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Development and status of MAPS, the MMT AO exoPlanet characterization System

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ABSTRACT

We are upgrading and refurbishing the first-generation adaptive-secondary mirror (ASM)-based AO system on the 6.5-m MMT in Arizona, in an NSF MSIP-funded program that will create a unique facility specialized for exoplanet characterization. This update includes a third-generation ASM with embedded electronics for low power consumption, two pyramid wavefront sensors (optical and near-IR), and an upgraded ARIES science camera for high-resolution spectroscopy (HRS) from 1-5 μm and MMT-POL science camera for sensitive polarization mapping. Digital electronics have been incorporated into each of the 336 actuators, simplifying hub-level electronics and reducing the total power to 300 W, down from 1800 W in the legacy system — reducing cooling requirements from active coolant to passive ambient cooling. An improved internal control law allows for electronic damping and a faster response. The dual pyramid wavefront sensors allow for a choice between optical or IR wavefront sensing depending on guide star magnitude, color, and extinction. The HRS upgrade to ARIES enables cross-correlation of molecular templates to extract atmospheric parameters of exoplanets. The combination of these upgrades creates a workhorse instrument for exoplanet characterization via AO and HRS to separate planets from their host stars, with broad wavelength coverage and polarization to probe a range of molecular species in exoplanet atmospheres.

Keywords: Adaptive optics, spectroscopy, exoplanets, infrared, instrumentation

1. INTRODUCTION

The 6.5-m monolithic MMT telescope was the first to host an adaptive optics (AO) system using an adaptive secondary mirror (ASM) as the high-order deformable mirror (DM). This MMT AO system was installed and first operated in 2002 (1). This AO system is now being updated after two decades with "MAPS," the MMT AO exoPlanet characterization System. MAPS is a project to update the ASM, to add two new pyramid wavefront sensors (WFS's), to upgrade the science cameras ARIES and MMT-POL, to carry out a science program to characterize exoplanet atmospheres, and to develop a short course in exoplanet instrumentation (the ExoTech Academy).

In this paper we give a general overview of the status of MAPS. For details about the Visible WFS development, see (2). For details about the ASM laboratory testing and calibration, see (3).

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2. ASM DEVELOPMENT

By leveraging the advances in electronics and optics since the installation of the MMT AO legacy system, MAPS will provide the following key upgrades:

- **Low power emission.** All 336 voice coil actuators have been replaced with a new design of actuators and control electronics optimized for low heat emissivity. The new ASM dissipates much lower power (300 W; $\approx$ 85% less) than the legacy system 2–3 kW. See Table 1 and Figure 1 for more details on the power dissipation. (The 6^{th} revision is the final design of the new system.) The legacy system required active water cooling, while the new system will use passive ambient cooling. By incorporating digital electronics in the actuator bodies themselves, this simplifies hub electronics such that power is signficantly reduced at the central hub.
- **Compact and low-cost design.** The MAPS-ASM design is optimized for compactness in size and low cost. The ASM follows a modular design so that the actuators can be increased if needed. Therefore, it can be considered a testbed for future ASM development for the Large Binocular Telescope (LBT) and Giant Magellan Telescope (GMT).
- **Better AO performance.** The legacy MMT AO system (4, 5) was equipped with a 12x12 Shack-Hartman wavefront sensor. It was able to correct only 55 modes with a 2.7 ms temporal delay response giving a residual wavefront error of approximately 450 nm RMS (6). MAPS uses high-sensitivity and high-spatial-order visible and infrared pyramid wavefront sensors (VPyWFS and IRPyWFS), which have been demonstrated successfully on the LBT (7), Magellan Adaptive Optics (MagAO) (8), Subaru's extreme AO system (SCExAO) (9), and the Keck Planet Imager and Characterizer (KPIC) (10). This new system will correct 150–220 modes with a faster temporal response of 1 ms delay. MAPS is expected to deliver two times better performance — residual wavefront error of approximately 200–300 nm rms. The availability of two wavefront sensors covering the visible and near-infrared wavelengths is a huge boost for the sky-coverage as the blue and red-type guide stars both can be used for guiding.

