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STUDY AND SIMULATION OF CUBESATS COMMUNICATION SYSTEMS FOR ISARA MISSION

REPORT

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STUDIES: GRAU EN ENGINYERIA EN VEHICLES AEROESPACIALS

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LIST OF ABBREVIATIONS

ADCS	Attitude Determination and Control System
ESA	European Space Agency
GS	Ground Station
HGA	High Gain Antenna
ISARA	Integrated Solar Array Reflectarray Antenna
ISIS	Innovation Solutions In Space
LEO	Low Earth Orbit
NASA	National Aeronautics and Space Administration
NPR	NASA Procedural Requirements
PCB	Printed Circuit Board
P/L	Payload
RF	Radio Frequency
RX	Receive
S/C	Spacecraft
TRL	Technology Readiness Level
TX	Transmit
UHF	Ultra High Frequency
VHF	Very High Frequency

CHAPTER 1: INTRODUCTION

1.1 AIM

The general purpose of this study is the analysis and simulation of the communication systems of a real aerospace vehicle. In particular, this study will be focused on the performance understanding and evaluation between an UHF antenna and the vehicle itself for NASA'S ISARA mission.

1.2 SCOPE

The scope of this study is composed by two different procedures.

On the one hand, the main work effort of this study will be the practical part, which, at the same time, is divided in three phases:

1) 3D CAD design of the ISARA satellites fuselage and structure.

2) Addition of the antennas and the other communication systems components to the 3D model.

3) 3D simulation of the communication systems with the professional software CST Microwave Studio.

On the other hand, complementary studies about radiofrequency regulations, environmental issues for ISARA mission and the current economic situation of commercial communication systems for CubeSats will be carried out to fulfill the academic research.

1.3 REQUIREMENTS

Previously to start the project up, because of the open sight of the proposed TFG topic, there were some initial requirements and constraints to face by the time to choose a specific spacecraft to work with:

- **Spacecraft size.** It should be noticed that the bigger the spacecraft was, the longer will be the time necessary for software simulations.

- **Communication systems characteristics**:
    - Devices and structure materials.
    - Antenna parameters: gain, directivity, dimensions, operation frequency, typology, etc.

- **Spacecraft mission.** The application of the communication systems give other essential information such as the capacity of the signal.

Afterward, the requirements to accomplish the goals of this study are:

- Get the radiation patterns and the antenna parameters of the satellite equipment.

- Evaluate the interactions between the UHF antenna and ISARA CubeSat structures and components.

- Fit the radiofrequency regulation standards with the characteristics and performance of the communication systems.

- Develop all the necessary documents to understand the ISARA communication systems operation, such as drawings, simulations, analysis, graphics, etc.

- Get a conclusion from a comparison between ISIS radiation patterns provided on their website in front of the results of the CST Microwave Studio simulation.

1.4 BACKGROUND

Antenna design is a very wide concept which can range from virtually impossible to very simple cases. Mainly, it depends on the situation and the constraints. If it is required to design an antenna from zero for certain application, there is no general formula or checklist one can follow in order to reliably solution. It starts with a firm understanding of all the requirements and the fundamental knowledge of the antenna types, and the study of some examples with similar applications.

This project is about the design of the UHF antenna used as on-board communications system on ISARA's CubeSat. This is a commercial antenna manufactured by Innovative Solutions In Space Company, designed specifically for nanosatellites.

The performance study of the antenna with CST Microwave Studio software will allow to determine key operation parameters such as the gain, the operation frequency, the efficiency and so on.

All the obtained results would be useful for a second stage of the design that could involve the manufacture of the antenna in question, and physical testing of the parameters. Since, recently, nanosatellites are being quite popular for a more accessible near space exploration, this study could help to bring a homemade solution in front of commercial options for communication systems.

1.5 METHODOLOGY

As it has said before, the aim of this study is the simulation of the communication systems performance between those systems and the vehicle itself for ISARA mission. This task will be carried out mainly with the CST Microwave Studio software.

This programme is one of the modules of CST Studio Suite and it is probably one of the best time domain (TD) solver for wakefields or beam coupling impedance calculations (MAFIA). Once geometry input is done it can be used both for TD and finite difference (FD) simulations. Moreover using the module Design Studio (DS) it can be combined with the other studios for multiphyisics and integrated electronics simulation.

However, the main advantage for this study is that it is both a powerful and user-friendly input that enables fast construction of models. Its popularity between antenna designers in front of other software and the amount of research articles based on CST solvers is another important point in favour to notice. As a result, there are forums and support services available where it is possible to get solutions to unexpected difficulties.

On the contrary, the problem that could bring about some setbacks is that EM simulations can be classified as high performance computing tasks. This means that computers used for CST applications should meet high requirements in terms of CPU, RAM, and graphical performance. Sufficient power supply and cooling also have to be ensured for the workstation.

1.6 DOCUMENT FORMAT

This project is composed by three separate documents to ease and speed up the lecture and understanding itself.

- REPORT
- ANNEX
- BUDGET

At first, there is the REPORT which includes the main explanatory information and the analysis of the simulation results. The gross of the work is contained on CHAPTER 4: UHF ANTENNA STUDY and complemented with the graphics of the ANNEX.

CHAPTER 2 and CHAPTER 3 work as an introduction into ISARA mission and define the role of the UHF antenna on it.

In CHAPTER 5 it is sight a set of possible future tasks to continue this study and get a more real and complete results and conclusions about the performance of the UHF antenna. At the same time, it adds a critical point of view of the realised work and possible improvements.

CHAPTER 6 exposes all the pros and cons related with the environmental aspects of the introduction of Cubesats as a new option for space exploration. Relevant topics such as space debris, atmospheric pollution of rocket launches and manufacturing issues are discussed.

In CHAPTER 7 it can be found a brief summary of the standards and regulations which were used to ISARA mission development and the CubeSat design.

Finally, all the matters related to the project management are exposed on CHAPTER 8. It includes a budget summary, which is complemented with the BUDGET document for more precise information, and the scheduling and interdependency relationship of the tasks realized during this study and some possible future tasks to improve actual work.

CHAPTER 2: STATE OF THE ART

Nowadays, continuous evolution of electronics have allowed to set a trend on the optimization of every daily used gadget and device to smaller sizes and more complex functionality. This tendency is also followed in Aerospace industry giving room to the CubeSats appearance.

CubeSats are a class of research spacecraft called nanosatellites, which are much cheaper, simpler and faster to build than standard satellites. These properties turn them into very interesting options for companies, organizations or even particular researchers without large economical resources. At the same time, these devices are suitable for some higher-risk missions.

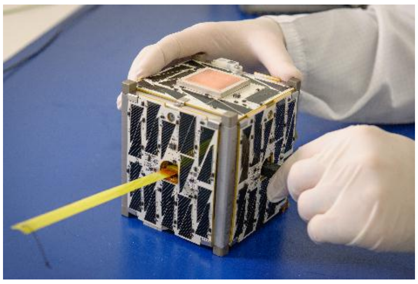


Figure 1. PhoneSat 2.5: 1U CubeSat built at NASA's Ames Research Center. Source: NASA Ames.

In fact, despite to date the vast majority of CubeSat activities belong to the category of radio amateur or university projects, lately, CubeSats have also started to show an increasing potential for commercial use, and are recognized as one of the current top trends in space activities.

In terms of measurements, CubeSats are built to standard dimensions called Units or “U” of 10x10x10cm. In practical applications, they used to be 1U, 2U, 3U, or 6U in size, and typically weigh less than 1.33 kg per U. For example, a 3U CubeSat, like the ones used in ISARA mission, has dimensions of 10x10x30 cm and weighs about 3-4 kg. This is usually the minimum size which can accommodate small technology payloads.

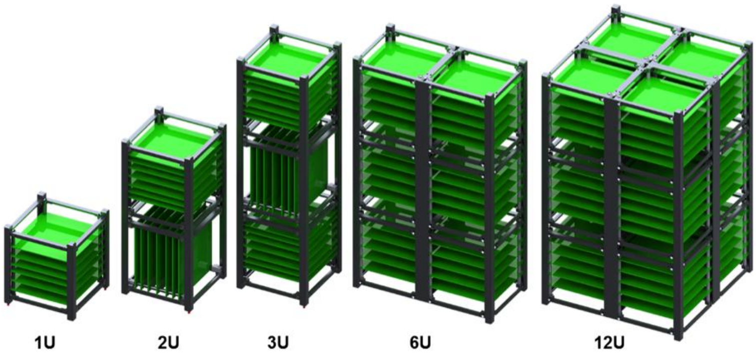


Figure 2. Different CubeSat sizes. Source: Radius Space.

2.1 CURRENT CUBESATS ROLE IN SPACE MISSIONS

All the great qualities and potential possibilities of this devices has not been unnoticed so that, today, it has already been carried out some space missions in charge of big organizations as ESA and NASA. The main goal for most of them have been space flight tests to prove this new technology and increase its reliability for future missions that could cover current necessities.

Indeed, besides ISARA mission, there are other several interesting planned missions which will become a reality on the following years:

- **MarCO (Mars Cube One).** When NASA launches its next mission on the journey to Mars (InSight) - a stationary lander - the flight will include two CubeSats. They will observe the landing on Mars and send back Data to Earth. The launch date of InSight has been scheduled in 2018.

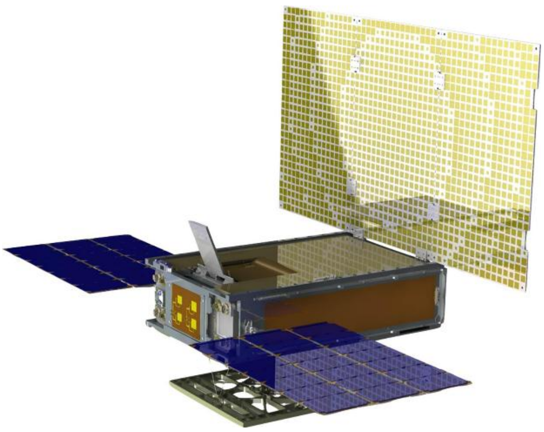


Figure 3. MarCO CubeSat CAD model.

- **INSPIRE (Interplanetary NanoSpacecraft Pathfinder In Relevant Environment).** The primary objectives of this mission are to demonstrate fundamental CubeSat functionality in deep space like command and data handling, telecommunication and navigation. This mission hasn’t launched yet and is planned for 2017.

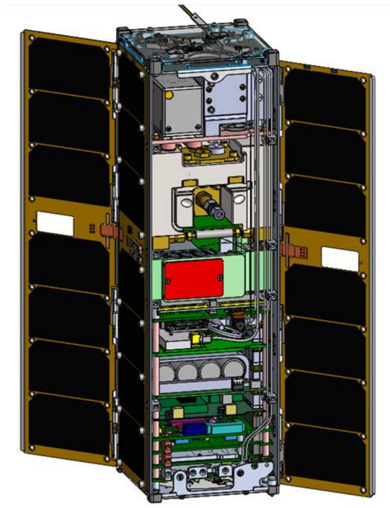


Figure 4. INSPIRE CubeSat CAD model.

- **ASTERIA (Arcsecond Space Telescope Enabling Research in Astrophysics):** The goal of ASTERIA is to achieve arcsecond-level line of sight pointing error and highly stable focal plane temperature control. These technologies will enable precision photometry, i.e. the careful measurement of stellar brightness over time. This in turn provides a way to study stellar activity, transiting exoplanets, and other astrophysical phenomena, both during the ASTERIA mission and in future CubeSat constellations. The delivery of the flight hardware is planned in summer 2016 and a launch short after that.

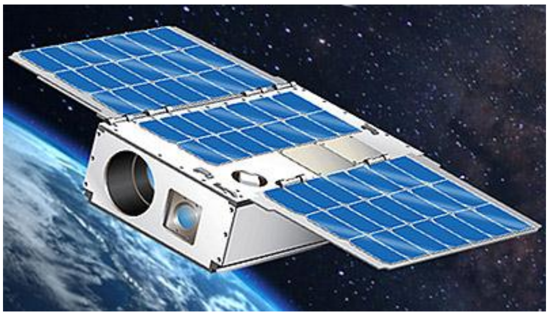


Figure 5. ASTERIA CubeSat CAD model.

2.2 COMMERCIAL CUBESAT ANTENNAS

2.2.1 ISIS UHF Deployable Antenna

The ISIS deployable antenna system contains up to four tape spring antennas of up to 55 cm length. The system can accommodate up to four monopole antennas, which deploy from the system after orbit insertion.

The wires are melted using two redundant heating elements per wire. RF phasing / BalUn circuitry ties the antennas together in for instance a turnstile configuration, two dipoles, or just one dipole. ISIS can configure the antenna system to be compatible with all UHF and VHF radios which are typically used for CubeSats.

Depending on the configuration, one or two radios in the CubeSat can connect to the antenna system by means of miniature RF connectors. Furthermore, the top face of the antenna system can accommodate a two solar cell solar panel and provisions have been made such that it can be customized for customers who require sensors or other systems to protrude to the exterior, e.g. camera apertures.

The antenna system has been designed for maximum compatibility with existing COTS CubeSat components. It is compatible with any UHF and/or VHF radio system. It can be mounted on top and bottom faces of all ISIS CubeSat structures and Pumpkin rev C and rev D CubeSat structures. For custom made structures, which adhere to the CubeSat standard mechanical envelope, mounting should also be possible.

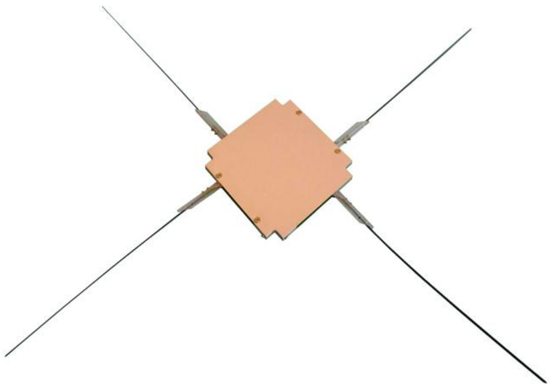


Figure 6. ISIS UHF Deployable Antenna.

2.2.2 GOMSPACE NanoCom ANT430 Antenna

A reliable antenna is paramount for safe operations of a satellite. This antenna for the 70cm band is a deployable, omnidirectional, canted turnstile antenna system with rigid antenna elements, which eliminates the risk of antenna deformation while.

The turnstile antenna system consists of four monopole aerials combined in a phasing network in order to form a single circular polarized antenna. The antenna radiation pattern is close to omnidirectional and there are no blind spots, which can cause fading with tumbling satellites.

The antennas are compatible with the 1U, 2U or 3U ISIS CubeSat structures and can be mounted on either the top or bottom of the structure.

The antenna PCB is designed to be the least obstructive to any top or bottom mounted payload or panels. It has a low profile that allows a solar panel to be mounted on top, and a large aperture in the center suited for a protruding camera lens, propulsion hardware or similar.

Figure 7. GOMSPACE NanoCom ANT430 Antenna.

CHAPTER 3: ISARA MISSION OVERVIEW

3.1 MISSION SUMMARY

The demonstration of Cubesats potencial applications is the main goal of NASA'S ISARA (Integrated Solar Array and Reflectarray Antenna) mission. It is a technology demonstration of a practical, low-cost Ka-band high-gain antenna on a tiny satellite that will increase downlink data rates from a baseline of 9.6 kilobits per second for existing UHF systems to more than 100 megabits per second with minimal impact on spacecraft mass, volume, cost and power requirements. That achievement is obtained by turning the back of its solar array into a reflector for the satellite's communications antenna.

The success of that increasing on the data transmission capability would make CubeSats ready for immediate infusion into commercial, government and military systems, giving rise to new possibilities of fractionated spacecraft sensors and radar/radiometry science missions that need high bandwidth telecommunications.

During the mission, the spacecraft's location and orientation telemetry data will be analyzed to reconstruct the antenna signal pattern, which will then be compared against pre-flight ground measurements. It will be validated in space during five-month to measure key reflectarray antenna characteristics, which include how much power can actually be obtained over its field of view.

ISARA is a NASA Jet Propulsion Laboratory led mission that will be carried out in close collaboration with Pumpkin, Inc. and Aerospace Corp. The mission budget is around approx. 5,5US$ million. It is scheduled as a secondary payload in Q2 2016 on a Falcon-9 vehicle. The primary mission on the flight is FormoSat-5 of NSPO, Taiwan. The launch site is VAFB (Vandenberg Air Force Base), CA.

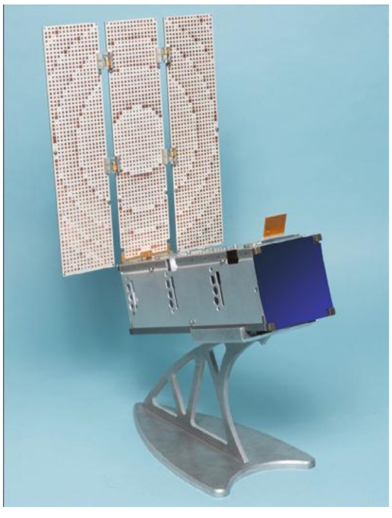


Figure 8. ISARA CubeSat prototype.

