The UMass Experimental X-Band Radar (UMAXX): An Upgrade of the CASA MA-1 to Support Cross-Polarization Measurements

Jezabel Vilardell Sanchez

Follow this and additional works at: https://scholarworks.umass.edu/masters_theses_2

Part of the Electrical and Electronics Commons, Electromagnetics and Photonics Commons, and the Signal Processing Commons

Recommended Citation

This Open Access Thesis is brought to you for free and open access by the Dissertations and Theses at ScholarWorks@UMass Amherst. It has been accepted for inclusion in Masters Theses by an authorized administrator of ScholarWorks@UMass Amherst. For more information, please contact scholarworks@library.umass.edu.
THE UMASS EXPERIMENTAL X-BAND RADAR (UMAXX): AN UPGRADE OF THE CASA MA-1 RADAR TO SUPPORT CROSS-POLARIZATION MEASUREMENTS

A Thesis Presented

by

JEZABEL VILARDELL SÁNCHEZ

Submitted to the Graduate School of the University of Massachusetts Amherst in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE IN ELECTRICAL AND COMPUTER ENGINEERING

May 2019

Department of Electrical and Computer Engineering
THE UMASS EXPERIMENTAL X-BAND RADAR (UMAXX): AN UPGRADE OF THE CASA MA-1 RADAR TO SUPPORT CROSS-POLARIZATION MEASUREMENTS

A Thesis Presented

by

JEZABEL VILARDELL SÁNCHEZ

Approved as to style and content by:

__________________________
Stephen Frasier, Chair

__________________________
Paul Siqueira, Member

__________________________
Michael Zink, Member

__________________________
Robert W. Jackson, Acting Department Head
Electrical and Computer Engineering
A mi hermanito, sempre et porto amb mi.
ACKNOWLEDGMENTS

I would like to thank all the people that have accompanied me through this journey. First of all, I would like to thank my advisor Professor Stephen Frasier for all the knowledge, guidance, support and patience. I have learned so much from you and that has made me a better engineer so, for that I am grateful.

Thanks to Professor Paul Siqueira and Professor Michael Zink for being part of the committee.

Big thanks to Eric for creating and managing the amazing webpage for the radar data and for always making sure the fiber connection is operating perfectly.

A special thanks to the MIRSL people, Max, Will and Casey, for your assistance whenever needed and for installing the radar at the tower. Tough job!

I would also like to thank my office mates Mahsa and Mahdad for being the best offices buddies, quiet times were much appreciated.

Being away from home is always hard, I would not have been able to do this without my Amherst support system, my family away from home, Rossy, you have been here from the very beginning, you have been my rock, my friend, my sister, my partner in crime, there for the good and the bad times, for the endless nights at the library, and the great times away from the course work. I can’t express with words how much it meant to me to have met you here in Amherst. Rosario, you came in late to this party but you rapidly became part of my Amherst family, I am thankful for
all the wisdom that you have transmitted me every time I doubted myself, our long
gym sessions, our lunches at blue wall, and how to forget, our endless support to
the UMass Hockey team, going to the games with you and Rossy was always the
highlight of the week. Em, what can I say, also part of my Amherst family given
your amazing mom has adopted all of us now. I am so happy we are roommates, I
could not have asked for anyone better than you, thanks for being there whenever I
needed to disconnect and just have a good time. John and Amy, the best Raytheon
people in my class, I am so happy we met, you guys are amazing, it’s been a great
pleasure sharing those tough emag moments with you, Amy, or those endless nights
working on computer networks with you, John. Ruben, thank you for being here
without actually being physically here. Thank you for all the support and advise that
I always get from you. You know your reviews were, as always, the best. Solveig, my
”american mom”, you were the first person who showed me how great this country
is, and how many things it has to offer, I really value our relationship and I am so
thankful for you always checking up on me and for your support throughout this
journey, it is great to know that I will always have family here. Aida, my actual
oldest friend, I can not believe we met when we were two tiny toddlers and we are
now both research engineers here in the USA. Having you close, right there in New
Jersey, so technically close, it is great, sharing the hard research times with someone
in the same situation is priceless.

Last but definitely not least, a huge thanks to my actual family for their support and
love, specially to my mom, thanks for taking care of my baby and my tabby chicken
while I am away.

Gràcies.
ABSTRACT

THE UMASS EXPERIMENTAL X-BAND RADAR (UMAXX): AN UPGRADE OF THE CASA MA-1 RADAR TO SUPPORT CROSS-POLARIZATION MEASUREMENTS

MAY 2019

JEZABEL VILARDELL SÁNCHEZ
B.S., UNIVERSITAT POLITÈCNICA DE CATALUNYA
M.S.E.C.E., UNIVERSITY OF MASSACHUSETTS AMHERST
Directed by: Professor Stephen J. Frasier

Ground-based radars are instruments commonly used to surveil the precipitation climate of the surrounding areas. Weather events are characterized by collecting backscatter data and analyzing computed products such as the Reflectivity Factor, the Doppler Velocity, the Spectrum Width, the Differential Reflectivity, the Copolar Correlation Coefficient and the Differential Propagation Phase. The ability of the radar to transmit different polarization waves, such as horizontal and vertical polarization, allow for further analysis of the weather given the capability to perform...
co-polar and cross-polar measurements. The Linear Depolarization Ratio is another computed product based on the difference in power between the co-polarized and cross-polarized channel used to, for example, classify and characterize the ice crystal types. In order to obtain this variable, the radar has to be able to receive in both horizontal and vertical polarizations but transmit in either of them.

This thesis presents the modifications performed on the MA-1 prototype radar from the CASA (Collaborative Adaptive Sensing of the Atmosphere) Engineering Center to support cross-polarization measurement studies. The new radar, now known as UMass eXperimental X-Band (UMaXX) Radar is a dual-polarization radar able to transmit in both horizontal and vertical polarizations or single horizontal polarization and receive in both, making it able to compute LDR. The radar is installed atop of a tower located on Orchard Hill at the University of Massachusetts Amherst, where it operates at all times. This thesis also presents the analysis of sample weather phenomena captured with the radar, including rain events and the Hardwick tornado, recorded on October 23rd 2018 and registered by the weather services.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>x</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>x</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>x</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>x</td>
</tr>
<tr>
<td>1 INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2 BACKGROUND</td>
<td>5</td>
</tr>
<tr>
<td>2.1 Weather radar equation</td>
<td>5</td>
</tr>
<tr>
<td>2.2 Key measurement parameters and definitions</td>
<td>7</td>
</tr>
<tr>
<td>2.2.1 Reflectivity Factor</td>
<td>7</td>
</tr>
<tr>
<td>2.2.2 Differential Reflectivity</td>
<td>9</td>
</tr>
<tr>
<td>2.2.3 Doppler Velocity</td>
<td>10</td>
</tr>
<tr>
<td>2.2.4 Spectrum Width</td>
<td>11</td>
</tr>
<tr>
<td>2.2.5 Co-Polar Correlation Coefficient</td>
<td>12</td>
</tr>
<tr>
<td>2.2.6 Differential Propagation Phase</td>
<td>13</td>
</tr>
</tbody>
</table>
2.2.7 Linear Depolarization Ratio (LDR) ........................................... 14
2.3 Measurement schemes for polarimetry ........................................ 15

3 SYSTEM DESCRIPTION ................................................................. 17
3.1 System control ................................................................. 17
  3.1.1 Antenna ................................................................. 17
  3.1.2 Positioners ............................................................... 19
  3.1.3 Power distribution of the system ........................................ 22
    3.1.3.1 Power distribution within the radar enclosure ............. 23
    3.1.3.2 Downconverter custom boards ................................. 24
3.2 Signal generation & data acquisition ........................................ 27
  3.2.1 Differential board .................................................. 28
  3.2.2 Ettus N210 ............................................................. 31
    3.2.2.1 FPGA .............................................................. 33
    3.2.2.2 Ettus customization ........................................... 34
    3.2.2.3 Transmission & calibration triggers ......................... 36
    3.2.2.4 Standard mode ................................................ 38
    3.2.2.5 Staggered mode ............................................... 38
    3.2.2.6 Networking setup ............................................. 39
  3.2.3 Modulator & Magnetron .............................................. 40
  3.2.4 LDR modification .................................................... 45
    3.2.4.1 Electro-mechanical switch ................................ 49
3.3 Downconverter ............................................................... 51

4 SYSTEM CALIBRATION ............................................................... 55
4.1 Pointing accuracy ............................................................ 56


**LIST OF TABLES**

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 UMaXX Radar characteristics.</td>
<td>4</td>
</tr>
<tr>
<td>3.1 Antenna specifications.</td>
<td>18</td>
</tr>
<tr>
<td>3.2 Netbooter outlet assignment.</td>
<td>22</td>
</tr>
<tr>
<td>3.3 Used input and output pins of the differential board.</td>
<td>30</td>
</tr>
<tr>
<td>5.1 Ping test on the two available connections to the tower top computer. 100 packets of 64 bytes each.</td>
<td>63</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Picture of the radar tower located on Orchard Hill at the University of Massachusetts Amherst, Amherst MA.</td>
</tr>
<tr>
<td>3.1</td>
<td>Picture of the dish antenna mounted on the base frame on top of the azimuth pedestal.</td>
</tr>
<tr>
<td>3.2</td>
<td>Picture of the radar assembly.</td>
</tr>
<tr>
<td>3.3</td>
<td>Block diagram of the UMaXX DC power distribution.</td>
</tr>
<tr>
<td>3.4</td>
<td>Picture of the custom DC-power distribution boards and switch driver board.</td>
</tr>
<tr>
<td>3.5</td>
<td>Block diagram of the signal generation process of the radar transmitted signal and the control signals for the modulator board and components in the downconverter chain.</td>
</tr>
<tr>
<td>3.6</td>
<td>Block diagram of the signal acquisition process.</td>
</tr>
<tr>
<td>3.7</td>
<td>Pictures of the differential board’s first design from 2016(1) and latest version(2).</td>
</tr>
<tr>
<td>3.8</td>
<td>ETTUS USRP N210. Top right corner board is the BasicRX daughterboard. Top left corner is the BasicTX daughterboard. Board underneath is the motherboard.</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>3.9</td>
<td>Standard pulse mode waveform. (1) depicts the transmission triggers waveform. (2) shows the pin diode switch control signal.</td>
</tr>
<tr>
<td>3.10</td>
<td>Staggered pulse mode waveform. (1) depicts the transmission triggers waveform. (2) represents the pin diode control signal.</td>
</tr>
<tr>
<td>3.11</td>
<td>Picture of the Raytheon Company Mark II transmitter modulator.</td>
</tr>
<tr>
<td>3.12</td>
<td>Simplified block diagram of the pulse forming network and magnetron of the Raytheon Mark II modulator board.</td>
</tr>
<tr>
<td>3.13</td>
<td>Picture of the M1458 X-Band magnetron.</td>
</tr>
<tr>
<td>3.14</td>
<td>MA-1 waveguide duplexer structure.</td>
</tr>
<tr>
<td>3.15</td>
<td>UMaXX waveguide duplexer structure.</td>
</tr>
<tr>
<td>3.16</td>
<td>Electro-Mechanical switch installation. Side view.</td>
</tr>
<tr>
<td>3.17</td>
<td>Electro-mechanical switch.</td>
</tr>
<tr>
<td>3.18</td>
<td>Electro-mechanical switch positions.</td>
</tr>
<tr>
<td>3.19</td>
<td>Block diagram of the MA-1 radar downconverter.</td>
</tr>
<tr>
<td>3.20</td>
<td>Block diagram of the UMaXX downconverter.</td>
</tr>
<tr>
<td>3.21</td>
<td>Frequency map.</td>
</tr>
<tr>
<td>4.1</td>
<td>Median of the received power in the horizontal channel for all the azimuth positions.</td>
</tr>
<tr>
<td>4.2</td>
<td>Graphic of the sun tracking experiment on 9/4/2018.</td>
</tr>
<tr>
<td>4.3</td>
<td>Birdbath scan, at elevation 90 degrees, of the Differential Reflectivity $Z_{dr}$ in dB averaged over 360 degrees azimuth scans for a 30 minute period.</td>
</tr>
<tr>
<td>5.1</td>
<td>Block diagram of the network setting of UMaXX radar on Orchard Hill, University of Massachusetts Amherst.</td>
</tr>
<tr>
<td>5.2</td>
<td>Block diagram of UMaXX software architecture.</td>
</tr>
</tbody>
</table>
5.3 Screenshot of file ppi_scan_tilt.sh using vi reader. 67

