitude of $S_{11}(f = f_0)$ is less than -23 dB. This marks the bandwidth requirement fulfilled.

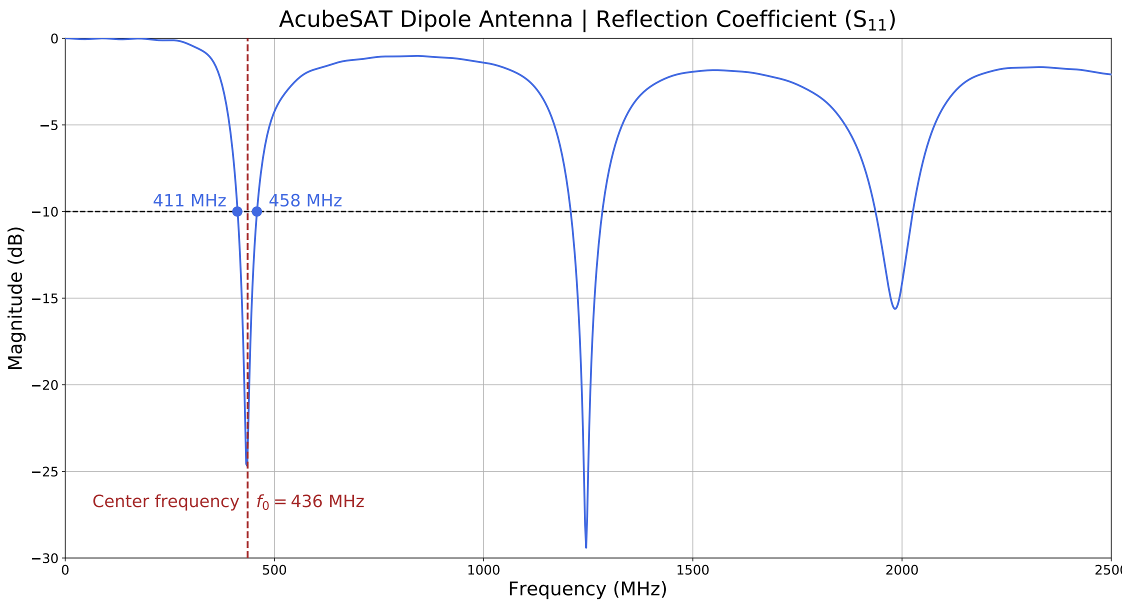

Figure 5: Simulated $|S_{11}|$ of the AcubeSAT UHF dipole antenna.

4.2 Complex Impedance

The complex impedance (resistance and reactance) of the dipole antenna is a key characteristic, as it provides important information concerning the impedance match between Z_{in} and Z_0.

4.2.1 Resistance

From Figure 6, the resistance of the antenna is equal to

$$\Re(Z_{\text{in}}) = 56.67\ \Omega \approx \Re(Z_0) = 50\ \Omega, \tag{11}$$

which indicates an acceptably good match in terms of resistance. This is essential, as it

