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ABSTRACT

The Magdalena Ridge Observatory Interferometer (MROI) is designed to operate 10 1.4m telescopes simultaneously, with baselines ranging from 7.8-347 m and limiting infrared fringe-tracking magnitudes of 14 – it is arguably the most ambitious optical/infrared imaging interferometer under construction today. In this paper we had intended to present an update of activities since the 2018 SPIE meeting as we approached a demonstration of first fringes with the facility originally anticipated for the fall of 2020. However, due to the global pandemic and a loss of funding for our project via AFRL, we have been unable to make the progress we intended. In this paper, we present results up through March, 2020 and a brief discussion of the path forward for the facility.

Keywords: optical/infrared interferometry, telescopes and enclosures, delay lines, beam combiners, fringe trackers, alignment systems, MROI, ICoNN

1. INTRODUCTION

The Magdalena Ridge Observatory Interferometer (MROI) has presented incremental progress updates many times at the SPIE conferences and in the literature [1, 2, 3] over the past 2 decades, as well as developed innovative designs for several critical subsystems for interferometric facilities including telescopes, delay lines, fast tip-tilt systems and beam combiners [4, 5, 6, 7]. The initial conception for the MROI was based on the Large Optical Array [8], a second-generation design from the late 1990's based on lessons learned from the COAST, NPOI and Mark series of interferometers in the UK and the US. At that time, a large fraction of the optical/infrared interferometric community across the world was focused on techniques associated with narrow-angle astrometry, differential phase, mid-infrared interferometry and nulling interferometry, none of which required an array capable of snapshot imaging simultaneously using multiple telescopes and multi-way beam combiners, nor the extensively long baselines required to attain sub-milliarcsecond angular scales. Over the intervening 20 years and two US Astrophysics Decadal surveys, while some of these specialized interferometric techniques have shown some progress [9] and recent exciting scientific results [10], multi-way beam combination for interferometric imaging using more than 4 telescopes is still rare. The promise of MROI's design, which adopts the best approaches from alternate facilities while trying to avoid known issues, especially those associated with vibrations and thermal stability, still holds to this day.

1.1 General Overview of Project

Today the MROI has successfully deployed all critical subsystems needed for the facility on the array at the Magdalena Ridge or in the lab at the New Mexico Tech campus. Until our recent funding issues, we were on track to attain first fringes with the facility this year. Our telescopes have been designed and are being built by AMOS in Belgium. They

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are an altitude-altitude design which serves several purposes: a) minimizing the number of reflections in the system (from 6 or 7 for alt-az systems) to 3 before entering the beam train, b) housing the tip-tilt sensing system on the Nasmyth platform which operates in closed-loop with the telescope secondary, and c) maintaining the polarization of the astronomical signal in a way that can be easily recovered and measured within the beam combining facility. The telescope enclosures have been designed and are being built by the EIE Group in Italy. They are used to: a) house and protect the telescopes while maintaining optimal airflow and temperature profiles within the immediate vicinity of the telescope itself, b) allow the telescopes to operate in a close-packed configuration of 7.8 m center-to-center telescope distances, tracking on targets for up to 6 hours without vignetting on neighboring enclosures, and c) safely transport the telescopes and allow for rapid relocation onto new kinematic pads on the array within a matter of hours. The delay lines are single-stroke long-delay (190 m) vacuum pipes within the delay line portion of the facility (see Figure 1) which extends directly to the east of the beam combining facility. The delay lines use trolleys employing a cat's eye design suspended in a cantilevered system and driven with voice coils. The trolleys maintain distance between the primary and secondary mirrors via a carbon fiber body, riding on compliant wheels within the aluminum vacuum pipe, and powered via an inductive wire laying in the bottom of the pipe itself. This design supports continuous observing, without the need for pop-ups or additional delay paths, which is needed to improve observing efficiency and sky-coverage available for imaging studies. This also reduces the need for additional reflections with their associated alignment and scattering issues and throughput losses.

