Development of a 21cm Multi-element Solar Radio Interferometric Array

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Abstract

Solar radio emissions account for different emission processes and the medium in which these are generated in the solar atmosphere. Radio astronomy is a field that is gradually growing in Colombia thanks to several projects aiming to a more viable way of performing astronomical studies in a country whose climate conditions are predominantly cloudy, as well as the contribution it presumes to the scientific and technological development that can have an impact on future generations of Colombian astronomers, scientists and engineers.

This work presents the development and implementation stages of a Solar Radio Interferometer with a novel antenna design, previously tested, located in the focus of a collector dish, on a fully-steerable mount and the proposed configuration for a 3-element interferometric array. We also discuss the implemented time correlation system implemented using the Reconfigurable Open Architecture Computing Hardware (ROACH-1) electronic system. The radio interferometer will study solar radio emissions at the frequency of 1.42 GHz, corresponding to the 21cm emission line, generated by gyro-resonance mechanisms.

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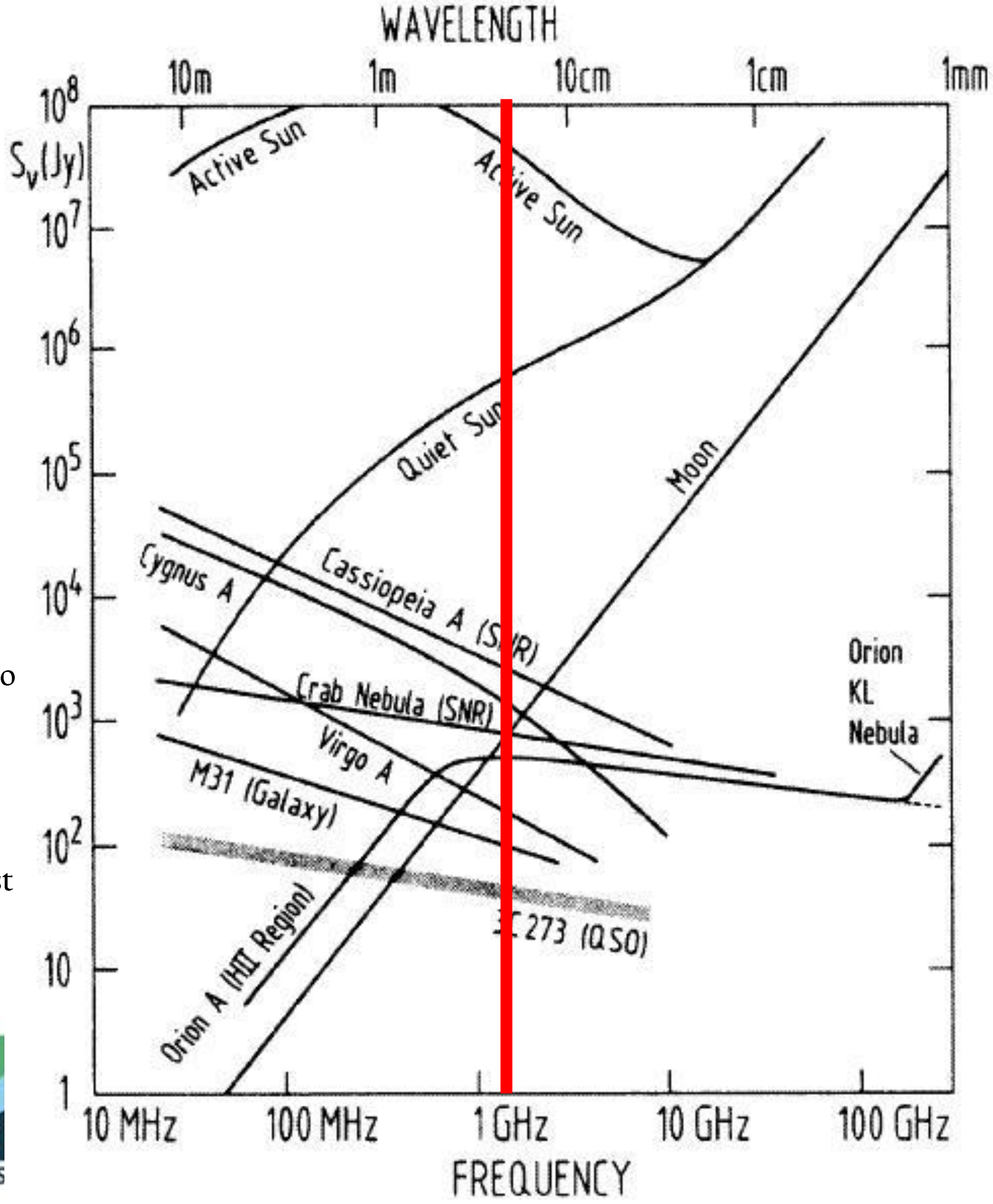
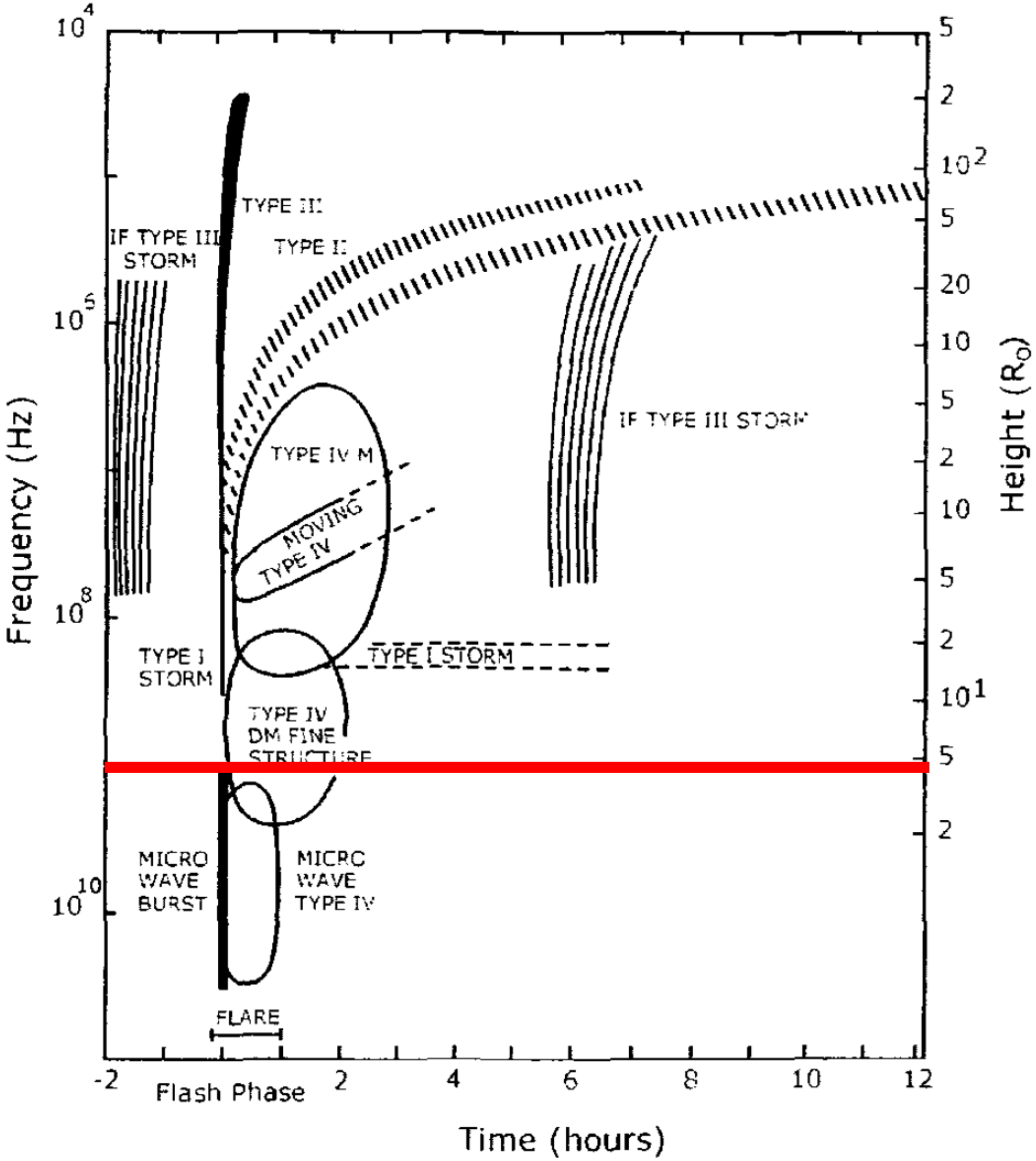
Background

Figure 1: Flux of Several Astronomical Sources in Radio Frequency (Left). Classification of Solar Radio Bursts (Right).

The red line highlights the 1,42GHz frequency of interest for our instrument.





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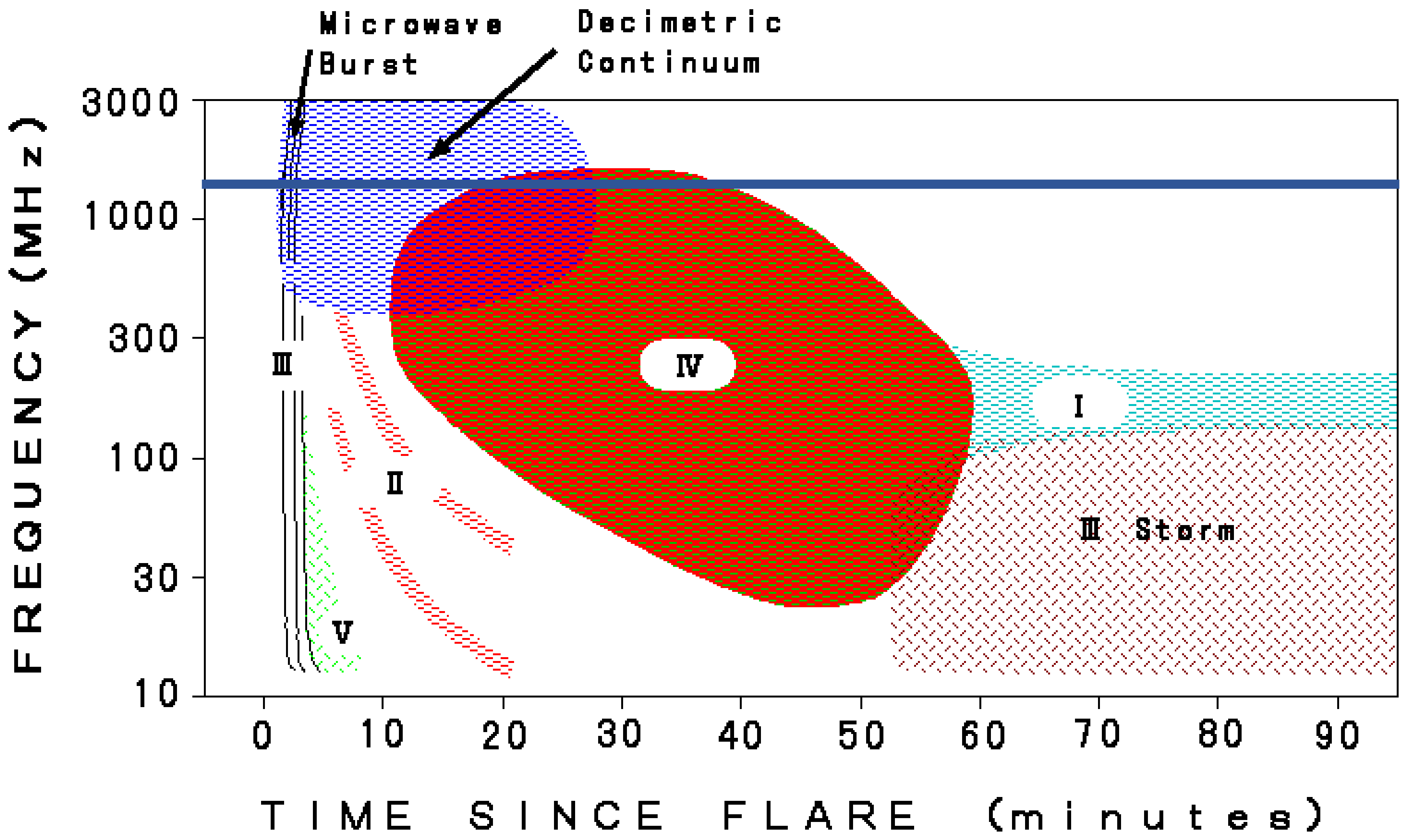