6.1 Plan Position Indicator display of the horizontal Reflectivity Factor in dBZ at elevation 2 degrees. 69

6.2 Plan Position Indicator display of Doppler Velocity in horizontal polarization at elevation 2 degrees. 70

6.3 Plan Position Indicator plot of the Co-Polar Correlation Coefficient \( \rho_{hv} \) at elevation 2 degrees. 71

6.4 Collection of PPI (Plan Position Indicator) plot at 2 degrees of elevation. 73

6.5 Collection of PPI (Plan Position Indicator) plots at 8 degrees of elevation. 74

6.6 Plan Position Indicator plots of (a) the horizontal Reflectivity Factor \( Z_h \) and (b) the Linear Depolarization Ratio (LDR) at 2 degrees in elevation. 77

6.7 Averaged azimuth LDR (dB), blue line, and minimum LDR(dB) in azimuth, orange line, over range(m) for elevation 2 degrees. 78

6.8 Averaged azimuth SNR (dB), blue line, and SNR (dB) value at minimum LDR(dB) position in azimuth, orange line, over range(m) for elevation 2 degrees. 79

6.9 Comparison of SNR (dB) value at minimum LDR(dB) position in azimuth and additive inverse minimum LDR (dB) over range(m) for elevation 2 degrees. 79
CHAPTER 1
INTRODUCTION

Surveillance, observation and classification of different weather phenomena experienced in the atmosphere is of major importance given that it provides better understanding of weather conditions to help predict events that may be hazardous for human life and property. Many resources are employed to study aforesaid topics such as infrared cameras, satellite data, radiosondes or automated surface observing systems (ASOS). Doppler radars are one of the most commonly used systems to study the atmosphere because of the robustness and capability of microwaves to penetrate clouds and rain, making Doppler radars a trustworthy instrument to further examine weather phenomena. Furthermore, the introduction of dual-polarization radars has helped provide additional information that extends the measurements utility and accuracy.

The main goal of this project is to present a detailed characterization of an X-Band dual-polarization ground-based radar deployed at UMass Amherst. The purpose of this instrument is to monitor the weather of the surrounding areas and to serve as a reference for polarimetric studies with the prototype Low Power Radar (LPR), an X-Band dual-polarization phased array radar[1].

Phased array radars are a growing interest in the weather forecast field. However,
phased array scans produce polarization biases when scanning off boresight. Hypo-
thetically, these biases can be mathematically described and consequently corrected. The Microwave Remote Sensing Laboratory (MIRSL) at University of Massachusetts Amherst will conduct a series of studies to characterize the performance of dual-polarization phased array radars by using the data obtained with a dual-polarized doppler radar with a reflector antenna in comparison with data obtained with the LPR.

Figure 1.1: Picture of the radar tower located on Orchard Hill at the University of Massachusetts Amherst, Amherst MA.
The dual-polarization Doppler radar introduced in this project is called UMass eX-perimental X-Band (UMaXX) radar. It is based on an older version known as MA-1, a prototype radar designed by the Collaborative Adaptive Sensing of the Atmosphere (CASA) Engineering Research Center. This radar, using a parabolic reflector antenna, was reproduced into a 4-node networked weather system to improve the coverage of the lowest portion of the atmosphere, the troposphere.[2]. The new radar version, UMaXX, implemented by UMass Amherst MIRSL, recycles many components from the MA-1 radar, such as the radar enclosure, the antenna and antenna frame as well as many RF components. The new introduced changes include the Linear Depolarization Ratio (LDR) mode, a new pedestal, a re-designed downconverter and a new signal generation and acquisition system. These aim to support cross-polarization measurements and improve the overall performance of the radar. These modifications allow the radar to operate in two different transmission modes: the dual-polarization mode, transmitting and receiving in both horizontal and vertical polarizations, or the LDR mode, which only transmits a horizontally polarized wave but receives in both polarizations channels.

The UMaXX radar is installed atop of a tower located on Orchard Hill at the University of Massachusetts Amherst. Figure 1.1 shows a picture of the tower. The radar assembly is enclosed in the radome shown at the top platform of the tower.

UMaXX is an X-Band radar with center frequency 9.41 GHz that transmits a signal with peak power of 12kW at a duty cycle of 0.1% for a maximum pulse width of 1µs and it transmits pulses at either single or staggered sequences. The installed pedestal allows the radar to rotate 360 degrees in both clockwise and counter-clockwise directions in azimuth as well as 95 degrees in range in elevation going from -5 degrees to 90 degrees. The speed and motion patterns are programmable. The radar employs a 4-foot (diameter) dual polarization parabolic reflector with 1.80 degrees beamwidth.
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center frequency</td>
<td>9.41 GHz</td>
</tr>
<tr>
<td>Peak Power</td>
<td>12 kW</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>0.1%</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>5 MHz</td>
</tr>
<tr>
<td>Polarization</td>
<td>Dual H,V</td>
</tr>
<tr>
<td>Beamwidth</td>
<td>1.80 degrees</td>
</tr>
<tr>
<td>Scan range azimuth</td>
<td>0 - 360 degrees</td>
</tr>
<tr>
<td>Scan range elevation</td>
<td>−5 - 90 degrees</td>
</tr>
<tr>
<td>Waveform</td>
<td>Pulse</td>
</tr>
<tr>
<td>Sequences</td>
<td>Single, Dual PRT</td>
</tr>
</tbody>
</table>

Table 1.1: UMaXX Radar characteristics.

Table 1.1 shows a summary of the mentioned characteristics of the radar.

This document unfolds presenting a description in depth of the UMaXX radar. Chapter 2 describes the background of weather radar and defines the computed variables such as the Reflectivity Factor, the Doppler Velocity or the Co-polar Correlation Coefficient. Afterwards, divided in three different chapters, the characterization of the radar. Chapter 3, system description, which includes detailed information on the antenna, the positioners, the power distribution, signal generation and signal acquisition. Chapter 4, system calibration, which describes two calibration methods used to estimate the correct pointing position and the Differential Reflectivity $Z_{dr}$ calibration. Chapter 5, system set up, breaking down all information related to the system software, including the system operation and the network architecture. A final chapter includes the analysis of data obtained with the radar.
CHAPTER 2
BACKGROUND

This chapter reviews the radar theory starting with the weather radar equation and following up with the description of the computed weather radar moments as well as the Linear Depolarization Ratio and the description of the two transmitting modes of the radar.

2.1 Weather radar equation

The weather radar equation takes into account the contribution to the average echo power from each scatterer. The sample time average power at delay $\tau_s$, in terms of radar parameters and target cross section, may be expressed through the use of the radar equation (2.1) bible,

$$
\bar{P}(\tau_s) = \frac{P_t \cdot g^2 \cdot \lambda^2}{4\pi^3} \cdot \sum_i \frac{l_i^2 \cdot \sigma_{bi} \cdot f_i^4(\theta_i, \phi_i) \cdot |W_i|^2}{r_i^4}
$$

(2.1)

where $P_t$ is the transmitted power, $g$ is the gain of the antenna (squared for monostatic radars as the same antenna transmits and receives) and the wavelength $\lambda = c/f$, 

5
where $f$ represents the center frequency of the radar. Considering a volume $\Delta V = 1 m^3$ that contains many hydrometeors, the summation of their backscatter cross sections ($\sigma_b$) over the unit volume defines the target volume reflectivity or cross section per unit volume, $\eta \equiv (\Delta V)^{-1} \cdot \sum \sigma_{bi}$. The one-way propagation loss due to scatter and absorption, $l_i$, the normalized one-way power gain of radiation pattern, $f^2(\theta_i, \phi_i)$, the range to target, $r_i$ and the range weighting function, $W_i$ are assumed to not vary significantly over the volume.

Considering the small size of the hydrometeors compared to the spatial extent of the weighting function, (2.1) may be written as:

\[
\mathcal{P}(r_0) \simeq P_t \cdot g^2 \cdot \lambda^2 \cdot l^2 \cdot \eta \cdot \frac{1}{(4\pi)^3 \cdot r_0^2} \cdot \int_{\mathcal{r}} |W(r)|^2 \cdot dr \cdot \int_{0}^{\pi} \int_{0}^{2\pi} f^4(\theta, \phi) \sin \theta d\theta d\phi
\]  
(2.2)

Where $r_0$ is the vector range to the resolution volume.

Moreover, if the antenna pattern is circularly symmetric, the bandwidth is finite, the receiver frequency transfer function is Gaussian and the echo pulse is rectangular, (2.2) may be written as: (2.3).

\[
\mathcal{P}(r_0) = \frac{P_t \cdot g^2 \cdot \lambda^2 \cdot \eta(r_0)}{(4\pi)^3 r_0^2 \cdot l^2(r_0) \cdot l_r} \cdot \frac{\pi \theta_1^2}{8(ln2)} \cdot \frac{ct}{2}
\]  
(2.3)

Where $\theta_1$ is the one-way beamwidth between half-power points.
2.2 Key measurement parameters and definitions

This section lists and briefly describes the key measurement parameters that can be computed with UMaXX. Given the polarimetric characteristics of the radar, all the following moments can be obtained:

1. Reflectivity Factor \( (Z) \)
2. Differential Reflectivity \( (Z_{dr}) \)
3. Doppler Velocity \( (V_r) \)
4. Spectrum Width \( (\sigma_v) \)
5. Co-Polar Correlation Coefficient \( (\rho_{hv}) \)
6. Differential Propagation Phase \( (\phi_{dp}) \)

Furthermore, the radar can also compute the Linear Depolarization Ratio (LDR).

2.2.1 Reflectivity Factor

The Reflectivity Factor \( Z \) is a measure of the amount of transmitted power returned to the radar receiver. This product is a function of size (radar cross section), shape of the target (round, oblate, flat, etc), state (liquid, frozen, etc) and concentration (number of particles in a volume). It is common to assume Rayleigh scattering from spherical particles, as the diameter is smaller compared to the wavelength. In this case, the volume reflectivity is given by:
\[ \eta = \frac{\pi^5}{\lambda^4} |K_w|^2 \sum_i (d_i)^6 \] (2.4)

Where \( K_w \) is the dielectric factor of water, which is 0.93, and the summation represents the sixth moment of the drop diameter distribution and is given the name, Reflectivity Factor \( Z = \sum_i (d_i)^6 \).

\( Z \) is commonly expressed in units of \( \text{mm}^6/\text{m}^3 \), and it is usually specified on a decibel scale (dBZ) given the wide range of signal covered, such that 1\( \text{mm}^6/\text{m}^3 = 0\text{dBZ} \). The value of Reflectivity is directly proportional to the returned signal power. The standard values in clear air range between -20 to 20 dBZ. On the other hand, in precipitation, the values range from 5 to 75 dBZ. There are different ways of computing \( Z \)[4]. One simple formulation is:

\[
Z(\text{dBA}) = C + (\text{SNR} \cdot P_n)(\text{dBm}) + 20 \log(r(\text{km})) \] (2.5)

Where \( P(r_0) = \text{SNR} \cdot P_n \), \( r \) is the range in [km], \( P_n \) is an estimate of the noise floor, and \( C \) is the radar constant.

\[ P_n = k(T_A + T_{rec})B \] (2.6)
\( P_n \) is obtained with (2.6), where \( k = 1.38 \times 10^{-23} \) J/K, is the Boltzmann constant, \( B \) is the Bandwidth, \( T_A \) is the antenna radiometric temperature and \( T_{rec} \) is the receiver noise temperature \( T_{rec} = (F - 1)T_0 \) where \( F \) is the noise figure of the system and \( T_0 \) is the room temperature, 290K.

The radar constant \( C \) is:

\[
C = 10 \cdot \log_{10} \left( \frac{1024 \cdot \ln(2) \cdot \lambda^2 \cdot L_r}{\sqrt{P_t \cdot G^2 \cdot \theta \cdot \phi \cdot \pi^3 \cdot |K|^2}} \right) \tag{2.7}
\]

Where

- \( L_r = \) attenuation (usually a factor about 1.6).
- \( \theta = \) azimuth beamwidth (degrees).
- \( \phi = \) elevation beamwidth (degrees).
- \( c = \) velocity of light [m/s].
- \( \tau = \) radar pulse width [s].
- \( |K|^2 = \) dielectric factor (0.93 for rain, 0.2 for ice and snow).