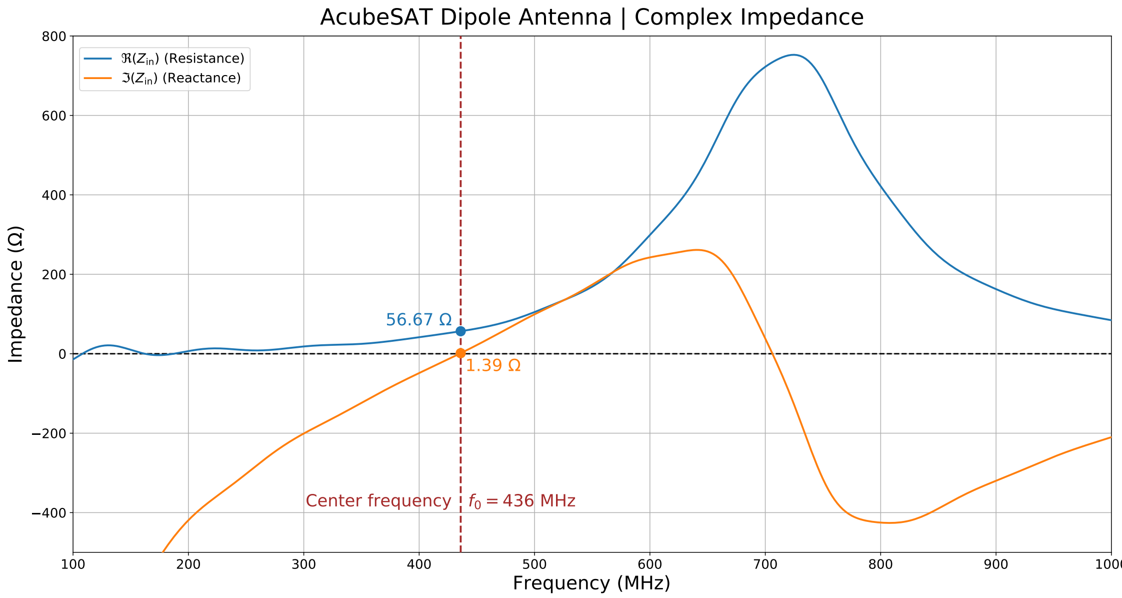

Figure 6: Simulated complex impedance of the AcubeSAT UHF dipole antenna.

enables the use of a balun with an impedance ratio (IR) of 1:1:

$$\mathrm{IR} = \frac{\Re(Z_0)}{\Re(Z_{\mathrm{in}})} = \frac{50\ \Omega}{56.67\ \Omega} = 0.88 \approx 1, \tag{12}$$

implying impedance transformation is virtually unnecessary.

4.2.2 Reactance

The imaginary part of the impedance of the dipole is equal to $1.39\ \Omega \approx 0\ \Omega$, suggesting a good match in terms of reactance.

4.3 Radiation Pattern

The radiation pattern of the antenna is best represented by Figure 8 as a 2D polar plot ($\phi = 0°$). The boresight gain is 2.64 dBi = 0.49 dBd, while the HPBW is 64.5°. The 3D radiation pattern at $f_0 = 436$ MHz is shown in Figure 9.

4.4 Mutual Coupling

In the case of AcubeSAT, mutual coupling refers to the unintentional electromagnetic interaction between the UHF and S-band antenna. If the assigned port numbers for the dipole and patch antenna are 1 and 2 respectively, the magnitude $|S_{21}|$ permits the determination of the unwanted input power at the dipole's feedpoint. Assuming an input power of 1 W = 30 dBm to the patch antenna during the transmission of payload