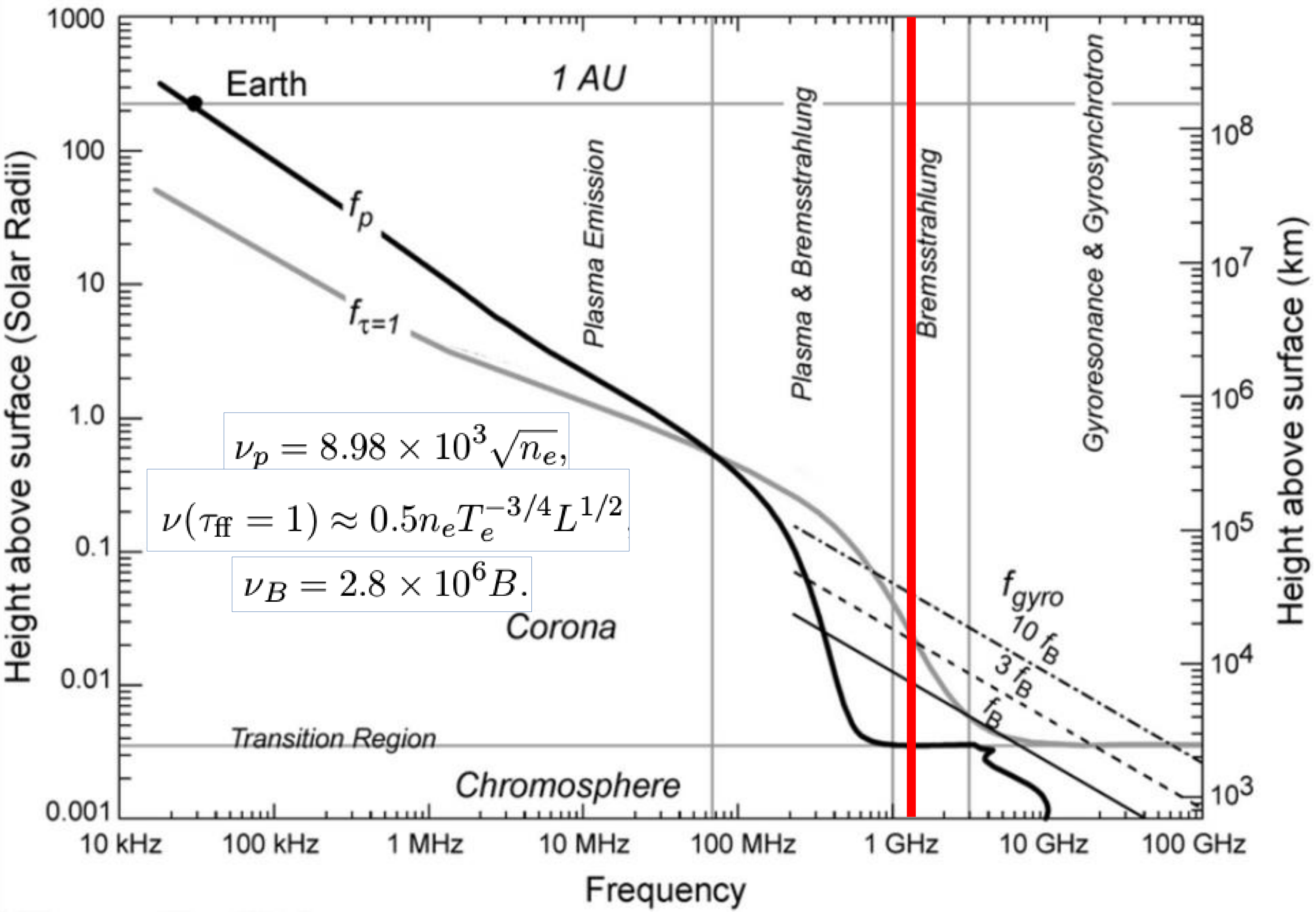
Figure 2: Schematic diagram showing the Classification of Solar Radio Bursts. Taken from NICT (http://sunbase.nict.go.jp/solar/denpa/hiras/types.html)

Background

III	Fast frequency drift bursts. Occur singularly, in groups or storms. Accompanied by a second harmonic	Single Burst: 1 - 3 s Groups: 1 - 5 min Storm: min - Hours	10 kHz -1 GHz	Active Regions, Flares
IV	Stationary Type IV. Broadband Continuum with fine structure	hours- days	20 MHz - 2 GHz	Flares, Proton emission
	Moving Type IV. Broadband, slow frequency drift with smooth continuum	30 min - 2 hours	20 - 400 MHz	Eruptive prominences MHD shock waves
	Flare Continua. Broadband, smooth Continuum	3 - 45 min	25 - 200 MHz	Flares, Proton emission

Figure 3: Classification of Solar Radio Bursts. Taken from Space Weather Services, Australian Bureau of Meteorology (http://www.sws.bom.gov.au/World_Data_Centre/1/9/3)

Background



$$\nu_p = 8.98 \times 10^3 \sqrt{n_e},$$

$$\nu(\tau_{\mathrm{ff}} = 1) \approx 0.5 n_e T_e^{-3/4} L^{1/2}$$

$$\nu_B = 2.8 \times 10^6 B.$$

Figure 4: Characteristic Radio Frequencies for the solar atmosphere and the dominating type of emisión mechanism (Gary, 2014)

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Introduction

The **Phased Array Radio Interferometer at 21cm in the Observatorio Astronómico Nacional (PhAraON)** is a novel prototype of radio interferometer, with Yagi-Uda antennas fabricated as printed circuit boards, with resonance frequency of 1.42GHz (λ=21 cm).

Stage 1 of **PhAraON** is a 2-element drift solar radio interferometer developed as a Bachelor's Thesis in Electronics Engineering at the Department of Electric and Electronics Engineering - Universidad Nacional de Colombia in 2016 [**1**], where antennas were deployed in a 2X2 array configuration. The antenna elements are separated 8 meters, forming the East-West baseline. Later a Sum-Difference coupler circuit working as an analog correlator, and USB dongles as signal receivers are used. This is considered as precursor stage of the ongoing project.

The current design uses these identical Yagi-Uda printed antennas at the focal point of a reflector dish, in order to enhance its directivity, hence its sensitivity.

Previous Stage

Figure 5: 2-element drift Solar Radio Interferometer Installation. Observatorio Astronómico Nacional, Campus Building. (Hincapié Tarquino *et. al.* 2016). **Left:** Array installation. **Top, Center:** Antenna element in 2x2 Yagi-Uda antena configuration. **Top, Right:** Rat-race coupler as analog correlator. **Bottom, Right:** Data acquisition & visualization sytem.

Antenna Design

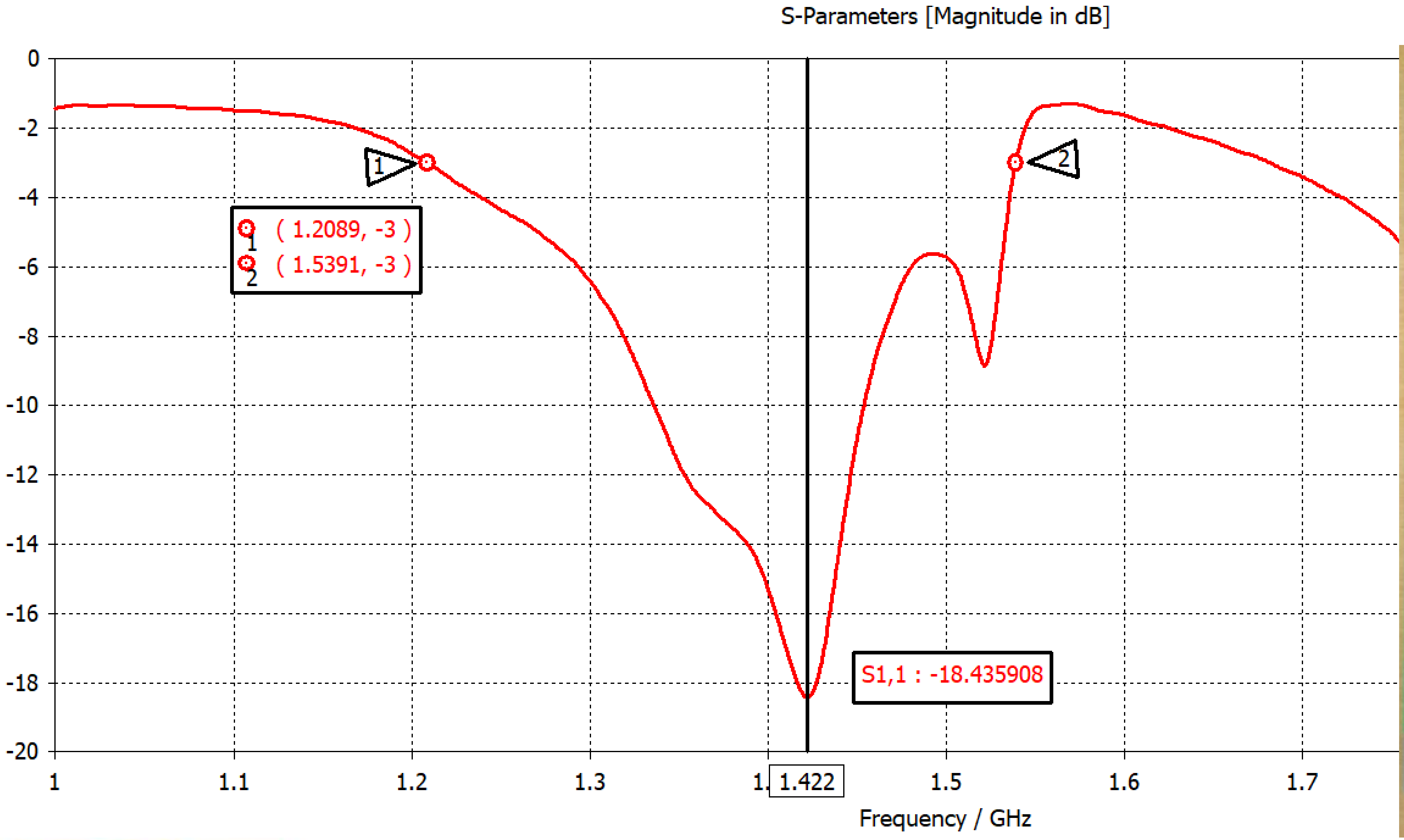


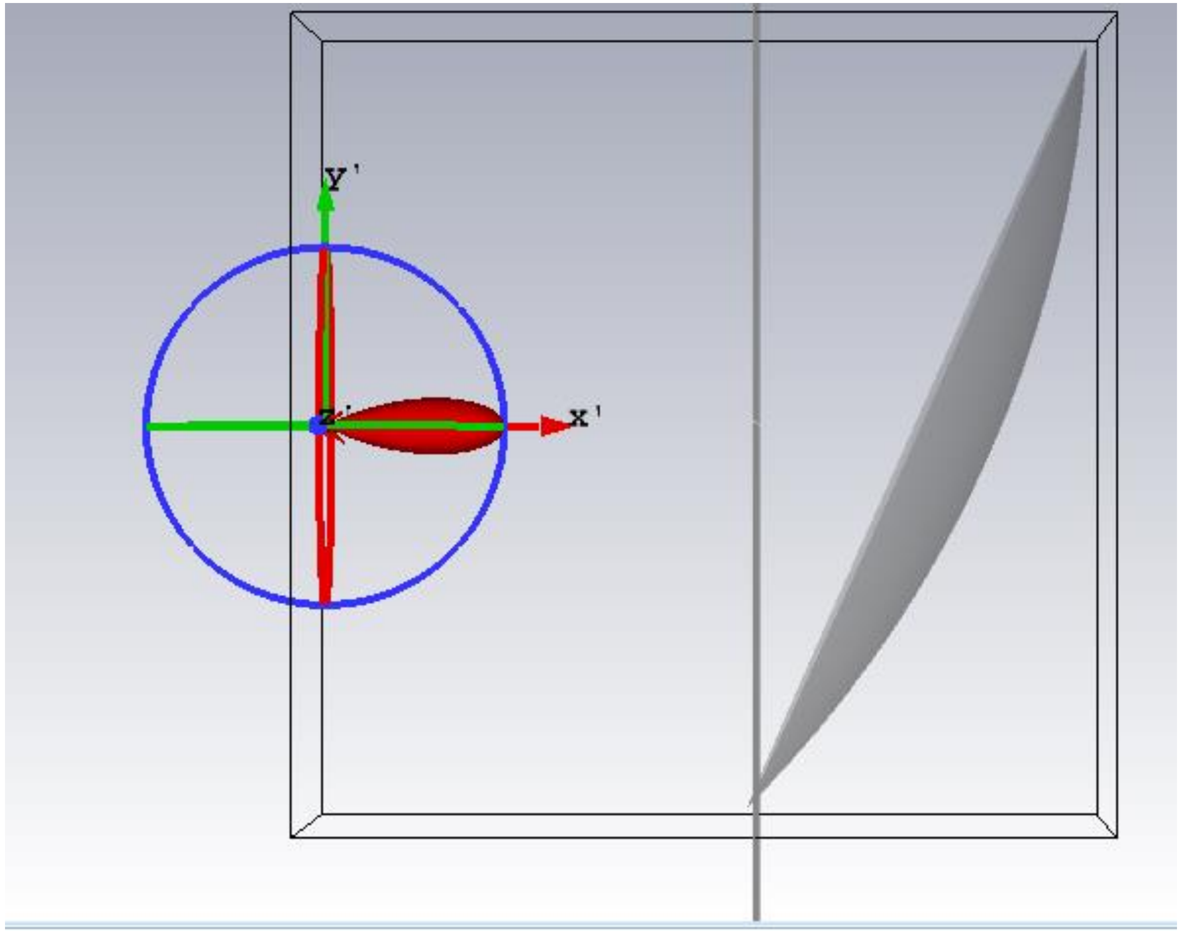
Figure 6: Antenna Simulation: S11 Parameter - Antenna Reflection Coefficient. (Hincapié Tarquino *et. al. in. prep.*)

Antenna Design

Simulations were performed in order to know the behavior of the antenna element, with the printed antenna on the focus of the parabolic reflector dish. This was done in two configurations for the feeding system: First as a single antenna (Figure 8), and then as a 2x2 array (Figure 9), as was used in the precursor drift interferometer.