3.2 PAYLOAD DESCRIPTION

The telemetry, command data handling and processing functions provide for the two-way flow of information between the satellite and its ground control station. There are transmission (downlink) and reception (uplink) functions to perform, as well as the tasks of gathering and processing data ready for transmission and the processing and routing command data from the ground receiver.

In this section is explained the functionality of the main components on the system context, divided on the two sides of space telecommunications network.

3.2.1 SPACE SEGMENT

In Figure 9 it could be appreciate all the different devices that include the ISARA nanosatellite subsystems.

Between brackets it is shown a NASA terminology to classify the current technology maturity of each component. For more information, it is explained in more details in CHAPTER 7.

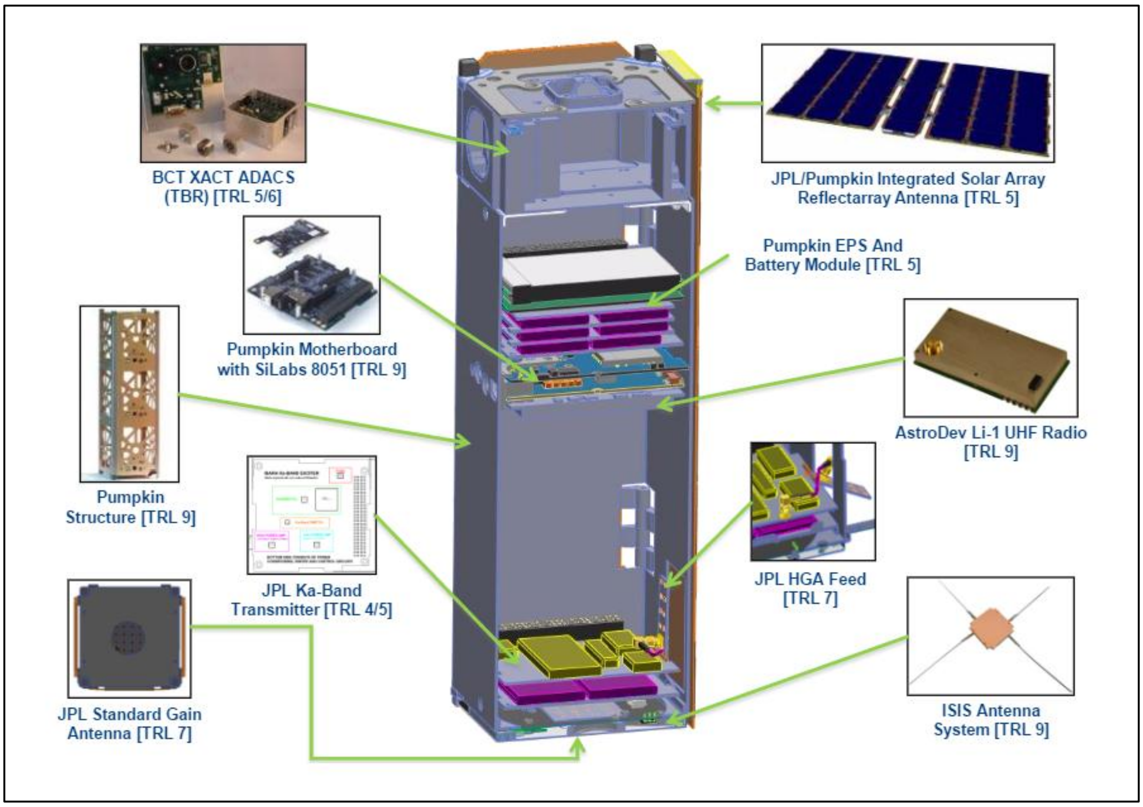


Figure 9. ISARA CubeSat global breakup.

a) CubeSat Structure

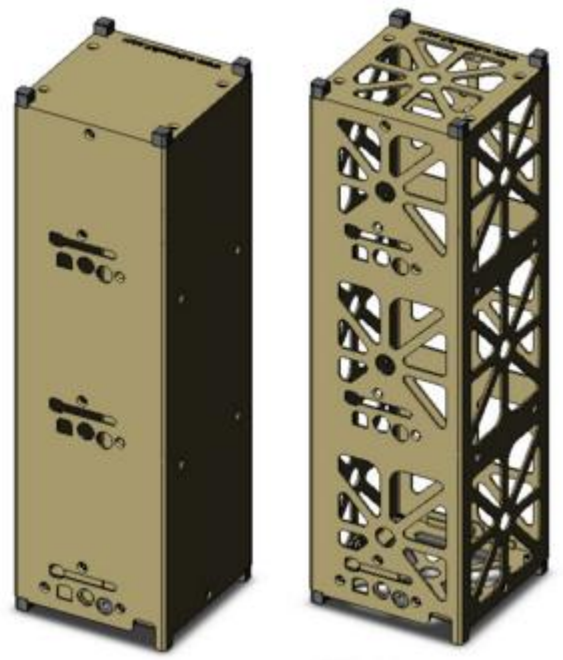


Figure 10. 3U Skeleton CAD model - RevC.

This structure is the unique part that separates all the electronic instrumentation of the S/C from the space environment. For this reason it has to fulfill some key requirements, among others:

- Maximal internal volume
- Lightness wherever possible
- Strength
- Thermal concerns satisfaction
- Good electromagnetic shielding

b) High Gain Antenna (HGA)

The ISARA design is comprised of three 33.9x8.26 cm reflectarray panels designed to achieve 33.5 dB of gain at 26 GHz. Its particularity comes from the incorporation of 24 solar cells on the side of the panels opposite the Reflectarray, so it can provide both prime spacecraft power and high speed datalink.

A reflectarray is a relatively new type of antenna fabricated from standard printed circuit boards with an array of square copper patches etched on them. The patches collimate divergent rays from a small feed antenna into a focused beam, behaving much like a parabolic reflector.

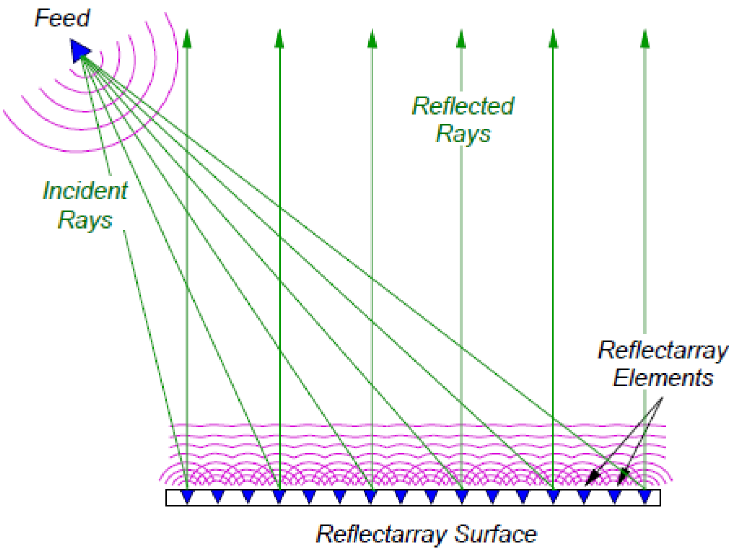


Figure 11. Reflectarray focused beam from feed divergent rays.

Since a solar panel is made of a compatible printed circuit board material, it is possible to print the reflectarray directly on the back of the solar panel. ISARA will use the Pumpkin Turkey Tail solar array configuration.

A small patch array feed antenna placed on the side of the bus completes the high gain antenna. Note that this antenna design can also be implemented in other frequency bands, though only for one frequency band at a time. If multiple frequencies are required, they could be implemented on multiple CubeSats.

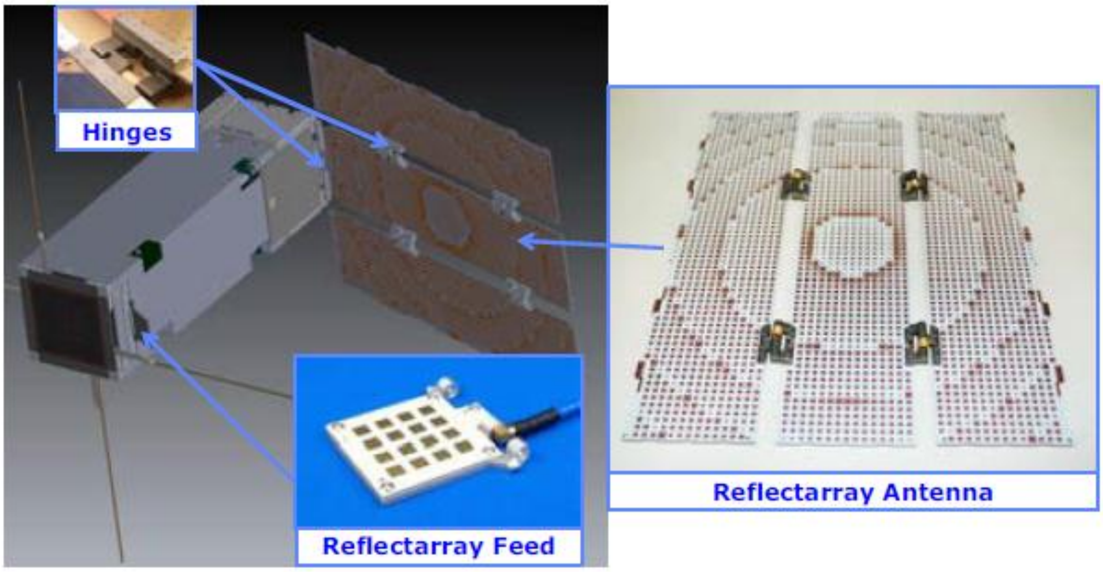


Figure 12. ISARA CAD model and photographs of components.

c) Standard Gain Antenna (SGA)

This antenna is another component developed by NASA on the Jet Propulsion Laboratory. It is designed to achieve 16dB and, currently, it is a demonstrated technology on a prototype test phase on space environment.

The SGA data received on the ground station is used to calculate the Gain of the Reflectarray antenna. It is obtained by the comparison between HGA and SGA data measured on orbit and on the ground.

d) Ultra High Frequency (UHF) Antenna

This element will be the angular stone of the study. It has been made several simulations to cover the operation of the antenna for different CubeSat configurations and mission stages, in order to evaluate its efficiency and suitability for the tasks it has to develop.

It is a commercial antenna developed by ISIS (Innovative Solutions In Space) and its main purpose is to make initial contact with the satellite and perform in-orbit checkout procedures.

e) Ka – Band Transmitter

The transmitter is the component used to amplify the signal to the level required for downlink transmissions. This Ka-band Tx is developed by the Jet Propulsion Laboratory and includes a Switch that alternates rapidly between SGA and HGA to allow the emission from the two antennas.

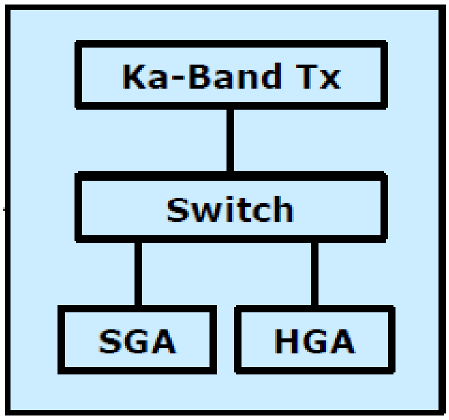


Figure 13. Ka-band payload diagram.

f) Blue Canyon Technologies XACT ADCS (Attitude Determination System)

ADCS system is used to point the antenna in nominal direction. The BCT star tracker maintains an approximate accuracy of 0.02º.

Figure 14. BCT XACT ADCS.

XACT is a reliable CubeSat attitude control system compatible with a variety of configurations and missions. The highly integrated XACT architecture leverages a processing core with a Micro Star Tracker and Micro Reaction Wheel assemblies to enable a miniaturized spacecraft. It features 3-axis Stellar Attitude Determination in a 0.5U micro-package.

3.2.2 GROUND SEGMENT

The ground station is located at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California. It is composed by three main instruments:

- Ka-band receiver with medium gain antenna.
- UHF telecom system.
- Data recording system.

During the in-orbit test, ISARA's Reflectarray antenna will transmit a signal that will be received by this ground station. There, the spacecraft's location and orientation telemetry data will be analyzed to reconstruct the antenna signal pattern, which will then be compared against preflight ground measurements.

The HGA and SGA power received are used to calculate the operative Gain from the HGA as:

$$Gain = measured\ HGA - measured\ SGA + known\ SGA\ Gain$$

CHAPTER 4: UHF ANTENNA STUDY

For more information, the whole results of the CST Microwave Studio simulations are organized in the ANNEX.

4.1 METHODOLOGY

4.1.1 Simulation process step by step

All the graphics and parameters which has been obtained in this study comes from CST Microwave Studio simulations. To cover the main considered scenarios for the antenna operation it has been solved several cases.

Then, the general procedure which should be followed in each simulation to get suitable results is explained:

1) Template creation

When software is open for the first time, it should be defined some general guidelines for the project it is going to be developed, such as the frequency range operation, the type of the desired antenna, the measurement units, and so on.

2) 3D CAD modeling

As a CAD model is required to perform the simulation, it is necessary to define the real dimensions of the components precisely.

To carry out this task, CST Microwave Studio provides a tool that allows the generation of simple geometries.

On the other hand, it is also possible to import the model from another specialized CAD software as ".IGS" or ".STP" file format.

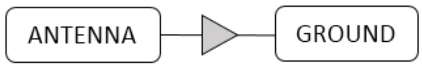
3) Material assignment

Then, the components materials are very important in order to obtain suitable results which could be correctly compared and analyzed.

CST Studio Suite includes a large and complete library for materials choice. Anyway, there is also the option to define new materials if it was necessary.

4) Ports disposition

A port is the feeding point of an antenna. It must be defined correctly from the transmitting element to the ground element of the antenna to achieve an appropriate operation.



5) Antenna operation frequency determination

Once the ports are determined, it is the time to run the solver.

As a result, the program draw up the scattering parameters. If precedent tasks were done correctly and the CAD model has a good design, in the graphic for return loss (S11) among the frequency range desired should appear a peak under -10 dB which determines the operation frequency of that antenna.

In case there were more than one port, it should take into account the other values of S-matrix apart from the diagonal ones, which give us the insertion loss produced by the coupling between ports signals.

6) Radiation pattern diagrams

Finally, with the correct operation frequency of the antenna it is possible to find the rest of the results. To get them, it is necessary to run the solver again.

For this study, it has been monitored the electric field, the magnetic field and the farfield at the aforesaid frequency.

7) ("parameter") vs. frequency graphics

In case it is desired to represent any antenna parameter in front of a frequency range, it also will be necessary to monitoring the farfield in transient broadband on 6^{th} step. Then, after the solver running, there will be available all the required data to draw up the graphics.

4.1.2 Study configurations

For a proper evaluation of the antenna operation it has been simulated in three different configurations to understand how the ISARA CubeSat structure affects to its properties and how are these properties modified along the different stages of the mission.

In Figure 15 it is shown the deployment process of the Integrated Solar Array Reflectarray mechanism. The initial moment, when the panels are still stowed, and the final moment, when the panels are fully deployed, determine the two main operation configurations.

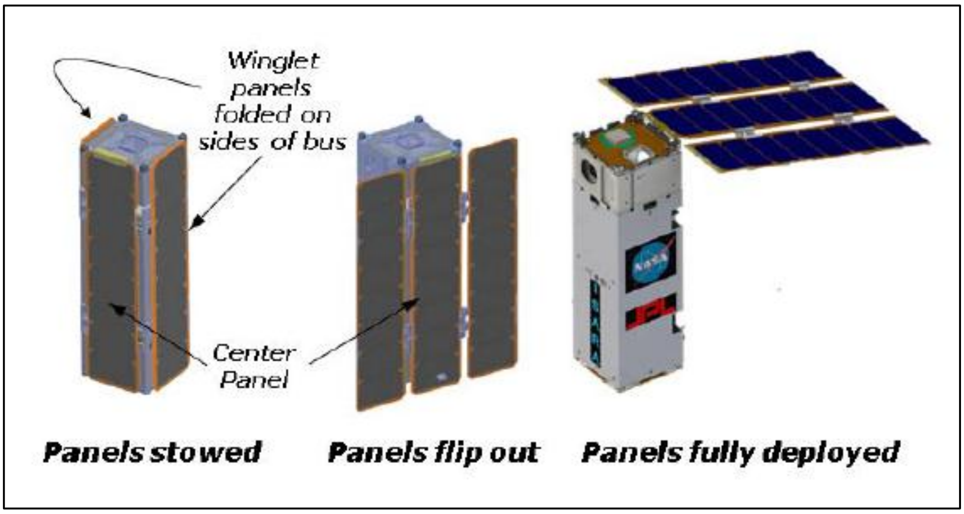


Figure 15. Illustration of ISARA deployment.