### 2.2.2 Differential Reflectivity

The Differential Reflectivity \( (Z_{dr}) \), is the ratio of the horizontally to vertically polarized Reflectivity Factor:

\[
Z_{dr} = \frac{Z_h}{Z_v}, \tag{2.8}
\]

\[
Z_{dr}(dB) = Z_h(dBZ) - Z_v(dBZ)
\]

It is a measure of mean particle shape. Particularly useful for rain, due to the fact that raindrops are essentially spherical but as the size increases they morph into an
oblate shape as they fall through the atmosphere in presence of friction. It ranges from -7.9dB to 7.9dB[6]. Positive values indicate the target is larger horizontally than it is vertically and negative values indicate otherwise. Usually the \( Z_{dr} \) values are positive because falling raindrops are wider in the horizontal direction. \( Z_{dr} \) is biased toward larger particles. The larger the particle, the more it contributes to the Reflectivity Factor. The physical composition and/or the density of the target also affects the variable. However, it is independent of particle concentration given that it is a ratio of the backscattered power at H and V polarizations and it is also not affected by absolute miscalibration of the radar transmitter or receiver.

### 2.2.3 Doppler Velocity

The Doppler Velocity \( (V_r) \) is a function of the mean component of scatterer motion in the radial direction from the radar. It measures the radial speed of targets and thereby the motion of the wind relative to the observation point. Note that, motion perpendicular to the radar beam is not measurable. In weather radar applications, \( V_r \) is useful to determine the wind direction. Winds that go away from the radar, (outbound), have positive values, whereas winds going toward the radar, (inbound), have negative values.

\( V_r \) has a limited range of observable radial velocity, due to the discrete pulse rate. If it surpasses that range, it folds back such that a strong outbound velocity will appear as a strong inbound velocity within the observable range.

Considering the phase difference between the transmitted signal and the echo from a target at range \( R_0 \), allows the estimation of the mean radial Doppler Velocity of the particles within the resolution volume. Let \( s(t) = e^{j\omega t} \) be the transmitted signal and \( r(t) = e^{j\omega(t-\frac{2R}{c})} = e^{j\omega t} \cdot e^{-j\frac{2\pi}{c}R_0} \cdot e^{-j\frac{2\pi}{c}ut} \) the received signal where \( u \) is
the radial velocity of the backscatterer \( u = \frac{dR}{dt} \). \( r(t) \) includes a factor of 2 because the signal has traveled the range \( R_0 \) twice. Discarding any arbitrary phase terms \( r(t) = e^{j(\omega + \omega_D)t} \) where \( \omega_D = -2ku \) and \( k \) is the wavenumber \( k = \frac{2\pi}{\lambda} \), resulting in the so-called Doppler-frequency \( f_D = -\frac{2u}{\lambda} \).

Doppler shift is usually estimated from pulse-to-pulse change in the echo phase. Let \( V(kT_s) \) and \( V[(k + m)T_s] \) be successive echoes from a moving target, where \( T_s \) is the separation in time between them, also commonly understood as the Pulse Repetition Time (PRT). The change between these two echoes is obtained through the computation of the autocorrelation function

\[
R(mT_s) = E\{V^*(kT_s)V[(k + m)T_s]\} = \langle V^*(kT_s), V[(k + m)T_s]\rangle.
\]

For Doppler Velocity calculation purposes, only the phase of the autocorrelation is required.

\[
v_{rh} = \frac{-\lambda}{4\pi \frac{1}{PRF_h}} \cdot \angle (R_{hh}(1)) \tag{2.9}
\]

\[
v_{rv} = \frac{-\lambda}{4\pi \frac{1}{PRF_v}} \cdot \angle (R_{vv}(1)) \tag{2.10}
\]

Each polarization has its own formula to calculate \( V_r \). (2.9) and (2.10) show the formulas to calculate horizontal and vertical \( V_r \) respectively. \( R_{hh}(1) \) and \( R_{vv}(1) \) are the autocorrelations of the horizontally and vertically polarized echoes at lag 1.

### 2.2.4 Spectrum Width

Spectrum Width \( (\sigma_v) \) is a measure of the velocity dispersion, shear or turbulence within the resolution volume[6]. It has the potential to improve the interpretation of
the radar data in severe weather, specially in storm turbulence. This radar moment provides a measure of variability of the mean radial velocity estimated due to wind shear, turbulence and/or quality of the velocity samples. Nevertheless, $\sigma_v$ is not as commonly used as other radar moments as the values are easily corrupted (e.g., by overlaid echoes) thus less reliable.

\[
\sigma_{vh} = \frac{\lambda[-0.5 \cdot \ln \left( R_{hh}(1) / R_{hh}(0) \right)]^{1/2}}{4\pi \cdot PRT_h},
\]

\[
\sigma_{vv} = \frac{\lambda[-0.5 \cdot \ln \left( R_{vv}(1) / R_{vv}(0) \right)]^{1/2}}{4\pi \cdot PRT_v},
\]

(2.11)

The Spectrum Width is calculated (2.11) for the horizontal and vertical channel, respectively.

### 2.2.5 Co-Polar Correlation Coefficient

The Co-Polar Correlation Coefficient (CC or $\rho_{hv}$) measures how the diversity of each scatterer in the sampling volume contributes to the overall H and V polarizations[19]. The diversity includes any physical characteristic of the scatterers that affect the return signal (amplitude and phase). The Correlation Coefficient decreases when a large variety in types, shapes and/or orientation exist.

It is not affected by the diversity of sizes with the same target shape, particle concentration, radar miscalibrations, attenuations or beam blockage. However, its accuracy is degraded by the distance.

It is unitless and ranges from 0 to 1. Spherical particles produce $\rho_{hv} = 1.0$ given that they contribute equally to both polarizations. Meteorological echoes have values between 0.8 to 0.98. Pure rain produces $\rho_{hv} > 0.98$, however, wet hail tends to have
values under 0.95 and very large hail, values below 0.85. High values of $\rho_{hv}$ indicate similar target behavior in the region and low values convey dissimilar behavior. The quantity $\rho_{hv}$ is defined with[6]:

$$\rho_{hv} = \frac{<S_{vv}S_{hh}^*>}{(<|S_{hh}|^2><|S_{vv}|^2>)^{1/2}}$$

(2.12)

Where $<S_{hh}>$ and $<S_v>$ are the complex terms of the backscattering covariance matrix averaged over a collection of scatterers.

### 2.2.6 Differential Propagation Phase

The Differential Propagation Phase ($\phi_{dp}$) is the difference in phase shift between H and V polarizations. As the EM radiation propagates through the precipitation, it acquires a phase shift. When the precipitation is not spherical, this shift is different for H and V polarizations. This moment is proportional to the concentration number of particles and increases with the size of the target. A higher concentration of smaller raindrops would have larger $\phi_{dp}$ than a smaller concentration of larger raindrops. It is not affected by the presence of hail. Snow and ice cause a phase shift of nearly zero degrees. Furthermore, given that this variable is a phase measure, it is also not affected by attenuation, partial beam blockage, radar miscalibrations and it is not biased by noise.

All these characteristics make $\phi_{dp}$ a good variable for attenuation correction, quantitative precipitation estimation and radar Reflectivity calibration.
Equation 2.13 shows how to obtain $\phi_{dp}$. This is a good approximation for Rayleigh-Gans particles, such as raindrops[7].

$$\phi_{dp} = \phi_h - \phi_v \sim \frac{1}{2} \angle <S_{vv}S_{hh}^*>$$

(2.13)

### 2.2.7 Linear Depolarization Ratio (LDR)

Linear Depolarization Ratio (LDR) is the ratio of power received in the cross-polarized channel to that received in the co-polarized channel when linearly polarized signal is transmitted.

$$LDR(dB) = 10 \cdot \log_{10} \left( \frac{Z_{VH}}{Z_H} \right)$$

(2.14)

Where $Z_{VH}$ is the cross-polar return at horizontal polarization for a vertical polarization transmission[7]. For hydrometeors, $Z_{VH} = Z_{HV}$ using the BSA convention [8].

It is used for the classification and characterization of ice and canting rain hydrometeors. The ability to differentiate and identify ice crystal types helps to provide details about the atmospheric conditions.

It can also be helpful toward masking out ground clutter echoes.

Only oblate particles falling with their major axis at an angle yield cross-polar return. The LDR result is influenced by the particle symmetry. For example, when a vertically polarized incident electric field aligns with one axis, the polarized backscatter can not be horizontal so the LDR tends to infinity[6]. This can also be applied
to horizontally polarized incident electric field. 

When particles become more oblate or their refractive index increases, the LDR value rises. Hydrometeors with irregular shapes can also cause an LDR increase. Wet oblate particles have larger difference in polarisability thus the highest values of LDR, $-15 dB$, are associated with melting snowflakes. Melting hail and dry high density ice crystals range between $-20$ to $-26 dB$. On the other hand, depolarization by rain is generally small, it has values below $-30 dB$[18].

The antenna isolation does limit the overall value of LDR because the antenna feed or the radome can depolarize the transmitted and received signals. Moreover, the LDR is more sensitive to noise contamination than $Z_{dr}$ or $\rho_{hv}$ given that the cross-polar power is usually more than two orders of magnitude below the co-polar signal. Furthermore, at short wavelength, less than $10 cm$, the depolarization caused by propagation through precipitation corrupts the measurements[6].

## 2.3 Measurement schemes for polarimetry

Polarimetric measurements include analysis of both polarizations and their phase relationship.

Depending on the characteristics of a polarimetric radar, it can simultaneously transmit and receive (STSR) in horizontal(H) and vertical(V) polarization, alternately transmit and simultaneously receive(ATS) or alternate in both transmission and reception (ATAR).

In order to perform cross-polar measurements, the radar has to be capable of alternate transmission but reception in both HV simultaneously. One of the main constraints of phased array radars is the fact that in order to perform ATSR they
require multiple beamforming networks. Nonetheless, polarimetric radars with reflector antennas are able to do so with much less effort. However, MA-1 radar could only simultaneously transmit and receive. Consequently, the system needed an upgrade to be able to transmit one single polarization but receive in both. These added changes allow the radar to switch modes between STSR and single transmit simultaneous receive, making it possible to compute Linear Depolarization Ratio.
CHAPTER 3
SYSTEM DESCRIPTION

3.1 System control

This section provides information on the hardware of the radar. The section is divided in three main subsections: two subsections providing specifications on the radar antenna and the positioners that manage the azimuth and elevation position and a subsection focusing on the power distribution of the whole assembly.

3.1.1 Antenna

The antenna of the UMaXX radar is the same antenna as the MA-1 radar, a dual linear polarized X-Band prime-focus parabolic antenna. It has a diameter of 122cm (4-foot). The antenna is made of formed aluminum and steel reinforcements. Table 3.1 shows the antenna specifications provided by the manufacturer, Micro-Ant, Inc.

These type of antennas have an aperture efficiency of only $e_a \sim 0.5 - 0.6$ due to the beam blockage caused by the feed and its support[11].
<table>
<thead>
<tr>
<th>Frequency</th>
<th>9.41GHz ± 30MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarization</td>
<td>dual linear</td>
</tr>
<tr>
<td>Power handling</td>
<td>25kW peak, 25W average</td>
</tr>
<tr>
<td>VSWR</td>
<td>1.66 : 1</td>
</tr>
<tr>
<td>Port-to-port isolation</td>
<td>45dB</td>
</tr>
<tr>
<td>Gain</td>
<td>38.5dBi</td>
</tr>
<tr>
<td>Beamwidth</td>
<td>1.80 degrees</td>
</tr>
</tbody>
</table>

Table 3.1: Antenna specifications.

The antenna gain is directly proportional to the aperture efficiency and it also depends on the physical diameter of the reflecting surface as well as the operational wavelength. Following equation $D \sim \left( \frac{\pi d}{\lambda} \right)^2 e_a$, where $d$ is the diameter of the antenna (122cm) and $\lambda$ is the wavelength ($\lambda = c/f = 3 \cdot 10^8 / 9.41 \cdot 10^9 = 3.188\text{cm}$), the approximate value of the antenna gain is $G \approx 39dB$. The antenna specifications provided by the manufacturer give a measured value of 38.5dBi for the gain.

