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EMC Verification Approach

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Radar Sounder in Interplanetary Mission: Hybrid EMC Verification Approach

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***Abstract*—The use of HF radar sounders for planetary exploration creates a substantial challenge with the electromagnetic emissions generated by modern spacecraft platforms and payloads. This paper reviews systemic EMC challenges in such missions, highlighting how stringent scientific requirements necessitate the tailoring of generic ECSS limits to ensure mission success. The fundamental physical limitations of pre-launch validation are analyzed, specifically the geometric constraints of anechoic chambers regarding large dipole antennas (16-40 m), the performance of the absorbing materials, and the inability to replicate the spacecraft's role as an electrically active part of the radiating system. By examining documented discrepancies between ground verification and in-flight behavior, this work exposes the complexity and limitations of current ground-based EMC testing for radar sounders, highlighting the urgent need to develop novel verification techniques to accurately predict the operational performance of such low-frequency radar sounders.**

Measuring large objects at low frequencies (below 30 MHz) in anechoic chambers is challenging, such as testing radar-sounders with 16 m dipole antennas at 30 MHz. This paper presents a method combining measurements and simulations to assess the anechoic chamber's impact on testing accuracy. A preliminary model using an electromagnetic solver simulates the chamber with ferrite materials and evaluates its effect on a monopole antenna over a ground plane.

***Index Terms*—Anechoic chamber, EMC, HF, radar sounder, space mission, verification methods.**

I. Introduction

Geophysical exploration of solid planetary bodies using radar sounders represents one of the most complex frontiers of modern aerospace engineering today. Unlike passive instrumentation or traditional Synthetic Aperture Radars (SAR), which typically operate in microwave bands to map surface, radar sounders are designed to penetrate the planetary crust and reveal subsurface dielectric discontinuities. This specific scientific interest dictates the use of low frequencies, typically in the High Frequency (HF, 3-30 MHz) and Very High Frequency (VHF, 30-300 MHz) bands. These frequency bands are necessary to minimize attenuation in ice and regolith and achieve penetrations on the order of kilometers. However, the use of HF and VHF places the instrument in a condition of intrinsic conflict with the electromagnetic environment of the host platform. A modern satellite constitutes a complex environment of EMI sources: DC/DC power converters, clock oscillators, solar array power generators, and actuators operate or generate harmonics exactly within the sounders' sensitivity bands. The fundamental engineering paradox lies in the need to integrate a radar receiver capable of detecting echoes attenuated by more than 100-150 dB with sensitivity close to the galactic noise limit just a few meters away from subsystems radiating high-power disturbances.

A. Evolution of EMC Requirements and Systemic Challenges

Managing this coexistence and guaranteeing the success of onboard scientific experiments requires a rigorous tailoring of standard Electromagnetic Compatibility (EMC) baselines to specific mission needs. Traditionally, the requirements for satellite platforms in Europe rely on the ESA ECSS-E-ST-20-07C standard [1], focusing primarily on emissions above 30 MHz. However, recent scientific missions such as JUICE (Jupiter Icy Moons Explorer), with the presence of highly sensitive HF/VHF radar sounders, demand highly customized limits. In the operational bands of HF/VHF radar sounders the tolerated emission thresholds are forced to drop dramatically, reaching levels as low as -10 dBμV/m (see Fig.1). Ensuring compliance at these extreme sensitivities at such low frequencies ultimately requires a complete rethinking of verification strategies.

