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An inexpensive turnkey 6.5-m observatory with customizing options

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ABSTRACT

A turnkey observatory with 6.5-m telescope has been developed for a broad range of science applications. The observatory includes the telescope, mount and enclosure, installed on site and ready for operation. The telescope's primary mirror is an f/1.25 honeycomb sandwich of Ohara E6 borosilicate glass, similar to that of the MMT and Magellan telescopes. The baseline optical design is for a Gregorian Nasmyth focus at f/11. A Gregorian adaptive optics secondary that provides a wide-field focus corrected for ground layer turbulence (0.25 arcsecond images over a 4 arcminute field) as well as a narrow-field diffraction-limited focus is optional. Another option is a corrected f/5 focus with a 1° field. The observatory, built by partners from academia and industry with extensive experience, can be delivered within five years at a fixed price.

1. INTRODUCTION

The University of Arizona (UA) is planning to build the Arizona Large Telescope Consortium (ALTC) Turnkey 6.5-m Observatory (ATO) on Mt. Lemmon as one of four planned observatories at different sites over the next decade. UA is soliciting substantial partners for these observatories in an effort to address important scientific objectives. The goal of the ATO is to produce a high value and low cost capability within five years to enable timely and forefront science.

Our immediate goal is to produce an ATO that meets the needs of a substantial number of science cases with the baseline design or with identified compatible options. The turnkey design is based on established performance specifications of other observatories and their success. This baseline design and options can be implemented within five years at a fixed price with known operations cost. To implement this in a timely manner it is critical to have pre-qualified sites ready for construction, the 6.5-m primary mirror casting underway and a highly efficient turnkey observatory design.

One of the main ATO objectives is to be affordable in capital cost and more importantly to have very low operating costs. This is key in being able to do high value low cost science in a timely manner. We intend to locate the first Turnkey Observatory on Mt. Lemmon. Mt. Lemmon has superior observing conditions and existing infrastructure and is anticipated to have the lowest operational costs of the candidate sites. A rendering of the ATO on Mt. Lemmon is shown in Figure 1. The observatory is designed so that it can be economically fabricated and delivered to site for relatively simple and quick installation. A finite predefined acceptance of key high level specifications on sky to verify performance and transition to operations is critical. These items are all critical in the ability to produce the observatory with a low fixed cost in a timely manner.

The ATO is based substantially on existing specifications and designs with modifications driven by technology improvements, improved cost-effective designs and other innovations that sustain performance and reduce cost. The enclosure is based on a heritage of multiple generations of design. The optical design is known and established from MMT and Magellan telescope designs. The primary mirror and support system are based on extensive infrastructure and heritage from five previous 6.5-m mirrors that have been successfully produced. The telescope design is in the process of being updated from one with a hydrostatic bearings to a roller bearing design as a result of similar performance at a significant cost savings in capital, assembly and operational cost. The telescope design is being fully evaluated to retain

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performance specifications and maximize overall cost saving. The goal is to produce a low-cost solution to enable a greater amount of science to be achieved.

Figure 1. Concept of the ALTC Turnkey 6.5-m Observatory on Mt. Lemmon in Arizona.

2. GREAT DIVERSITY OF IMPORTANT SCIENCE ENABLED BY 6.5-M OBSERVATORIES

Astronomical research depends on the adequate availability of appropriate observing capabilities. State-of-the-art observing capabilities are the combination of a modern telescope and a diversity of instruments and observing modes. The combination of a modern telescope, an optimized instrument, skilled researchers, and adequate observing time can be transformative for addressing important research problems in astronomy and astrophysics, but no single capability (combination of telescope, instrument, and observing mode) can address the full diverse set of ideas that come from the astronomical community.

The significant cost of telescopes, the fore-optics for an astronomical observing capability, can be the limiting factor in the development of a capability needed for an innovative investigation. The ALTC is working to provide an affordable, but customizable large telescope that through some standardization of design and engineering can reduce the total cost of bringing new observing capabilities on-line. Through the reduction of the total cost of building and operating a modern, large observatory while still allowing a great diversity of science to be possible with the proposed design, we expect to increase both the amount and quality of data acquisition for addressing the most pressing astronomical questions being studied by researchers. Deploying multiple 6.5-m telescopes, each focused on a subset of the possible diverse science cases the community wishes to pursue, is one of our goals.

In this section we describe research topics that represent the diversity of interests of the community and that require new or augmented observing capabilities. We have selected topics that are not only important, but may be particularly well addressed by developing a new capability, in particular a new capability making use of an affordable ATO and an appropriate choice of instrument(s) and observing mode(s). We are not trying to present an exhaustive list of all needed capabilities, but to highlight that there is a strong demand for such capabilities. Specifically, we present a range of potential projects.

- The early growth of black holes can be traced using luminous quasars at high redshift. With over 100 known quasars at $z > 6$ and the highest redshift at $z = 7:1$,[1] these already indicate the existence of billion solar mass black holes a few hundred Myr after the first star formation in the Universe. Pushing to higher redshifts, masses, and larger sample size can be done with a 6.5-m telescope and instruments like MMT/MMIRS and Magellan/FIRE.

- The largest ultra-diffuse galaxies are as massive as the Milky Way galaxy, but dark matter dominated at all radii.[2] Confirming larger samples, to find the most extreme examples, and measuring internal kinematics to determine the dark matter distribution are programs for 6.5-m or larger telescopes, ideally with integral field spectrographs to collect as much of the light from these low surface brightness objects. Such studies may finally be able to constrain the mass profile of dynamically undisturbed dark matter halos.

- Because of the long relaxation times, the stellar halo likely contains a vast number of stellar streams and other structures that record the hierarchical assembly history of the Galaxy.[3] Spectroscopy is needed to confirm and trace the structures in phase- and element abundance space. Highly multiplexed, high resolution spectroscopy on a 6.5-m telescope, such as provided by MMT/Hectochelle, is needed to obtain the spectra for the hundreds of thousands of stars needed to do such surveys over thousands of square degrees of sky.

- The study of astronomical transient and variable sources (supernovae, GRBs, stellar eruptions, tidal disruption flares, binary stars, etc.) is an area of fundamental importance to astronomy that will experience exponential growth with the advent of the LSST.[4] A 6.5-m telescope with a variety of instruments will allow for classification and further study of new and unexpected classes of transients.

- Low resolution transmission spectroscopy of transiting planets, even as small as super-Earths, probe the atmospheric composition and structure (e.g. [5]). A long-term program on a 6.5-m telescope with an instrument such as Magellan/IMACS will measure the atomic and molecular absorption features and the continuum slope of the transmission spectra.

