Design and Implementation of a Multi-element radio interferometric array

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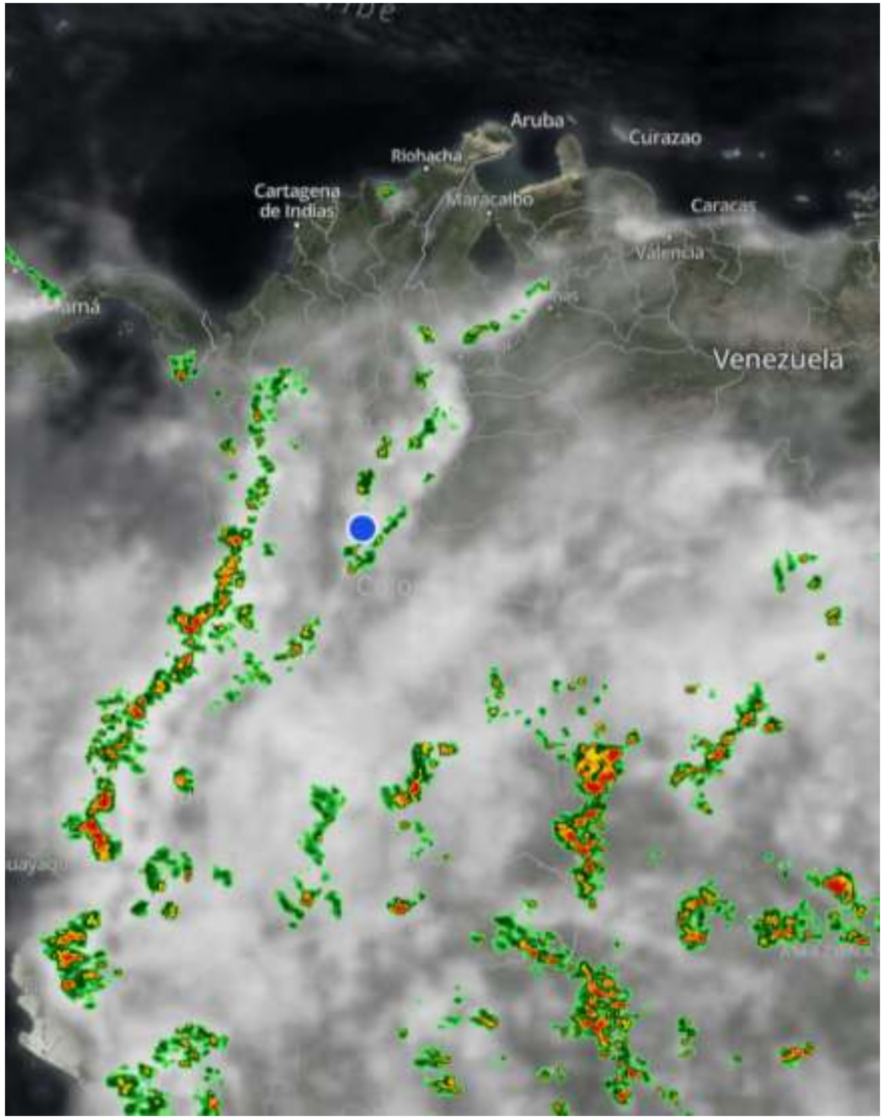
2024

UNIVERSIDAD NACIONAL DE COLOMBIA
OBSERVATORIO ASTRONÓMICO NACIONAL DE COLOMBIA
GOSA GROUP OF SOLAR ASTROPHYSICS UN - COLOMBIA

Introduction



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.

Solar radio emissions account for different emission processes and the medium in which these are generated in the solar atmosphere.

Main Goal:

Design and implement a multi-element radio interferometer, each one with a collector dish, for observations at 1,42 GHz.

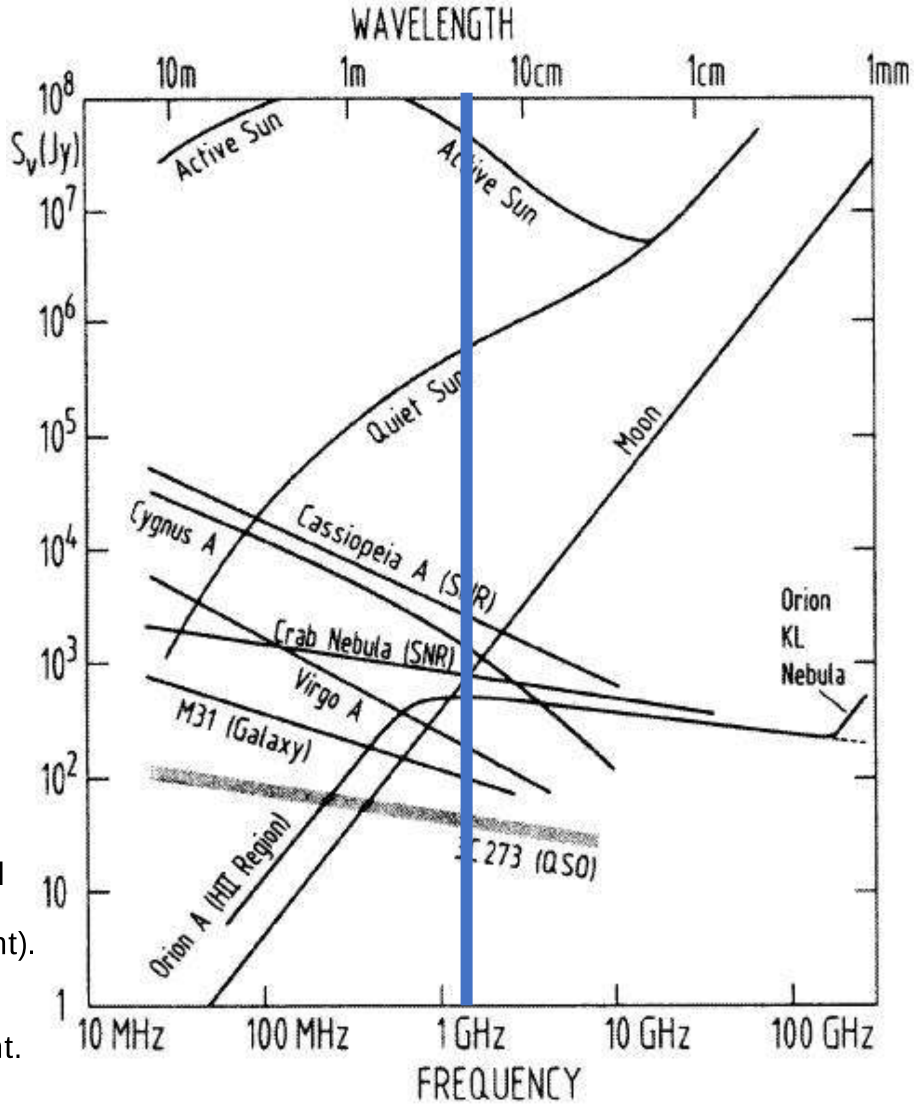
Introduction

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 [7], where antennas were deployed in a 2X2 array configuration, on an 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.

Background



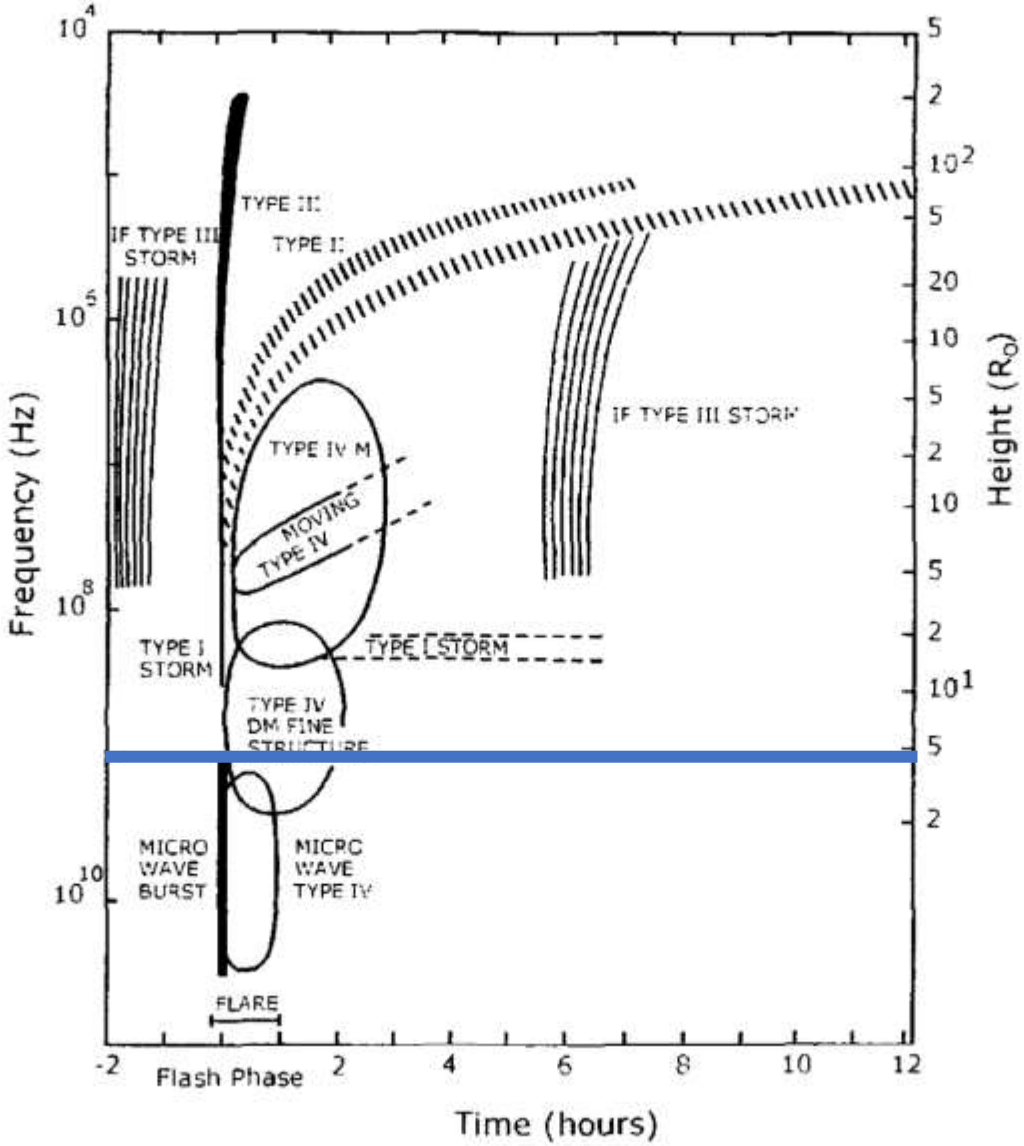


Figure 1: Flux of Several Astronomical Sources in Radio Frequency (Left). Classification of Solar Radio Bursts (Right).

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

Background

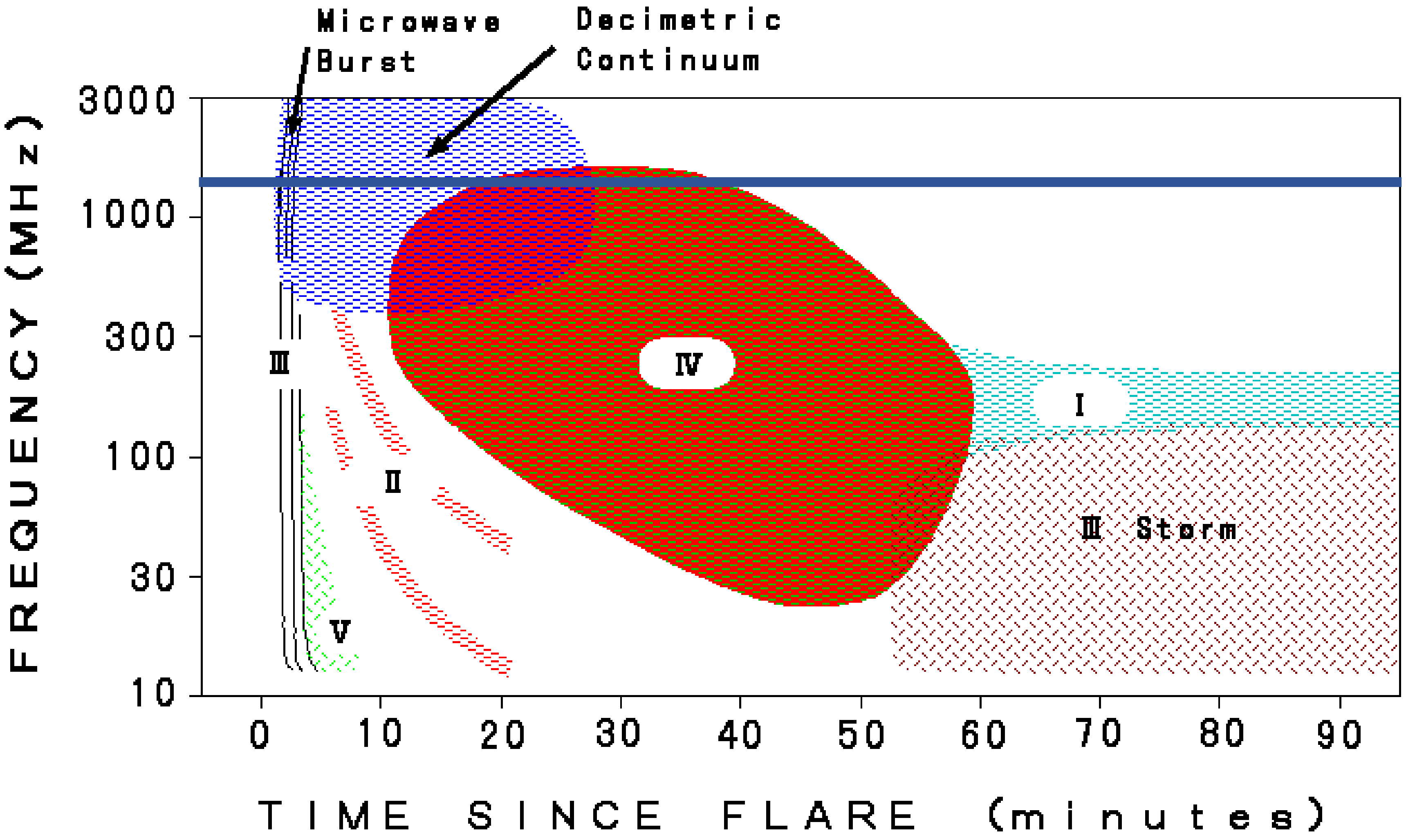
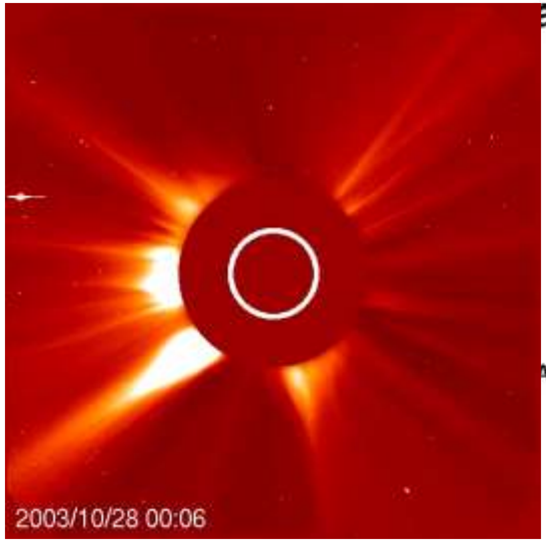
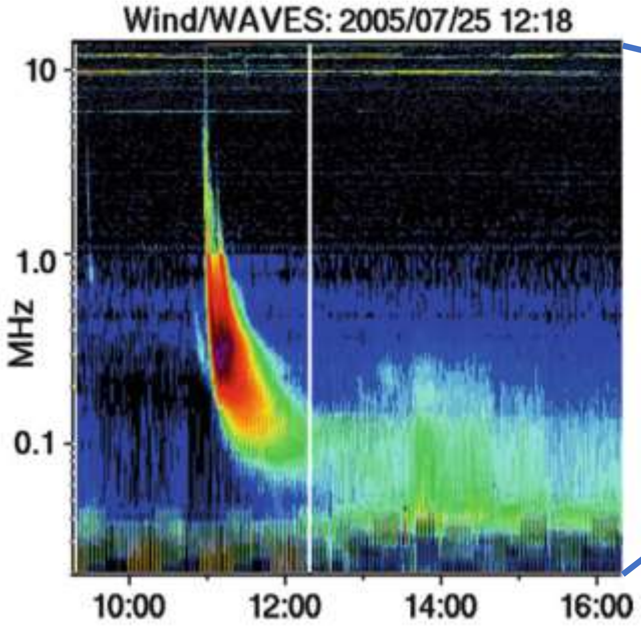


Figure 2: Schematic diagram showing the Classification of Solar Radio Bursts. Taken from NICT (http://sunbase.nict.go.jp/solar/denpa/hiras/types.html)

Background





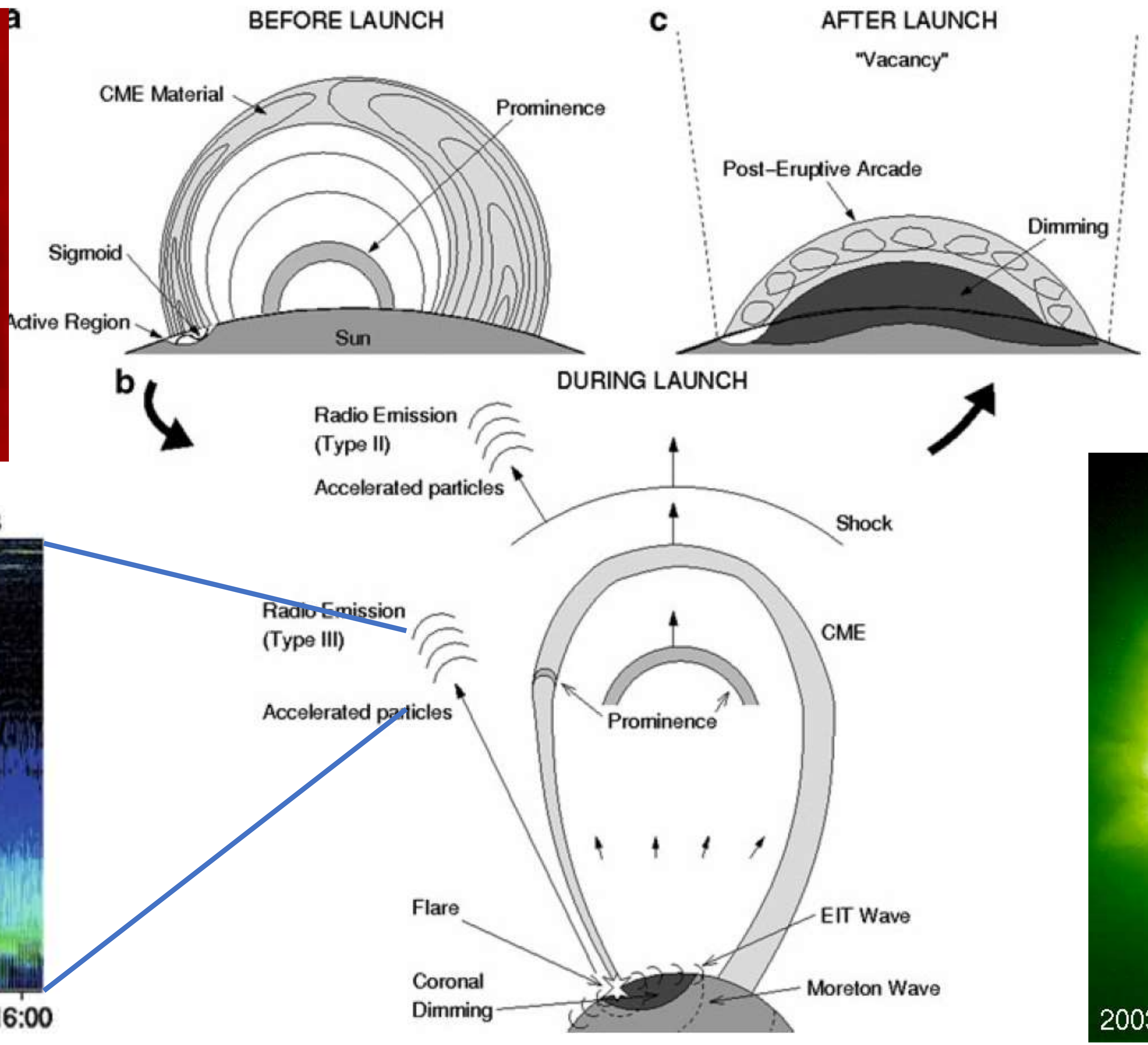
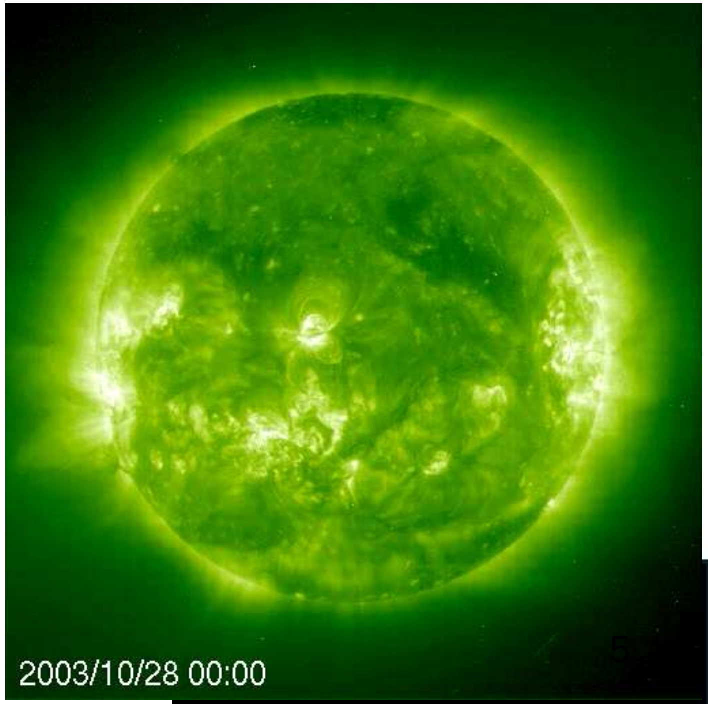


Figure 3: Eruptive phenomena on the solar Surface and estimate of their physical relationship with a CME. (Howard, 2011).

