The LWDA Array: An Overview of the Design, Layout and Initial Results

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1 Introduction

The Long Wavelength Demonstrator Array (LWDA) is a 16-element phased array radio telescope that operates in the frequency range from 60-80MHz. Located in western New Mexico, on the grounds of the Very Large Array (VLA), the LWDA is a prototype for the much larger, and more ambitious Long Wavelength Array (LWA). The LWDA is designed to provide the capabilities for time-domain beamforming and all-sky monitoring. In this paper, we will describe the design and configuration of the LWDA, and discuss some of the initial LWDA results.

Our overview is guided by the priniciple of following the photon, and we offer the following brief summary of the elements of our discussion.

- The LWDA antennas collect dual, orthogonal, linear polarizations. The linearly polarized signals are then handled independently in the signal processing chain. They are not currently combined into circularly polarized states.

- At the antenna, each signal is amplified by an dual-polarization active balun (24 dB of fixed gain) that was designed for the LWDA by NRL. The balun is mounted inside the antenna mast, and the signal for each polarization is passed out of the balun on a separate cable.
- A short cable run connects the balun outputs to a lightning arrestor, mounted inside the antenna mast.
- From the arrestor, the amplified signals are then passed over LMR-240 cable to the LWDA electronics. The cables are enclosed in PVC conduit (0.75" diameter), and buried. The conduit runs from each antenna to a junction box at the edge of the array. At the junction box the cables are consolidated into two large conduits (4" diameter), which carry the cables to the electronics, housed in a shelter about 30m from the edge of the array. The total cable runs vary, but are between 50 to 60m.
- At the shelter, the incoming signals are passed through the shelter walls via N-type bulkhead connectors. On the inside of the shelter the cables are passed into a rack via SMA connectors.
- In the rack the incoming signals are passed to a Level One Enclosure (LOE). In the LOE,the signal is further amplified and filtered in three separate gain stages. The first gain stage is a fixed 24dB amplification stage. The remaining two gain stages provide variable gain control in a total of 6 dB steps, as well as anti-aliasing filtering in a 50 to 100MHz passband.
- After amplification the signal is passed to the LWDA receiver where it is digitized and in-phase and quadrature components are generated. The signal is time delayed and filtered to its final bandwidth (1.6 MHz). It is important to note that the time delays inserted here are what provide the "beamforming" capabilities, accounting for internal delays as well as the geometric component of the delay. The I/Q components from the two polarizations are interleaved and passed downstream, over CAT5 cable.
- Downstream of the receiver is the "level one adder" board. Each adder board can take up to eight (8) incoming signals. In each adder board the incoming coherent signals are either summed (beamforming) or interleaved (all-sky imaging) across all eight antennas. The signal can then be passed on to another adder board (over CAT5) or passed to a computer through a USB port.
- In the LWDA, the final stage is a second adder board with two incoming data streams. This adder collects the signal from the two level one adders and, again, either sums or interleaves the results. The final data stream is then passed off to the station computer over a USB port and archived.

Figure 1 provides an overview of the station design. In this figure, the different colored blocks correspond to the different levels of RF shielding that have been introduced in order to meet the NRAO standards.

2 Components and Layout

We will now provide a detailed description of the LWDA layout and receive chain components.

2.1 Array Layout

The LWDA antenna locations were chosen as a subset of a larger planned configuration [3],[4]. The full configuration calls for 256 antennas, and is optimized for sidelobe reduction, and appears, to the eye, to be a pseudo-random array. The 256 antennas are distributed over a circular area 50m in radius. The 16 antennas of the LWDA, shown in Figure 2, are located in the north-east quadrant of the full array, shown in Figure 3.

2.2 The Antenna

The antenna element is designed to operate with good reception over the band 60-80 MHz, collecting dual orthogonal linear polarizations. This operating band was chosen to minimize the response to strong radio-frequency interference in the FM band (88-108 MHz). The antenna is designed to be fairly compact and inexpensive to construct ($530 each in quantity). The antenna and mount are designed to withstand 90 mile/hour peak wind loading, and have a lifetime of more than 10 years.

2.2.1 Antenna - Mechanical

The antenna, shown in Figure 4, is composed of a number of different components which we will now describe

The antenna elements, termed "blades", are made from aluminum sheet, cut and trimmed to 28 cm wide by 1.05 m long. Along each side of the length, there is a 1.6 cm wide strip which has been bent at 90 degrees to the main blade body. This provides stiffness and prevents flexing in high winds. The upper 13 cm of the blade are tapered, with a bend across the blade at 5 cm from the upper end. The tapering allows for easier mounting of the antenna to the top plate. The bend allows the blade to droop at 45 degrees to the horizontal. An evaluation of the antenna electrical properties determined that this was the optimal angle for the antenna blades. A threaded stud at the antenna mount point is used to provide a good electrical connection to the cables running to the balun.

The blades are mounted to the mast via a top plate, made from machined PVC. This is the most detailed antenna piece. The antenna blades mount to the top plate via threaded inserts that are placed in the PVC.

A weather proof cover and gasket are used to keep moisture away from the balun and the interconnects between the balun and the blade. The gasket and weatherproof cover mount to the antenna top plate, and serve to keep moisture out. The cover is formed from molded polycarbonate at a cost of about $12 each.

The antenna is supported by a single mast and by additiona support struts. The mast is made out of square aluminum tubing (10.6x10.6 cm) and is slightly over 1m in length. Antenna blade support struts run from the mast to the blades, providing structural support. Angle brackets mount near the base of the antenna serve to anchor the support struts. The support struts are fiberglass, with threaded inserts placed to make assembly easy.

Foundations for mounting the the antennas in the ground needed to be designed to account for the sandy nature of the soil at the site. The foundation is circular aluminum tubing driven 5 feet into ground. The antenna mast is mounted to the foundation using two bolts passed through the mast and foundation. The soil at the LWDA site is sandy, and so it is actually possible to physically rotate the antenna even after it is fastened to the foundation. To prevent accidental rotation, and piece of steel rebar is driven through offset holes placed in the foundation. This provides enough friction to make rotation unlikely.

2.2.2 Antenna - Electrical

Input impedance and mutual coupling measurements were taken on two sample LWDA antennas using a vector network analyzer in order to verify that the antenna operation is in-line with simulations used in the design process [2]. Tests were conducted with the antennas placed in an open field, roughly 20 m from the nearest building. The measured input impedance of one of the dipoles of the blade antenna is shown in Figure 7; the impedance of a second dipole was found to be nearly identical. Also provided for comparison is the simulated impedance of the blade given by the Numerical Electromagnetics Code (NEC) application. The measurements give good agreement at lower frequencies, but deviate from NEC simulation somewhat at higher frequencies. We believe that the discrepancy between measurement and simulation at higher frequencies is due to both reduced accuracy of NEC at those frequencies and the interaction between the antenna elements and the mounting structure (e.g., mast, top plate) that is not included in the simulation. The spike that appears in the blade measurements around 96 MHz is due to FM radio signals leaking into the measurement. The VSWR corresponding to these impedance results is given in Figure 8. The measured and simulated VSWR responses agree reasonably well in character. Some differences exist, though, due to the factors mentioned above. Cross coupling measurements between two blade dipoles for three different dipole orientations are shown in 11. For crossed dipoles on the same antenna stand, it can be seen that the coupling between them is very low across the LWDA frequency band, less than -40 dB. For two dipoles separated by 4 meters, the coupling between them is higher than for crossed dipoles, but still relatively low, less than -26 dB across the LWDA band for both parallel and colinear dipole arrangements. The spikes evident between 90 to 100 MHz are again due to FM radio signals leaking into the measurements.