- About a dozen known objects beyond 50 astronomical units are on high eccentricity orbits that enable us to probe the extreme outer solar system. Due to detection biases, the number of such objects is likely to be much larger. A large program with a 6.5-m telescope and a wide field imager, like Magellan/Megacam, will improve detection and classification of such objects and eventually lead to the hypothesized massive (> 10 Earth mass) planet at a distance of several hundred astronomical units.[6]

- A 6.5-m telescope with adaptive optics (AO) can characterize extrasolar planets from the visible to mid-IR with photometry and spectroscopy. The 6.5-m MMT and Magellan Clay telescopes are equipped with adaptive secondary mirror (ASM) AO systems, providing correction of atmospheric turbulence, as are the two LBT telescopes with Gregorian deformable secondaries. An AO-equipped 6.5-m telescope is capable of diffraction-limited resolution 2.7 times sharper than the Hubble Space Telescope at a given wavelength, and this has been demonstrated at wavelengths as blue as 624 nm.[7]

- The University of Arizona's Catalina Sky Survey (CSS) has had great success using repurposed 0.5-m to 1.5-m telescopes, discovering nearly half of all known Near-Earth Objects (NEOs) in support of planetary defense, both manned and unmanned in-situ resource utilization, as well as diverse solar system science. CSS is the only survey to have discovered asteroids prior to impact with the Earth, over Sudan in 2008, the North Atlantic in 2014, and Botswana in 2018.[9] Discovery and orbital catalog maintenance of NEOs requires both blind surveying and targeted follow-up and the most interesting objects are often at a telescope's limiting magnitude. A wide-field, 6.5-m telescope would be transformative for the NEO community for either survey or astrometric follow-up, as well as for photometric or spectroscopic characterization of the different classes of objects. CSS is evaluating large format, large pixel, CMOS detectors to efficiently tile the focal plane, avoiding the need for a shutter and supporting fractional-second non-destructive readouts into data cubes. While an efficient NEO survey requires both a very wide field (several square degrees, likely prime-focus) and near-monopoly scheduling during dark-time, very effective follow-up can benefit from nimble queue scheduling with a moderately wide field of ~1 square degree at the Nasmyth foci. There would be a vast number of useful solar system targets on any given night accessible to a 6.5-m aperture and these could provide a default target list for the queue. A large survey telescope located in the northern hemisphere would directly complement LSST in the south and NEOCam IR targets on the eastern and western horizons. A large follow-up telescope able to target near-horizon would overlap current northern NEO surveys, but also a significant fraction of both the LSST and NEOCam footprints.

- The utility of a 6.5-m telescope can extend beyond traditional astronomy to the characterization and study of man-made satellites in Earth orbit. If basic non-sidereal tracking capabilities are provided that can support rates of 10-50 arcsec/sec, most deep space satellites and space debris can be acquired and tracked. Currently, the space surveillance and space debris research communities have very limited access to telescopes larger than 2 m with advanced instrumentation and satellite tracking capabilities. Considering one such example, a 6.5-m telescope would contribute significantly to understanding space surface aging with medium and high-resolution spectroscopy, like MMT/RedChannel, especially in the 700-1200 nm spectral range which is especially diagnostic of different spacecraft material. The community is lacking high resolution studies of on-orbit satellites to inform our understanding of aging effects, and to aid in the interpretation of lower resolution spectrophotometric data which is available from smaller telescopes.

3. CONSORTIUM

The Arizona Large Telescope Consortium (ALTC) is led by The University of Arizona in conjunction with M3 Engineering & Technology Corporation and CAID Industries. These three entities have come together to produce the ATO. This is the result of what has been learned from the Magellan Baade, Magellan Clay, MMT, Large Binocular Telescope (LBT), Giant Magellan Telescope (GMT) and many other telescopes. By incorporating knowledge learned from these telescope experiences and the enormous investments made to produce these and other observatories, a highly refined system can be economically produced with low risk.

The intention of the consortium is to combine the extensive investments already made by academia/research and industry in observatories to produce a highly cost effective turnkey product. M3 Engineering and Technology Corporation has more than three decades of unmatched experience in producing enclosures and facilities for observatories worldwide. It is drawing heavily on recent mature enclosure and facility designs to adapt one for the ATO. CAID Industries is an innovator of manufacturing technology of large structures for mining, transportation, defense, aerospace and astronomical applications. Both companies have extensive experience, being heavily involved in telescopes and observatories for decades. The UA has more than ninety years of experience in astronomy, telescopes and observatories. It has extensive experience in optical design and fabrication of large and challenging optics and optical systems. The UA is involved with its partners in operating more than 20 telescopes on six sites worldwide and currently involved in more than seven telescope developmental projects worldwide. UA also operates telescopes on Mt. Lemmon and is in the process of obtaining site access for the ATO. These three entities have an established, successful record working together on telescope projects.

4. OPTICS DESIGNS AND OPTIONS

4.1 Optical designs

The starting points for the optical design and layout of the ATO system are the 6.5-m MMT and Magellan telescopes and the 8.4 m LBT telescopes. The MMT has f/15 and f/5 direct Cassegrain secondaries, while the Magellan telescopes are primarily designed around f/11 Gregorian Nasmyth ports; both also have a wide-field f/5 focus.

As a baseline, we adopt the Magellan optical design for these systems.[10] The Gregorian design supports a broad range of use cases with a single optical design. Specifically, a concave secondary provides:

- Field curvature that is a good match to refractive collimator designs, for wide field observations
- Optical conjugation of the deformable secondary mirror to the ground layer of atmospheric turbulence
- Access to prime focus, providing straightforward calibration of an adaptive secondary mirror (ASM).

The focal ratio is set at f/11 to provide sufficient space in the collimator and camera design for a large reflective grating. This choice, plus the design around the folded, Nasmyth port, allows us to define the optical parameters. The primary is a 6502 mm diameter f/1.25 paraboloid. The concave secondary mirror, sized for a 30 arcminute field of view, has a diameter of 1360 mm, with a radius of 2863 mm and a conic constant of -0.63. It is located 9726 mm above the primary vertex. The tertiary is assumed to be placed 700 mm above the primary vertex. The Nasmyth focus is located approximately 4740 mm from the axis of the telescope.

The Gregorian Nasmyth focus is designed is designed for a 30 arcminute diameter field-of-view when used with refractive field correction elements placed just after the tertiary mirror. The lenses are 800 mm diameter pairs of doublet lenses using FK5 and LLF6 glass. The field correction elements are wedged to provide atmospheric dispersion correction. These optics can be placed in a rotating turret for removal when using infrared and/or narrow field instrumentation. The spot diagrams in Figure 2 show all the images over a 30 arcminute diameter field are less than 0.17 arcsec (100% encircled energy).