Moreover, as it could be appreciate on the images above, the UHF antenna studied has two different sized types of monopoles. It is made up by four monopoles of two different longitudes. For this reason, for each configuration case it has been studied every monopole separately and, finally, all together. As they are sized in twos, it was just required to simulate two of them (P1 = P3 and P2 = P4).

As an exception, in case "3U UHF antenna", it is also simulated a dipole case with short monopoles P1 and P3. The reason is that

Totally, it has been made 10 different simulations.

1) Isolated UHF antenna

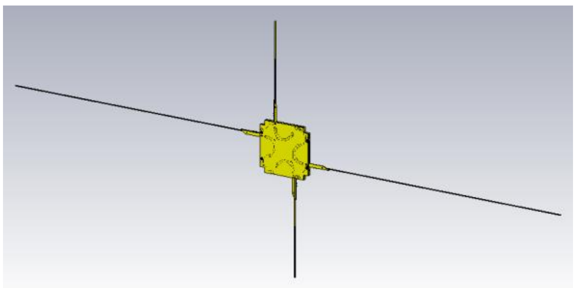


Figure 16. ISIS antenna CAD model.

With this configuration will be determined the real values for the UHF antenna parameters. This will be helpful to determine the interaction with the other elements of the satellite when all the results were compared.

2) 3U UHF antenna

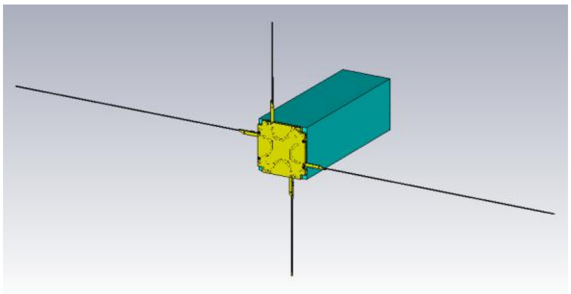


Figure 17. 3U UHF antenna CAD model.

The UHF antenna has two main purposes during the mission. The first of them is to make initial contact with the satellite when it is deployed in space.

When this happens, the HGA is still fold on the walls of the CubeSat. This configuration represents this moment.

3) ISARA UHF antenna

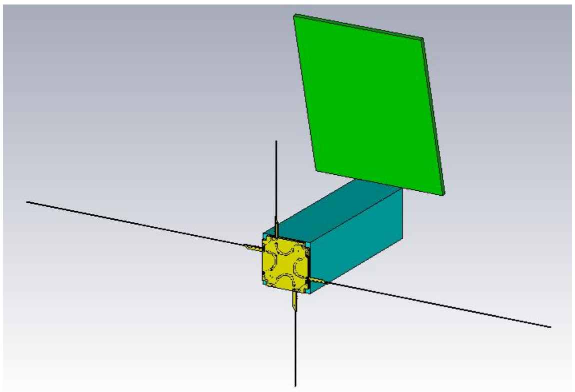


Figure 18. ISARA UHF antenna CAD model.

Finally, the other purpose is to perform in-orbit checkout procedures. On this scenario, the Reflectarray antenna is already deployed so, due to its size, it could modify the operation of the UHF antenna. This third configuration will demonstrate those variations.

4.2 COMPONENTS PROPERTIES

This section presents all the required technical details about the elements that are going to be simulated. It is necessary to approximate as much as possible the data introduced to the computer program to the real values in order to get reliable results.

Although, it has been used some hypothesis which simplify the simulation process without reducing significantly the quality and the validity of the conclusions.

4.2.1 ISIS UHF Deployable Antenna

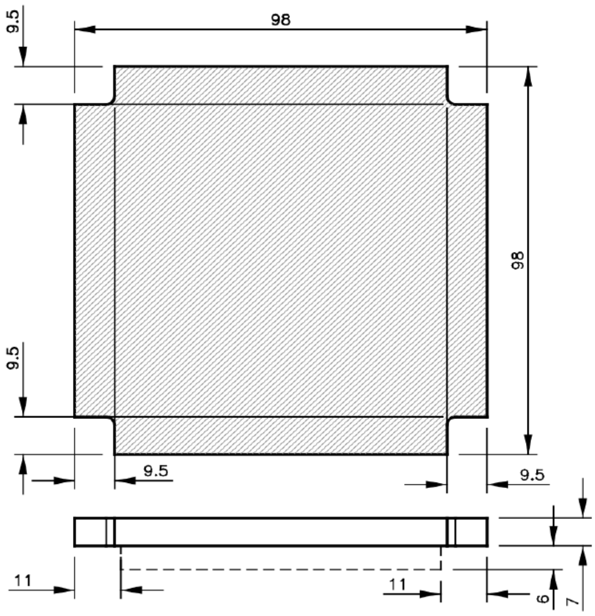


Figure 19. ISIS UHF antenna envelope dimensions.

RF Impedance	50 Ohm
Frequency Range	130 – 500 MHz
Envelope stowed: (l x w x h)	98 x 98 x 7 mm
Supply Voltage	3V (5V and 8V available on demand)
Max. RF Input power	2 W
Configuration	4 UHF monopoles
Material	Aluminum

Table 1. ISIS UHF antenna main properties.

4.2.2 PUMPKIN CubeSat Kit structure

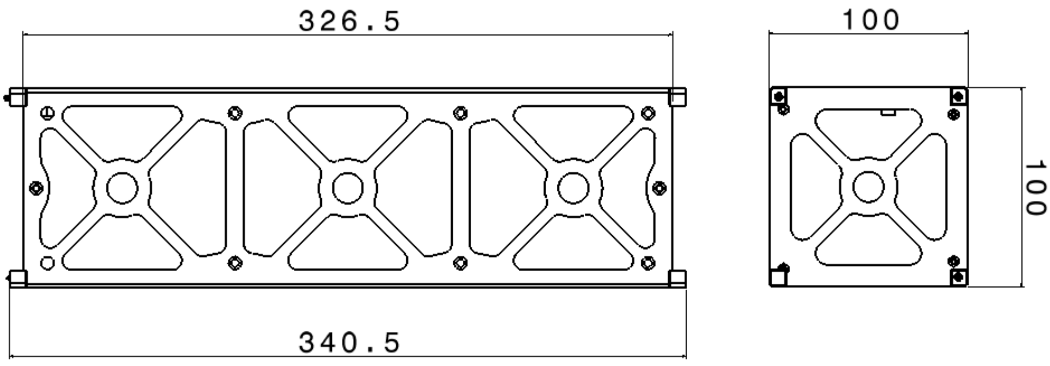


Figure 20. Pumpkin CubeSat structure dimensions.

The main materials of the structure are:

- 5052-H32 Aluminum. For sheet-metal components.
- 7075-T6 Aluminum. For machined components.

Since for simulations it is only relevant the material of the external part of the components, it has just considered the sheet-metal covering components.

Aluminum 5052-H32 Properties	
Density	2.68 kg/m3
Modulus of Elasticity	70.3 GPa
Poisson's Ratio	0.33
Electrical Resistivity	4.99e-006 ohm-cm
Thermal Conductivity	138 W/m-K
Specific Heat Capacity	0.88 kJ/kg-K

Table 2. Aluminum 5052-H32 Properties.

4.2.3 JPL High Gain Reflectarray Antenna

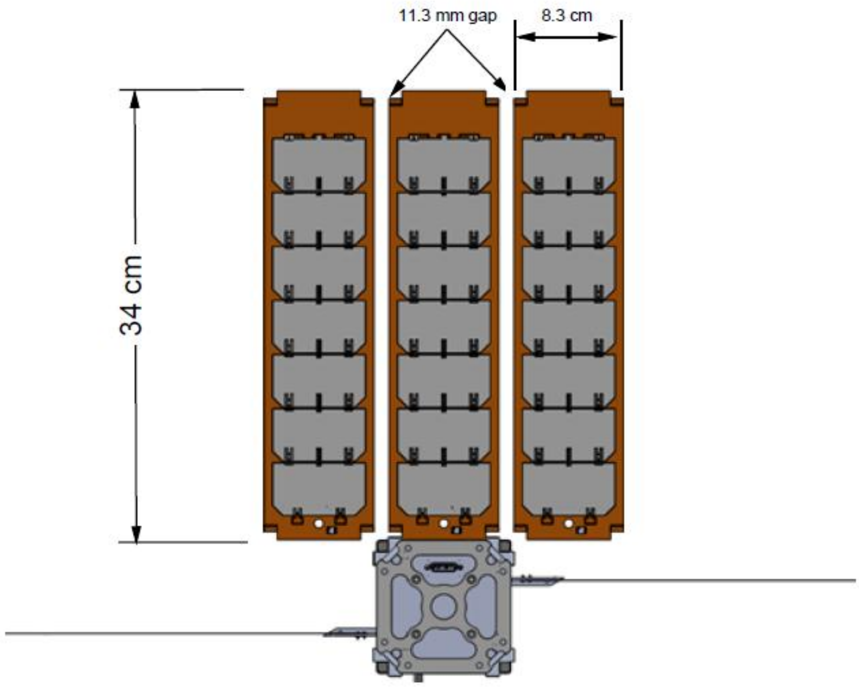


Figure 21. ISARA back view.

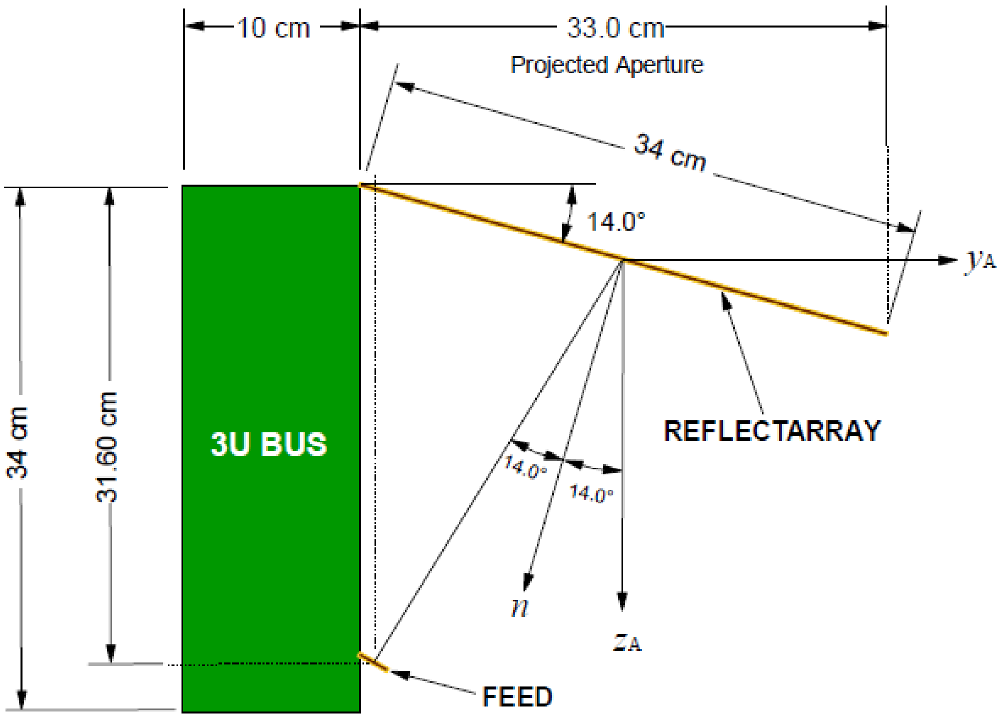


Figure 22. ISARA reflectarray antenna optics design.

4.2.4 Hypothesis and approximations in simulations

a) UHF antenna material is an average Aluminum by default from CST Microwave Studio library.

There isn't specific information about the UHF antenna material but it is an aluminum alloy.

b) CubeSat structure material is Aluminum 5052 – H32.

Since for simulations it is only relevant the material of the external part of the components, it has just considered the sheet-metal covering components. This aluminum alloy had to be introduced by hand to the CST Microwave Studio library.

c) CubeSat structure shape is a rectangular prism of 10x10x30 cm in second configuration and 10x10x34 cm in third configuration.

Because of the antenna radiation patterns provided for ISIS website are obtained with a standard 3U CubeSat model, real dimensions of ISARA mission CubeSat are only applied to the ISARA UHF antenna configuration.

d) High Gain Reflectarray antenna material is Rogers RO4003.

The HGA is an array of square copper patches etched on a 12-mil Rogers RO4003 dielectric substrate.

e) High Gain Reflectarray antenna shape approximated to a 34x27.16 cm sized rectangle.

The real HGA surface was made by 3 panels with 1.13 cm gap between each other to make possible the fold and deploy procedure. In order to simplify the CAD modelling and accelerate the time of simulations it has been omitted these gaps.

4.3 RESULTS ANALYSIS

Unlike the ANNEX, where all the graphics and images were classified as a complementary documentation to facilitate the search of any specific obtained graphic, the main goal of this section is to understand the simulation results and provide a critical view of them.

For this reason, it has been organized differently in three main parts which allows easier comparisons between different configuration simulations.

First of all, as the main reason of this study is determine the performance of the UHF antenna on ISARA Cubesat and evaluate the influence of the other components to its properties, it is necessary to establish a starting point from where it will be possible to compare more complex configurations.

This reference is given by the simulation of the isolated UHF antenna. Here it can be appreciate the clean pure values of the antenna operation without any interference or attenuation caused by an external element.

At the same time, the first part 4.3.1 and the next one 4.3.2 have been subdivided in three simulations to evaluate individually each monopole and also the interactions between them.

The turnstile configuration, which allows the evaluation of all the monopoles working together, gives quite bad results in front of the great ones with the simulation of the monopoles individually. For this reason, those results haven't took into account to the most of antenna parameters evaluation, but only to realize that the insertion loss produced by the monopoles interaction are much lower than the insertion loss in the operation frequencies.

Also, the turnstile configuration is useful to verify that opposed same sized monopoles work at the same operation frequency (P1 = P3 and P2 = P4).

In second place, in section 4.3.2 there are shown every antenna parameter group together with the results of each configuration, Isolated, 3U and ISARA respectively. This distribution is visually understanding to compare the effects of ISARA components to the UHF antenna performance.

Finally, there are a summary with some determining antenna parameters: Operation frequency, maximum realized gain and antenna efficiency.

To transform the logarithmic decibels efficiency to lineal percentage it has been used the following expression:

$$[dB] = 10\log(\%)$$

Where the percentage % is obtained in "so much per one".

4.3.1 Basic UHF antenna parameters

4.3.1.1 Monopole 1 (P1 and P3)

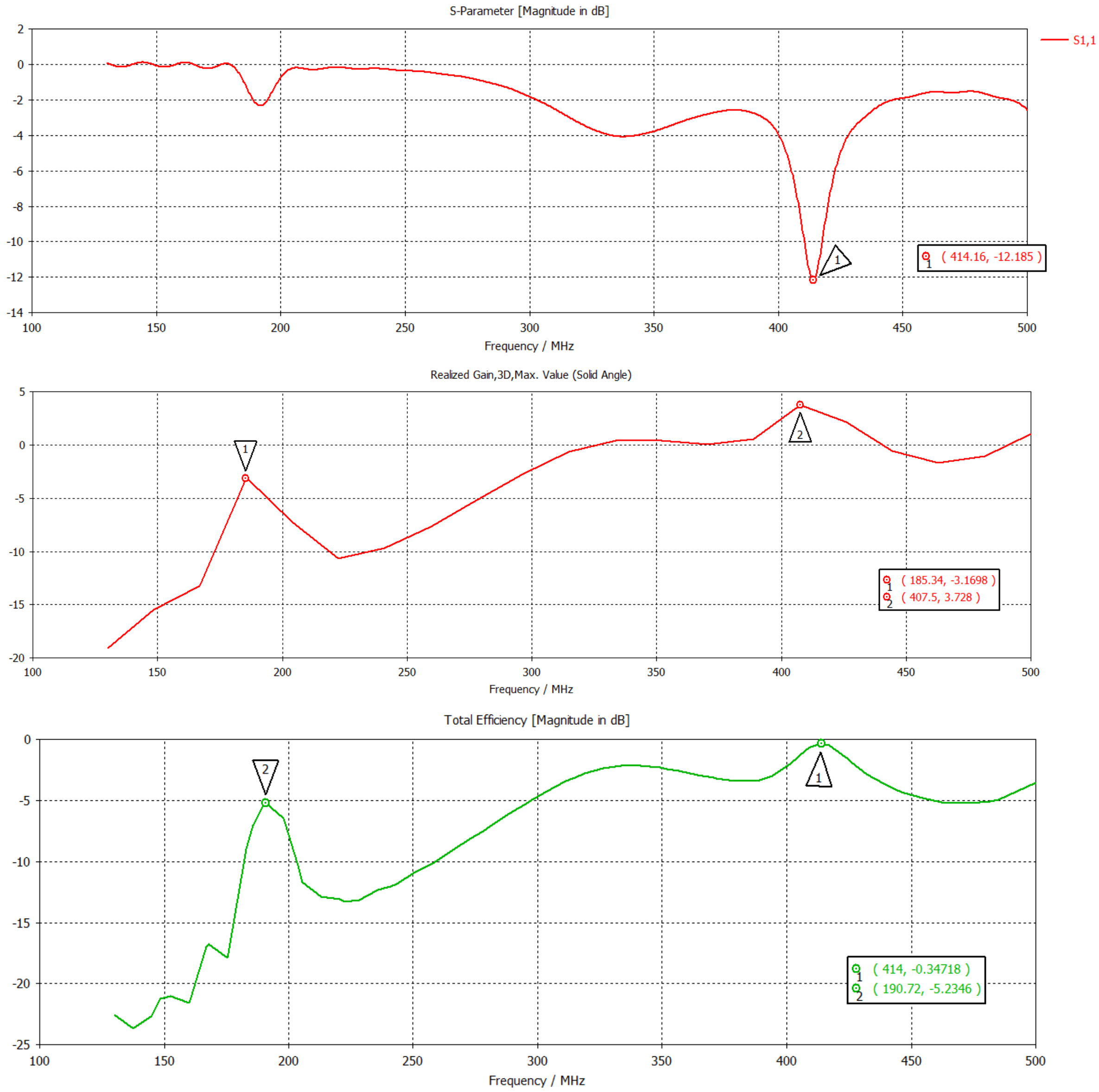


Figure 23. Isolated UHF antenna parameters for P1 and P3. From top to bottom: Return loss, Realized Gain vs frequency range, Efficiency vs frequency range.