Simulations results for the single antenna feed configuration yield higher gain and smaller side lobes in comparison with the 2x2 array. This means that the dish is sub-utilized with the 2x2 array. This was verified during the validation for all mechanical and RF systems, so the design chosen for the project is the single antenna configuration.
All simulations were performed in CST Microwave Studio Suite.

Antenna Design



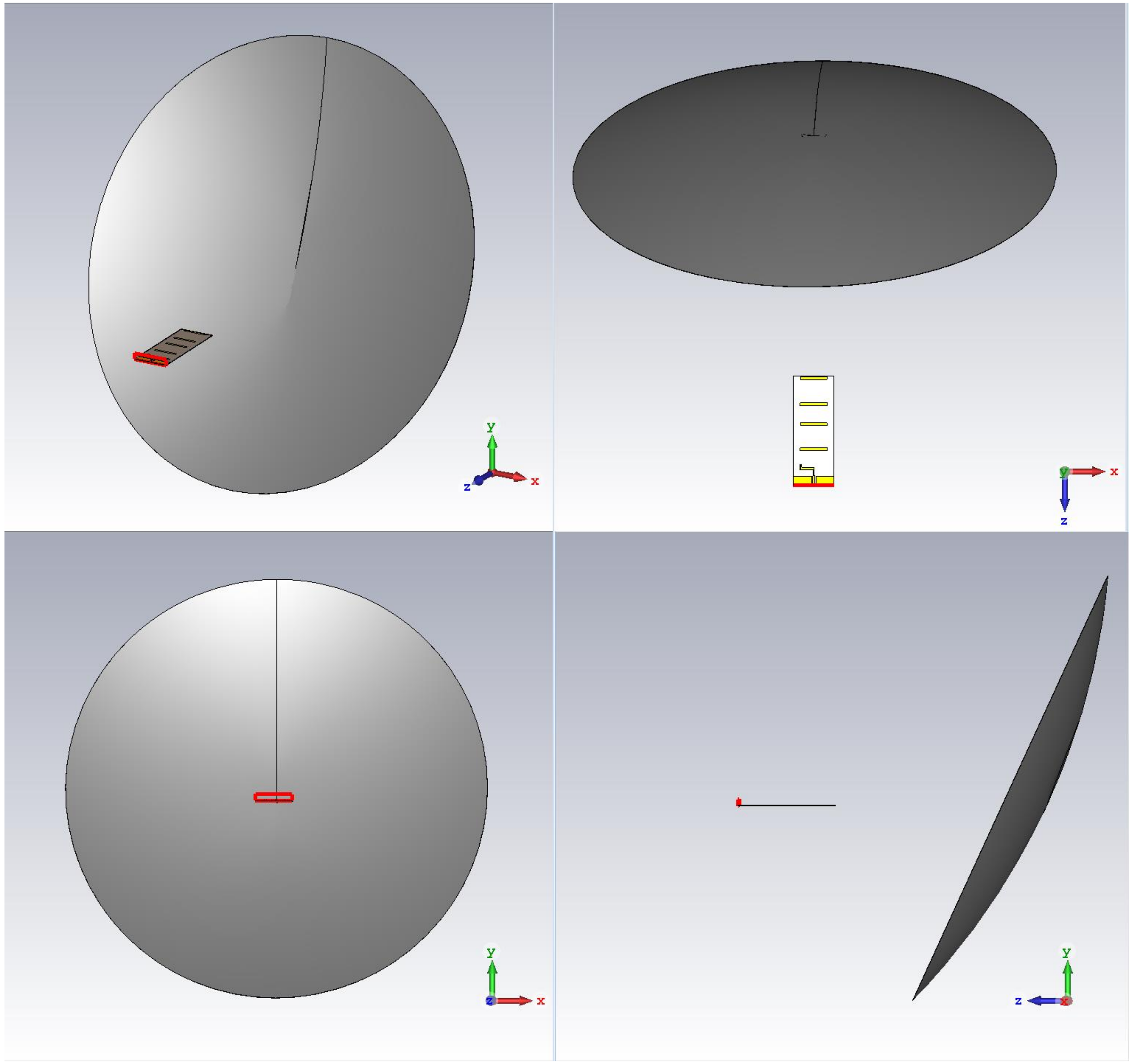


Figure 7: Antenna Element Simulation Design. Single Yagi-Uda antenna in the focus of an offset-fed reflector dish.

Antenna Design

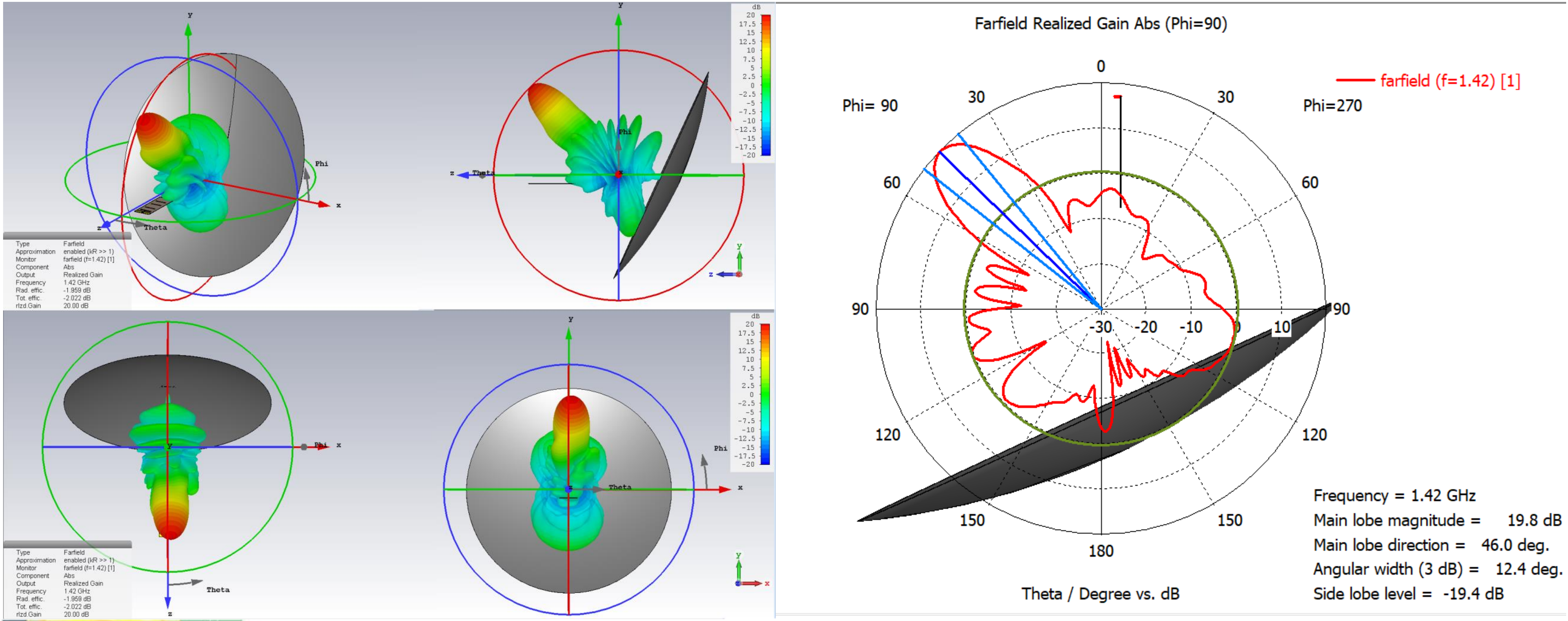


Figure 8: Antenna Simulation: 1 Antenna + Reflector. Realized Gain. (Hincapié Tarquino *et. al. in. prep.*)

Antenna Design

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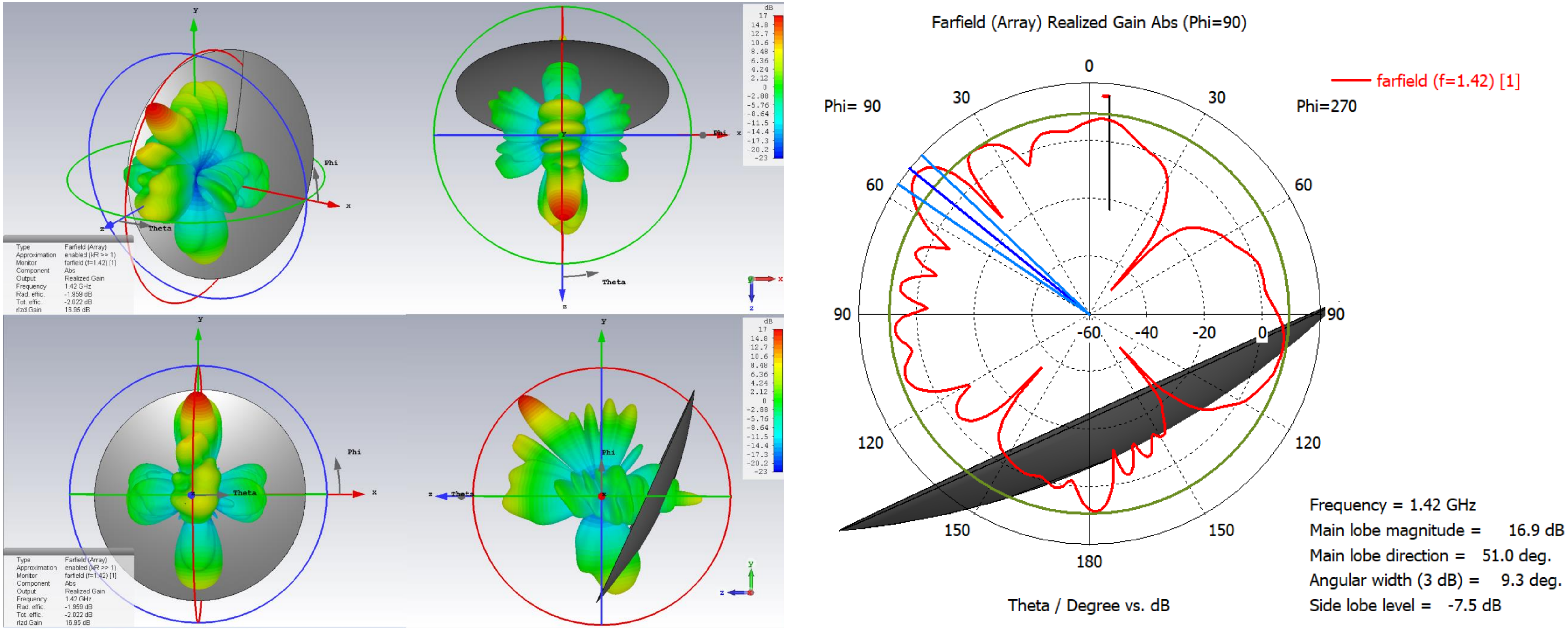

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Figure 9: Antenna Simulation: 2x2 Antenna Array + Reflector. Realized Gain. (Hincapié Tarquino *et. al. in. prep.*)

Steerable Pier: Preliminary and Final Design

Figure 10: Steerable Pier Preliminary Design: DC motor for Azimuth & DC actuator for Elevation

Preliminary design for steerable pier consisted on a DC motor for azimuth motion and a DC actuator for elevation motion (Figure 10).

After preliminary tests were conducted for validation of RF and mechanical systems, we changed the design for a configuration of Stepper motors, each with reducer gearbox (Figure 11).

This, in order to get more torque and control for the antena motion. Additionally the actuator for elevation did not have uniform motion during the full range.