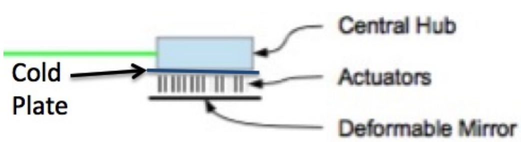

Figure 1 Diagram to illustrate components dissipating power in the MAPS ASM. (ASM is looking down as if telescope is at zenith.) Power is dissipated in the 336 actuators via their electronics and electromagnetic coils, as well as in the central hub electronics (consisting of 1 motherboard and 6 daughterboards).

Source [W]	**Legacy System**	**4^{th} Rev.**	**5^{th} Rev.**	**Final Rev.**
Actuator Electronics	10	168	111	111
Coil Power†	112	112	112	139
Subtotal at Cold Plate	*122*	*280*	*223*	*250*
Hub Electronics	1680	50	50	50
TOTAL	**1802**	**320**	**273**	**300**

Table 1 Measured power consumption in Watts of the ASM system, for the original legacy system, as well as the fourth through final revisions of the MAPS ASM.
†Coil power is for a quiescent flat.

The MMT ASM was the first-generation high-order DM for astronomical AO installed on a major telescope. The second generation ASM was then installed on the LBT (11) and a clone on MagAO (8). Our upgrade to the MAPS ASM can thus be thought of as the third generation ASM. In Table 2 we compare these three generations of ASMs.

The MAPS ASM uses the same thin-shell, reference body, cold plate, and mechanical support structure as the legacy MMT-AO ASM from two decades ago. Figure 2 (left) shows the legacy shell, which was re-coated for MAPS. Figure 2 (right) shows the new actuators installed in the legacy optics, which was a milestone achieved in December 2019.

Table 2. Comparison of ASMs across 3 generations.

Parameter	unit	MMT336	LBT672	MAPS
Shell diameter	cm	64.0	91.1	64.0
Shell thickness	mm	1.8–1.9	1.6	1.8–1.9
Shell shape		Convex Hyperboloid	Concave Ellipsoid	Convex Hyperboloid
Shell + magnet mass	kg	2.60	4.37	2.60 + bias magnets
# of actuators		336	672	336
Optical compression		10	9.0	
Ave. act. spacing on M1	cm	31.0	28.1	
Act. accessibility		Low: bolted, inserted from back	High: clamped, inserted from front	
Total mass	kg	128	250	
# of acts. per DSP		2	2	1
Tot. # of DSPs		168	336	336
DSP model		ADSP-2181	ADSP-21160	STM32F446
DSP architecture		16bit integer 1xALU, 16bit DMA	32bit floating-point 2xALU, 32bit DMA	32bit f-p, 1xALU, 32bit DMA
DSP comp. power	Mop/s	80	360	
Tot. DSP comp. pow.	Gop/s	13.4	121	60
On-board WF real-time reconstructor		No	Yes	No
Communication link		Fiber Link	2x2Gbit Fiber Channel	1Gbit Ethernet
Eff. transfer rate	Mbit/s	160 (full duplex)	2900 (full duplex)	1000
Sep. diag. link		Yes (added later)	Gbit Ethernet	Yes
Eff. transfer rate	Mbit/s		400	100
Cap. sens. ref. signal	kHz	40	156	100
Electronic damping		Possibly, digital	Yes, analog & digital	Yes, digital
Position digital samp.	kHz	40	80	200
Cap. sens. bandwidth	kHz (-3dB)	26	90	600
Coil current driver b.w.	kHz (-3dB)	56	56 (possibly 74)	
Actuator efficiency	$N/\sqrt{W}$	0.5	0.5	0.6
Pow. diss. in crates	W/act.	4.7	3.8	0.8
Pow. diss. at act. level	W/act.	0.41	0.19	0.7
Fitting error	nm rms	72	64	72

Note. — Adapted from (11).