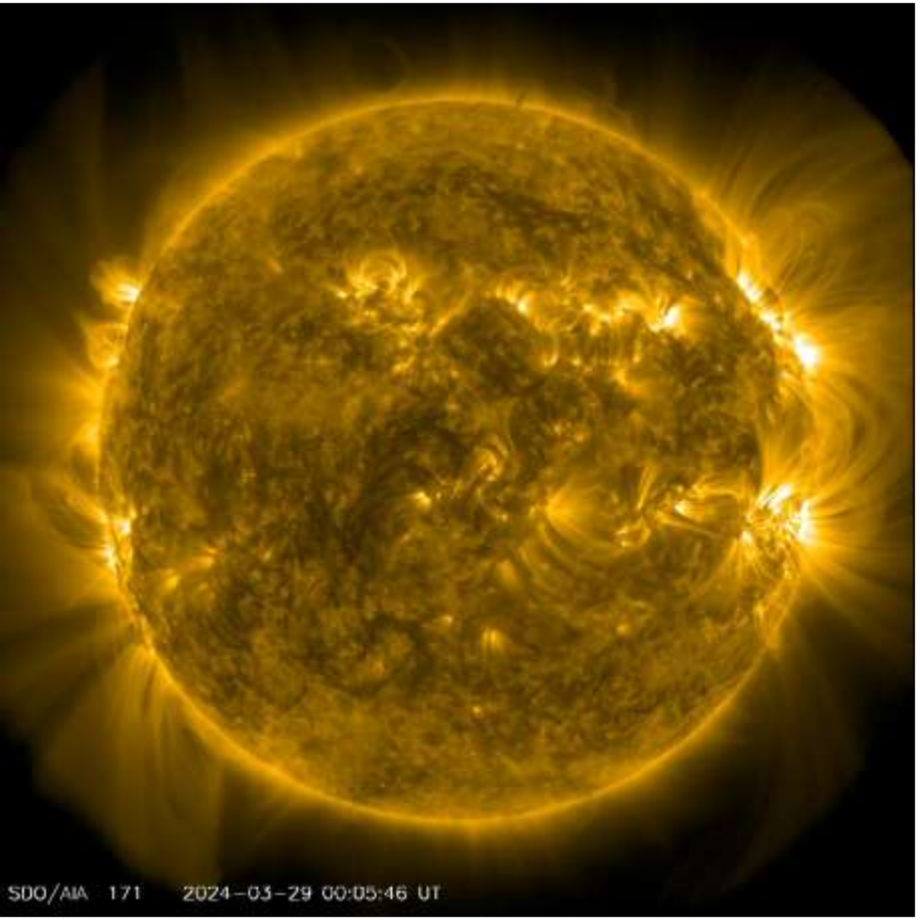


Background

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 4: 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



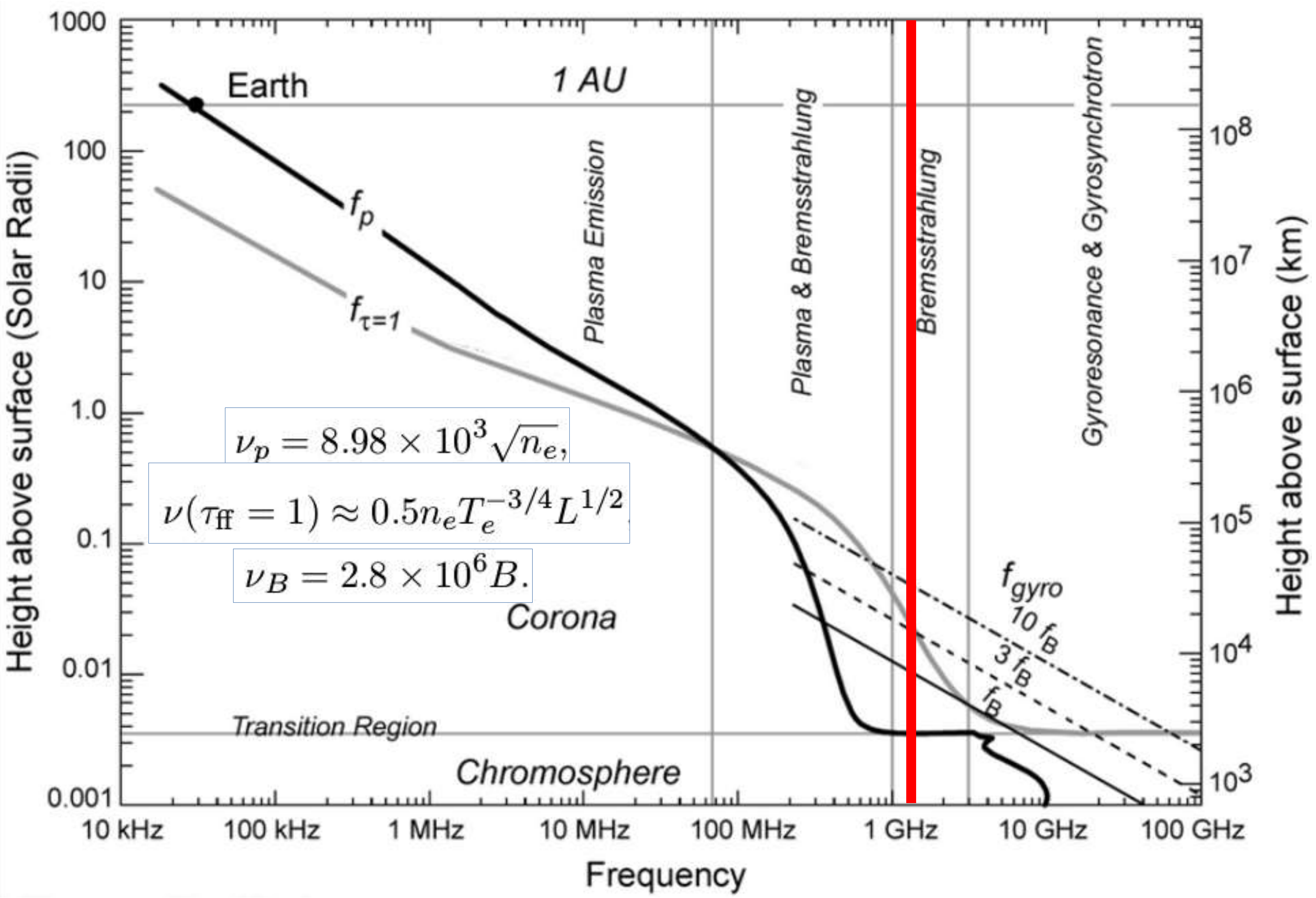
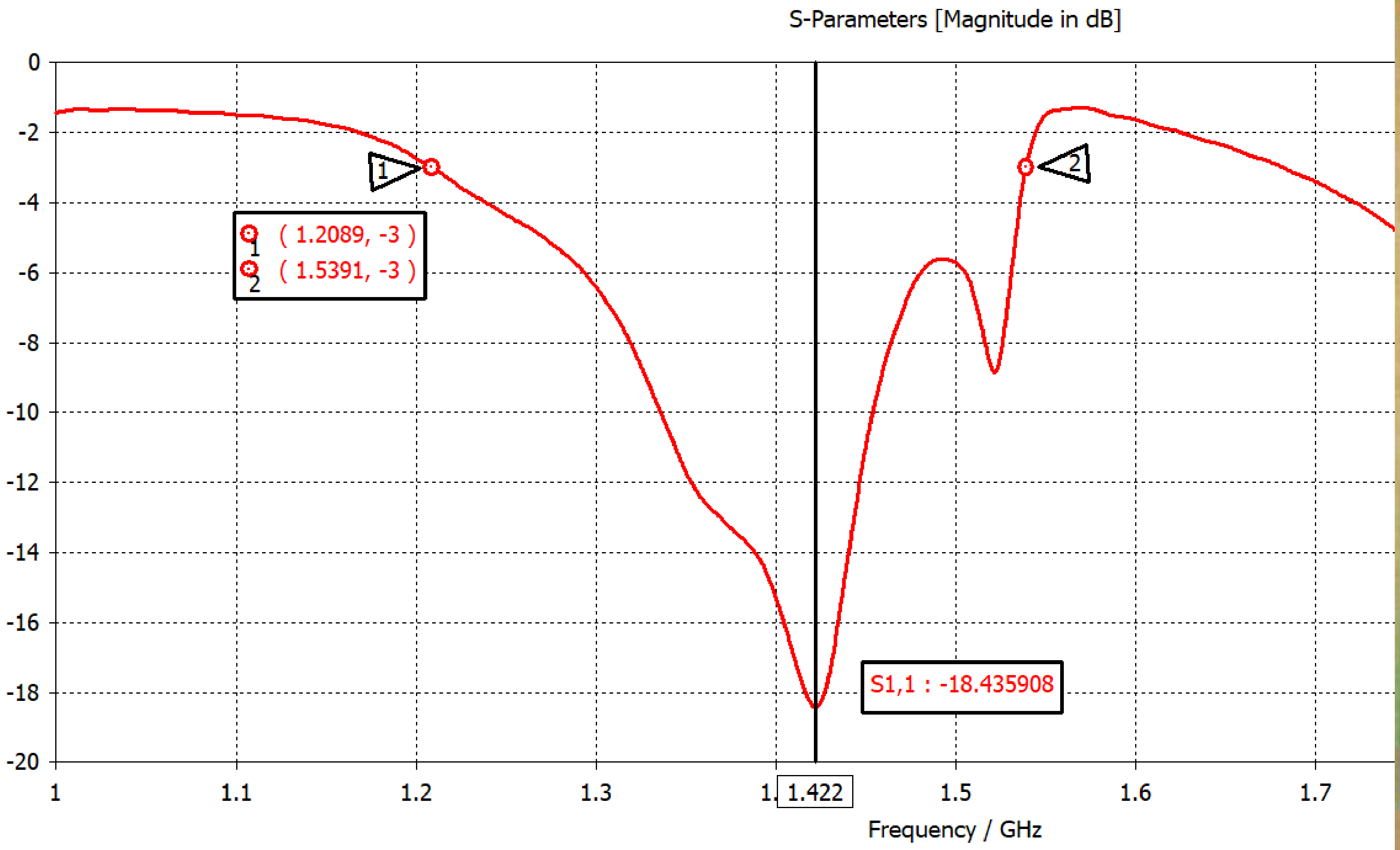


Figure 5. Left: EUV image from the Solar Dynamics Observatory (SDO) in the Fe IX line at 171 Å (March 29, 2024 – 00:05 UTC) Right: Characteristic Radio Frequencies for the solar atmosphere and the dominating type of emission mechanism (Gary, 2014)

Previous Stage

Figure 6: 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 antenna configuration. Top, Right: Rat-race coupler as analog correlator.
Bottom, Right: Data acquisition & visualization system.

Antenna Design



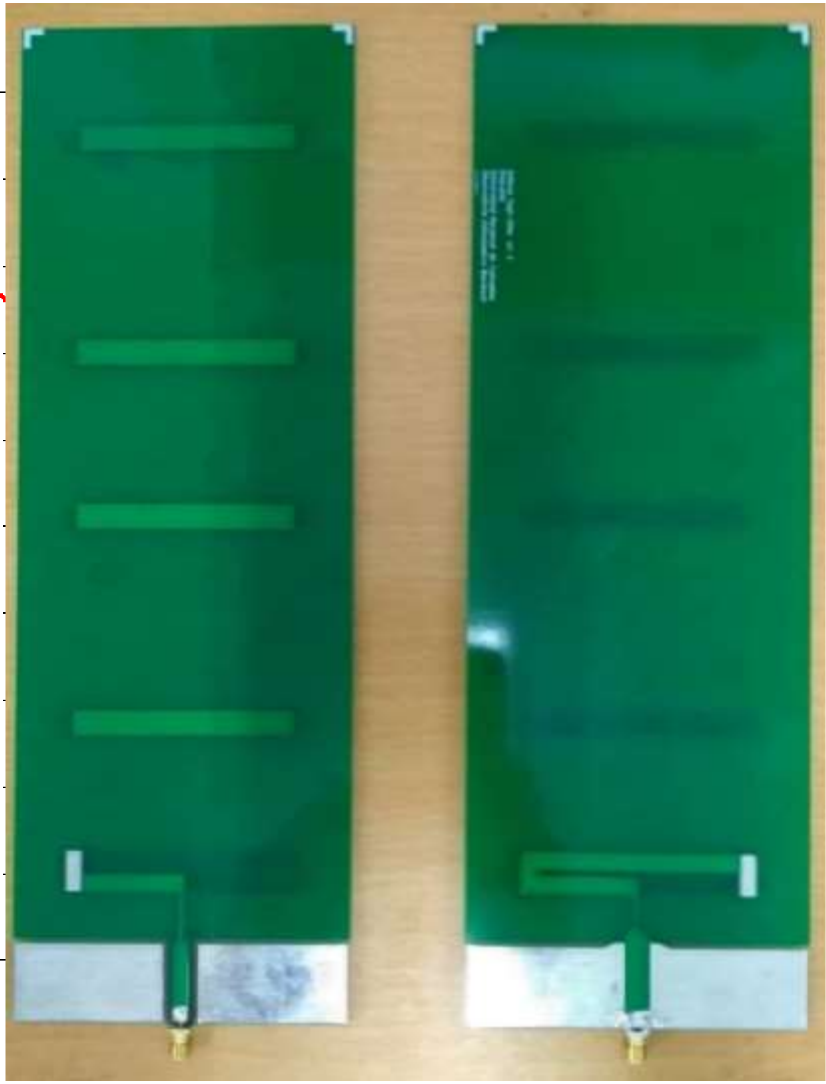


Figure 7. *Left:* Antenna Simulation: S11 Parameter - Antenna Reflection Coefficient. *Right:* Printed circuit Yagi-Uda antenna.

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 9), and then as a 2x2 array (Figure 10), 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 [1].

Antenna Design

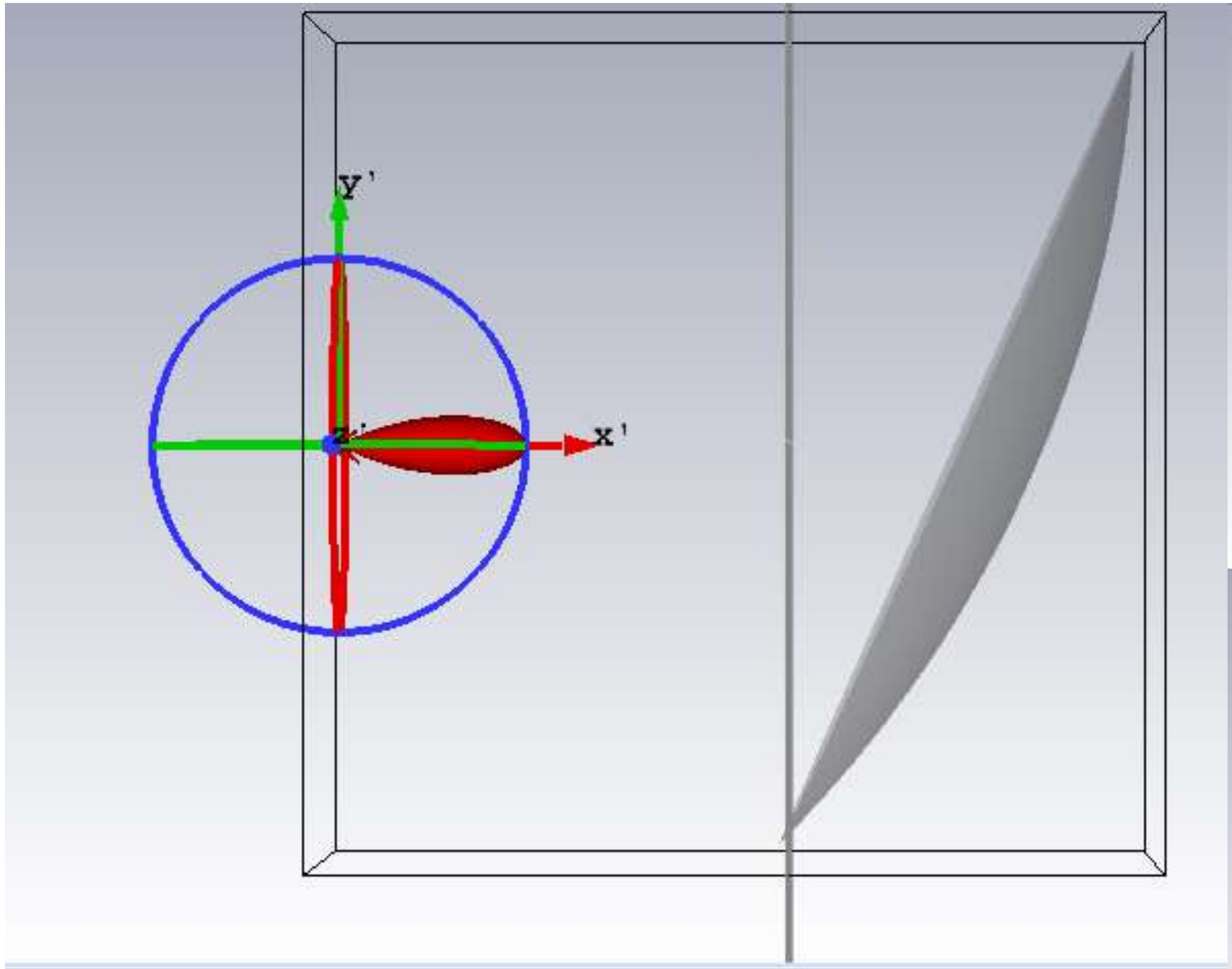
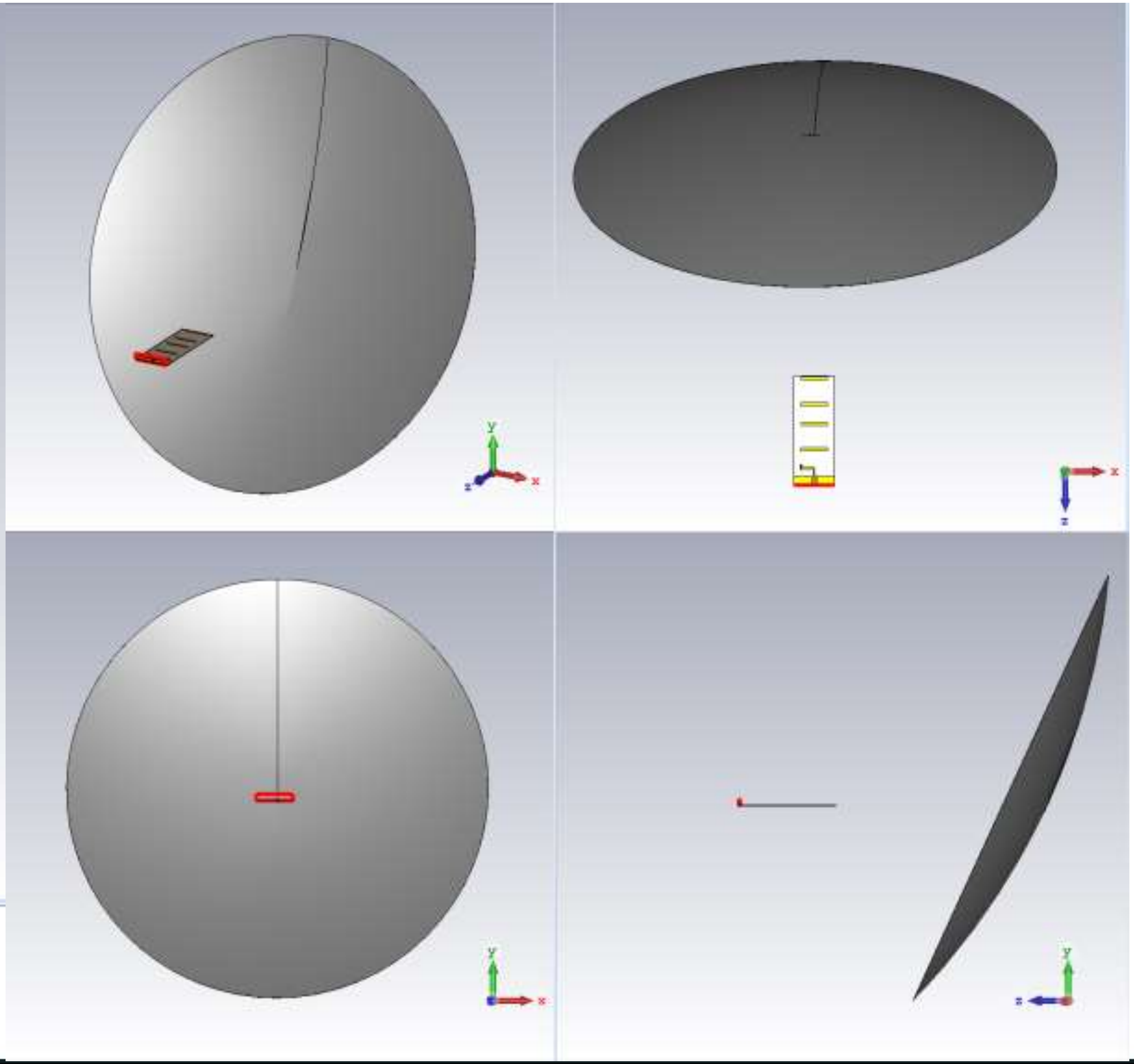


