

Upgrading the Instrumentation of the Long Wavelength Array

Honors Thesis

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May 14, 2026

Abstract

This project focuses on upgrading, building, and testing key hardware systems for the Long Wavelength Array (LWA), a low-frequency radio telescope used for studying the sky. The work involved assembling and checking important components such as ARX boards, digitizers, daughter cards, and ZCU-based processing units. These parts make up the main signal path and are needed to correctly collect and process radio signals from the telescope.

A large part of the work included installing and integrating this new hardware at both LWA-1 and LWA-SV. This required replacing old systems, connecting a large number of cables, and testing the full signal chain to make sure everything worked properly from start to finish. We also made several trips to the Sevilleta station to help fix problems and improve how the system was running.

In addition to the stations already operating, much of the board testing and validation work was done to prepare for new planned LWA stations that are currently being constructed. This ensured that the hardware is reliable and ready for future deployment.

Some work was also done to support calibration and interferometry of the array by making sure the signal chain was stable and consistent, which is needed for combining signals from different antennas and for later data calibration and processing.

These upgrades are part of a larger effort to improve and expand the LWA system. By making the hardware more reliable and efficient, this work helps prepare the telescope for future observations of pulsars, fast radio signals, and other astronomical sources.

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1 Introduction

The Long Wavelength Array (LWA) is a low-frequency radio telescope that's designed to explore the sky within the 10–88 MHz frequency range. It primarily focuses on studying pulsars, transient radio sources, the early Universe, and the structure and dynamics of the ionosphere.

A common question is: why do we want to investigate the Universe at such low radio frequencies? Right on the heels of that, people often wonder: isn't radio frequency interference (RFI) a major issue in this range?

The straightforward answer is that this part of the electromagnetic spectrum is still largely unexplored territory. We don't fully know many astrophysical processes at these frequencies yet, so diving into them can uncover new information about familiar sources and possibly even reveal entirely new phenomena. That said, it's true that RFI is a significant challenge, as many human-made signals fall within or close to this frequency range. However, with thoughtful system design, effective signal processing, and careful data selection, we can still obtain valuable scientific information.

This thesis focuses on the hardware upgrades and instrumentation development required to maintain and improve the capabilities of the LWA. Specifically, it looks at improvements in the signal chain electronics and the integration of systems at operational stations. It also supports interferometry by helping ensure stable and consistent signals across the array. All of this is aimed at making the telescope more stable, sensitive, and reliable for future observations.

The upgrades to the Long Wavelength Array (LWA) support several important areas of time-domain and low-frequency radio astronomy. Because it works at frequencies below 88 MHz, the LWA is very sensitive to effects caused by plasma. This makes it especially useful for studying pulsars, fast radio bursts, and the ionized gas in space, including the interstellar medium and the solar wind.[7, 8]

One of the main goals of the LWA is studying pulsars. At low frequencies, pulsar signals are strongly affected by dispersion and scattering. This helps scientists measure how many free electrons are along the path of the signal. These measurements are important for improving pulsar timing and for studying the structure of space between stars and the solar wind. Low-frequency data is also useful for detecting small changes in dispersion, which helps with very precise timing studies and tests of fundamental physics.[15, 14]

The LWA is also useful for studying fast radio bursts (FRBs). These are very short, powerful bursts of radio waves that last only a few milliseconds, and their origin is still not fully understood. Because their signals are strongly affected by frequency-dependent delays, low-frequency observations help scientists understand how the signal changes as it travels through space. Even though many FRBs are found at higher frequencies, low-frequency observations help study effects like scattering and absorption, which give hints about where

they come from and how they are produced.[12, 13]

Another important area is solar and ionospheric science. The solar wind and the Earth's ionosphere can change how radio signals travel by adding delays. The LWA can measure these effects directly by observing how signals change over time. This helps improve models of the solar wind and ionosphere and also helps correct these effects when studying distant sources.[14]

Finally, the LWA is important for finding and studying many types of fast or changing radio signals. This includes also other events like meteors, lightning-related signals, and unknown fast phenomena. Because it can observe a large part of the sky at once and continuously monitor it, the LWA is very good at detecting rare and short events.[15, 8]

Together, these science goals show why it is important to keep improving the LWA. Better sensitivity, stability, and data processing help the array detect weaker, faster, and more dispersed signals from across the low-frequency radio sky.[7]

2 Background

2.1 The Long Wavelength Array

The Long Wavelength Array (LWA) is a radio telescope situated in New Mexico, operating within the low-frequency range of 10–88 MHz. Unlike the traditional radio telescopes that rely on a single large dish, the LWA is composed of several stations spread out across the state. Each of these stations is made of numerous individual dipole antennas (Fig. 1) that work together, acting as a single instrument.

The signals captured by all these antennas are merged using digital signal processing techniques and then transmitted to a central computing system. This setup allows the array to function like one massive telescope, even though it's physically divided into smaller components.

Thanks to the wide spacing of the stations, the LWA operates as an interferometer. This means it uses a method called aperture synthesis to combine signals from various locations. In practice, this combines the telescope to act like a much larger antenna, improving its angular resolution. Consequently, the LWA can detect much fainter radio sources and create more detailed images of the radio sky than a single small station could ever hope to achieve on its own. [7]

The Long Wavelength Array is designed as a distributed instrument made of multiple stations. At the moment, we have four stations that are built, with a few more that are in construction or in the planning phase. The main stations include LWA1, LWA-SV (Sevilleta), LWA-NA (North Arm), and OVRO-LWA in California. Plus, there are other stations like MC, CS, and BB that are part of future expansion plans or are currently under development as part of the larger LWA network. As shown in Fig. 2, the LWA stations are distributed

