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Assembly and Integration Activities moving Toward Commissioning of the Magdalena Ridge Observatory Interferometer

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ABSTRACT

The design phase of the Magdalena Ridge Observatory Interferometer (MROI) has been completed and the project is currently in the construction phase. The first telescope will be deployed at the MROI site in 2011. Five different vendors are involved in the design and fabrication of a unit telescope, and a much larger number of vendors for the design and construction of the full observatory.

This paper addresses the steps that the MRO Interferometry project will undertake to integrate subsystems developed by different parties, through commissioning into an operational optical interferometer.

Finally we present the commissioning plan to bring the interferometer to an operational mode. We have developed "performance verification milestones (PVM)" that successively increase the "science readiness" of the interferometer and transitions to an operational phase.

Keywords: Optical interferometry, commissioning, system integration, operations

1. THE MAGDALENA RIDGE OBSERVATORY INTERFEROMETER

The Magdalena Ridge Observatory Interferometer (MROI) [1] is designed to be a 10 element interferometer operating in the visible and the near-infrared. MRO is funded by an appropriation from the US Congress, and the funding is administrated by the Navy Research Laboratory (NRL). The interferometer will serve astronomers by collecting unique high-spatial resolution data, providing a tool for space situational awareness, being an educational tool, and providing economic development. MRO is hosted by the New Mexico Institute of Mining and Technology (NMT), a Ph.D. granting university located in Socorro, New Mexico. The MRO Interferometer is expected to see first light in 2011 and first fringe in 2012.

1.1 Science drivers

The key science mission for the MROI is focused on three main areas:

1. Studies of the environments of Active Galactic Nuclei (AGN);
2. Stellar formation and the earliest phases of planet formation;
3. Fundamental physics: stellar diameters, mass-loss, mass-transfer, convection and pulsation of single and multiple star systems.

1.2 Design goals

The design goals for MROI are multi-faceted and developed to meet the science drivers for the facility. Two of the most critical features of this design are:

1. To detect fringes on objects as faint at H=14;
2. To provide model independent images.

The design goal relevant for this paper is that MROI is designed to be a "facility class" observatory. This poses requirements on the efficiency and reliability of operating the observatory and the user support.

1.3 2010 Status of construction

At the time of submitting this paper (July 2010), the design of all major subsystems for the interferometer has been completed. Major progress has been achieved in construction of the building (the interferometric laboratory (Figures 1 & 2), the delay line area, and the office space). The first telescope (Figure 3) is in its final stage of testing at AMOS in Liege (Belgium). The optics for 6 telescopes are being fabricated by OST (Figures 5, 6, and 7). EIE has completed the delivery of the final design and fabrication documents for the enclosure (Figure 4). A request for qualifications (RFQ) to fabricate the enclosure has been issued. A request for bids (RFB) is planned for fall 2010. A detailed discussion on the current status of the design and construction activities, as well as additional design details are presented by numerous authors during this conference [1 to 7].

Figure 1: aerial view of the Magdalena Ridge Observatory Interferometer in its close-packed configuration. The telescopes and facility building are shown as renderings in this view of the MROI site. The main facility building, however, was completed in 2008. Picture courtesy of M3 and EIE.

Figure 2: MRO Interferometry building at the observatory site.

Figure 3: picture of the first MROI telescope in the fabrication hall at AMOS in Belgium (December 2009). Picture courtesy of AMOS.

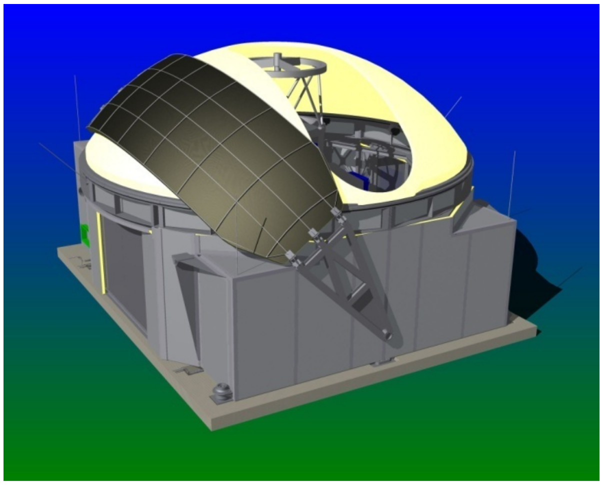

Figure 4: CAD drawing of the enclosure at the final design review. Picture courtesy of EIE.