Figure 8: Antenna Element Simulation Design. Single Yagi-Uda antenna in the focus of an offset-fed reflector dish.



Antenna Design

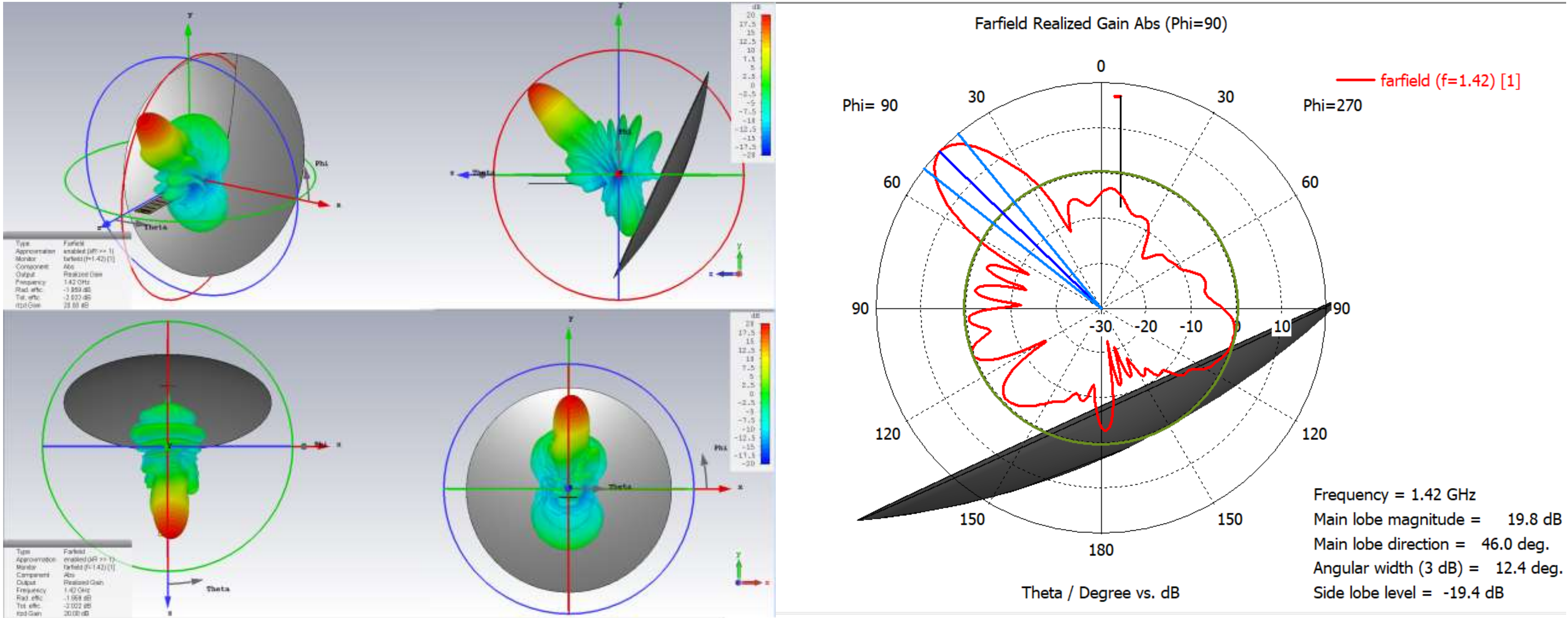


Figure 9: Antenna Simulation: 1 Antenna + Reflector. Realized Gain

Antenna Design

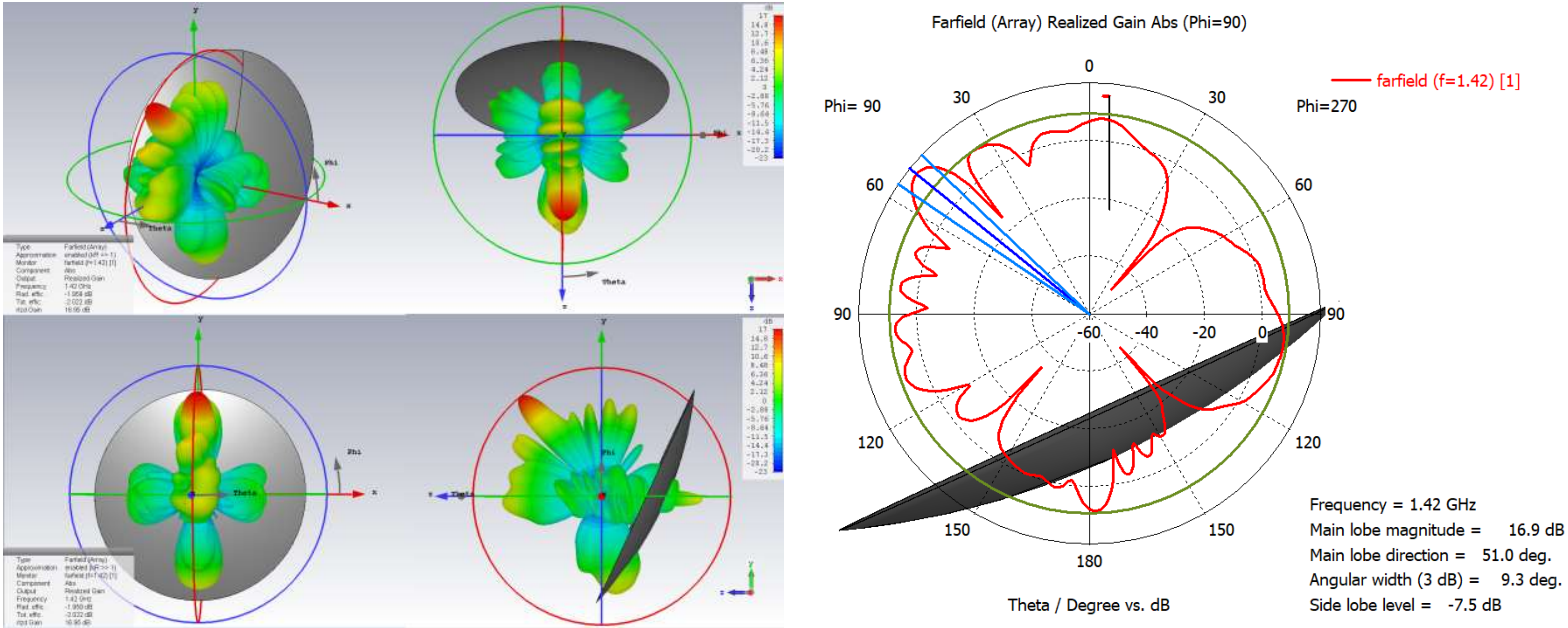


Figure 10: Antenna Simulation: 2x2 Antenna Array + Reflector. Realized Gain

Antenna Design

PARAMETER	Isolated Antenna without Reflector Dish [10]	2×2 Antenna Array without Reflector Dish [10]	Single Antenna with Offset-Fed Reflector Dish	2×2 Antenna Array with Offset-Fed Reflector Dish
Input Reflection Coefficient (S11 Parameter)	-34.3583 dB (at 1.422 GHz)	-34.3583 dB (at 1.422 GHz)	-24.3591 dB (at 1.422 GHz)	-24.3591 dB (at 1.422 GHz)
Half-Power (-3 dB) Bandwidth	317.6 MHz	317.6 MHz	321 MHz	321 MHz
Directivity	10.99 dBi	15.56 dBi	21.96 dBi	20.07 dBi
Gain (IEEE)	9.397 dB	13.97 dB	20.18 dB	18.29 dB
Realized Gain	9.394 dB	13.96 dB	20.16 dB	18.28 dB
Half-Power Beamwidth (HPBW)	48.8 deg	31.1 deg	13.2 deg	9.9 deg
Front-to-Back Ratio	18.928 dB	18.924 dB	24.583 dB	22.002 dB

Figure 11: Simulation Result Summary for Single Yagi-Uda Antenna and 2X2 Antenna Array with Offset-Fed Reflector Dish

Steerable Pier: Preliminary and Final Design

Figure 12: 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 12).

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 13).

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.

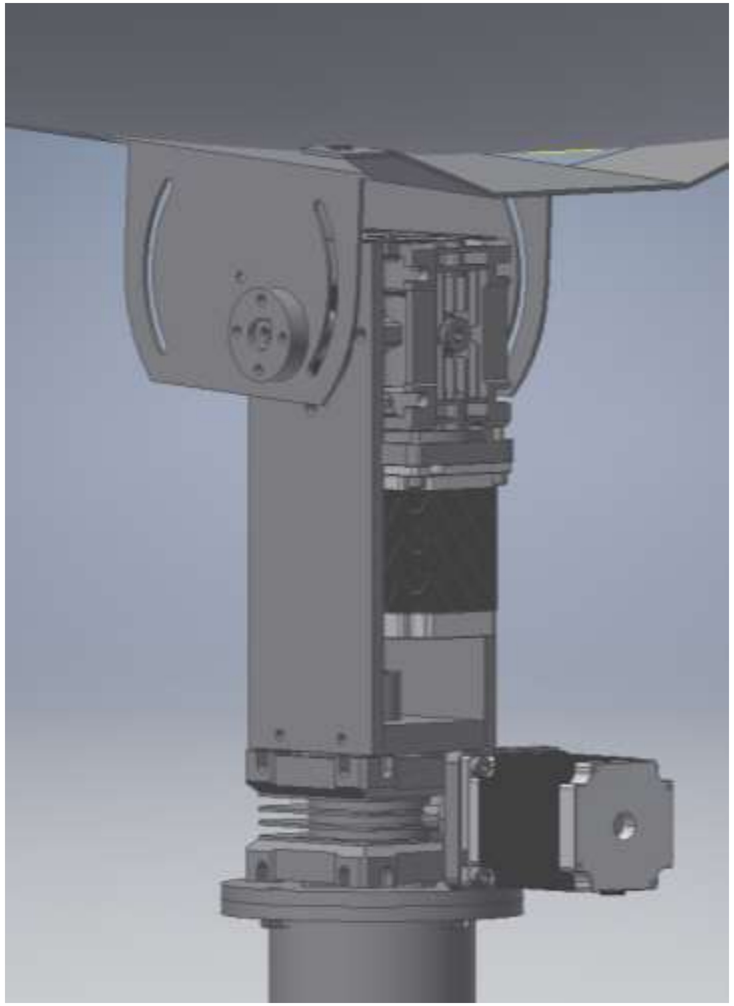


Figure 13: Steerable Pier Final Design: Stepper motor and reducer gearbox for Azimuth & Elevation motion (Hincapié Tarquino *et. al. in. prep.*)

First Testing Phase

Figure 14: First Testing Phase with 2x2 Array Feed (Hincapié Tarquino *et. al. in. prep.*)

First Testing Phase

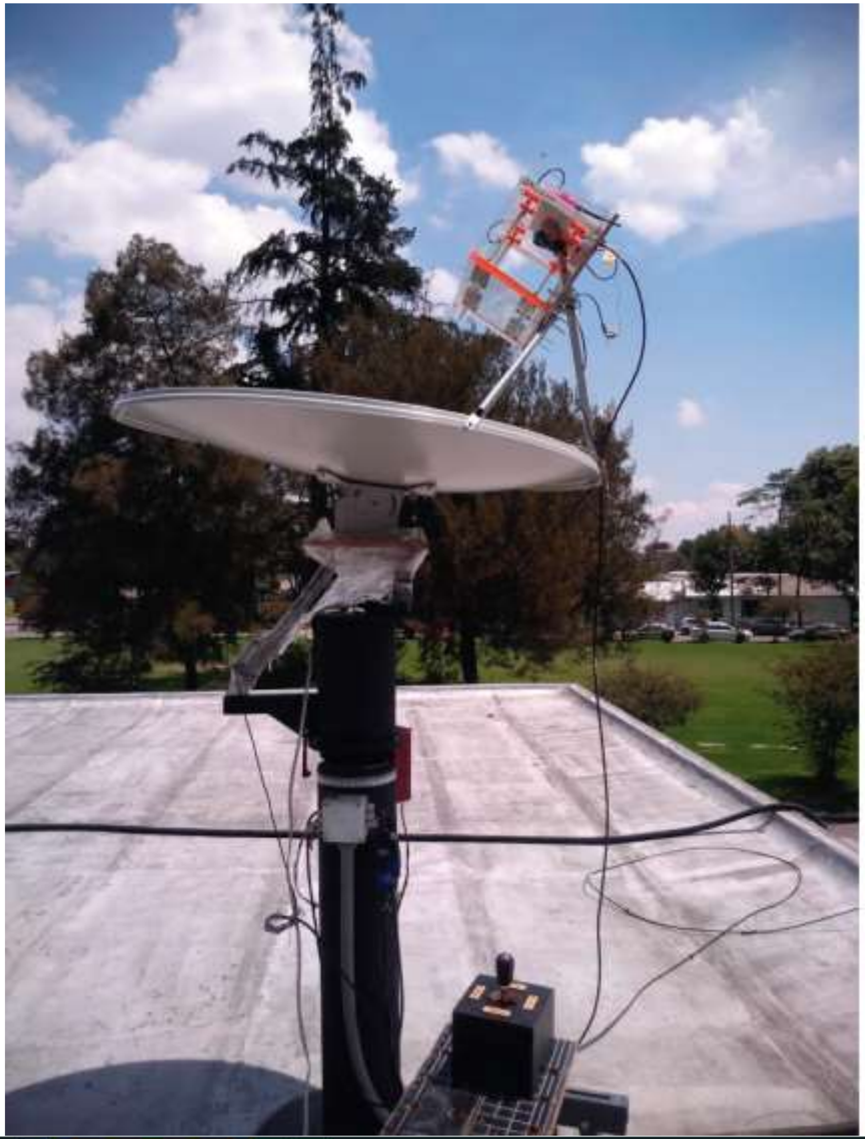


Figure 15: First Testing Phase with 2x2 Array Feed (Hincapié Tarquino *et. al.* *in. prep.*)