The E- and H-plane antenna radiation patterns are shown in Figure 9. The blade dipole exhibits wide beamwidth and slowly varying radiation patterns in both prinicipal planes over the entire LWDA band. The axial ratio (or quality of circular polarization) resulting from a pair of crossed dipoles can be approximated by the difference between the E- and H-plane gain patterns at each elevation angle for a single dipole, and is shown in Figure 10 for the blade dipole at 70 MHz. A pair of blade dipoles exhibits reasonably good circular polarization, with an axial ratio of less than 3 dB for all elevation angles. The blade dipole exhibits similar axial ratio performance at other frequencies in the LWDA band.

The effective sky noise temperature referenced to the blade antenna terminals as a function of frequency and measured with an LWDA receiver is shown in Figure 12. The sky noise frequency response of the blade antenna as predicted by simulation is also included in the figure for comparison. These measurements were conducted at a site roughly 70 miles south of Austin where the RFI levels are much lower than Austin, but still higher than those at the LWDA site at the VLA. While RFI is evident over much of the measurement band, good agreement between simulation and measurement is exhibited at frequencies free of RFI (e.g. near 63 MHz, 73 MHz, and 85 MHz.)

2.3 Signal Chain

Each individual signal chain in the LWDA consists of one antenna, a balun, cables and lightning arrestors, amplification stages and a digitizing receiver. The adder will be described separately.

At the antenna, the balun [1] is connected to the antenna blades via four short cables (a few cm long). The balun amplifies the antenna signal (24dB of fixed gain), matches the cable impedance

(50 Ohm) and sends the amplified RF signal out over two coax cables (LMR-240). One of these cables carries power for the balun. A lightning arrestor sits about 10 inches below the balun, mounted inside the antenna mast, and is grounded directly to the antenna mast.

The signal travels over about 60m of cable, and then passes through three amplification stages. The first stage is a fixed 24 dB of gain provided by a Minicircuits amplifier. Then follow two custom gain stages, each of which provides anti-aliasing filtering (the passband is 50-100 MHz), as well as variable gain. The gain is adjustable in 6 dB steps (3 dB for each stage), and provides up to a maximum of 48 dB total gain. At the front end of the digital receiver is an ADC which digitizes the RF signal at 100 MSPS and then time-delays, filters and decimates the signal (see the next section for details).

2.4 Receiver and Signal Processing

The receiver signal processing chain is reconfigureable on the fly. As a result, this section is subject to change without notice. However, as of the LWDA first light, here's how the digital receiver signal DSP flow works. Beginning in the digram below, our description proceeds bottom to top.

- The incoming RF data stream is digitized at the ADC. The ADC used in the receiver is dual channel, so both polarizations are digitized. The output data stream is 100 MSPS.
- The signal routing can then be controlled. We have two identical signal processing chains, but the parameters controlling these chains are independent. We can route the incoming signals as desired through the two chains. This means we can operate on two different frequencies, or over a wider bandwidth, or handle both polarizations. Currently, this design consumes about 50% of the FPGA resources, so there is room for expanded capabilities.
- After switching, the first stage of digital processing is a FIFO which provides a integer sample delay. We term this the fine integer sample delay as this provides an ability to delay the incoming signal by up to 150ns in 10ns increments. Thus, geometric path delay and system time delays can be partially compensated for at this stage.
- In the next stage of processing, the in-phase and quadrature components are generated using a CORDIC rotator.
- The data is then low-pass filtered using a Cascaded Integrator-Comb filter and decimated (by a factor of 14).

- There then follows another FIFO. This is termed the coarse sample delay, and it provides for sample delays in excess of 2 microseconds in 140 ns increments.
- Finally a FIR filter is used to further low-pass filter the signal, compensate for the CIC bandpass, provide any fractional sample delays and reduce the data by an additional factor of 3.
- The final stage is to interleave the signals and pass them onto the adder board.

Power to the receiver is received over the RJ45 connector and is passed directly to a power output pin for powering co-located devices. There is no onboard non-volatile storage of FPGA code, as the FPGA is configured at power up over either the LVDS input pair, or the USB port. Internal clocking is provided through means of a 100 MHz Voltage Controlled Crystal Oscillator, which is steered by a PWM output from the FPGA filtered through a single pole RC filter with a time constant of 1 second. The device is protected to some degree against reverse and over-voltage power application through a Zener diode at the power input.

2.5 Beamformer

The beamformer, is also known as the adder, or the USB, board. The beamformer was designed to take the incoming digital signals from up to 8 LWDA receivers For these devices the beamformer board provides power management, remote FPGA configuration, clock synchronization, command/control signaling, and aggregation of collected data. The aggregated data is available to streaming over a USB2 port into a PC, and/or over a downstream LVDS port to a higher-level beamformer board. Power to the beamformer can be received over the RJ45 connector or be supplied via a power input pin.

2.6 Time Distribution

Each receiver and adder board is equipped with a voltage controlled crystal oscillator. When the array is operating, these independent devices are synchronized. Since the LWDA has a hierarchical design, each device is synchronized to the next higher level of device. Each receivers is syncronized to the level one adder board to which it is connected. Each level one adder board is synchronized to a level-two adder board, and so on. Ultimately, a single device is the root source for all distributed timing within the array. For the LWDA, this is the single level-two adder board. Thus, the array primary clock is a 100MHz sampling clock, to which a GPS derived 1 pps signal is timestamped.

In the LWDA, there are two modes of clock recovery: Acquistion and Tracking. In acquistion mode the upstream board produces a 50 MHz square wave, which any downstream device is able to use to provide steering information for clock differences. Less abstractly, receivers generate a square wave which the adders compare with their own internally generated square waves. Steering commands are then passed back upstream from the adder to the receiver. When the timing phase lock is acheived on the 50 MHz square wave, the system transitions to tracking mode. In this mode the upstream board produces a normal 8b/10b encoded data stream. The downstream board monitors this data stream, and when there is a bit transition in the data stream, the sample in between determines if the upstream clock is leading or lagging. If the sample is the same as the later bit, the upstream clock is leading; if the sample is the same as the earlier bit, the upstream clock is lagging. This information is collected and slow steering corrections are fed back to the upstream device.