Figure 3.1 shows a picture of the front and back of the antenna mounted on the pedestal. Figure 3.1b highlights with red arrows the custom waveguides that forward the transmitted pulse to the antenna feed. These waveguides have to be perfectly aligned with the radar enclosure.
3.1.2 Positioners

The UMaXX radar has two different positioners, the azimuth and the elevation positioners. The former MA-1 radar assembly used a Kollmorgen SRP-1 for azimuth motion and an IDC motion servo driver controller with a worm gear drive that allows vertical pointing of the antenna. This was not the original elevation positioner as the first MA-1 radar prototype used a linear actuator instead of the worm gear drive, which limited the range for the elevation. The new system setup inherits only the elevation positioner with the worm gear drive.

The Kollmorgen positioner is substituted with an RPM PSI direct-drive azimuth rotator (model number RT-0507) and a controller (model number DE-1010). This rotator model allows remote control as well as status feedback through UDP/IP ports. The controller receives data commands on the UDP data port and acts on them. All information regarding the RPM can be found in the Digital Interface.
The azimuth positioner allows the radar to rotate 360 degrees continuously or in sectors, from 0 to 360 degrees clockwise or counterclockwise.

The elevation positioner allows the antenna to move from -5 degrees to 90 degrees in elevation. The worm gear drive allows the antenna to have a wide range in elevation compared to the original MA-1 prototype linear actuator, which permitted elevation from -5 degrees to 30 degrees.

Both the azimuth positioner and the elevation positioner are controlled via a computer. The control commands can either be set manually or scripted (Section 5.2).

Figure 3.2: Picture of the radar assembly. (1) shows a full view of the radar. (2) shows the connectors on the top of the azimuth pedestal. The tags denote the connectors.
Regarding the system connections to the radar control server, the pedestal provides AC power, ethernet and a serial data link through a slip ring assembly.

Figure 3.2 shows all the connection ports and power ports in the azimuth pedestal, as follows:


2. J2: Ethernet port for the azimuth positioner.


4. J4: Serial port for the top port that connects to the elevation positioner.

5. J5: Input power for the top power connector.


7. J7: Connector for the elevation positioner.

8. J8: Power for the radar enclosure and elevation positioner.
3.1.3 Power distribution of the system

The UMaXX radar has four main components that need to be powered: the radar transceiver, the azimuth positioner, the elevation positioner and a computer. Additionally, the system has three components that need to have an ongoing data connection with the main computer: the Ettus N210, the azimuth positioner and the elevation positioner.

This section breaks down how is the required power provided to the system and how are the positioners and the Ettus connected to the main computer.

<table>
<thead>
<tr>
<th>OUTLET</th>
<th>ASSIGNMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>wireless link box</td>
</tr>
<tr>
<td>2</td>
<td>Ethernet switch 1</td>
</tr>
<tr>
<td>3</td>
<td>PC monitor</td>
</tr>
<tr>
<td>4</td>
<td>Ethernet switch 2</td>
</tr>
<tr>
<td>5</td>
<td>EMPTY</td>
</tr>
<tr>
<td>6</td>
<td>J1 pedestal</td>
</tr>
<tr>
<td>7</td>
<td>EMPTY</td>
</tr>
<tr>
<td>8</td>
<td>J5 pedestal</td>
</tr>
</tbody>
</table>

Table 3.2: Netbooter outlet assignment.

All the instruments installed in the tower that require power are connected to a network controlled power switch, or netbooter, that itself is powered by an Uninterruptible Power Supply (UPS). Table 3.2 shows the netbooter outlet assignments.

The radar computer in the tower has two network access points: a wireless link with a public IP address and a high-speed(fiber optic) private link. Each of the links
have their own ethernet switch (ethernet switch 1 and 2, respectively). Moreover, the ethernet switch 2, that connects the computer in the tower with the high-speed link, also allocates all the radar ethernet connections, creating a Virtual LAN that includes, the radar control server, the Ettus N210 and the RPM pedestal (Section 5.1).

3.1.3.1 Power distribution within the radar enclosure

![Block diagram of the UMaXX DC power distribution.](image)

Figure 3.3: Block diagram of the UMaXX DC power distribution.

Figure 3.3 shows a block diagram of the DC power distribution of the radar enclosure. First, the power supply in the radar is powered through a power strip plugged in connector J8 in the azimuth positioner. The power supply has three different outputs, two 24V outputs and a 5V output. The 5V are used to power the Ettus N210 and the other 24V power the MKII modulator board and a custom 24V power
supply board.
The custom 24V power supply board has twelve power connectors that each provide 24V. This custom power board provides power to the LDR switch, the downconverter custom boards, that provide power and the required control signals to the downconverter components, and the DC-DC converter that powers the amplifiers in the IF stage.

3.1.3.2 Downconverter custom boards

There are three different types of downconverter custom boards being powered by the custom 24V power supply board:

1. Switch driver board.

2. ±5V flyback power board.

3. 15V Single-Ended Primary-Inductor Converter (SEPIC) power board.

Figure 3.4 shows a picture of the boards, respectively.

All these boards were custom made for the prior version of the radar, MA-1, by the CASA Engineering Research Center.

The switch driver board delivers the Transmit/Receive control signal, generated by the Ettus N210 to the downconverter pin-diode switches. There are three switches in the downconverter that need a control signal to operate: a switch that connects the noise source to the downconverter, and two switches for the horizontal and vertical channels that control the downconverter input.

As figure 3.4(1) shows, the switch driver board has four power connectors, one powers the board with 24V from the custom 24V power supply board, another connector inputs the control signal generated by the ettus N210 and then there are two connectors
Figure 3.4: Picture of the custom DC-power distribution boards and switch driver board. (1) Switch driver board. (2) $\pm 5V$ flyback power board. (3) $15V$ SEPIC power board.

that output the control signal to the switches. The two pin diode switches controlling the downconverter input get the control signal from the same switch driver board and the pin diode connecting the noise source to the downconverter gets the control signal from the other switch driver board.

The $\pm 5V$ flyback power board provides the required $\pm 5V$ to the pin diode switches. Furthermore, one of the flyback power boards also provides $+5V$ to the differential board. This type of board is a switch mode power supply. The flyback converter can be used to generate DC output from DC or AC input. It is basically a circuit that includes an input capacitor, a primary switch, usually a MOSFET, a coupled inductor, called flyback transformer, an output rectifier and an output capacitor. When the switch turns on, energy from the input is stored in the transformer. When enough energy is stored, the switch is turned off and the energy from the transformer is delivered to the output. Figure 3.4(2) shows a picture of one of the installed boards. There are three flyback power boards in total, one per switch. The board powering
the pin diode switch that connects the noise source to the downconverter also powers the differential board.

The SEPIC power board provides $+15V$ to the LNAs in the horizontal and vertical channels, the noise source and the Local Oscillator (LO). Each component has its own power board so there are four SEPIC power boards. The Single-Ended-Primery-Inductor (SEPIC) converter is a type of DC-DC converter that allows the output voltage to be greater than, less than or equal to, the input voltage. The output is controlled by the duty cycle of the control transistor. The topology of a SEPIC converter is similar to the flyback converter, however, in the SEPIC topology both the switch and the diode voltages are clamped by the capacitors, so there is a bit of ringing.
3.2 Signal generation & data acquisition

This section describes the signal generation and data acquisition process of the system. It is divided in 4 subsections, each of which describe an essential part of the signal generation or acquisition process.

Figure 3.5: Block diagram of the signal generation process of the radar transmitted signal and the control signals for the modulator board and components in the downconverter chain.

Figure 3.6: Block diagram of the signal acquisition process.

Figure 3.5 shows the signal generation process including all the components involved to generate the transmitted signal of the radar and any logic signal that the system may need to activate or control a component, such as chips, switches and so on. First, the data acquisition (DAQ) server enables the Ettus N210 so it can generate the transmission triggers using its programmable FPGA logic. The triggers are sent to the differential board whose main purpose is to transform the single-ended TTL
input signal into a differential TTL signal, given that the MK2 modulator requires such type of input in order to generate the transmitted signal of the radar. The output differential TTL signal of the differential board goes into the MK2 modulator board, which generates a high-voltage pulse to the magnetron. The magnetron radiates an RF pulse which travels through the waveguide duplexer structure into the antenna.

Other control signals, are generated by the Ettus N210, sent to the differential board for conversion from low voltage TTL (3.3V) to standard TTL (5V) and sent to the respective components.

The signal acquisition process, depicted in figure 3.6, starts when the antenna receives a signal, which is sent to the waveguide duplexer structure and to the downconverter, which transforms the RF signal into IF signal. Afterwards, it is sent to the Ettus N210 ADC, where the signal gets sampled and later on, stored in a file in the DAQ server. The following sections describe all the components involved in both processes.

### 3.2.1 Differential board

The differential board is a custom made board by the Microwave Remote Sensing Laboratory, designed to transform single-ended low voltage TTL (LVTTL) signals into either differential or standard TTL signals.

The design of this board is based on a preceding version from 2016. Figure 3.7 shows pictures of the 2016 version(1) and the installed version(2). This board requires 5V of supply voltage to operate. The two main components are a quadruple differential line driver (AM26LS31) from Texas Instruments and a hex non-inverting TTL buffer(HCF4010Y) from ST-microelectronics. They both require a supply voltage $V_{cc}$ of 5V.
The differential driver includes an enable function that offers the choice of an active-high or active-low enable input. The driver does not operate if the enable function is not active, therefore, the Ettus N210 generates a control signal for both active-high and active-low inputs. Figure 3.7 highlights the two pins used to send the enable signal with a purple box. However, before reaching the driver, both signals go through an XOR logic gate to ensure only the correct signal is reaching the differential driver and the buffer converter. This enable is necessary to prevent the Ettus from
independently triggering the magnetron. During power up, the Ettus toggles all the
digital I/O liners, and if permitted to propagate to the MK2 modulator board, it
would result in damage to the high-voltage portion of the modulator.
The differential driver converts an input signal into a ±5V differential signal.
In figure 3.7, the yellow box denote the input pins for the signals that require to
be differential TTL. The blue box shows the output pins with differential TTL.
The orange and red boxes denote the input and output of the single end signals,
respectively.

<table>
<thead>
<tr>
<th>INPUT PIN</th>
<th>VOLTAGE</th>
<th>OUTPUT PIN</th>
<th>VOLTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>3.3V</td>
<td>J9</td>
<td>+5V</td>
</tr>
<tr>
<td>J1</td>
<td>3.3V</td>
<td>J10</td>
<td>-5V</td>
</tr>
<tr>
<td>J5</td>
<td>3.3V</td>
<td>J17</td>
<td>5V</td>
</tr>
<tr>
<td>J6</td>
<td>3.3V</td>
<td>J18</td>
<td>5V</td>
</tr>
<tr>
<td>J7</td>
<td>3.3V</td>
<td>J20</td>
<td>5V</td>
</tr>
<tr>
<td>J8</td>
<td>3.3V</td>
<td>J19</td>
<td>5V</td>
</tr>
<tr>
<td>J39</td>
<td>3.3V</td>
<td>J21</td>
<td>5V</td>
</tr>
</tbody>
</table>

Table 3.3: Used input and output pins of the differential board.

Table 3.3 shows all used pins on the differential board. The differential TTL is only
needed for the transmission triggers. The rest of the signals are single ended.
3.2.2 Ettus N210

The Ettus N210 board, also known as Universal Software Radio Peripheral (USRP), is a software-defined radio (SDR). SDR is a radio communication system created in a way that substitutes components that traditionally were implemented with hardware, such as mixers, filters, modulators, detectors and so on, with software on an embedded system or a computer. It is designed and marketed by Ettus Research owned by National Instruments.

The USRP hardware are products designed to aid engineers design and implement radio systems in a flexible and quick way. Specifically, the N210 hardware is designed for applications requiring high RF performance, high bandwidth and high dynamic range processing capability. The Ettus N210 architecture includes:

1. Xilinx Spartan 3A-DSP 3400 FPGA (Field Programmable Gate Array).
2. 100 Megasample per second (MS/s) dual channel ADC (analog to digital converter RX daughterboard).
3. 400 MS/s digital to analog converter TX daughterboard.
4. Gigabit Ethernet connectivity to stream data to and from the DAQ (data acquisition) server.
5. 100MHz clock rate that can be locked to an external 10MHz reference.

The USRP N210 has a modular design, meaning the motherboard accepts daughterboards and other accessories to obtain different performances out of the same board. For this project, UMaXX uses the USRP motherboard as well as the BasicTX and BasicRX daughterboards.
Figure 3.8: ETTUS USRP N210. Top right corner board is the BasicRX daughterboard. Top left corner is the BasicTX daughterboard. Board underneath is the motherboard. The blue and red boxes highlight the BasicRX board ADC input channels A and B, respectively. The purple box shows the output pins for the control signals on the BasicTX board.