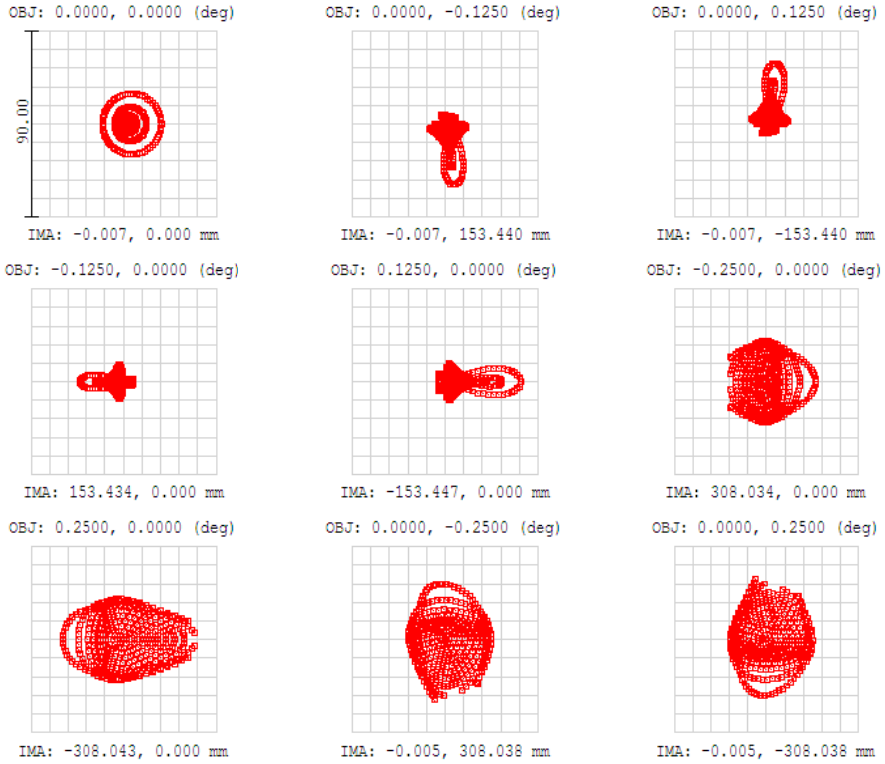

Figure 2. Spot diagrams for the wide-field imaging performance of the 6.5 m turnkey telescope. The boxes are 0.25 arcsec on a side. Spot sizes are shown for on-axis and for 7.5 and 15 arcminutes off-axis. The largest spot size (100%EE) is 0.17 arcseconds.

The Gregorian design is well-suited for use with an adaptive secondary mirror. This operational mode would enable correction of ground layer turbulence, as well as supporting diffraction-limited imaging with no additional background at infrared wavelengths beyond 2 µm where telescope emission contributes. The secondary mirror is optically conjugate to ground layer turbulence up to 100 m above the primary mirror which typically accounts for a large fraction of seeing, and is naturally corrected over a wide field. Thus it is well-suited for correcting turbulence from the ground layer, providing improved imaging over a wide field of view.

4.2 Opto-mechanical specification, design and manufacture of primary mirrors

The 6.5-m primary mirror is a honeycomb mirror made of Ohara E6 borosilicate glass and cast in the spinning furnace at UA's Richard F. Caris Mirror Lab. The honeycomb mirrors have the advantage that they can be ventilated by air at ambient temperature, to minimize mirror seeing and thermal distortion. The ventilated honeycomb mirrors at the MMT and Magellan telescopes have strong records of superb imaging performance.[11],[12] With a thickness of 711 mm at the outer edge and a mass of about 10,000 kg, they are the stiffest and lightest mirrors ever made at this size, providing minimal distortion due to self-weight deflection and wind. The maximum glass thickness is 28 mm, and this along with internal ventilation produces a thermal time constant of about 40 minutes.

The primary mirror system includes a support cell with 6 adjustable hard points for precise alignment, 104 active pneumatic mirror supports, ventilation with temperature-controlled air, and electronics to read roughly 50 thermocouples in the mirror, cell and surrounding air.[13] The basic support system adjusts the 104 actuator forces to null the hard-point forces, resisting gravity and wind with a 1 Hz bandwidth. The active-optics system uses a wavefront sensor in the focal plane to control positioning of the secondary and bending of the primary with roughly 0.01 Hz bandwidth. The bending forces are applied as modal patterns using about 20 modes.[14]

The manufacturing process for primary mirrors is mature and predictable. Spin-casting has produced five 6.5-m blanks and eight 8.4-m blanks with no failures.[15] To date all mirrors have been machined with the Large Optical Generator at the Mirror Lab, shown in Figure 3, to define dimensions, make the rear surface an accurate interface to the support system, and bring the optical surface to an accuracy of 20-40 µm rms.[16] The early 6.5-m primaries were polished and figured at the Mirror Lab.[17],[18] The most recent 6.5-m mirror was polished in the upgraded Optical Engineering and Fabrication Facility at the UA's College of Optical Sciences. Starting from the machined surface at 40 µm rms surface, the computer-controlled polishing system achieved an accuracy of 20 nm rms surface in only 39 calendar weeks. Figure 4 shows this 6.5-m primary being polished.

Figure 3. The 8.4-m class freeform Large Optical Generator set up for front surface generating of a 6.5-m primary mirror at the UA Richard F. Caris Mirror Lab.

Primary mirrors are measured with an instantaneous interferometer and refractive null corrector to provide a null test (no interference fringes for a perfect mirror). To verify the accuracy of the test wavefront, the test system is used to measure a small reflective computer-generated hologram (CGH) that mimics a perfect primary mirror.[19] The design and manufacture of the CGH are independent of the null corrector (the CGH depends only the ideal primary mirror), so any departure from a null result indicates an error in either the test system or the CGH, an issue that must be resolved before the primary can be finished.

The primary mirror will be aluminized prior to delivery. Long-term coating possibilities are being explored as a potential cost effective option. A coating plan on-site is an option. UA is exploring a mobile 6.5-m coating facility and has done this once before for a specific one-time project.

4.3 Design and manufacture of adaptive secondary mirrors

The adaptive secondary design builds on optical and electronics fabrication carried out for the MMT, LBT, and Magellan ASMs. The commonality in all of these designs is a thin glass shell and glass reference body with "voice-coil" actuators and co-located position sensors that control the shape of the shell. Co-located electronics enact the control law for measuring position and adjusting the actuators accordingly. An upgrade of the MMT ASM at Steward Observatory is currently underway to demonstrate low-cost, low-power actuators. Improvements in electronics have allowed this version to have the electronics embedded in each actuator. The devices also have low power compared to previous designs, allowing for a simplified cooling system.