Figure 2 **Left:** The back side of the thin shell for the MAPS ASM. The magnets are glued to the back side that is being cleaned in this photo. **Right:** This photo shows all 336 actuators installed in the cold plate and poking through the reference body. In this photo the ASM is looking up (whereas on the telescope at zenith it will be looking down towards the primary mirror).

There are two thin-shells for the MMT ASM. The spherical shell is 2-mm-thick throughout, and matches the figure of the reference body on both sides. This is a shell used for testing, but not on the telescope. The actual telescope shell is aspherical, ranging in thickness from 1.8–1.9mm, and creates the convex hyperboloid shape needed for the MMT. The spherical shell was installed first, in Spring 2020, before the aspherical shell was installed in Summer 2020. The procedure for mounting the shell onto the reference body is quite nerve-wracking the first time it is done, as the actuators have not yet been tested *in situ* with a thin delicate glass shell. The shell is slowly raised with a lifting fixture mounted on a scale, where the scale is watched for the weight to start to decrease, which means the magnets have started to capture the shell. Figure 3 shows a little bit about the procedure.

In our previous proceedings (12), we reported on the design of our new ASM electronics, as well as the status of the prototype nineteen-actuator testbed. Since that time we have achieved the following milestones:

1. Fabricated all 336 actuators, 6 daughterboards, and 1 motherboard — completion 2019
2. All actuators tested working — Summer 2019
3. Motherboard talking to actuators via daughterboards — Jun. 2019
4. Nineteen-actuator testbed working in closed loop — Fall 2019
5. Reference signal upgraded — 2019
6. All 336 actuators installed — Dec. 2019
7. Error-free 1-Gbit communication —- Jan. 2020
8. Remote operations completed —- Mar. 2020
9. Spherical shell integrated —- Spring 2020
10. Electrical flat —- Summer 2020
11. Aspherical shell integrated —- Summer 2020
12. Critical Design Review for both WFS's —- Jul. 2020
13. Test stand Phasics aligned — Aug. 2020
14. Zernike functions applied on mirror (electrical) —- Aug. 2020
15. ASM operation on test stand with Phasics interferometer —- Sep. 2020

Figure 3 **Left:** Mounting the thin shell onto the reference body. **Right:** A look through the gap in the shell.

16. Zernikes applied on mirror (optical) —- Oct.–Nov. 2020
17. Currently analyzing optical data with Phasics interferometer — Dec. 2020 (present time)

We are currently analyzing the optical data, taking data to simulate a variety of astronomical conditions, and preparing for a review of the ASM system. For more about the ASM testing, see (3).

3. MAPS AO SYSTEM

The AO system using an ASM as the DM and has two swappable pyramid WFS's: a visible-light PyWFS with a low-noise CCID-75 detector (2), and an infrared PyWFS with a low-noise Saphira detector (13). The WFS's make up the "W-unit" which is mounted in the Top Box of the MMT, at the Cassegrain port. Mounted below the Top Box is the science camera, which are currently planned to be swapped between ARIES, MMT-POL, and MIRAC. Figure 4 illustrates the entire MAPS system on the telescope, while Figure 5 illustrates the WFS in the Top Box. For more details about the WFS design, see (2).

While much of the PyWFS design was planned to follow the successful designs of our Arizona PyWFS systems on LBTI and MagAO, one component of those systems that was untenable for MAPS were the Bayside 3-axis translation stages. On LBTI and MagAO the Bayside stages hold the entire W-unit and slew it in a 3-axis xyz motion to fine-tune natural guide star (NGS) acquisition, as well as to compensate for telescope nods. However, because MAPS's W-unit is mounted at the Cassegrain focus and encounters all possible gravity vectors, and also because MAPS has 2 WFS's with the added weight of a crystat to keep the Saphira cool, the stages we explored from various companies were going to require an enormous mass and extremely difficult precision, and we were not able to find stages to fit these requirements while also fitting within the envelope of the height of the Top Box. Therefore, we have instead elected to go with a periscope design for steering and nodding. A pair of steering mirrors will point and center to fine-tune the alignment of the NGS as well as to compensate for the telescope nods. The periscope is illustrated in Fig. 6 and specifications given in Table 3.