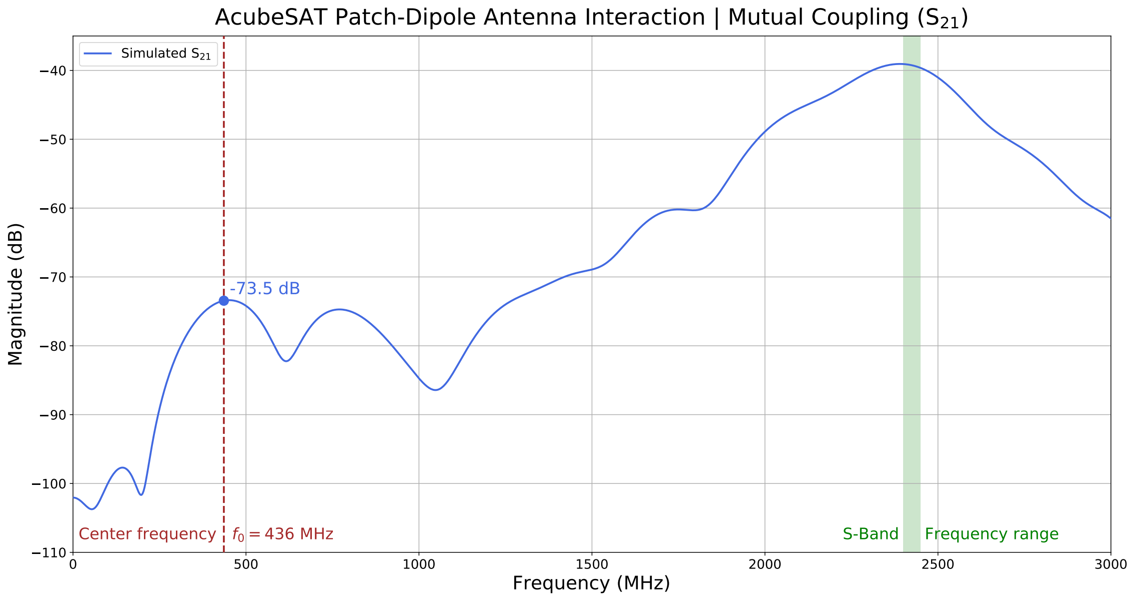

Figure 7: Simulated mutual coupling between the S-band patch antenna and the UHF dipole antenna.

data, Figure 7 provides an upper limit of -43.5 and -9 dBm for the UHF and S band respectively.

5 Conclusion

In conclusion, link budget analyses have shown an acceptable system link margin with the aforementioned antenna design. However, in order to verify the actual performance of the antenna, it is important to conduct a few more tests:

- Implement a 1:1 balun and measure the $|S_{11}|$ with a VNA, comparing the results of the test with the simulation;
- Measure $|S_{11}|$ with the dipole loosely swinging vertically to simulate instability;
- Conduct simulations and/or measurements with the dipole folded to check the severity of unexpected antenna deployment problems on the mission.

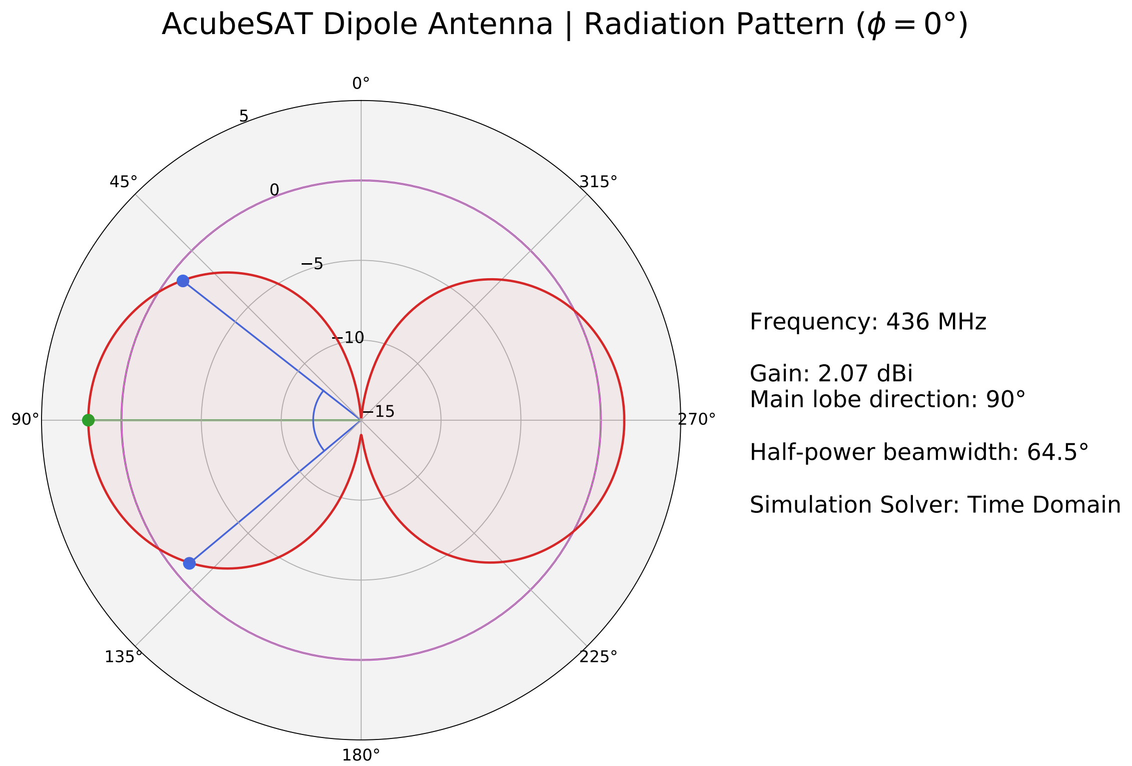

Figure 8: 2D radiation pattern of the AcubeSAT dipole antenna (constant $\phi = 0°$).