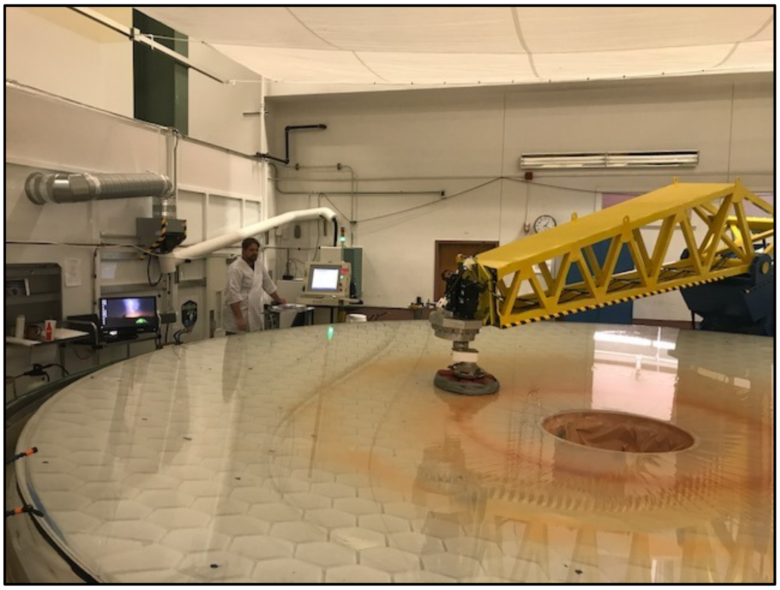

Figure 4. A 6.5-m primary mirror being polished using the computer-controlled polishing system at the UA Optical Engineering and Fabrication Facility.

An adaptive secondary constructed with the same actuator density as the ASMs for the LBT would result in approximately 1500 actuators. This would provide a projected spacing onto the 6.5-m aperture of 0.08 m per actuator. This is smaller than the typical Fried parameter at visible wavelengths. Thus this mode of operation could provide good visible wavelength adaptive optics correction.

UA has broad experience manufacturing thin shells for adaptive secondaries, having made the shells for the MMT, Magellan and LBT secondaries.[20] Starting with a thick zero-expansion substrate, the optical surface is ground and polished to a smooth and accurate surface. The thick mirror is turned over and the optical surface is temporarily bonded with pitch to a rigid substrate. The rear surface is then ground to the finished thickness and polished to create a strong, smooth interface to the actuators and a stiff reference body. As the mirror is thinned from the back, the optical surface remains smooth and accurate on scales up to several times the actuator spacing. In operation, the large-scale figure is determined by the actuators.

5. TELESCOPE

5.1 Overall specifications and telescope design

The ATO is both effective and simple. When designing a telescope there are many systems that affect its performance: site, optics, thermal environment, dome shape, wind magnitude and direction, heat sources, servo tracking and so on. The realistic affordable telescope is based on an error budget to make the best performance for an acceptable cost. For instance, the primary mirror can be polished to an extremely fine figure which can double the cost, but astronomers would see no improvement on the sky because the seeing is several times worse than the optics. Using only a fraction of that money, one can build a fast tip-tilt or adaptive optics system and realize huge improvements in the image quality. Our goal is to provide scientists a telescope baseline with flexibility of upgrades and unprecedented rapid availability for first light.

The specifications for the baseline ATO telescope are as follows for a basic design, but can be tailored to special environments and options:

- 6.5-m diameter primary mirror with a focal ratio of 1.25
- Telescope mount altitude-azimuth with ball bearing, gear and pinion drive with strip encoders
- Site median seeing <0.85”
- Optical and infrared observations at Nasmyth foci, Cassegrain focus and other options possible
- Observatory altitude up to 5,600 m (18,372’)

- Operating temperature range -25°C to 20°C
- Survival temperature range -35°C to 30°C
- Operations with wind up to 17 m/s in various directions
- Survival wind is 50 m/s or site specific environmental requirements
- Humidity <95% non-condensing
- Seismic specification is 0.8g in addition to gravity in all directions or per site specific requirements
- Operational elevation axis range 15° to 90°
- Azimuth axis range ±270°
- All sky pointing <1.2" RMS
- Sidereal tracking of astronomical objects <0.07" RMS (no wind influence)
- Offset pointing from a bright setup star for faint targets: 0.08" if within 20' of set-up star
- Non-sidereal tracking:
  - Maximum angular velocity: > 1°/s in elevation
    > 1.5°/s in azimuth
  - Maximum angular acceleration: > 3°/s^2 in elevation
    > 6°/s^2 in azimuth
- Electrical power: Electrical compatibility as required and to match site voltage and frequency

The baseline telescope concept is a 6.5-m primary mirror on an altitude-azimuth mount as shown in Figure 5. The telescope azimuth bearings are ball bearing with a drive system being two counter opposing pinions on a ring gear. The elevation bearings are also ball bearing with a drive system on each side of the yoke arms. This elevation drive system is a bull gear on each side of the mirror support ring with two pinions on each side. Strip encoders are used on both axes. The telescope mount is designed to have Nasmyth, Cassegrain and prime foci. The secondary mirror is Gregorian and supported by a hexapod on a Quad Tripod. The Nasmyth foci have a port on each side of the telescope elevation bearings 1 m in diameter. Access and platforms are provided to support the Nasmyth instruments and equipment. The telescope is designed to accommodate a variety of optics and instruments for a broad spectrum of science. In addition, it is designed to be low-cost by being easily fabricated and shipped to the telescope site, and once at the site assembled and tested quickly and effectively to minimize on-site costs and lengthy acceptance testing. Another important part of the overall design is to ensure there are low operations and maintenance costs.

5.2 Integrated primary mirror support system

The performance goal of mirror support is to hold the mirror (M1) in the telescope so that the forces of gravity, wind, telescope acceleration, and thermal effects do not significantly distort the surface of the mirror. This is achieved by the M1 actuator system and the M1 thermal control system. Top level requirements for the M1 assembly are derived in and allocated to its subsystems in [21].

M1 actuator system – The forces applied by the actuators have three tasks to accomplish simultaneously: "floatation" of the weight of the mirror while the direction of gravity is changing, resistance against external force impulses such as wind or telescope acceleration, and correction of temporary or permanent figure errors in the mirror surface. The M1 actuator system uses a hexapod geometry for positioning M1 and is essentially a hexapod with the fixed plate being the cell and the movable plate being the primary mirror. The six hexapod actuators (positioners) are called the hardpoints. The M1 hexapod differs from a standard hexapod in that we don't want any load on the hard points. During operation, the M1 actuator system uses 104 pneumatic actuators that react to remove any load on the hardpoints. When the mirror is commanded to move, the hardpoints extend or retract and the control system reacts to the changing load generated on the hardpoints by adjusting the pneumatic actuators to remove this load. Prior evaluations were performed of four different types of actuators: pneumatic, electromechanical, piezo-electromechanical, and piezo-hydraulic . All four types were characterized in open- and closed-loop situations. Comparisons were made based on weight, power dissipation, stiffness, frequency response, resolution, size and complexity. From this study, the pneumatic actuator was selected for use with the honeycomb mirrors and has been implemented and proven by almost one hundred years of combined service in 6.5-m and 8.4-m telescope cells. Pneumatic actuator systems for honeycomb mirrors are the least complex and therefore the least expensive to build and maintain. The pneumatic actuator also has the lowest power dissipation inside the mirror cell. Minor mechanical design changes in the actuator and hardpoint designs coupled with evolutionary changes in the electronics and control architecture have resulted in improved performance and reliability. We allocate r_0 = 214 cm wavefront error for the M1 actuator system's error budget.