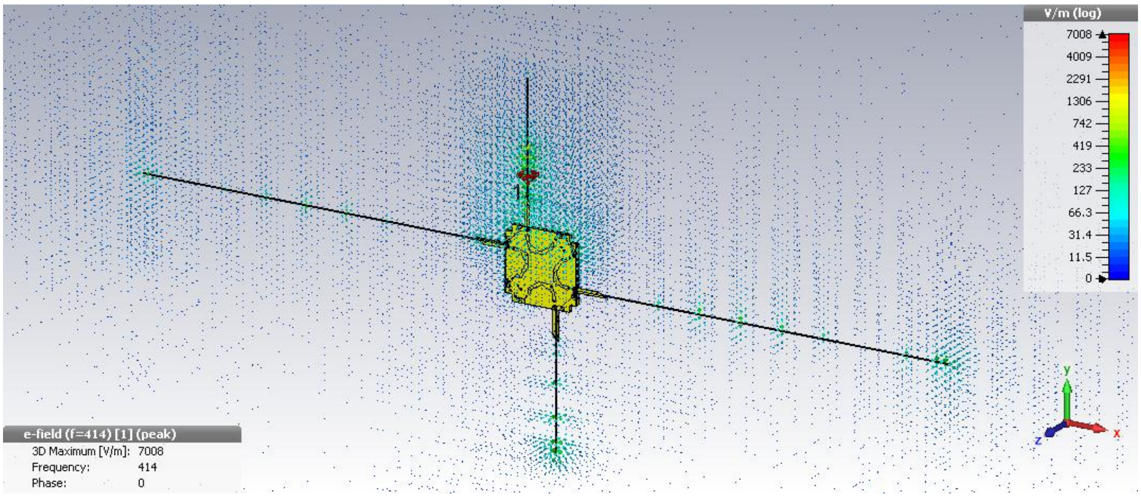


Figure 24. Isolated UHF antenna. Electric field for monopole P1 and P3.

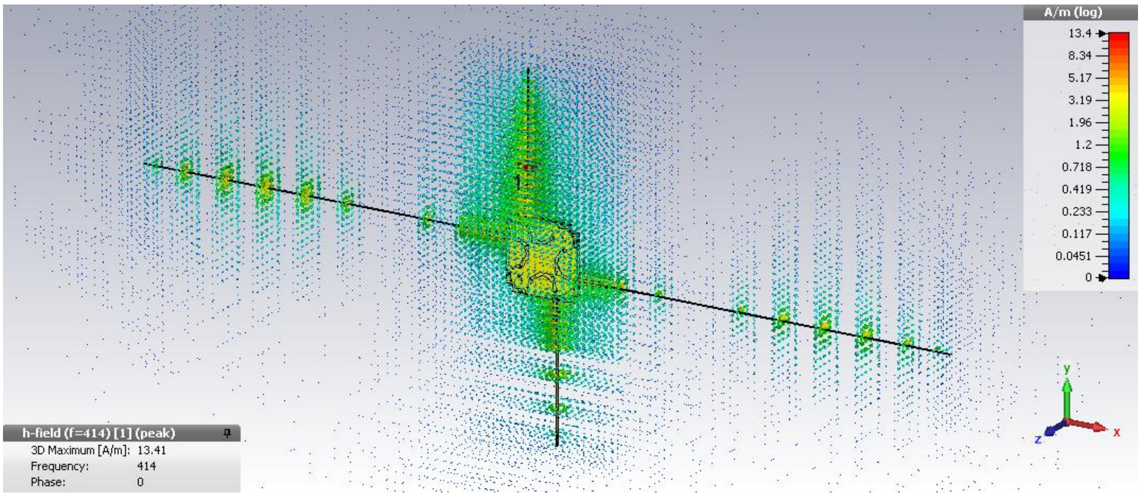


Figure 25. Isolated UHF antenna. Magnetic field for monopole P1 and P3.

4.3.1.2 Monopole 2 (P2 and P4)

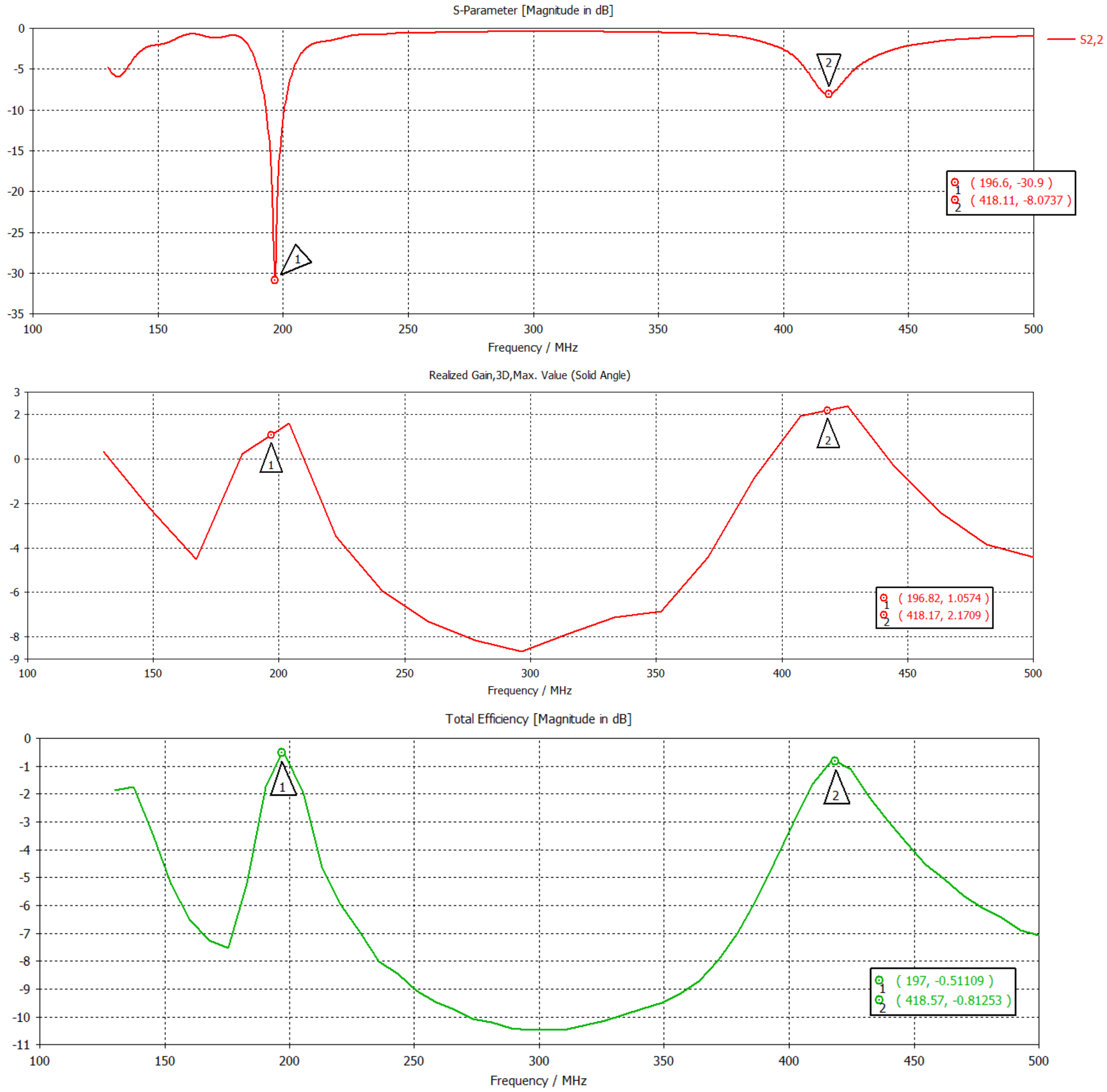


Figure 26. Isolated UHF antenna parameters for P2 and P4. From top to bottom: Return loss, Realized Gain vs frequency range, Efficiency vs frequency range.

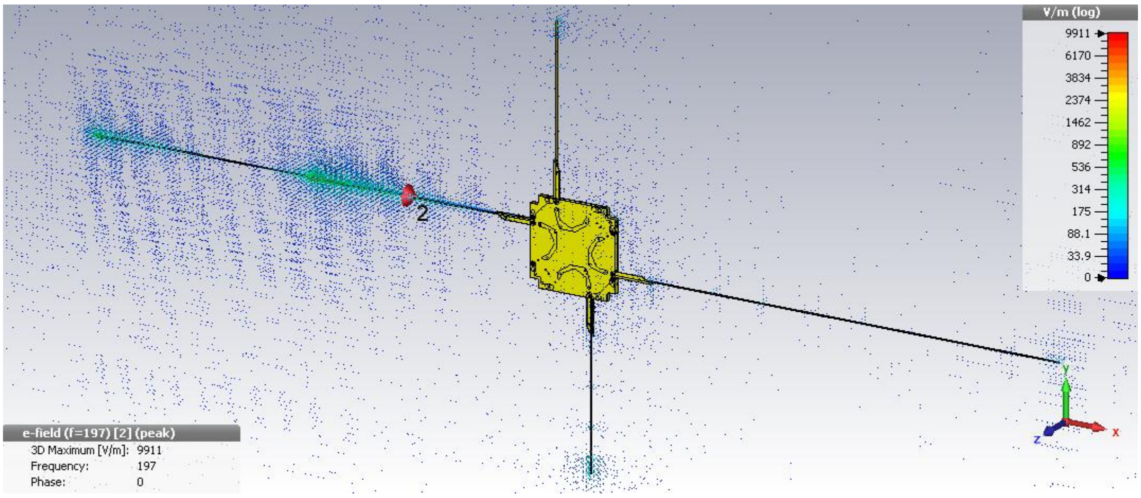


Figure 27. Isolated UHF antenna. Electric field for monopole P2 and P4.

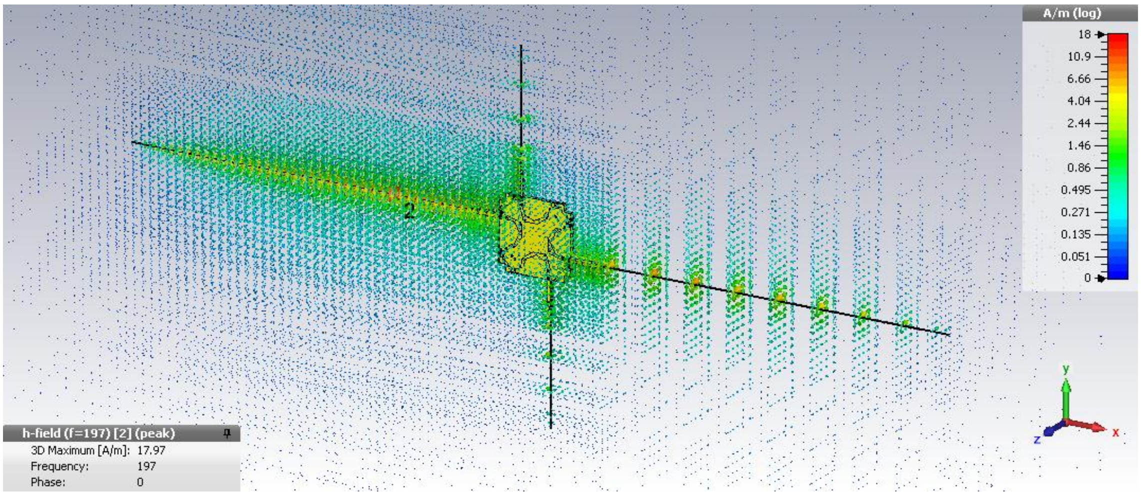


Figure 28. Isolated UHF antenna. Magnetic field for monopole P2 and P4.

4.3.1.3 Monopoles interaction

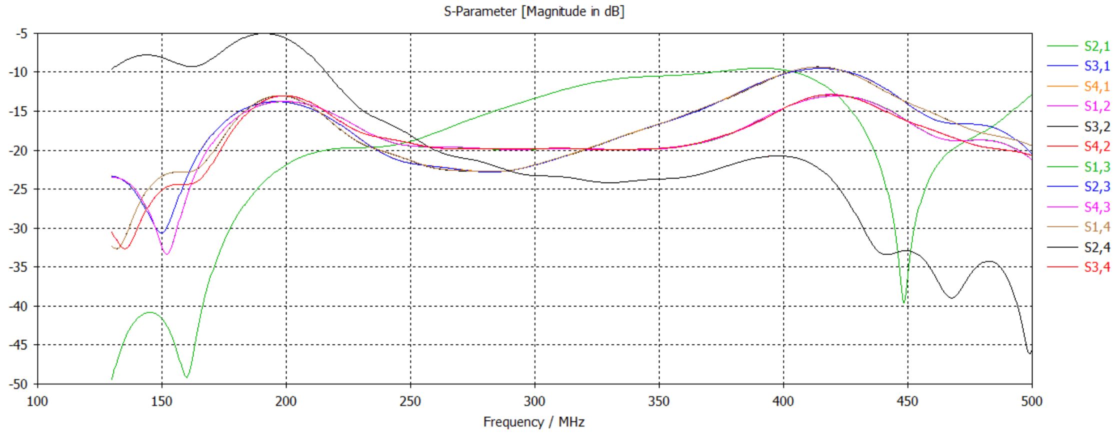


Figure 29. Isolated UHF antenna. Insertion loss for turnstile configuration.

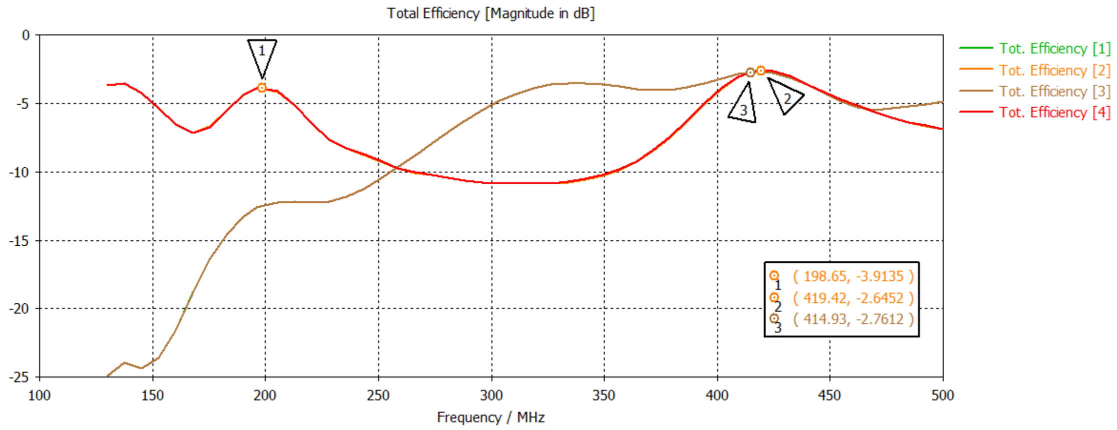


Figure 30. Isolated UHF antenna. Total efficiency for turnstile configuration.

