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Inspection of the Very Large Array Radio Telescopes

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In early 2022, the National Radio Astronomy Observatory (NRAO) was in search of an engineering firm to perform an inspection of a sample number of telescopes of the Very Large Array Radio Telescope (VLA) facility. In August of 2022, mechanical, electrical, and structural engineers were sent to New Mexico to work with VLA personnel to perform a full in-depth inspection of the structural, mechanical systems, and lightning protection systems. The engineers also worked with the VLA staff to review maintenance procedures, and to identify areas of improvement in the preservation of the telescope array.

Photo 1 The VLA Telescope Array

Part I - Overview of the VLA

The VLA is short for the Karl G. Jansky Very Large Array. Karl Jansky was an American physicist who first discovered that radio waves were being emitted from the Milky Way galaxy. While working at Bell Laboratories, he was assigned to determine the source of static that plagued Bell's trans-Atlantic radio telephone service. In his search, he determined that the radio waves had to be coming from an outside source, and eventually turned his eye to the cosmos. He is considered one of the founders of radio astronomy. Congressional approval for the VLA project was granted in Summer of 1972, and the construction of the telescopes began. The first telescope was placed in Fall of 1975, and by 1980 the facility was fully operational. The cost of the project was $78,500,000. The site chosen for the facility is in the New Mexico high desert between the sparsely populated towns of Datil and Magdelena. The facility sits at 6,970 feet of elevation. Its remote nature and elevation make it an ideal location for radio astronomy, with little interference from terrestrial radio.

The VLA consists of twenty-eight 82-foot diameter telescopes, each weighing 230 tons. The telescopes are 94-feet tall. They are arranged in three linear arrays in a Y-shape, with each leg being 120° apart. Each leg has nine telescopes for a total of twenty-seven telescopes in use for the array. The twenty-eighth telescope is cycled out for maintenance. There is a designated maintenance shed where this is performed. The telescopes work in tandem to perform data collection. There are four commonly used configurations that allow the telescopes to change their focus. This works much like adjusting the aperture on a camera. The smallest configuration is Configuration A, with the telescopes being distributed over a 2,000 ft radius. Configuration D is the largest with a 13-mile radius. There are railroad tracks that run the length of each arm that allow the telescopes to be moved. The telescopes are set on pedestals that are located on spur tracks off the main arms. A specially designed lifter is used to move the telescopes along the rail tracks. The configurations are moved at intervals throughout the year to mitigate the down-time required to the relocate the structures.

The VLA was built to accommodate radio astronomy. The frequency range detected by the VLA is 74MHz to 50GHz. The science for the VLA is run out of the Domenici Science Operations Center (DSOC) located on the campus of the New Mexico Institute of Mining and Technology in Socorro, NM. In addition to the VLA, there is a Very Long Baseline Array (VLBA) that was built as a single 5,531-mile linear array. The telescope locations range from Hawaii to the US Virgin Islands and the array is made up of 10 telescopes. The telescopes are physically similar to the telescopes used at the VLA facility. The science for the VLBA is also run out the DSOC.

The VLA has been fully operational since 1980 and has been used in a wide array of scientific explorations. Perhaps the most notable was the discovery of the presence of ice on Mercury in 1991. The VLA is commonly used in stellar astronomy. The discovery that many stars emit strong waves in the radio frequency was made at the VLA. This had previously thought to be untrue as our sun emits only weak radio waves. In addition, the VLA has been used to discover protoplanetary discs around young stars and has been significant in the study of black holes. A notable ongoing study is the VLA Sky Survey. It began in September on 2017 and is will collect data for 80% of the earth's sky before its conclusion. Astronomers expect to find about 10 million new objects with the survey, which is about four times what is presently known. Needless to say, the VLA is a very active instrument with a high demand for its use.

Photo 2 One of the Radio Telescopes

Part II - Construction of the VLA Telescopes

Each of the VLA telescopes is comprised of three main parts. The pedestal room, the yoke, and the dish. The pedestal room is what grounds the telescope to the pedestals that it sits on. This houses much of the controls for the telescope, and connects power, fiber, etc. to the main control center at the VLA facility. The Yoke is spun on top on the base along a vertical axis for horizontal positioning. The dish sits on top of the yoke and contains all of the radio wave collection equipment. This includes the main reflector dish along with the focus rotation machinery (FRM) that can adjust the sub-reflector to allow the radio waves to be reflected back down to the center of the dish to various collection horn instruments. The Dish rotates on top of the yoke along a horizontal axis, allowing for vertical positioning of the dish. These three components working together allow the radio wave collection equipment to be pointed at any visible location in the sky.