Figure 1: A merged photograph and CAD drawing of the completed MROI telescope array. At top of the picture (farthest north) is the MRO 2.4m stand-alone telescope used for asteroid research. Intermediate are two facilities along the road, a small balloon hangar (grey) for atmospheric research to the west of the road, and the visitor's center (red) and maintenance facility (beige) (VCMF) to the east of the road where telescope assembly is conducted. At center-bottom of the photo is the completed MROI beam combining facility; the long portion of the building off to the south-east is the delay line section of the building. The array arms clockwise from the bottom are south, west and north respectively. The arms and telescopes are a CAD drawing superimposed on the photo of the array in its most expanded configuration. Photo by Tyson Eakman and CAD image of array by Andres Olivares.

The beam combining facility itself was designed from the outset as part of the astronomical experiment under contract with M3 Engineering in Tucson, AZ. The building's design philosophy is based on the idea of a "building-within-a-building" – external walls and footings are physically separated from the "technical" portion of the facility where delay lines, beam combining tables and detectors are located. Environmental controls (heating/cooling, water pumps, emergency generators, etc.) are located far away from the technical portion of the facility in their own housing, and a philosophy of passive thermal control (to better than 1^{o} C diurnally) in a "smart building" is used wherever possible to greatly reduce the possibility for vibrations from mechanical equipment to disturb the scientific measurements. The delay lines are supported on a technical slab which floats on repacked ground with strict subsidence requirements – all of which the facility has easily met. In the inner beam combining laboratory care has been taken to design a thermally stable, dead-air space with vibrationally stable tables on custom concrete legs and conditioned power isolated from the rest of the facility. Overhead cable trays and thermal enclosures above optical tables will allow us to maintain the strict thermal and vibrational requirements for the space where beams are travelling in open air. Finally, the optical tables themselves (see Figure 8) have been laid out to support the philosophy that photons are "sacred" and we will make every effort to not steal light and use it for multiple functions within the facility. As such, fringe tracking takes place at H or K band, where the telluric seeing effects are more benign. The design is based on a nearest-neighbor concept, which means that only the fringes from neighboring telescopes will be used for phasing the array [11]. This has the effect of allowing the facility to fringe track on fainter, unresolved targets more successfully – but requires important planning for the beam switchyards in the case that a telescope drops out. The 10-way beam combiner and multi-beam fringe tracking cameras follow beam switchyards which allow us to compensate for any potential telescope drop outs, as well as switching in different telescopes to rapidly mix beams together on the science instruments allowing us to combine the input of all 10 telescopes in a few minutes, harnessing the full power and promise of the MROI facility.

Scientific observations will use the phase-stabilized array's output on other higher (spectral) resolution beam combiners and cameras in the optical or near-infrared, working at different wavelengths than is being used for the fringe tracking in the system. Finally, a visitor instrument table is included in the facility to allow for new developments and visiting instruments/experiments to be brought to the facility. End-to-end beam control and computer controlled alignment has been planned into the system from the outset, coined the Automated Alignment System (AAS). Included in this system are artificial light sources in the optical and infrared for beam alignment, pop-up quad-cell style detectors, and a back end Shack-Hartmann system to sense the beam alignment and correct throughout the observing night (discussed by Luis et al. in this conference [12]). Finally, the most critical and yet unseen subsystem in the entire facility is the real-time end-to-end computer control accomplished via an Interferometry Supervisory System (ISS) which uses a publish subscribe philosophy for the majority of interferometer communications. Some subsystems using Xenomai Linux as the backbone for hard real-time control; these are discussed at more length in a companion paper also in this conference by Seneta et al. [13]. First fringes will be achieved using ICoNN with upgraded infrared photon-counting detectors [7, 11]; initial science will be accomplished as soon as feasible using a simple 2 or 3-way moderate resolution infrared science combiner, FOURIER [14]. After all this initial deployment, we will continue to secure funding and complete the facility first conceived many years ago by our colleagues at Cambridge. Ultimate success and scientific utility of the facility will depend on the astronomical and defense communities for their support in terms of future scientific components and unique experiments, as well as operations funding. We await the results of the US National Academy of Sciences Astrophysics 2020 Decadal Survey to determine if there is adequate interest from the community to support a bid from MROI for NSF, NASA or other publicly funded support.

Below we discuss a few areas of significant progress for the MROI since the previous SPIE Astronomical Telescopes and Instrumentation meeting in 2018 in Austin, TX.