2.7 Rack Configuration

The LWDA equipment rack is shown in Figure 14. This photo was taken during emissions testing at the VLA test chamber. The rack is an "FCC compliant" Equipto rack. The enclosures each contain eight receivers and one adder board. Power is supplied to each level one enclosure by three dedicated power supplies, contained within one power supply enclosure. The rack also contains a UPS and a network switch, used for communications with the external network.

2.8 Software

The software which serves to operate the LWDA is composed of three separate components. Firmware for the receivers and adder boards is implemented in Verilog, a hardware description language. The firmware is uploaded to all devices at runtime. Low level routines, which send commands to individual devices, or control individual devices, are implemented in C. Higher level software routines, which allow the user configuration or operation of the array, are written in Python. Python is an object-oriented scripting language, and has proven quite flexible during the development of the LWDA.

2.9 First Light

The final installation of the LWDA occurred during October, 2006. During the installation trip, the final RFI emissions testing was performed in the NRAO test chamber, the array electronics was installed and network connections were established, and a hardware calibration of the receive chains was performed. The first light images were obtained at the completion of this trip. This image is shown in Figure 15. The images shown in Figure 16, was taken during November 2006 during a solar flare. In this image, the sun has become the dominant object in the sky at 74MHz.

References

[1] R. Bradley and C.R Parashare, *Evaluation of the NRL LWA Active Balun Prototype*, LWA Memo Series (19), Feb 2005.

[2] A Kerkhoff and S.W. Ellingson, *A Wideband Planar Diploe Antenna for Use in the Long Wavelength Demonstrator Array*, vol. 2005 International Antennas and Propagation Symposium, IEEE, Jul 2005, pp. 553–556.

[3] E. Polisensky, *Preliminary LWA Station Configuration Studies*, LWA Memo Series (14), Dec 2004.

[4] ———, *Which 128 Elements for LWDA Phase I*, LWA Memo Series (24), Sep 2005.

Figure 1: Schematic view of the LWDA architecture, showing all of the major components.

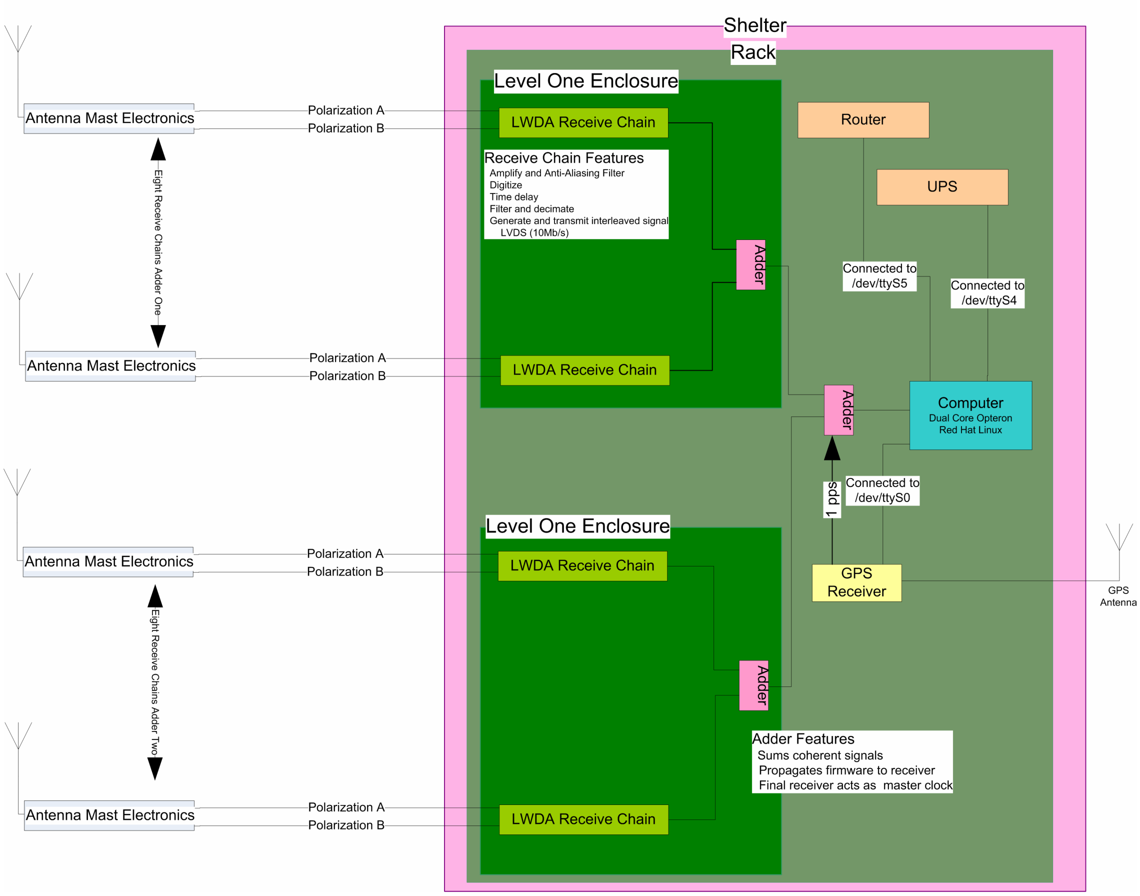

Figure 2: The LWDA (25m VLA dish in the background)

Figure 3: LWDA Site Layout.