In-between the base and the yoke is the azimuth machinery. This controls the tilt of the yoke about the vertical axis. Tilt occurs about a single large bearing with an integrated internal ring gear in the inner race. The outer race of this bearing is mounted on top of the pedestal room, and the inner race is mounted to the bottom of the yoke. The race is driven by two pinions that are mounted 180° apart. The pinions are connected to vertical shaft speed reducers that are each attached to a motor with an integrated brake.

Photo 3 Azimuth Machinery

In-between the yoke and the dish is the elevation machinery. This controls rotation about the horizontal axis. There are two spherical roller trunnion bearings connected to an elevation shaft. The shaft connects to the dish on one side to a counterweight on the other side. There is a segmental rack mounted about the radius of the elevation shaft that is used to control movement of the dish. The rack is driven by two pinions that are mounted to the yoke and are located a few degrees apart on the rack. The pinions are connected to horizontal shaft speed reducers that are each connected to a motor with an integrated brake.

Photo 4 Elevation Machinery

The focus rotation machinery is mounted in the apex above the dish. The FRM is attached to an offset sub-reflector at the focus of the dish and is used to focus radio waves reflected by the dish to one of the several collection horns. There is a set of machinery that rotates a barrel with the sub-reflector attached to the bottom. There are stepper motors that drive through a gear reduction mounted in the FRM housing that rotate a ring gear that rotates the barrel and sub-reflector. There is a brake integrated into the reduction. The distance from the dish to the sub reflector is adjusted by four equally spaced ball screws with pinions mounted to the top of each. The nuts for the ball screws are mounted to the barrel. There is a thin ring gear that meshes with each of the pinons on the ball screws. The ring gear is driven by a stepper motor that drives some gearing inside the FRM and connected to a fifth pinion on the ring gear. There is a brake integrated into the machinery as well. The ring gear is spun by the motor, causing equal rotation in the pinions mounted to the ball screws. Next to each ball screws is a rod with a linear bearing attached that keep the barrel oriented to the apex.

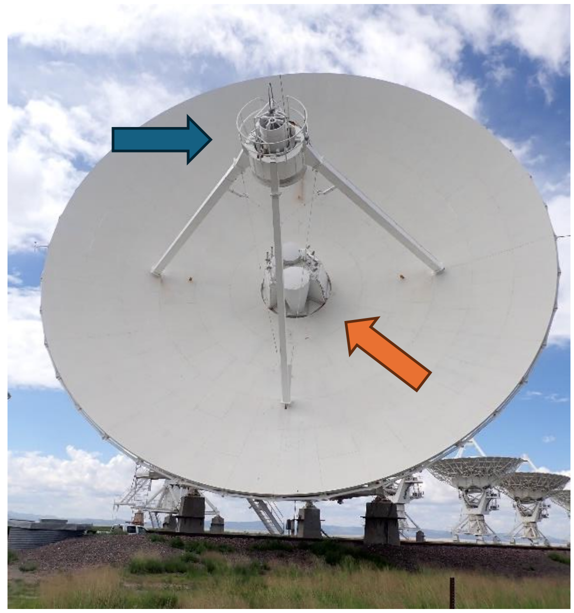

Photo 5 The FRM (blue) and Collection Horns (orange)

Part III – Engagement with the Client

A contract was let in 2022 to perform an in-depth structural, mechanical, and lightning protection inspection. The purpose of the inspection was to serve as an audit of the VLA staff's normal inspection and maintenance program. Since the inception of the VLA there have been staff performing routing maintenance and inspections, but they had never had an outside firm put a "second set of eyes" on the equipment they are charged with keeping operational. The VLA was interested in engineering firms with experience in other heavy types of movable structure inspections, as well as firms with experience with other large telescopes. While the VLA has mechanical and electrical staff who are very familiar with the mechanics of the structure and the scientific instrumentation, there is less expertise from the structural side. Staff had been noting select structural deficiencies, and part of the scope of work was to provide a full structural inspection and provide solutions and repair priorities to maximize the life of the telescopes. The electrical and mechanical inspections were mostly to catch anything the staff may have missed, and to provide recommendations based on our experience with other movable structures.

Part IV - Inspection Means and Methods

Three telescopes were identified by the client that represent three different stages of maintenance and scheduled machinery replacement. Because the maintenance schedule, it takes several years to cycle all 28 telescopes through the maintenance shed before returning to the first telescope. This means that some of the telescopes that were inspected had had maintenance performed recently, while some of them had been in use for quite some time. The different maintenance statuses helped illuminate how the antennae wear over time.