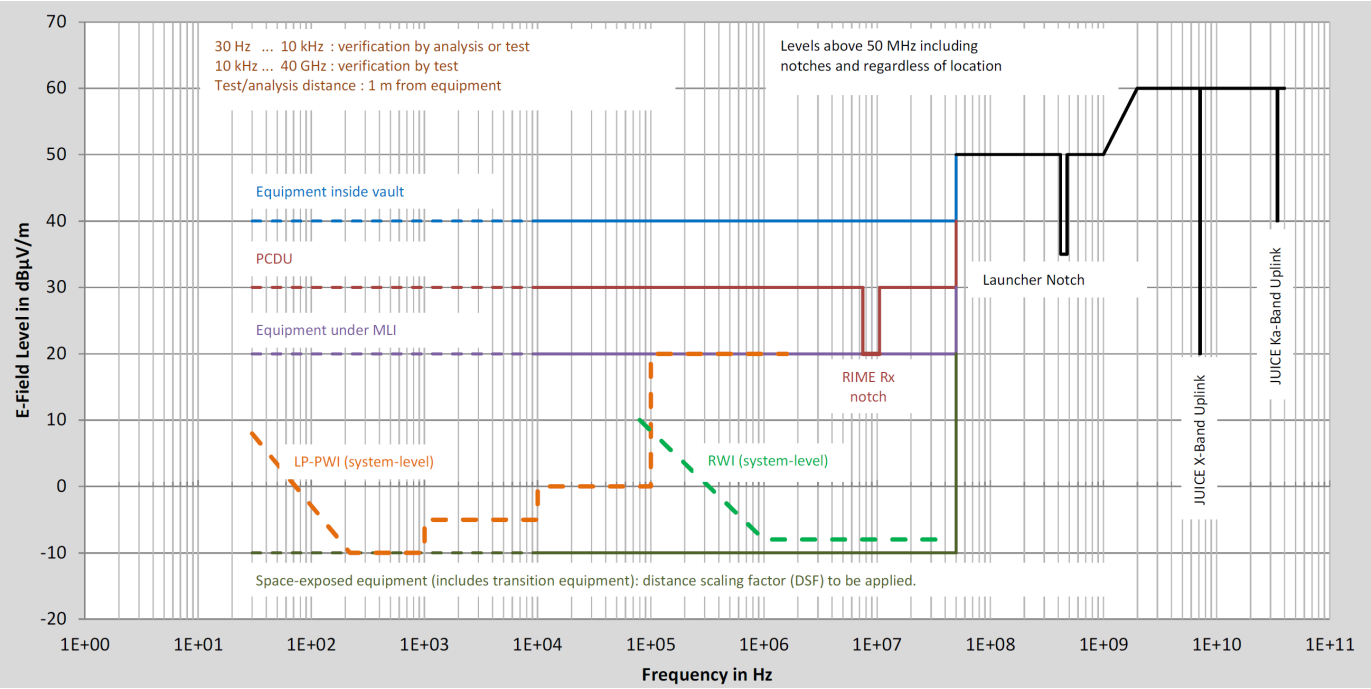

Fig. 1. JUICE Radiated Emission mask. Reproduced from [2]

This paradigm shift implies that equipment can no longer be considered as an isolated unit. System engineering assumes a crucial role since at such low frequencies and faint levels, cabling (harness) and common-mode currents become the primary interference vectors. Units seemingly compliant during individual tests have been shown to generate unacceptable emissions once integrated, due to the radiation of common-mode noise through interconnection cables. In this context, [2] emphasize that suppressing common-mode currents at the unit level and implementing a dedicated Ground Reference Rail (GRR) are essential strategies to limit the conversion of conducted noise into radiated interference via the satellite harness. Furthermore, the complexity of managing these emissions is evidenced by in-flight data from the JUICE mission, which revealed that PCDU-generated noise couples to instrument antennas specifically via solar array interactions, a path that often cannot be fully replicated during on-ground testing [3]. To mitigate these effects in future designs, lessons learned from these experiences have led to architectural improvements in instruments like the EnVision SRS, such as relocating input filters to the front of the low-noise amplifier to enhance receiver robustness against saturation and damage [4].

B. Limitations of Test and Validation Methods

Pre-launch validation of these complex systems clashes with fundamental physical limitations that compromise the core ”Test-As-You-Fly” principle. Traditional verification methods fail to provide a reliable picture of the in-orbit behavior due to three main factors: 1) the physical inability of standard anechoic chambers to accommodate and correctly absorb HF/VHF wavelengths; 2) the impossibility of measuring signals close to the galactic noise limit using standard facility setups; and 3) the failure of ground support equipment to replicate dynamic in-flight impedance. These criticalities, which drive the urgent need for a new verification paradigm, are analyzed in detail in the following sections.

C. Goal and case study

This paper analyzes systemic EMC challenges related to planetary radar sounders, examining ground test protocols and flight anomalies encountered in major missions over the last two decades, including Mars Express, MRO, JUICE, Europa Clipper, and EnVision. By analyzing the critical discrepancies between ground verification and in-orbit reality, this work demonstrates the inadequacy of traditional testing standards. Ultimately, the primary objective of this review is to lay the foundation for a novel pre-launch verification methodology. Moving beyond isolated unit-level testing, this paper aims to define and propose a comprehensive system-level approach, integrating physical test setups with advanced electromagnetic modeling, to accurately predict the in-flight EMC performance of future deep-space instruments.