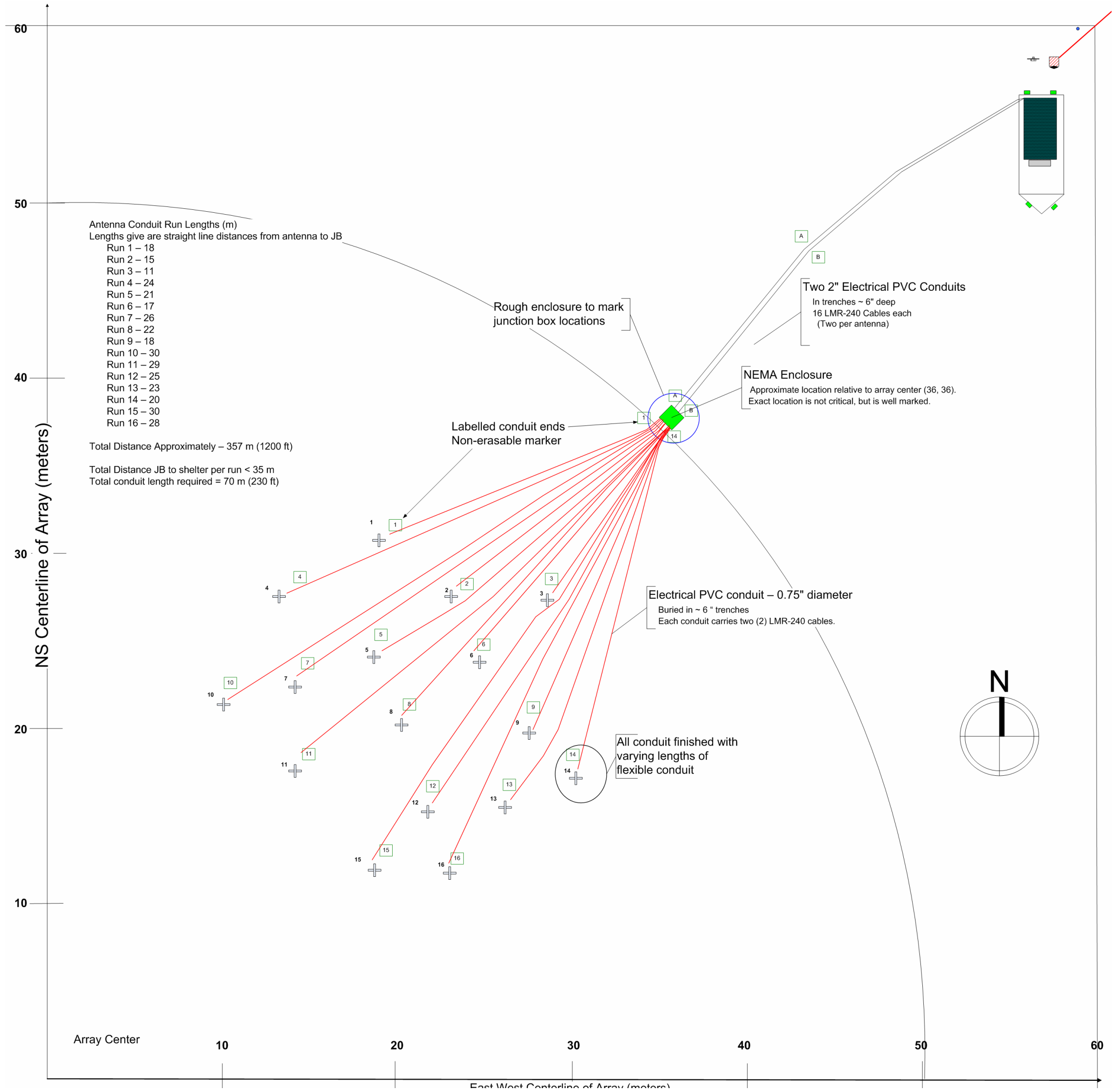

Figure 4: The LWDA Blade Antenna.

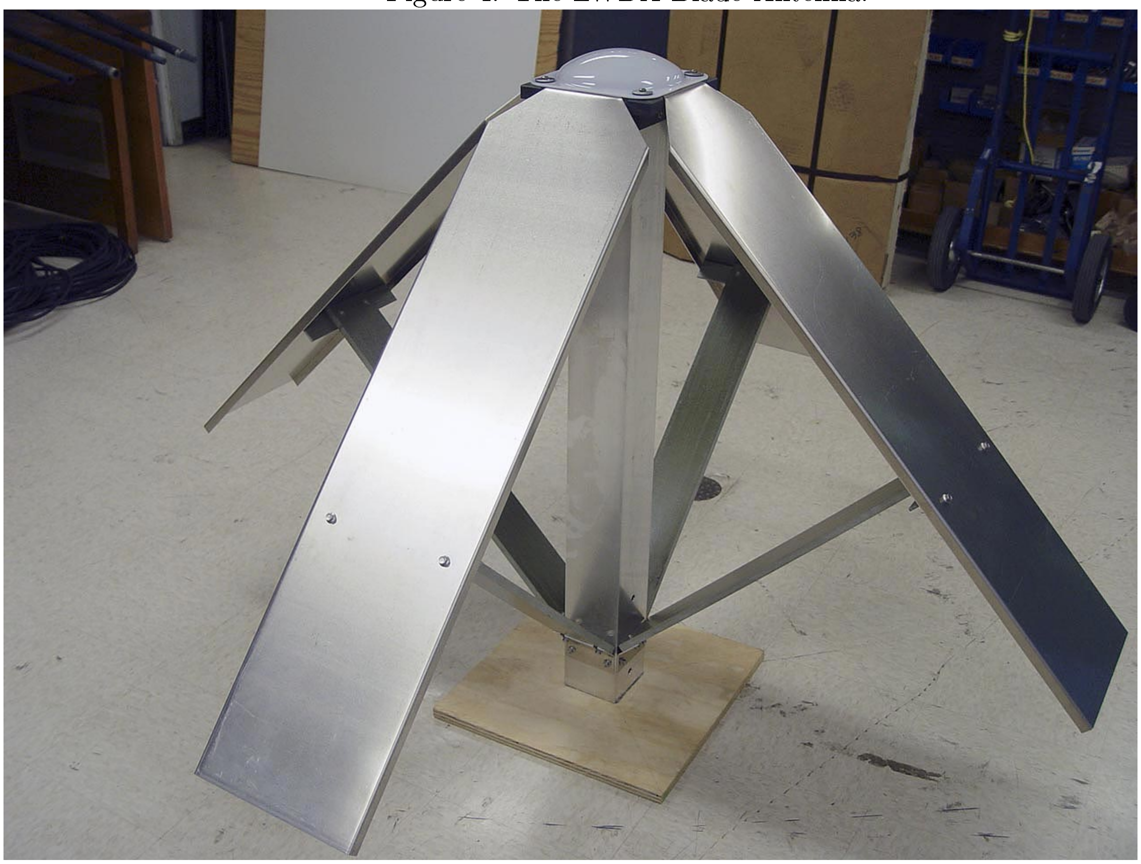

Figure 5: A top plate without blades attached.