Photo 6 An Inspector using TARA Methods

Some of the structure was accessible via man-lift. Because of tight truss work that supports the main reflector, critical parts of the structure were not accessible through conventional access methods. Because of this, inspectors qualified in Technical and Rope Access Program (TARA) were required for the job. TARA is a collection of techniques and methods of access used by trained and qualified individuals to safely gain access to remote points on a structure for conducting inspections and limited testing in compliance with a written program. The inspection of the dish was performed mainly through solo climbing and short rappels. A set of ropes was established on the dish to allow climbers access to the reflector backup structure. Once there, climbers used rated slings and shock absorbing lanyards to protect the access while climbing to different points in the reflector backup structure. In addition to accessing remote points on the structure, TARA climbing was used to augment the use of the manlift to accelerate the inspection of the structure. The VLA staff has one man lift on site that was available for use. The remote nature of the structure made providing addition equipment cost and schedule prohibitive.

A full in-depth mechanical inspection of the telescopes was performed. This included inspection of the motors, brakes, couplings, bearings, open gearing, and enclosed gearing. Components were observed during operation for abnormal noises, vibrations, or heat. Components were visually inspected for signs of damage and wear, and to ensure they functioned as originally intended. Because the outside race and seal of the azimuth bearing was inaccessible through conventional means, technical access was used to position the inspector. With the dish in the fully vertical position, vibration analysis was used to determine the tension in the wire ropes supporting the FRM machinery at the apex.

Photo 7 Strain Gage Installed on Dish

Strain gages were installed in the support linkages of the either side of the counterweight. Because these could not be reached using conventional access, technical access was used to install the gages. A clinometer was attached to the dish, and the elevation machinery was operated through its full range of motion. From this data, the center of gravity and balance of the dish was calculated.

Photo 8 Taking Bearing Signatures for the Azimuth Machinery

Accelerometers were attached to the elevation bearings and to the azimuth bearings. The telescope was operated for the full range of each of these machinery systems, and bearing signatures were determined. These were compared to the rotational frequencies of the components in the machinery and used to determine if any components were failing.

The lightning protection and ground system was inspected on each of the telescopes identified. This included visual and hands-on inspection of the lightning antennae, the grounding wires, and the connection points between the pedestal room and the pedestals.

All load bearing elements of the telescopes were inspected by hands-on and visual means. This was performed using a combination of conventional access, a man-lift, and TARA. This included the pedestals on which the telescopes sit, the structural elements of the pedestal room, the yoke, the reflector backup structure, and the apex support members.

Part IV - Design Differences Between the VLA and Typical Heavy Movable Structures

For the most part, the machinery setup and practices were similar to other heavy movable structures. However, there were notable exceptions. For the vertical rotation controlled by the azimuth machinery, a large rim bearing was used to support the yoke and dish on top of the pedestal room. This is different than what would typically be used in a swing bridge, where a center bearing with balance wheels or a rim bearing with large wheels would be seen. This bearing type closely resembles large crane bearings that are used to position the boom relative to the tracks. The integrated brakes in the motors that act as the prime movers are also unusual for the heavy movable structures industry. This arrangement is common in sub-system machinery such as span locks, however, and is commonly seen in motors for other industries. One of the stark differences between the telescopes and typical heavy movable structures is the way in which they operate. Most HMS applications operate to discreet positions to allow different functions to occur. This is true for movable bridges that operate to open or closed positions for highway/rail traffic or marine traffic. Stadium roofs are operated to be open or closed to create and enclosed or an open environment for the enclosure. Train transfer cars and turn tables operate to discreet positions to allow trains to move from one track position to another. However, the telescopes are not trying to achieve movement between set positions, but to allow movement to any position in the sky. Furthermore, because the earth is constantly in motion relative to celestial objects, the telescope not only has to be able to operate into any position, but then to track that position as it moves in the sky. Furthermore, because the objects are so far away, the telescope has to be able to maintain a high level of accuracy in its positioning. This is accomplished by using precision bearings to allow movement, spherical bearings for the elevation machinery, and roller bearings for the azimuth machinery. This leaves the issue of controlling the open gearing to allow movement in the machinery, but eliminating backlash in the system. This is done by using a two motor system in each machinery set. Unusually, these are not redundant systems that drive together, but these are systems that drive against each other to ensure full face contact on both directions of the rack. One motor overcomes the torque in the other to allow movement of the system. Because the motors are constantly providing torque to the drive system there are blowers set up for the enclosed azimuth motors that supply fresh air to cool them during operation.