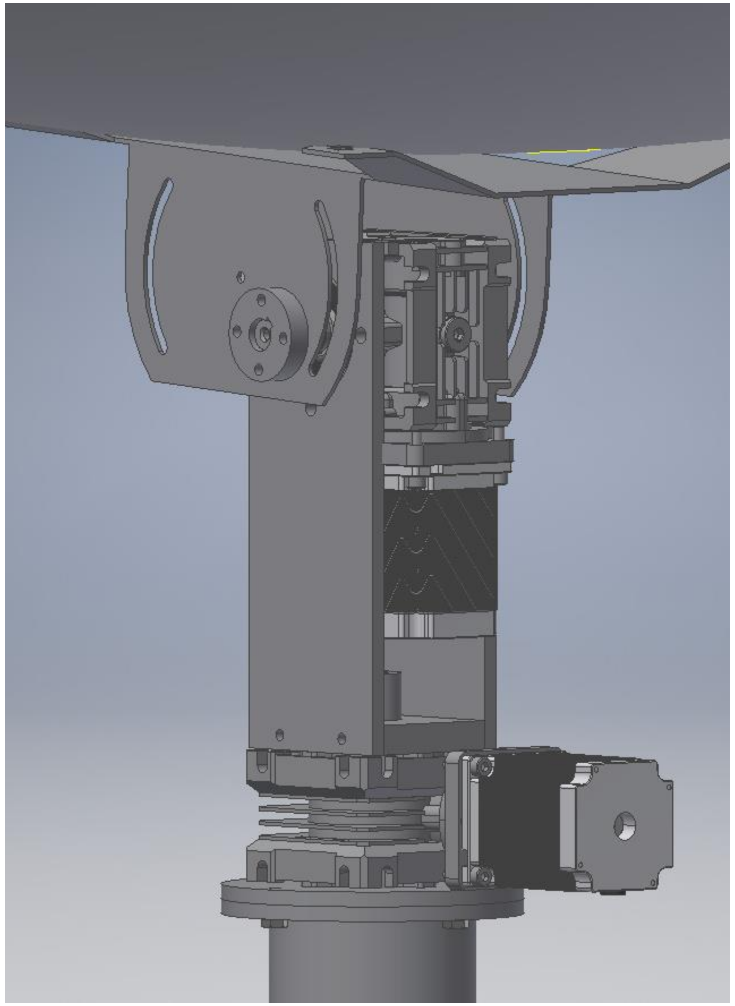
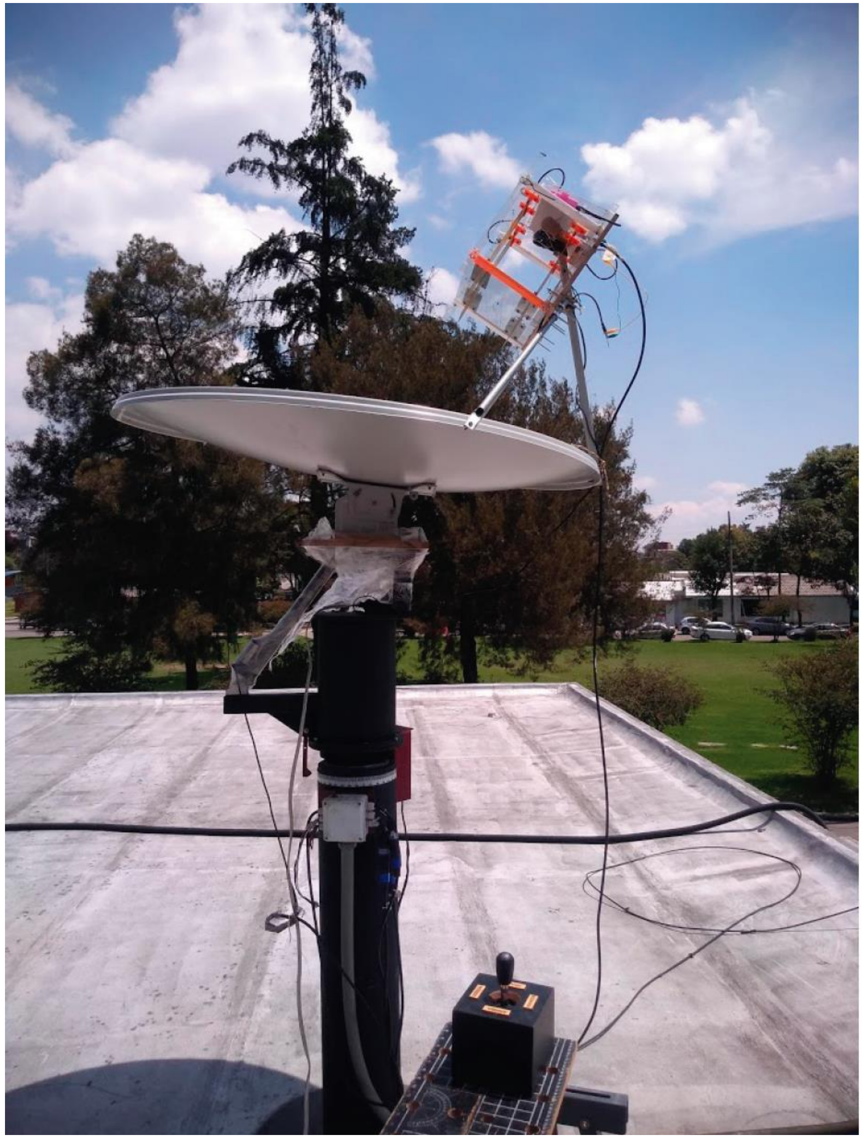


Figure 11: Steerable Pier Final Design: Stepper motor and reducer gearbox for Azimuth & Elevation motion (Hincapié Tarquino *et. al. in. prep.*)

Mounting and First Testing Phase

Figure 12: First Testing Phase with 2x2 Array Feed (Hincapié Tarquino *et. al. in. prep.*)

Mounting and First Testing Phase



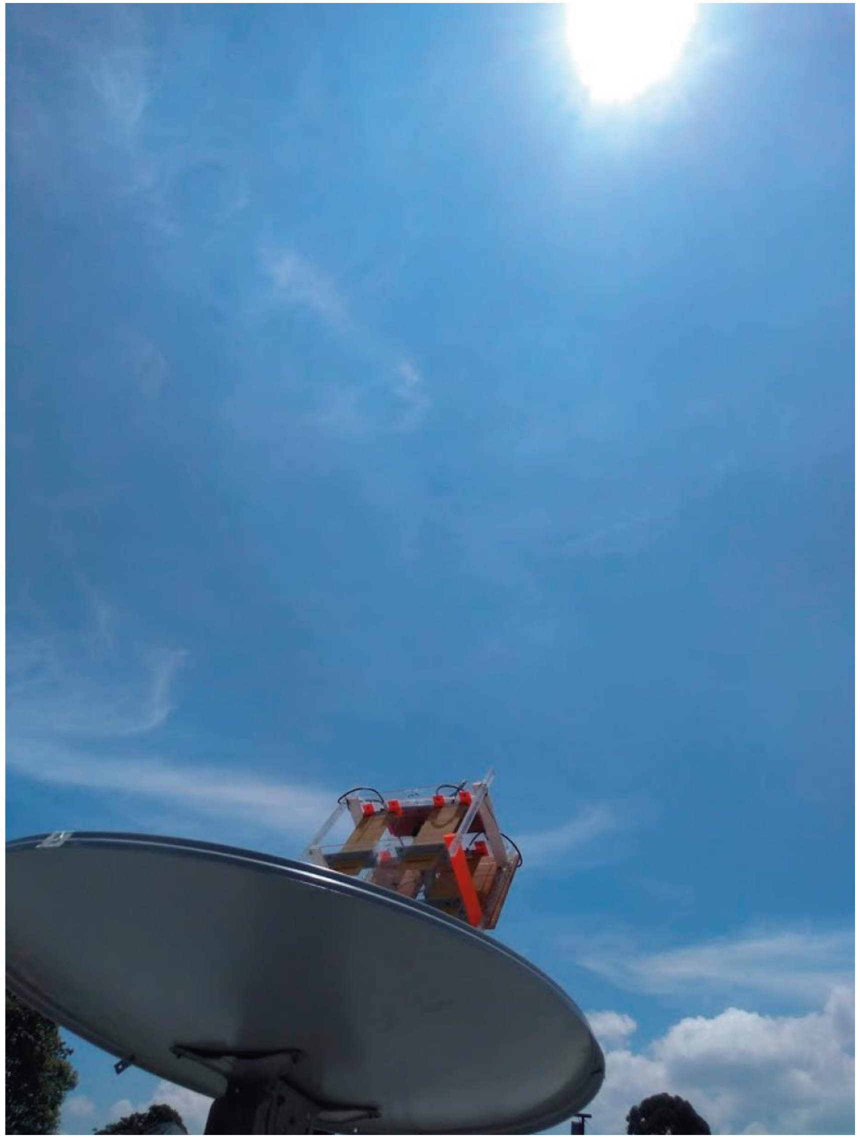


Figure 13: First Testing Phase with 2x2 Array Feed (Hincapié Tarquino *et. al. in. prep.*)

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Preliminary Results

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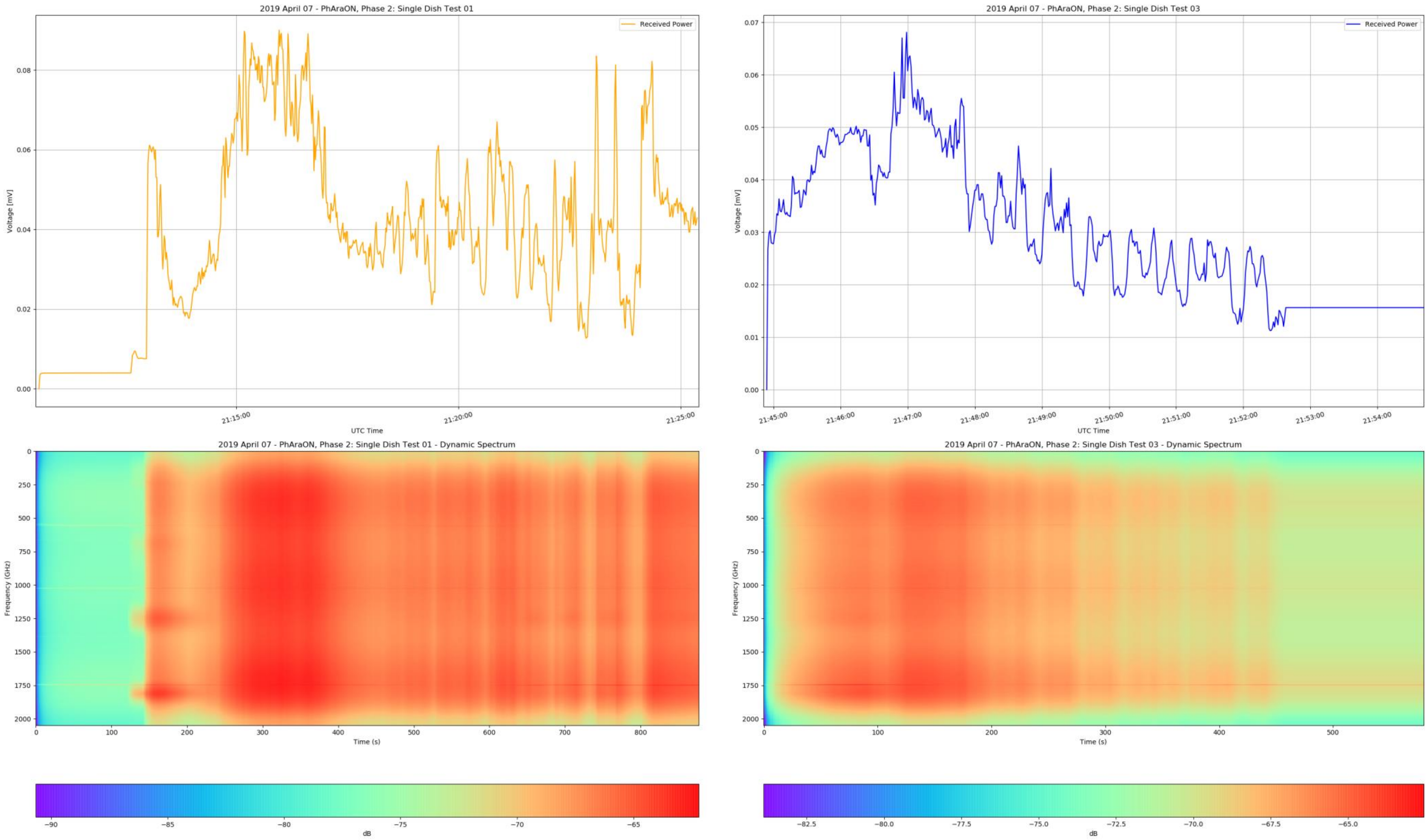