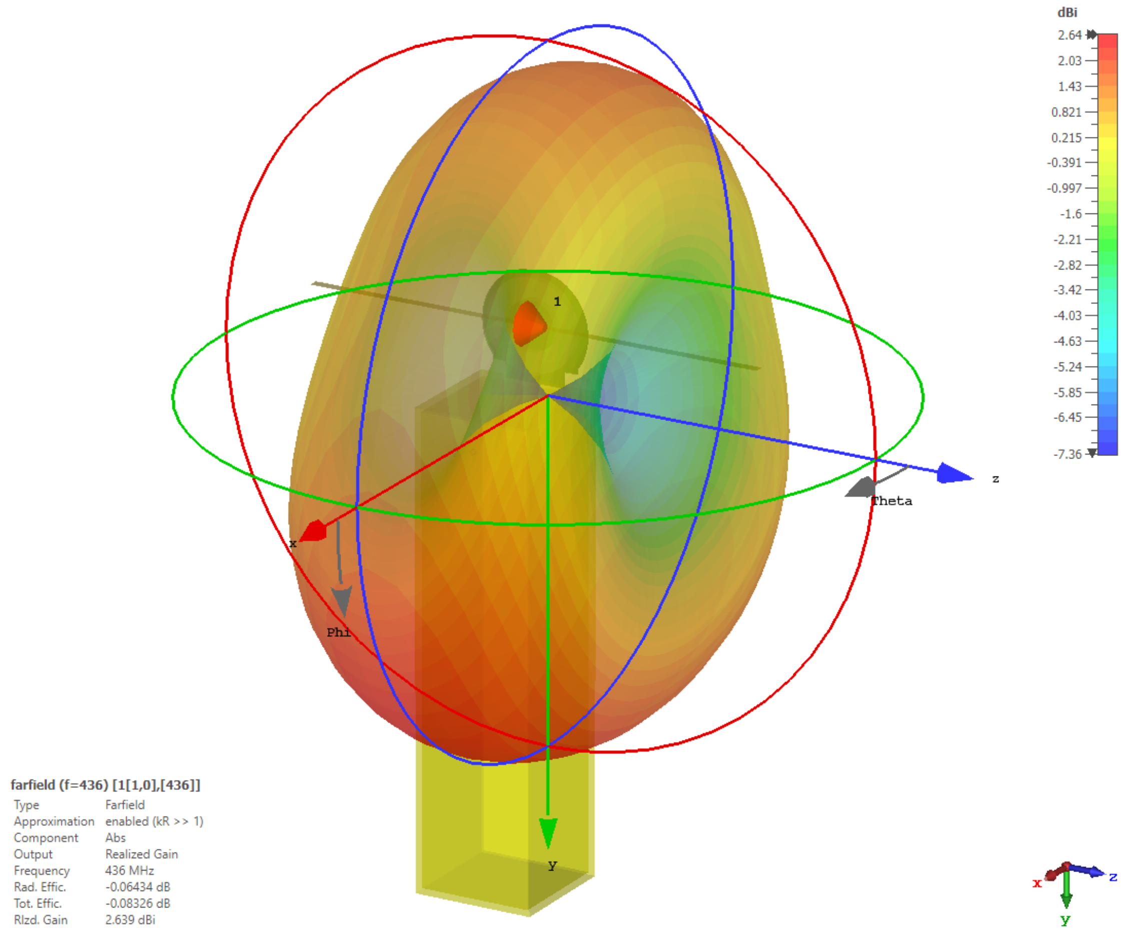

Figure 9: 3D radiation pattern of the AcubeSAT dipole antenna.

A Document-ID reference

AcubeSAT - COM - G - 025 1

1 → Version number

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