The motors and reducers also differ from what is typically seen in heavy movable structures. Because the motors are constant duty, they are not the same style motors that are typically specified for periodic duty. The motor and brakes are specially designed assemblies designed and supplied by Reliance Electric Company (currently owned by Baldor). The azimuth bearing reducers too are different from typical heavy movable structures arrangements. Because of spatial constraints, these motors are arranged with the high-speed input shaft vertically coming from the bottom of the reducer.

The lightning ground protection system on the VLA telescopes is unusual for movable structures in a few ways. Because the telescopes can change locations to form the different array configurations, there are hookups for power, data, etc. at each pedestal arrangement. One of these hookups is for the lightning protection grounding system. There are three connection points for each telescope at the base of the three pedestals. This allows the telescopes to be mounted in any arrangement on the pedestals. The grounding system for the pedestals is unusual as well. There are three 30-foot diameter rings of copper that are buried underground. This allows any accumulated energy from a lightning strike to be safely discharged into the ground.

The other interesting feature of the VLA lightning protection and grounding system comes from the movement of the dish. Because the dish is located at the top of the structure, it is always the highest elevation component on the telescopes. However, because the apex of the dish tilts during science, there are 3 antennae along the dish so that they are always the highest elevation member on the dish. There is one on top of the apex, and one on each side of the dish normal to the axis of rotation so that if the dish is pointed towards the horizon, one of the two antennae on the dish will point upwards.

Structurally, the telescopes are made up of sub-assemblies that were constructed in the field. While this is typical for large structures, the extent of field welding present on the antennae surpasses that of typical Heavy Movable Structures. Because much of the welding was performed in the field at the time of construction, the quality of welds found on the antennae is less than that of the primarily shop-welded members typically seen.

Part VI - Findings

The most outstanding finding from the inspection was that the staff of the VLA were very dedicated to the preservation, upgrade, and maintenance of the telescopes. This was evident from the meticulous maintenance logs they kept, the innovations they had made for the maintenance program, and their general understanding and dedication to the structure. The maintenance program is overseen by an engineer who works full time to establish maintenance procedures and address improvements in the program. Because there is a full-time staff dedicated to the telescopes, and because of the number of telescopes they have and their detailed record keeping, the staff has a very thorough understanding of the issues that the telescopes face. The staff directs the maintenance program around the failures they see and when problem areas are identified, they are incorporated into the inspection of the telescopes. The VLA facility houses several shops that provide tailored services for the telescopes. There is a full electronics shop, a dedicated maintenance shed, a machine shop, a fabrication shop, and a few other specialized shops. The maintenance is very streamlined with dedicated equipment and well thought out shop space to perform maintenance on each of the components of the telescopes. As evidence of the attention to detail, they create custom scrapers for lubricating the racks. They have the tooth profile cut out of them so that the maintenance personnel can use them to scrape grease from the full tooth space in one movement.

The structural inspection performed by the inspectors differed from the mechanical and electrical inspections. As the VLA staff does not have the structural personnel or experience that outside consultants do, this portion of the inspection was not as much of a review and investigation into maintenance practices as the rest of the inspection. Many of the findings from the structural team had been previously identified by VLA staff. The structural inspectors were able to offer lifecycle estimates and repair priorities based on many years of work in the Heavy Movable Structures industry and from many years of inspection work at the Green Bank Radio Telescope.

Photo 9 Damage to the Reflector Backup Structure

The reflector backup structure is made up of radial beams, ring beams, and supporting diagonal members. The members in the backup structure are connected by a combination of welds and bolts. As previously mentioned, many of these welds were performed in the field, and are of a lower quality than that typically seen for Heavy Movable Structures. The welds commonly have porosity and discontinuities which allow water to infiltrate the hollow tube members. Water was observed actively draining form multiple tube members during the antenna movements. The presence of water inside the tube members has induced advanced corrosion in many places, resulting in holes, bulges and ruptures, cracking, and general section loss. Moisture intrusion, paint failure, and corrosion were found in several other locations, although were not as prevalent. The pedestals were also inspected and found to be cracked.

Photo 10 Damage to the Azimuth Bearing Race

The major mechanical finding was the damage in the azimuth bearing. This damage is typical of the telescopes, and the bearings are in the process of being replaced as part of a long-term maintenance program. One of the recently replaced bearings was disassembled and made available for inspection. It was noted that there is significant damage to the bearing, especially to the outer race. The bearing configuration is different than typical bearings for the heavy movable structures industry. The cross section of the bearing has the inner race concentric inside of the outer race. In-between the two races is a square cutout that is rotated 45° to accommodate the rolling elements. Every other element sits 90° rotated from the previous element, so that the elements not only bear on the upper side of the inner race and the bottom side of the outer race, but on the bottom side of the inner race and the upper side of the outer race as well. The elements are separated by individual races that maintain the element orientation.