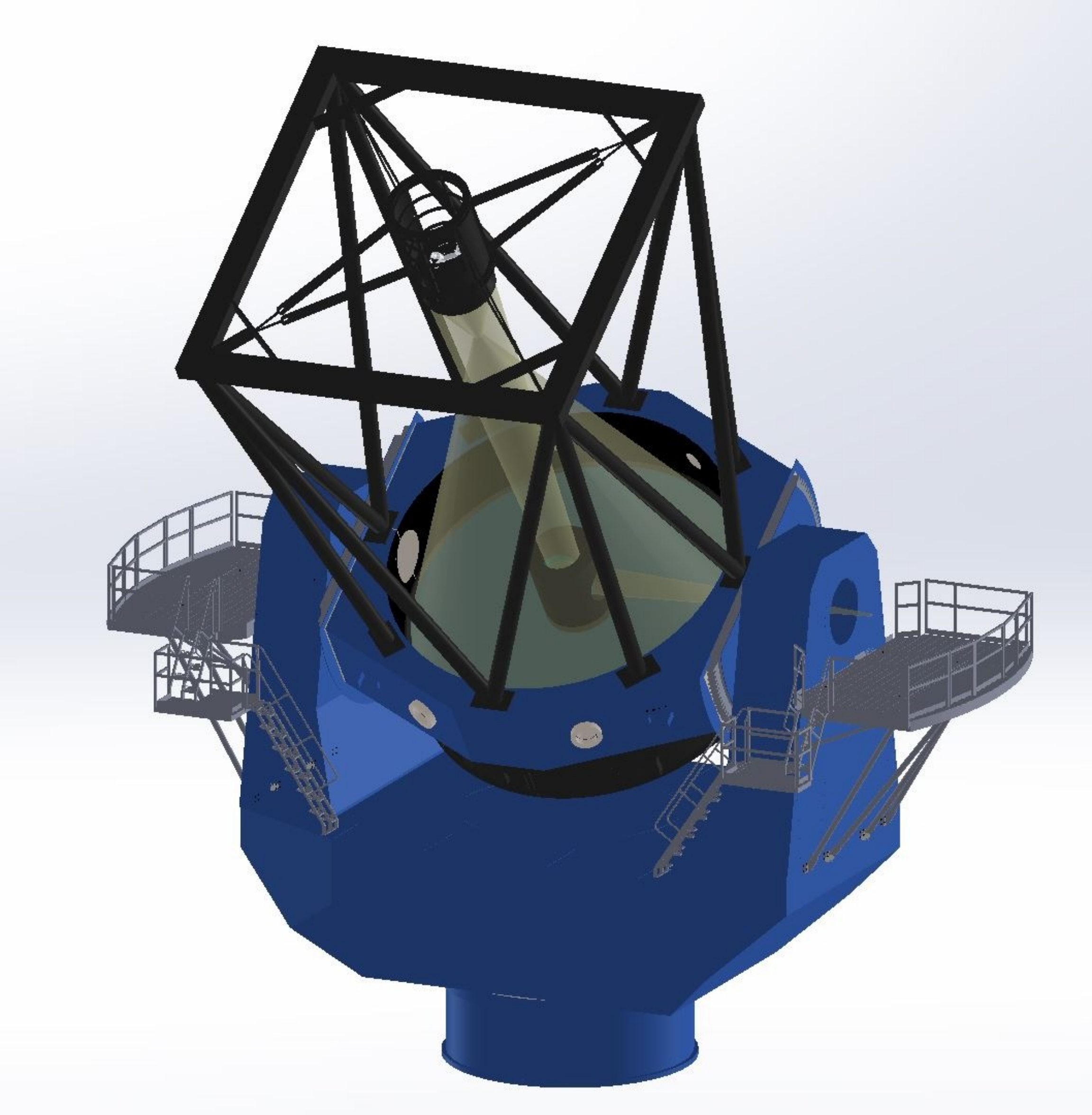

Figure 5. Rendering of the ATO telescope mount.

M1 thermal control system - The ideal telescope is one whose structure and optics do not suffer from thermal distortion and remain in equilibrium with ambient air. The M1 thermal conditioning system's two primary functions are to minimize image degradation from thermal effects and to provide for the thermal safety of M1. Two main sources of thermal errors that impact performance are temperature variations in the mirror and thermal expansion coefficient variations of the glass substrate. For each of these sources, we allocate $r_0 = 180$ cm wavefront error for the M1 thermal system's error budget. Another consideration for thermal control is the ability of the M1 temperature to track the ambient air temperature. Based on these error budget allocations, the two most important specifications for the cell thermal design are to match ambient temperature to 0.15°C and to limit temperature differences within the mirror substrate to about 0.1°C. The face of the mirror must also be within 0.2°C of ambient to control mirror seeing. The typical mountaintop cooling rate is 0.25°C/hour, so our design goal for M1 is to have a thermal time constant of approximately 45 minutes. We have designed and demonstrated two different types of thermal control systems with our legacy telescope mirror cells. These two types are best described as remote and local conditioning. The remote conditioning system uses a single blower and heat exchanger which are located off the M1 cell. The local conditioning system has between 40 and 62 fan/heat exchanger assemblies (quantity depending on site environmental requirements) within the M1 cell. Common to both types is the introduction of conditioned air into each of the over 1100 mirror “cells” that make up M1’s honeycomb structure. The decision on which type is best suited is based on the customer’s needs of system redundancy, maintainability, and operational costs.

In addition to providing force and thermal support for M1, the cell M1 resides in must also protect M1 against infrequent accelerations. These accelerations might arise from earthquakes, telescope collisions, drive failures, etc. Our proven approach uses wire rope isolators which are uniformly positioned around the back plate of M1, located at each loadspreader to M1 puck interface. These passive isolators will take the gravity load of the mirror in any telescope orientation plus an additional 0.8g load, allowing for safe displacements of M1 in any direction. This constraint system has been named static supports (where static refers to the state when all the other mirror supports are non-functional). During observations, M1 is supported by the actuator system as described above and this protective system of static supports is close to the mirror but not in contact with the glass.