Preliminary Results

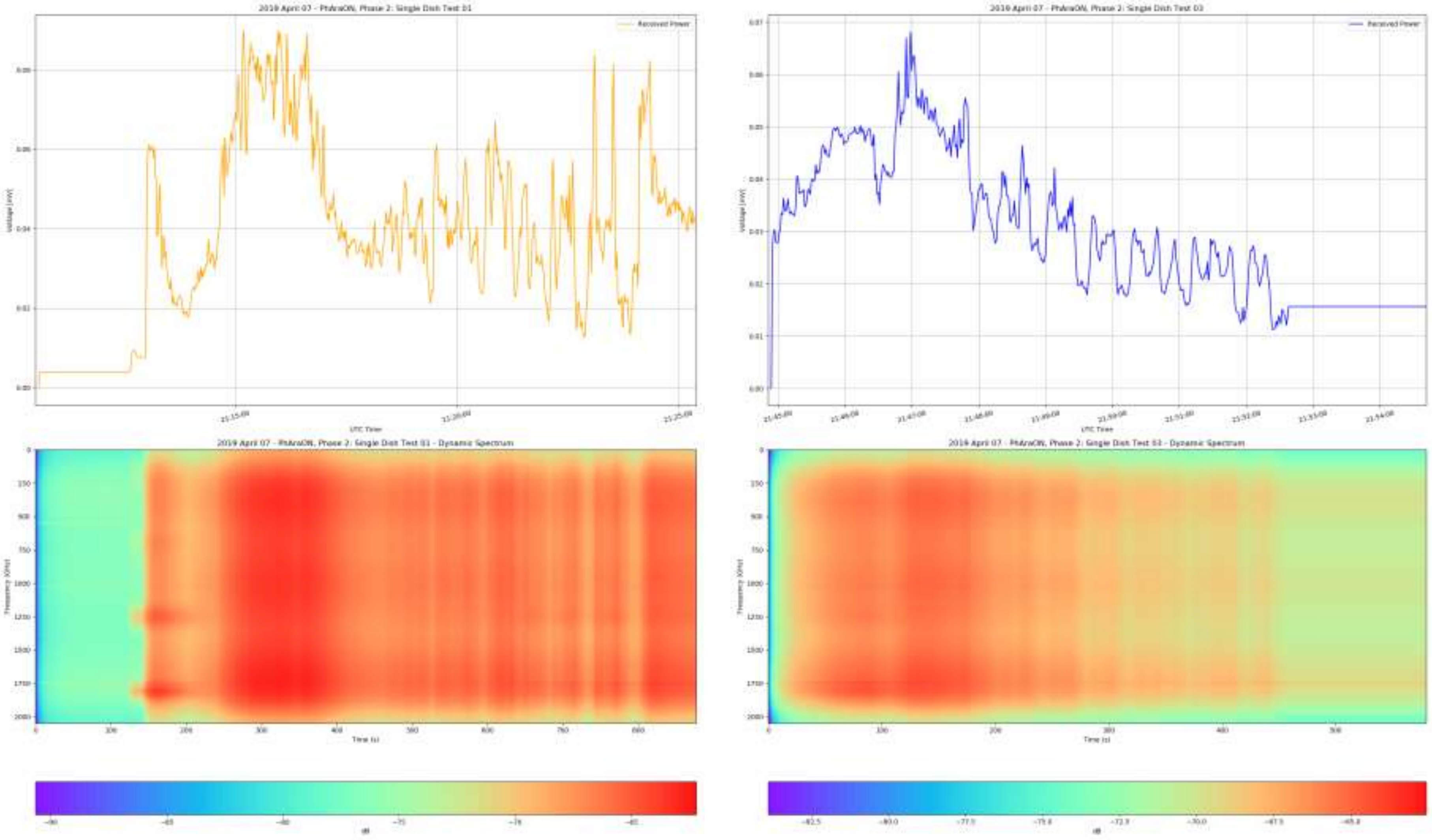


Figure 16: Preliminary Results: Solar Scan with 2x2 Array Feed

Preliminary Results

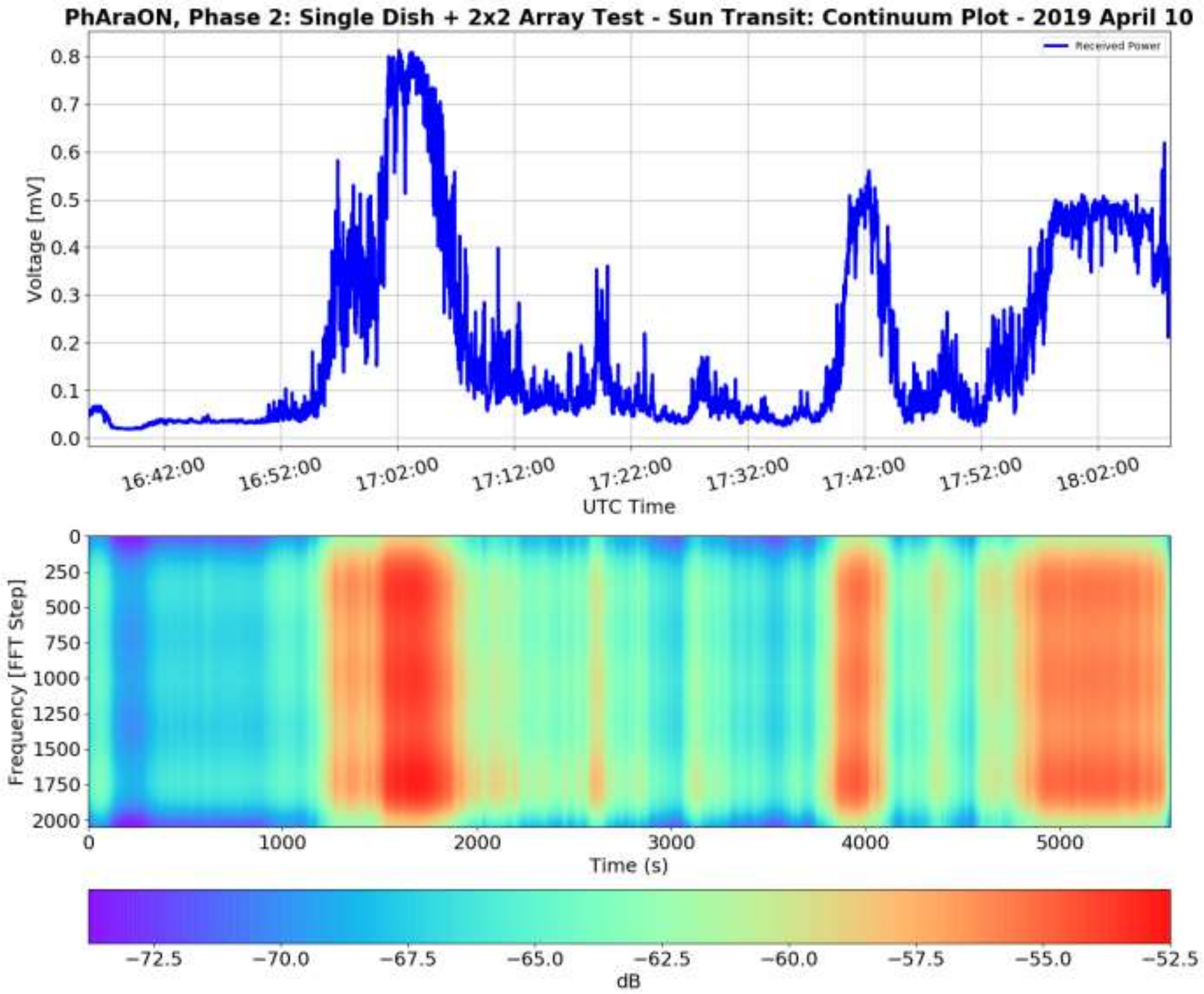


Figure 17: Preliminary Results: Solar Scan in Azimuth and Elevation *(Single Dish Result)*. (Hincapié Tarquino *et. al. in. prep.*)

Preliminary Results

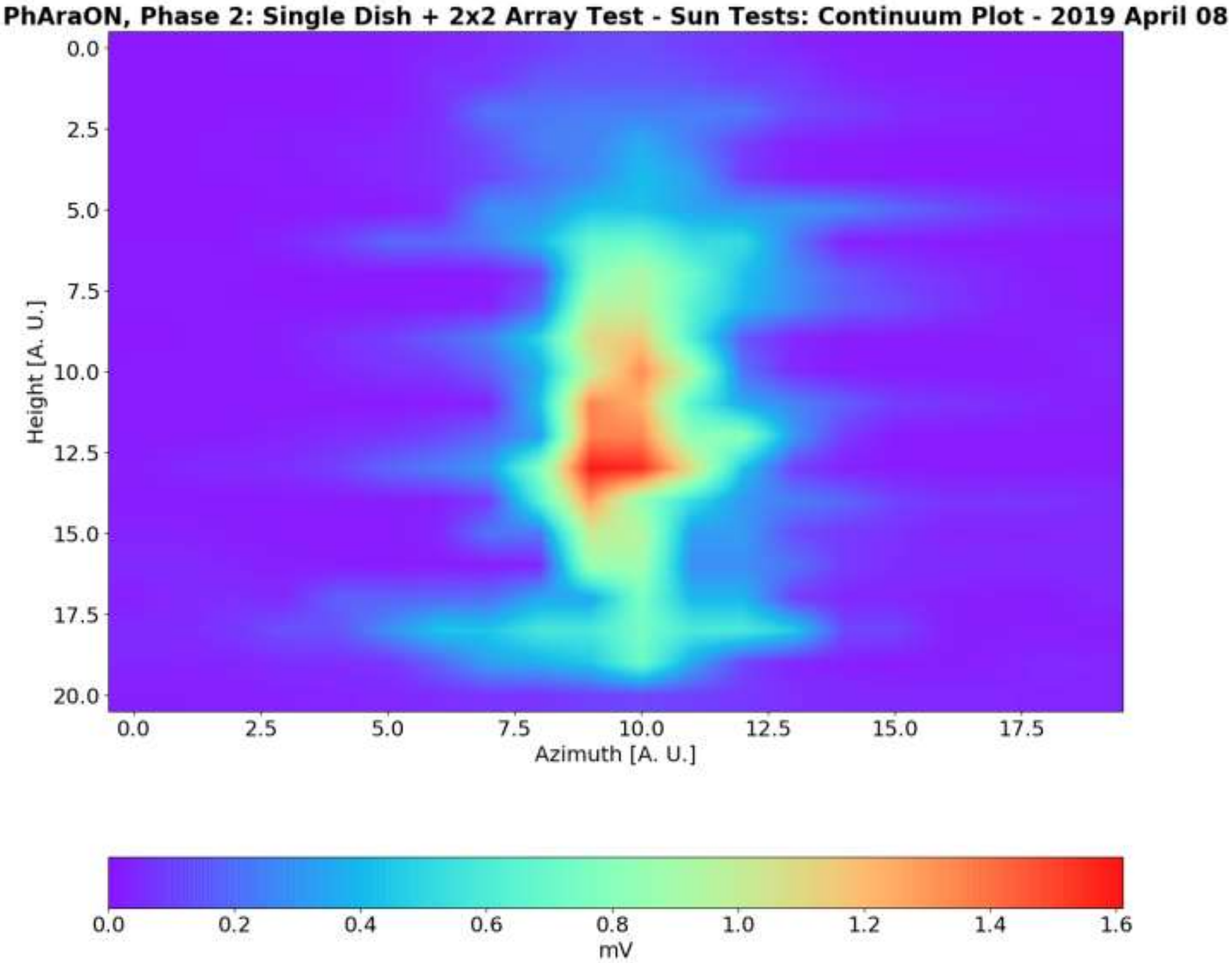


Figure 18: Preliminary Results:
Solar Scan with 2x2 Array Feed.
(Hincapié Tarquino *et. al. in. prep.*)

Steerable Pier: Motor Assembly

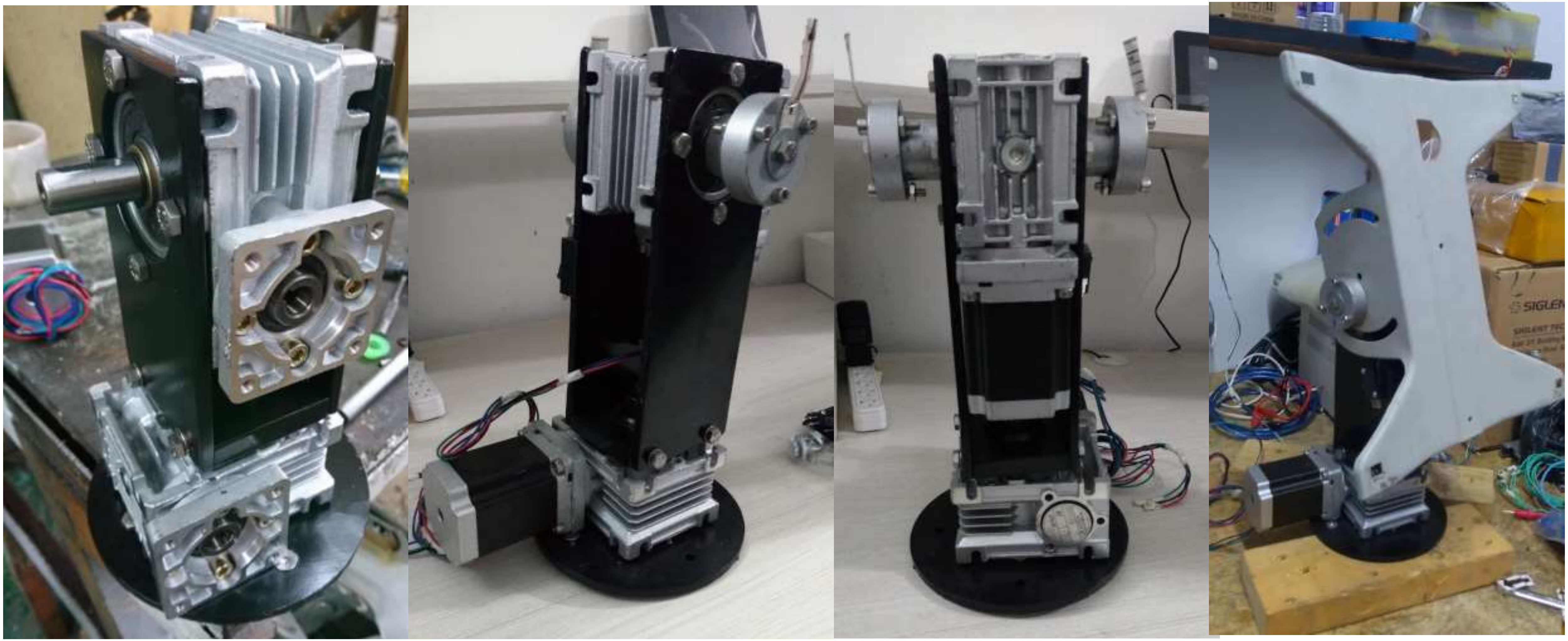


Figure 19: Steerable Pier Assembly: Stepper Motor & Reducer Gearbox for each axis in Alt-Az motion. (Hincapié Tarquino *et. al.* *in. prep.*)

Steerable Pier: Assembled elements

Figure 20: 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 with an additional option for manual adjustment.

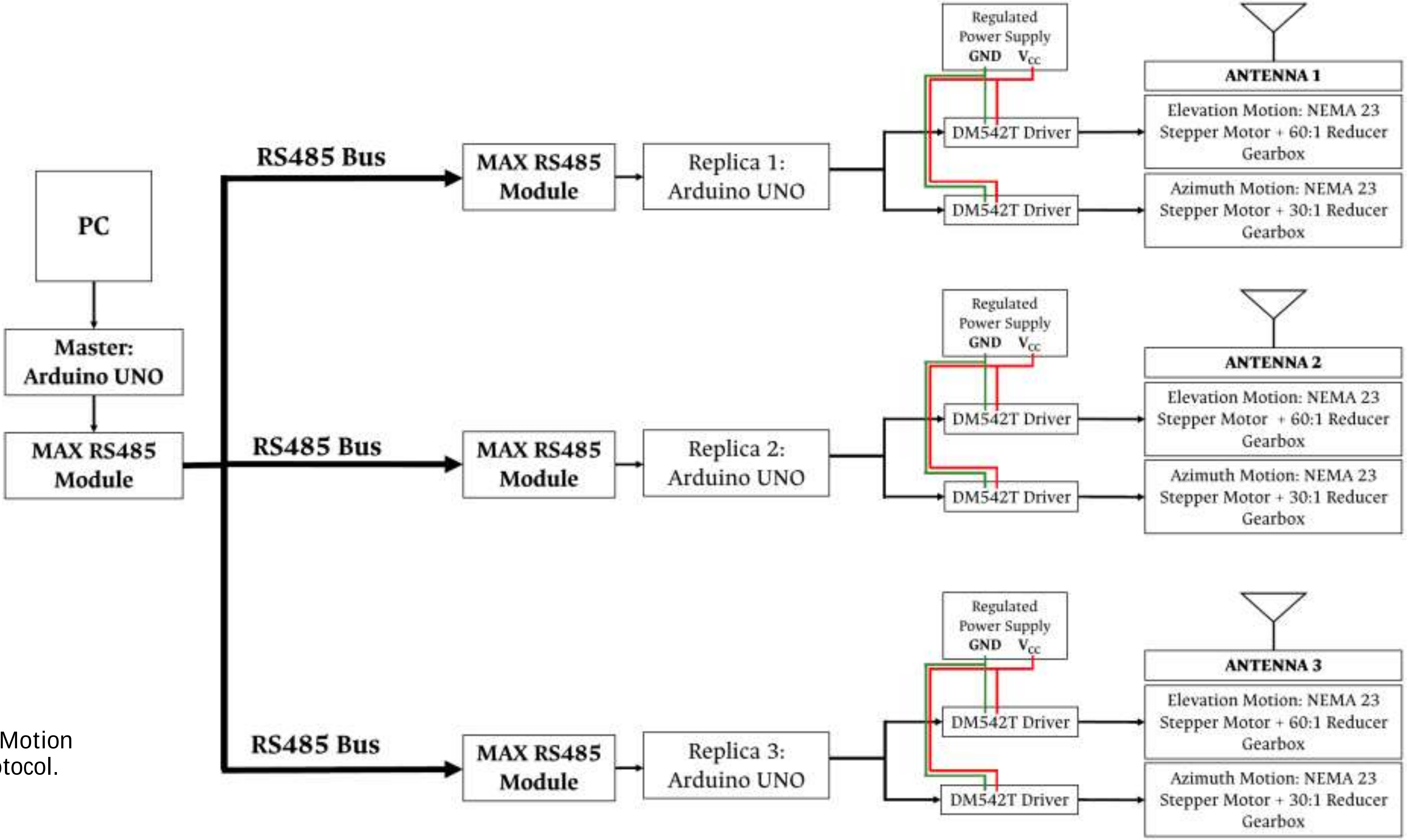


Figure 21: Block Schematics for Antenna Motion Control Stage: Master-Replica RS485 Protocol. (Hincapié Tarquino *et. al. in. prep.*)

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.

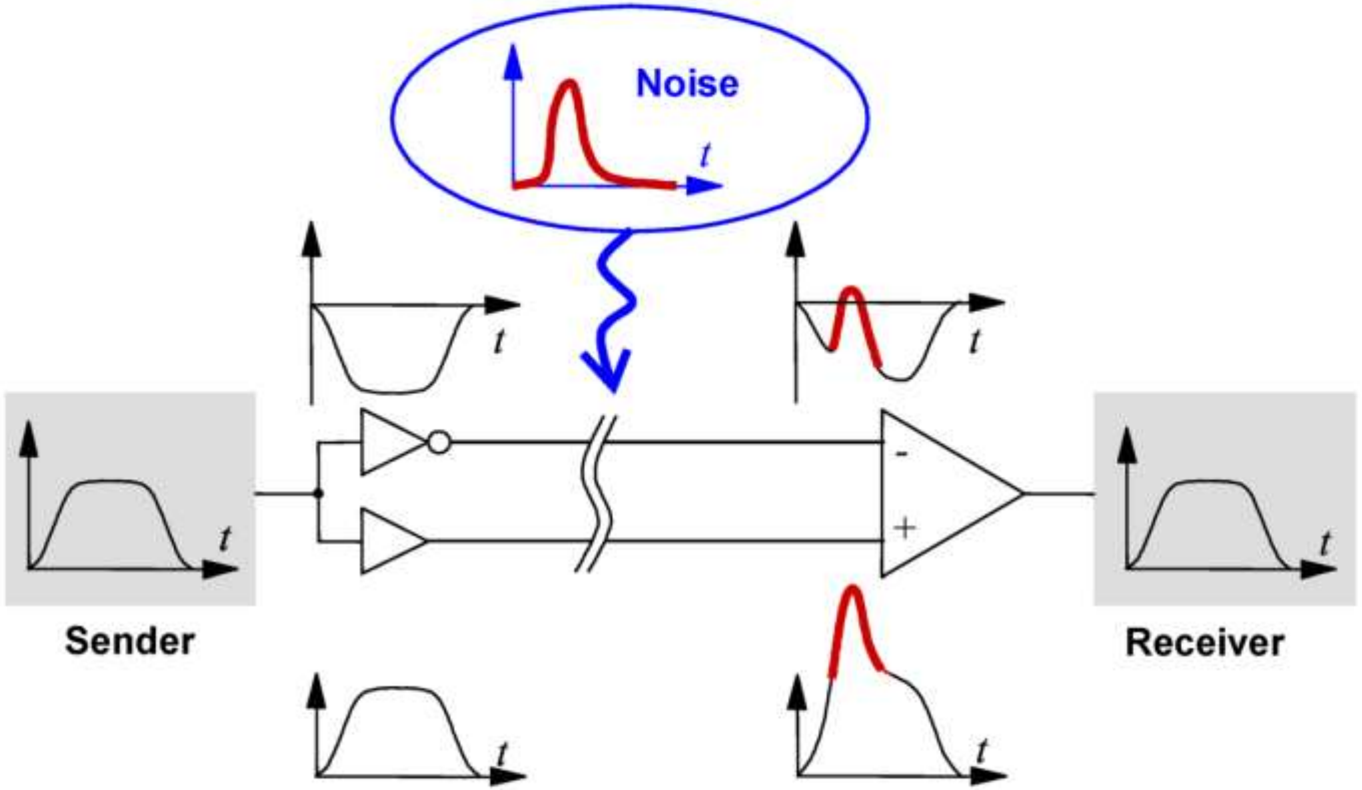


Figure 22: Schematics for communication using RS485 serial protocol.