In July 2020 we held a critical design review (CDR) of both wavefront sensors. The purpose of this review was to bring in outside expertise to assess the design before procurement of most components began. (However, some

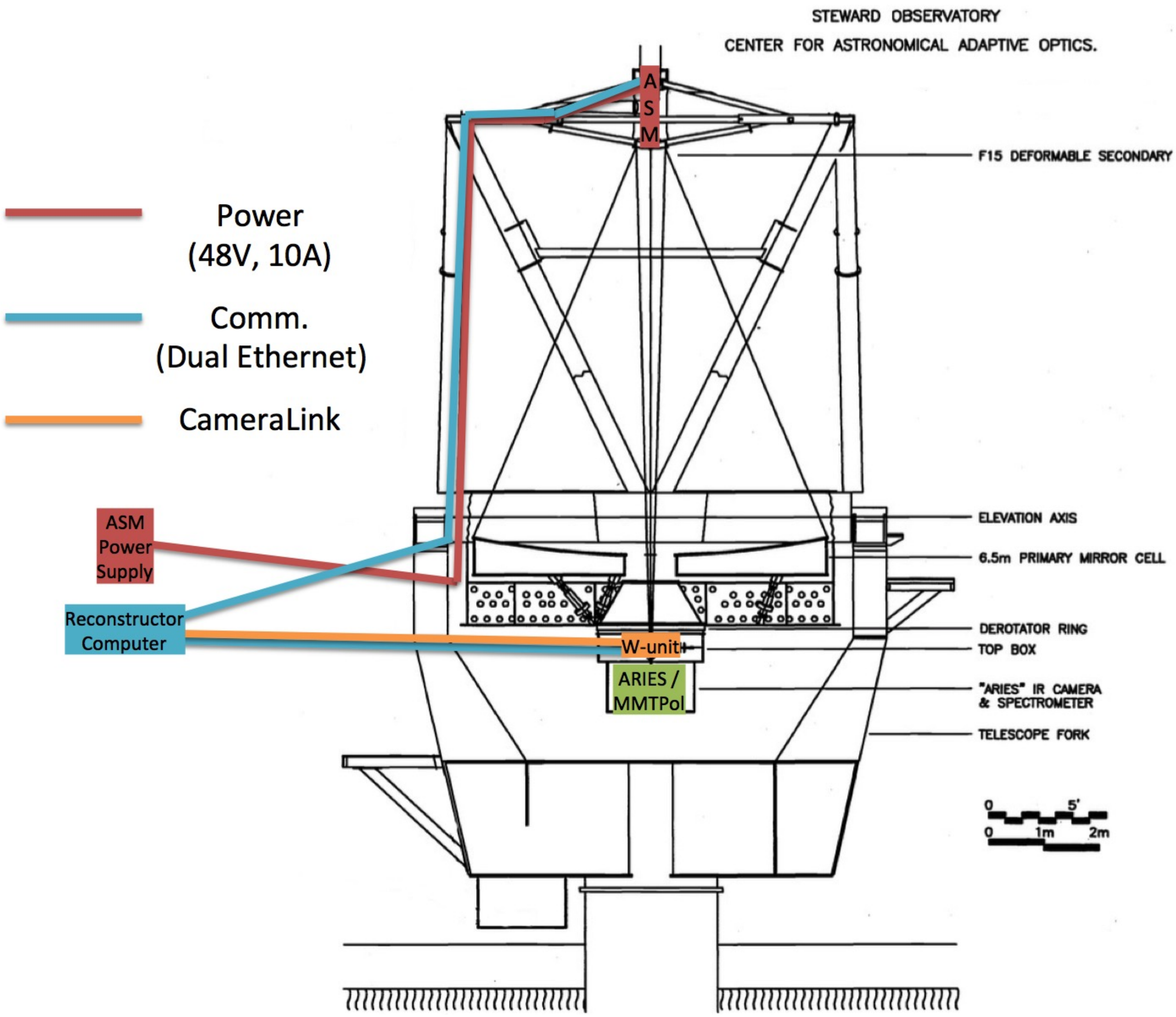

Figure 4 Diagram illustrating MAPS on the MMT 6.5-m telescope. The ASM is mounted above the primary and in the Top Box below the primary we have the W-unit, which contains the acquisition camera and both PyWFS's. A dichroic beamsplitter below the Top Box splits light between the W-unit and the science camera, which can host various AO-fed science cameras such as the originally planned-for ARIES and MMT-POL, as well as MIRAC-5 and possibly others. The control computers and ASM power supply are not mounted on the telescope itself. (Telescope diagram modified from (14)).

long-lead items had already begun procurement.) Reviewers suggested further analysis into such topics as long-wavelength characterization of the Saphira, non-common path wavefront error