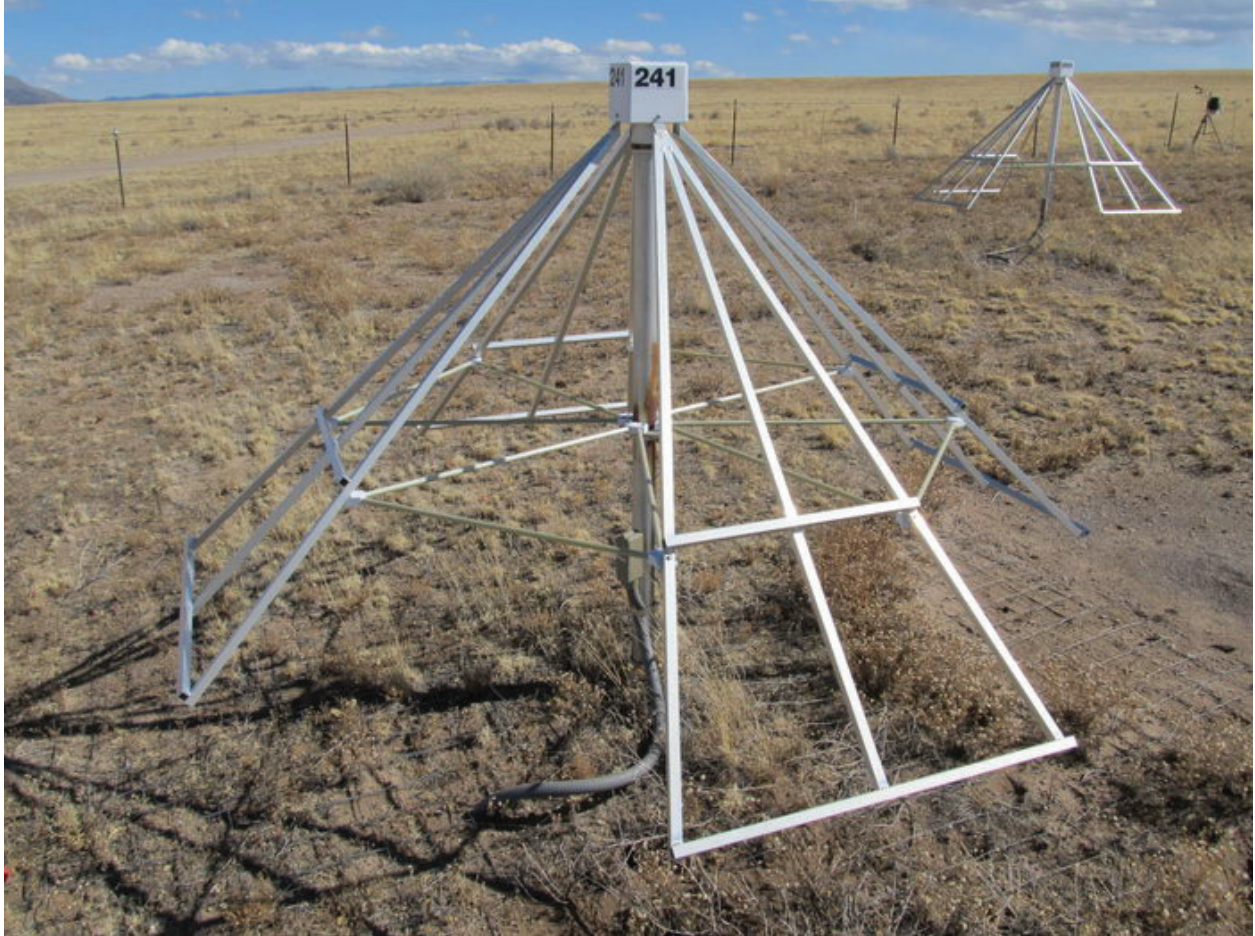


Figure 1: LWA dipole antenna used in the Long Wavelength Array.

across the southwestern United States, forming a wide interferometric network with both regional and long-baseline coverage.

2.1.1 LWA1: The First Station

LWA1 stands out as the very first and most crucial station, and it is the reference for the design of the entire array. It is located in central New Mexico, near the Very Large Array (VLA), on the Plains of San Agustin [7].

This station is made up of around 256 dual-polarization dipole antennas, all spread out over an area that is about 100 meters in diameter. The dipoles are arranged in a pseudo-random pattern, which helps improve the quality of the synthesized beam and reduces systematic effects [5]. The signals from each antenna are individually digitized and then combined using beamforming techniques, creating multiple independent beams on the sky [5].

In terms of performance, LWA1 operates as the first fully functional station of the array and demonstrates the system design in practice. When combined with other stations



Figure 2: Geographical distribution of the Long Wavelength Array (LWA) stations across the United States, including operational and planned sites. The different colors indicate standard, swarm, and super-station configurations.

through interferometry, the array can achieve much higher angular resolution, reaching a few arcseconds at higher frequencies (around 80 MHz) due to the large baselines [7, 4]. The effective aperture of a single station is determined by the physical distribution of the antennas, but when multiple stations are combined, the system acts like a much larger telescope, significantly increasing both resolution and sensitivity [4].

Overall, LWA1 demonstrates how a large number of simple dipole antennas, when properly combined, can act as a powerful radio telescope. It serves as the first operational step of the LWA and as the foundation for the development of the full array system [5]. (See Fig 3)

2.1.2 LWA-SV and LWA-NA

The LWA-SV station is situated at the Sevilleta National Wildlife Refuge in central New Mexico. Like LWA1, it is a full-scale station consisting of 256 dual-polarization dipole antennas arranged over an area of about 100 m in diameter [10, 20]. The antennas are distributed in a random pattern, similar to LWA1, to improve imaging quality and reduce systematic effects. The analog signals from each dipole are amplified, filtered, digitized, and then processed using a more modern digital backend compared to LWA1. In LWA-SV was also introduced improved real-time processing capabilities, permitting high time-resolution



Figure 3: View of the LWA1 station located near the Very Large Array (VLA) in New Mexico. The nearby VLA dishes are visible in the background, highlighting the proximity of the two radio observatories.

imaging and more flexible observing modes [9]. This makes the station particularly useful for studying fast transient events such as lightning, meteors, and disturbances from the ionosphere.

The LWA-NA station is a newer and smaller setup located near the North Arm of the Very Large Array, also in central New Mexico [11]. Unlike LWA1 and LWA-SV, LWA-NA is a reduced-size swarm station with 64 dipole antennas instead of 256. Even if its smaller, it follows the same design principles as the other stations and integrates with the other stations. Its reduced size allows for quicker deployment and lower costs while still contributing to long-baseline observations when combined with other stations.

Together, LWA-SV and LWA-NA show the evolution of the LWA concept from a single-station instrument (LWA1) into a distributed interferometric array. By combining data from multiple stations, the array improves both sensitivity and angular resolution, enabling a wide range of time-domain and imaging science at low radio frequencies (see Fig. 4a- 4b).

2.1.3 OVRO-LWA: The Owens Valley Station

The OVRO-LWA is the expansion of the Long Wavelength Array located at the Owens Valley Radio Observatory in California. Unlike the New Mexico-based stations, this site extends the LWA network to a geographically distant baseline, significantly improving the overall



(a) LWA-SV station at Sevilleta.



(b) LWA-NA station.