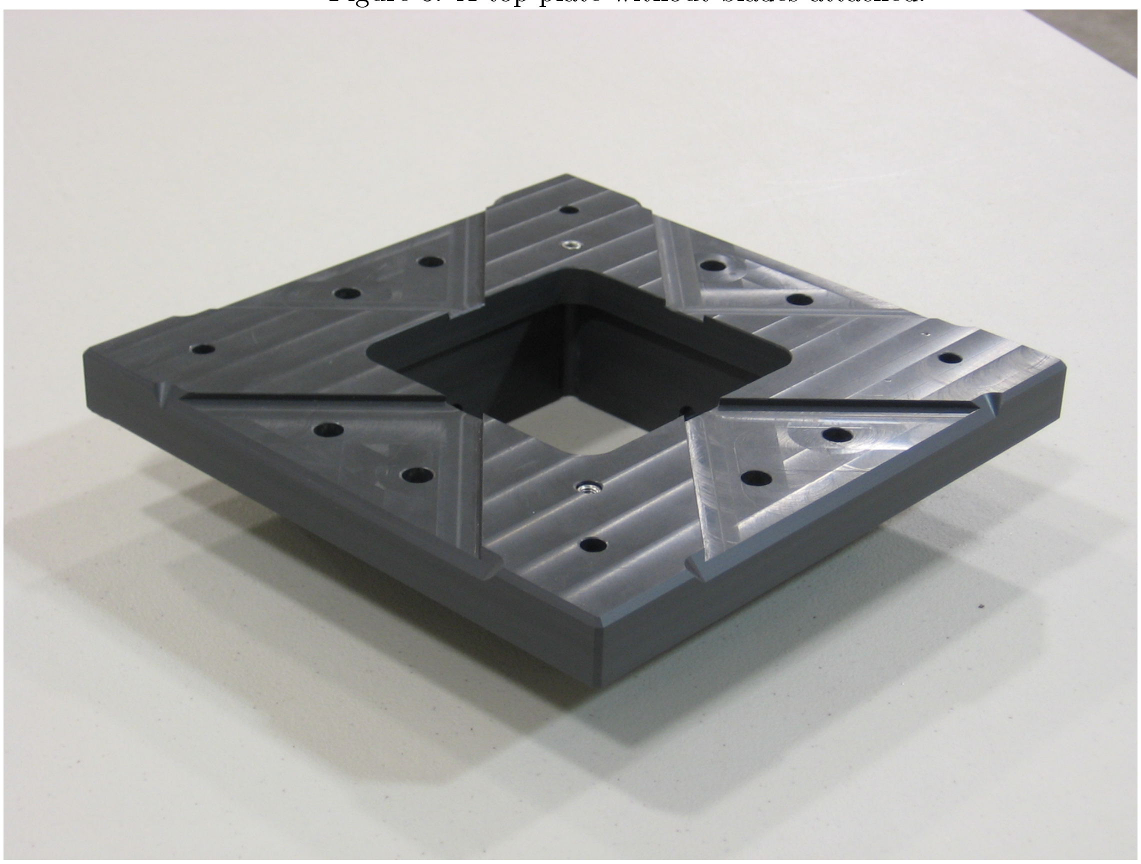

Figure 6: Antenna Dome.

Figure 7: Antenna Measured and Simulated Impedance.

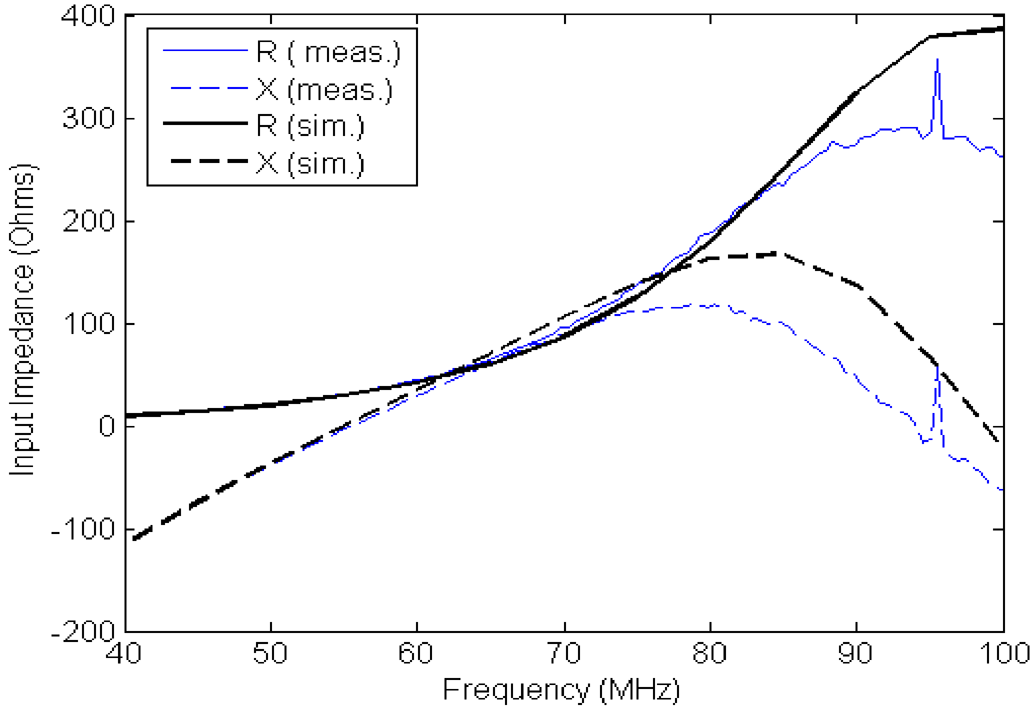

Figure 8: Antenna Measured vs Simulated VSWR.

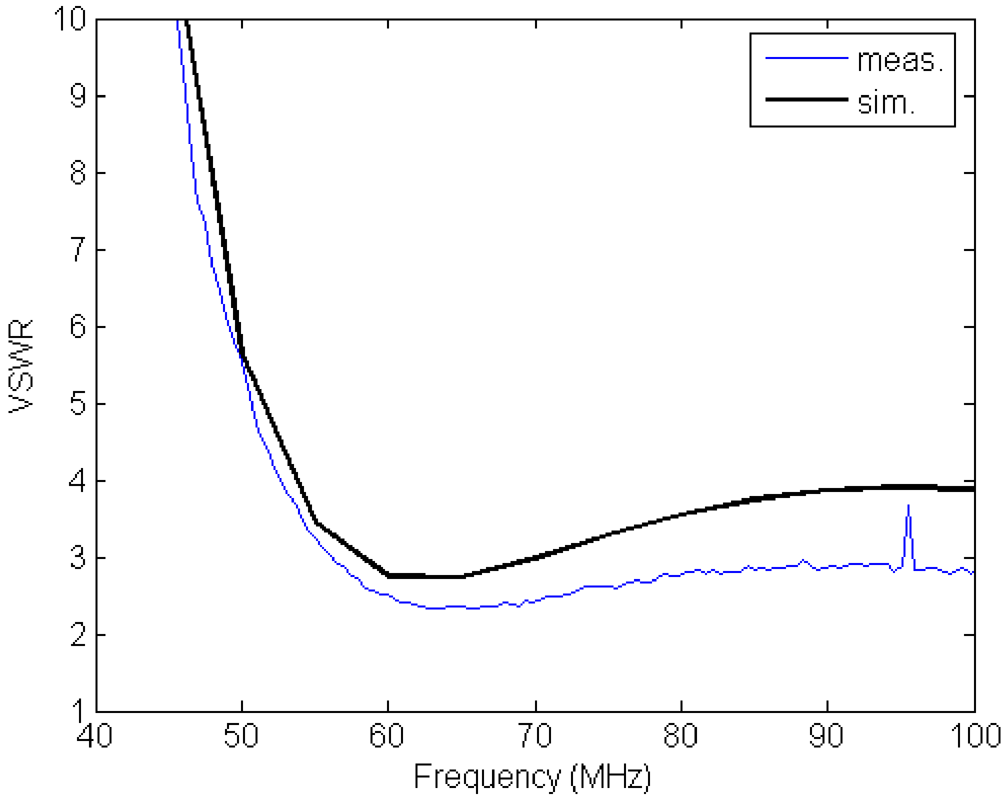

Figure 9: Antenna Simulated Co-Polarization Radiation Pattern at 50,70, and 90 MHz.