budget, structural thermal optical performance (STOP) modeling, power dissipation in the Top Box, performance analysis of various wavefront sensing modes, field-of-view details for the periscope design, pixel separation for the VisPyWFS, SciMeasure controller temperature sensitivities, vibrations from the Saphira cryocooler, and electrical grounding for ARIES. Our team is working on these items.

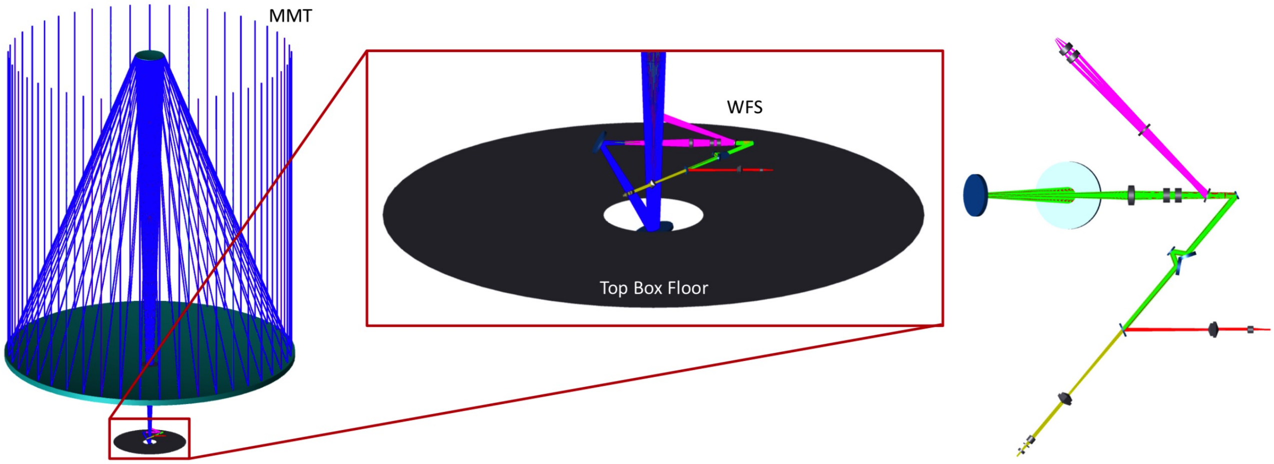

Figure 5 **Left:** Illustration of light path from MMT telescope into the Top Box. **Right:** W-unit in Top Box. In this diagram, light enters from the left side beamsplitter. There is a common-path atmospheric dispersion compensator (ADC), then a selection of the visible light is sent to the acquisition channel (top, magenta). In the lower green channel, there is a common K-mirror (common to both WFS's, but not common to the acquisition channel) for rotating the pupil. A fold mirror can be set to send the light either to the visible PyWFS (right, red), or to the IR PyWFS (lower/left, yellow).