Figure 4: Comparison of LWA SV and NA.

interferometric coverage and imaging capabilities of the array.[6]

The station (also called super-station) consists of 352 dual-polarization dipole antennas distributed over a large area, following a random layout similar to LWA1 and LWA-SV. This setup is meant to give better uv-coverage, which helps produce clearer and more accurate reconstructed images. The signals collected by the antennas are amplified, filtered, digitized, and processed on-site using a modern digital system, which allows data to be combined and analyzed almost immediately.[3]

Because of its large distance from the New Mexico stations, OVRO-LWA helps make the array much larger. This directly improves the angular resolution of the interferometer, allowing for more detailed observations of compact radio sources and improving sensitivity. The station also contributes significantly to time-domain studies, in particular for transient and variable radio sources.[6, 7]

Overall, OVRO-LWA is an important step in turning the LWA from a regional telescope into a multi-site array spread across large distances. This greatly increases the size of the baselines and expands its scientific capabilities.[6]

2.1.4 Planned and Future LWA Stations

In addition to the currently operational stations, the Long Wavelength Array (LWA) is continuing to expand with several new stations under construction. These upcoming sites will extend the array's baseline coverage and improve its interferometric performance.

The stations currently under development are:

- LWA-CS (Comanche Springs), owned and operated by Texas Tech University (TTU)
- LWA-MC (Meteor Crater), owned and operated by Arizona State University (ASU)
- LWA-BB (Big Bend), developed in collaboration with the Smithsonian Institution and Texas A&M University (SHS/TAMU)

These new stations follow the same general design principles as existing LWA sites, including dual-polarization dipole antennas, distributed layouts, and scalable digital backend systems. However, they also incorporate improvements in electronics, digitization, and real-time processing based on lessons learned from current stations.

The addition of these stations will increase the number of baselines and extend them over larger distances. This will improve (u, v) -coverage, leading to better image reconstruction, higher angular resolution, and increased sensitivity to faint and extended radio sources. It will also enhance the array's ability to detect and localize transient events such as fast radio bursts and ionospheric disturbances. [7]

Beyond expanding the array, these stations also serve as platforms for testing new hardware and signal processing techniques. This allows continued development and refinement of the LWA system, ensuring it remains adaptable for future radio astronomy research.

2.2 Signal Chain Overview

The Long Wavelength Array (LWA) signal chain is designed to capture, condition, digitize, and process those low-frequency radio signals. It follows a very simple diagram (Fig. 5):

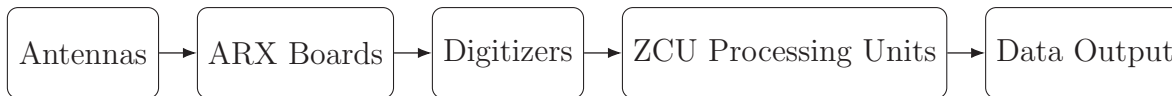


Figure 5: Simplified LWA signal chain from antennas to data output.

Since the signals at these frequencies are faint and often affected by radio frequency interference (RFI), each step of the signal chain is really important for preserving signal integrity, which is crucial for calibration and interferometry.

The signal path begins at the dipole antennas, which transform incoming electromagnetic radiation into voltage signals. The signals get amplified from a low frequency amplifier that is located on the antenna [7].

Once the signals are amplified, they make their way to the Analog Receiver (ARX) boards. Here, the ARX system takes charge of defining the band, and managing additional gain. These processes ensure that only the intended observing band is preserved while other signals and strong RFI are filtered out before digitization. The ARX stage also helps balance signal levels across antennas to optimize the dynamic range of the digitizers [1].

The signals are then sent to the digitizer system, where they are sampled and converted into digital data. It's very important to have precise timing synchronization across all digitizers because even the smallest timing delay can destroy coherence. The digitized data preserves both amplitude and phase information necessary for later correlation and beamforming.

After digitization, the data is sent to the ZCU processing units. These units split the signal into smaller frequency parts, organize it into packets, and sometimes combine signals from different antennas (beamforming). They can process data in real time and keep all signals precisely synchronized across the array.

Finally, processed data is transferred to a computing systems. These outputs are then used in offline pipelines for calibration, imaging, and time-domain analysis.

2.3 Calibration and Interferometry

The Long Wavelength Array operates as a distributed interferometer, meaning that instead of taking a picture of the sky with one big dish, the LWA uses many small antennas spread out over a large area. Each pair of antennas compares the radio signals they receive and tells us how similar those signals are. Each pair gives a small piece of information about what the sky looks like, but not a full image on its own. When you combine all these pieces from many different antenna pairs, you can reconstruct a detailed image of the sky. This method

of combining many small measurements to build a full image is called aperture synthesis. This idea is what lets the LWA see details in the sky, much better than a single antenna could. The more distance there is between stations, the sharper the final image can be. The quality of the image depends also on how well the antenna pairs cover something called the (u,v) plane, which is just a way of mapping all the different distances and directions between antennas. If the coverage in the (u,v) plane is dense and evenly spread out, then the LWA has more complete information about the sky, and the final image is clearer and more accurate. If the coverage is patchy or uneven, then some information is missing, and the image can look less sharp or show distortions.

A useful way to see this process is shown in Fig. 6, which displays the (u,v) coverage obtained from observations of the calibrator source 3C147. The plot is taken from the LWA calibrator survey paper [18]. It shows how different pairs of stations sample the spatial frequency space of the sky signal. Each point in the (u,v) plane corresponds to one baseline measurement, and together these points describe how well the array can reconstruct the source structure. A more complete and uniform coverage leads to higher image quality and more reliable interferometric imaging.