RS485 serial protocol

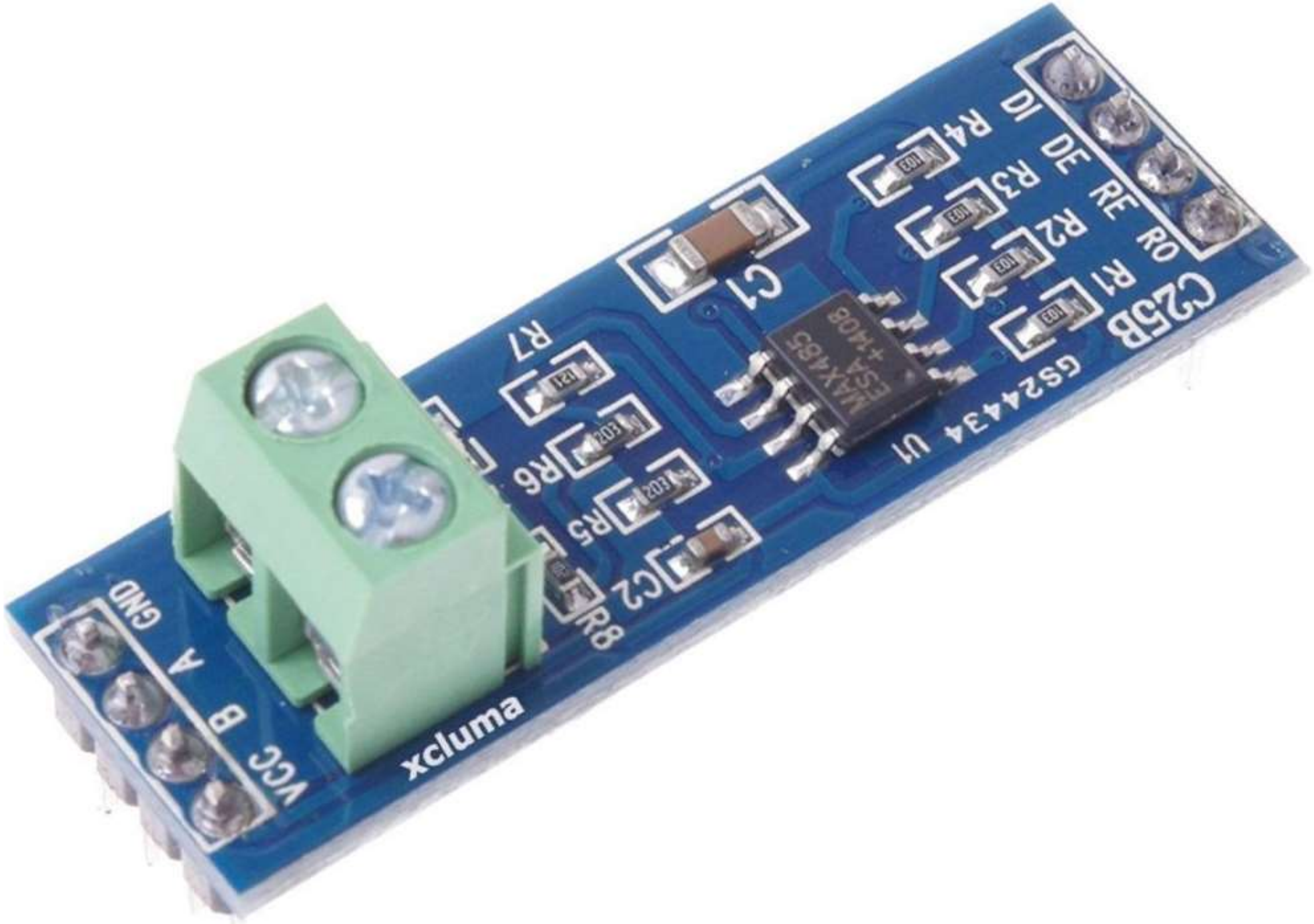


Figure 23: MAX RS485 serial module and pin descriptions.

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

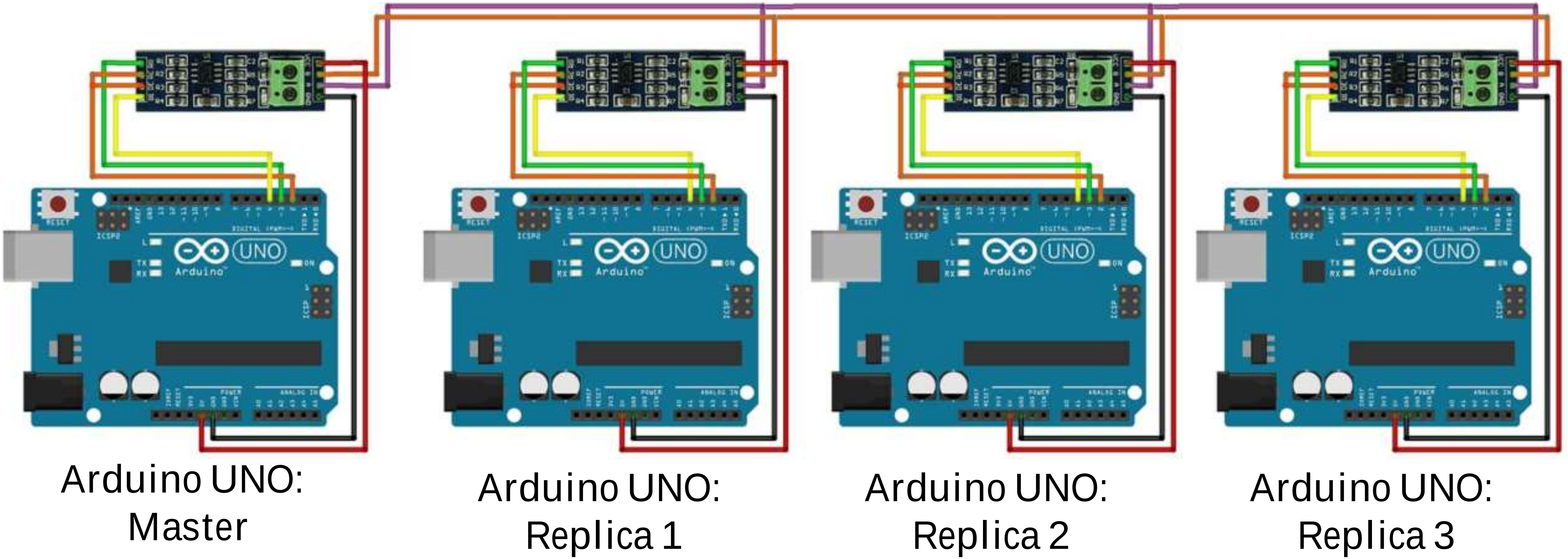


Figure 24: Connection diagram for Antenna Motion Control Stage: Master-Replica RS485 Protocol. (Hincapié Tarquino *et. al. in. prep.*)

Steerable Pier: Motion Control

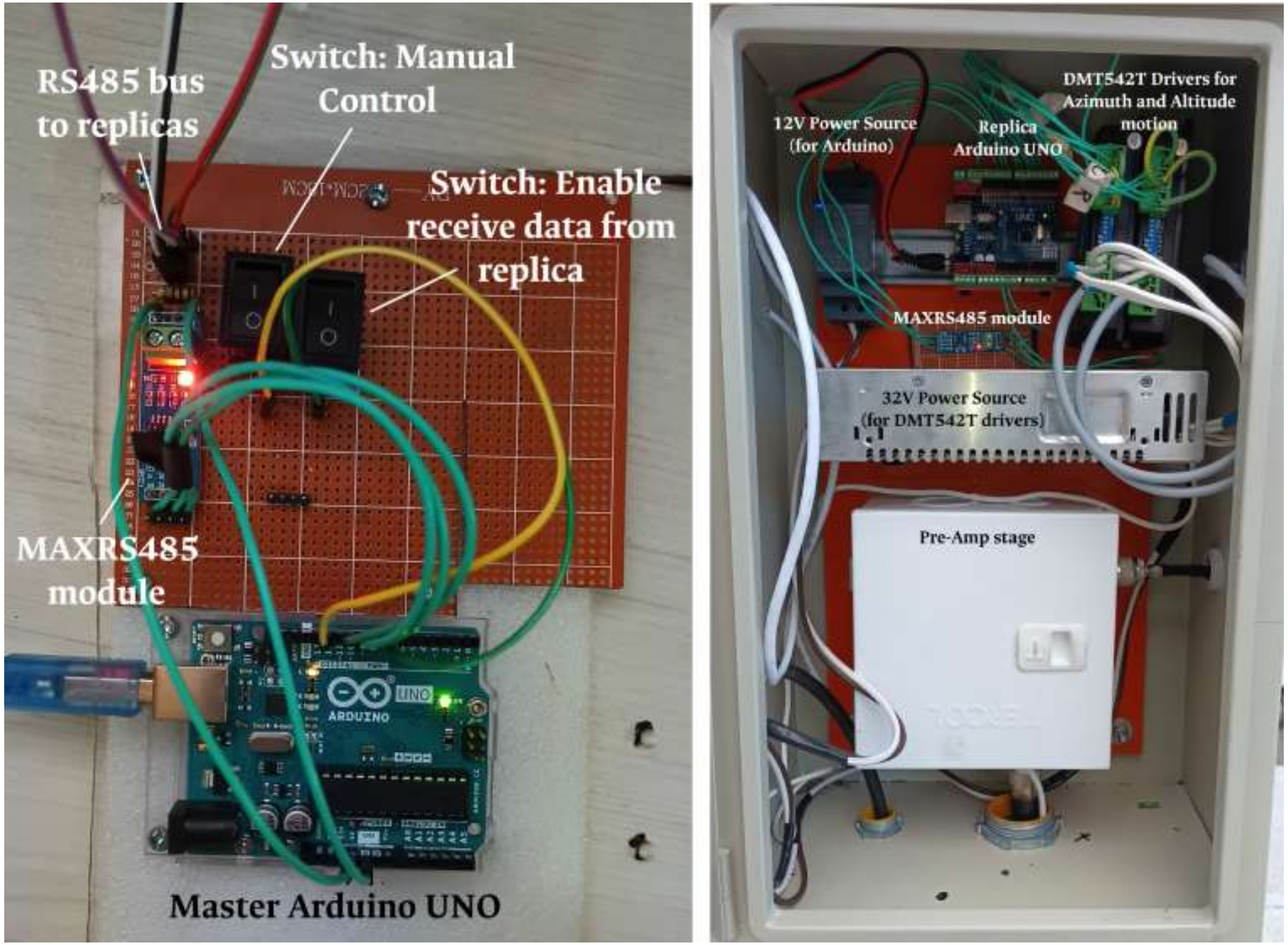


Figure 25: Control system for antenna motion control stage. *Left:* Master Arduino UNO with MAXRS485 module and bus to all replicas; *Right:* Isolated box with Replica Arduino UNO, MAXRS485 module and DMT542T drivers for each antenna element

Design: Array Implementation

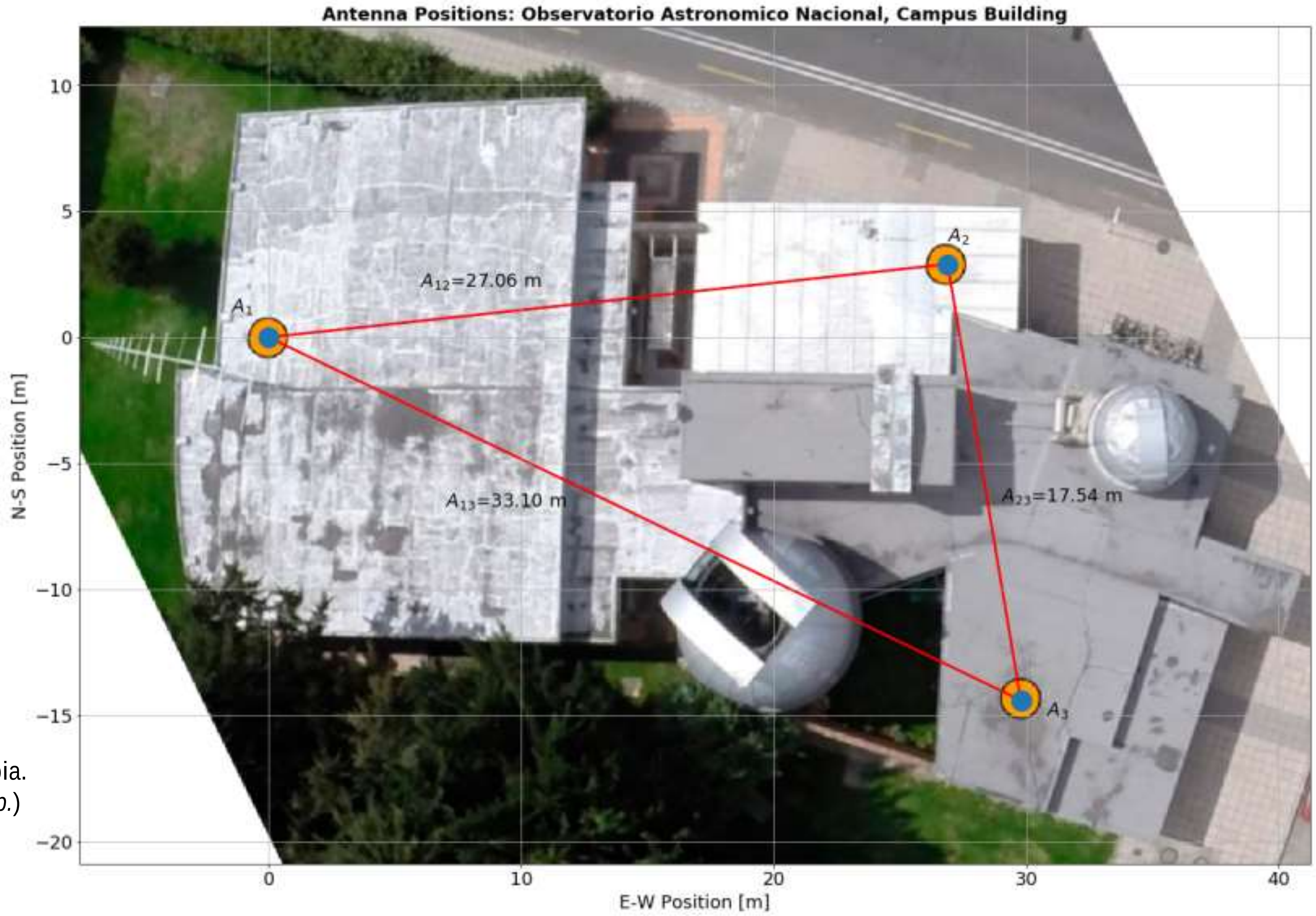


Figure 26: Array Location at Observatorio Astronómico Nacional, Campus Building – Universidad Nacional de Colombia. (Hincapié Tarquino *et. al. in. prep.*)

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Design: Array Implementation

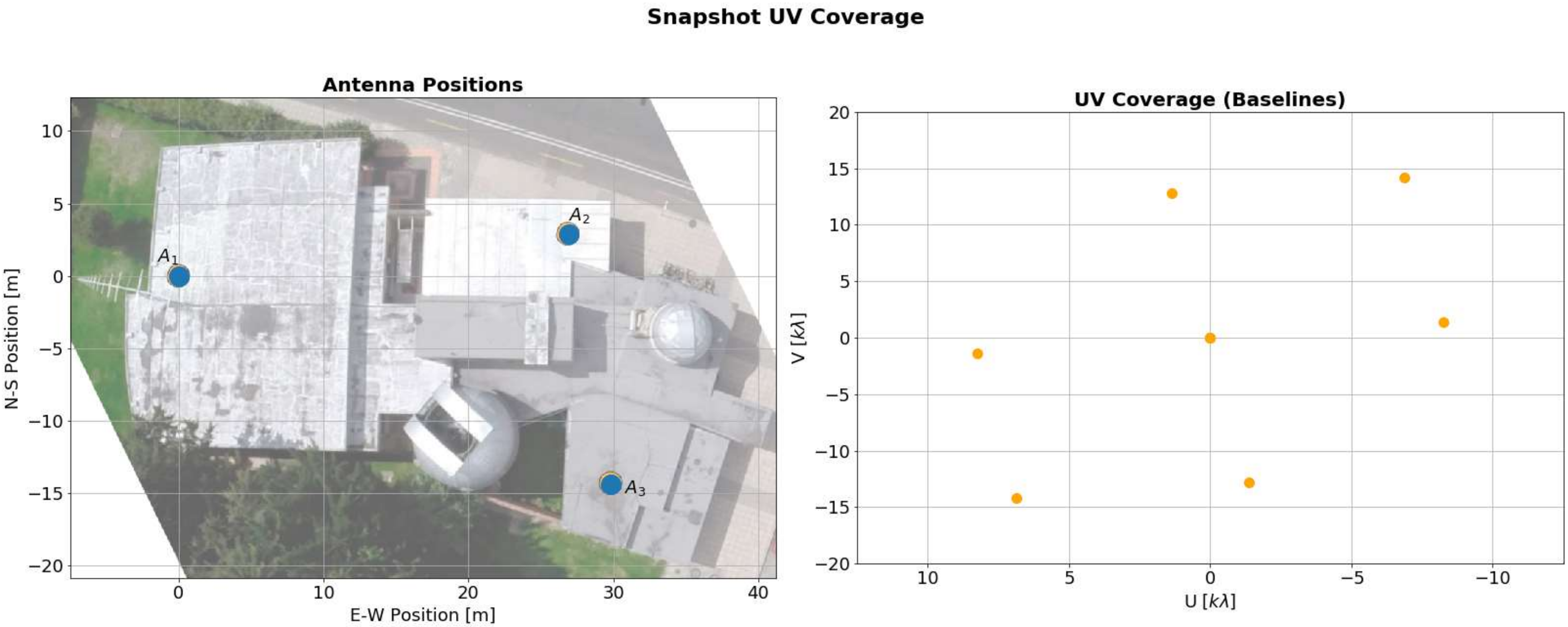


Figure 27: Snapshot UV Coverage for the interferometric array. (Hincapié Tarquino *et. al. in. prep.*)

Design: Array Implementation

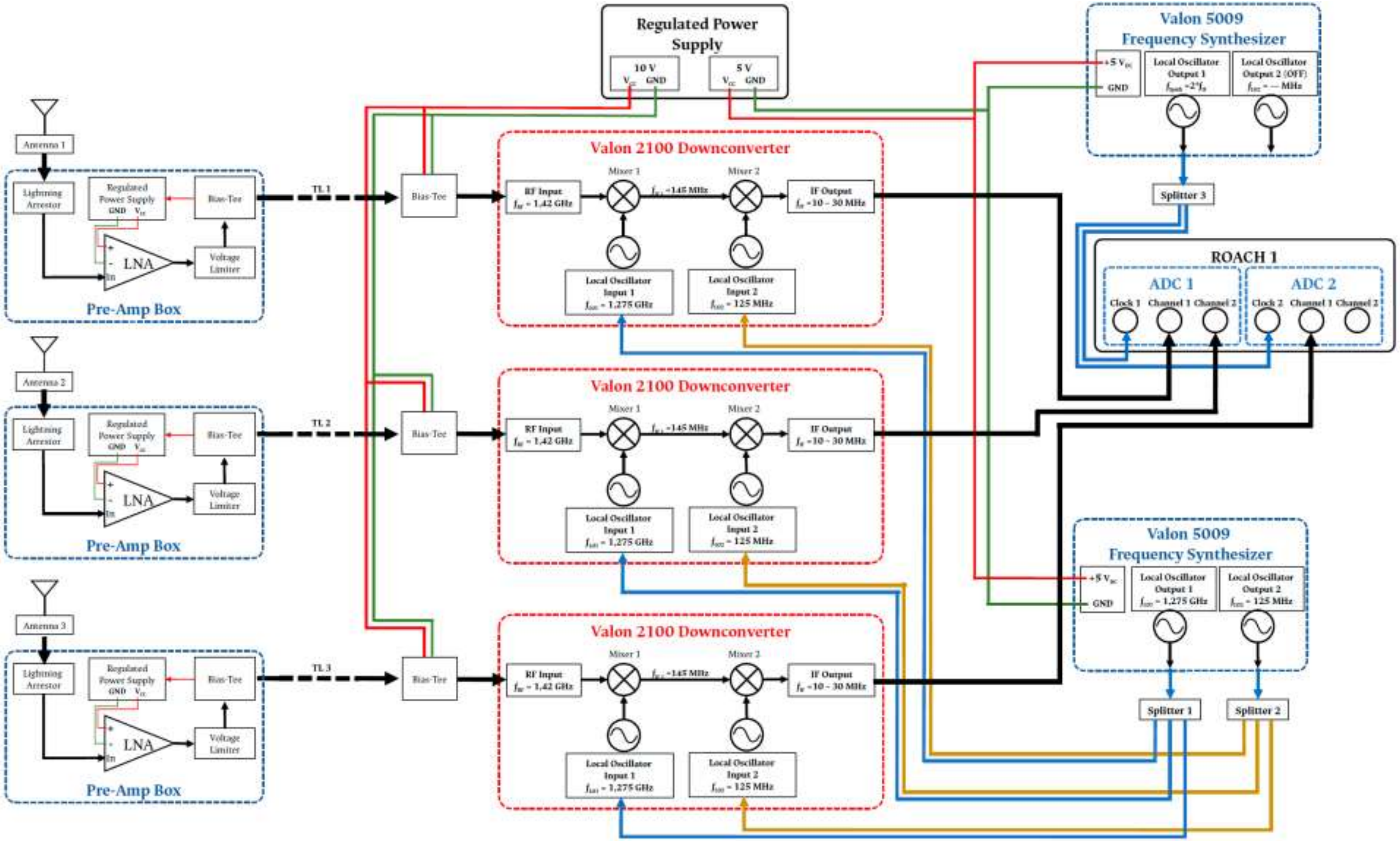


Figure 28: Block Schematics for full interferometric array. (Hincapié Tarquino *et. al. in. prep.*)

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).