4.3.2 ISARA structures impact on UHF antenna parameters

4.3.2.1 Monopole 1 (P1 and P3)

Return loss

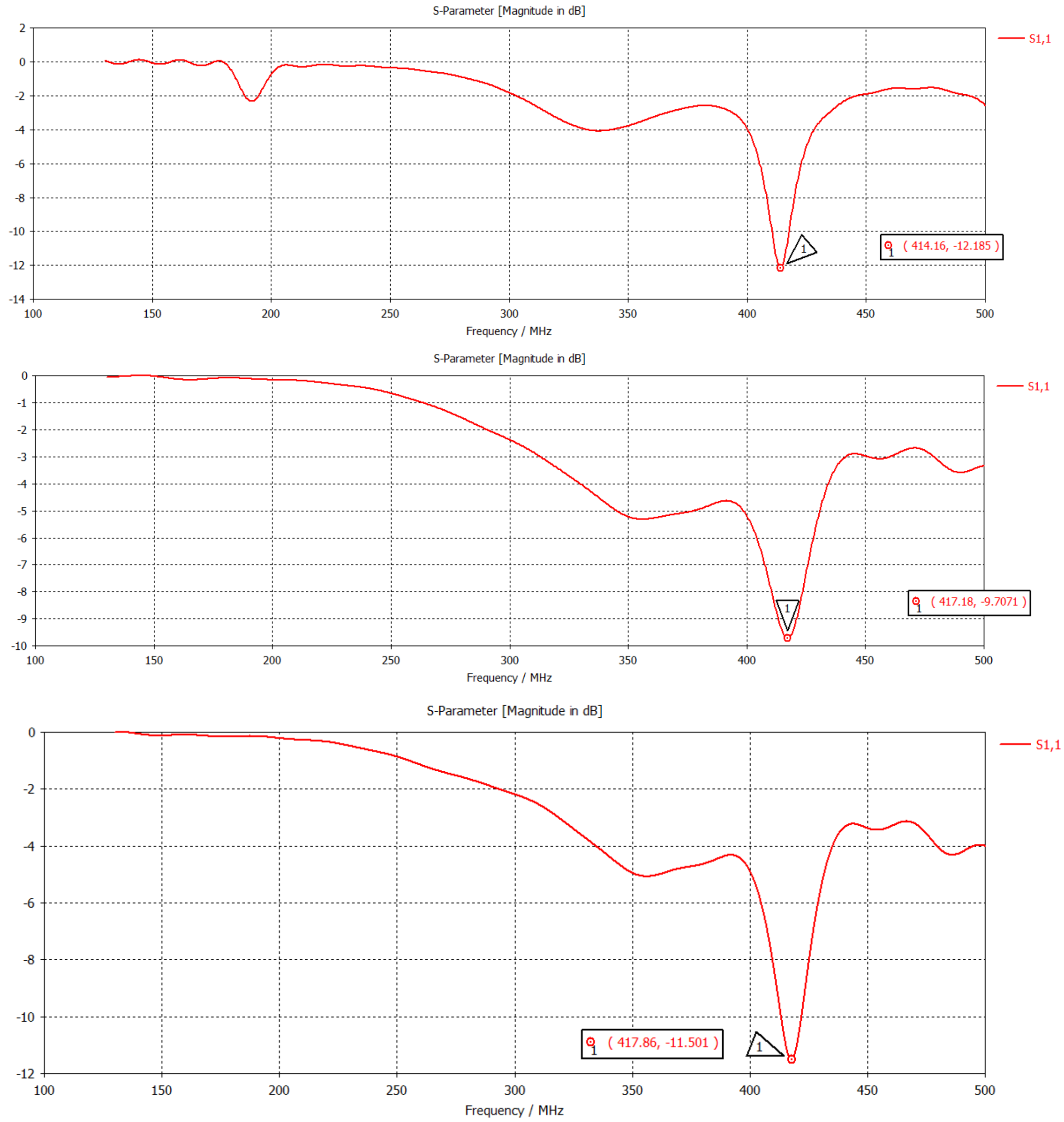


Figure 31. P1 Return loss results for different configurations. From top to bottom: Isolated UHF antenna, 3U UHF antenna, ISARA UHF antenna.

Realized Gain

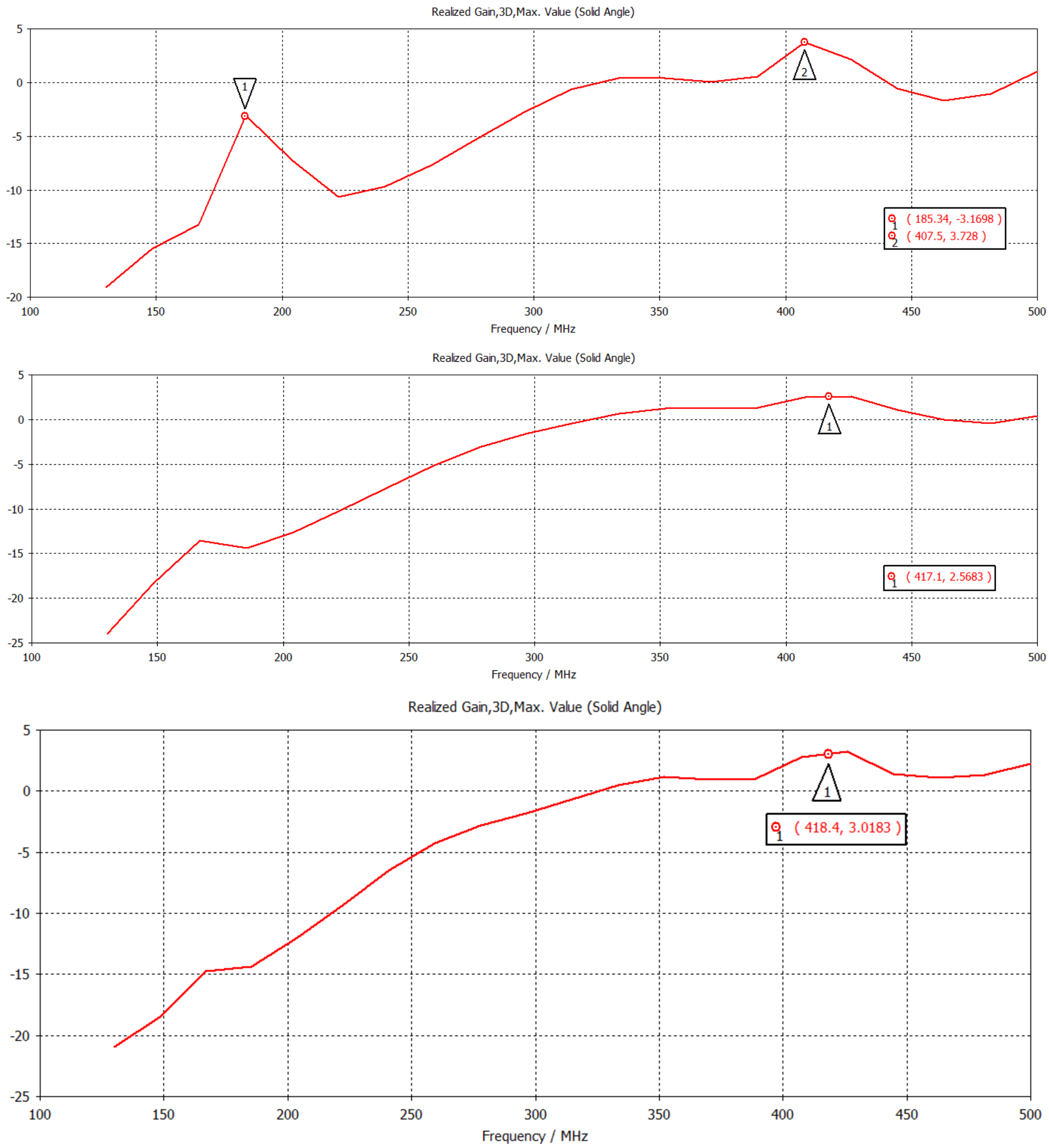


Figure 32. P1 Realized Gain vs frequency results for different configurations. From top to bottom: Isolated UHF antenna, 3U UHF antenna, ISARA UHF antenna.

Efficiency

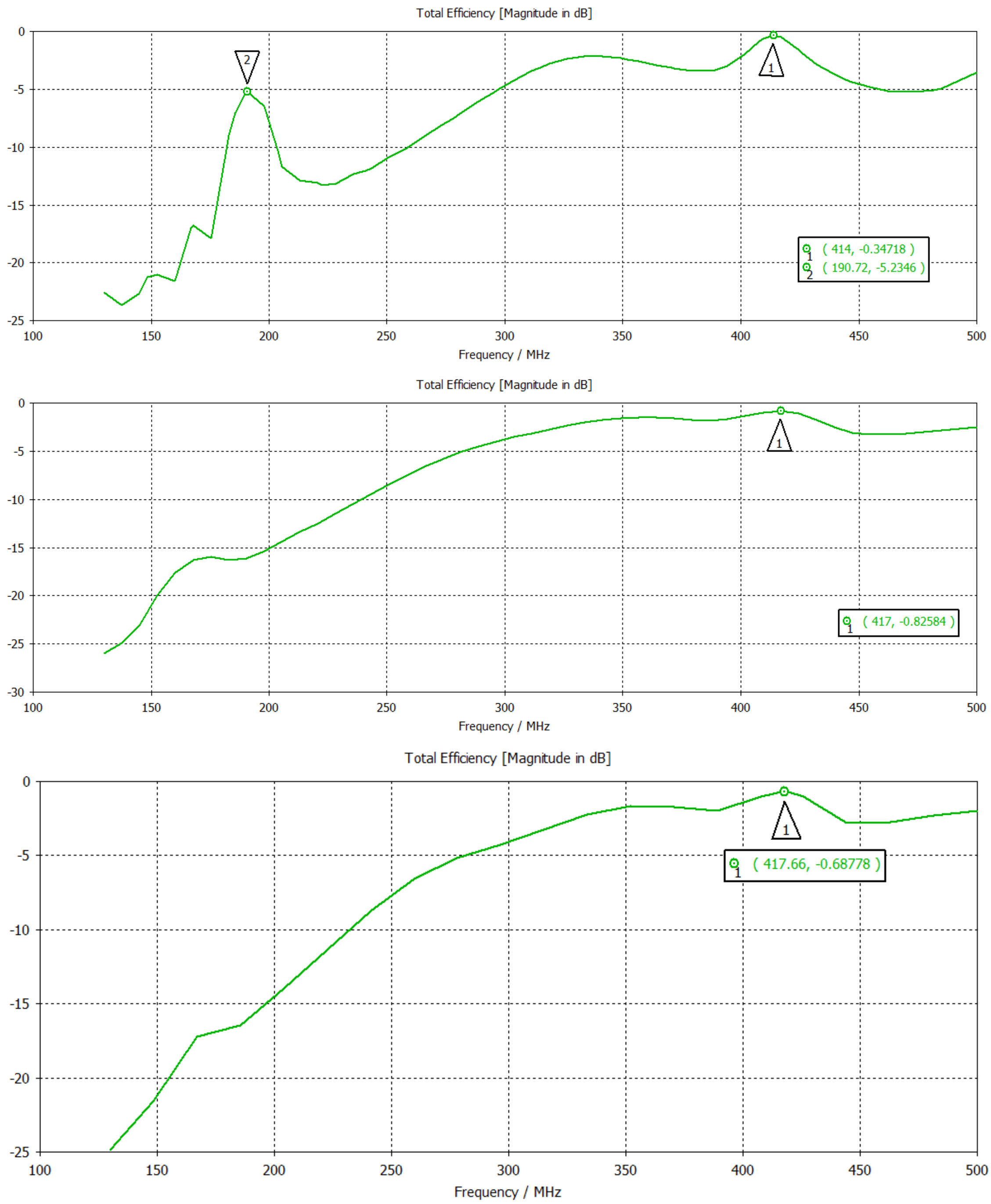


Figure 33. P1 Efficiency vs frequency results for different configurations. From top to bottom: Isolated UHF antenna, 3U UHF antenna, ISARA UHF antenna.

4.3.2.2 Monopole 2 (P2 and P4)

Return loss

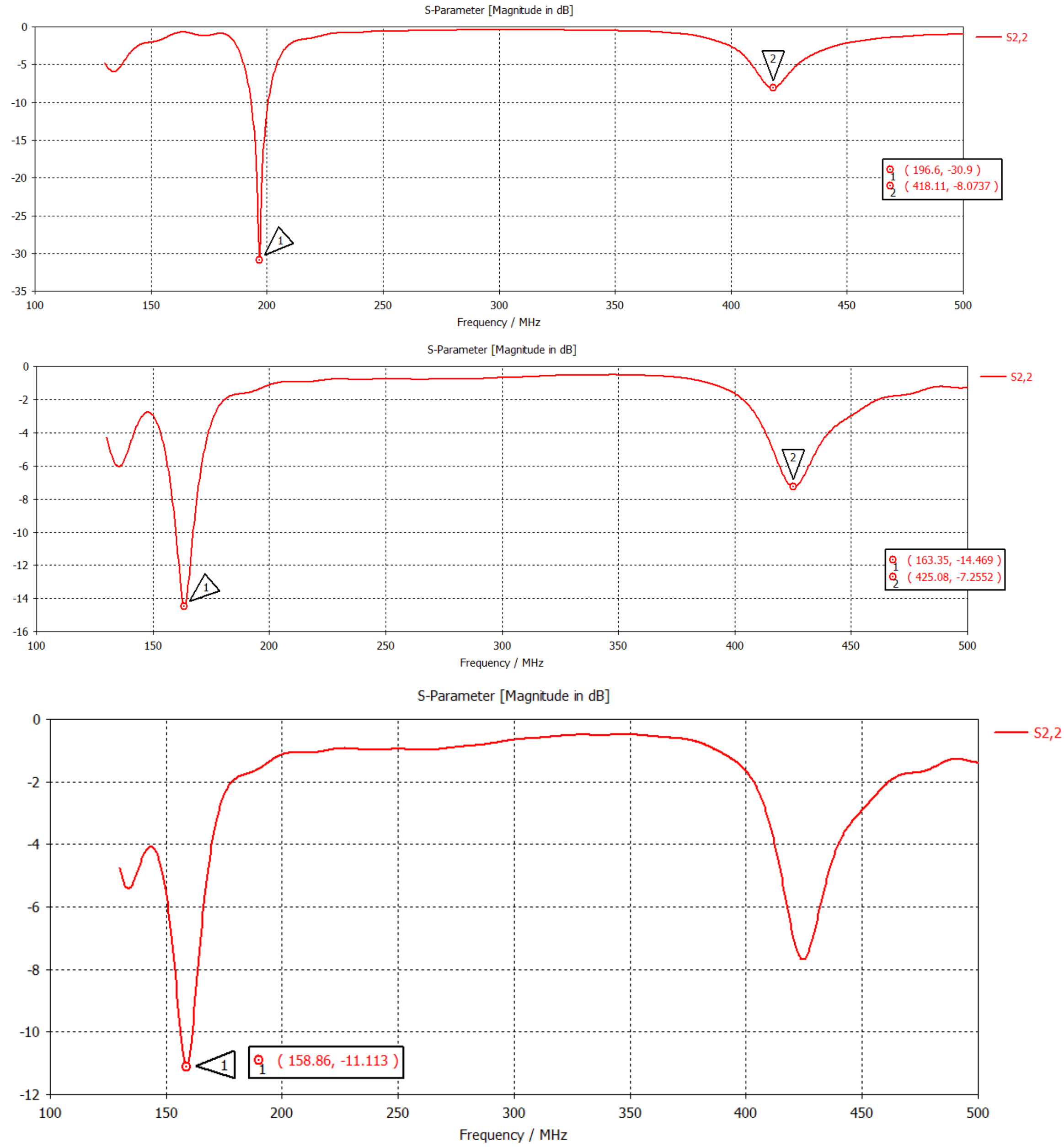


Figure 34. P2 Return loss results for different configurations. From top to bottom: Isolated UHF antenna, 3U UHF antenna, ISARA UHF antenna.