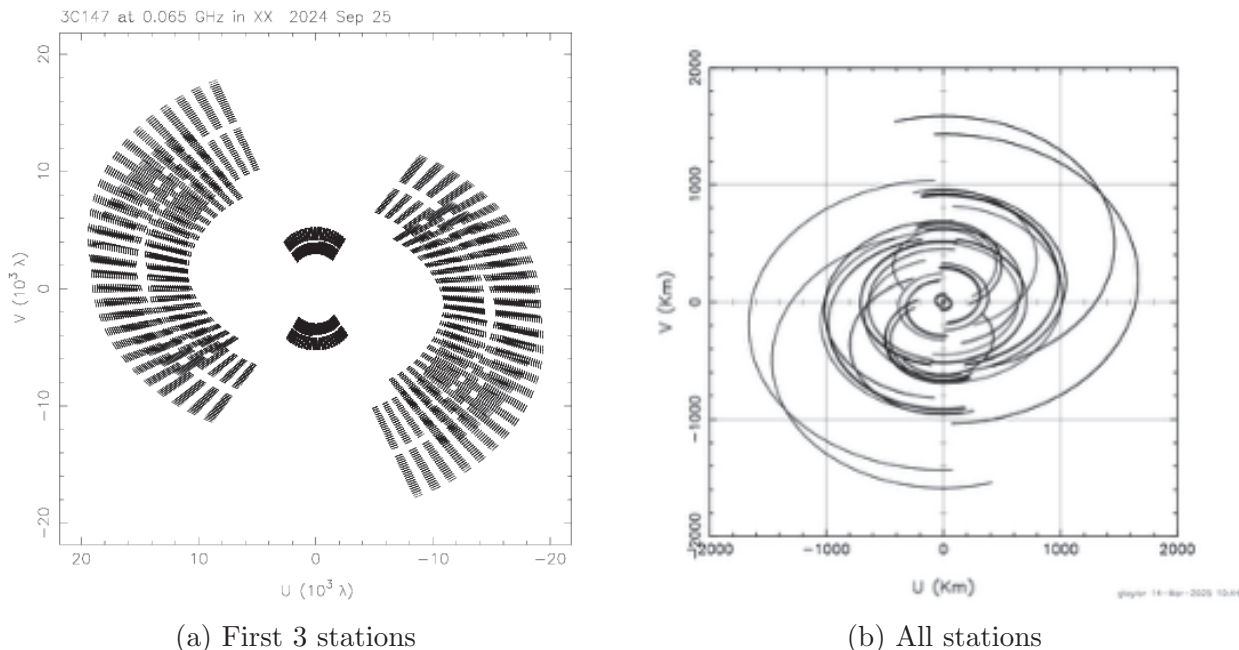


Figure 6: (u,v) coverage comparison for observations of the calibrator source 3C147 with the LWA. Left: coverage using the first three stations. Right: coverage using all available stations. Each point represents a baseline measurement between two stations, illustrating how increased station count improves sampling of spatial frequencies and leads to better image reconstruction.

The LWA Swarm Calibration Survey improves the system by using multiple ways to compare and match signals between different stations, following the procedures described in

the LWA instrumentation and calibration memo [19]. This helps keep the signal strength (gain) stable and makes sure the signals stay properly aligned in time (phase coherence) across the whole array.

This is especially important for low-frequency radio astronomy, because the Earth’s atmosphere and ionosphere can distort the signals, and there is also a lot of radio interference (RFI). These effects can change with time and direction, which makes the data harder to combine correctly. By combining better hardware stability with these calibration methods, the LWA can keep all stations working together properly. This allows the array to produce sharp images and also to detect fast and short radio events more reliably.

3 Hardware Components

The LWA signal chain is made of many hardware components that work together to capture, condition, digitize, and process low-frequency radio signals. The main components include ARX boards, digitizers, ZCU processing units, and daughter cards.

3.1 ARX Boards

The Analog Receiver (ARX) boards (Fig. 7) are the first step after the antenna. They operate over the full LWA observing band of approximately 10–88 MHz and provide selectable filtering and gain control to optimize the incoming signals before digitization. Because low-frequency observations are strongly affected by man-made RFI, the filtering stage is important for preventing strong unwanted signals from saturating later stages of the signal chain. The ARX system also helps maintain a stable dynamic range across antennas, which is necessary for accurate calibration and interferometric observations. [5, 1].

3.2 Digitizers

The digitizers (Fig. 8) take the analog signals at high sampling rates and convert them into digital data so they can be processed by the FPGA systems. The digitization stage must preserve both amplitude and phase information with high precision because interferometric observations depend on coherent signals across all antennas. The system also requires accurate clock synchronization between digitizers, since timing errors on the order of nanoseconds can introduce phase offsets that reduce calibration accuracy and image quality. Digitization is essential to make sure signals from different antennas can be correctly combined later. [7, 4].

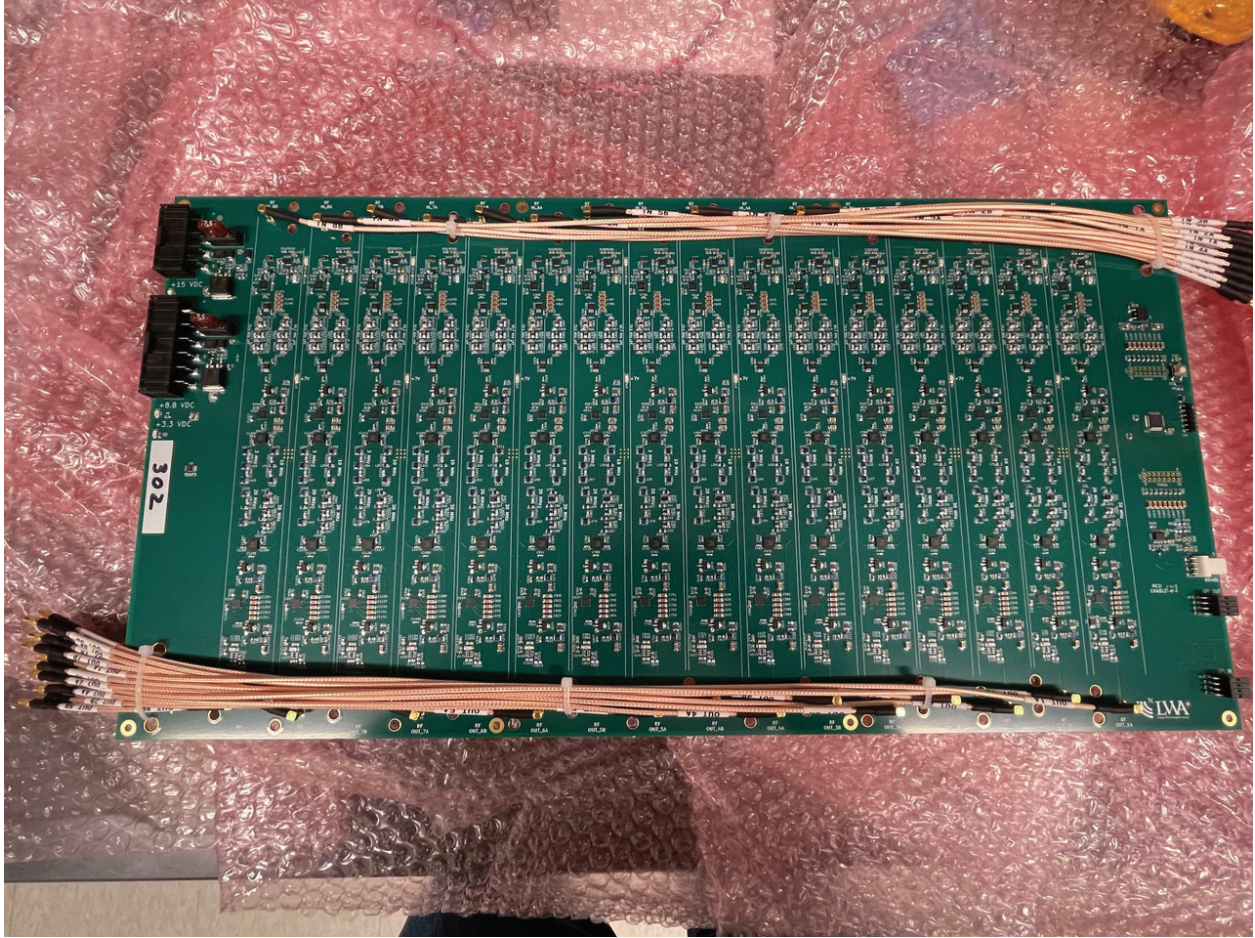


Figure 7: ARX board used in the LWA signal chain.