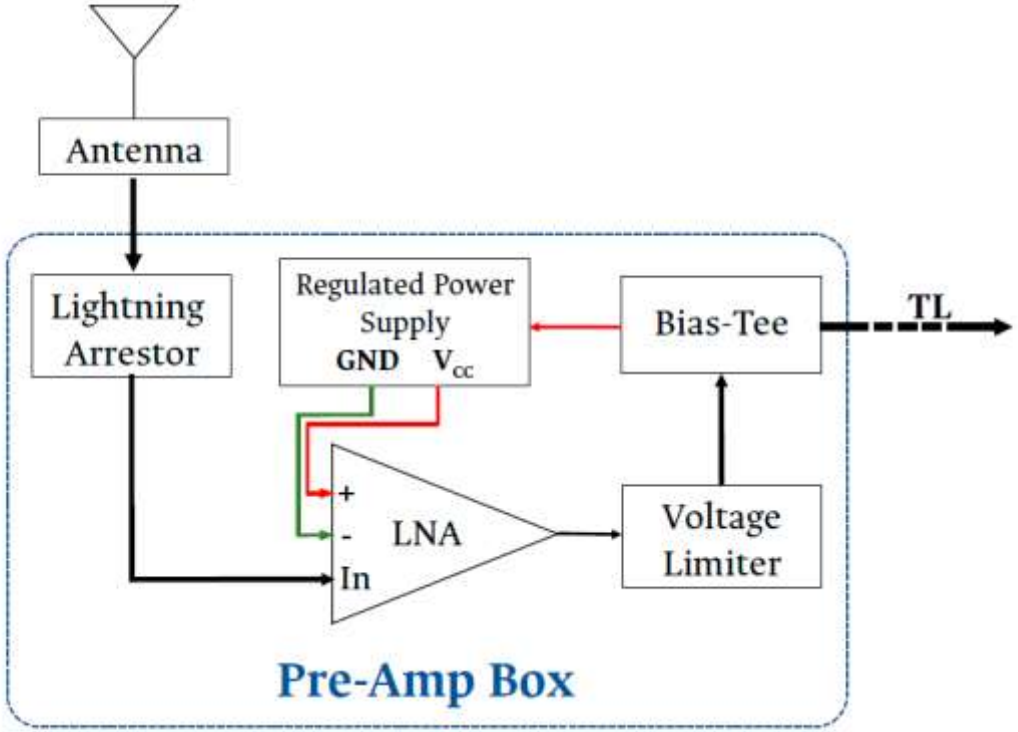


Figure 29: Block Schematics (*Left)* and implemented Pre-Amp stage (*Right)* .

Downconversion

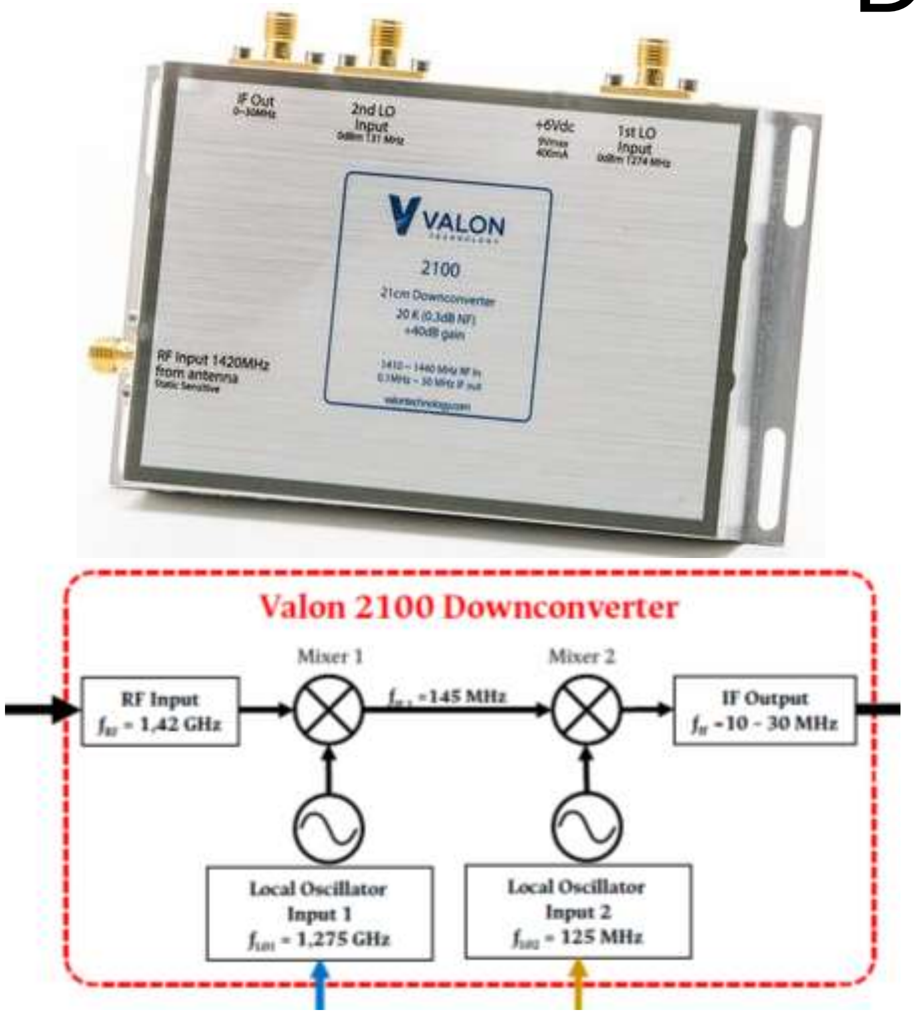


Figure 30: Valon 2100 21cm Downconverter. *Top:* Circuit; *Bottom:* Block schematics.

Downconversion shifts the signal to a lower frequency and reduces its sampling rate to facilitate subsequent processing stages.

DDCs are widely used in digital communication receivers to convert radio frequency (RF) or intermediate frequency (IF) signals to baseband.

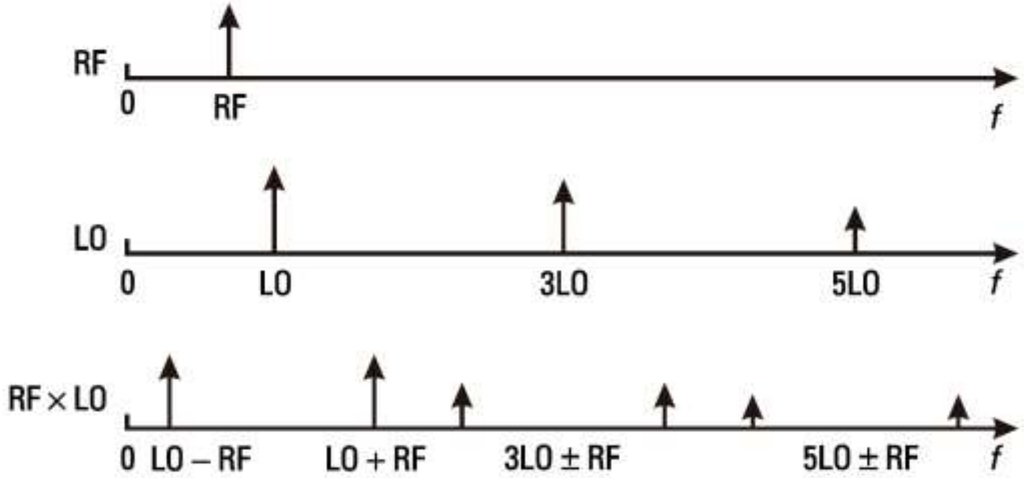


Figure 31: Downconversion frequency domain plot. Taken from Rogers & Plett, 2003.

Front-End: Downconversion Stage

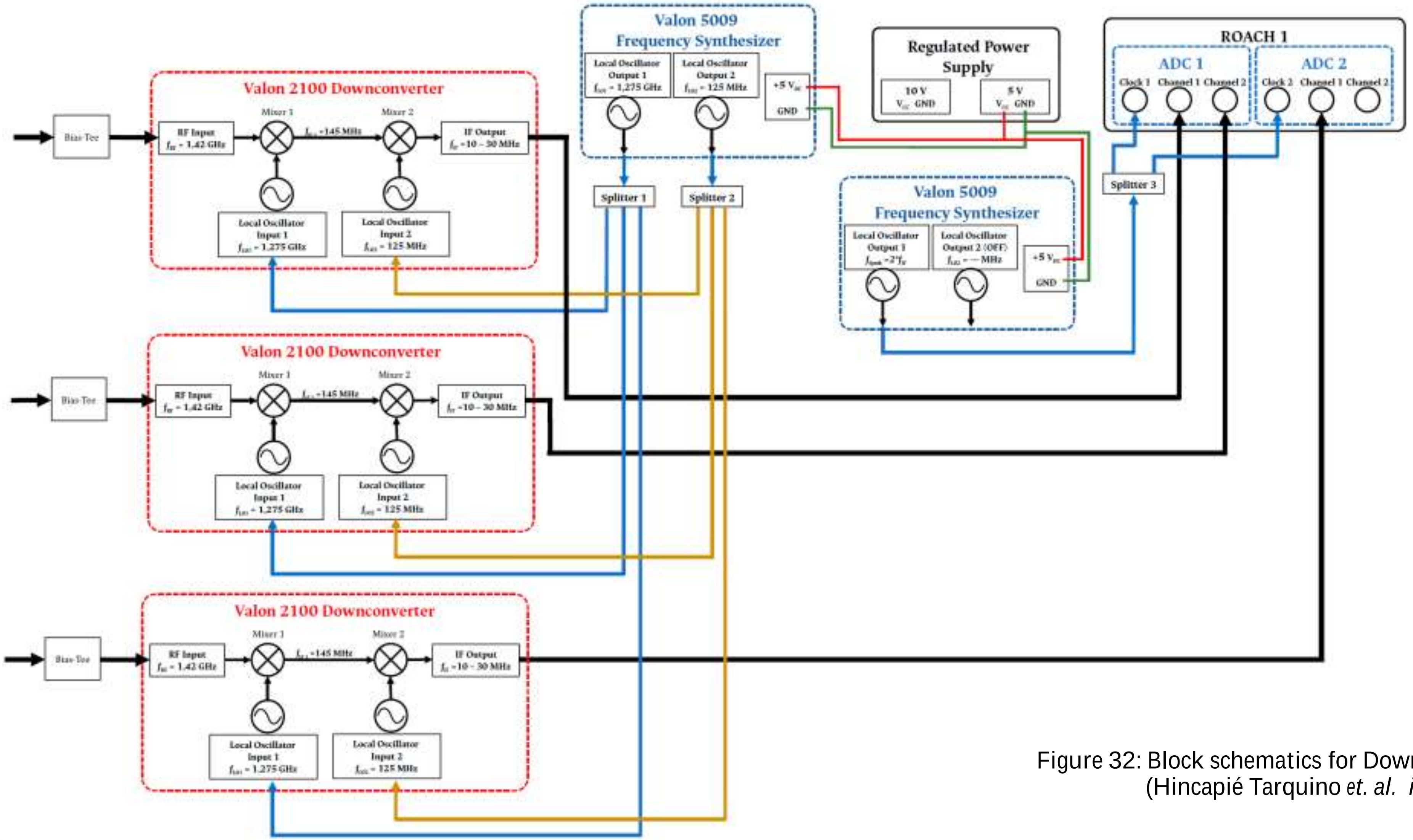


Figure 32: Block schematics for Downconversion stage. (Hincapié Tarquino *et. al. in. prep.*)

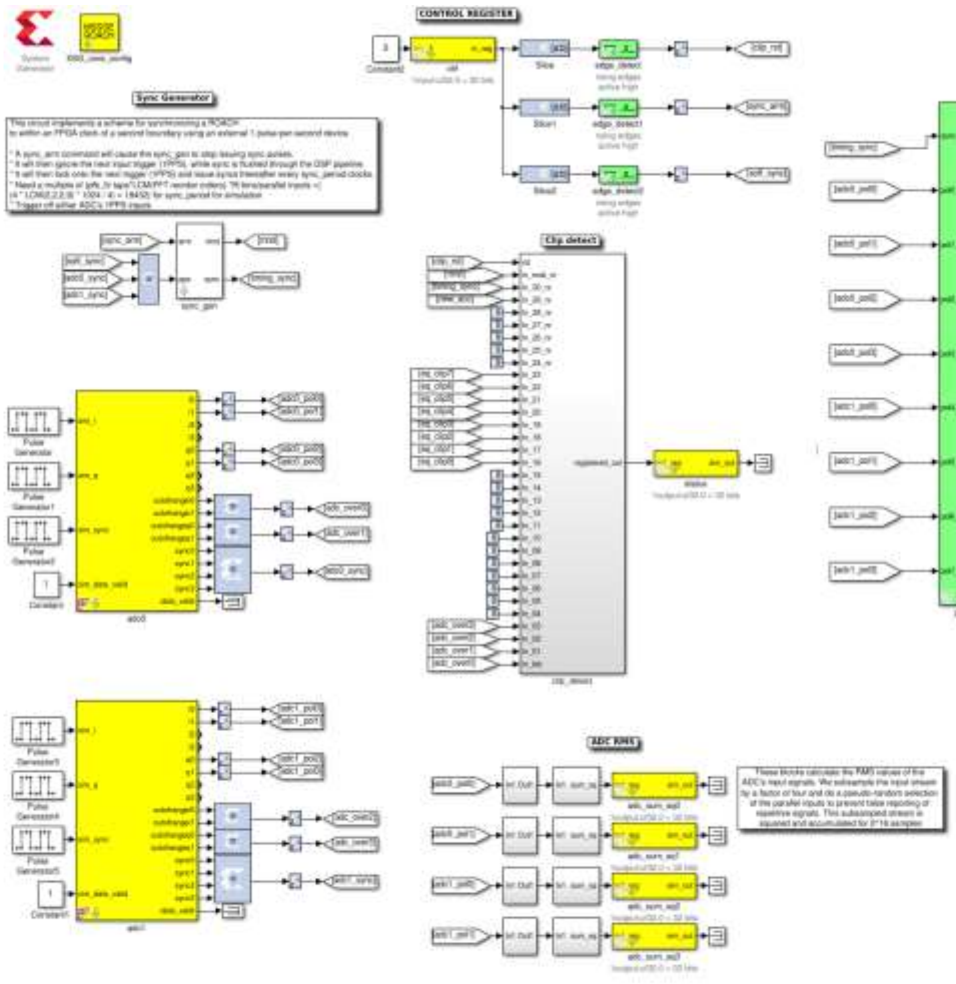
Back-End: Correlator

- The ROACH (Reconfigurable Open Architecture Computing Hardware) is a standalone FPGA processing board.
- Developed by the Collaboration for Astronomy Signal Processing and Electronics Research (CASPER) group
- Centerpiece: Xilinx Virtex 5 FPGA

ROACH
RECONFIGURABLE OPEN ARCHITECTURE COMPUTING HARDWARE

Figure 33: ROACH-1 standalone board

Back-End: Correlator



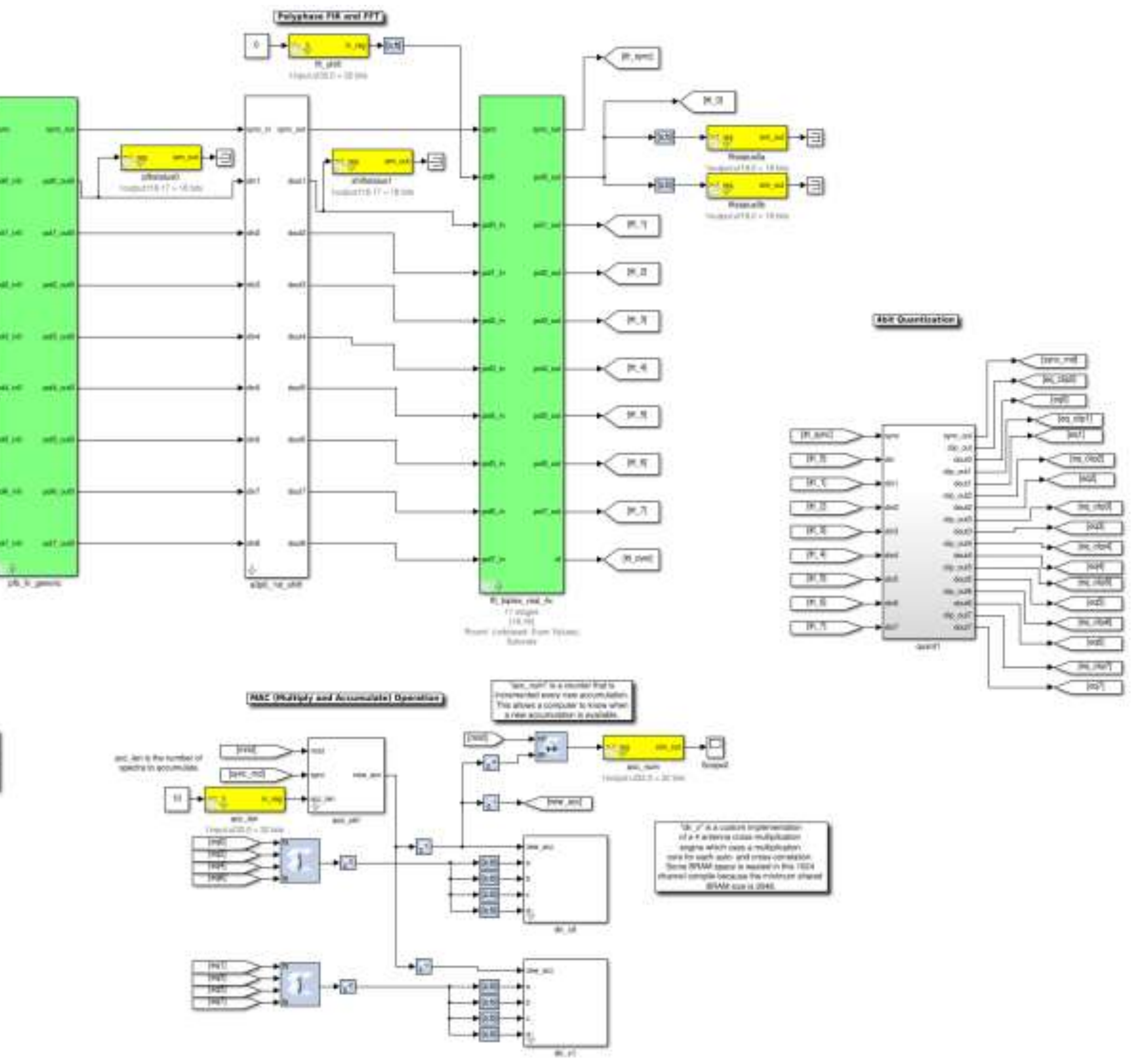


Figure 34: Block schematics for the correlator, implemented in MATLAB/Simulink.

Back-End: Correlator

Figure 35: Correlator Implemented with ROACH-1 board.

Full Array Implementation

Figure 36: Full interferometric array implemented at Observatorio Astronómico Nacional, Campus Building – Universidad Nacional de Colombia.