The BasicTX daughterboard provides transmission capabilities from 1 to 250 MHz. It uses two wideband transformers to match the dual DAC outputs of a USRP to 50Ω SMA connection. This daughterboard is essentially used to output the trigger signal and the control signals of the system.
Figure 3.8 shows the correspondent pins on the BasicTX board.

On the other hand, the BasicRX daughterboard provides direct access to the ADC inputs. It can accept real-mode signals from 1 to 250MHz. Wideband transformers couple each RF input to a single channel of the USRP’s ADC. The signals sampled by the ADC are shaped in the FPGA.

Figure 3.8 shows the ADC inputs. Channel A receives the horizontal polarization data and channel B, the vertical polarization data from the downconverter outputs. The Ettus N210 BasicRX board is configured to operate as an IF receiver. The IF analog receiver channels, channels A and B, digitize at 100MS/s rate and then digitally demodulates to baseband I and Q data, which later on is stored in a file which is sent to the DAQ server through an Ethernet connection.

It is very important to understand the different time domains. The ADC always runs at 100MS/s whereas the baseband section runs at a user-defined rate $fs_{rx}$. Nevertheless, all logic is run by the same 100MHz clock.

3.2.2.1 FPGA

The FPGA included in the USRP N2x0 series motherboard features:

- 2 receiver digital downconversion chains (RX DDC).
- 1 transmission digital upconverter chain (TX UDC).
- Timed commands.
- Timed sampling.
- 16-bit sample mode with up to 25MHz of RF bandwidth.
- 8-bit sample mode with up to 50MHz of RF bandwidth.
Every USRP device must have a loaded FPGA image and firmware. The USRP N2x0 series requires the user to load those manually onto the SD card. UMaXX FPGA image and firmware are files `usrp_n210_r4_fpga.bin` and `usrp_n210_fw.bin`, respectively. These files can be modified to change the configuration of the board and daughterboards. In order to do so, software (Xilinx ISE) is needed. A license is required to use the Xilinx tools.

### 3.2.2.2 Ettus customization

The UMaXX Ettus has a custom FPGA image that modifies the configuration of the digital I/O (input and output) pins on the daughterboards as well as the digital inputs into the data stream to receive the radar data.

There are 32 digital I/O pins available, `io_rx[15:0]`, on the BasicRX board and `io_tx[15:0]`, on the BasicTX board. The name only indicates the location of the headers on the daughterboards. The pins can be configured as LVCMOS (Low Voltage Complementary Metal Oxide Semiconductor) inputs or outputs. As default, these pins are configured so that if there is no logic element driving a pin, it is understood as an input, otherwise, it is an output.

UMaXX uses only pins on the BasicTX board (`io_tx[14:0]`) as output control signals and `io_tx[15]` as an input. Pins `io_tx[7:0]` are configured so that they can be set from the host code to active high(1) or low(0). However, pins `io_tx[8:15]` can only be modified by changing their configuration on the FPGA image.

The configured pins on the BasicTX board are defined as follows:

- `io_tx[2]` - OUTPUT: Modulator board enable. This pin sends a control signal to enable the high-voltage portion of the MK2 modulator board. When set to active high (1), HV is enabled. This enable can be used to suppress transmission
(i.e., operate the radar without transmitting a pulse).

- **io.tx[3]**-OUTPUT: Noise source switch controller. This pin sends the control signal for a pin-diode switch that connects the noise source to the downconverter. When the pin is set to high (1), the noise source is disabled, otherwise, 0V (switch on).

- **io.tx[4]**-OUTPUT: Differential board enable high. This pin sends one of the two required signals to enable the differential board output signals. When set to high (1), enables the differential board to send trigger signals to the modulator.

- **io.tx[5]**-OUTPUT: Differential board enable low. This pin sends the other required signal to enable the differential board output signals. For the differential board to work, this pin has to be set to low (0).

- **io.tx[6]** & **io.tx[7]**-OUTPUT: LDR mechanical switch controllers. These pins send the two required signals that control the LDR electro-mechanical waveguide switch. When set to high (1) the pins output a 3.3V constant signal, otherwise 0V.

- **io.tx[12]**-OUTPUT: Transmission triggers. This pin outputs the transmission triggers that are sent to the modulator to generate the transmitted signal of the radar. There are two types of transmission triggers, standard and staggered. The radar operator can choose which one to transmit and can modify some of its characteristics as well. However, the code sets some limitations.

- **io.tx[14]**-OUTPUT: Calibration path controller. This pin sends out the signal that controls the pin diode switch with two paths. One connects the antenna to the downconverter and the other, connecting the noise source path to the
downconverter. This pin is set on the FPGA image and can not be changed by the computer host. It follows the same pattern as the transmission triggers but with an offset.

• \texttt{io\_tx[15]}-INPUT: Transmission triggers to receiver board. This pin behaves as an input pin. It receives the transmission triggers sent by pin \texttt{io\_tx[12]} to synchronize the BasicRX board.

### 3.2.2.3 Transmission & calibration triggers

The Ettus N210 is in charge of generating all the transmission triggers and the control signal for the calibration pin diode switch that connects the radar antenna to the downconverter. This control signal is the same as the transmission triggers with a delay offset, as illustrated in figure 3.9.

The radar has two different pulse modes available, standard mode and staggered mode.

Figure 3.9: Standard pulse mode waveform. (1) depicts the transmission triggers waveform. (2) shows the pin diode switch control signal. $\tau$ denotes the pulsewidth of the rectangular pulse. PRT is the pulse repetition time. The green dashed line represents the offset in (2) compared to (1).
Figure 3.10: Staggered pulse mode waveform. (1) depicts the transmission triggers waveform. (2) represents the pin diode control signal. $\tau$ denotes the pulsewidth of the rectangular pulse. PRT1, PRT2 and PRT3 are the pulse repetition times between all pulses. T1 and T2 are the pulse repetition times between pulses in the same pulse pair. Pulses in red denote first pulse pair. Pulses in blue denote second pulse pair. The green dashed line represents the offset in (2) compared to (1).

Figures 3.9 and 3.10 show a representation of the standard pulse mode and the staggered pulse mode, respectively. Each figure includes the waveform of the transmission trigger (1) and the control signal for the pin diode switch (2). The difference between waveforms is the control signal’s offset relative to the transmission trigger. The purpose of this offset is to collect a few samples of the transmitted pulse of the radar before collecting the received data from the antenna.
3.2.2.4 Standard mode

The standard pulse mode is a waveform with a rectangular pulse signal, pulsewidth \( \tau \), and pulse repetition time PRT. These values are set in the code that handles the Ettus N210. The radar operator can change the pulsewidth value in `xdata-long.inp` file (section 5.2). The predetermined values for the standard mode pulse scheme are \( \tau = 1000\,\text{ns}(\text{nanoseconds}) \), \( PRT = 1\,\text{ms}(\text{milliseconds}) \) and \( offset = 200\,\text{ns}(\text{nanoseconds}) \).

3.2.2.5 Staggered mode

Staggered PRT is a radar transmission technique developed to resolve the range and velocity ambiguities encountered during observation of weather phenomena[9]. Implementing staggered PRT results in an increase of the unambiguous range and velocity compared to the standard, non dual-PRT, pulse scheme[3]. The maximum unambiguous velocity given by the two PRTs are \( v_{a1} = \lambda/4T_1 \) and \( v_{a2} = \lambda/4T_2 \), PRT1 and PRT2, respectively. Where \( \lambda \) is the radar wavelength. The maximum unambiguous range for T1 is \( r_{a1} = cT_1/2 \) and \( r_{a2} = cT_2/2 \) for T2. Where \( c \) is the speed of light. By themselves, the range-velocity product satisfies equation \( r_a v_a = c\lambda/8 \), therefore, with dual PRT this equation can be expresses as (3.1).

\[
r_{a1}v_{a1} = r_{a2}v_{a2} = c\lambda/8 \quad (3.1)
\]

Generally, it is assumed that \( T_2 > T_1 \), hence the range-velocity product for staggered PRT equals to \( r_{a1}v_{a1} = c\lambda/8 \).

In terms of velocity, in staggered PRT mode, there are two velocity estimates, \( \hat{v}_1 \) and \( \hat{v}_2 \) from echoes samples spaced by \( T_1 \) and \( T_2 \), respectively. Each single velocity
estimate is computed from the argument of the autocovariance estimate such as

\[ v_1 = -\lambda/4T_1 \angle (\hat{R}_1) \text{ and } v_2 = -\lambda/4T_2 \angle (\hat{R}_2). \]

Consequently, the estimated velocity for a dual PRT scheme is obtained from the phase difference of the two autocovariances \( \hat{R}_1 \) and \( \hat{R}_2 \) at lag \( T_1 \) and \( T_2 \), respectively.

\[ \hat{v} = \frac{\lambda}{4\pi(T_2 - T_1)} \angle \left( \frac{\hat{R}_1}{\hat{R}_2} \right) \]  

From equation (3.2), the velocity estimate becomes ambiguous when the phase difference between autocovariances falls outside the \([-\pi, \pi]\) interval. Accordingly, the unambiguous velocity for the staggered PRT scheme becomes \( \hat{v} = \pm \lambda/4(T_2 - T_1) \).

For the staggered pulse mode, the waveform is also a rectangular pulse, however, there are two different pulse pairs with pulse repetition times, \( T_1 \) and \( T_2 \). The predetermined values for the PRTs between all pulses are \( PRT_1 = 416.67 \mu s(\text{microseconds}) \), \( PRT_2 = 625 \mu s(\text{microseconds}) \) and \( PRT_3 = 1958 \mu s(\text{microseconds}) \), which are a pulse repetition time per pulse pair of \( T_1 = PRT_1 + PRT_2 = 1041.67 \mu s(\text{microseconds}) \) and \( T_2 = PRT_2 + PRT_3 = 2583 \mu s(\text{microseconds}) \). Both pulsewidth and offset are the same as the standard mode.

### 3.2.2.6 Networking setup

The Ettus is connected to the host computer through an Ethernet port (eth1) thus it needs to be configured properly.

This project only uses one Ettus N210, however the USRP allows multiple device configuration setup.

For single device configuration, the USRP must have a unique IPv4 address on the host computer so it can be identified through it.
In this case, the IP address is set to 192.168.10.2. In order to check if the device has been booted and connected correctly, the user can ping it, if everything is set up, the device will reply to ICMP (Internet Control Message Protocol) echo requests.

### 3.2.3 Modulator & Magnetron

UMaXX radar uses a magnetron to generate the transmitted signal. The magnetron is excited by a high-voltage pulse produced by a modulator board. The modulator board is a Raytheon Company product called MK II transmitter modulator. This board is in charge of generating the RF signal at the proper frequency and power level based on a received trigger signal. It has two different types of transmitters for frequency bands: X-Band and S-Band. The modulator has filament jumpers to set the board accordingly.

Modulators can be either low power or high power. The Mark II modulator is high power. Among high power modulators, there are three methods that can be used to implement them[10]. These are: 1) line type modulator using pulse forming networks (PFNs), 2) magnetic modulators, and 3) switching modulators. The Raytheon MK II modulator is of the first type.

Figure 3.11 shows a picture of the Raytheon modulator.

High power modulators are generally bulky and heavy because of the required capability to handle large instantaneous power.

The operation of high power modulators is based on an energy element that is charged up by a power supply and then discharged during the transmission of the RF pulse. Discharge can be partial, as in switch modulators, or complete, as in PFN modulators.
Figure 3.11: Picture of the Raytheon Company Mark II transmitter modulator. The yellow box highlights two chip sockets subsequently added to ease the process of substituting damaged hardware. The cyan box marks the spot where the MOSFET housing sits, underneath the board. The purple box shows the capacitive storage elements.
The storage element, which can either be capacitive, inductive, or a combination of both, is reloaded during the inter-pulse intervals. Figure 3.11 highlights the capacitive units with a purple box.

PFN modulators perform complete discharge of the charged up element, however, this characteristic causes the pulse width to be of a fixed value. In order to achieve some degree of pulse width flexibility, the modulator board integrates switches to allow partial discharge. MOSFET switch modules support a much more flexible modulator configuration.