3.3 ZCU Processing Units

The ZCU102 FPGA processing units (Fig. 9) are the main real-time digital system for the upgraded LWA system. They are a commercially programmable Field Programmable Gate Array (FPGA) board from Xilinx/AMD to process large data rates directly in hardware, allowing operations such as channelization, packetization, synchronization, and beamforming to occur in real time. Compared to traditional CPU-based processing, FPGA systems provide much lower latency and can handle continuous high-bandwidth data streams more efficiently. This flexibility also allows future firmware upgrades and observing modes to be implemented without major hardware changes. [5, 2].

3.4 Daughter Cards

Daughter cards provide high-speed electrical interfaces between the digitizers (Fig. 8) and the ZCU102 FPGA boards. Because large amounts of data are transferred continuously between systems, maintaining signal integrity across these connections is important for preventing

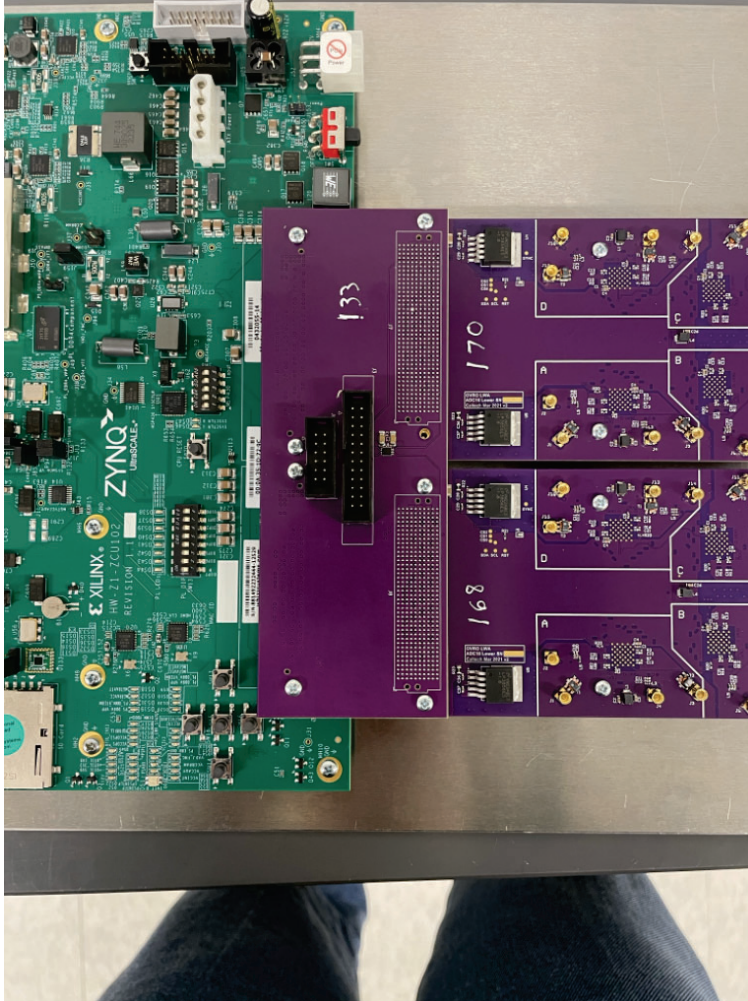


Figure 8: Digitizer boards and daughter card installed onto a ZCU102 FPGA board.

data corruption and synchronization errors. It is easy to replace or upgrade parts when needed. In large systems like the LWA, this flexibility is important for keeping the system reliable and easy to expand over time. [7].

4 Testing and Validation

A large part of this project was focused on testing and checking each hardware component, as well as looking at how the whole system performs. These tests were important to make sure the upgraded hardware works well enough for reliable observations.

4.1 Board-Level Testing

We tested individual hardware boards such as ARX boards, digitizers, and ZCU boards before installation. These tests focused on basic functions like signal response, timing stability,