2. TELESCOPE, ENCLOSURE, FTT AND FIRST LIGHT ON THE ARRAY

Under the initiation of the current cooperative agreement funding with the AFRL, the MROI team restarted contracts with multiple vendors that had been previously conducted under NRL funding and support after an approximately 2.5-year hiatus. In 2016 we assembled and installed the first unit telescope mount (UTM) in the maintenance facility (see Figures 1 and 2) and began first light testing of the system via a large, north-facing roll-up door. At the time of the prior SPIE meeting in summer 2018 we were in the process of assembling the first unit telescope enclosure (UTE) in the same maintenance facility bay and preparing to mate it with the UTM at the integration station located directly east of the facility, before moving it to the MROI array. The UTE had undergone full assembly and factory acceptance testing

Figure 2a and 2b: At left is shown the lifting of the unit telescope mount (UTM) using a crane to place it on the integration station located outside the VCMF. In the background can be seen the unit telescope enclosure (UTE) ready to be moved as well. At right is shown the integrated UTM and UTE into one unit telescope (UT). The 28 ton UT was moved from the VCMF to the MROI array station on a leveling truck and placed on the kinematic pad using a crane with the custom lifting fixture instead of a reach stacker.

earlier in 2018, and was then disassembled, packaged in several shipping containers, and sent from Italy to the port in Houston, TX. The UTE was then driven to the top of Magdalena Ridge in late spring and assembly was completed over several weeks. We initially assembled the telescope assembly using a crane, transporting it to the array via leveling truck and crane across approximately 0.5 km and mounting the system on the second station along the west arm 7 m from the center of the array, referred to as W7. Integration of the UTM and UTE into a unit telescope (UT) and relocation onto the array was expected to take only a few days, but poor weather, winds and a miscalculation of the counter-balance needed for lifting the UT resulted in a procedure that took approximately 1 week. Ideally in the future the MROI project will purchase a reach stacker and modify it for use with a custom handling fixture in order to more easily integrate the UTM and UTE, or for relocating a UT in approximately 4 hours to a new station anywhere along the array arms.

After installation on the MROI array, we undertook site acceptance testing of the UTE and the UTM with each of the individual vendors over about 3 months of time. Software to operate the telescope was delivered by Observatory Sciences in the UK and was ready to be operated both in standalone mode and integrated with the ISS system for the interferometer. The UTE, however, was delivered with stand-alone software which had to be integrated with the ISS and programmed to perform sequencing tasks properly under anticipated control conditions for the UTs on the array. At this same time, in Nov of 2018, the first fast tip-tilt system (FTT) was fully integrated with the UT on the Nasmyth table adjacent to the UTM by our collaborators at Cambridge University. On-sky tests of closed-loop performance were carried out on two nights, for a range of pointing directions and target star magnitudes in the range 8-14. These tests confirmed that the system is fully functional, and delivered two-axis tip-tilt residuals of 30 mas on bright stars, degrading to 88 mas at 12th magnitude and 130 mas at 13th magnitude. Independent verification of nightly (spatial) astronomical seeing over the Ridge was conducted simultaneously by Dr. John Briggs (Magdalena, NM) using his DIMM seeing equipment. These measurements confirmed the potential for excellent seeing on the Magdalena Ridge, the measured seeing being in the range 0.5-0.8 arcseconds most of the time. Importantly, a comparison of the DIMM measurements with data from the FTT system revealed a negligible contribution from dome seeing in the UTE. In late December 2018 several snow storms hit the mountain in rapid succession and due to a failure of one of our pieces of road equipment led to a period of 5 weeks without regular access to the facility or opportunity to continue in situ testing. In Figure 3 we show a fish-eye lens view from inside the UTE of the UTM located on the array.

Figure 3: A fish-eye lens photograph inside a UTE looking at the UTM (see text for details). To the far right hand side one can see the inner edge of the Nasmyth platform. When moved, the entire assembly (UTM + UTE + UT optics (UTO) = UT) is moved as a single object, ideally using a reach stacker. Photo by Colleen Gino.