Figure 3.11 highlights where the MOSFET housing sits underneath the board. The yellow box highlighting two driver sockets shows a modification on the purchased board. Those two drivers are non-inverting power drivers and they are easily damaged, thus having driver sockets instead of the drivers directly welded on the board makes the substitution process of the defective hardware much easier. The drivers require heat sinks which are purchased separately as well.

Figure 3.12: Simplified block diagram of the pulse forming network and magnetron of the Raytheon Mark II modulator board.
Figure 3.12 shows a simplified block diagram of the PFN on the modulator board. The magnetron connects to the PFN through the anode and cathode cables, labeled as E3(green) and E4(yellow), respectively. The capacitors named $HVC1$ and $HVC3$, are the ones highlighted with the purple box in figure 3.11. The MOSFET is denoted as $FET\; Q13$.

The magnetron is an M1458 X-band magnetron designed for radar systems with a range frequency between 9380 and 9440 MHz. The peak power output is 12 kW.

In essence, the magnetron is a high-power vacuum tube that works as an oscillator. It generates microwaves using the interaction between a stream of electrons and a magnetic field while passing through a series of open metal cavities. The starting phase of each generated pulse is random, thus phase sampling is required to establish coherent on-receive operation for both horizontal and vertical channels[7]. On each pulse, the measured phase of the magnetron pulse sets the phase, to achieve a coherent receive signal[4].

![M1458 X-Band Magnetron](image)

Figure 3.13: Picture of the M1458 X-Band magnetron.
The M1458 magnetron is a fixed tune magnetron with waveguide output, forced air cooling, with a permanent integral magnet and a wire lead input.

For waveguide magnetrons, the center frequency may vary with temperature. The center frequency drifts downwards as the magnetron heats up and the resonant cavity expands, hence the downconverter oscillator must be tuned in accordance. Usually, after continuous operation, the magnetron reaches a stable center frequency, so the oscillator in the downconverter may be tuned to that frequency.
3.2.4 LDR modification

When the radar is transmitting, the TX signal generated by the magnetron, travels through a waveguide duplexer structure before reaching the antenna.
Using a waveguide structure to feed the antenna is useful because waveguides are low loss RF components capable of handling high power signals, with high isolation.

Figure 3.14: MA-1 waveguide duplexer structure.
The former radar configuration, had a waveguide duplexer structure with two identical branches, as shown in figure 3.14, one for the horizontal polarization (bottom), one for the vertical polarization (top).

From left to right, the magnetron connects to an H-type T junction, which divides the propagating wave to vertical(V) and horizontal(H) polarizations. Each polarization has half the power. Each branch includes a cross-guide directional coupler to sample the transmitted signal (to perform cohere on receive). The SMA port of the coupler connects to the downconverter. Next, a circulator, configured as an isolator, it protects the magnetron from any reflected signals that might have accessed the transmission path coming from the antenna. Another circulator guides the TX wave out to the antenna and any incoming RX wave into a limiter followed by a SMA female waveguide adapter that connects to the downconverter.

This structure allowed the former configuration of the radar to transmit and receive simultaneously in both horizontal and vertical polarizations (STSR). However, the new design required the ability to switch between simultaneous transmission of H and V polarization and transmission of a single polarization.

Figure 3.15 shows the new layout of the waveguide duplexer structure. The main difference is the addition of an electro-mechanical switch on the vertical polarization branch. This way, UMaXX can transmit in either both H and V polarizations simultaneously or just H polarization. In the former case, the electro-mechanical switch passes the V polarization transmission signal, and in the latter case, it directs it to a load. It is not possible to transmit in just vertical polarization because of the physical constraints imposed by the radar enclosure. It was not feasible to install a second electro-mechanical switch on the horizontal branch or to rearrange the whole structure.
Not only the radar enclosure limited the design but also the waveguide sections that connect the waveguide duplexer structure to the antenna. These sections were custom designed rigid waveguides, so the output of the duplexer structure had to maintain its former position. Another added change is the directional coupler on the V branch. In order to fit the electro-mechanical switch, the directional coupler was substituted for a shorter one and two additional spacers placed at the input and output of the H-plane waveguide bend that connects the T junction to the V-channel branch.
Furthermore, the aluminum plates enclosing the waveguide structure had to be altered to fit the new design. Two windows were cut in both upper and lower mounting plates. Figure 3.16 shows how the mechanical switch fits into the radar enclosure, from a side view. In order to save space, the connection between the electro-mechanical switch and the circulator to the antenna goes underneath the waveguide level through an E-plane bend and the load connected to the mechanical switch goes through the top aluminum plate.

This new design wastes half of the transmitted signal power in the LDR mode. But, this tradeoff was deemed acceptable given the complexity required to retain all the transmitted power.
3.2.4.1 Electro-mechanical switch

The electro-mechanical switch used to achieve LDR mode is a WR-90 waveguide electromechanical relay latching switch from Fairview Microwave.

Figure 3.17: Electro-mechanical switch.

Figure 3.17 shows a picture of the electro-mechanical switch, which has 4 operational ports, one shorted with a removable plate. It features latching TTL logic, and it is configured for single pole double throw (SPDT) operation. Moreover, the motor drive housing supports a viewable position indicator window and a cover that can be removed for manual override access (red indicator at the top of the black cylinder). The switch requires 24Vdc nominal bias voltage and two logic commands to manage the switch positions. It has a quick connect circular 10 pin MILSPEC DC bias connector with mate that provides the required voltage, the logic commands and a continuity circuit that supervises the current position, however, this resource is not being used in this application.
The electro-mechanical switch has two different positions, as figure 3.18 shows. Position 1 connects port 1 with port 2 and port 3, which is shorted, with port 4. This position allows only the horizontal polarization to be transmitted as the vertically polarized signal gets redirected into a load connected to port 2.

On the other hand, position 2 connects port 1 with port 4 and port 2 with port 3. This position allows both polarizations to propagate.

In order to switch positions the Ettus N210 is in charge of sending the control signal. The 10 pin connector has two pins dedicated to the position control, pins D and F. The Ettus sends 5\(V\) continuous signal to pin D and 0\(V\) to pin F to put the electro-mechanical switch on position 1. Otherwise, the Ettus sends 5\(V\) to pin F and 0\(V\) to pin D to shift to position 2.
3.3 Downconverter

The downconverter is an assembly of components required to convert microwave signals to an intermediate frequency (IF) range for further processing\[7\]. This section describes the downconverter structure of UMaXX and compares the new design to the prior configuration, MA-1.

The MA-1 radar, had a dual-channel analog receiver composed of a low noise-figure connectorized front end, followed by a mixed-signal surface-mount circuit board that integrated two downconverting stages and an Automatic Gain Control (AGC) board. Figure 3.19 shows a block diagram of the analog downconverter.

Figure 3.19: Block diagram of the MA-1 radar downconverter.
Much of the functionality of the custom AGC and double downconversion was unused in practice and it required an additional control computer to operate, hence to simply the design, a single downconversion scheme is now employed.

UMaXX, implements a single downconversion scheme with image-reject mixers and an IF amplification stage. This design mirrors that of the X-Pol Mobile Doppler Radar. Figure 3.20 shows the new structure.

The new structure has two operational modes, dictated by the pin diode switch positions. One path connects the antenna to the downconverter. The antenna is connected to the rigid waveguide structure and then connects to the downconverter with a waveguide to SMA adapter. The other path, connects the noise source to the
downconverter, for calibration purposes. The downconverter has two symmetrical branches, one per each polarization, horizontal and vertical. The previous configuration, as figure 3.19 shows, the directional coupler was installed in a separate path from the downconverter, so the sampled transmitted signal would get amplified and filtered by the Low Noise Amplifier (LNA) and the Band Pass Filter (BPF) of the downconverter. The new configuration installs the directional coupler after the LNA, with 18dB gain, and the BPF, 9.41GHz center frequency and Bandwidth 5MHz, which avoids the unnecessary amplification and filtering of the sampled transmitted signal that the previous configuration performed. The mixer after the LNA and the BPF changes the signal frequency from RF to IF.

The frequency change is achieved by mixing the RF signal, center frequency 9.41GHz and the Local Oscillator (LO), center frequency 9.35GHz. The new IF frequency is 60MHz, $f_{IF} = |f_{LO} - f_{RF}|$. Figure 3.21 shows the frequency map of such frequency change.
Afterwards, the signal travels to an amplification stage with a $25dB$ amplifier followed by a $15dB$ attenuator, a $27dB$ amplifier and a BPF center frequency $60MHz$ and Bandwidth $4.8MHz$. The decision to install such amplifiers and attenuators in the IF stage was made after testing multiple ranges of amplification in order to reach a desired received signal power at the ADC.

Overall, the downconverter design amplifies the received signal $55dB$, which is the resulting sum of the LNA, $18dB$, and the IF stage, $37dB$.

The sampled transmitted signal also gets amplified by the downconverter. The magnetron generate a $12.5kW$ signal, which gets equally split into two, thus $6.25kW$ of transmitted power per each polarization channel. This signal gets sampled by the directional coupler in the downconverter and it is attenuated by $40dB$, which is the resulting sum of the directional coupler attenuation and the $30dB$ attenuator connected at the output of the coupler. Afterwards, in the IF stage the signal gets amplified $37dB$.

Given the frequency at which the radar works, the attenuation caused by the cables that connect the components in the downconverter is negligible.
CHAPTER 4
SYSTEM CALIBRATION

This chapter introduces two procedures of calibration that have been followed in this project to analyze the accuracy of the radar.

The first section presents the method used to evaluate the accuracy of the radar positioning. This analysis is done using the sun radiation.

The second section explores a $Z_{dr}$ calibration technique which uses the new integrated ability to point the radar antenna upwards 90 degrees in elevation and scanning 360 degrees in azimuth.
4.1 Pointing accuracy

Accurate positioning of the radar while collecting data is of importance for georeferencing and comparison of the acquired data with other sources. Given that the azimuth and elevation positions are relative to the angles set by the positioners, the radar needs a reference to set the angles at a proper position and correct any errors caused by the positioners. There are multiple ways of calculating the correct position of the radar, such as sun tracking. This method uses the radiation and known position of the sun throughout a day to calculate the correct position of the radar. The sun is a source of microwave radiation which can be detected by a radar and used for accurate pointing position[12]. Knowing these two factors, the corresponding deviation of azimuth and elevation position can be computed.

During the acquisition process, the radar is set up in receive mode only, which makes it easier to detect the sun radiation[13].

The radar is set up to perform a Plan Position Indicator (PPI) scan for each unit angle between 0 and 90 degrees in elevation, repetitively. Afterwards, the computations are based on the received power, which is noise, given that the radar is not transmitting.

Note that, the information on the sun position is obtained using available tools on the internet that provide the solar azimuth and elevation position based on the point of observation.

The data to compute the position accuracy is obtained in a clear sky day. The goal is to analyze the received power and detect the sun signature in order to obtain the position and the time when the antenna was facing the sun.
Figure 4.1: Median of the received power in the horizontal channel for all the azimuth positions. The X axis and Y axis represent the azimuth and elevation position of the antenna, respectively. The spikes of power denote position where the radar antenna directly faces the sun.

Figure 4.1 shows the received power in the horizontal channel in a 3D plot where the azimuth and elevation position are represented by the X and Y axis, respectively. It is easy to spot the positions where the antenna is facing the sun as the received power is substantially higher. The measured position is obtained by taking the median of the received power in the horizontal channel at each different azimuth position for all the elevation position. Given a set threshold of the received power, the program is able to sort out all the positions, and time of the positions, where the radar was facing the sun.

Figure 4.2 shows the result of the pointing accuracy experiment, showing a compar-
Figure 4.2: Graphic of the sun tracking experiment on 9/4/2018. It represents the position of the sun in azimuth (horizontal axis) and elevation (vertical axis). The solid line shows the measured position of the sun with the radar. The dotted line represents the true position of the sun provided by NOAA Sun Calculator.

Comparison of the measured position of the sun relative to the positioners position and the true position of the sun, data provided by a trusted third party source, the Earth System Research Laboratory, Global Monitoring Division, NOAA Solar Calculator. The azimuth has a 0.85 degrees of deviation relative to the true position and the elevation has a more noticeable deviation of 2.17 degrees. These corrections are added to the offsets of the positioners.
4.2 Differential Reflectivity calibration

Dual-polarization radars are commonly used in weather monitoring motivated by the improved algorithms for better classification of the meteorological targets[15]. It is important to assure the quality of the radar input moments such as the horizontal Reflectivity Factor $Z_h$, the Differential Reflectivity $Z_{dr}$, the Cross-Correlation Coefficient $\rho_{hv}$, and so on.