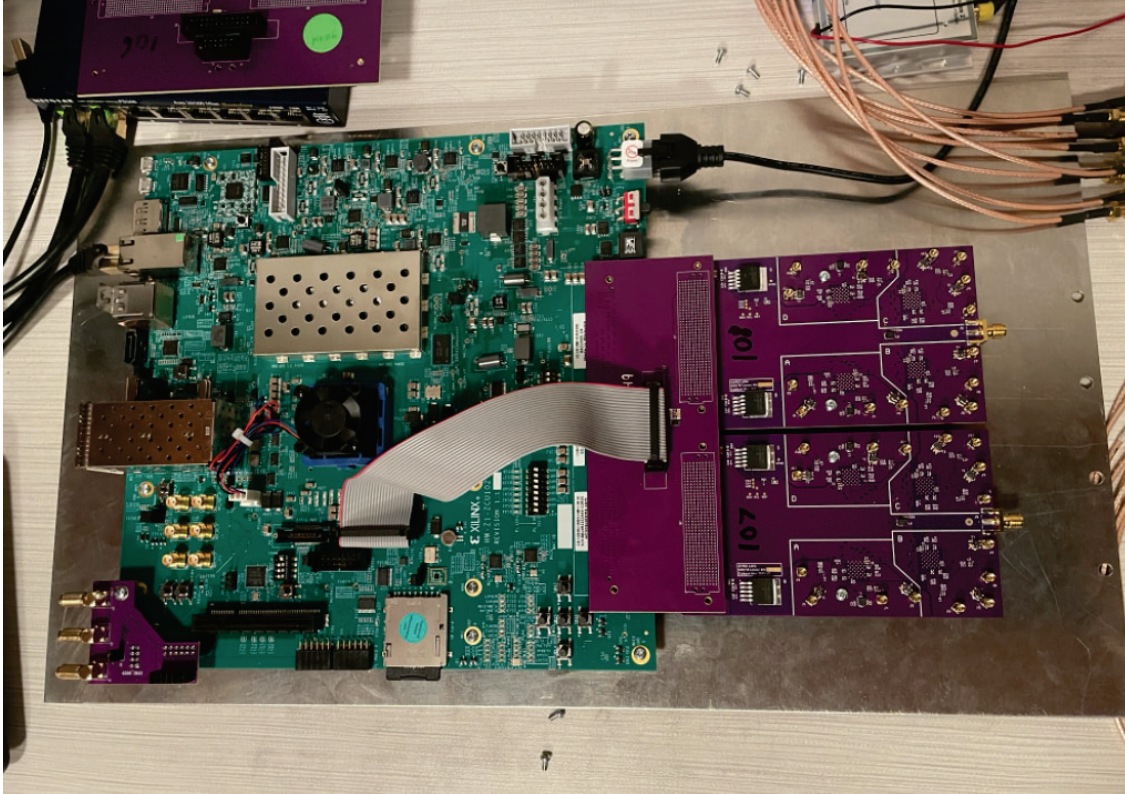


Figure 9: ZCU processing unit board used for real-time FPGA signal processing.

and whether the data output was correct.

For the ARX boards, testing included checking that the correct frequency range was passing through the system and making sure the gain levels stayed stable across all channels. We also looked for unusual noise or unexpected signal loss, since these could indicate damaged components or problems with the filters.

For the digitizers, we checked that the analog signals were properly sampled and converted into digital data without missing channels or timing problems. This also included verifying that the digitizers stayed synchronized and that the data output remained stable during long observation periods.

The ZCU processing units were tested by confirming that data packets were correctly sent and received between the different systems. We also checked communication between the FPGA boards and the digitizers, since unstable communication could interrupt observations or create synchronization issues in the signal chain.

By checking each board on its own, we made sure every component worked properly before being added to the full system. This helped reduce the chance of larger problems once everything was installed and connected.

4.2 System Troubleshooting

During installation and operation at Long Wavelength Array stations LWA-SV, LWA-NA, and LWA1, several hardware and signal problems were found while connecting the upgraded systems to the existing infrastructure. Many of these problems only appeared after the entire signal chain was connected, so careful and systematic troubleshooting was important during deployment.

One common issue involved unstable communication between the digitizers and the ZCU processing units. In some cases, the FPGA systems did not consistently detect the incoming data streams, causing interruptions in the signal chain. To find the source of the problem, connections between boards were tested one at a time, daughter cards were reseated, and cable continuity checks were performed. Several problems were eventually traced to connectors that were not fully seated and unstable cable connections that caused intermittent communication errors.

Another issue involved uneven signal levels across some antenna channels after installation. Some channels showed higher noise levels or weaker signals compared to nearby antennas. To investigate this, signal levels were compared across channels while checking the ARX gain settings, power delivery, and cable integrity. Suspected components were replaced with known working hardware to determine whether the problem came from the ARX boards, digitizers, or cabling. These tests helped identify unstable connections and hardware components that needed replacement or reconfiguration.

We also encountered synchronization issues during the early stages of system integration. Since interferometric observations require very precise timing stability, even small timing errors can reduce phase coherence across the array. Timing and stability tests were repeated multiple times during deployment to make sure all systems stayed synchronized during continuous operation. This was especially important after replacing older hardware with the upgraded FPGA-based systems.

Part of the troubleshooting and repair process followed documentation from the LWA Front-End Electronics Repair Guide and other internal hardware references used by the collaboration [17].

4.3 Performance Checks

We have been running performance checks to see how stable the system is. This included monitoring noise levels, checking that signals stayed consistent across antennas, and making sure the system can run reliably over long periods. Performance checks also included making sure that astronomical signals could still be detected correctly after the hardware upgrades. Known pulsars such as PSR B0950+08 were used as test sources because their signals are well known at low radio frequencies. Successfully detecting these pulsars confirmed that the upgraded signal chain was working properly from the antennas through the digitizers and

FPGA processing systems. Signal-to-noise ratios from repeated observations were compared to look for unstable channels, synchronization issues, or changes in system sensitivity. These observations also helped confirm that the upgraded hardware could operate stably during long observing sessions without adding extra systematic noise to the array. The results are still being evaluated, since these checks are ongoing. These checks are important to make sure that no new systematic errors are introduced into the array.

4.4 Field Deployment Challenges

Deploying upgraded hardware at remote Long Wavelength Array stations created additional practical challenges beyond normal laboratory testing. Many installations required working directly inside station shelters while managing large numbers of RF, power, and networking cables at the same time. Environmental conditions such as dust, temperature changes, and limited time for on-site troubleshooting made reliable hardware integration especially important. Because many systems were connected together, even small connection problems could affect multiple parts of the signal chain and require repeated testing of the entire system. Another challenge was integrating the newly upgraded FPGA systems with older station infrastructure that had already been operating for many years. In some cases, older hardware configurations had to be adjusted to remain compatible with the upgraded signal chain. This required careful testing and verification to make sure the new and old systems could operate together reliably without introducing timing, communication, or signal stability problems.’

5 Instrumentation Upgrades

This thesis describes several hardware upgrades and improvements to the LWA signal chain. The main goal of these upgrades was to improve system reliability, replace older parts, and make sure all parts of the telescope work properly across different stations.

5.1 System Replacement at LWA-1

At LWA1, we replaced older hardware in the signal chain that was no longer reliable. This involved removing outdated electronics and installing newer ARX boards, digitizers, and other supporting parts. The goal was to reduce system failures and improve the long-term stability of the station.

During the work, we carefully checked how cables were connected, how power was distributed, and whether the signals stayed clean. This was important to make sure the new setup worked as well as the original system. We followed the standard LWA hardware procedures and documentation throughout the process. [16, 1].

The replacement process required disconnecting large parts of the existing signal chain and carefully labeling cable locations before installing the upgraded hardware. Since the station infrastructure contains hundreds of signal and power connections, staying organized during installation was important to avoid creating new signal routing problems. After the older systems were removed, the upgraded boards were installed and connected step by step so that each subsystem could be tested before connecting the entire signal chain.

After the installation was finished, several rounds of verification tests were performed. These included checking power stability, confirming communication between the digitizers and FPGA systems, and verifying that signals were being correctly received from the antennas. In some cases, hardware had to be reseated or reconfigured after early testing showed unstable communication or inconsistent signal levels between channels.

One challenge during the upgrade process was integrating the newer FPGA-based processing hardware with older station infrastructure that had already been operating for many years. Small differences in hardware configurations and synchronization settings required repeated adjustments before stable operation across the full system was achieved. These checks were especially important because interferometric observations depend on maintaining phase coherence and precise timing stability across all antennas.