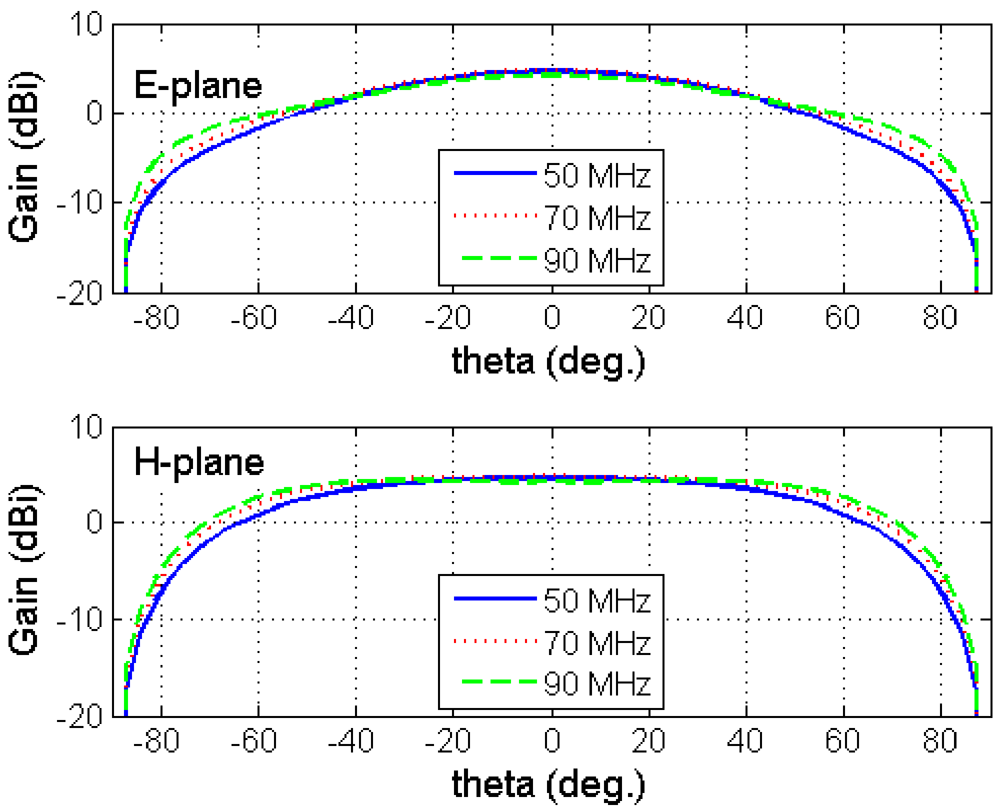

Figure 10: Antenna Simulated Axial Ratio as a Function of Zenith Angle at 70 MHz.

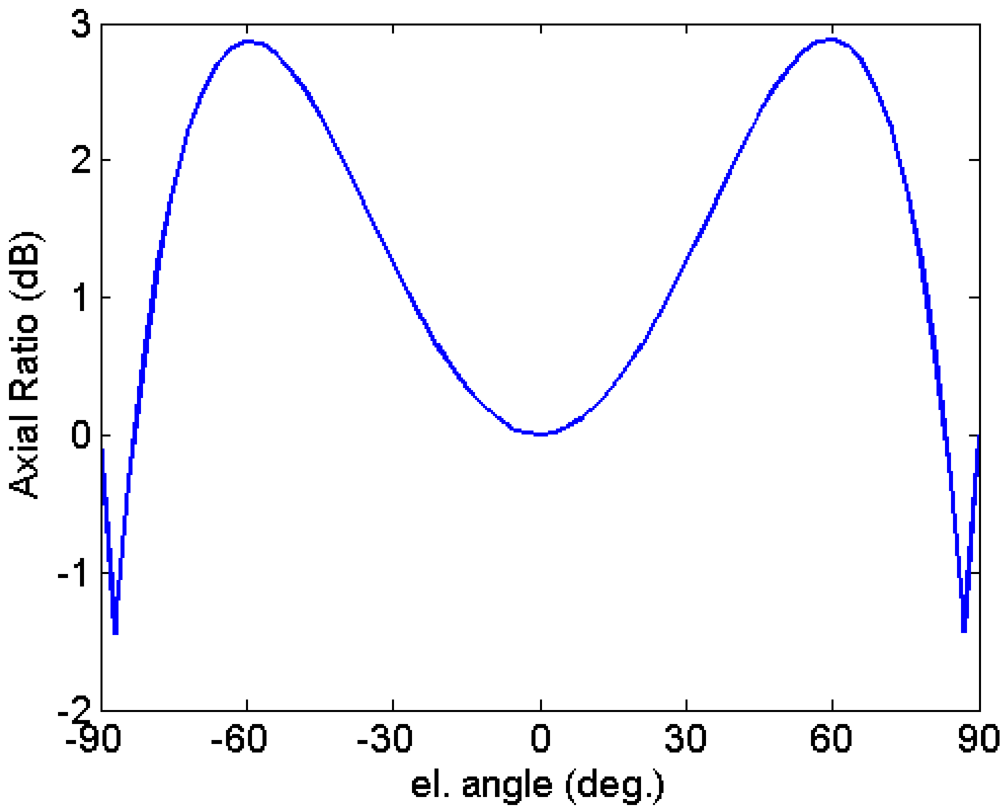

Figure 11: Cross Coupling Measured for the Antenna for Different Dipole Orientations.