A known method used to calibrate the Differential Reflectivity $Z_{dr}$ is the birdbath scan. Generally, a birdbath scan is employed to evaluate the $Z_{dr}$ offset[16]. It is assumed the $Z_{dr}$ is zero when looking at falling raindrops from below. This method collects data at 90 degrees in elevation for 360 degrees of rotating azimuth. At a given range, the radar moments are averaged over all azimuth angles, thus only evaluating a certain range bin in the antenna far field within the Troposphere, where most of the weather phenomena occur, that goes up to 10-15 km.

Figure 4.3 shows the resulting averaged $Z_{dr}$ of 360 degrees azimuth scans of a birdbath scan over a period of time. The Y axis represents the height in meters, even though the radar has a maximum range of 60km, the main focus of this experiment is the region where weather phenomena can be observed, thus the plot only shows the $Z_{dr}$ measured in the Troposphere.

The event recorded on September 25th 2018 consisted of light rain. It is observable that most areas present positive values around 1dB. If the radar was properly calibrated the expected value for light rain observed from a zenith position is 0dB as the raindrops are understood to be circularly shaped when observed from that point of view, hence they contribute equally to the Reflectivity Factor of the horizontal and vertical polarizations.
Figure 4.3: Birdbath scan, at elevation 90 degrees, of the Differential Reflectivity $Z_{dr}$ in dB averaged over 360 degrees azimuth scans for a 30 minute period. The X and Y axes represent the time in UTC and the height in meters, respectively. The $Z_{dr}$ ranges between -1.5 - 1.5 dB. The constant yellow line at 3500m is the bright band signature.

The observed values in the plot, indicate a miscalibration where the horizontal polarization has greater gain than the vertical one, given that the $Z_{dr}$, in logarithmic scale, is the difference between the $Z_h$ and $Z_v$. It is also noticeable at approximately 3500m the signature of the bright band, which is the radar signature of the melting layer where snow melts into rain. As the ice crystals fall toward the Earth, they encounter warmer temperatures at lower heights, as the temperature passes the 0°C threshold, the particles begin to melt from surface inward and finally collapse into raindrops. Given this analysis, it can be concluded that the radar was not accurately calibrated for $Z_{dr}$ as the horizontal channel presents more gain that the vertical channel. This can be corrected using an offset parameter to even out the difference between polarizations in the data processing stage. A calibration procedure has to be performed periodically to make sure the offset parameter is well adjusted.
CHAPTER 5
SYSTEM SOFTWARE

This chapter provides information on everything related to the radar network setting and the software designed to operate the radar. Section 5.1 describes the network which the radar is connected to and how to access the computer that runs the radar. Section 5.2 briefly describes the software of the system.

5.1 Network architecture

The UMaXX radar is installed at the top of a rectangular steel frame tower on Orchard Hill at the University of Massachusetts Amherst. The radar’s purpose is to monitor the weather uninterruptedly and/or assist the LPR radar (see Chapter 1), thus there is a need to have constant communication with the computer that runs the radar from the tower top, not only to control it but to obtain the generated output files.

Figure 5.1 shows a simplified block diagram of the network that connects to the radar tower and the speed of the existing links between terminals.

Essentially, the block diagram is divided in three different sections: the tower top, the outdoor rack pica8 and LGRC A110 pica8.
Figure 5.1: Block diagram of the network setting of UMaXX radar on Orchard Hill, University of Massachusetts Amherst. The numbers between terminals denote the speed link.

There are two routes to access the radar computer. The radar operator can either log in through a public wireless link with public IP address or through a fiber link installed and managed by the CASA Engineering Research Center. Connecting through the wireless is simpler as it directly connects to the computer that manages the radar from any point of the world with internet access. However, the connection is slower. On the other hand, connecting to the tower top through the fiber link gives a much faster connection but is only available if the radar operator has access to the emmy9 CASA server. That is, in order to connect to the tower top computer through the fiber link, the radar operator has to first, log in to emmy9 server and then log in to the radar control server at the tower top.

Table 5.1 shows the statistics obtained using the network utility program `ping`, of
the two available links to the tower. The return value of ping is the round trip time (RTT), and the tool returns a minimum RTT, an average RTT over all the packets sent, a maximum RTT and a moving standard deviation RTT. As expected, the fiber

<table>
<thead>
<tr>
<th>CONNECTION</th>
<th>RTT min</th>
<th>RTT avg</th>
<th>RTT max</th>
<th>RTT mdev</th>
</tr>
</thead>
<tbody>
<tr>
<td>wireless link</td>
<td>1.896 ms</td>
<td>2.992 ms</td>
<td>28.649 ms</td>
<td>3.457 ms</td>
</tr>
<tr>
<td>fiber link</td>
<td>0.147 ms</td>
<td>0.702 ms</td>
<td>7.309 ms</td>
<td>1.162 ms</td>
</tr>
</tbody>
</table>

Table 5.1: Ping test on the two available connections to the tower top computer. 100 packets of 64 bytes each.

link is more than 400 times faster, on average, than the wireless link. Hence, it is the preferred path, specially for the output data downloads, as the radar outputs approximately 2 files every minute.

Besides the connection to the tower top computer, the network configuration defines the connections between the radar control computer, the Ettus N210, and the RPM pedestal (azimuth).
5.2 Software architecture

The UMaXX system has three main instruments, the radar control computer, the radar enclosure and the pedestal. These are all interconnected through the radar software which is divided in three main sections: 1) main acquisition program (xdatalog), 2) Ettus interface (setup) and 3) Positioner.

Each of the listed sections is in charge of a significant part of the radar system. Figure 5.2 illustrates a block diagram of the overall operational system. The radar control computer box consists of the software architecture and it shows a general overview of how the system operates, how it interacts with the other parts of the radar, such as the radar itself or the pedestal, and it also highlights the scripts which the radar operator (user) uses to interact with the system.

![Figure 5.2: Block diagram of UMaXX software architecture. The black highlighted box denotes the main program. The green boxes indicate the files which the radar operator (user) has access to and permission to modify.](image_url)
5.2.1 Theory of Operation

The software of the system comprises two main programs, xdatalog and poscont. Xdatalog is the main program of the software and it manages the overall operation of the system. It is in charge of reading in the specifications of the desired transmission signal from \textit{xdatalog.inp} file, such as the pulse duration, LDR mode, pulse scheme, and so on. Xdatalog also handles the data acquisition process. It keeps constant communication with the Ettus, forwarding all information related to the transmitted signal as well as the signal acquisition process, to collect the received data.

Poscont is a system-level background process (or daemon) that continuously monitors communications to or from the pedestal. It provides position read out to the data acquisition program, xdatalog.

The user is able to control the radar by interacting with two different scripts, highlighted with green in figure 5.2, by modifying file \textit{xdatalog.inp} to customize the transmitted signal, and the scan script (\textit{file.sh}) to control the azimuth and elevation position of the radar.

5.2.2 XDATALOG

Xdatalog is the main program of the system. Basically, when the program starts running, first it reads the parameters from file \textit{xdatalog.inp}, a file that contains relevant information regarding the radar operation. The radar operator uses this file to control certain settings of the radar such as the pulse width, the pulsing scheme and so on. Afterwards, it forwards the information to the Ettus so that it can generate the desired transmit signal. The program also stores the provided information from the read in file in the header of the output data file. Based on the provided information on the desired output data (raw or/and processed), xdatalog
creates the output files to later on store the acquired data.
In order to start transmitting, it sends a command over to the Ettus so that it starts sending triggers. Once the triggers have started the program enters a loop where it reads in the received data, it estimates the center frequency with a defined function as well as the peak power of the transmitted pulses in logarithmic scale.

5.2.3 POSCONT

Poscont is the background process that handles the connections with the positioners. It creates socket connections (Transmission Control Protocol(TCP) and User Datagram Protocol (UDP)) to the azimuth and elevation positioners to communication between them and posclient, the position manager process.
This process creates a pid file, which contains the process id number of POSCONT and it is useful because it is an easy way to check if the process is running. Furthermore, it makes the termination of a program simple, as it can be done by issuing a kill command.
The communication with the elevation positioner goes through a serial port connection set up by poscont. The communication between poscont and posclient, the program in charge of controlling the positioners, is set up as TCP and the connection and the azimuth positioner connection as UDP.
In a nutshell, poscont handles requests from posclient and forwards them to the positioners and sends back the positioners responds to posclient. The calculated antenna position offsets are defined in file offsets, read by poscont. These can be modified at any time by the user in the offsets files or using posclient.
5.2.4 POSCLIENT

Posclient manages the positioners by interacting with them through the UDP sockets created by poscont. The program can request the positioners to move to a new position, change the offsets of the positioners or obtain the current position.

Posclient is called in the scan script file (filename.sh) to continuously change the position of the radar, or by the main program, xdatalog, to obtain the current position. The scan script files terminated in .sh contain a predefined path for the azimuth and elevation positioners. These files contain a series of commands calling POSCLIENT with different azimuth and elevation ranges so that the radar operator does not have to enter them manually.

Figure 5.3, shows a screenshot of file ppi_scan_tilt.sh which is the script that matches the plots shown at emmy7.casa.umass.edu/umaxx webpage. Basically, this script has an infinite loop that tells the radar to perform PPI scans at 4 different elevations. The radar goes in azimuth from 0 to 360 degrees and repeats this move at 2, 4, 6 and 8 degrees in elevation and then start all over at 2 degrees in elevation.

```bash
#!/bin/bash
minel=2
maxel=8
del=2
el=$minel
posclient -s 0,0,0,el:10
sleep 4
while [ $el 
  do
    posclient -s 0,359,el:15 -d8 -a
    sleep 2
    let nel=el+del
elem = nel
    if [ $nel -gt $maxel ]
        then
            nel=$minel
    fi
    posclient -s 0,el:8,nel:10
    el=$nel
    sleep 3
done
```

Figure 5.3: Screenshot of file ppi_scan_tilt.sh using vi reader.
CHAPTER 6
RESULTS

This chapter presents a compilation of different weather phenomena calculated moments observed with UMaXX radar.
Some of the displayed plots are taken from https://emmy7.casa.umass.edu/umaxx/webpage, set up by the CASA Engineering Research Center, that features the UMaXX data plotted over the map of the area. The webpage has available for consultation the PPI scan of the horizontal Reflectivity Factor in dBZ, the horizontal Doppler Velocity, in miles per hour, and the Co-Polar Correlation Coefficient, at two, four, six and eight degrees in elevation. Furthermore, the webpage not only displays the current weather but it also includes the possibility to browse for data of a particular monitored past time. The rest of the displayed plots are generated using a computational tool, MATLAB MathWorks.
6.1 October 23rd 2018

Figure 6.1: Plan Position Indicator display of the horizontal Reflectivity Factor in dBZ at elevation 2 degrees. The green to red areas with values ranging between 20 and 65 dBZ depict rain. The blue circle highlights the Hardwick tornado signature and the grey circle defines the maximum range of the radar. (DATE: 10/23/2018 15:02:58 EST. SOURCE: emmy7.casa.umass.edu/umaxx)

The presented plots illustrate weather phenomena captured on October 23rd 2018 at 15:00 EST. Figure 6.1 shows the horizontal Reflectivity Factor in dBZ at elevation angle two degrees. The Z values in this plot range between 30dBZ and 60dBZ, which are characteristic values for rain[3]. Given this range, it is observable a front of rain moving eastwards. Denoted with a blue circle, there is a barely noticeable hook signature, which indicates a potential tornado.
By looking at figure 6.2, this notion is confirmed. Observing the Doppler Velocity, the presence of a mesocyclone is much more evident, due to the sudden Doppler Velocity shift from negative values to positive values, highlighted by the blue circle, where the Doppler Velocity goes from red to green, indicating a sudden change of wind direction. This tornadic vortex signature was spotted close to Hardwick, Massachusetts. Later on, this meteorological event was registered by the weather services as an EF-1 tornado.

This is a clear example of how the Reflectivity Factor is not as reliable to detect potential tornado signatures. However, it is frequently used during tornado monitoring as it may appear to capture circulatory features or hook echoes[3].
Figure 6.3: Plan Position Indicator plot of the Co-Polar Correlation Coefficient ($\rho_{hv}$) at elevation 2 degrees. The displayed values ranging between 0.7-1 are indication of weather phenomena, mostly rain. The blue circle indicates the Hardwick tornado signature. 2018/10/23. 20:04 UTC.