While our team in New Mexico and Cambridge worked diligently with the vendors to continue to understand and safely operate the first UT system, we undertook restarts of all the telescopes, enclosure and optics contracts in order to deliver the second UTM and UTE as quickly as possible. Along with the components on the array, the second FTT system and second delay line (DL) trolley from Cambridge were being completed and tested at their labs in the UK. We spent much of 2019 monitoring and making progress on these contracts and were a few months from delivery of the second UTM and UTE when we had to issue a stop work order to all our vendors due to a lack of funding from Congress in our AFRL cooperative agreement. Figure 4 shows the metal frame of the second UTE in EIE Group's assembly facilities in Italy.

Figure 4: Metal skeletal frame of the lower half of UTE #2 seen in 2019 at the EIE Group facility in Italy.

3. OPTICS, AUTOMATED ALIGNMENT AND BEAM COMBINING FACILITY

Six sets of UT optics were purchased in the early 2000's in support of the MROI project. The secondary and tertiary mirrors were all completed under an earlier contract with a vendor who unfortunately went bankrupt during the Great Recession. Upon inception of funding with AFRL a new bid process was initiated to identify a new vendor capable of completing the primary mirrors for the project. The first primary mirror had been partially completed with the previous vendor, but no vertical tower tests using a CGH (computer generated hologram) were undertaken, so the exact figure of the primary mirror in UT#1 is to this day unknown. The winning bid was from Arizona Optical Systems (AOS) in Tucson, AZ (see Figure 5). They completed the primary mirror for UT#2 reaching 17.0 nm RMS wavefront prior to coating. Our requirement for the primary mirror is 19.5 nm RMS, and so this development was an excellent milestone. When the primary mirror was sent out for aluminum coating an issue with the coating chamber caused a slightly uneven coating to be applied, taking the mirror slightly above our RMS specifications to 23.3 nm RMS. At a future date we will recoat the mirror in the hopes of recovering the excellent surface quality attained during polishing. The third primary mirror surfacing and polishing was started in late 2019 and was about 6 months from completion when the stop work order was issued. Once completed, we anticipate swapping out this third primary for the primary mirror currently in use in UT#1 and measuring that optic with the CGH in order to determine the overall surface quality and also recoat the mirror. Ideally, the MROI primary mirrors will be CO_2 washed on a regular schedule and recoated every few years in order to maintain good throughput and have reduced surface scattering.

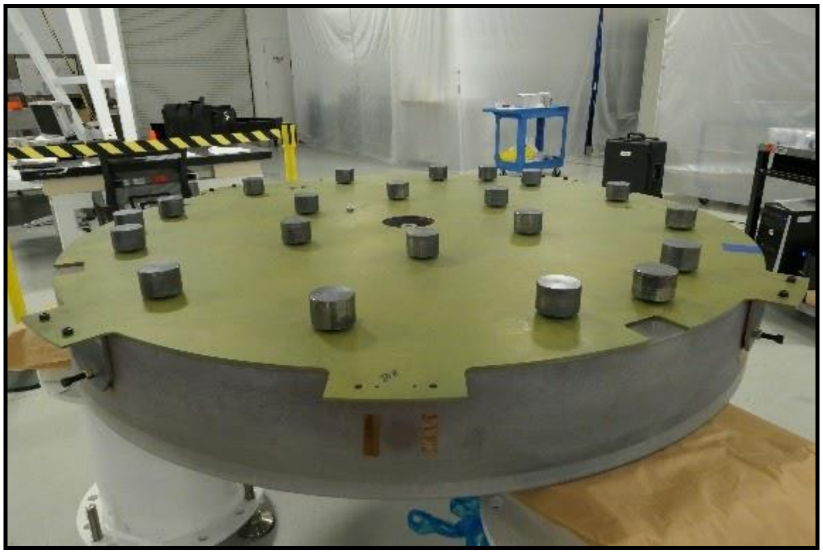

Figure 5: An MROI primary mirror under inspection in 2019 at the vendor's facility at Arizona Optical Systems in Tucson, AZ.