Realized Gain

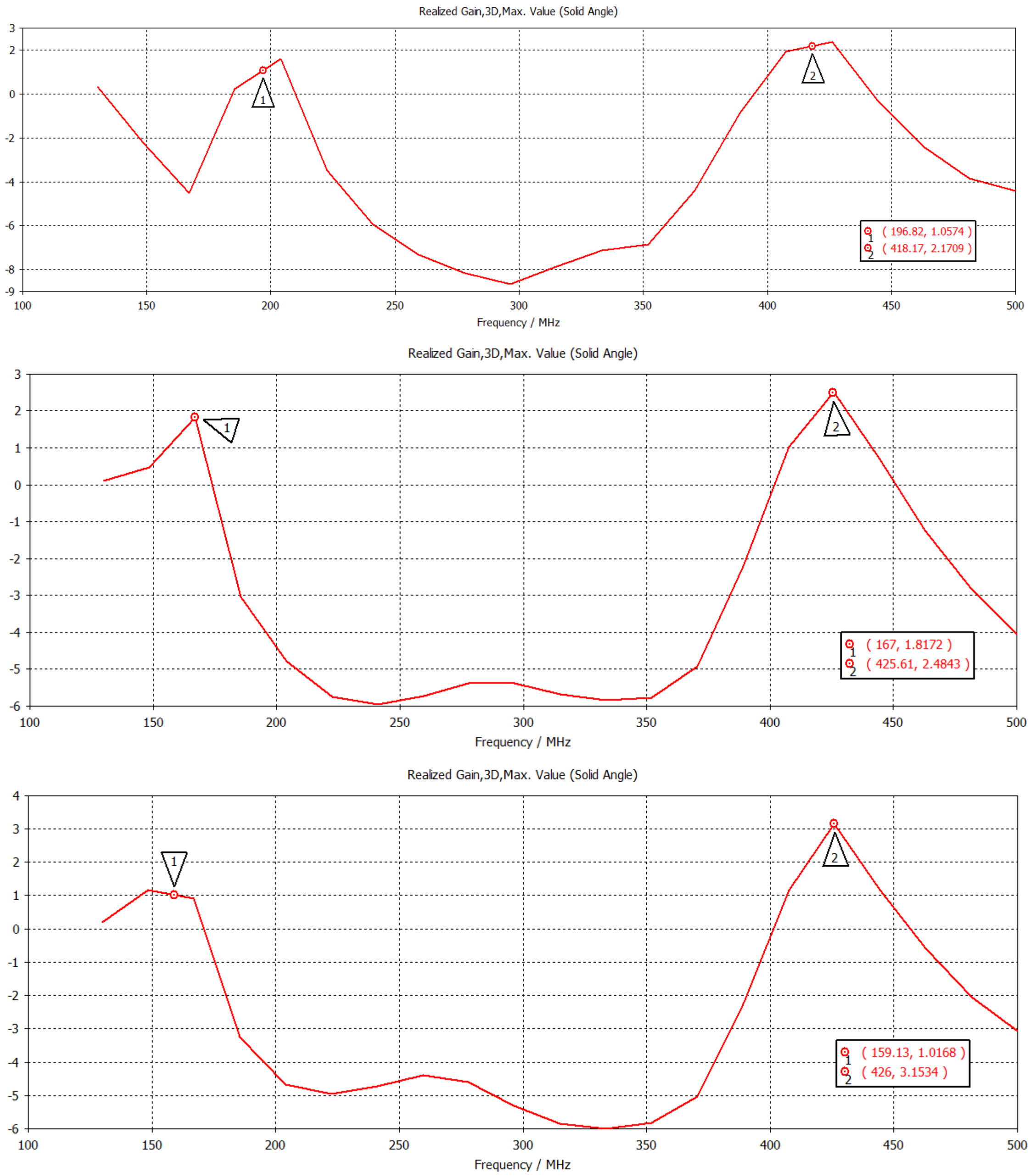


Figure 35. P2 Realized Gain vs frequency results for different configurations. From top to bottom: Isolated UHF antenna, 3U UHF antenna, ISARA UHF antenna.

Efficiency

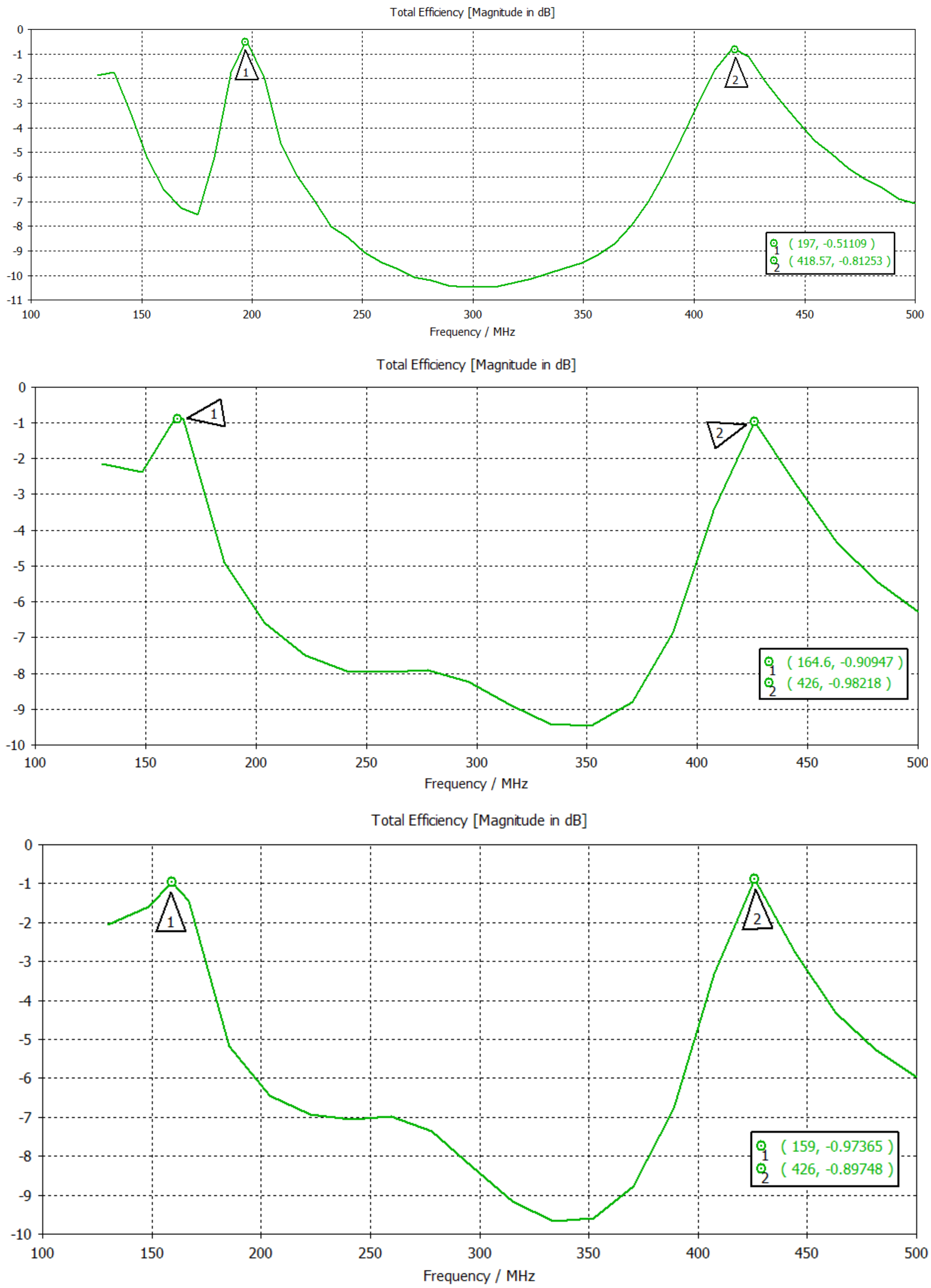


Figure 36. P2 Efficiency vs frequency results for different configurations. From top to bottom: Isolated UHF antenna, 3U UHF antenna, ISARA UHF antenna.

4.3.2.3 Monopoles interaction

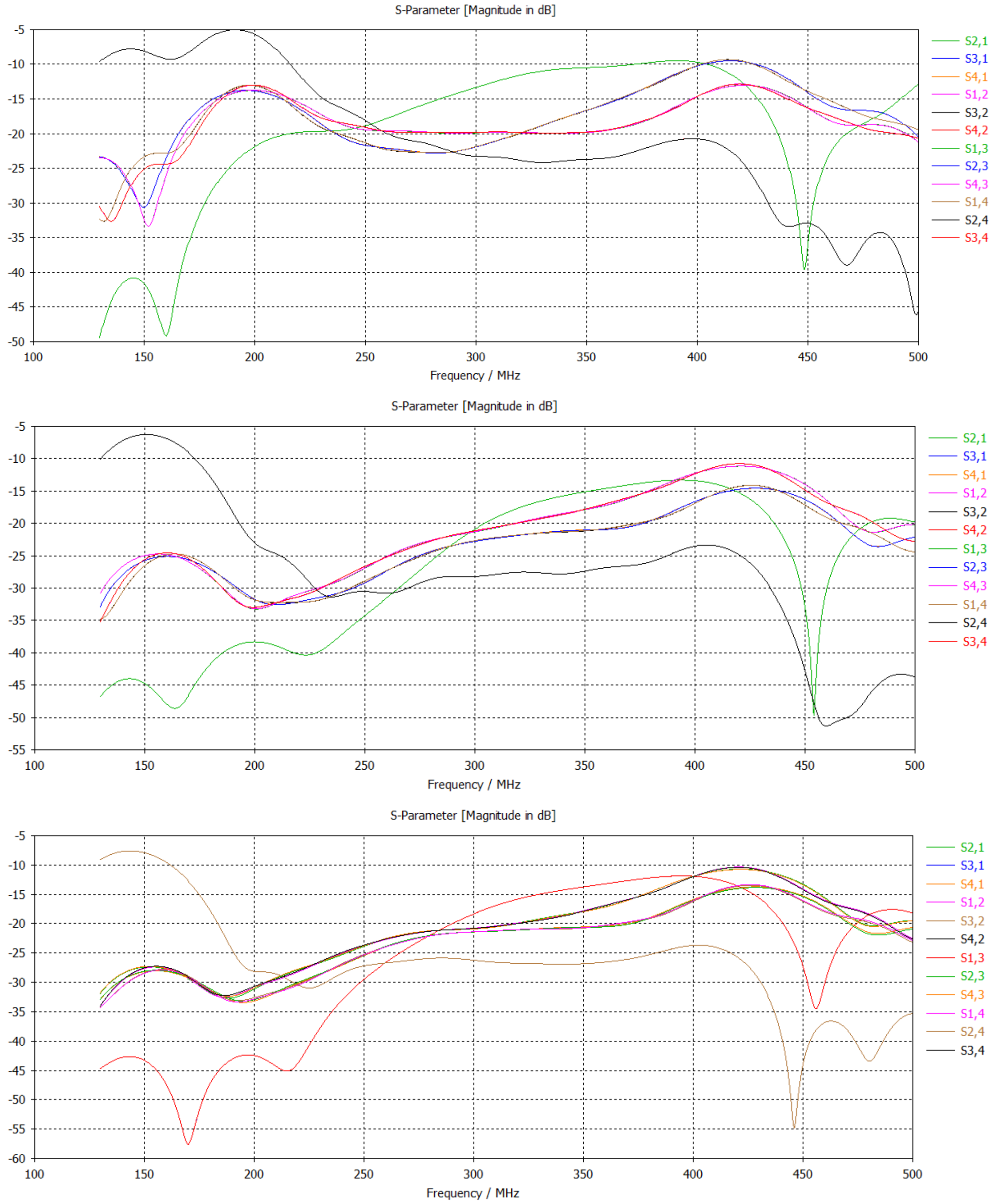


Figure 37. Turnstile Insertion loss results for different configurations. From top to bottom: Isolated UHF antenna, 3U UHF antenna, ISARA UHF antenna.

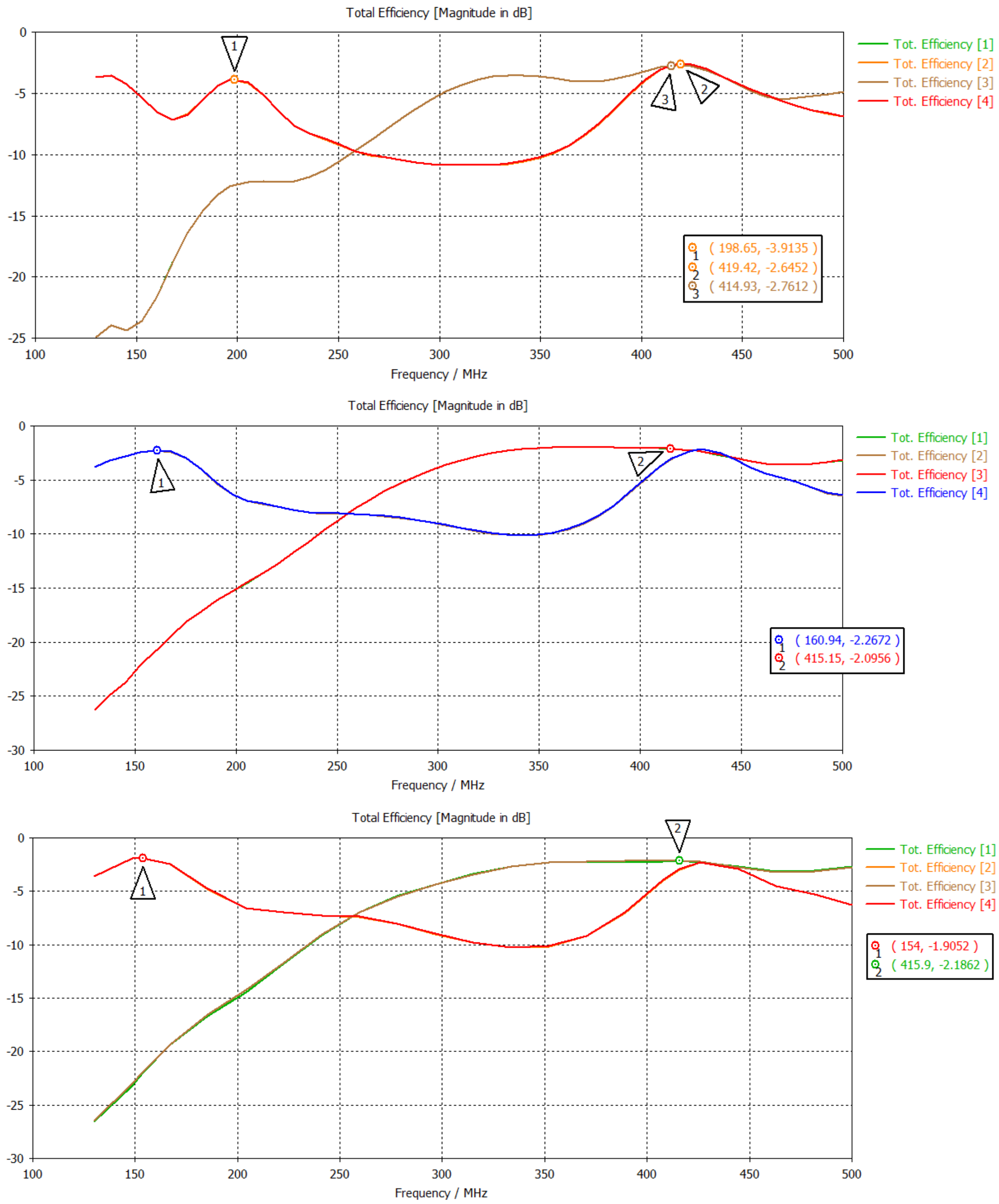


Figure 38. Turnstile Efficiency vs frequency results for different configurations. From top to bottom: Isolated UHF antenna, 3U UHF antenna, ISARA UHF antenna.

4.3.3 Results summary

	Monopole P1	Monopole P2
Isolated UHF	414 MHz	197 MHz
3U UHF	417 MHz	163 MHz
ISARA UHF	418 MHz	159 MHz

Table 3. Operation frequency summary.

	Monopole P1	Monopole P2
Isolated UHF	4.17 dB	3.17 dB
3U UHF	2.55 dB	2 dB
ISARA UHF	2.81 dB	1.84 dB

Table 4. Maximum Realized Gain summary.

	Monopole P1	Monopole P2	Turnstile
Isolated UHF	92.32 %	88.9 %	40.61 %
3U UHF	82.7 %	81.11 %	59.33 %
ISARA UHF	85.35 %	79.92 %	36.93 %

Table 5. Antenna efficiency summary.

4.3.4 CST Simulation results vs. ISIS information

The main problem of ISIS radiation patterns downloaded from its website is the relevant information they don't provide. It has to be assumed many significant data such as the simulation frequency of the diagrams, the structure dimensions, applied materials and so on.

Moreover, that radiation patters were obtained with a different software which could translate into some minor mismatches.

4.3.4.1 Monopole

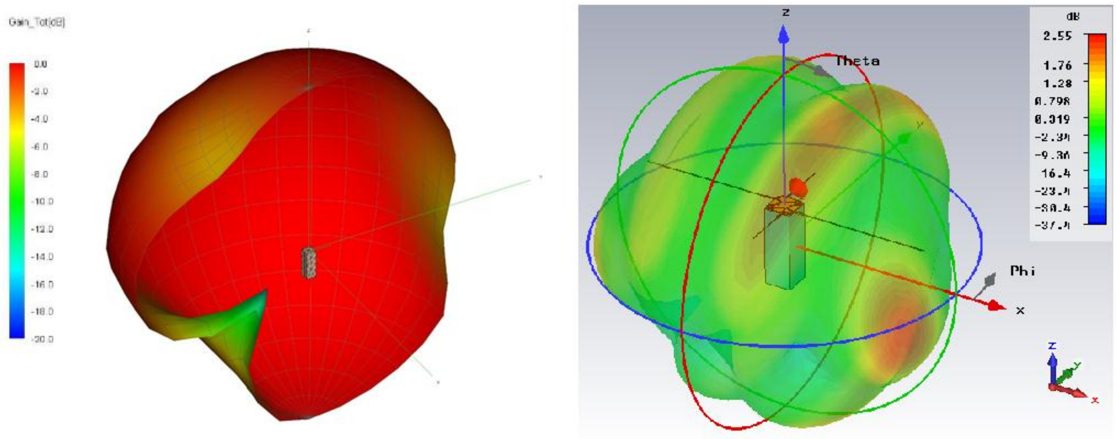


Figure 39. Left: ISIS gain pattern. Right: CST Microwave Studio Realized Gain pattern.