Figure 14: Preliminary Results: Solar Scan with 2x2 Array Feed

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Preliminary Results

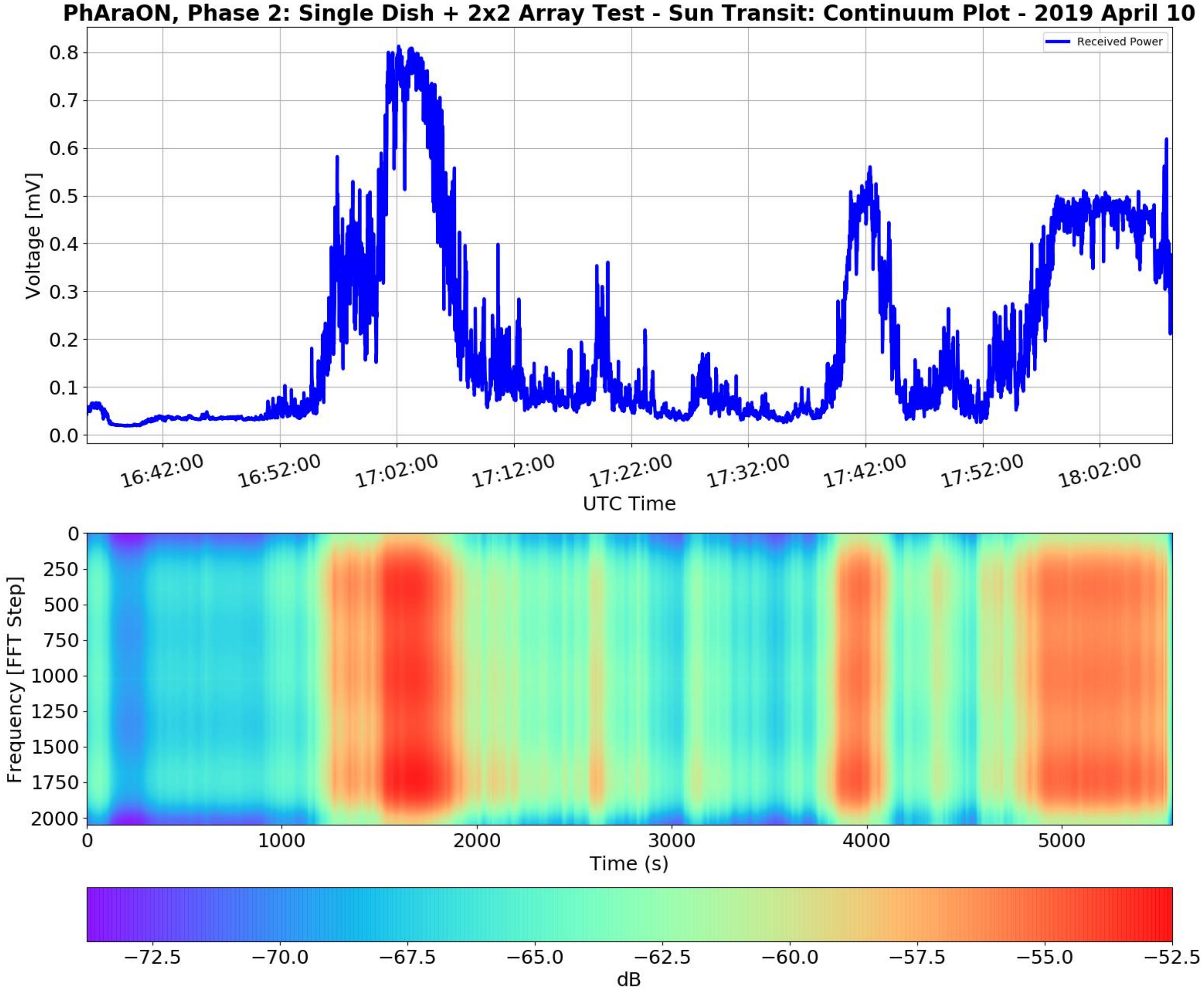

Figure 15: Preliminary Results: Solar Scan in Azimuth and Elevation (*Single Dish Result*). (Hincapié Tarquino *et. al. in. prep.*)

Preliminary Results

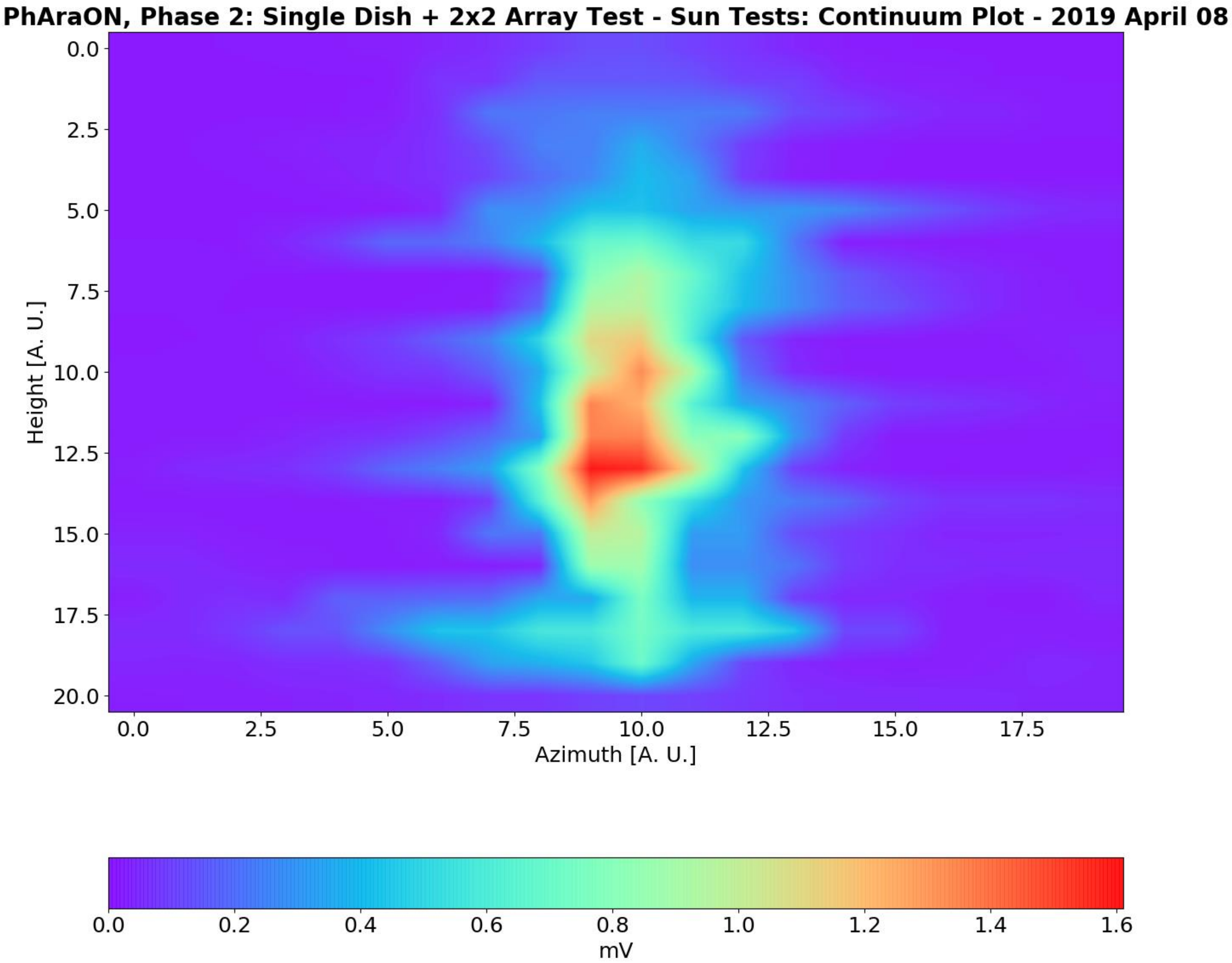

Figure 16: Preliminary Results: Solar Scan with 2x2 Array Feed. (Hincapié Tarquino *et. al. in. prep.*)

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Steerable Pier: Motor Assembly

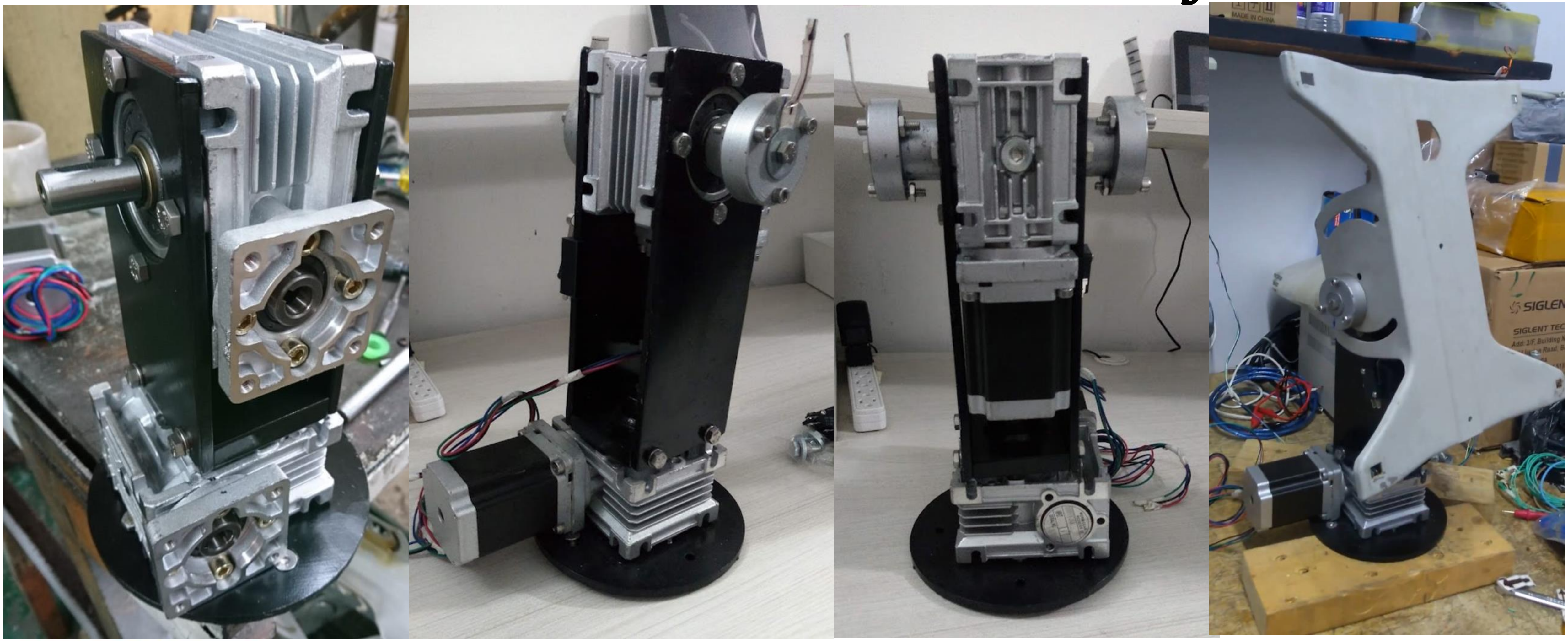

Figure 17: Steerable Pier Assembly: Stepper Motor & Reducer Gearbox for each axis in Alt-Az motion. (Hincapié Tarquino *et. al. in. prep.*)

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Steerable Pier: Assembled elements

Figure 18: Installation of Antenna elements: Steerable Pier Assembly with reflector dish. (Hincapié Tarquino *et. al.* *in. prep.*)

Steerable Pier: Motion Control

Antenna Motion Control Stage is implemented using RS485 serial protocol and Stellarium for automated control. Validation tests were already successfully performed.

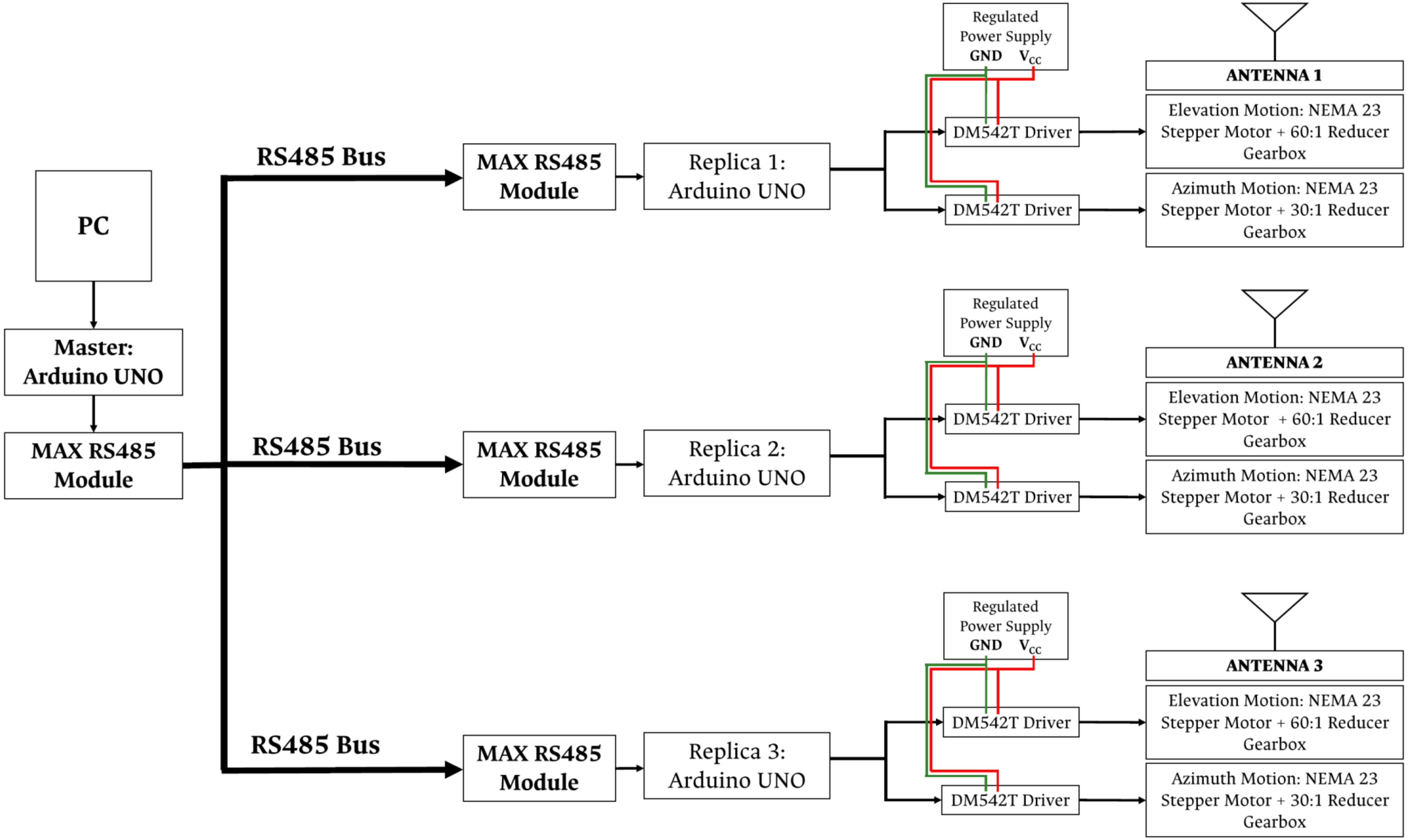


Figure 19: Block Schematics for Antenna Motion Control Stage: Master-Replica RS485 Protocol. (Hincapié Tarquino *et. al. in. prep.*)