The Automated Alignment System (AAS) has been covered in several earlier SPIE papers by our team; a companion paper on the status of recent work on the Unit Telescope Light Injection System (UTLIS) and the Back-End Active Stabilization of Shear and Tilt (BEASST) sub-system is being presented by Luis et al. [12] as part of his dissertation work at Cambridge. In addition, a new partnership was started in 2019 with researchers in the photonics group at INOAE in Mexico to develop next-generation photovoltaic quad-cell detectors to be used in the vacuum system to sense the position and alignment of the beams as they travel down the beam transport system from the telescopes to the beam combining facility. A Dahl-Kirkham beam compressor was purchased from Optical Surfaces Limited (OSL) in the UK in a pilot project to test the accuracy of our end-to-end alignment and field-of-view performance for the interferometer. After being placed in the inner beam combining area (IBCA) it completed the beam path so that star light from the first unit telescope passed through the FTT, beam relay, delay line and compressor before arriving at the BEASST camera in fall of 2019 (see Figures 6 and 7). Detailed results and performance are discussed in the Luis et al. paper, however, as a result of these experiments we have learned that there is significant diurnal beam motion between the telescopes and IBCA. This motion is mainly thermal and can be tracked well using temperature sensors at multiple locations along the beam train. However, there remains a non-thermal motion component still under investigation today. During science operations, our realignment strategy will be to feed temperature readings from the beam train to a predictive model that will decide how to compensate for the drift to first order. During pauses in stellar observations, UTLIS will be switched on so that BEASST can diagnose and clean up residuals left behind by this model-based correction. Measurement and control of shear and tilt to 1% of a beam diameter, 15 milliarcseconds on sky (equivalent to 0.2 arcseconds in the beam relay or 1.6 arcseconds in the IBCA), is essential to maintaining excellent throughput and high-contrast fringes in order to attain our goal of an H band fringe tracking limit of 14th magnitude.

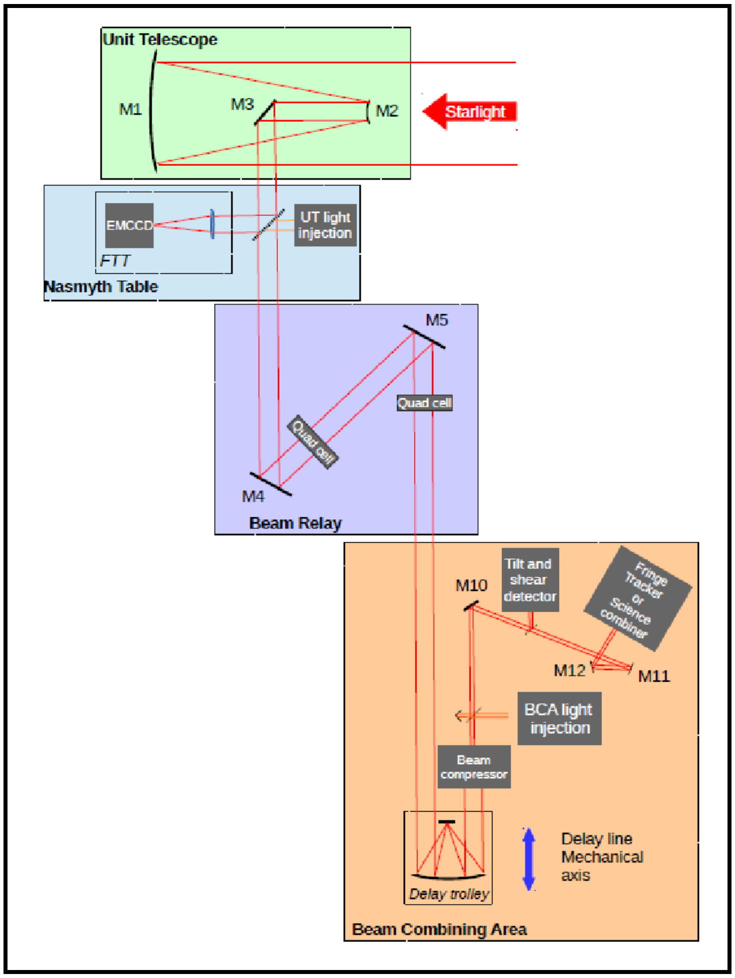

Figure 6: The conceptual layout of the MROI optical beam train. The four color-coded boxes represent 4 different optical systems requiring alignment with respect to each other via the Automated Alignment System (AAS). Everything within the MROI beam train is aligned to the 3-dimensional space defined by the delay lines. All tilt and shear measurements and adjustments are conducted in order to align the incoming stellar beams from the telescopes with the delay lines, and after the delay lines via the M10-12 mirrors into the fringe tracking and science cameras.