Figure. 5: MROI 1.4 meter primary mirror. Courtesy of OST.

Figure 6: MROI 110 mm light weight secondary. Courtesy of OST.

Figure 7: MROI 260 x110 mm flat tertiary mirror. Courtesy of OST.

1.4 Initial operational status

The interferometer is a scalable, modular, research infrastructure. The minimum requirement to obtain an interferometric measurement is two telescopes, with all associated hardware and software to perform fringe tracking. For this paper we assume that imaging capabilities will begin once light can be combined on an imaging beam combiner, likely sometime after 3 or more telescopes become available.

The plan is to have the inner 13 stations (Y-shaped array configuration with 4 stations on each arm, and a central station) available on which to position three telescopes. This configuration is referred to as the close-packed configuration and allows for a maximum baseline of 47 meters, mimicking a telescope with a diameter of 47 meters.

Three levels of maturity for the MROI infrastructure are identified in table 1. An overview of the initial operational capabilities is presented in table 2.

Table 1: levels of maturity of the MROI infrastructure.

	Description
3T-NIR	Coherent combination of near-infrared light from 3 telescopes using a fringe tracker.
6T-NIR	Coherent combination of near-infrared light from 6 telescopes using a fringe tracker, and closure phase data obtained with a science beam combiner;
10T-VIS	Coherent combination of near-infrared light from 10 telescopes using a fringe tracker and closure phase data obtained with a science beam combiner operating in the visible. The telescopes are equipped with an adaptive optics system to be able to use the full aperture.

Table 2: initial operational capability of the MRO Interferometer.

Parameter		Initial operational capabilities	Design goals
Nr. of telescopes		3	10
Maximum baseline (meters)		47	343
Limiting magnitude	H-band	10*	14

* initial minimum capability based on the currently available focal plane array

2. SUBSYSTEM INTEGRATION

The MRO Interferometer is a complex set of subsystems. In many cases the subsystem is designed, manufactured, and installed on the observatory site through a commercial contract. Each telescope will produce a collimated beam of light which is directed towards a fixed location, after which it will enter a vacuum system and will be transferred to the beam combiners many hundreds of meters away. Table 3 shows which vendor of instrument team designed and manufactured the different subsystems that compromise an MROI unit telescope.

Table 3: subsystems that compromise an MROI unit telescope.

	Subsystem	Responsible party	
		Design	Manufacturing
1	Array infrastructure (foundations, utilities)	M3	MRO
2	Telescope enclosure + transporter	EIE	RFB summer 2010
3	Telescope mount	AMOS	
4	Telescope optics	MRO/AMOS	OST
5	Wide field acquisition sensor	MRO	
6	Fast-tip tilt system	AMOS/PI/Cavendish Laboratory	
7	Interferometric supervisory system	MRO	
8	Environmental monitor system	MRO	