RS485 serial protocol

Asyncronous serial communication. Uses Differential signal to transfer binary data from one device (Master) to another (Replica)

- RS-485 supports a higher data transfer rate (30Mbps max).
- Maximum data transfer distance up to 1200 meters.
- Main advantage: multiple replicas with a single Master. (maximum of 32 devices connected).
- Immune to noise.
- RS-485 is faster compared to the I2C protocol.

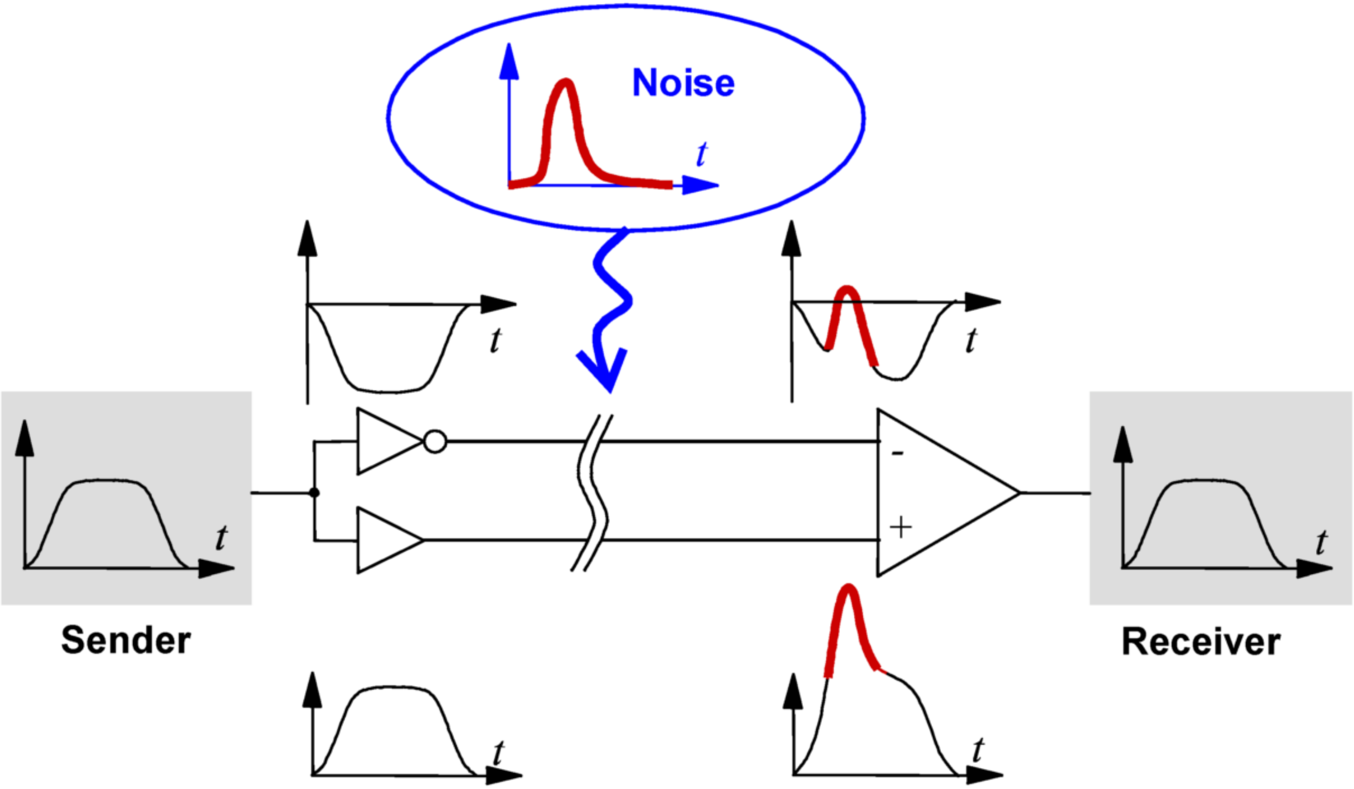


Figure 20: Schematics for communication using RS485 serial protocol.

RS485 serial protocol

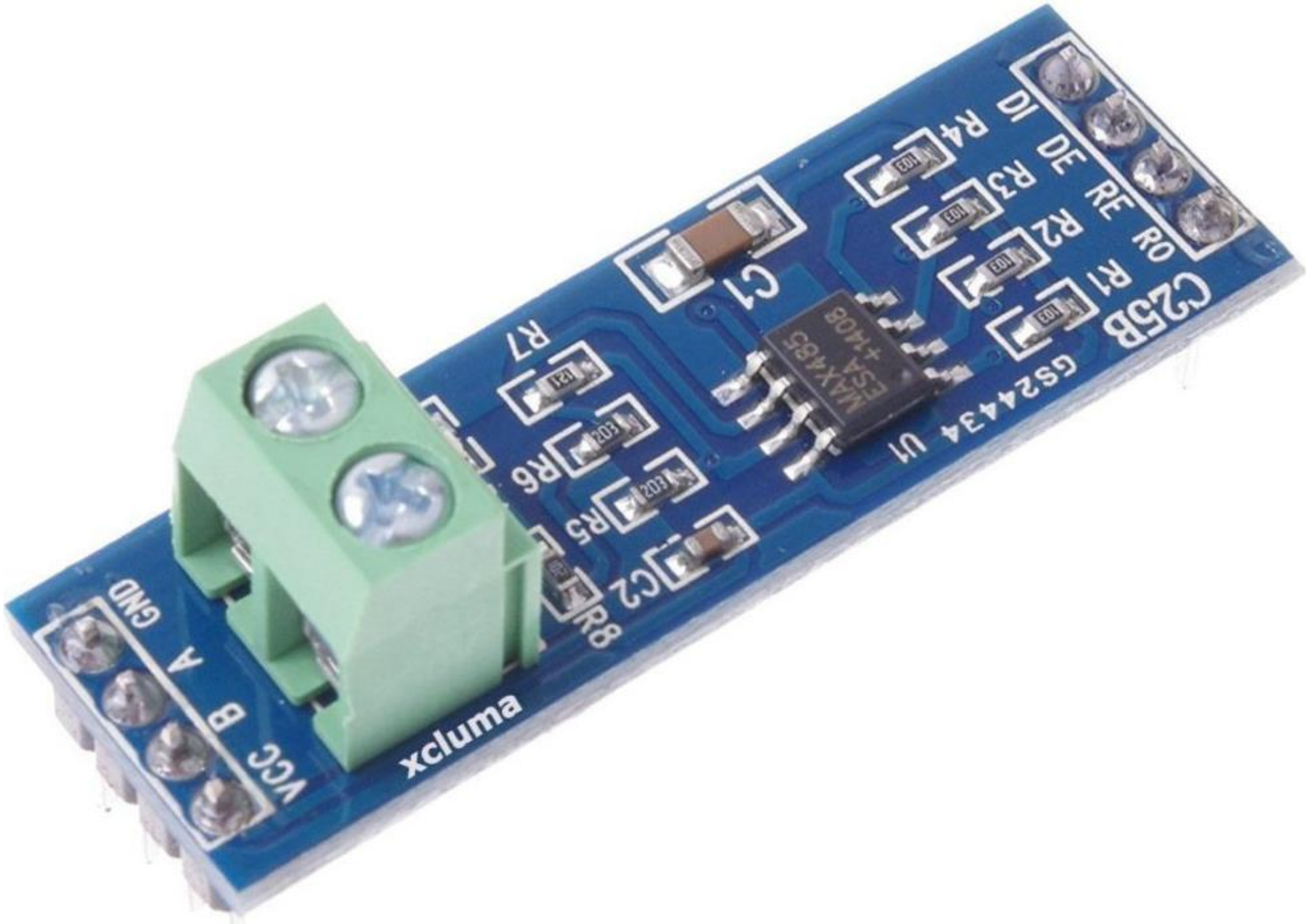
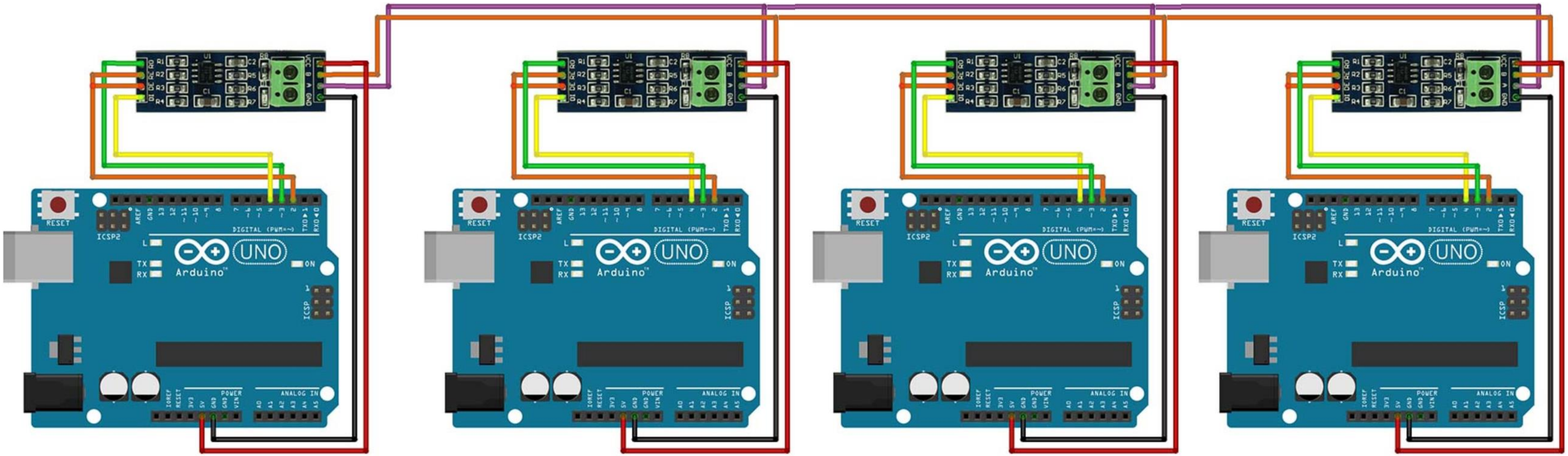


Figure 21: MAX RS485 serial module and pin descriptions.