Specification, purchase and installation of the optical tables for the IBCA was reinitiated in late 2019 after extensive vibrational testing of the existing tables was completed; a redesign of the table layout was also accomplished in order to optimize the beam switchyards (see Figure 8). Despite high vibrational requirements and installation of tables using legs developed by the manufacturers, unacceptable levels of vibration continued to plague the metrology table in the IBCA. An extensive study of the vibrations, including by actively exciting the tables from both the floor and on the tables themselves, as well as a full Finite Element Analysis (FEA) showed that in order to reduce the vibrations from 16 Hz, a factor of 3X that was called for in our specifications, we needed to take a more drastic approach. We tested and found a successful answer in creating customized concrete table legs and fixing them to the floor directly via gluing. A small fixture is built into each leg at the top to allow for table leveling. Using a Leica laser tracker we purchased via a DURIP grant from AFOSR we are able to locate the legs and tables at the 10 micron absolute level with respect to fiducial markers in the IBCA (see Figure 7b). This level of precision allows us to ensure that the rectilinear hole patterns on the tables are aligned optimally with respect to the beam paths within the facility. After the delay lines have adjusted the stellar beams to remove delay and place all the beam paths on the same phase plane, the beams exit the vacuum system, are reduced in diameter, and travel tightly controlled geometric paths within the IBCA until they reach the beam combiners in front of each of the fringe tracking and science instruments. Redesign of the table layout was required to improve the combination process and resulted in beam combiner optical tables shifting down (east within the facility) in order to better optimize turning angles, beam pitch and layout for the fast switchyards for the beams within the IBCA. New custom tables had to be specified out front of the beam combiner tables for the switchyard layouts based on our experience with vibrational testing of the existing tables (see Figure 8). The tables are shown in grey on the right hand side of the figure and the extended boxes seen on the top of each table represent the slide sizes required to move optics in and out of the beams for the switchyard functionality. These tables have been designed and will be completed and installed as soon as funding resumes.

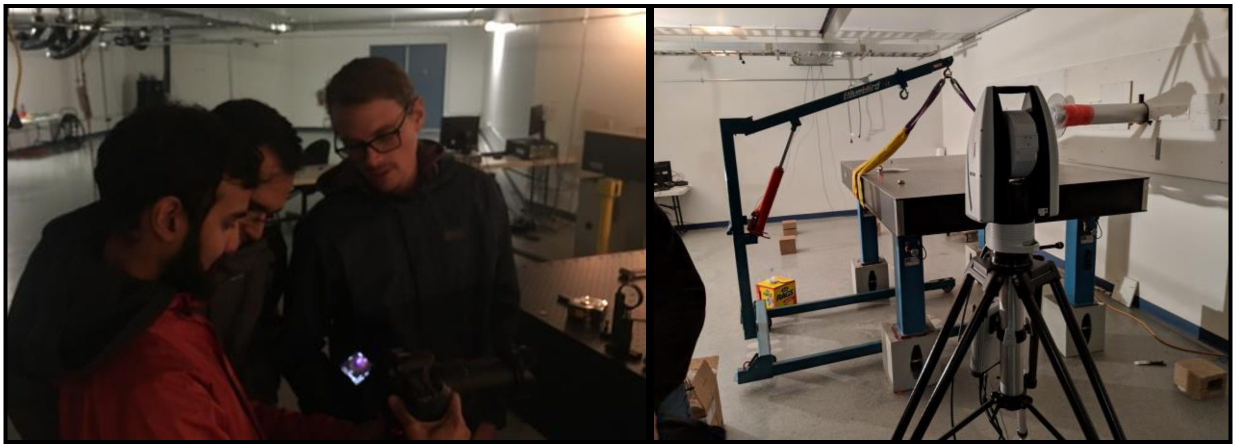

Figure 7a and b: At left we see graduate students Luis, Norouzi and Dooley (left to right) working on the installation and an interrogation of the BEASST system. At right we see the installation process for an optical table in the inner beam combining area using a lifting mechanism and a Leica laser tracker.