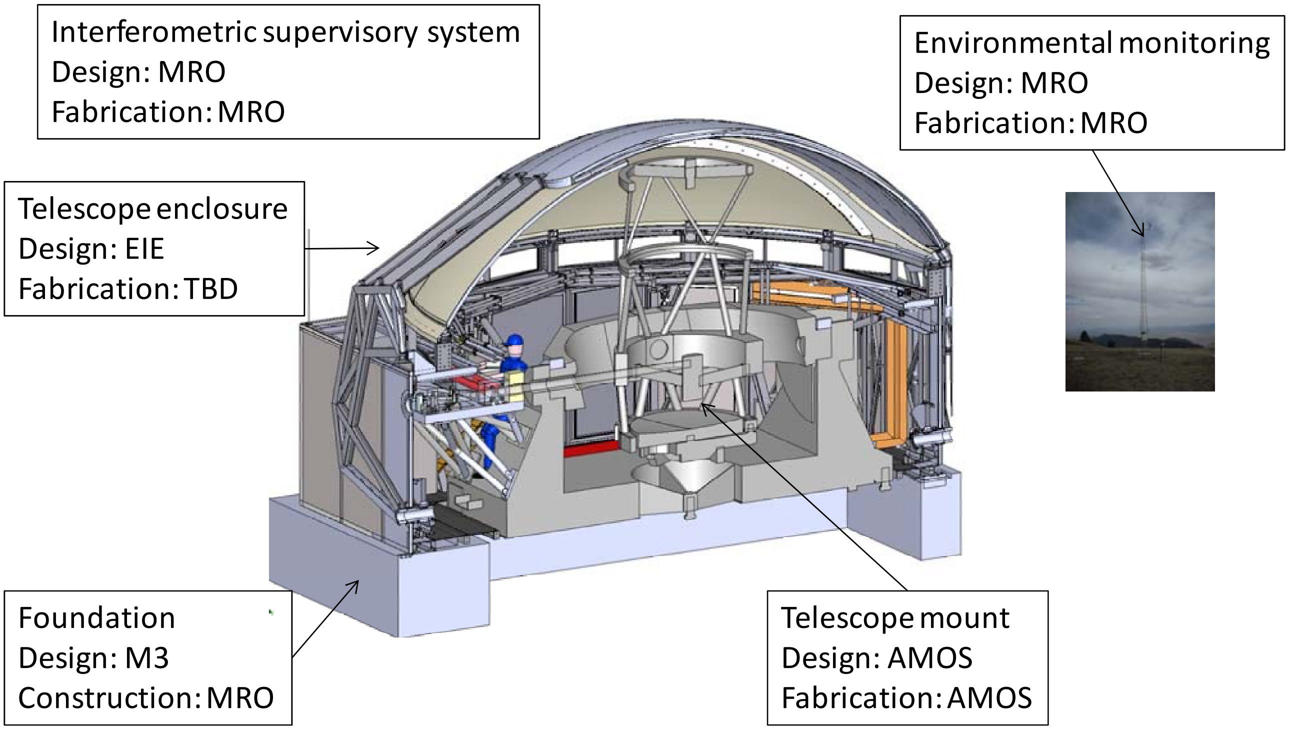

Figure 8a: schematic overview of the different subsystems involved in building a functional unit telescope.

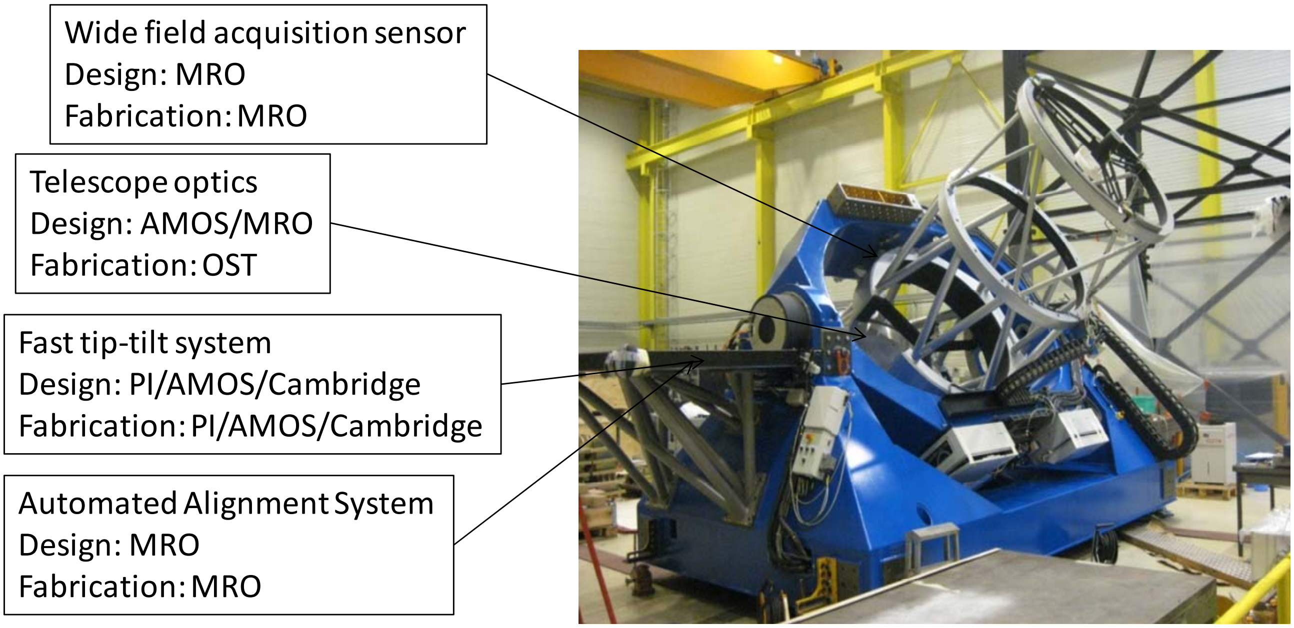

Figure 8b: continued: schematic overview of the different subsystems involved in building a functional unit telescope.