5.2 Integration at LWA-SV

At the LWA-SV station, older hardware was also replaced (Fig. 10). A large part of the work focused on connecting new hardware and fixing issues during installation. This included connecting new hardware to the existing system, handling many signal and power cables, and checking that each part of the signal chain worked correctly.

The installation process at LWA-SV involved mounting the upgraded FPGA processing systems inside the station shelter, reconnecting the digitizer outputs, and verifying communication between all stages of the hardware. Because the station contains many interconnected systems, cable management and signal organization were important parts of the installation process. Incorrect or unstable connections could affect synchronization, data transmission, or overall system stability.

Several troubleshooting steps were needed during installation. These included checking cable continuity, reseating daughter cards, verifying power delivery to the boards, and monitoring signal outputs while the system was running. Some hardware showed unstable behavior after installation, requiring repeated testing and reconfiguration before stable operation was achieved. Communication checks between the digitizers and ZCU processing units were especially important because interruptions in the FPGA data streams could affect observations across multiple antennas at the same time.

Field deployment at LWA-SV also created practical challenges compared to laboratory testing. Since repairs and debugging had to be done directly on site, troubleshooting often

required quickly isolating problems while working within the existing station infrastructure. Multiple rounds of testing were performed after installation to verify long-term stability and ensure that the upgraded hardware could operate continuously during normal observing conditions.

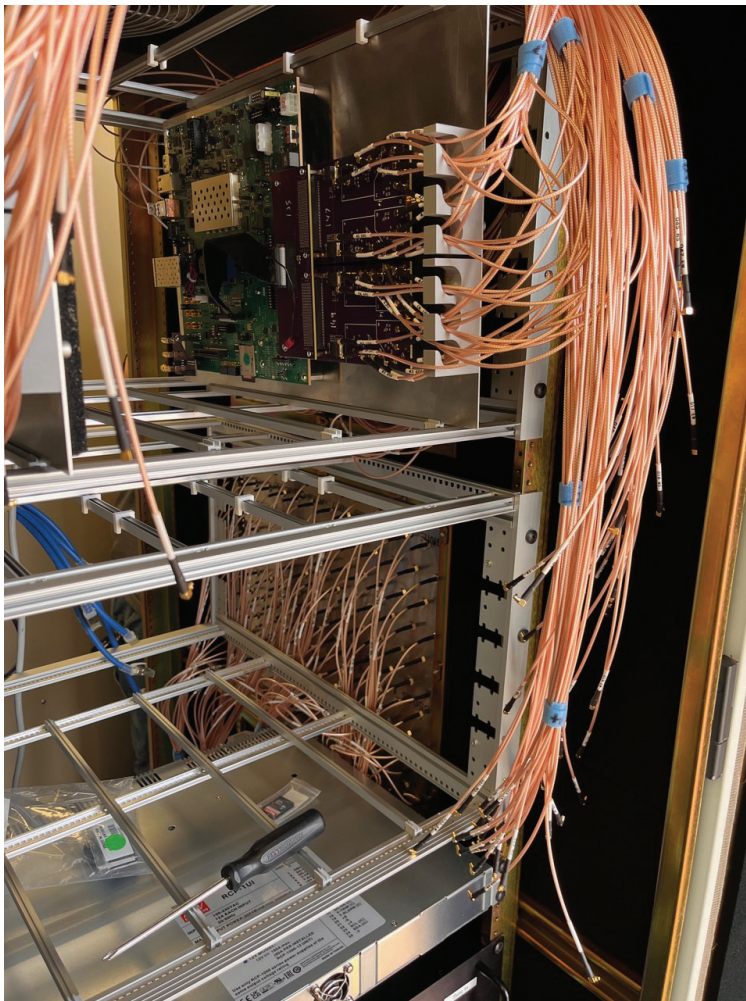


Figure 10: ZCU boards mounted inside the shelter at LWA-SV.

The main installation, testing, and verification procedures performed during hardware integration are summarized in Table 1.

5.3 Signal Chain Verification

After the installation and hardware upgrades, a complete verification of the signal chain was performed to confirm that all systems were working correctly together. These tests followed the signal path from the antennas, through the ARX boards and digitizers, and finally into the ZCU FPGA processing systems. The goal was to make sure signals could pass through the

Table 1: Main procedures performed during hardware integration and signal chain verification at LWA-SV and LWA1.

Procedure	Purpose and Verification Method
Hardware Installation	Mounted upgraded ZCU FPGA systems, digitizers, and supporting hardware inside the station infrastructure
Cable and Power Verification	Checked RF, networking, and power connections to ensure stable communication and signal transmission
Communication Testing	Verified stable data transfer between digitizers and FPGA processing systems during operation
Signal Monitoring	Monitored channel outputs for abnormal noise levels, unstable signals, or synchronization problems
Synchronization Checks	Repeated timing and stability checks to maintain phase coherence across the upgraded signal chain
Pulsar Verification Observations	Observed PSR B1919+21 to confirm successful end-to-end signal acquisition and stable system performance after installation

entire chain without major distortion, synchronization problems, or communication failures. The major verification procedures carried out during this process are summarized in Table 1.

The verification process included checking signal continuity across channels, monitoring noise levels, confirming synchronization between digitizers, and validating communication between the FPGA systems and downstream computing hardware. Known test signals and astronomical sources were used to confirm that the upgraded systems were correctly receiving and processing data. Pulsar observations were especially useful because they provided clear evidence that the signal chain was operating properly during long observing sessions.

Special attention was given to maintaining timing stability and phase coherence throughout the upgraded system. Because the Long Wavelength Array operates as an interferometric array, even very small timing offsets between stations can reduce calibration accuracy and image quality. For this reason, repeated synchronization and stability tests were performed after installation and after any hardware changes.

Signal chain verification continues as additional hardware upgrades and future station deployments are completed. Continuous testing is important to ensure that the upgraded systems remain reliable for future interferometric observations, pulsar studies, and transient radio detection.

5.3.1 Pulsar Verification Observations

To verify that the upgraded signal chain was working correctly after installation, observations of known pulsars were used as functional validation tests. Pulsars are useful test sources because their radio signals are very regular and easy to identify when the system is operating properly. Successful pulsar detections confirm that the antennas, ARX boards, digitizers, FPGA processing systems, and synchronization stages are all working together correctly.

Observations of PSR B1919+21 (Fig. 11) were used as part of these verification tests after the hardware integration. The pulsar signal was successfully detected after passing through the upgraded signal chain, confirming stable operation of the installed systems. These observations were also useful for checking timing stability, signal consistency, and overall system sensitivity during long observing sessions.