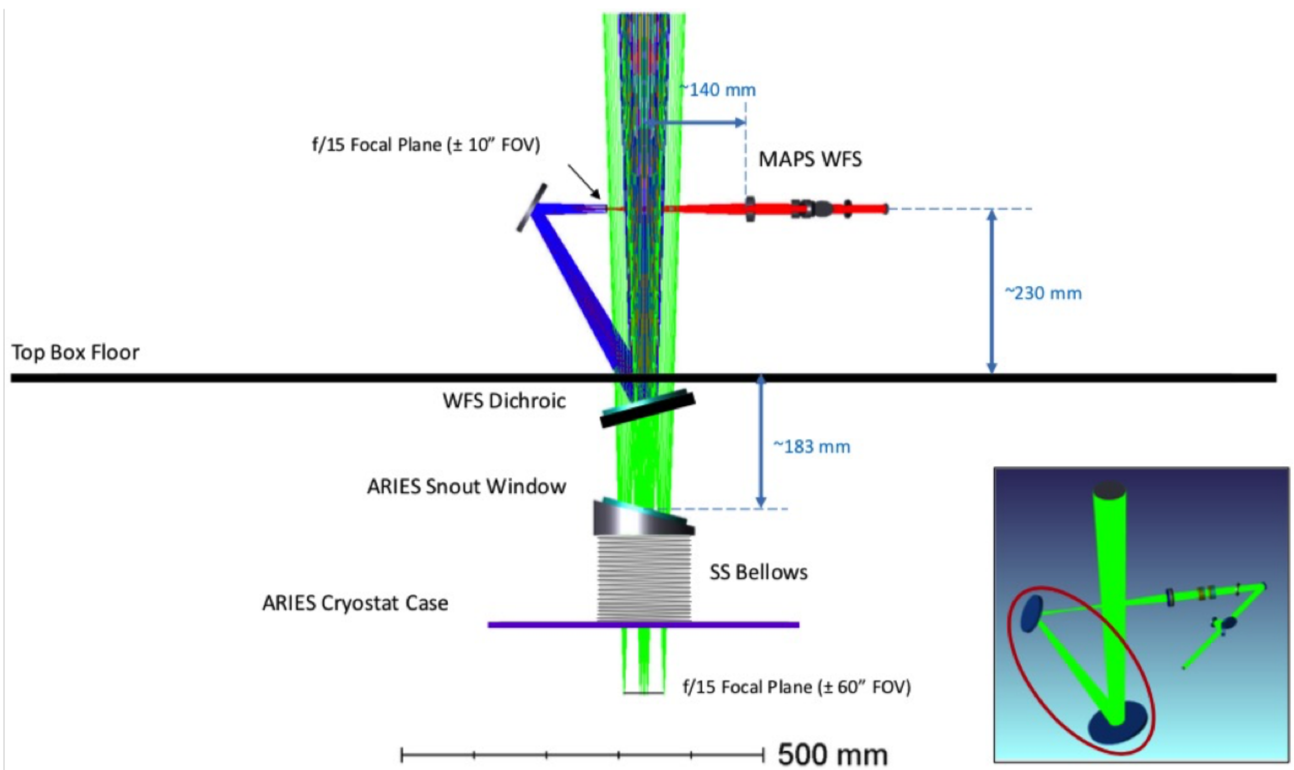

Figure 6 Periscope design for steering and nodding. The two steering mirrors are the WFS dichroic and the periscope fold mirror, which will both be able to nod in xy. The periscope fold mirror will also piston in z, to provide the fifth degree of freedom required. Specifications are given in Table 3.