5.3 Bearing, drives and encoders

The baseline drive system for the ATO telescope consists of motors with drive pinions engaging a large bull gear and this configuration has proven to be accurate, inexpensive and robust. A strip encoder mounted on a large radius about the elevations axis is also well proven and highly accurate. The gear form is straight involute teeth at a relatively small pitch to achieve the required smoothness of motion. The encoder is the heart of the servo. The very fine resolution one can achieve with a large diameter strip encoder will allow the servo to react to very small changes in position. Multiple heads are necessary to discriminate a rotation reading from an axis shift. The accuracy is not as important as resolution since one can correct for distortion and the mount with an all sky-pointing map which is used with all telescopes.

An efficient design is one that lends itself to cost effective verification during the build. Once the fabrication, stress relieving, and machining are complete, there is significant work remaining in the inspection, integration, and testing the telescope components. There is major value in the consortium’s ability to provide a large temperature controlled environment with 60 tons of overhead crane where this work can be performed efficiently, and in convenient proximity to personnel as well as fabrication and machining tools. This portion of the work requires intense planning, organizing, and safety preparations in order to be done properly, economically and reliably. Decisions are made years ahead of time to ensure the design accommodates the integration and test scheme. The ability to reliably determine the costs and schedules necessary is invaluable in prioritizing what can be done. The consortium has laser tracking capabilities, a dedicated Deck Plate Manufacturing System for mirror cells, and the capacity to design and fabricate test fixtures for major components of this size and weight.

5.4 Quad-Tripod

The potential for wind induced vibrations and gravity deflections of the optical support structure make it desirable to find a high stiffness truss solution that adds the least additional top end weight to the rotating structure. The proposed truss is a modified Quad-Tripod design with a square shape head ring. This truss design is known for its good stiffness to weight ratio since the load is carried equally by all truss geometrical elements. The square head ring provides ample space to attach the secondary mirror spider supports without increasing primary obscuration while maintaining the smallest “footprint” at the head ring location. The truss can then be optimized to use standard steel tube shapes with thin walls and common welding practices for construction. Further optimization of the overall height will be done based on optical throughput, performance and opto-mechanical considerations.

5.5 FEA

A necessary step in telescope design is the analysis of the structural components using finite element analysis software to predict structure performance in varying conditions. The goal is to find the best stiffness to weight ratio for all rotating masses. Of course this can be a challenge, but the resulting design weight can have a great effect on the selection of bearings and motors. Rolling element bearings selected specifically for their contribution to structural stiffness while maintaining a small cross section, which keeps the mass effect low, and the use of common steel plate sections and welding practices facilitate a more direct approach to design optimization through analysis.

Increasing the structural stiffness appropriately throughout the system will also directly affect the resonant frequency of the telescope. The goal is to increase the lowest overall resonant frequency without significantly increasing the system mass. The resonant frequency will have an effect on the optical performance of the system as well as the telescope pointing and tracking stability. Typically telescopes of this size achieve lowest resonant frequencies around 4 or 5 Hz.

During the FEA step, the goal is to find a design solution that results in a lowest resonant frequency around 10 Hz or higher as a rule of thumb.

5.6 Telescope model optimization

We plan to use the readily available part optimization programs which are found within most FEA software packages to quickly realize the efficient baseline telescope detail design. We will take advantage of our partner's extensive large scale fabrication experience to bring into the optimization exercises, not only the design constraints, but to also include the material selection, fabrication, processing, and integration and testing constraints from our partners. In the past, telescope structural designs have been derived after some level of "manual" optimization, and for the most part, the engineers can track manually 3 or less parameter sensitivities. However, it is not possible for optimization of dozens of parameters simultaneously in a manual manner, therefore will use will take advantage this very useful design tool.

6. FACILITIES AND ENCLOSURE DESIGNS

The design for the ATO incorporates more than 30 years of experience in the design and construction of astronomical observatories as well as other remote facilities. This experience brings an advantage in cost and time as the systems employed has a proven record of excellent performance and longevity.

The observatory facilities are composed of two major components: the fixed base, which houses numerous support spaces and the telescope pier, and the rotating enclosure, the operable structure that protects the telescope from the exterior environment while providing an operable aperture for the telescope to see through.

6.1 Fixed base structure

The fixed base structure provides numerous supporting functions critical to the operation of the telescope. Located below the observing level, this area provides a control room, computer/electronics room, electrical equipment room, and service areas for both instruments and general maintenance. See Figure 6 for a preliminary first floor plan of the facility. A mechanical plant will be provided on site in a separate building away from the telescope to minimize thermal signatures and vibration transfer. See Figure 1 above for an exterior view of the facility.

Equally important, the fixed base must provide the aforementioned functions without detrimental impact on telescope performance. To reduce the thermal signature of operations taking place directly below the telescope, the facility is cladded with insulated metal panels which reduce thermal bridging in comparison to many other cladding systems. As an added layer of protection, the main service vestibule and the entire second level of the fixed base are ventilated by large operable doors to control the direct transfer of convection to the observing level.

The telescope pier is isolated from the rest of the surrounding structure using perimeter isolation joints. These joints provide a nominal gap between structural joints; flexible connections are provided for electrical and mechanical utilities. The telescope pier will be protected from thermal signatures from the adjacent operations by reflective and resistive insulation methods. See Figure 7 for a cross section of the overall facility.

6.2 Enclosure

The enclosure consists of an octagonal dome, rotating on a pair of ring girders elevated above the observing level. Two bi-parting shutters are provided to create an operable aperture for the telescope to view through. To reduce the impacts of the enclosure on telescope seeing, steel profiles with a minimal thickness are utilized to reduce the thermal mass present within the enclosure envelope. Additionally, ventilation doors are provided to flush the interior space and promote equilibration with the exterior environment during observing. To prevent overcooling of the roof and wall panels that can otherwise cause thermal gradients within the telescope optical path, the cladding system will include low emissivity coatings to reduce the rate at which thermal energy is radiated to the night sky.

The enclosure also serves maintenance and operational functions that will occur on the observing level and telescope itself. A large overhead crane is provided that, when combined with the structures rotation, will be able to reach most of the observing level and anything located within its outer footprint.