Figure 8: A new inner beam combining area (IBCA) table layout was developed to optimize the beam locations and fast switchyard system. On the left side from bottom to top are the delay line metrology table, the beam compressor table, the table for the automated alignment system and the table for the M10 turning mirrors. From left to right across the IBCA are the visible instrument table, infrared instrument table, infrared fringe tracking table and visitor instrument table. Across the top on the right side of the room are the switchyard tables (in grey) for reorienting and selecting the beam for each of the instruments on the adjacent tables.

4. FUTURE PLANS

Once funding is restarted for MROI, hopefully in early 2021, we anticipate a great deal of restart activity in order to recover our schedule and attain first fringes with the facility. While all contracts have to be restarted, we hope that all our vendors are still capable of supporting us given the trying times associated with the pandemic. The first UT will be relocated to the central station on the array (W0) where it will likely remain in perpetuity. Once the second UT is assembled and completed it will be placed on W7 where the first UT is today. The temporary cooling hut seen in Figure 9 next to UT#1 is capable of supporting the first telescope, however upgrades to a system capable of supporting 3 UTs, and then the permanent cooling system for all 10 UTs and associated infrastructure will have to be installed and plumbed into the array infrastructure in the coming years. Today 7 of the 28 stations are located and partially installed (in terms of services) on the MROI array. In the next few years the central portion of the array (13 or 16 stations depending on how one counts) needs to be completed, and then work down each arm (4 or 5 stations each) so that the full promise of the MROI's angular resolution may be achieved. Along with concrete telescope stations and optical beam transport piers, a few thousand meters of aluminum vacuum pipe will have to be installed. All of this external infrastructure includes power, ethernet and cooling loops and must meet subsidence and lightning protection requirements for the entire array facility. Inside the beam combining facility, along with the optical tables discussed for the IBCA, delay lines pipes, stanchions for their mounting, and appropriate power receptacles will need to be installed. Delay line pipes must be installed from the center outward due to the tight spacing laterally within the delay line area. Finishing of the ends of the pipes (for vacuum purposes), as well as many components of the beam transport cans and cryogenic dewars for the fringe tracking and science cameras are all being developed and manufactured at Universal Cryogenics in Tucson, AZ. We anticipate fringes at deeper magnitudes (K magnitudes of 10 or better) than are routinely accomplished today with similar sized telescopes about 15 months after all contracts are restarted.

Figure 9: South facing drone photograph of completed beam combining and delay line facility for the MROI with the first unit telescope located on the west arm of the array. Next to the telescope is a temporary cooling system used to operate the telescope and electronics cabinets in UT#1. It is capable of supporting one telescope; the permanent system will have to be installed shortly. This will be located to the left, away from the array arms, in this picture. To the far right in the picture can be seen a yellow metal lifting frame used to assemble and relocate the telescopes.

5. CONCLUSIONS AND ACKNOWLEDGEMENTS

The MROI has been under design and development for more than 15 years now. Despite ongoing funding challenges, we are confident that new funding can be secured as we close out this $20M 5-year cooperative agreement with the AFRL. With luck, by the time of the next SPIE conference we will be attempting to combine light from two telescopes to get first fringes at MROI. At that time, we hope to demonstrate the promise and feasibility of faint fringe-tracking on complex targets. With the completion of MROI's ten-telescope facility, we will be the most ambitious optical/infrared interferometer built to date. Its existence at a continental site in the US will readily allow access for many groups and will be helpful in the development of future interferometric facilities as the visitor instrument table can be used to deploy and test new technologies. The total cost of the MROI facility is estimated to be around $150M, still considerably less expensive than either extremely large telescopes under development today or most space-based facilities capable of high angular resolution imaging. We eagerly anticipate the results of the 2020 US Astrophysics Decadal Survey and of developing new, expanded partnerships as we forge ahead with this ambitious project.

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