Alignment Type	On-Axis Focus	*yz* plane Boresight	 **Boresight & Focus**	*xz* plane Boresight	 **Boresight & Focus**	**Specs**
DoF required	3	2	3	4	5	**5**
ARIES dichroic x-tilt [°]	±1.4	±2.4	±3.9	±0.2	±1.5	**±3.9**
ARIES dichroic y-tilt [°]	0	0	0	±2.4	±2.5	**±2.5**
Periscope fold mirror x-tilt [°]	±1.4	±2.4	±3.9	±0.2	±1.6	**±3.9**
Periscope fold mirror y-tilt [°]	0	0	0	±2.4	±2.4	**±2.4**
Peri. fold mirror z-piston [mm]	±10	0	±10	0	±10	**±10**

Table 3 Periscope degrees-of-freedom (DoF) specifications. This allows for observations up to ±60 arcseconds (radius) off-axis of the NGS.

4. SCIENCE INSTRUMENTS AND PLANNING

The goals for the science instruments are to upgrade the Arizona Infrared Echelle Imager and Spectrometer (ARIES) and the 1–5 μm imaging polarimeter (MMT-POL), to comprise a facility with unique astronomical capabilities. We will then deploy the new instruments at the MMT and carry out a 60-night study to characterize ∼100 exoplanets. The ARIES upgrade involves the replacement of the spectrometer's detector and an improved cross disperser designed for the broader wavelength range. The upgrade of the infrared imaging polarimeter, MMT-POL is being carried out to enable use with the new AO Secondary.

When operational, MAPS will be used to perform a survey of the atmospheres of transiting and directly imaged exoplanets. The goals of the core science project are to characterize ∼100 exoplanets, including Hot Jupiters, Super Earths, Warm Neptunes, and Warm Jupiters. The high spectral resolution will enable extraction of atmospheric parameters and molecular abundances. A new grating will be deployed in the ARIES spectrometer to improve the spectral resolution of the system. MMT-POL will be upgraded for better imaging and faster readout for use with the ASM on the MMT.

ARIES (15). The design for the ARIES upgrade was reviewed. We prepared the ARIES instrument development plan and began targeted analysis of the implementation. The upgrades span detector upgrades for the spectrometer half, improvements to the cross-dispersing prism, a focal expander for high resolution, enhanced echelle slit substrates, and initial design elements for a new R6 grating. A quote for the R6 grating from Richardson Gratings Lab was obtained and the integration of the device into the ARIES spectrometer cryostat was explored. A potential space constraint was identified, and is currently being analyzed for how to modify the grating, the mount or the optical design to fit the upgraded system in the cryostat.

MMT-POL (16). A new, low order 1/2 waveplate has been installed in an upgraded mechanism in MMT-POL. Imaging at 2.2μm was not as good as it should have been, and we traced the problem to the very thick achromatic half waveplate we were using. The new waveplate is a single, thin disk of Sapphire that works as a 3/2 (5/2) waveplate at 2.2 (1.3) μm.

Science planning. Based on collaborative meetings and a workshop with input from ASU/Arizona/UCSC members, a procedure to identify specific wavelength ranges available for each combination of grating/optics/mount position was developed. Exoplanet systems for case studies were identified from a literature review to find published results to be compared with MAPS simulations; these targets have different molecules present in their atmospheres which will test the different wavelength regimes of the instrument. An investigation into the line lists to be used for the cross-correlation analysis was initiated. Two exoplanet systems were identified as the best to simulate for the design studies, a tool to simulate the wavelength coverage on the detector in each mode of MAPS was used to begin the study of what retrievals are possible with a given type of observation.

We have identified the following procedure to be followed when observing. Software for observing, including integration with the AO system, telescope, and science cameras, will use these steps below.