Each subsystem will go through its design, fabrication, and AIV phase, and will be tested by the Vendor, or the instrument team, to demonstrate that performance meets the requirements. The vendors and instrument teams are identified in Figure 8 and Table 3. The interfaces between all these different subsystems are maintained through a complex set of "Interface Control Documents (ICD)" that are continuously updated and checked for consistency. The first time all these different subsystems will need to be integrated into one system, and work as one system, is on the observatory site which is remote from the MROI administration office. Obviously that it a difficult working environment to make any last minute changes to hard and software. Also the weather conditions can be very difficult during the winter and monsoon periods of the year.

The phases and major milestones each subsystem passes through are well defined. At the factory, the subsystem goes through a factory acceptance test (FAT), after which it will be shipped to the MRO site. At the MRO site the vendor will provide assembly, integration and verification (AIV), and perform site acceptance test (SAT). This will lead to provisional acceptance site (PAS). The subsystem will then enter the commissioning phase in which it will be operated as part of an integrated system. Finally, once the interferometer has made pre-defined performance criteria, it will enter the operational phase.

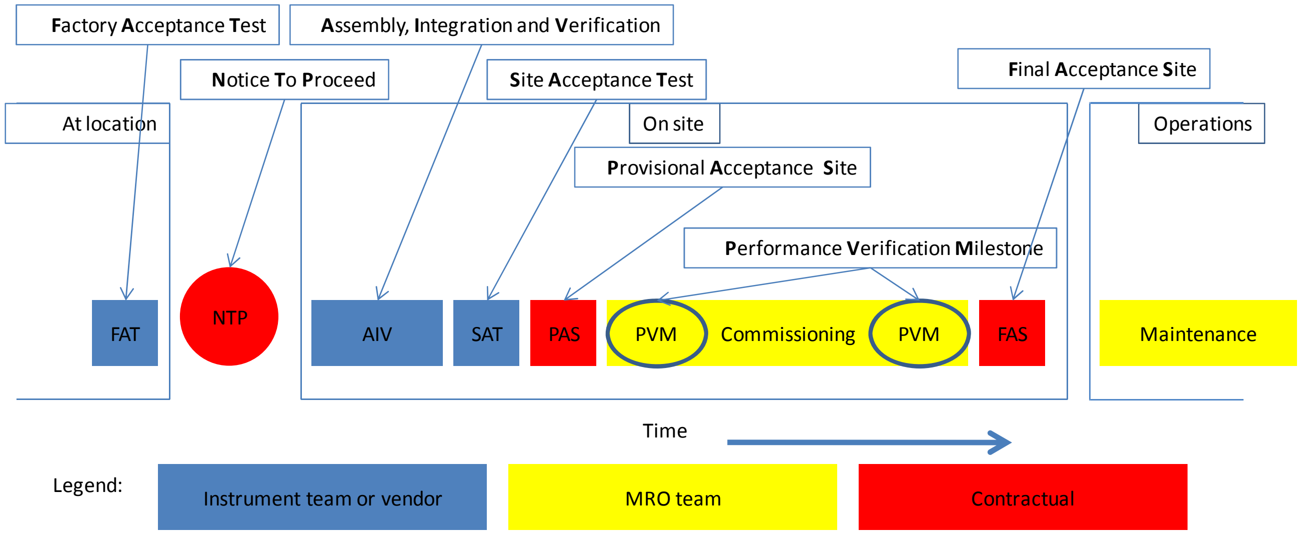

Figure 9: flow of activities and milestones for each subsystem. It shows the major phases and major milestones each subsystem passes through. From left to right, it starts with the work at the vendor's location (factory acceptance test), to the on-site activities (AIV and commissioning) and finally to an operational status.

3. ASSEMBLY, INTEGRATION, AND VERIFICATION

Assembly, Integration, and Verification (AIV) is the activity pursued by a vendor or the instrument team, with support from MROI.