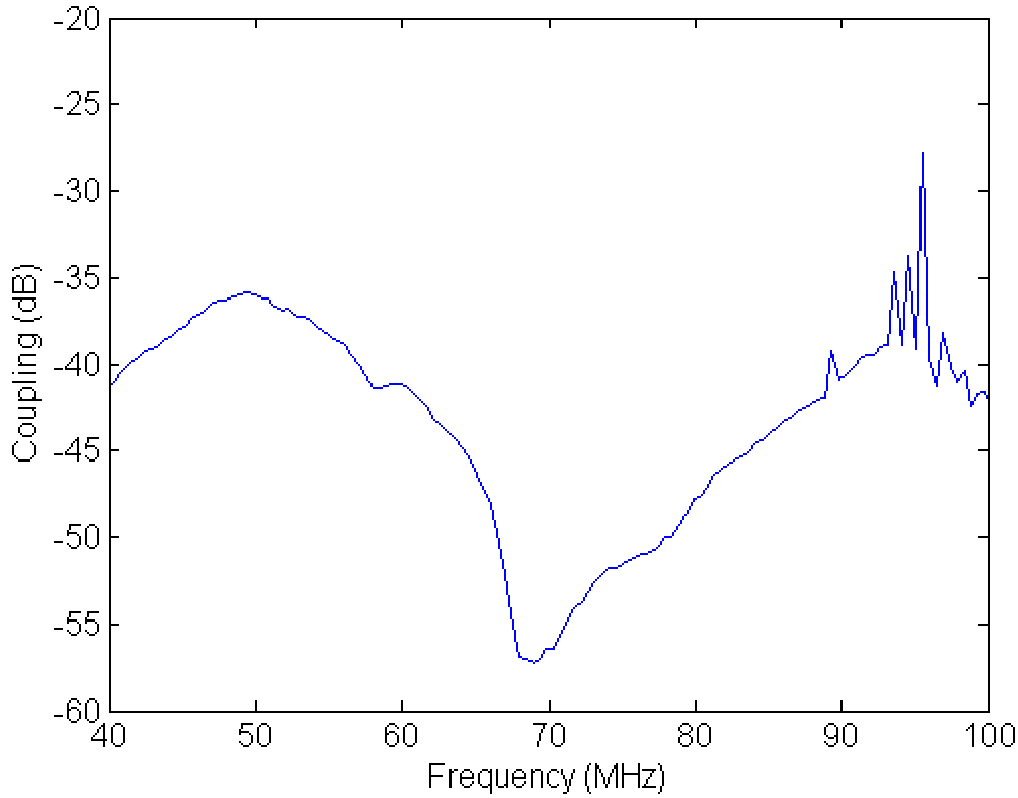

Figure 12: Antenna Sky Noise Response - Measured and Simulated.

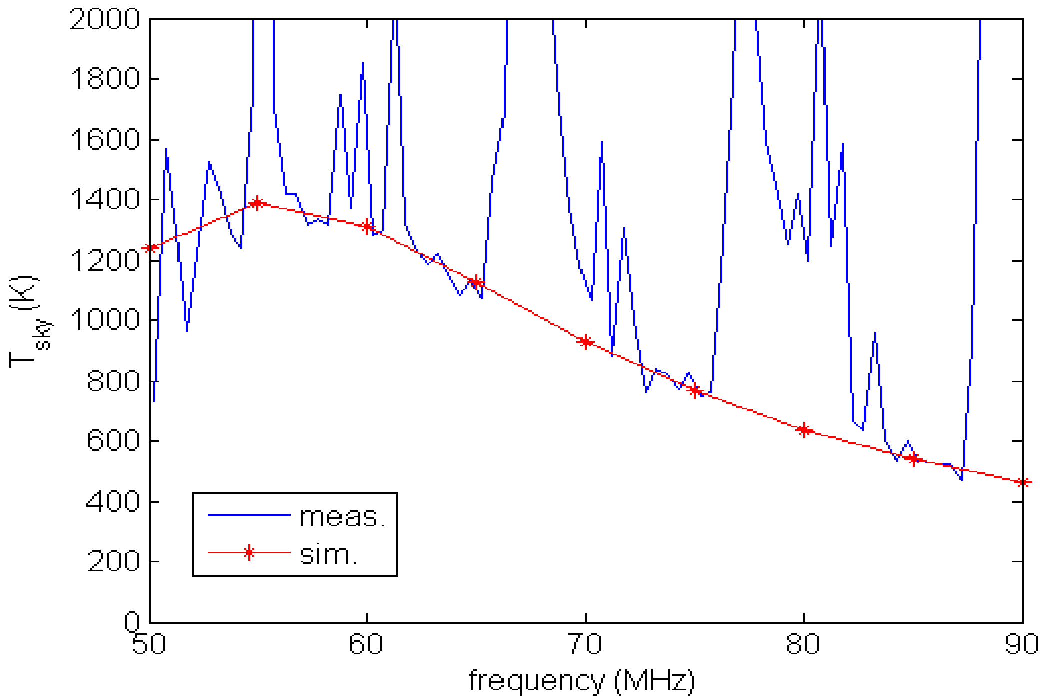

Figure 13: LWDA digital receiver signal processing.

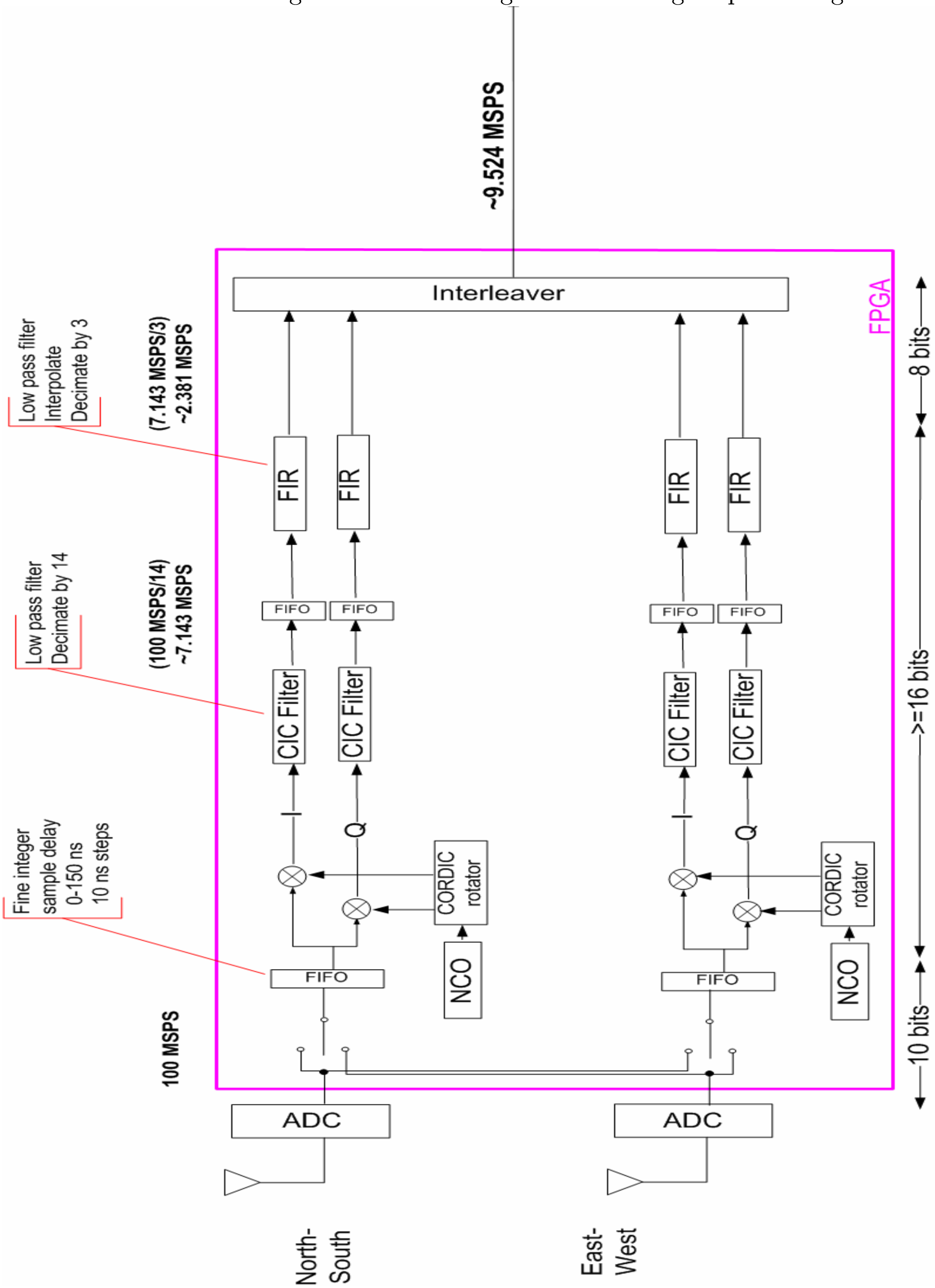

Figure 14: Labeled LWDA equipment rack.