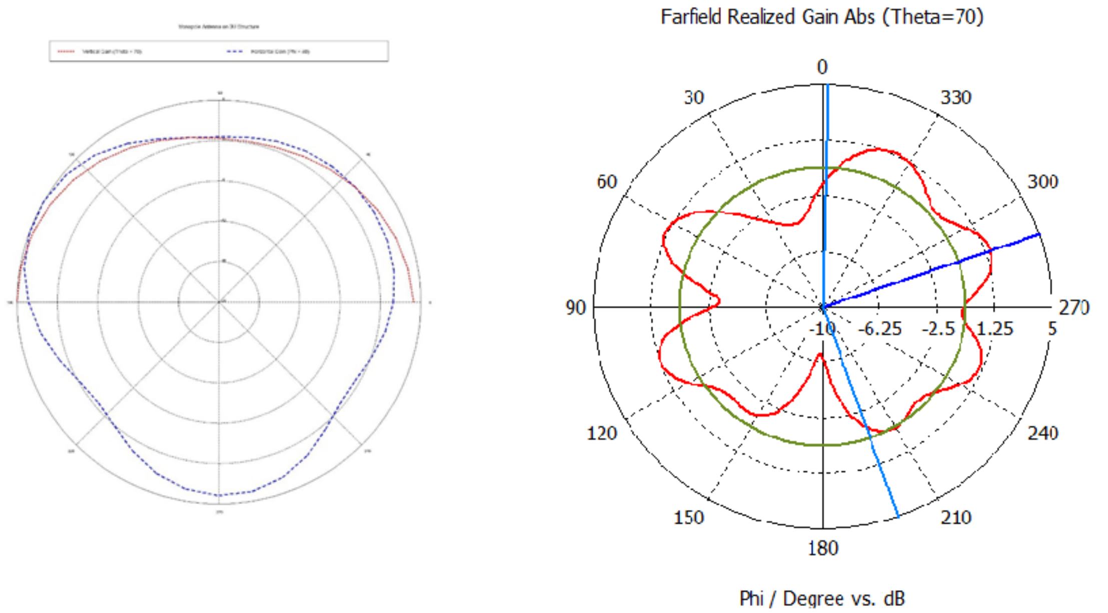


Figure 40. Left: ISIS gain polar diagram for theta = 70 deg. Right: CST Microwave Studio realized gain polar diagram for theta = 70 deg.

4.3.4.2 Dipole

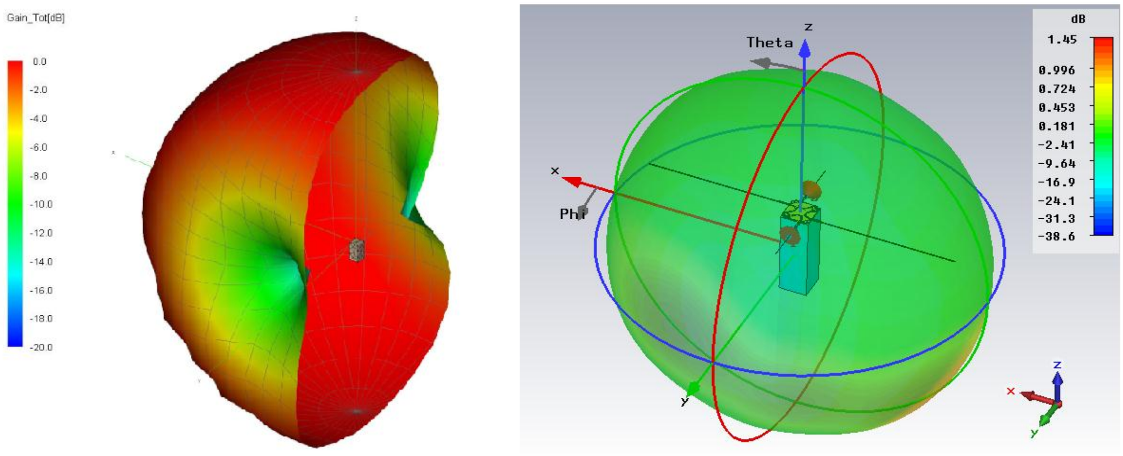


Figure 41. Left: ISIS gain pattern. Right: CST Microwave Studio Realized Gain pattern.

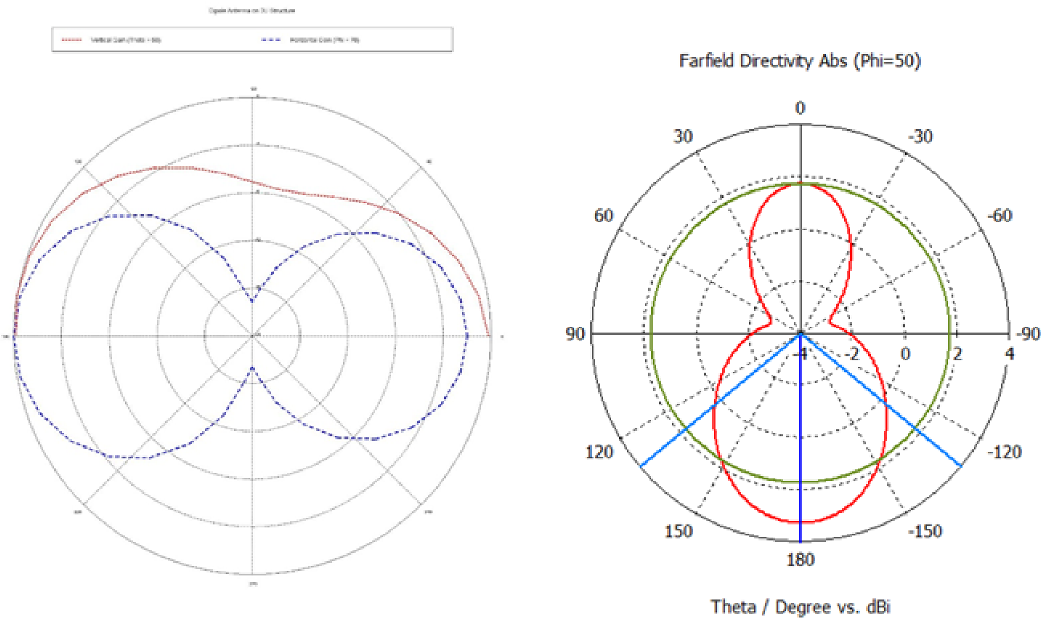


Figure 42. Left: ISIS gain polar diagram for phi = 50 deg. Right: CST Microwave Studio realized gain polar diagram for phi = 50 deg.

4.3.4.3 Turnstile

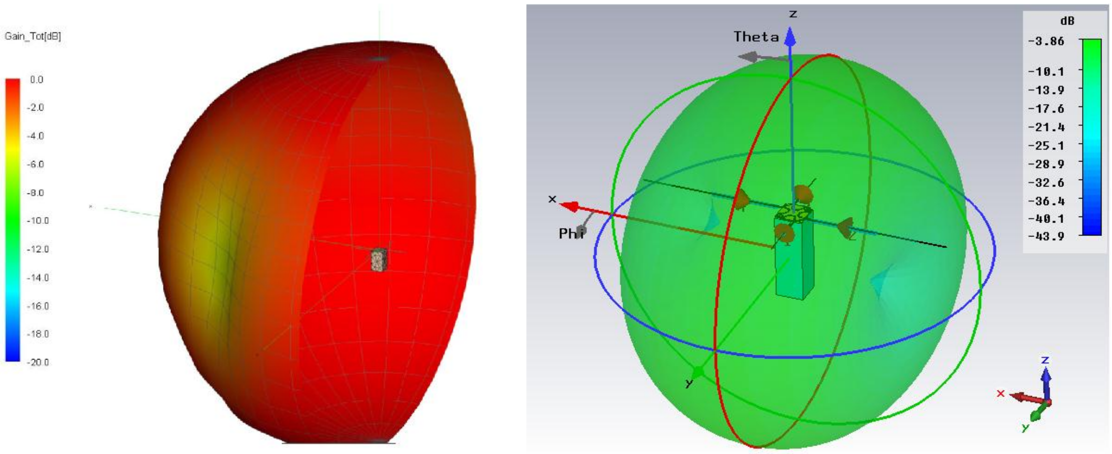


Figure 43. Left: ISIS gain pattern. Right: CST Microwave Studio Realized Gain pattern.

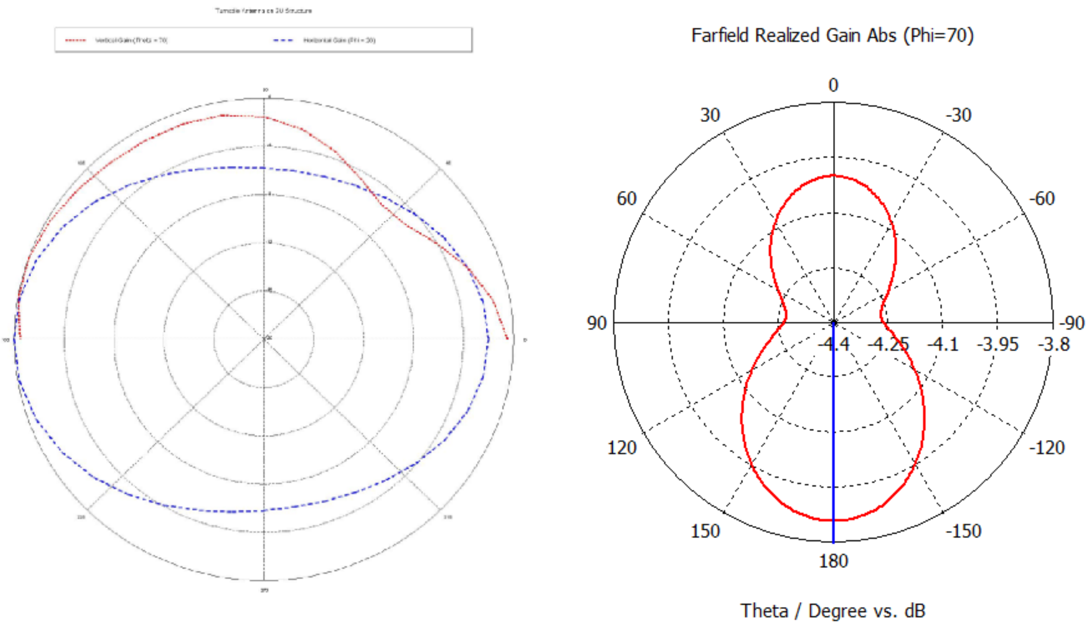


Figure 44. Left: ISIS gain polar diagram for phi = 70 deg. Right: CST Microwave Studio realized gain polar diagram for phi = 70 deg.

CHAPTER 5: FUTURE WORK AND IMPROVEMENTS

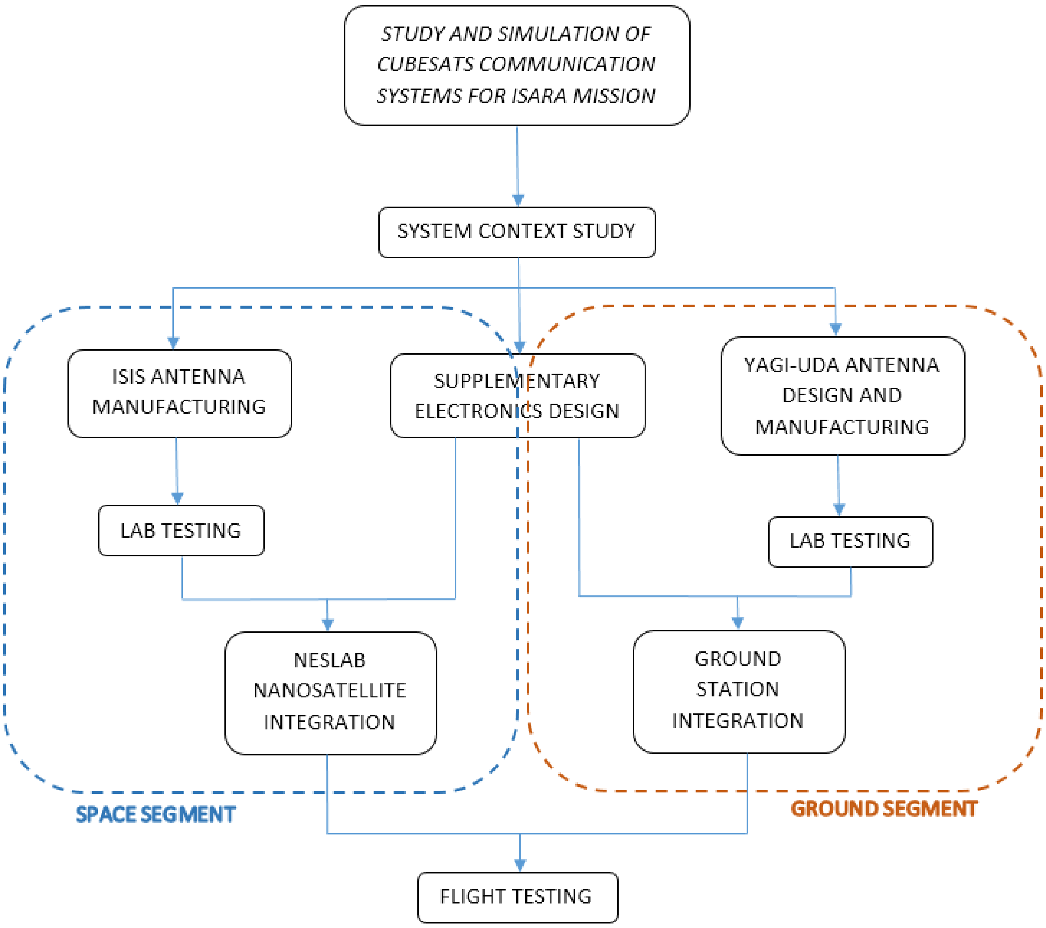
Once the results have been analyzed, it has been detected that some of the initial information that were assumed as without much influence or directly as true fact have been more determining on the final conclusions.

For this reason, the main way to improve all the work done in this study could be make contact with the project manager or the chief engineer in charge of current ISARA mission and try to get some specific information from him or her.

The two basic details that would make the difference in relation to the reliability of this study would be:

- Exact operation frequency of each monopole. Or what it would be the similar, the exact length of each monopole.
- The specific material of each component of the UHF antenna.

On the other side, as every engineering project or study has its practical side, it could be very interesting a future development of this antenna design which involves the manufacturing of the device and real testing on the laboratory and in a flight scenario. On the following flux diagram are detailed the interdependency relationship of a possible way for future work project.



CHAPTER 6: ENVIRONMENTAL ISSUES

CubeSats are a class of research spacecraft called nanosatellites, which are much cheaper, simpler and faster to build than standard satellites. These properties turn them into very interesting options for companies, organizations or even particular researchers without large economical resources. At the same time, these devices are suitable for some higher-risk missions.

In fact, despite to date the vast majority of CubeSat activities belong to the category of radio amateur or university projects, lately, CubeSats have also started to show an increasing potential for commercial use, and are recognized as one of the current top trends in space activities.

Moreover, as it is well known, sending any amount of mass to space in large missions runs immediately into more power required or, which is the same, more fuel. So, in this case, CubeSats also provides interesting opportunities to “greener” space exploration.

However, all these pros could be eclipsed by a drawback that comes next to the fact of an easier access to space: the space debris.

The space debris is the collection of defunct man-made objects in space, such as old satellites, spent rocket stages, and fragments from disintegration, erosion, and collisions, including those caused by debris itself.

It is one of the most popular problems of current Low Earth Orbit Missions and there are many scientific teams working to come up with a reliable solution.

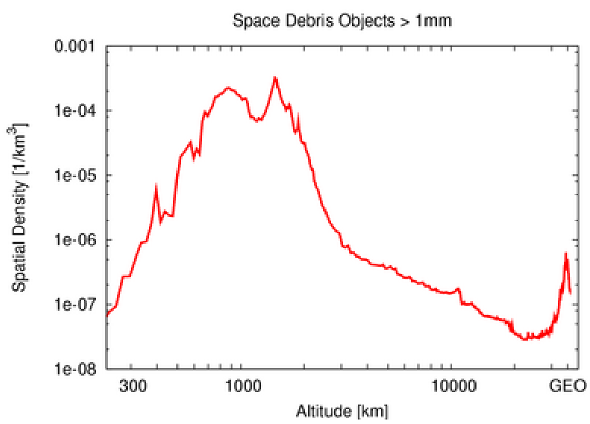


Figure 45. Spatial density of space debris by altitude according to ESA MASTER-2001, without debris from the Chinese ASAT and 2009 collision events.