A to **A**ssemble the subsystem at the MROI site;

I to **I**ntegrated the subsystem to the software and control infrastructure of MROI, and to "connect" it to other relevant subsystems;

V to **V**erify that the subsystem meets performance with minimal dependency on other subsystems.

Each vendor or instrument team will be responsible for AIV of their subsystem. During AIV tests will be performed to demonstrate that the subsystem meets its requirements.

In the following sections the major subsystems will be discussed, one by one. The different vendors are identified for the external work, and the instrument teams for the in-house developments. The most challenging requirements are addressed for each subsystem.

3.1 Foundation and utilities

The telescope, enclosure foundations and the utilities are designed by M3 Engineering & Technology Corporation from Tucson, AZ. The actual construction will be performed by the MRO in-house team. Construction will start in the fall of 2010.

For the foundation and the utilities, the most important performance requirements are the position accuracy of interface points for the telescopes and enclosures. The foundation position accuracy will be measured with a Total Station theodolite. In the case of the telescope mount foundation, the horizontal accuracy for the installation of the interface plates is approximately ± 3 mm within a telescope station (it's defined as within a 6 mm diameter circle from the nominal location).

3.2 Telescope enclosure

The enclosure has been designed by European Industrial Engineering Srl (EIE) from Mestre, Italy [6, 7]. The Final Design Review (FDR) took place on November 11, 2009, and a Request for Qualification (RFQ) was issued in June 2010. Delivery of the first enclosure is anticipated in 2011.

The enclosure is a complex housing that is designed to deal with the severe space constraints of an array of telescopes. The minimum distance requirements between the telescopes of 7.8 meters, the relocation capabilities, and the requirements to manage the thermal conditions of the enclosure have resulted in a highly sophisticated design. Critical requirements on the enclosure are related to thermal management during the night (opening of louvers to reduce dome seeing).

The thermal management system of the enclosure is designed to meet the following thermal criteria one hour after sunset:

- The temperature of any part of the enclosure within 15 cm of the optical beam (in air) from the telescope shall differ in temperature from the outside air by no more than ± 2° C;

- The temperature of any exposed surface inside the enclosure shall differ in temperature from the outside air by no more than ±5° C.

3.3 Telescope optics

The unit telescope optics (3 sets of mirrors M1, M2, and M3) are being fabricated by Optical Surface Technologies (OST) in Albuquerque, NM. The first primary mirror is in the final polishing phase and delivery of the first mirror set for the first telescope is anticipated in 2011.

Because of the long-lead time required to manufacture the large 1.4 m optics, it was decided in an early phase of the project to procure the optics well in advance of the other subsystems. A critical performance goal for the optics are the wavefront quality of the mirrors which for the primary mirror is 31 nm RMS wavefront (table 4). This wavefront quality will be measured at the vendor's location using a computer generated hologram (CGH) and HeNe interferometer. A similar test will be performed for the secondary and tertiary mirrors.

Table 4: wavefront error budget for MROI unit telescope optics.

Wavefront error allowance	Root-mean-Square (RMS)	Peak-to-Valley in waves @ (HeNe)
Primary mirror	31 nm	~ 0.20
Secondary mirror	22 nm	~ 0.15
Tertiary mirror	15 nm	~ 0.10
Total allowed wavefront error	41 nm	~ 0.25

3.4 Telescope mount

The telescope mount has been designed and fabricated by Advanced Mechanical and Optical Systems (AMOS) Liege, Belgium. Final design review took place on November 5, 2008, and the first telescope is in its final acceptance testing at the manufacturer. Details can be found in the paper by Pirnay [5].

The most complex part of the unit telescope is the mount. The design of an alt-alt configuration allows for directing the beam toward a fixed location for further transport by the vacuum systems. Critical performance requirements on the telescope are the optical path length difference (OPD), introduced by the telescope and pupil stability. The optical path length variation from the telescope will not exceed the RMS values specified in table 5.

Table 5: optical path length stability requirements on the MROI telescopes

Time interval	RMS path length fluctuations over interval
12 msec	23 nm
17 msec	30 nm
26 msec	44 nm
35 msec	57 nm
52 msec	78 nm

In addition, the Vendor will provide a model such that the difference in path length between any two telescopes can be calculated to an accuracy of better than ±0.5 mm over the operational field of regard. Whereas any un-modeled changes in path length will vary smoothly with angle such that there is less than 700 nm RMS of un-modeled optical path length variation for a change in pointing corresponding to tracking a star at sidereal rates for 1 second.