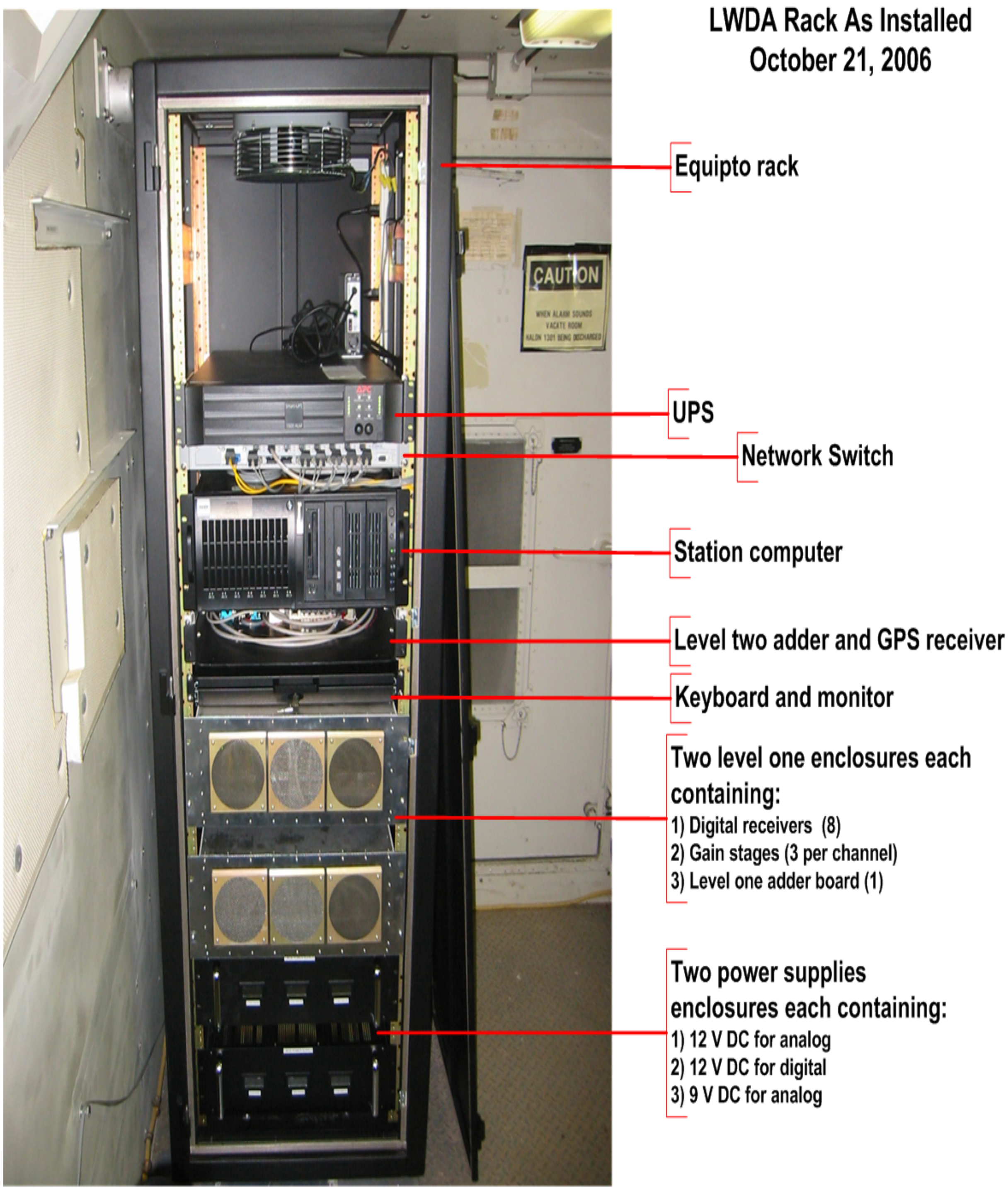

Figure 15: LWDA First Light - October 2006.

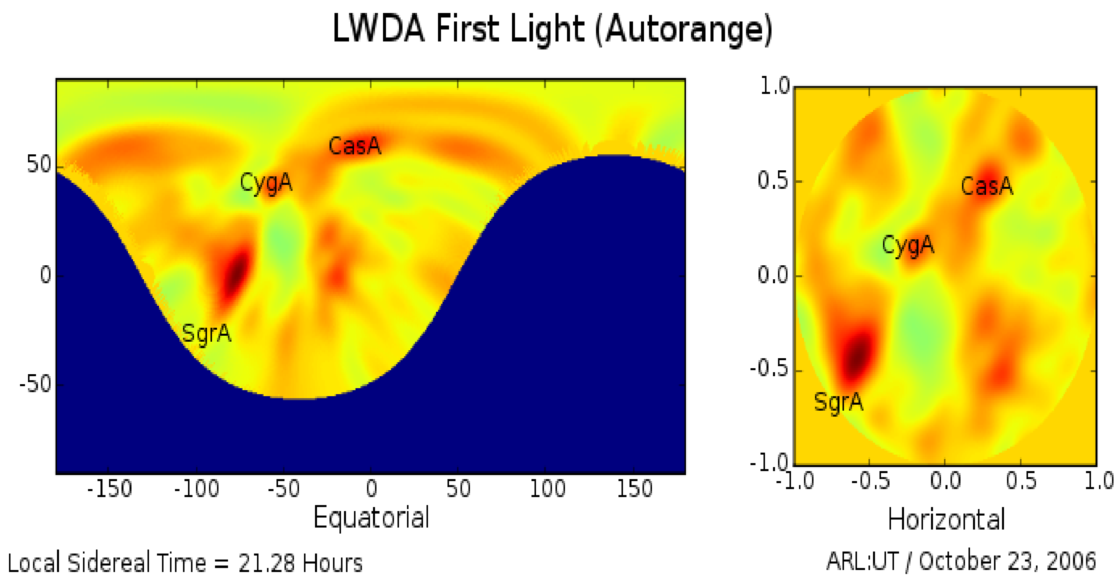

Figure 16: November 2006 image capturing a solar flare.