CHAPTER 7: STANDARDS AND REGULATIONS

This section presents the main regulations this mission had to fulfill. To be consciousness of these guidelines allows to get a better understanding of the present requirements and conditions which determines the design or the chosen components of the nanosatellite.

ISARA is a class D mission, developed using tailored NASA 7120.5E standard and classified as a Category 3 project. In terms of technology maturity, all their components are at TRL 5 or higher.

7.1 TECHNOLOGY READINESS LEVEL (TRL)

Technology Readiness Levels are a type of measurement system used to assess the maturity level of a particular technology during the acquisition process. They are determined during a Technology Readiness Assessment (TRA) that examines program concepts, technology requirements and demonstrated technology capabilities.

There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest.

TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and “flight qualified” through test and demonstration (ground or space)
TRL 9	Actual system “flight proven” through successful mission operations

Table 6. Technology Readiness Levels description.

In ISARA mission the Critical Technology Elements are in TRL 5/6 which means they are between a technology development and a technology demonstration stage. Indeed, the main goal of the mission is the study of the performance of this components to become reliable technology for future missions.

7.2 NASA PROCEDURAL REQUIREMENTS

7.2.1 NPR 7120.5E: NASA Space Flight Program and Project Management Requirements

This document establishes the requirements by which NASA formulates and implements space flight programs and projects, consistent with the governance model contained in NASA Policy Directive (NPD) 1000.0, NASA Governance and Strategic Management Handbook.

This NPR applies to all NASA space flight programs and projects. Also, it applies to reimbursable space flight programs and projects performed for non-NASA sponsors and to NASA contributions to space flight programs and projects performed with international and interagency partners.

Projects are Category 1, 2 or 3 and shall be assigned to a category based initially on:

1) Project life-cycle cost (LCC) estimated.
2) Inclusion of significant radioactive material.
3) Human space flight.
4) Priority level:
    a) Importance of the activity to NASA.
    b) The extent of international participation.
    c) The degree of uncertainty surrounding the application of new or untested technologies.
    d) Spacecraft/payload development risk classification (**NPR 8705.4**).

Priority Level	LCC < \$250M	\$250M ≤ LCC ≤ \$1B	LCC > \$1B, significant radioactive material, or human space flight
High	Category 2	Category 2	Category 1
Medium	Category 3	Category 2	Category 1
Low	Category 3	Category 2	Category 1

Table 7. Project Categorization Guidelines.

7.2.2 NPR 8705.4: Risk Classification for NASA Payloads

This NPR establishes baseline criteria that enable a user to define the risk classification level for NASA payloads on human, or nonhuman, rated launch systems or carrier vehicles and the design and test philosophy and the common assurance practices applicable to each level. The establishment of the risk level early in programs and projects provides the basis for program and project managers to develop and implement appropriate mission assurance and risk management strategies and requirements and to effectively communicate the acceptable level of risk.

This document applies to programs and projects governed by NPR 7120.5E.

Characterization	**Class A**	**Class B**	**Class C**	**Class D**
Priority (Criticality to Agency Strategic Plan)	High priority	High priority	Medium priority	Low priority
National significance	Very high	High	Medium	Low to medium
Complexity	Very high to high	High to medium	Medium to low	Medium to low
Mission Lifetime (Primary Baseline Mission)	Long, > 5 years	Medium, 2-5 years	Short, < 2 years	Short, < 2 years
Cost	High	High to medium	Medium to low	Low
Launch Constraints	Critical	Medium	Few	Few to none
In-Flight Maintenance	N/A	Not feasible or difficult	Maybe feasible	May be feasible and planned
Alternative Research Opportunities or Re-flight Opportunities	No alternative or re-flight opportunities	Few or no alternative or re-flight opportunities	Some or few alternative or re-flight opportunities	Significant alternative or re-flight opportunities
Examples	HST, Cassini, JIMO, JWST	MER, MRO, Discovery payloads, ISS Facility Class Payloads, Attached ISS payloads	ESSP, Explorer Payloads, MIDEX, ISS complex subrack payloads	SPARTAN, GAS Can, technology demonstrators, simple ISS, express middeck and subrack payloads, SMEX

Table 8. Classification considerations for NASA Class A-D Payloads.

CHAPTER 8: PROJECT MANAGEMENT

8.1 BUDGET SUMMARY

It has been considered some parameters in order to obtain an approximated value of the cost for the development of this study.

At first, the main expenses are those related with the cost per hour of human work. It has been dedicated 600 hours of work with an estimated cost per hour of 10 euros.

Since the main work has been related with computer simulations, the other important expense is the licences of the software required. Mainly, it has been used two computer programs:

- CST Studio Suite
- CATIA V5

It should be noticed that CST Microwave Studio is a module of the entire group of software CST Studio Suite.

Finally, the price for the computer amortization used to develop the study is taken into account.

CONCEPT	COST (€)
Personnel expenses	6000
Material amortization	75
Software licences	2116.67
TOTAL	**8191.67**

Table 9. Budget summary.

The total estimated cost for the study will be about 8191.67 €.

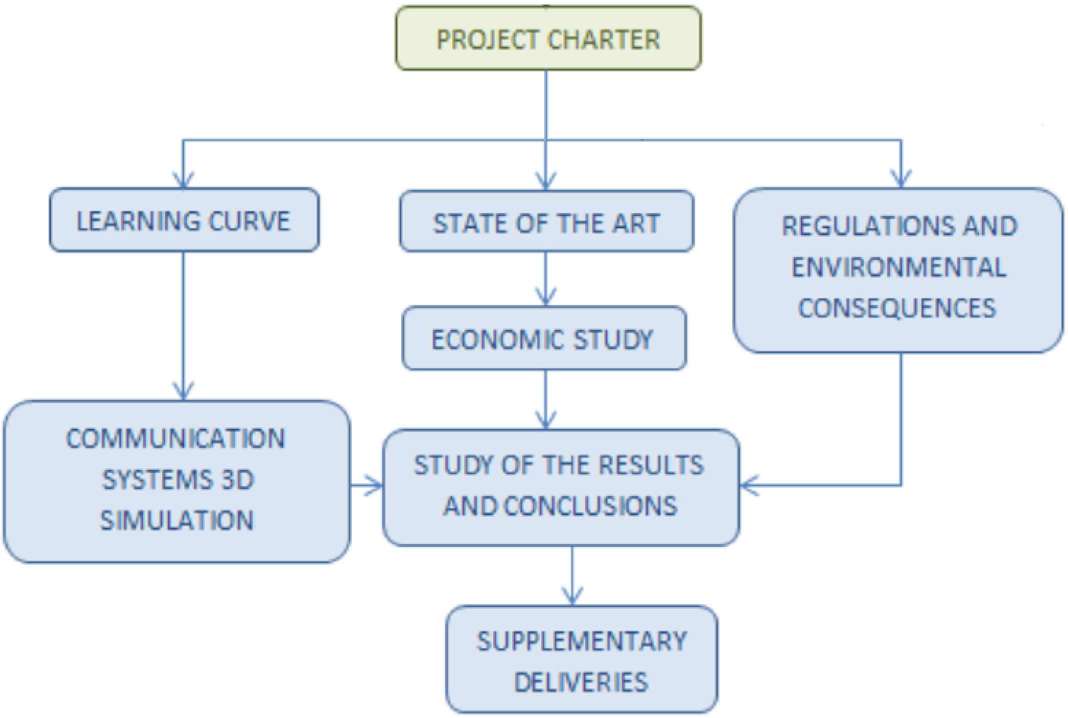
8.2 PLANNING

At the beginning of this study it was made an analysis of all the tasks that should be carried out in order to organize and planning the available time properly.

At first, it was made a flux diagram that describes the interdependency relationship between the global tasks graphically, and then, it was treated more deeply in Table X with the related subtasks and the time dedication required.

Finally, from that distribution of resources, it was made the scheduling with a Gantt diagram to finish all the work on time.

8.2.1 Task identification from Work Breakdown Structure (WBS)



8.2.2 Interdependency relationship and level of effort estimation of the tasks

CODE OF TASK	TASK IDENTIFICATION	PRECEDING TASK(S)	LEVEL OF EFFORT (HOURS)	%
-	FINAL PROJECT	-	600	100
A	Learning curve	A1, A2, A3	78	13
A1	Research of information[1]	-	30	5
A2	Antenna theory	-	24	4
A3	CST Microwave Studio	-	24	4
B	State of the art	-	42	7
C	Communication systems 3D simulation	C1, C2, C3	240	40
C1	CAD 3D satellite design	-	60	10
C2	Communication systems addition	C1	18	3
C3	Antenna simulation with CST Microwave Studio	A3	162	27
D	Study of the results and conclusions	C	102	17
E	Regulations and environmental consequences	-	24	4
F	Economic study	F1, F2	42	7
F1	Budget	-	24	4
F2	Benchmark	B	18	3
G	Supplementary deliveries	G1, G2	72	12
G1	Drawings	C1, C2	30	5
G2	Attachments	B, C, D, E, F	18	3
G3	CD	B, C, D, E, F	12	2
G4	Bibliography	B, C, D, E, F	12	2

Table 10. Interdependency relationship and level of effort estimation of the tasks.

[1] A1 corresponds to a support task performed concurrently to the development of the project. Because of the main research of information has been done before the project charter delivery, it does not appear on future planning. Thus, it does not appear also as a preceding task.

8.2.3 Scheduling. Gantt chart

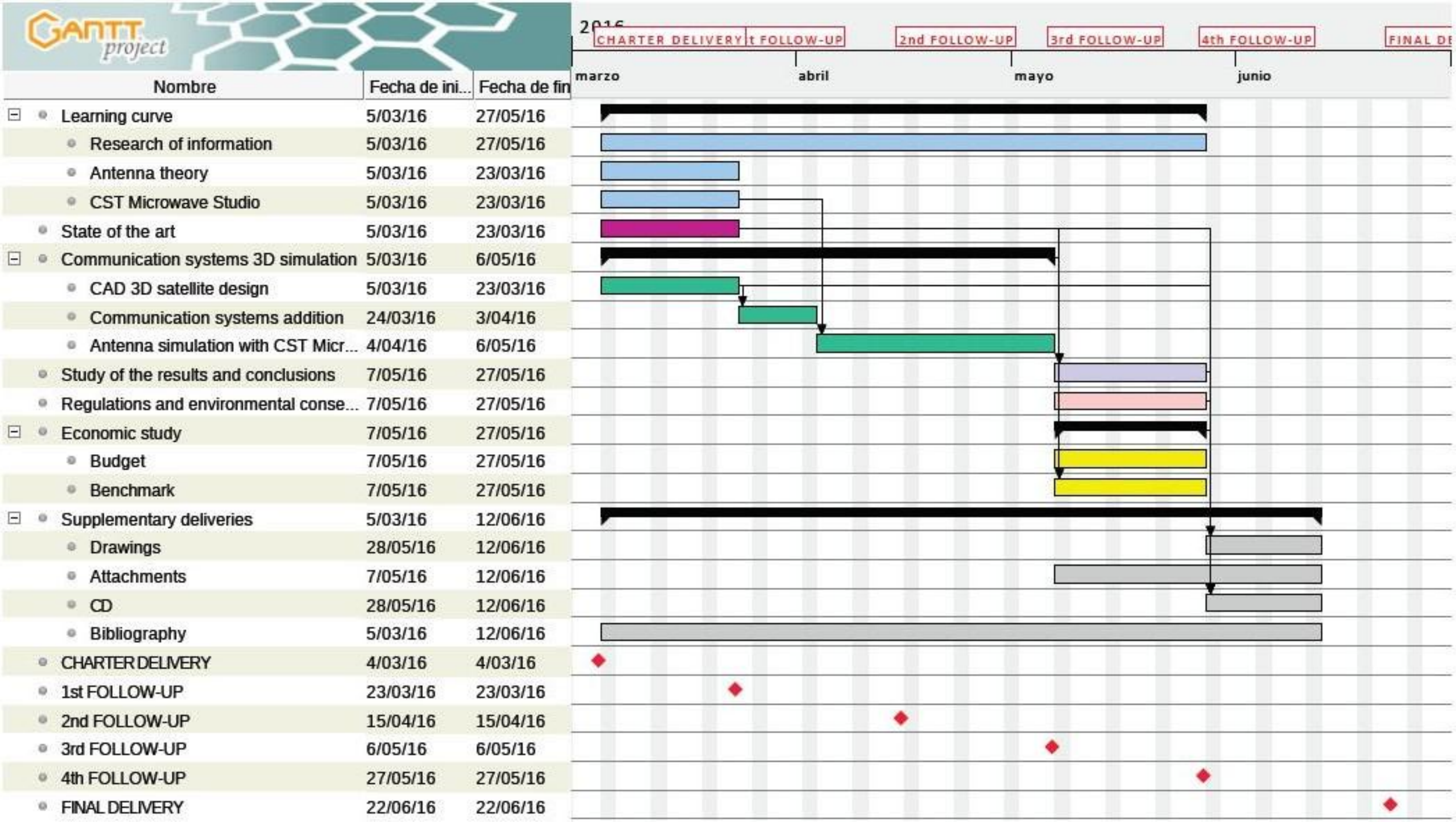


Figure 46. Gantt diagram.

CONCLUSIONS

This study comprehend the antenna design process for an UHF application on telecommunications subsystem of ISARA mission CubeSat. It has been carried out an analysis and evaluation of the nanosatellite body effects to the ISIS UHF deployable antenna performance by computer simulation with CST Microwave Studio software.

To reach a complete understanding of the antenna operation it has been obtained the radiation patterns, efficiency, electric and magnetic field over the S/C, and so on, for the main CubeSat configurations during the in-orbit stage development of the mission. That includes the CubeSat with the HGA folded and the CubeSat after the HGA deployment. The obtained results and conclusions from simulations are exposed on this report, but all the graphics and images required have been organized in an annex to facilitate the read of the study.

Generally speaking, after working with this upcoming technology of CubeSats systems, it has been took consciousness about the potential applications and all the great benefits it could mean to space exploration, both, near space almost today and deep space in a very close future. Just to give some examples, its faster and cheaper manufacturing in front of bigger and more complex satellites put them into very attractive solutions for high risk missions or, at the same time, it move closer the space access not only to biggest organizations.

Coming back to the UHF antenna study, it could be said that the obtained results for isolated antenna configuration have been quite satisfactory. It has been achieved very high efficiencies about 90% for both types of monopoles and higher maximum gains than expected according to ISIS datasheets.

With the adding of 3U structure to the CAD model, all the antenna parameters are slightly soften. Even though, the efficiency remains around 80% for each monopole and still giving higher maximum gains than ISIS radiation patterns. Then, with the ISARA configuration with the HGA deployed, the values are kept very similar to the 3U configuration and even better in case of shortest monopole (P1).

In terms of operation frequencies, for the monopoles P1 and P3 it is established between 414MHz – 418MHz, almost at the same for the three configurations. On the other hand, for the monopoles P2 and P4, however it is very close for 3U and ISARA configurations, 163MHz and 159MHz respectively, it change significantly for Isolated configuration, being 197MHz.

Also, it has been made three other simulations with turnstile monopoles configuration with a phase difference of 90 degrees between each other. The quality of the results for these configurations are reduced meaningfully. First, the return loss rise enough so that the bests values where should be the operation frequency reach -9dB. From this scenario it could be concluded that the turnstile configuration defined on the simulations of this study don't work properly. Another clue that point at the same way are the low values of the efficiency which are about 40% - 60% for each configuration.

For this reason, those results haven't took into account to the most of antenna parameters evaluation, but only to realize that the insertion loss produced by the monopoles interaction are much lower than the insertion loss in the operation frequencies, which is what is expected to be.

On the other side, as it is explained in CHAPTER 4, all the simulations have been made under the acceptance of some hypothesis. The origin of all those suppositions has been the lack of specific information about some details of the mission and components properties, but, in the end, they don't compromise the validity of the study.

However, there is one restriction which has to be taken that strongly condition the results of the study. On the mission information it has could find that the antenna was composed by 4 monopoles instead of two dipoles or other configurations. Although, there weren't any information about the exact operation frequency of the antenna and neither about the exact length of each monopole. This means that the antenna CAD model used for simulations could be different from the ISARA one. So all the results will change a lot.

The antenna CAD model used was downloaded directly from ISIS website so it could be only an example of their offer. This could explain the existence of two different sized monopoles considering that the simulations demonstrate that any of two monopoles reduce significantly its efficiency and gain to be substituted by the other when the HGA are folded or deployed.

Anyway, this study shows the performance of a certain UHF antenna that fulfill CubeSat requirements technology and successfully operates in two different frequencies.

Finally, as every engineering project or study has its practical side, it could be very interesting a future development of this antenna design which involves the manufacturing of the device and real testing on the laboratory and in a flight scenario.

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