Results: Solar Transit

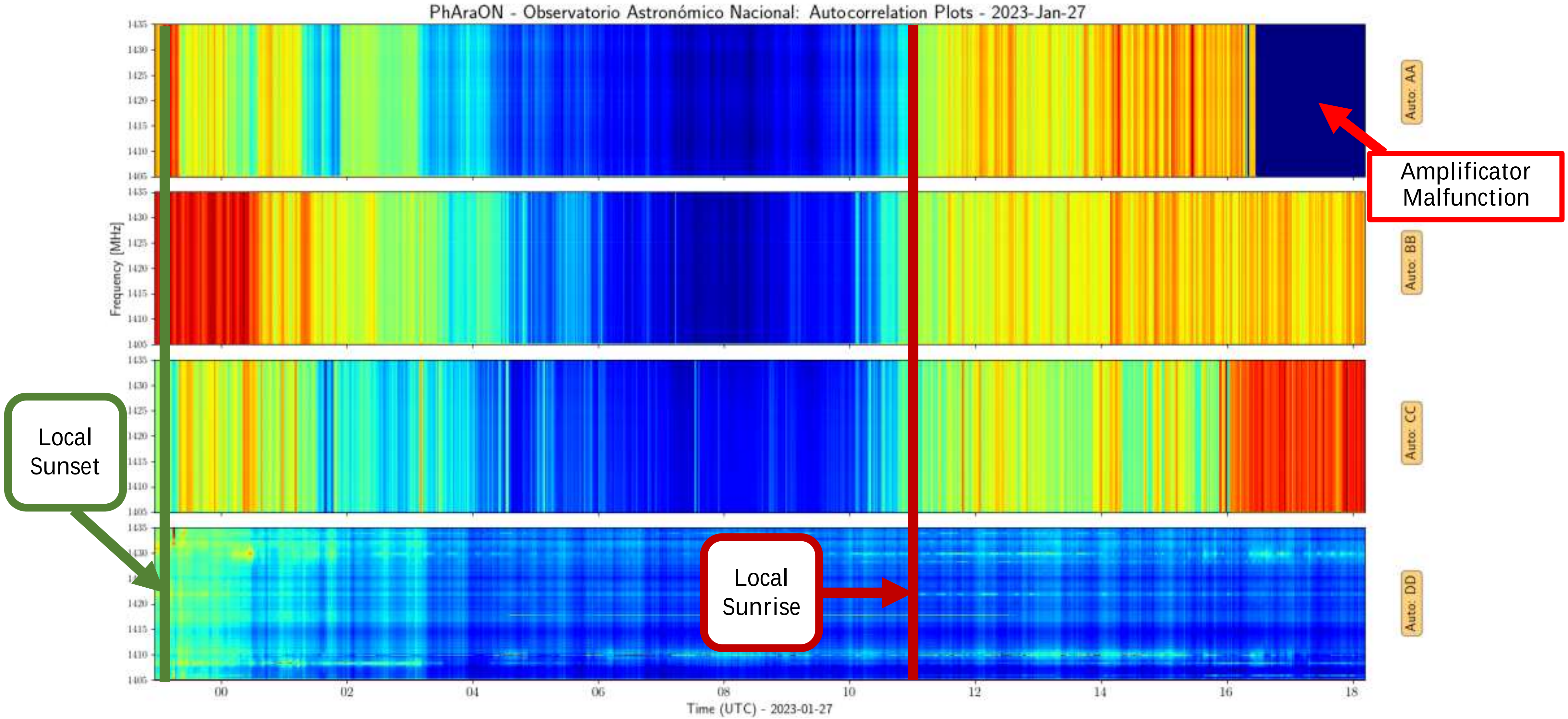


Figure 37: Results – Solar Transit: 2023 January 26, 18:00 – January 27, 13:00 (GMT -5). Auto-correlation plots (*Hincapié Tarquino, et al. In prep.)*

Results: Solar Transit

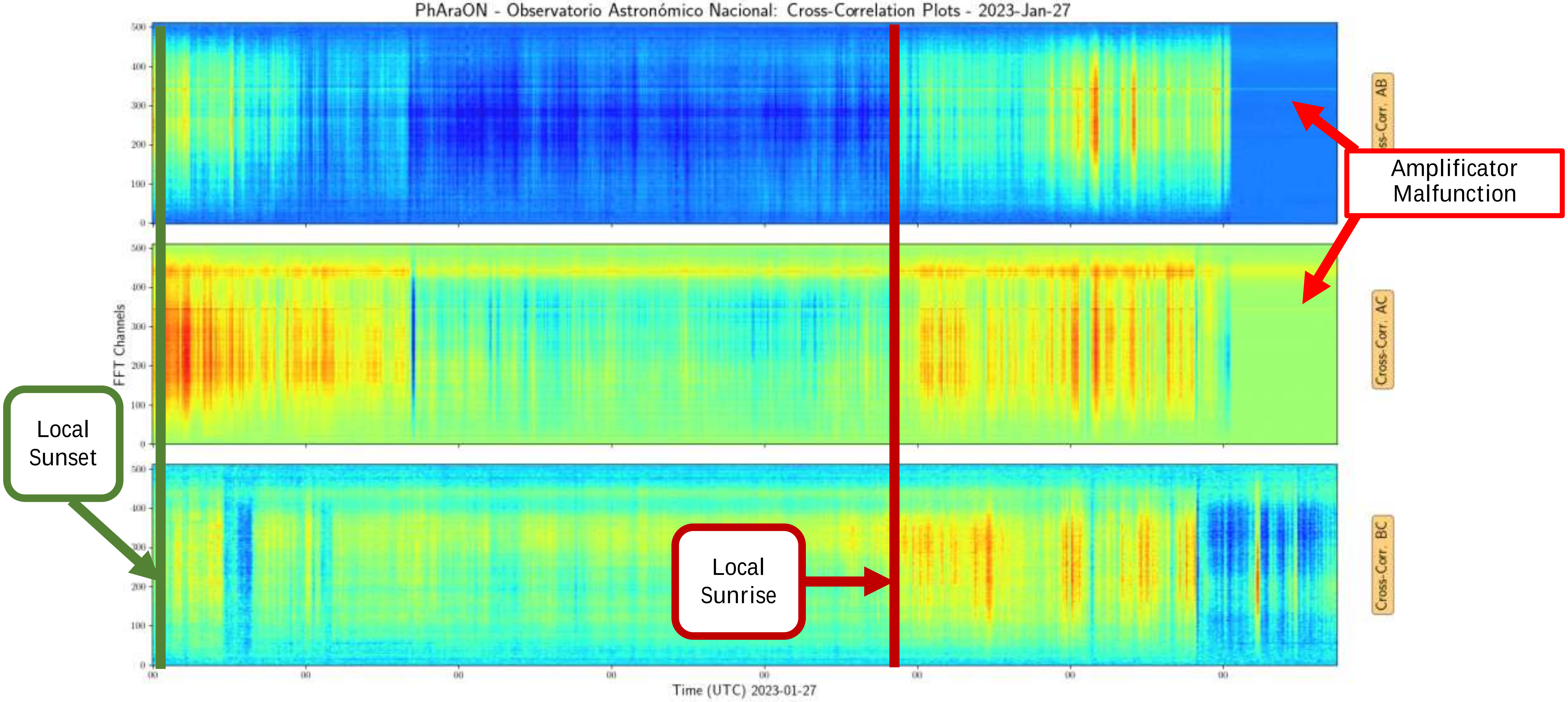


Figure 38: Results – Solar Transit: 2023 January 26, 18:00 – January 27, 13:00 (GMT -5). Cross-correlation plots. (*Hincapié Tarquino, et al. In prep.)*

Results: Source Tracking

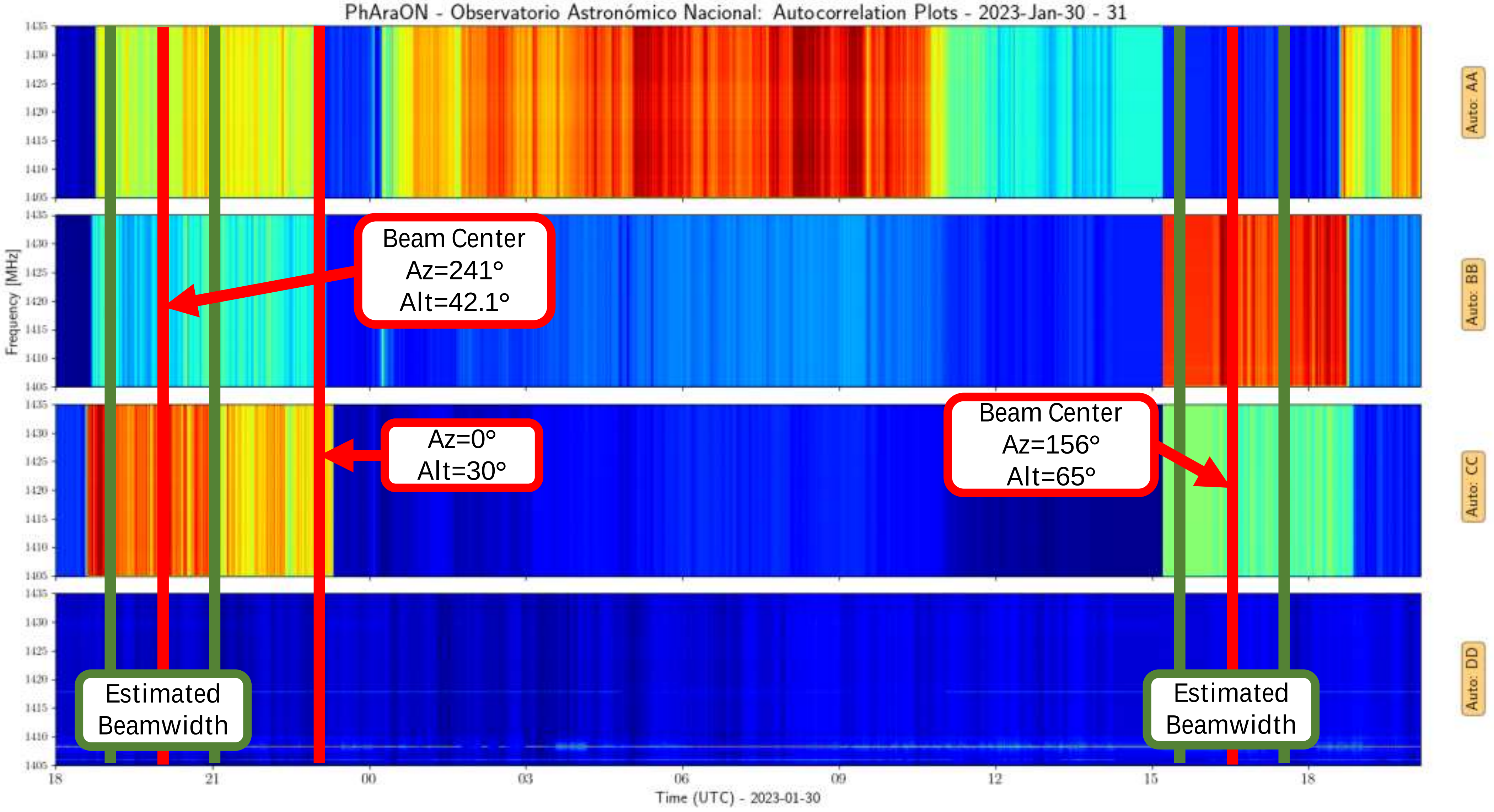


Figure 39: Results – Source Tracking: 2023 January 30, 13:00 – January 31, 14:00 (GMT -5). Auto-correlation plots. (*Hincapié Tarquino, et al. In prep.)*

Results: Source Tracking

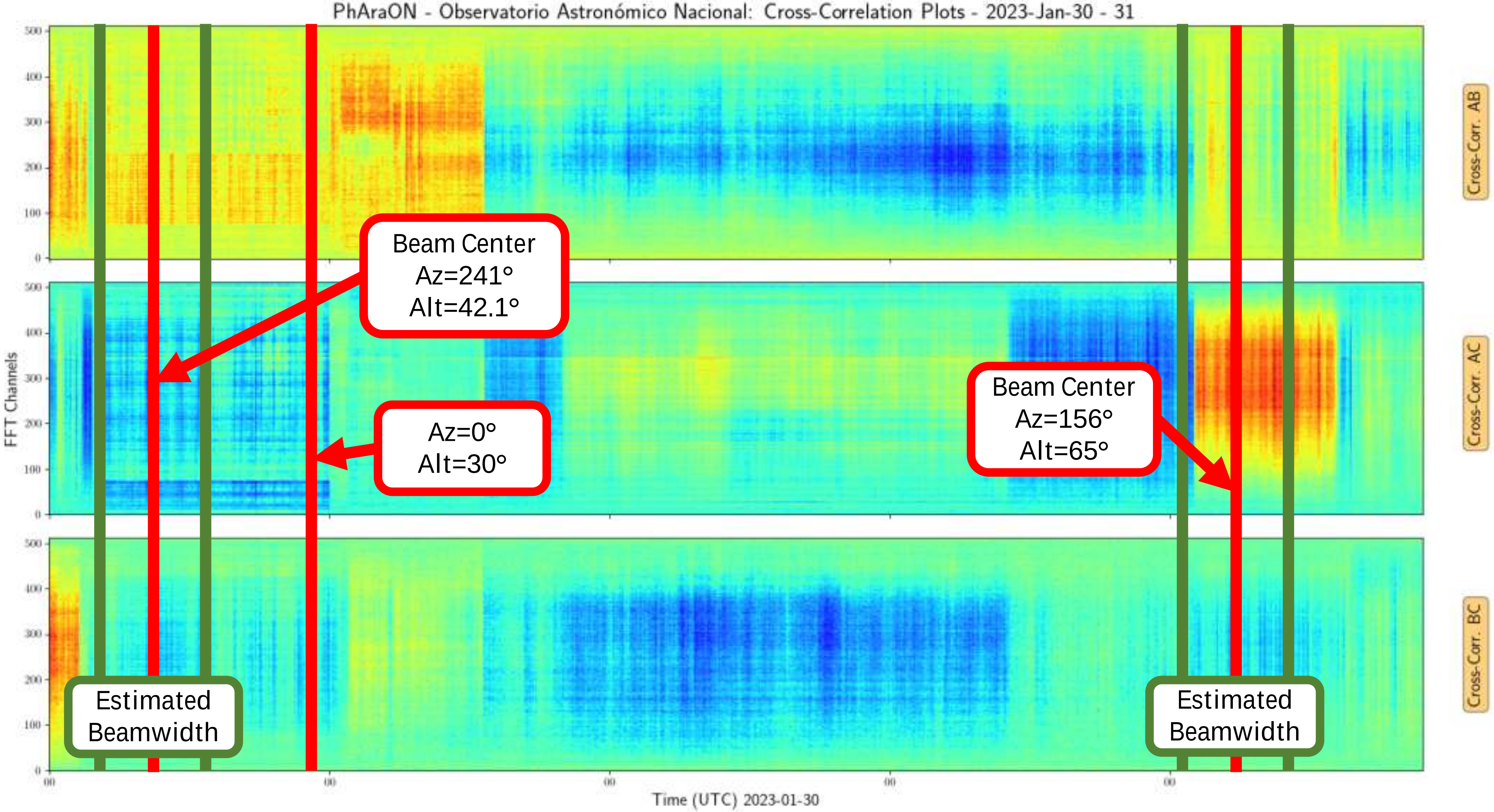


Figure 40: Results – Source Tracking: 2023 January 30, 13:00 – January 31, 14:00 (GMT -5). Cross-correlation plots. (*Hincapié Tarquino, et al. In prep.)*

Results: Source Tracking

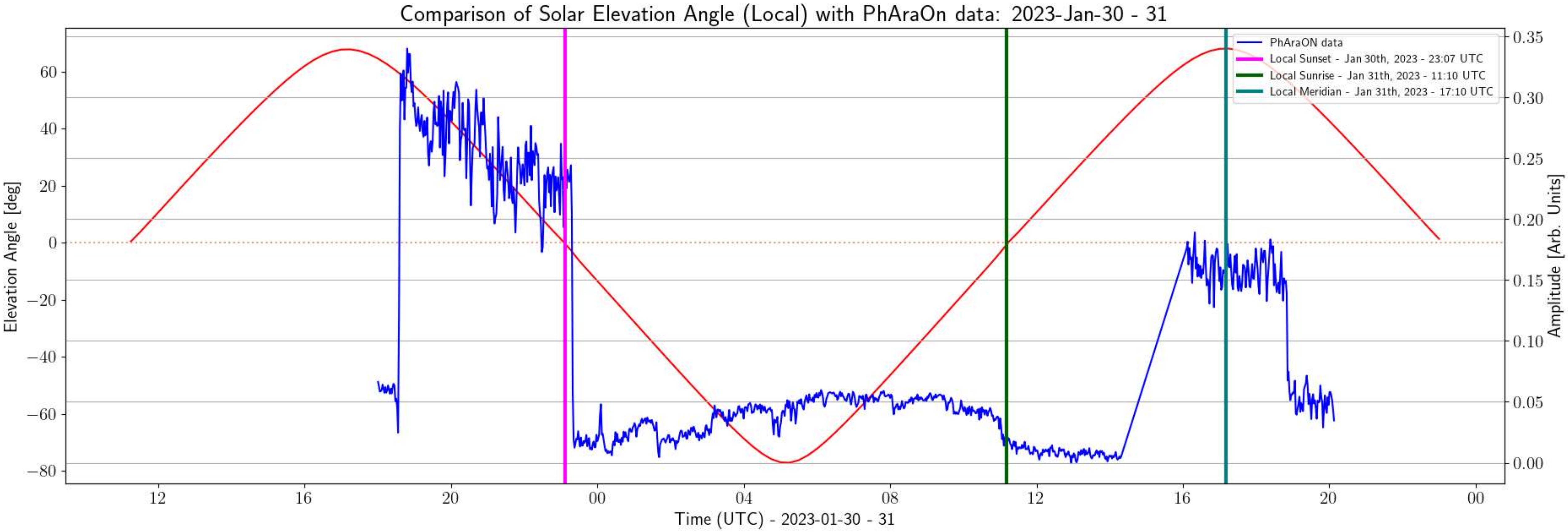


Figure 41: Comparison of obtained data with local solar elevation angle for Jan 30-31, 2023