To achieve this, we outline a procedure to estimate the potential impacts on the anechoic chamber testing process using both measurements and simulations. This is particularly critical since performing measurements in an anechoic chamber at low frequencies (below 30 MHz) is extremely challenging when the objects under test have great physical dimensions, such as radar-sounders working with dipole antennas of 16 m. To bridge this gap, a preliminary analysis modeling an anechoic chamber with ferrite and considering its effect on a monopole antenna on a ground plane is presented.

II. Historical review

The integration of radar sounders on interplanetary missions has historically presented a unique set of Electromagnetic Compatibility (EMC) challenges. A retrospective analysis (see Table I) reveals how verification strategies have had to evolve from reactive mitigation to proactive hybrid modeling.

A. The Pioneer: MARSIS

MARSIS represented the first attempt to integrate a massive low-frequency dipole (40 meters) on a standard spacecraft bus. Operating in the 1.3–5.5 MHz band, it faced unique verification challenges that established the baseline for all subsequent missions.

- The "Gravity Gap" in Testing: unlike compact microwave antennas, the MARSIS dipole consisted of lightweight Kevlar/fiberglass tubes designed solely for the microgravity environment. As explicitly stated in the deployment operations analysis, these structures "cannot support their own weight" in Earth's gravity [5]. Consequently, pre-launch verification was forced to rely on component level testing and numerical simulations, leaving the behavior of the fully integrated radiating system unverified in a representative physical environment.
- In-Flight Reality: while the instrument generally achieved sensitivity limited by the galactic noise background, in-flight operations revealed unexpected behavior in the antenna system. Specifically, Band 4 (4.5–5.5 MHz) was not stable since a deviation of about 6 dB was seen between the lowest and the highest frequencies [6]. This instability indicated that the pre-launch numerical models, which relied on a wire frame model of the spacecraft and antennas, could not perfectly predict the complex impedance of the deployed system in the actual flight configuration.

B. JUICE paradigm shift

The JUICE mission represents a turning point because traditional verification methods turned out to be insufficient. The RIME instrument (9 MHz) utilized a 16-meter dipole which, due to geometric constraints, required an extensive and multi-scale validation campaign.

- Multi-scale testing (1:18 to 1:1): to overcome the limitations of standard facilities, engineers employed a tiered approach
  - Scale model (1:18): a passive 1:18 scale model was used in anechoic chambers to validate antenna radiation pattern and ensure the absence of physical obstructions [7].
  - Helicopter test (1:1): a full-scale (1:1) mock-up of the antenna was suspended 320m above the ground with a helicopter in a "free-space" environment. This test was crucial to measure the impedance of the antenna and to characterize its resonance without ground-level interference or confinement of a chamber [8], [9].
- Issue of standard verification: despite these efforts, a critical gap remained. The physical mock-ups were "silent" passive structures and could not replicate the active noise generated by the Power Conditioning and Distribution Unit (PCDU). Crucially, the standard laboratory integration setup proved inadequate for HF/VHF frequencies. The commercial Solar Array Simulators (SAS) used to load the PCDU were designed to replicate DC power generation but could not represent the complex HF impedance—specifically the parasitic capacitance to structure—of the deployed solar arrays [3]. This lack of a representative impedance stabilization network in the test setup masked the reflection and radiation of common-mode noise, which only became apparent in the flight configuration.
- Development of post-launch diagnostic: an investigation combining physical measurements with a custom Line Impedance Stabilization Network (LISN), mimicking the real solar array impedance missed by standard SAS, and full 3D electromagnetic modeling. This method enabled engineers to virtually reconstruct the mechanisms of the radiated electric field with accuracy beyond that of passive physical tests alone.