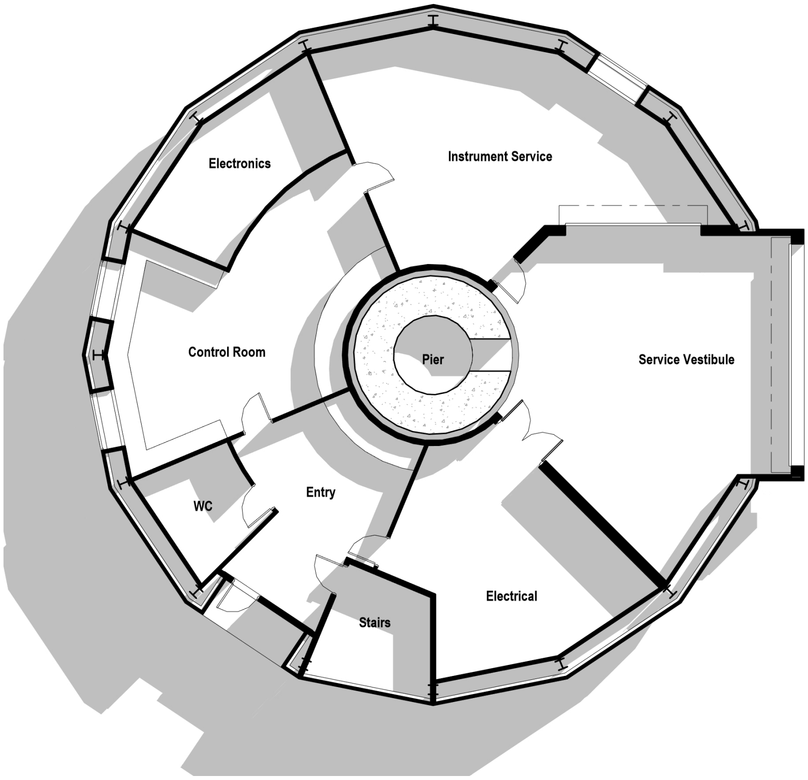

Figure 6. First level floor plan

6.3 Pier and enclosure foundation design

The telescope pier and enclosure foundation are primary elements in the soil-structure interaction. Their design incorporates the site-specific geotechnical properties as well as the demands from the telescope and enclosure building.

The telescope pier is a large cylindrical concrete structure that provides vertical and lateral support for the telescope, forming a highly stable foundation. A bottom mat slab provides additional stiffness and stability at the soil/rock – pier interface. Geometrically speaking, the telescope pier dimensions are locked with a specific height above the ground and diameter, incorporating multiple ports or openings for utility and user access. The base foundation of the pier is tuned to the site-specific geotechnical properties to achieve the best dynamic properties as well as stability against load demands.

In turn, the enclosure foundation design incorporates reinforced concrete elements that balance structural performance with minimum excavation while complying with the site-specific geotechnical requirements. In addition, when site conditions demand it, supplementary structural components are provided in the design to counteract high uplift or sliding conditions.

6.4 Enclosure structural framing system

As previously discussed, ATO's design incorporates the experience drawn from several observatories such as the Discovery Channel Telescope as a baseline. ATO uses a steel structural framing system for both the rotating and fixed enclosure, a system that offers several advantages for the scale of the project including: repeatability of component fabrication, reduction in need for field adjustments, ability to pre-fabricate components in a quality-controlled environment including pre-assembly testing of critical components.

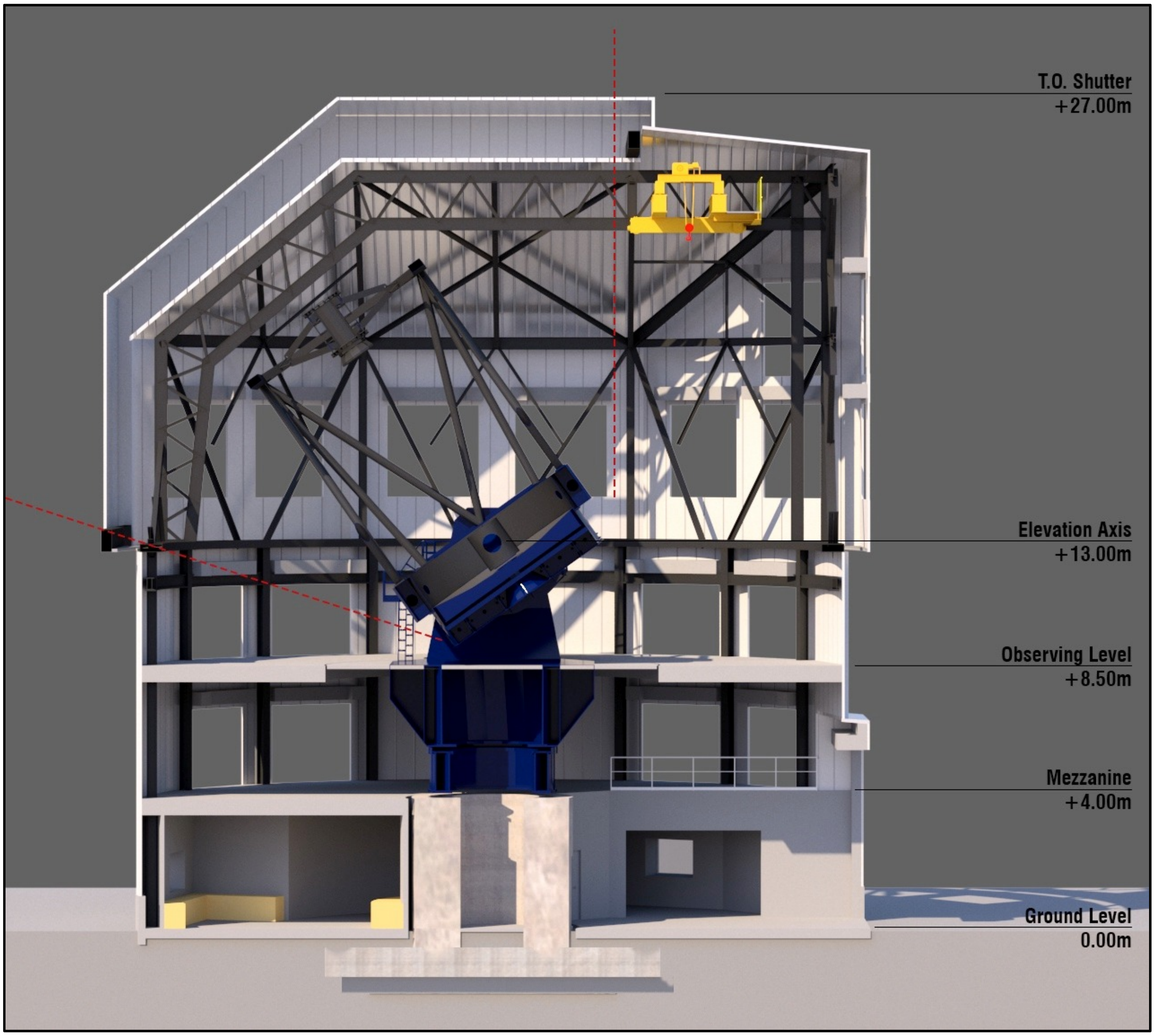

Figure 7. Cross section of facility concept

The steel structure incorporates vertical and lateral force resisting systems that have been previously employed, such as braced frames and bolted beam connections. The braced frames are designed with a seismic response coefficient in tune with the mechanisms while considering the wind pressures. This produces a symbiosis of structure and mechanisms to render an optimal cost-benefit result. Furthermore, the use of prefabricated components and bolted connections allows for expedited construction on site and repeatable results.