Results

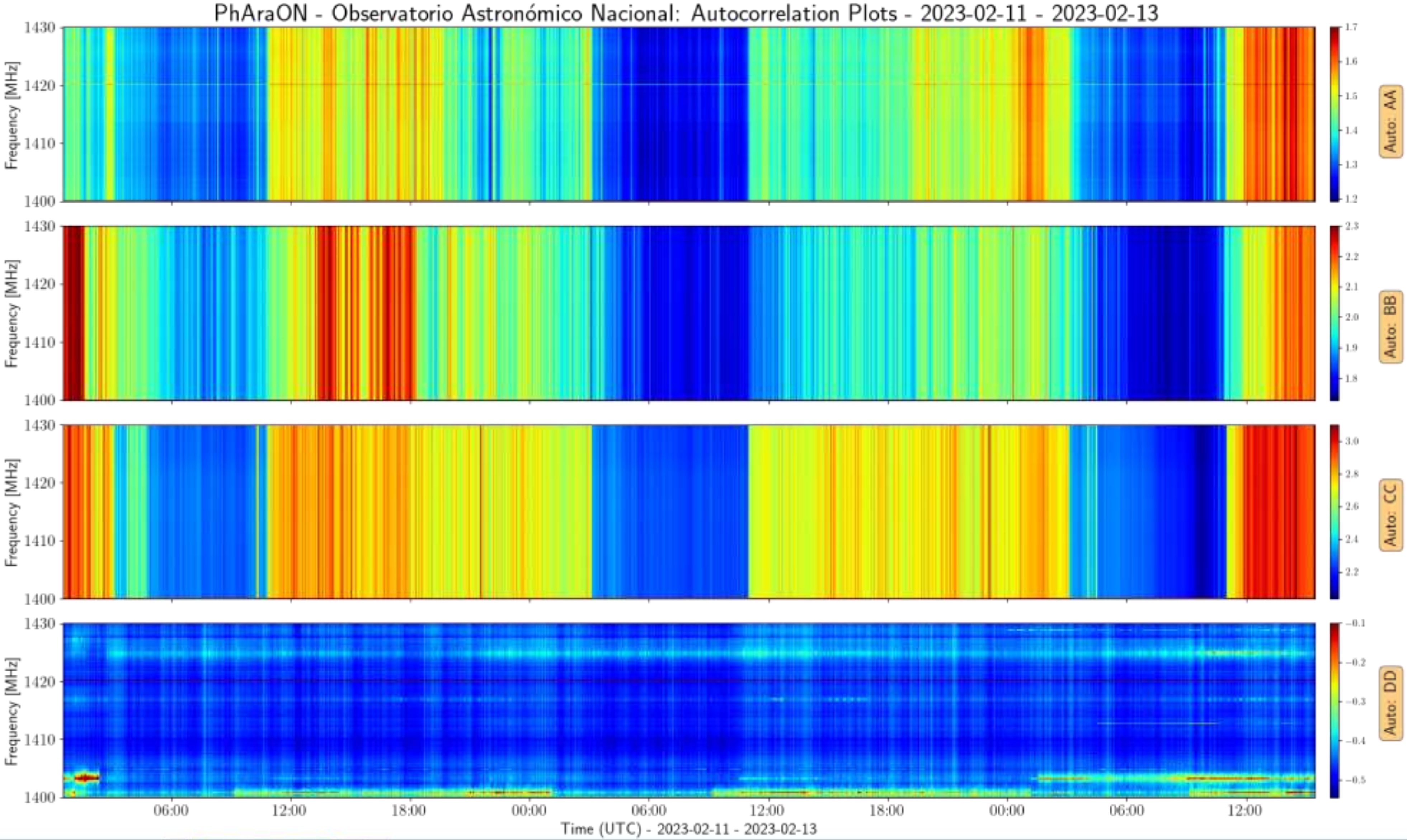


Figure 42: Solar transit results. February 11 – 13, 2023. Auto-correlation plots

Results

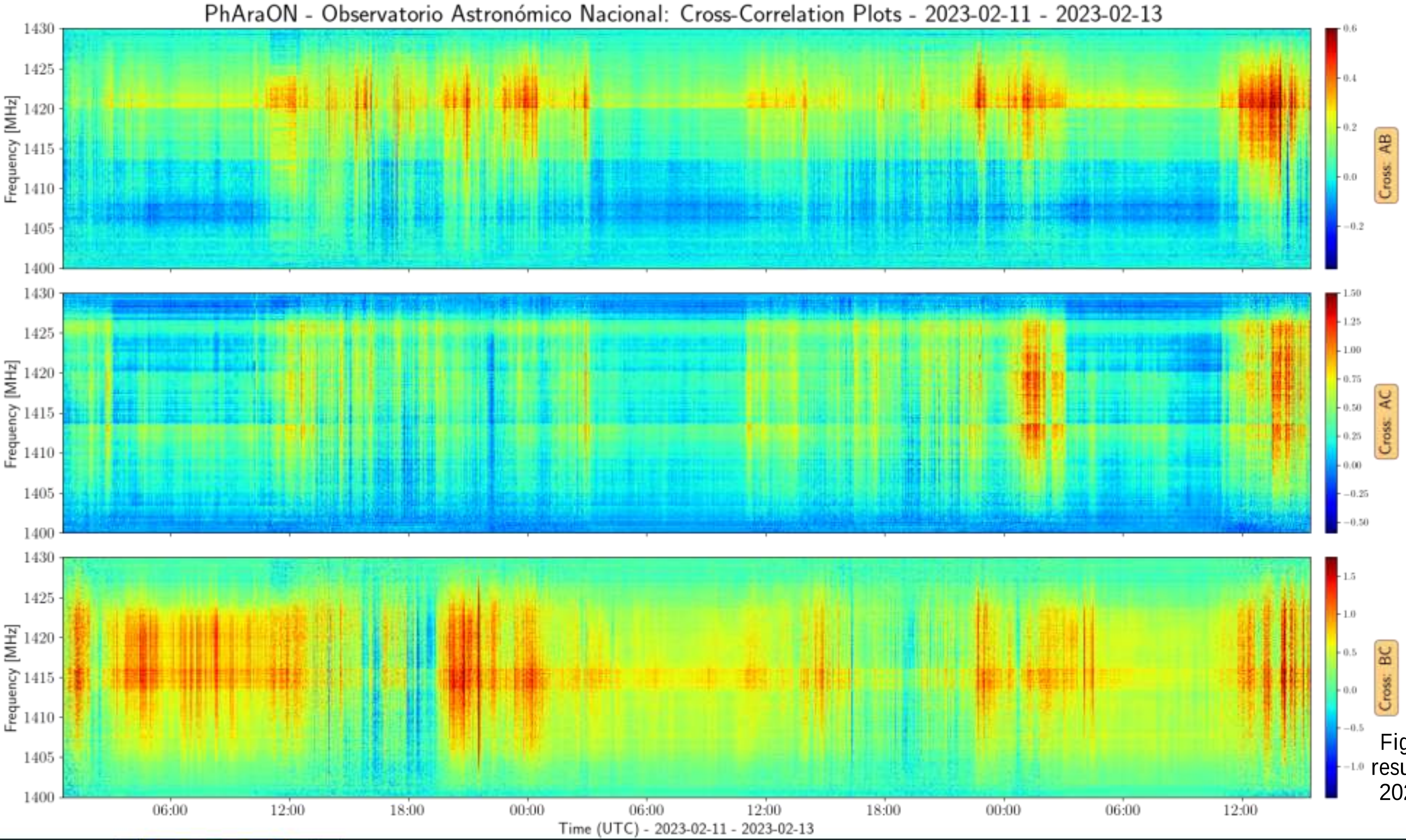


Figure 43: Solar transit results. February 11 – 13, 2023. Cross-correlation plots

Results

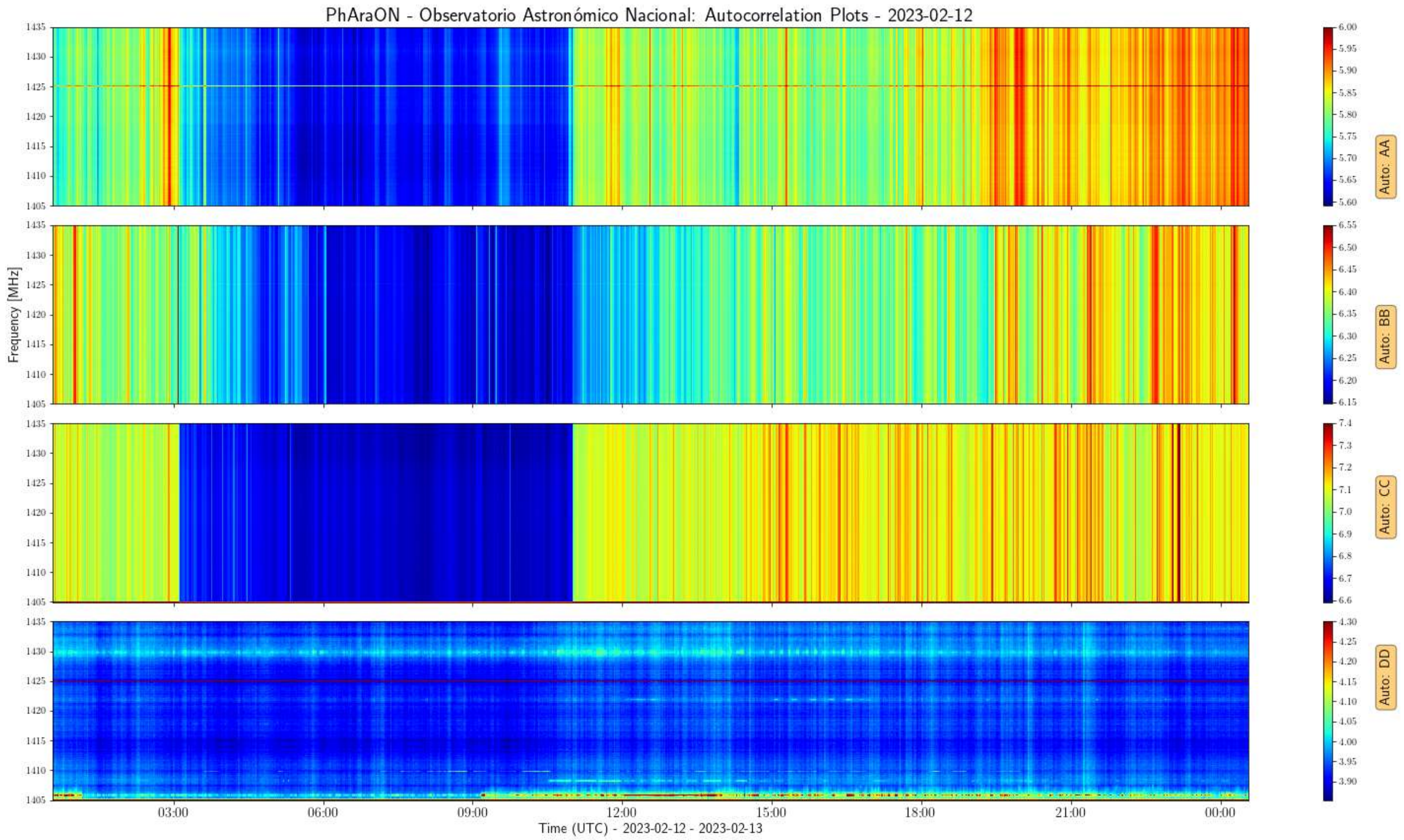


Figure 44: Solar transit results. February 12, 2023. Auto-correlation plots

Results

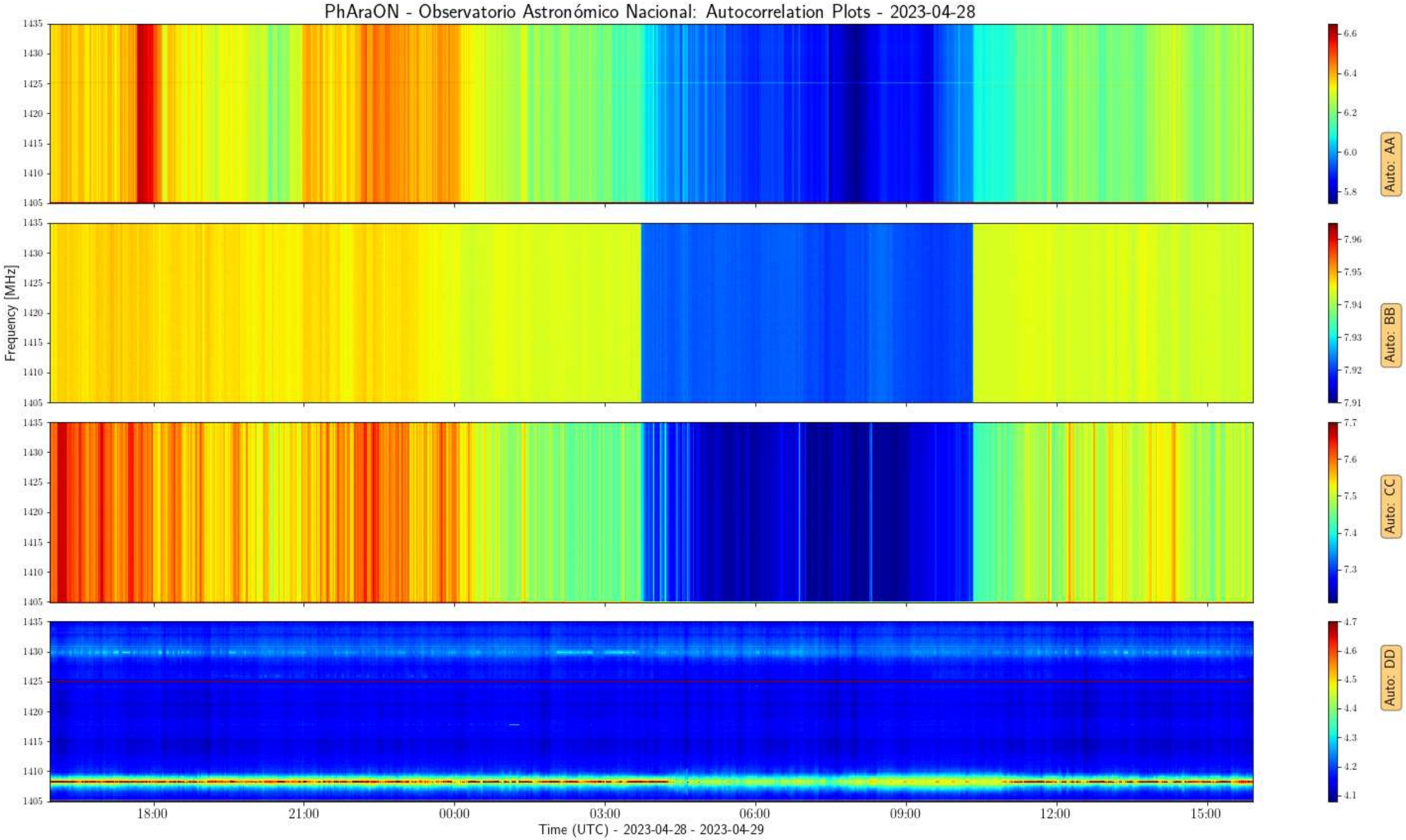


Figure 45: Solar transit results. April 28, 2023. Auto-correlation plots

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Results

Single dish:

- Validation of the Antenna element operation. System works!
- Redesign the pier motor assembly.

Full Array:

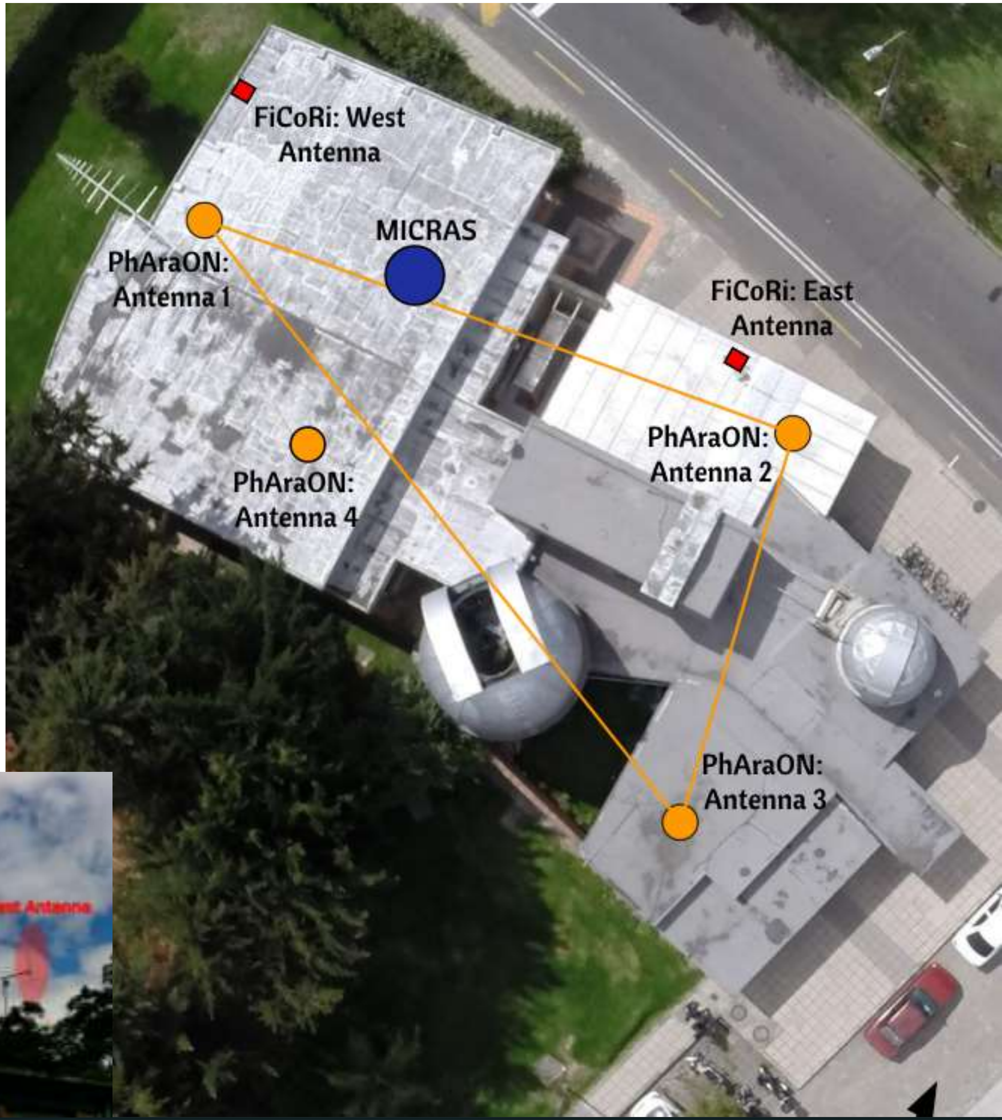
- Successful detection of the Sun, both as a transiting source and with tracking. Verified when comparing the data to the local Solar elevation angle.
- RFI visible at 1,408 GHz (Radiolocation applications)

Conclusions

- Successful design, development, implementation and testing of a multi-element radio interferometer, for astronomical observations at 1.42 GHz.
- Correlator implemented with a ROACH-1 board makes the system versatile and easy to modify and update (Special considerations because of downconversion stage).
- Instrument operation: Successful detection of an extended source.
- Implementation of a dedicated filtering stage would improve the results.
- Current stage of implementation and operation is very close to a fully implemented passive phased array, pending on an evaluation of an appropriate transmitter and phase switching stage to be integrated.

Next Stage: Research

- Implementation of a dedicated filtering stage.
- Improvement of the instrument control stage: Source tracking
- Observation of other cosmic radio sources emitting at 21cm (HI Line).
- Integration with other radio interferometers on-site: "*Solar Radio-Interferometric Network of the Observatorio Astronómico Nacional (RRIS-OAN): Inter-calibration and Instrumental Integration*" (Sánchez González *et. al.*)



References

[1] – ARNOLD, Steven. Getting Started in Radio Astronomy. Beginner Projects for the Amateur. The Patrick Moore Practical Astronomy Series, Springer Verlag, 1988
[2] - BALANIS, Constantine A. "*Antenna Theory: Analysis and Design*". Third Edition. Wiley-Interscience. 2005.
[3] - CONDON, James J. ; RANSOM, Scott M.: Essential Radio Astronomy: Chapter 7. 2016
[4] - FIELDING, John: Amateur Radio Astronomy. 1st Edition, Reprinted. Radio Society of Great Britain, 2008
[5] - GARY, Dale E. ; HURFORD, Gordon J.: Radio Spectral Diagnostics. In: GARY, Dale E. (Ed.); KELLER, Christoph U. (Ed.): Solar and Space Weather Radiophysics: Current Status and Future Developments. Springer Science + Business Media, 2005, Chapter 4.
[6] - GUEVARA GÓMEZ, Juan Camilo: Design and Development of a Solar Radio Interferometer of Two Elements, Observatorio Astronómico Nacional, Facultad de Ciencias. Universidad Nacional de Colombia, M.Sc. Thesis, 2017
[7] - HINCAPIÉ-TARQUINO, Juan Sebastián. Diseño y Construcción de un Radiointerferómetro Solar de dos elementos. Department of Electric and Electronics Engineering, Faculty of Engineering. Universidad Nacional de Colombia. B.Eng. Thesis. 2016.
[8] - POZAR, David M. "*Microwave Engineering*". Fourth Edition. John Wiley & Sons, Inc. 2012.
[9] - THOMPSON, A. Richard.; MORAN, James M.; SWENSON George W. Jr. "*Interferometry and Synthesis in Radio Astronomy*". Third Edition. Springer, 2017.
[10] - WILSON, T. L. ; ROHLFS, K. ; HÜTTEMEISTER, S: Tools of Radio Astronomy. 6th Edition. Springer Verlag, 2013
[11] - ZOTTI, Georg ; HOFFMANN, Susanne M. ; WOLF, Alexander ; CHÉREAU, Fabien ; CHÉREAU, Guillaume: The Simulated Sky: Stellarium for Cultural Astronomy Research. In: Journal of Skyscape Archaeology 6 (2021), Mar., Nr. 2, p. 221–258

Thanks!

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