C. EnVision: Toward a Hybrid Approach

The persistent "verification gap" identified in previous missions suggests that traditional standards may not be sufficient for the extreme sensitivities of modern sub-surface radar sounders. To meet the ambitious scientific objectives of upcoming missions like EnVision (SRS), which require penetrating the Venusian crust despite the severe environmental noise from solar radio emissions and the ionosphere [10], there is an urgent need to address weak points in EMC verification. Specifically, relying solely on standard testing is inadequate; overcoming these weaknesses requires early 3D electromagnetic modeling and hybrid verification strategies to manage complex system-level interactions, such as those between the dipole antenna and the solar arrays of the spacecraft [11].

This research tackles the limitations of standard anechoic chambers below 30 MHz, where absorber depth and ferrite performance decline, causing resonances. It proposes a multi-stage digital twin approach, incrementally modeling facility components to create a trusted test environment baseline. Combining high-fidelity simulations with novel measurements and specialized hardware like custom LISNs, the aim is to develop a more accurate verification protocol. This synergy of advanced modeling and ground testing seeks to better bridge terrestrial constraints and in-flight conditions.

III. Physical Limitations of Anechoic Chambers

The verification of electromagnetic compatibility for HF and VHF radar sounders faces obstacles that fundamentally challenge feasibility of pure and direct verification by physical testing to observe the important "Test-As-You-Fly" principle. Unlike standard communication systems operating in microwave bands, low-frequency scientific instruments interact with the

TABLE I
RADAR SOUNDER SPECIFICATIONS, ANOMALIES AND MITIGATION STRATEGIES

Mission	Sounder	Frequency	RF Power	Aperture	Anomalies	Test/Mitigation
Mars Express	MARSIS	1.3-5.5 MHz	10 W	40 m dipole 7 m monopole	Impedance mismatch	Mitigation: Frequency agility
MRO	SHARAD [13], [14], [15]	20 MHz	10 W	20 m	Interference from internal units; Distorted antenna pattern caused by solar panels	Mitigation: Onboard signal attenuation and ground post-processing; Roll maneuver
JUICE	RIME	9 MHz	10 W	16 m	Interference during commissioning; Coupling with solar panels	Mitigation: Ground post-processing; Test: Development of high fidelity SAS and hybrid models; Mock-up 1:18 and 1:1
EnVision	SRS	9 MHz	200 W	16 m	TBD	TBD
Europa Clipper	REASON [16], [17]	9 MHz 60 MHz	11.75 W 5.5 W	2x17.6 m 4x2.76 m	Unforeseen EMI from the fully deployed, massive antennas; Data noise from Internal Electrostatic Discharge (IESD).	Mock-up at Mesa JPL facility; Pre-launch mathematical modeling and in-flight calibration.

testing environment in ways that standard facilities cannot fully mitigate. The transition from the unbounded environment of space to the confined volume of an anechoic chamber introduces boundary conditions and reflection phenomena that are non-existent in the operational scenario. Consequently, the ground validation process becomes a compromise between theoretical requirements and the physical realities of terrestrial test facilities.

A. Geometric Constraints and Material Ineffectiveness

The fundamental problem lies in the physical dimensions of radiating systems operating in the HF and VHF bands. The dipole antennas necessary for subsurface sounding at MHz frequencies reach considerable physical extensions, typically between 16 and 40 meters. Although some exceptionally large anechoic chambers might accommodate the isolated antenna, the true complication arises because the operating wavelength being comparable to the spacecraft dimensions. At these frequencies, the satellite body and fully deployed solar panels do not act as mere mechanical supports; they become an electromagnetically interactive, integral part of the radiating system. Accommodating and testing this complete, fully integrated configuration—with both the radar dipole and the solar arrays fully deployed—within the confined volume of an anechoic chamber is often practically impossible. Complementing these geometric constraints is the ineffectiveness of absorbing materials. Standard anechoic chambers are based on a combination of pyramidal absorbers and ferrite tiles, both of which fail at the HF frequencies required by radar sounders due to different physical limitations. The geometric thickness of pyramidal absorbers becomes negligible compared to the operating wavelengths (tens of meters), rendering them effectively transparent. Similarly, ferrite tiles lose their magnetic loss characteristics at these low frequencies. Consequently, the chamber walls fail to absorb the radiated energy, generating severe reflections that completely invalidate the 'free-space' assumption required for representative testing.