The races, especially the outer races, had concentrated damage when inspected. The failure mechanism seems very similar to case crushing in hardened gears. Loose flakes of metal were found in the grease. These loose flakes break off and interact with the elements and races at other points in the bearing, causing stress concentration and additional damage. The damaged surfaces of the races incur stress concentration around the damaged edges and have a tendency to grow. This interaction damages the rolling elements as well, and depressions can be seen where they have rolled over damaged surfaces. The elevated levels of ferrous debris and elemental iron in the grease confirm the suspicion that the bearing is deteriorating and that the detached pieces are engaging in the mesh. Interestingly, the advanced wear of the bearing has not yet caused an issue with the operation of the telescopes. The positioning of the dishes is still quite accurate and has not disrupted the science being performed. The bearings have been in use since the telescopes were commissioned and have been in service for around 50 years. The failures seen in the bearings that we observed are typical according the VLA staff. Because of the typical nature of the failures, the bearings are being replaced in all of the telescopes as part of a long-term maintenance project.

In addition to the failure of the rolling elements of the bearing, failures in the azimuth bearing seals are typical as well. There are lip seals mounted on both sides of the bearing. The inner lip seal is mounted on the outer race and rides on the inside face of the inner race, inside of the pedestal room. The outer seal is mounted on the inner race, and rides on the top of the outer race, outside of the pedestal room just below the yoke. The seals are torn at regular intervals both the inner and outer seals. Because the inner seal works against gravity to maintain contact with the inner race, failures cause the seal to completely loose contact with the race opening up the bearing area to the elements. Because the outside seal sits up on top of the outer race, it is open to debris from the outside environment. These factors compound the wear and failure of the seals. An analysis of the grease samples from the azimuth bearings found elevated levels of moisture. The failure of the outer seal especially contributes to the introduction of moisture to the bearing, especially since the seal is exposed on the front and back side of the yoke. The seals are original to the bearings, and have been in service for about 50 years. They are being replaced along with the new bearing replacement program.

The other significant issue with the telescopes is the azimuth rotation machinery. Because of the layout of the pedestal room and the arrangement of the rack, vertical shaft speed reducers had to be used to drive the antenna. Because there is not space to mount the reducer above the rack, the machinery arrangement is that the low speed shaft that the pinion is mounted on sticks up through the top housing of the reducer, while the high speed shaft coupled to the motor protrudes from the bottom of the reducer. Because the high speed shaft needs circulating lubrication to keep the bearing cool and well oiled, the bottom seal of the high speed shaft sits below an oil bath. This causes leaking in the seal. Because the motor and brake assembly is oriented vertically, the leaking oil runs through the motor and pools in the brake housing. This causes issues to both the motor and to the brakes. The C flange mounts have been modified with a channel that directs oil away from the motor, and into a bucket via a hose. This is mostly effective, but oil leaks are still quite common in the reducers. The brake at the end of the motor still collects some oil, reducing the braking torque provided. The other issue with the brakes is that they frequently do not fully release. Because of the vertical mounting, they do not pull away to fully release when energized. The VLA staff have modified the brakes to add springs to the assembly so that the brake pads fully release from the brake when the motor is in use.

While investigating the balance of the dish, it was determined that they are apex-heavy. It is interesting to consider an ideal balance of the dish. Because the drive motors are designed to take out all of the backlash from the system, there may not be any real effect from the center of gravity rotating about the elevation shaft axis. The only affect the dish balance would have would be in the event of a full failure of the positioning system, in which case it would come to rest with the dish down. This may not be a desirable condition, however, since the operation of the dishes is reportedly not inhibiting the collection of data, no recommendations were made for the balancing of the dish.

Part VII – Conclusion

Photo 11 Telescope in the Maintenance Shed

In the end, the inspection of the Very Large Array Telescope mostly provided confirmation of the competency of the VLA staff's understanding of the telescope and their ability to maintain it. While several new findings were made and reported, no large concerns arose that were not already identified by the VLA. Mechanical and structural teams were able to make suggestions for improvement of the maintenance of the structures, and the structural team provided several repair recommendations. As an owner, the VLA is very diligent about the upkeep, maintenance, and improvement of their structures, and is very competent in their area of work. It was an exciting opportunity to be able to work on these structures and see how other purpose-built heavy movable structures are designed, operated, and maintained.