1. Telescope slews to target
2. Enter guide-star magnitude into software

3. Look-up table selects WFS frequency and binning based on magnitude of NGS
4. Modulator begins modulating at WFS frequency, WFS begins reading out at frequency and binning
5. Acquire star on acquisition camera (Nod the telescope)
6. Acquire star on pyramid (Nod the periscope/steering mirrors, and the Camera Lens as needed)
7. Close loop on low-order modes (A lot of things happen here)
8. Close loop on high-order modes
9. Begin science observations (A lot of things happen here)
10. End science observations
11. Open AO loop — Modulator stops modulating, WFS stops reading out

In 2021 we will review the ASM performance, complete the WFS builds, integrate the AO system, install it on the telescope, and hope to have first light. Commissioning is planned in phases to tackle each component of the system at a time. First will be the on-sky interaction matrices using a pseudo-synthetic approach. Then we will close the loop and take images with whichever of the MAPS science cameras is most available. Finally, both science cameras will be commissioned, and the science program will begin.

5. EDUCATION PROGRAM

We have included in the MAPS plan a winter school on exoplanet instrumentation that we are calling the "ExoTech Academy" (no intentional relation to or overlap with the AstroTech Summer School, which we heard about after we had conceived and named our school).

Students interested in instrumentation face diminishing opportunities to contribute to major instruments as we enter the era of big data and big telescopes. Therefore, we are designing a student-led, student-scaled program in developing exoplanet instrumentation. Early-career astronomers will come to the "ExoTech" short course to be trained in exoplanet instrumentation. Future instrument-builders, observers, and theorists alike will benefit from the school, which will build literacy in instrumentation. Instrumentation literacy is critical to counter the greater separation between most astronomers and their observations in the GMT/Rubin era.

6. EFFECTS OF COVID-19

Not only did the MAPS project face some delays in 2019 due to unforeseen technical challenges as well as on-boarding of new personnel (change of PI from Phil Hinz to Katie Morzinski; new software engineer and AO specialist as retirement replacement), but we also faced the effects of the COVID-19 pandemic. Our work has gone on through sicknesses and deaths, furloughs, COVID research waivers, a general slow-down of lab work due to remote operations, daily tag-up meetings, new safety protocols, and extra paperwork and logging. In March when the University of Arizona shut down due to COVID, we quickly moved to finalize remote operations capabilities. The ASM and Phasics are operated via a webpage gui, while a webcam was installed to provide visual confirmation of ASM safety and the power supply status. Throughout the remainder of 2020, we have been allowed to occasionally send someone into the lab to do in-person work as needed. Nevertheless, the bulk of the ASM testing and calibration has been done while working remotely from home. This has been a learning curve and made lab work slightly more difficult and time-consuming than otherwise expected. Therefore the occurrence of COVID has indeed caused a delay in the MAPS project.

7. INCLUSIVE TERMINOLOGY

The MAPS team strives to use inclusive terminology wherever possible. We have decided to deprecate certain words and phrases for more inclusive terminology as noted in Table 4.

External Documents with this terminology shall be marked:

> The following external documentation uses terminology that refers to slavery. In internal MAPS documentation, we use the terms initiator/target rather than master/slave.

Table 4. Inclusive terminology.

Instead of This Term	Please Use This Term
Slaved Actuators	Coupled Actuators
Master/Slave	Initiator/Target
Male/Female (connectors)	Pin/Socket
Grandfathered In	Legacied In

and/or

> PLEASE NOTE: Some files in this directory use terminology that refers to slavery. For code and documentation internal to MAPS, we use the terms "initiator/target" rather than "master/slave". Where possible, e.g. when the word is part of a comment, the terms "master/slave" should be replaced with "initiator/target". Where the term is itself part of the code, add a comment to acknowledge it and note the preferred "initiator/target" language.

ACKNOWLEDGMENTS

The MAPS project is primarily funded through the NSF Mid-Scale Innovations Program, programs AST-1636647 and AST-1836008. This research has made use of NASA's Astrophysics Data System. The University of Arizona sits on the original homelands of Indigenous Peoples who have stewarded this Land since time immemorial. Aligning with the university's core value of a diverse and inclusive community, it is an institutional responsibility to recognize and acknowledge the People, culture, and history that make up the Wildcat community. At the institutional level, it is important to be proactive in broadening awareness throughout campus to ensure our students feel represented and valued.

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