B. Facility Limits and Instrumentation Artifacts

Beyond geometric and material constraints, the new electric field emission requirements are so stringent that they challenge the standard capabilities of test facilities. Very few commercial test facilities are capable of reaching the ambient silence levels necessary to verify extreme scientific requirements (e.g. down to -10 dBμV/m) using standard radiated emission setups. A critical limitation in these environments is the testing instrumentation itself. Even advanced FFT-based EMI receivers can introduce measurement artifacts [12]. The digital electronics necessary for signal processing (DSP) inside modern receivers generate internal spurs that, at these extreme sensitivities, appear as artifacts in the measurement range. While using optimized configurations such as specific IF filters, low-noise pre-amplifiers (LNA), and a hybrid use of standard and FFT-based receivers can partially mitigate these issues, definitively distinguishing true apparatus disturbances from chamber thermal noise or internal receiver artifacts remains practically very challenging. Consequently, traditional radiated measurements eventually have to be tailored or complemented. To overcome these facility and instrumentation limitations, the verification paradigm should include characterizing the coupled noise directly at the instrument level. This is achieved by utilizing the payload's own highly sensitive Receive (RX) chain itself or a high-fidelity test equivalent (EGSE) to measure the true interference floor within its operational band.

IV. HYBRID VERIFICATION METHODOLOGY

Direct free-space measurements of large, low-frequency radar antennas present limitations on the ground due to environmental noise, reflections, and structural constraints. While pre-launch testing is traditionally shifted inside anechoic chambers, standard absorbing materials and ferrite tiles lose effectiveness below 30 MHz, creating an environment that introduces some artifacts. To address these limitations, a hybrid methodology is proposed. The long-term goal of

this approach is to develop a trusted digital twin of the testing facility, which could eventually enable the evaluation of chamber reflections and predict the payload's in-flight performance at deep HF frequencies. As a first step toward this low-frequency extension, the methodology is currently being evaluated at a higher frequency (70 MHz) to validate the baseline modeling workflow before scaling down to the more critical HF bands.

The proposed verification framework consists of the following sequential steps:

- Identification of key parameters for antenna characterization: the first step requires defining the foundational figures of merit needed to evaluate the antenna's behavior and its interaction with the environment. Specifically, the reflection coefficient S_{11} is identified to evaluate impedance mismatch and resonance shifts. Concurrently, the radiation pattern and the Antenna Factor (AF) are selected as critical parameters. Characterizing the AF is essential to accurately translate the voltage received at the instrument terminal into the actual incident electric field, while the radiation pattern maps how the confinement of the facility alters the directional properties of the radiating system compared to an ideal free-space scenario.
- Modeling of the measurement environment: this step involves the high-fidelity numerical replication of the entire test setup within a 3D electromagnetic simulator (in this case CST Microwave Studio). The virtual environment incorporates the chamber's metallic enclosure, the structural dimensions of the workbench, and its respective grounding bars. Particular emphasis is placed on the electromagnetic characterization of the absorbent walls; the ferrite tiles are modeled by implementing their complex frequency-dependent magnetic permeability (μ_r) and dielectric permittivity (ϵ_r). Accurately capturing these dispersive material properties is crucial, as the non-ideal behavior and reduced loss mechanisms of the ferrite at lower frequencies dictate the facility's baseline reflection profile.
- Validation of the chamber model via reference antenna: to verify the accuracy of the simulated environment, experimental measurements are performed using a well-known reference antenna.
- Simulation of the antenna under test (AUT): once the numerical model of the chamber, ferrites, and workbench is validated, the reference antenna is replaced in the simulation environment with the actual antenna under test.

V. Case Study: Monopole Antenna

A preliminary case study was conducted within a semi-anechoic chamber with dimensions of 6×4×3 m. The chamber features metallic walls lined with a ferrite absorber layer, while the floor consists of a reflective metallic surface. A copper workbench measuring 1×2.27 m is positioned along one side of the room and is electrically bonded to the chamber structure via 1.2 m long grounding bars. To complete the experimental setup, a monopole antenna is placed at a distance of 1.8 m from the workbench and approximately 2 m away from the chamber walls. (see Fig.2)