Pin Name	Pin Description
VCC	5V
A	Non-inverting Receiver Input Non-Inverting Driver Output
B	Inverting Receiver Input Inverting Driver Output
GND	GND (0V)
R0	Receiver Out (RX pin)
RE	Receiver Output (LOW-Enable)
DE	Driver Output (HIGH-Enable)
DI	Driver Input (TX pin)

RS485 serial protocol



Arduino UNO: Master

Arduino UNO: Replica 1

Arduino UNO: Replica 2

Arduino UNO: Replica 3

Figure 22: Connection diagram for Antenna Motion Control Stage: Master-Replica RS485 Protocol. (Hincapié Tarquino *et. al. in. prep.*)

Design: Array Implementation

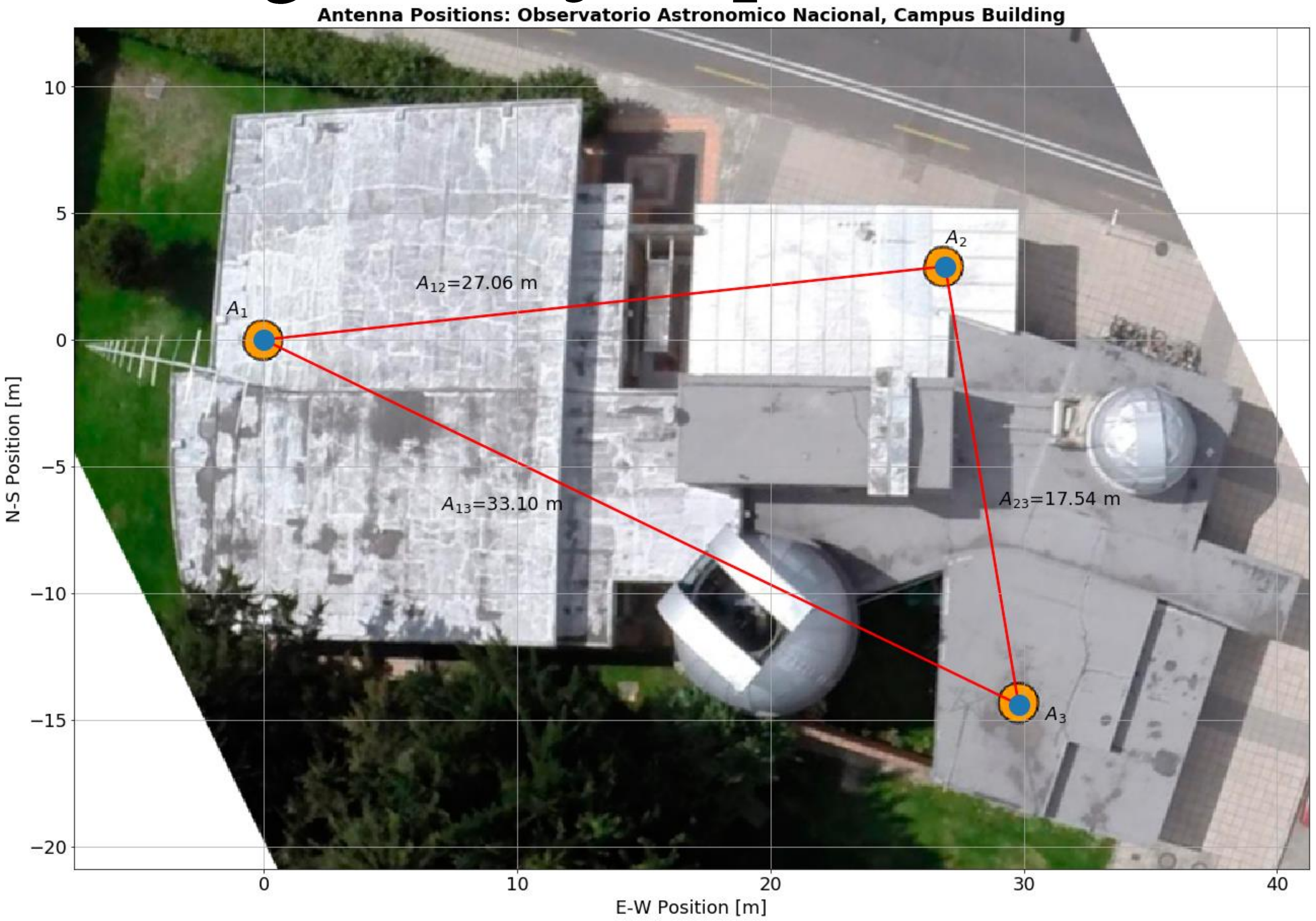
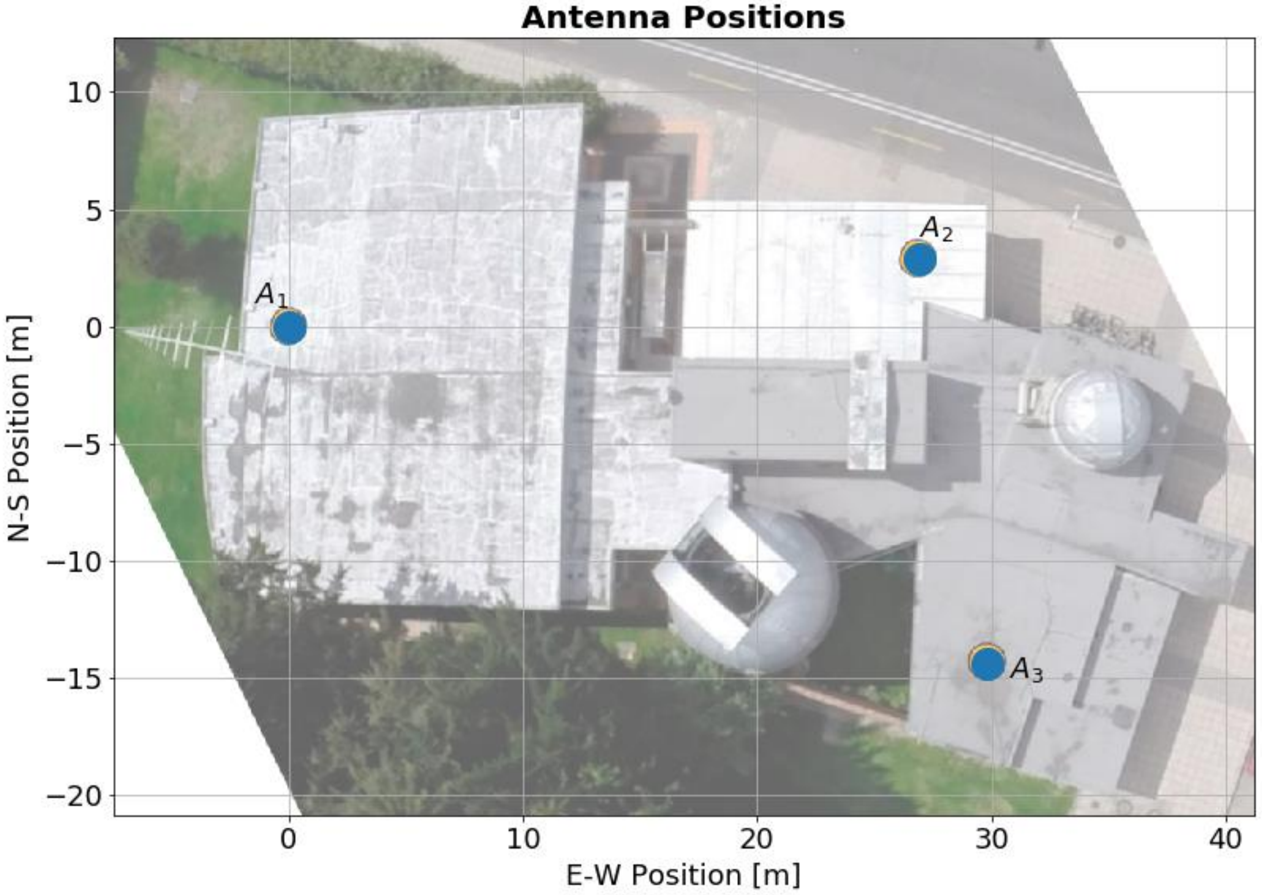


Figure 23: Array Location at Observatorio Astronómico Nacional, Campus Building – Universidad Nacional de Colombia. (Hincapié Tarquino *et. al. in. prep.*)

Design: Array Implementation

Snapshot UV Coverage



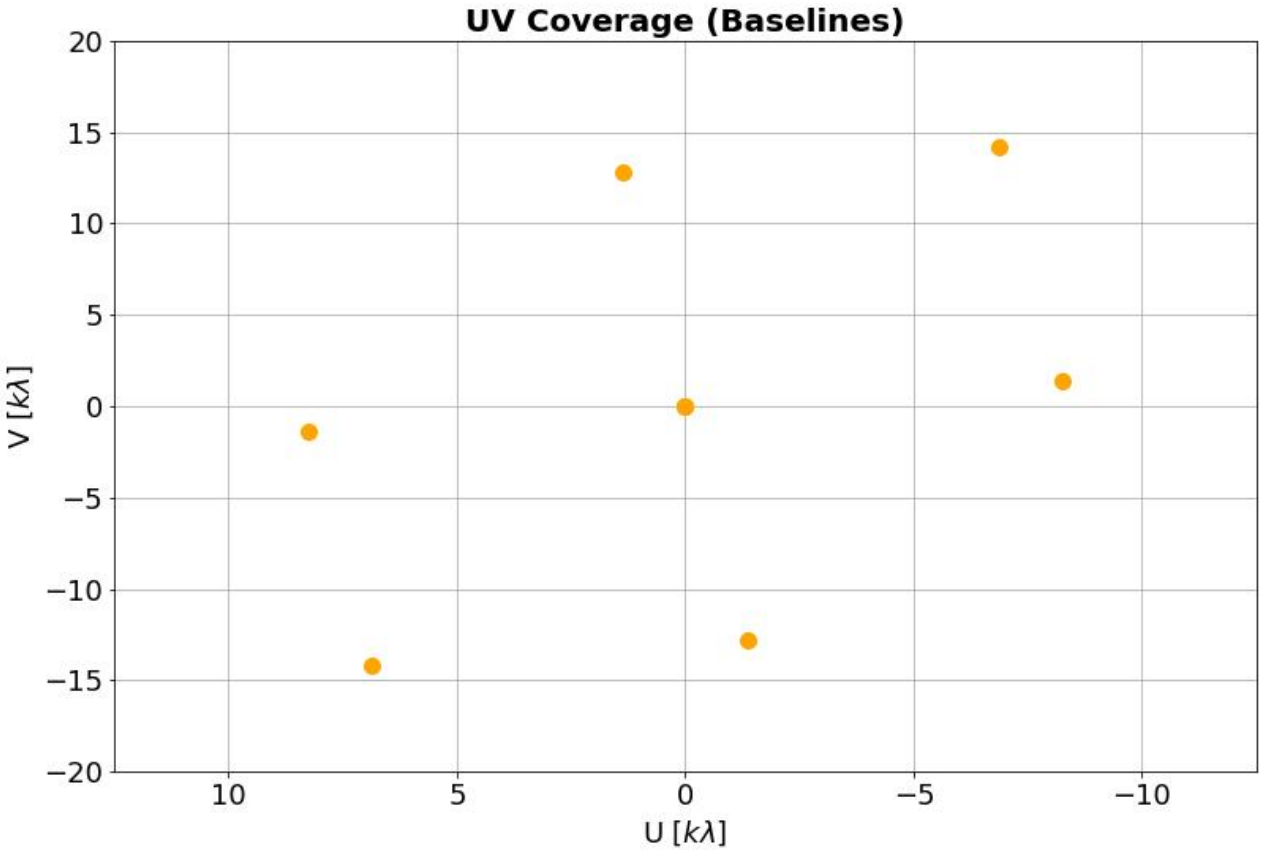


Figure 24: Snapshot UV Coverage for the interferometric array. (Hincapié Tarquino *et. al. in. prep.*)

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Design: Array Implementation

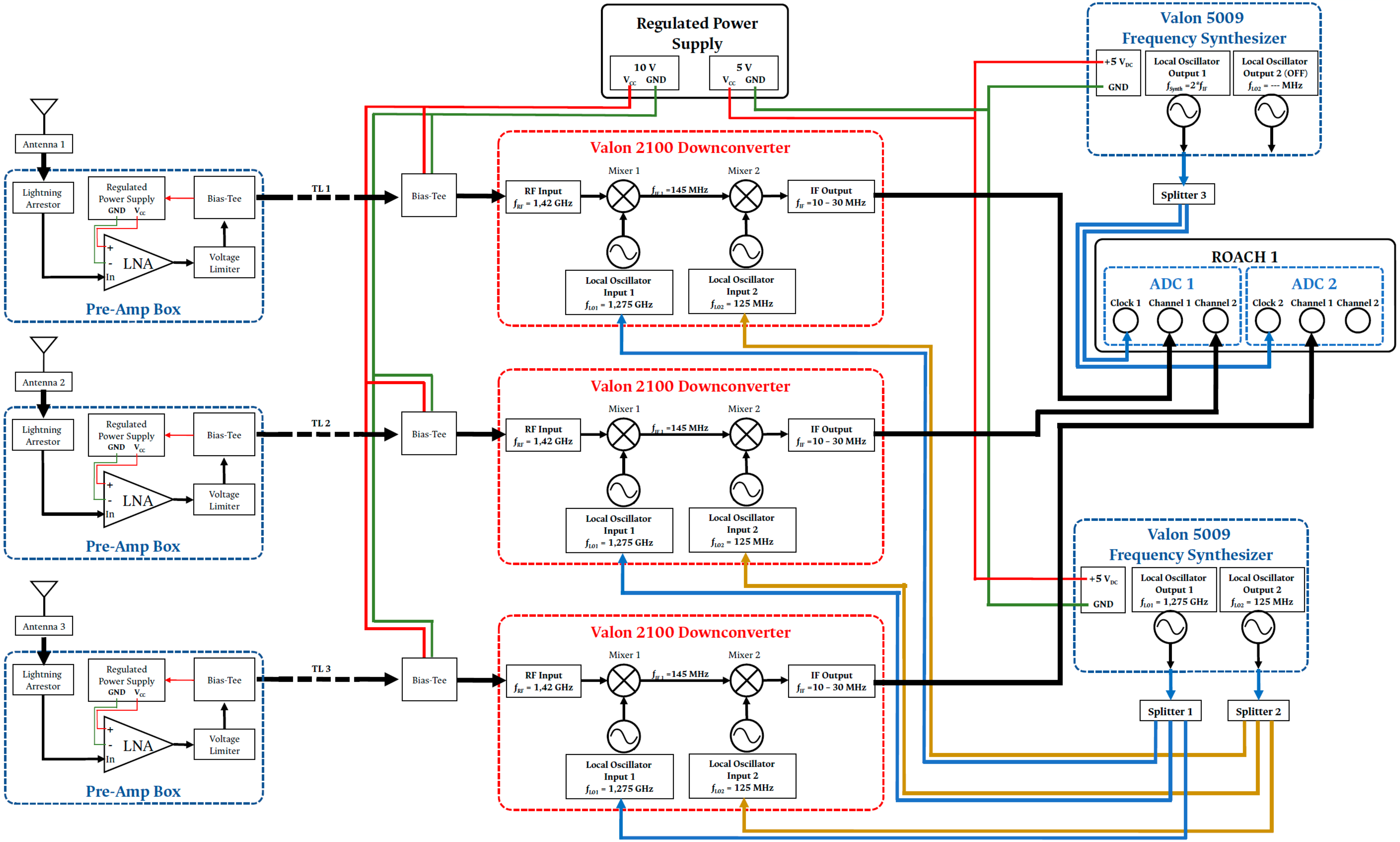

Figure 25: Block Schematics for full interferometric array. (Hincapié Tarquino *et. al. in. prep.*)