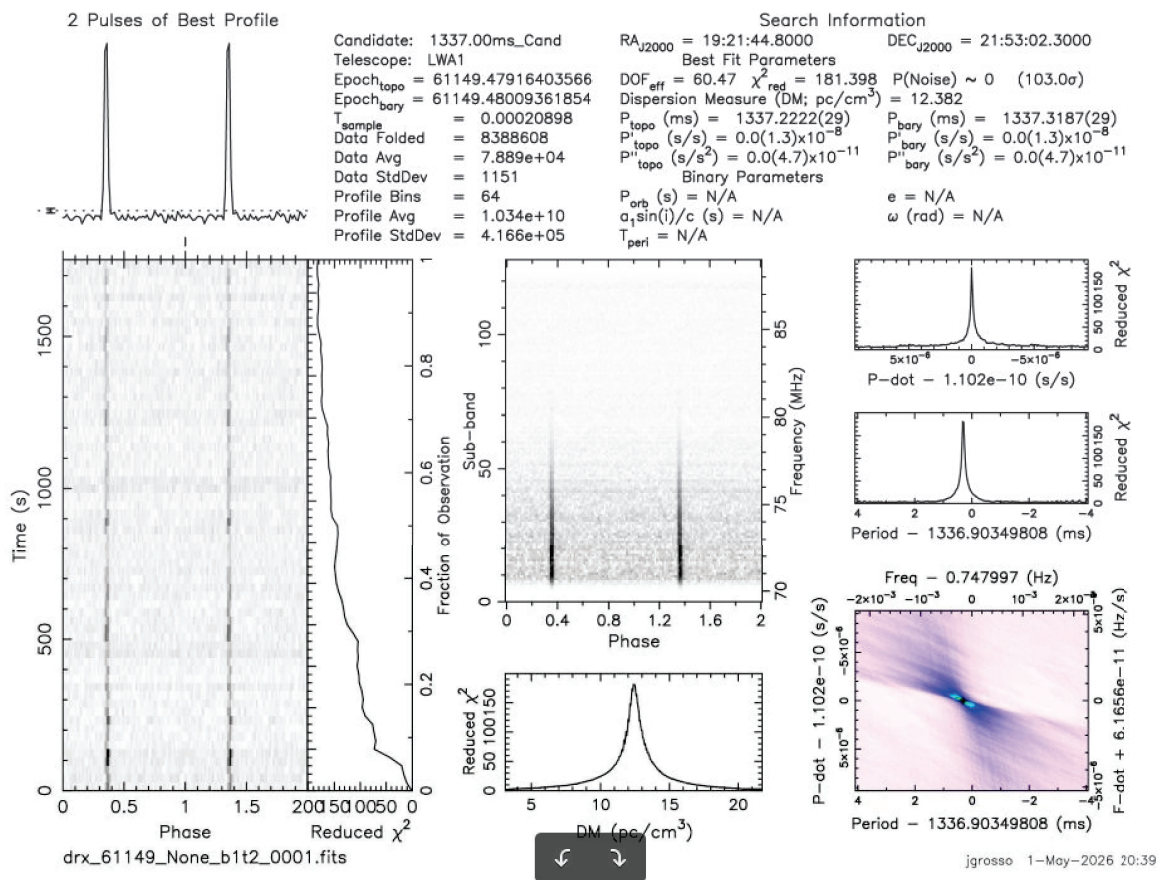


Figure 11: Detection of PSR B1919+21 using the upgraded LWA signal chain after hardware integration. The folded pulse profile, dispersion measure fit, and frequency-dependent pulse structure confirm successful end-to-end signal acquisition and stable synchronization across the upgraded hardware systems.

The folded pulse profile in Fig. 11 shows a clear detection of the pulsar signal during the observing period. The dispersion measure fit and the stable pulse alignment across the frequency channels indicate that the upgraded signal chain preserved the timing and phase information correctly during digitization and processing. These results provided additional confirmation that the upgraded systems were operating reliably after deployment.

6 Conclusion

In this thesis, I worked on improving, testing, and installing important hardware for the Long Wavelength Array (LWA). The main focus was on the signal chain, including ARX boards, digitizers, daughter cards, and ZCU FPGA processing systems, with the goal of improving system reliability, stability, and overall performance for low-frequency radio observations.

A large part of this work involved testing individual hardware components before deployment and validating the full signal chain after installation. This included checking signal integrity, synchronization stability, communication between FPGA systems and digitizers, and long-term system performance during continuous operation. Troubleshooting and repair work were also important parts of the project, especially during field deployment at remote LWA stations where unstable connections, synchronization problems, and communication issues had to be identified and corrected directly on site.

The installation and integration work completed at LWA1 and LWA-SV helped replace aging hardware systems and improve the reliability of the existing station infrastructure. Careful verification of the upgraded systems was required to ensure stable operation across the entire signal chain, from the antennas to the real-time digital processing systems. Particular attention was given to maintaining timing stability and phase coherence, since interferometric observations depend strongly on accurate synchronization between antennas and stations.

Verification observations using known pulsars such as PSR B1919+21 confirmed that the upgraded systems were successfully receiving, digitizing, and processing astronomical signals after installation. The successful pulsar detections demonstrated stable end-to-end signal acquisition and provided additional confirmation that the upgraded hardware was functioning correctly during real observing conditions.

These upgrades improve the scientific capabilities of the LWA by reducing hardware failures, improving system stability, and supporting more reliable calibration and interferometric observations. Improved hardware performance is especially important for future studies of pulsars, fast radio bursts, ionospheric effects, and other transient low-frequency radio phenomena that require stable long-duration observations and accurate timing synchronization.

This work also contributes to the continued expansion of the Long Wavelength Array as a distributed interferometric system. As additional stations are completed and integrated into the array, reliable instrumentation, synchronization, and verification procedures will be

come increasingly important for maintaining phase coherence and overall system performance across large baselines. Overall, this project represents an important step toward improving the long-term reliability and scientific capabilities of the LWA for future low-frequency radio astronomy research.

Acknowledgments

I would like to thank my advisor Greg Taylor for his guidance, support, and patience throughout this project. His experience helped me understand both the technical work and the practical side of working with a large radio telescope.

I also want to thank the Long Wavelength Array (LWA) team for their help and collaboration, in particular Jacob Grosso that worked directly with me this past semester on part of the project.. Working with them was a great learning experience, both in the lab and during trips to the stations.

I am grateful to the University of New Mexico for providing the resources and environment that made this work possible.

Finally, I want to thank my friends and family for their support during this time.

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