3.5 Telescope fast tip-tilt system

The fast tip-tilt system is being designed and built by the MRO consortium collaborator, Cavendish Laboratory at the University of Cambridge. The first order adaptive optics correction will be performed by the fast tip-tilt system. The secondary mirror will be articulated in tip and tilt to compensate for atmospheric effects. A critical performance requirement of V=16 is the limiting magnitude at which correction can still be made.

3.6 Interferometric supervisory software

The interferometric supervisory software system (ISS) administers the commands to the various subsystems on a high-level (Figure 10). This will be the software tool that the user and/or telescope operator will interact with. Details are presented in the paper by Farris in these proceedings [4].

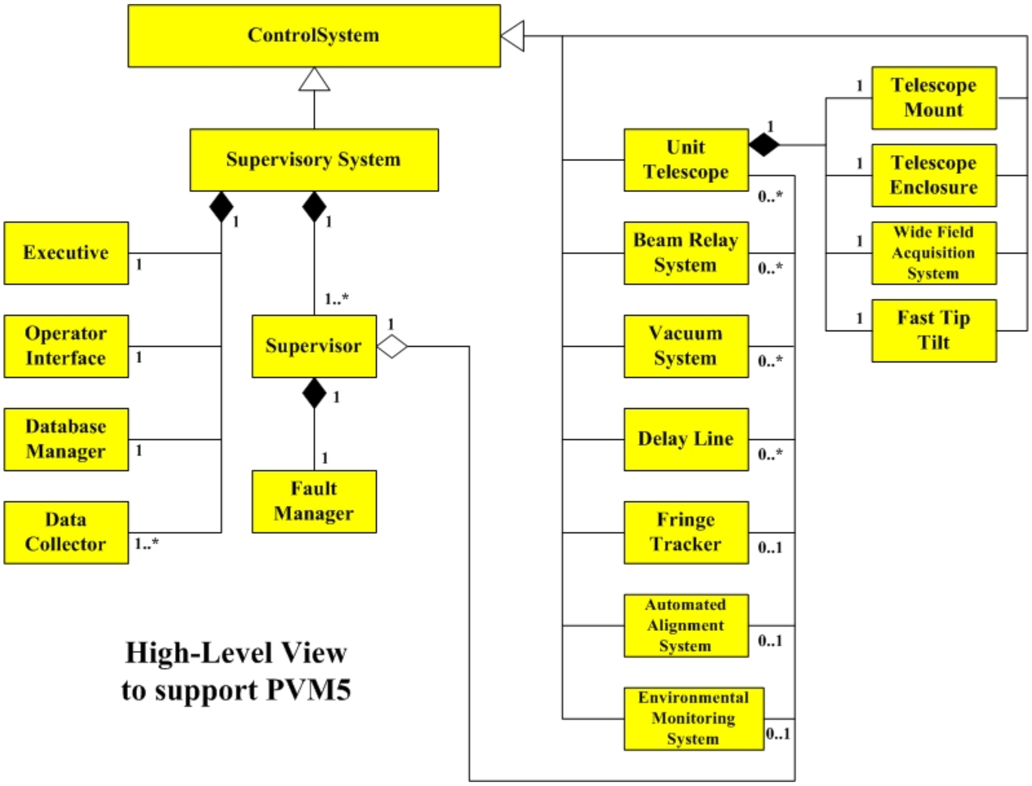

Figure 10: Structure of the ISS (shown using UML notation).

4. COMMISSIONING ACTIVITIES

Following Provisional Acceptance Site (PAS) of a subsystem, the construction phase for that subsystem ends and the commissioning phase begins. For a modular system like an optical interferometer, this commissioning phase in essence starts with first light of the first telescope, and the end for initial commissioning is defined at sustained closure phase with three telescopes. After that individual new subsystems will go through a commissioning phase but the interferometer, as an observatory, will have completed commissioning phase I and will be in the operational phase.

The goals of the commissioning phase are to:

1. Understand the performance of each major subsystem of the interferometer;
2. Understand the performance of the subsystem as an integrated system;
3. Determine if any changes or additions to the subsystem are needed to perform the science detailed in the science case.