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Front-End: Pre-Amp Stage

Pre-Amplification stage is based on the amplification stage used for several systems of the e-Callisto Solar Spectrometer Network. A similar stage is also used for **FiCoRI**, an interferometer dedicated to solar observations at the Observatorio Astronómico Nacional - Campus Building (Guevara Gómez, 2017).

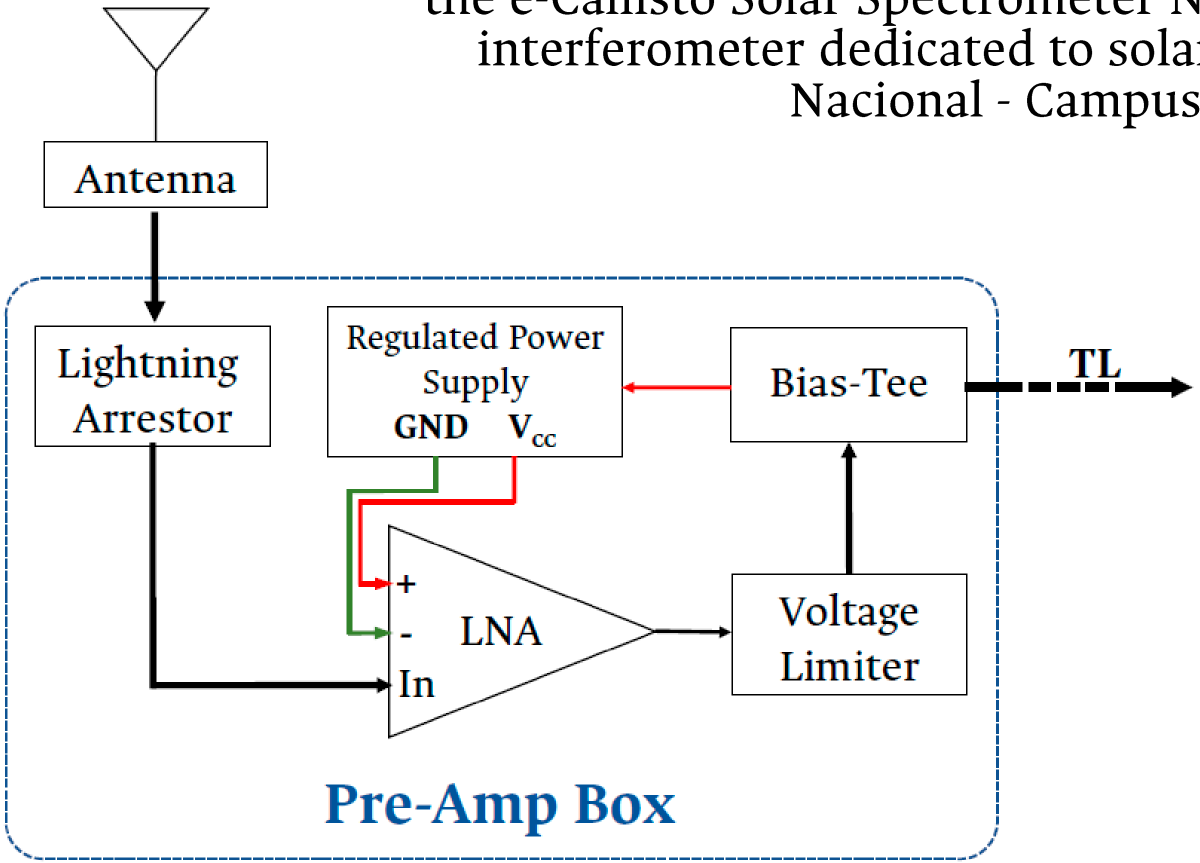

Figure 26: Block Schematics for Pre-Amp stage. (Hincapié Tarquino *et. al. in. prep.*)

Figure 27: FiCoRI Pre-Amp box (Guevara Gómez, 2017)

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Front-End: Downconversion Stage

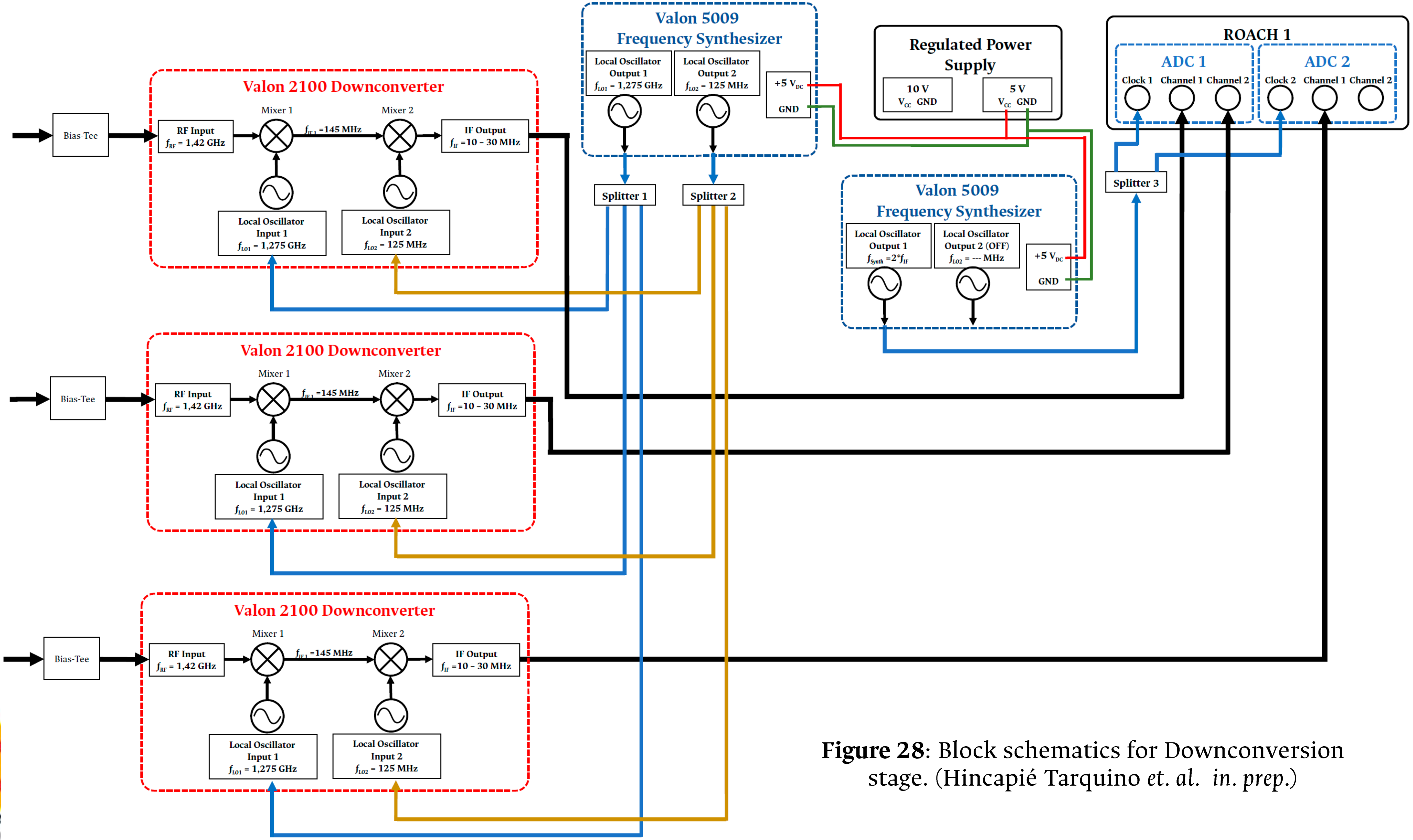

Figure 28: Block schematics for Downconversion stage. (Hincapié Tarquino *et. al. in. prep.*)

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Back-End: Correlator

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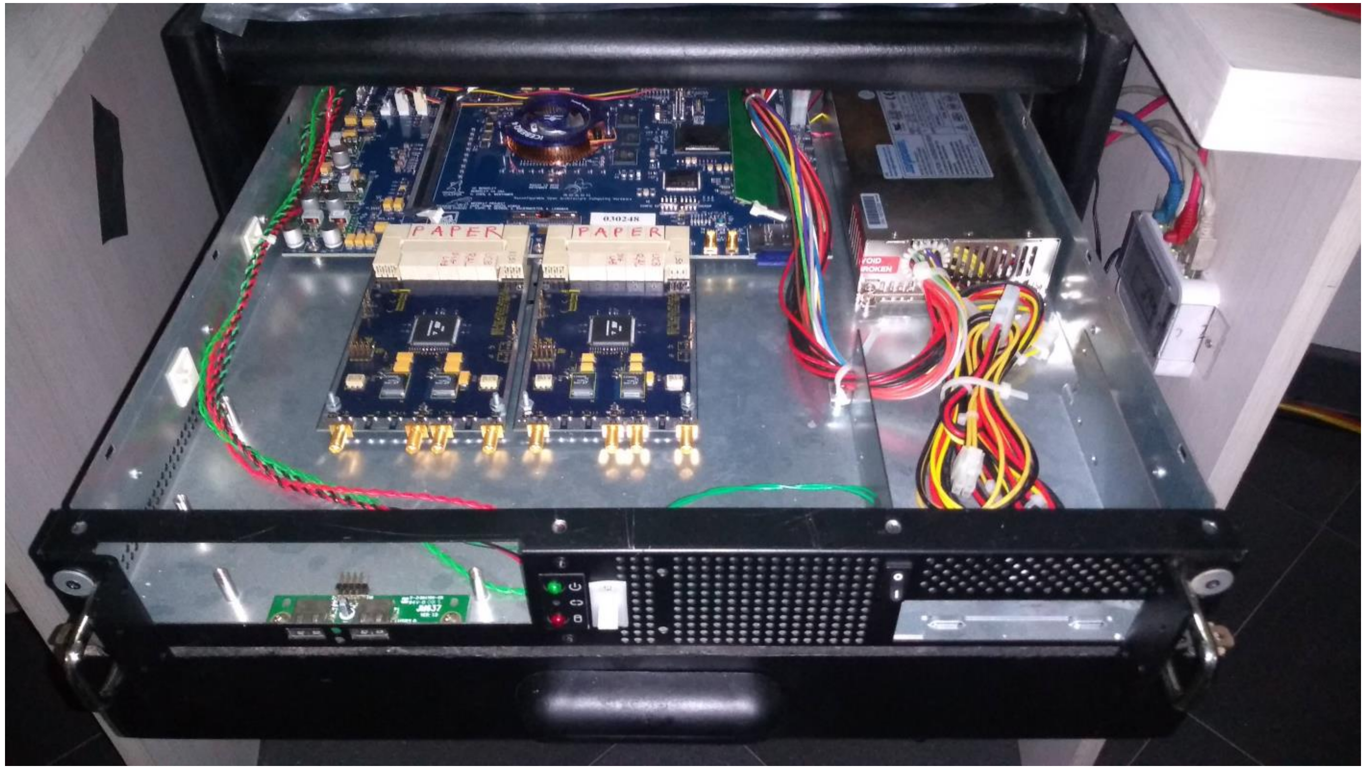

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Figure 29: Correlator Implemented with ROACH-1 board. .
(Hincapié Tarquino *et. al. in. prep.*)

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