7. SITES

In the context of a turnkey 6.5-m telescope, site selection becomes a critical trade that must find a balance between the superior astroclimate appropriate for a large aperture telescope and the need to minimize the cost and risk developing the observatory. Installation of new dedicated infrastructure or supplementing existing infrastructure can add significantly to both the cost and the risk of an observatory project. Additionally, geotechnical conditions, access for construction, and the availability, lodging, and travel time of local construction trades can have significant impact on the overall budget while contributing little to the final product. Site development costs and delays can both directly and indirectly impact the total cost to deliver a 6.5-m telescope at a fixed price. For the turnkey 6.5-m telescope we strive to find a balance between these considerations that allows the observatory system to achieve its scientific goals, while containing both the cost and the cost risk. In consideration of these factors, the consortium is actively considering several candidate sites for the first turnkey 6.5-m that we believe strike a balance between these often-competing considerations.[1]

Our primary site for our first turnkey 6.5-m telescope is Mt. Lemmon. A brief overview of each of the sites is offered in the following discussion, followed by an outline of our intentions for site survey work over the next year to inform our future commitment to a site for our first turnkey 6.5 m telescope.

Mt. Lemmon is located the Catalina Mountains approximately 28 km northeast of Tucson AZ. Facilities on Mt. Lemmon were originally developed by the United States Air Force Air Defense Command as an air defense radar and command and control facility. After decommissioning, the site was transferred to the University of Arizona Steward Observatory and developed as an astronomical observatory. Currently Mt. Lemmon hosts several telescopes ranging in size from 0.6 m to 1.52 m. At 9157', Mt. Lemmon is the highest elevation site within an hour drive of Tucson. At Mt. Lemmon, the University has significant infrastructure to support a new large telescope, and three candidate locations within the facility that are being evaluated. Astroclimate measurements at Mt. Lemmon have not been published, but unpublished measurements show that the astroclimate is comparable to Kitt Peak and Mt. Hopkins. Because of Mt. Lemmon's proximity to Tucson, the southwestern sky is impacted at higher airmass than the other two Tucson area mountain sites. Regular observing programs at Mt. Lemmon routinely measure sub-arcsec seeing at the summit.

Kitt Peak is located 68 km WSW of Tucson and has an elevation of 6877'. Steward Observatory operates several telescopes at Kitt Peak National Observatory, including the Bok 90", SuperLOTIS, and the Spacewatch Telescopes. Kitt Peak has an extensive suite of historical night sky background and night sky spectroscopic data taken at approximately 10-year intervals at a variety of azimuths and elevations to sample and track the light pollution environment at the site.[22]-[24] Of the three prospective locations near Tucson, Kitt Peak is the least affected by light pollution, especially to the south.

Mt. Hopkins is located approximately 60 km S of Tucson at an elevation of 8585'. The MMT 6.5-m telescope is located at the summit, and other nearby ridges offer the potential for future development. Of the candidate sites near Tucson, Mt. Hopkins has the most difficult road access. Sky brightness at Mt. Hopkins is comparable to Kitt Peak and has been shown to be relatively stable despite the growth of Tucson over the last several decades.[23]

The Observatory Astronomico Nacianal (OAN) San Pedro Martir is operated by the National Autonomous University of Mexico (UNAM) and located in central Baja California, Mexico approximately 245 km SSE of San Diego CA and 185 km west of Puerto Penasco. Access to San Pedro Martir is via a 100 km two lane road from the small town of Rancho Cepeda. The OAN currently hosts six telescopes at the mountaintop location, ranging in aperture from 2.1 m to 0.28 m. The Telescopio San Pedro Martir Project is developing a 6.5-m telescope for the site.[25]-[27] Many of the design concepts of this telescope are being incorporated into this project. The San Pedro Martir site has a superior astroclimate that has been well documented in the recent literature. Typical moonless night sky brightness at zenith has been measured to be 21.84 in V and 21.04 in R.[28] Sky clarity is exceptional, with 70-80% of nights being reported as photometric.[29] Median seeing varies from 0.50 to 0.79 arcsec (c.f. [30]). Atmospheric extinction is typically low, 0.15 mag/airmass in the V band.[31] The extreme remoteness of the site guarantees it to be a pristine astronomical site for decades to come.

Of the candidate site locations, Mt. Lemmon has the most limited suite of published astroclimate survey data. Consequently, through the summer and fall of 2018, the Steward Observatory is conducting a full-hemisphere night sky brightness (NSB) characterization study that will provide comparative data between Mt. Lemmon, Mt. Hopkins, and Kitt Peak. The NSB survey will be performed by a portable Takahashi E-180 Epsilon Astrograph with a multi-color filter wheel. We anticipate that these measurements will allow direct comparison and monitoring of the full-hemisphere impact of light pollution on each of these sites. The consortium also intends to deploy multiple differential image motion monitors to provide simultaneous measurements at our final candidate sites. These measurements are intended to quantify any potential local degradation in seeing due to nearby structures and terrain prior to selection of a final location for the telescope. Figure 8 shows the location that we believe will be the best of our options at Mt. Lemmon. These measurements will allow direct comparison of local seeing effects on each mountaintop and inform our selection of a final location. A geotechnical field survey of the three candidate locations at Mt. Lemmon is also planned for fall 2018.

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[1] It is noted that the telescope owner may have access to other sites that also trade favorably with sites the consortium can offer.

Figure 8. The prime location for the first ATO on Mt. Lemmon, on the ridge just west of the old Air Force Station radar tower. The large building on the left (Army barracks) is planned to be removed from the site.

8. OPTIONS AND CUSTOMIZING

The baseline ATO does have options and can be customized to the customer's specific requirements and needs. These options include different sites to the addition of a deformable secondary mirror with a full adaptive optical system for high-resolution imaging. The list of identified options are shown below. They come at an increase in the cost and may increase the duration of the project to greater than five years.

- Site options: Mt. Lemmon, Mt. Hopkins, San Pedro Mártir in Mexico, Chile and other possibilities
- Instruments: visible, IR, imagers, spectrographs, polarimeters and other customer required instruments
- Secondary mirrors: static f/5, f/11, deformable f/11 for AO, prime focus, Cassegrain, Nasmyth, bent Cassegrain and other optical configurations
- Coating options: On-site coating plant, mobile coating service, and potential long-term coating possibilities
- Adaptive optical systems: natural guide star and laser guide star
- Fast motion: various slewing, tracking and motion options including satellite tracking and other specialized requirements
- Maintenance: full observatory, telescope, instruments and sub-systems, annual, lifecycle and upgrades
- Operations: operate telescope and/or produce remote operations
- Science and data products: support science at telescope and produce prescribed data products as specified
- Robotic telescope options: semi-robotic to full robotic operational capability
- Expanded on-site building and facilities: requirements to be determined by customers

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