4.1 Performance verification milestones

The interferometer will be commissioned following a sequence of “Performance Verification Milestones” (PVM). These are:

Single-telescope standalone milestones:

PVM1 First starlight on unit telescope tip-tilt sensor: demonstrates telescope and wide-angle sensor loop;

PVM2 Closed loop operation of the fast tip-tilt (FTT) system: demonstrates FTT system operations and supervisory control of FTT loops to secondary mirror and unit telescope mount;

Single-telescope milestones that require the main beam combining laboratory:

PVM3 First light on the fringe tracker table: demonstrates beam relay, delay lines, beam compressors, vacuum system, switchyard and alignment systems;

Two-telescope milestones:

PVM4 First fringes at the beam combiner: demonstrates the beam combiner and detector system;

PVM5 First closed-loop fringe tracking: demonstrates closing the delay line loop on a single baseline, stable fringe tracking and initial quick-look data analysis.

Three-telescope milestones:

PVM6 Closed-loop fringe tracking on long baselines: demonstrates the bootstrapping capability of the array using a two-leg baseline. Verifies robustness to atmospheric fluctuations.

PVM7 Sensitivity on long baselines: confirms the sensitivity of the beam combiner under realistic observing conditions and with bootstrapping operational.

PVM8 First closure phase: confirms the delivery and operation of the science beam combiner. Verifies the parallel operation of two beam combiners and multi-baseline fringe tracking. Tests initial data analysis capability for science combiner.

PVM9 Sustained closure phase measurements on long-baseline triangles: demonstrates robust bootstrapping with parallel combiners over long timescales. Verifies data analysis techniques for science combiner.

PVM10 Sensitivity on long baselines: confirms the sensitivity of the science beam combiner as advertised.

Multiple-telescope milestones only worth performing when the number of telescopes is greater than 3:

PVM11 First "rapid" relocation: verifies the ability to reconfigure the array and return to scientific operations reliably and efficiently. All major subsystems now operational in largely "automated" modes so as to support rapid return to operational capability when the configuration is changed.

Six-telescope milestones

PVM12 First "snapshot" image with 6 telescopes: demonstrates the system robustness for a ~4-6 hour tracking observation.

4.2 Performance metrics

As more hardware becomes available, more subsystems will be commissioned. The inspection points, where light can be intercepted to assess the performance of the interferometer, will move from the primary mirror, secondary mirror, tertiary mirror, to what is referred to as M4, M5 …. all the way to M10, just in front of the fringe tracker. At each mirror, and also in between, the quality of the star light can be assessed. Performance metrics that are currently under consideration are listed in Table 6.

Table 6: MROI commissioning metrics.

Priority	Metric
High	Beam stability
High	Optical path length stability
High	Characterize collimated beam
Medium	Throughput
Medium	Tracking performance

Performance verification will follow the same process as applied at many other observatories and is presented in Figure 11 [8, 9, 10, and 11]. During the design process (that starts in the upper left corner), the science case is translated into top-level system requirements, then split up into subsystem requirements (level 2), and to the component level (level 3). This leads to design and fabrication. During fabrication, verification starts at the component level, to the subsystem level and, finally, observatory wide. The commissioning activities described in this paper all fall in the upper right box, they are observatory wide and commission the observatory as an integrated system.