Figure 6.3 illustrates the Co-Polar Correlation Coefficient of the Hardwick tornado in a Plan Position Indicator (PPI) plot. The black regions of the plot indicate lack of meteorological events in those areas, typically a $\rho_{hv}$ shows random values for areas where there are no meteorological targets, in this case, these random values are filtered out as they do not provide any relevant information. For rain, it is expected
to obtain high values of $\rho_{hv}$, around 0.9\textsuperscript{[3]}. This can be observed at the right side of the PPI plot, which mostly indicates presence of rain with $\rho_{hv}$ values higher than 0.9, meaning uniform behavior of the hydrometeors. However, taking a closer look at the area highlighted with a cyan circle, it is noticeable that the values of $\rho_{hv}$ significantly drop to 0.7. This is expected due to the irregularity and variability of sizes, shapes and tumbling nature of a tornadic event. Even though, the $\rho_{hv}$ is not a radar moment commonly used to identify tornadoes it can contribute to the tornado identification process, as the particle behavior differs significantly from a regular storm with rain. Nonetheless, $\rho_{hv}$ values around 0.7 can also be an indication of hail, melting snow and so on.
Figure 6.4: Collection of PPI (Plan Position Indicator) plot at 2 degrees of elevation. (a) Horizontal Reflectivity Factor (dBZ). (b) Differential Reflectivity (dB). (c) Co-Polar Correlation Coefficient. (d) Differential Propagation Phase (degrees). (e) Doppler Velocity (mph). (f) Spectrum Width (mph). 2018/10/11 18:01 UTC.
Figure 6.5: Collection of PPI (Plan Position Indicator) plot at 8 degrees of elevation. (a) Horizontal Reflectivity Factor(dBZ). (b) Differential Reflectivity(dB). (c) Co-Polar Correlation Coefficient. (d) Differential Propagation Phase(degrees). (e) Doppler Velocity(mph). (f) Spectrum Width(mph). 2018/10/11 18:03 UTC.
The plots presented show an episode of rain, recorded on October 11th 2018, catalogued by the weather services as light rain with fog.

Figures 6.4 and 6.5 show all the computed radar moments at 2 and 8 degrees in elevation, which are the minimum and maximum scanned angles in elevation. All the plots, the horizontal Reflectivity Factor $Z_h$, the Differential Reflectivity $Z_{dr}$, the Co-polar Correlation Coefficient $\rho_{hv}$, the Differential Propagation Phase $\phi_{dp}$, the Doppler Velocity $V_r$ and the Spectrum Width $\sigma_v$, are Plan Position Indicators with 360 degrees in azimuth, generating a complete view of the radar surroundings. Both X and Y axes show the distance from the radar position in meters, indicating the range.

Figure 6.4 illustrates data at 2 degrees in elevation.

Figure 6.4a shows a $Z_h$ ranging between $20 - 40 \text{ dBZ}$, these values are commonly interpreted as an indication of rain[3]. The Differential Reflectivity data shown in figure 6.4b, suggests a storm composed by particles relatively spherical as the contribution to both horizontal and vertical Reflectivity Factors are similar, around $0 dB$ between $-2.5 dB$ and $2.5 dB$. Corroborating the $Z_h$ reading analysis, in figure 6.4c, which depicts the Co-polar Correlation Coefficient, the same areas where $Z_h$ had values between $20 - 40 dBZ$, show values of $\rho_{hv}$ around 0.85-0.9, identifying the target as rain, given the nearly spherical nature of raindrops, causing a high correlation between polarizations[3].

In figure 6.4d, it can be noticed the increasing nature of $\phi_{dp}$ with range, since the phase shift for the horizontal polarization is more notorious given the longer dimension in horizontal axis of drops. Note that, in this case, $\phi_{dp}$ has relatively small values, between 0 to 2.5 degrees, indicating that the raindrops are quite spherical, making the phase shift between polarizations small.

The Doppler Velocity indicates the direction of the particles relative to the observa-
tion point. The plot in figure 6.4e shows a uniform storm moving in one direction, as the velocity does not present any abrupt changes. There are no wind formations that could indicate presence of a mesocyclones or other hazardous weather phenomena. Negative values imply an inward particle direction, the particles move towards the observation point, depicted mostly in green. Positive values identify with those particles moving in an outward direction, away from the observation point, colored in red. Non-moving targets, which in weather analysis are understood as non-moving clutter such as buildings, are shown in grey. However, the zero band zone, point where the particles surpass the radar location changing the observation point orientation resulting in a sign change of $V_r$, also presents 0 mph.

Figure 6.4f depicts the Spectrum width, representing the variation of motion within an observed area. The low values, from 2 to 6 mph, are an indication of a smooth flow of particles, reiterating the expected light rain readings.

Figure 6.5 shows the same moments but at 8 degrees of elevation, which is the maximum elevation angle at which the radar scans. The data presented in the plots is very similar to figure 6.4, however, it is interesting to highlight figure 6.5b, which shows the Differential Reflectivity. In this plot, it can be distinguished the signature of the bright band, as the values of $Z_{dr}$ approximate to zero, creating a green circle at 3500m from the radar. The particles at this point present an spherical shape as they melt from the surface inward and collapse into raindrops.
6.3 Linear Depolarization Ratio

The main purpose of the MA-1 radar transformation into UMaXX was to achieve the ability to transmit in one polarization and receive simultaneously in two, so that the Linear Depolarization Ratio (LDR) could be computed. The following plots illustrate the LDR and the $Z_h$ calculated on October 11th, 2018 at 19:33 UTC.

When operating in LDR mode, the radar only transmits in horizontal polarization but receives the echoes with both horizontal and vertical polarization channels. The LDR is a variable that depends on the amount of incident radiation that is depolarized by a particle, so this ratio is influenced by the shape and size of the target. Oblate spheroidal particles fall with an irregular rocking motion, causing a distribution of canting angles, which increases the LDR value.

Figure 6.6: Plan Position Indicator plots of (a) the horizontal Reflectivity Factor $Z_h$ and (b) the Linear Depolarization Ratio (LDR) at 2 degrees in elevation. Rain is depicted in (a) with values around $40\, dBZ$ and in (b) between $-25dB$ to $-30dB$. 2018/10/11, 19:33 UTC.
Figure 6.6 shows two plots, figure 6.6a is the $Z_h$ and figure 6.6b is the calculated LDR. By observing figure 6.6a, the $Z_h$ shows low values around $25 - 30dBZ$, which indicates light showers[17].

For rain, the expected values of LDR are around $-25dB$ to $-30dB$ given the oblate shape of raindrops. However, the values shown in figure 6.6b are closer to $-20dB$. This difference could be caused by the cross-polar isolation of the antenna and the radome. This bias induced by the antenna coherent cross-channel coupling effect could be potentially corrected applying Eigenvalue Signal Processing (ESP), a signal processing procedure that corrects the bias caused by the cross-polar coupling of the antenna[21].

Figure 6.7: Averaged azimuth LDR (dB), blue line, and minimum LDR(dB) in azimuth, orange line, over range(m) for elevation 2 degrees. 2018/10/11. 19:33 UTC.
Figure 6.8: Averaged azimuth SNR (dB), blue line, and SNR (dB) value at minimum LDR(dB) position in azimuth, orange line, over range(m) for elevation 2 degrees. 2018/10/11. 19:33 UTC.

Figure 6.9: Comparison of SNR (dB) value at minimum LDR(dB) position in azimuth and additive inverse minimum LDR (dB) over range(m) for elevation 2 degrees. 2018/10/11. 19:33 UTC.
In order to determine the cross-polarization isolation of the system, figures 6.7, 6.8 and 6.9 are analyzed. The LDR decreases with range as the Signal to Noise Ratio (SNR) worsens, after a certain point the LDR values are no longer valid because the signal is below the noise level, so the plotted values are an image of the SNR.

Figure 6.7 shows in blue the LDR values averaged over azimuth for all the range bins and, in orange, the minimum value of LDR for each scan over the range. On the other hand, figure 6.8 shows in blue the SNR values averaged over azimuth for all the range bins and, in orange, the SNR values at the azimuth position over range of the minimum LDR value. Comparing these two figures, it is noticeable that the orange lines mirror each other after the 10km mark. Figure 6.9 shows a comparison of the SNR value at minimum LDR position in azimuth and minimum LDR for all the range bins. The LDR values have a sign change for comparison purposes. Observing this figure it is clear that the LDR values are only valid for close range, up to approximately 10km, after this mark the LDR curve follows the SNR. It can also be observed the cross-polarization isolation of the system does not exceed 25dB, below this level the system can not distinguish LDR.
CHAPTER 7
CONCLUSIONS

This chapter summarizes the final conclusions of the thesis. The following six sections focus on the major modifications that the system went through and observations of performance.

7.1 Pedestal

The UMaXX radar inherited only the elevation control system of MA-1, based on a IDC motion server driver controller, and a worm gear drive that allows the radar to have a wide range in elevation, specifically from -5 degrees to 90 degrees, allowing the radar to point to zenith. The azimuth positioner was substituted with an RPM PSI direct-drive rotator which allows continuous scanning clockwise or counterclockwise, 360 degrees.

7.2 Downconverter

The UMaXX downconverter was simplified from a dual down conversion architecture to into a single downconversion stage with image-reject filters and an IF stage for
amplification.

7.3 Trigger Generation and Data Acquisition System

The UMaXX radar now uses an Ettus N210 Universal Software Radio Peripheral (USRP) that integrates an FPGA, a dual channel ADC, a DAC, and an internal clock. These features allow the Ettus to act as both the data acquisition system and the trigger generator for the transmitted signal and the transceiver hardware control signals. Using the Ettus N210 makes the reconfiguration of the transmitted pulse scheme (standard or staggered mode) or the management of the control signals easy and straightforward.

The system incorporates a custom board that transforms LV TTL signals generated by the Ettus into differential and standard TTL, as required by the radar hardware. The board also acts as a protection stage for the modulator board against spurious signals from the Ettus, generated during power up. This added protection stage is quite necessary as the high-voltage portion of the modulator board could be damaged by the Ettus toggling during power up.

7.4 LDR Modification

The LDR modification is done by changing the waveguide duplexer structure that guides the high-power signal generated by the magnetron to the antenna feed. In order to allow either transmitting in both horizontal and vertical polarizations or just horizontal polarization, an electro-mechanical switch is integrated in the vertical
polarization branch so that whenever the radar operates in LDR mode, the vertically polarized wave gets redirected into a load. This design is not ideal as half the power is wasted when operating in LDR mode as the signal still gets split in two different polarizations, dividing the power, but only half of it is transmitted. Many designs were considered so that the radar was able to transmit in either or horizontal and vertical polarizations, however, the assembly of the antenna with the radar enclosure presented a major physical constraint, making it difficult to integrate such structure.

7.5 Software and Network Architecture

The radar software has two main components, one that controls all the interactions with the positioners and another that actually controls the radar (sends the commands to transmit, collect data, change the pulse scheme and so on). Having such structure makes the system easy to operate and understand as everything is handled by one program.

Regarding the network architecture, the UMaXX radar has two accessing routes, one through a public IP wireless link and a fiber link which does not have a public IP but can be accessed through the CASA Engineering Research Center servers. The fiber link provides a faster connection, however, the wireless link offers a backup connection option in case the fiber link is down.

7.6 Observations

Upon operating the UMaXX radar for several months, the following are a few notes on observed behavior of the radar that call for future work and improvement.
1. The magnetron is sensitive to temperature, so if there is a drastic temperature change in the radome, the frequency drifts and the Local Oscillator in the downconverter may require readjustment so that the received signal is not filtered out by the IF filters. Improved temperature monitoring and control in the radome would remedy this.

2. By using the birdbath scan method it has been noticed a small gain misbalance between the horizontal channel and the vertical channel, which requires a periodic recalibration of the radar. This is to be expected.

3. It has been observed that sometime the Ettus overflows and malfunctions, causing it to output random nonsense data and requiring a reboot to fix the problem. This will require further study in the future.

4. The differential board design does not protect the board against power surges, given the case, the XOR logic gate can be damaged hence leaving the modulator board unprotected against spurious signals from the Ettus. This can be fixed for example by adding a Transient-Voltage-Suppression (TVS) diode to protect against voltage spikes.

5. The fiber link from the CASA servers to the tower top seems to be occasionally unstable which would be a major problem if that was the only link to the tower top.
BIBLIOGRAPHY