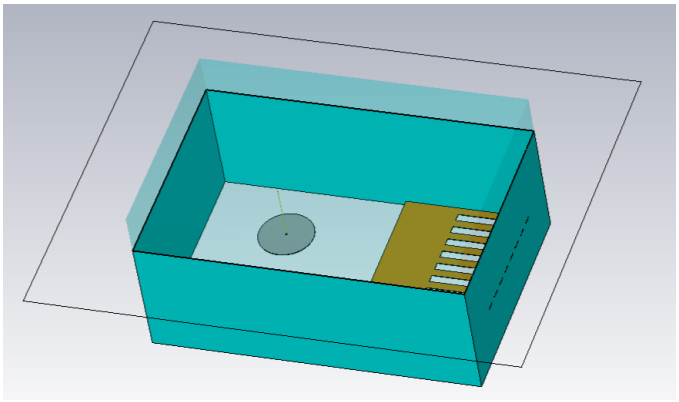

Fig. 2. CST Anechoic chamber geometry

Fig. 3. Case study: picture of the measurement setup

The ferrite on the walls and ceiling were simulated considering the values of real and imaginary part of permeability as a function of frequency as reported in [18]. As test antenna was chosen a $\lambda/4$ monopole antenna with a circular ground plane (diameter 0.25 λ) operating at around 70 MHz. In this preliminary analysis, the variation of the reflection coefficient only is analyzed. The experimental setup is shown in 3. The reflection coefficient is measured within the physical facility and directly compared against the numerical results obtained from the 3D simulation. A close correlation between the measured and simulated S_{11} curves serves to validate the electromagnetic model of the chamber, proving that the boundary conditions and the ferrite properties have been correctly captured 4.

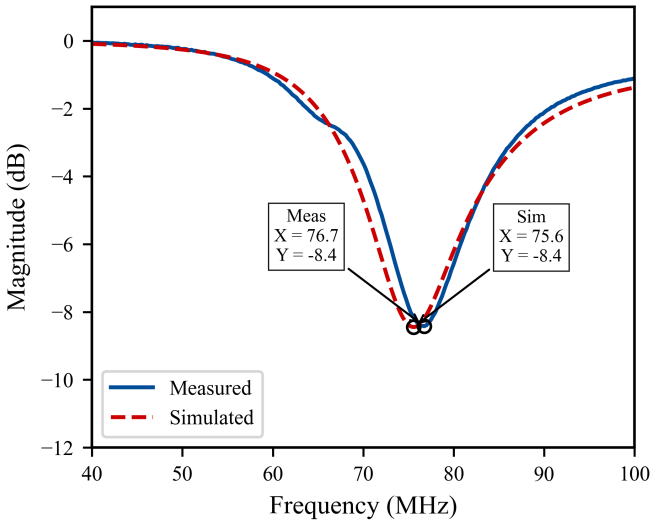

Fig. 4. Case study:S_{11} of a monopole antenna with circular ground plane.

VI. Conclusion and Future Work

The evolution of planetary radar sounders, from the early missions like MARSIS to the upcoming EnVision SRS, highlights a fundamental shift in the management of Electromagnetic Compatibility. Traditional standard test methods have encountered insurmountable physical barriers, such as the geometric constraints of anechoic chambers. The JUICE mission highlighted a critical fragmentation in current protocols: while full-scale helicopter-borne tests can characterize antenna radiation in "free-space," they utilize passive mock-ups that cannot replicate the spacecraft's internal electromagnetic life. Conversely, standard laboratory integrations often fail to capture the radiation of common-mode noise, for example because they lack a representative high-frequency impedance of the large solar arrays.

The successful mitigation of these issues through post-launch analysis and hybrid modeling stresses the need for system-level verification to now integrate high-fidelity electrical simulations with specialized hardware, such as Line Impedance Stabilization Networks (LISN). This hybrid approach is expected to allow for the characterization of complex interactions between the spacecraft bus and the radiating system that were previously undetectable. For future missions like EnVision, the early adoption of these lessons is no longer optional but could become a prerequisite for scientific success. Ultimately, as radar sensitivity requirements continue to push toward the galactic noise limit, the synergy between advanced numerical modeling and representative ground testing could become the only viable path to ensure the electromagnetic silence necessary for deep-space geophysical exploration.

The effect of the anechoic chamber with ferrite on the reflection coefficient of a monopole antenna at 70 MHz has been analyzed with measurements and simulations. Future work will be to consider other parameters such as impedance, antenna factor, radiation pattern and to apply this approach to dipoles and radar-sounder antennas. Additionally, the entire setup and analysis will be rescaled to the frequencies of interest, specifically below 30 MHz.

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