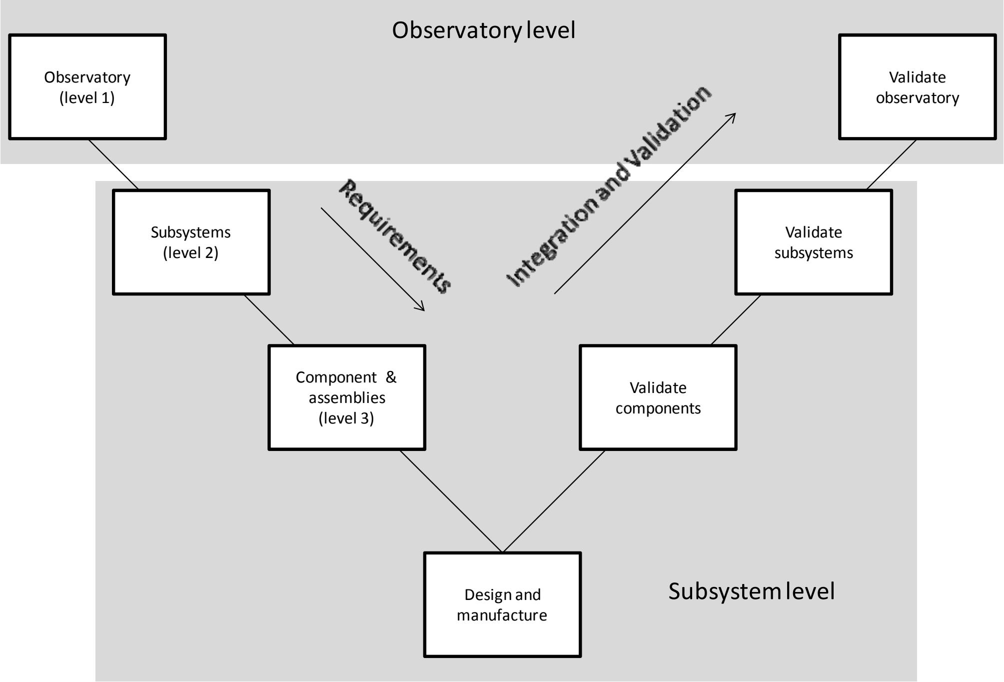

Figure 12: overall flow of requirements from science drivers (level 1 observatory), to lower level for design and manufacture, up again to commissioning.

5. EMERGING CAPABILITIES

As the MRO Interferometer enters the commissioning phase in 2011, capabilities will emerge to assess the performance of the interferometer. The first emerging capability will be a single telescope on-sky (December 2011).

This same process is repeated for every new telescope that is installed at the MRO site. The following emerging capabilities of the MROI will be: first fringes with two telescopes (November 2012), first closure phase with 3 telescopes, and finally initial operational capabilities.

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REFERENCES

[1] Creech-Eakman, M.J., Romero, V.D., Cormier, C., Haniff, H.A., Buscher, D.F., Young, J., Westpfahl, D.J., "Magdalena Ridge Observatory interferometer: advancing to first light and new science," proc. SPIE 7734, (2010).

[2] Santoro, F.G., Olivares, A., Salcido, C., Jimenez, S., Cormier, C., Creech-Eakman, M.J., Bakker, E.J. Jurgenson, C.A., Shtromberg, A.V., Sun, X., Haniff, C.A., Buscher, D.F., Young, J.S., Fisher, M. Donald, M., Wilson, M.A., "Mechanical design of the Magdalena Ridge Observatory interferometer," Proc SPIE 7734, (2010).

[3] Jurgenson, C.A., Santoro, F.G., McCracken, T.M., McCord, K.M., Buscher, D.F., Haniff, C.A., Young, J.S., Creech-Eakman, M.J., "The MROI fringe tracker: laboratory fringes and progress toward first light," Proc. SPIE 7734, (2010).

[4] Farris, A., Klinglesmith, D., Seamons, J., Torres, N., Buscher, D.F., Young J.S., "Software Architecture of the Magdalena Ridge Observatory Inteferometer," Proc. SPIE 7740, (2010).

[5] Pirnay, P., Pierard, M., Moreau, V., Verheyden, P., Mayer, C., "Magdalena Ridge Observatory Interferometer: assembly, integration, and verification of the unit telescopes," Proc. SPIE 7734, (2010).

[6] Marchiori, G., Busatta, A., Payne, I., "Innovative enclosure dome/observing aperture system design for the MROI Array Telescopes," Proc. SPIE 7739, (2010).

[7] Payne, I., Marchiori, G., Busatta, A., "Innovative enclosure design for the MROI array telescopes," Proc. SPIE 7739, (2010).

[8] Wallander, A., Spyromilio, J., Wirenstrand, K., "Commissioning VLT unit telescopes: methods and results," Proc. SPIE 4004, p. 234-245 (2000).

[9] Enard, D., "VLT Commissioning Plan", VLT-PLA-ESO-10000-0937, (1996).

[10] Gray, P.M., "Assembly and integration to first light of the four VLT telescopes," Proc. SPIE Vol. 4004, p. 2-13, (2000).

[11] Leibundgut, B., De Marchi, G., Renzini A., "VLT science verification plan,", ESO, (1998).

[12] Pierre Y. Bely, [The Design and Construction of Large Optical Telescopes], Springer-Verlag, (2010).