The Magellan Telescope Adaptive Secondary AO System: A Visible and Mid-IR AO Facility

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ABSTRACT

The Magellan Clay telescope is a 6.5m Gregorian telescope located in Chile at Las Campanas Observatory. The Gregorian design allows for an adaptive secondary mirror that can be tested off-sky in a straight-forward manner. We have fabricated a 85 cm diameter aspheric adaptive secondary with our subcontractors and partners, the ASM passed acceptance tests in July 2010. This secondary has 585 actuators with <1 msec response times (0.7 ms typically). This adaptive secondary will allow low emissivity AO science. We will achieve very high Strehls (~98%) in the Mid-IR (3-26 microns) with the BLINC/MIRAC4 Mid-IR science camera. This will allow the first "super-resolution" and nulling Mid-IR studies of dusty southern objects. We will employ a high order (585 mode) pyramid wavefront sensor similar to that now successfully used at the Large Binocular Telescope. The relatively high actuator count will allow modest Strehls to be obtained in the visible (0.63-1.05 µm). Moderate (~20%) Strehls have already been obtained at 0.8 µm at the LBT with the same powerful combination of a next generation ASM and Pyramid WFS as we are providing for Magellan. Our visible light AO (VisAO) science camera is fed by an advanced triplet ADC and is piggy-backed on the WFS optical board. We have designed an additional "clean-up" very fast (2 kHz) tilt stabilization system for VisAO. Also a high-speed shutter will be used to block periods of poor correction. The VisAO facility can be reconfigured to feed an optical IFU spectrograph with 20 mas spaxels. The entire system passed CDR in June 2009, and is now finished the fabrication phase and is entering the integration phase. The system science and performance requirements, and an overview the design, interface and schedule for the Magellan AO system are presented here.

1. INTRODUCTION: SCIENCE WITH AN ADAPTIVE SECONDARY AT MAGELLAN

The biggest sensitivity gains to be had from Adaptive Optics (AO) may be in the thermal (~3-25 µm) IR (Mid-IR AO), where it is possible to routinely achieve "perfect" >98% Strehl images (past 8µm). In particular, one can discern, uniquely well, the details of pre-planetary disks (Liu et al. 2005, 2006), debris disks (Liu et al 2004), dust shells and outflows (Close et al. 2003b; Biller et al. 2005; 2006), circumstellar disks around tight (<0.1") young binaries (Skemer et al. 2008) and from 3-5µm: cool extrasolar planets (Heinze et al. 2006; Hinz et al. 2006). In general, it is now possible to discern which of the stars in a tight young binary have circumstellar disks; moreover, through 10 µm silicate imaging determine if the disk orientations are similar (Skemer et al. 2007). The silicate 8-14 µm dust spectra of

Figure 1. The world's first adaptive secondary: a 65cm 336 actuator ASM at the MMT.

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Adaptive Optics Systems II, edited by Brent L. Ellerbroek, Michael Hart, Norbert Hubin, Peter L. Wizinowich,
Proc. of SPIE Vol. 7736, 773605 · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.857924

tight young binaries informs us how dust evolves and grows in grain size, which is the first step of planet growth. In addition, many solar system bodies such as comets, asteroids, KBOs, gas giants (and their moons) all have a need of Mid-IR imaging to constrain albedos and morphologies. Moreover, Magellan Mid-IR AO has >6x the resolution of Spitzer and so this is a needed capability for high resolution follow-up of bright (>1 mJy) Sptizer galactic and extragalactic sources. For example, the Spitzer Glimpse survey (of the Galaxy's mid-plane, where AO guide stars are common) alone has discovered ~10^5 new sources of this flux density, all of which could benefit from Mid-IR AO imaging with 6x higher angular resolutions.

The most recent (3ird) US observational "System" meeting noted that diffraction limited 2-20 μm imaging on large telescopes was badly needed to match HST's optical/NIR resolutions (recommendation 3, Origins Science talk #2).

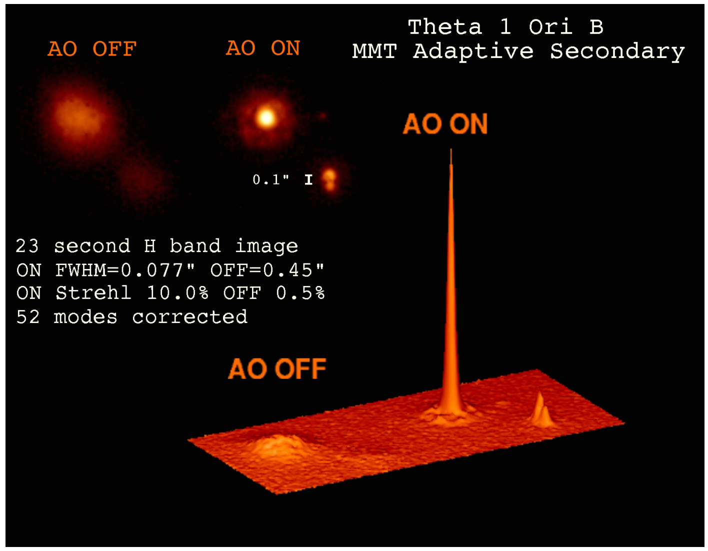


Figure 2. Adaptive correction with the MMT adaptive secondary at H band in a 30 second exposure (Close et al. 2003a). These MMT AO H band (77 mas – AO ON) images of the Theta 1 Ori B complex have positions good to 0.002" (Close et al. 2003a).

1.1 How can you build a low emissivity Mid-IR AO system for Magellan?

The technique of thermal IR astronomy demand different observing methods, and optical configurations compared to "classical" AO. A classical AO system can easily squander the gains to be had in Mid-IR AO through the use of warm, dusty, relay and deformable optics (Lloyd-Hart 2000; Close et al. 2008). However, if the secondary mirror of the telescope is itself the deformable optic in the AO system then there is no extra emissivity introduced. Therefore, it is possible to have an optimal Mid-IR AO system by use an Adaptive Secondary Mirror (ASM). That is the deformable optic is the telescope's secondary mirror itself. We have proven that this is possible with the world's first adaptive secondary over the last 7 years at the 6.5m MMT telescope (Wildi et al. 2003; Close et al. 2003a; Kenworthy et al. 2004; Liu et al. 2005; Hinz et al. 2006, Skemer et al. 2008;2009;2010 – see figs 1-4).

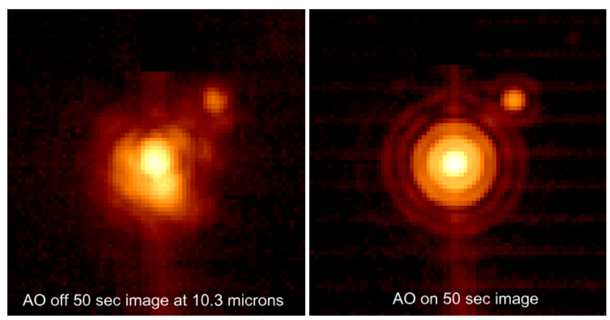


Figure 3. The great improvement in PSF quality with the MMT deformable secondary at 10 μm (Strehls improve from ~50% to 98±2% with AO).

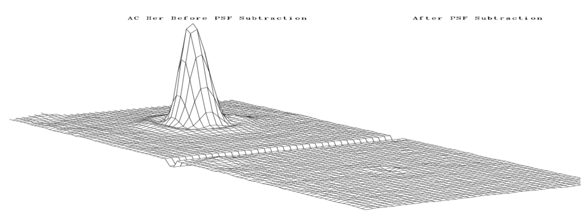


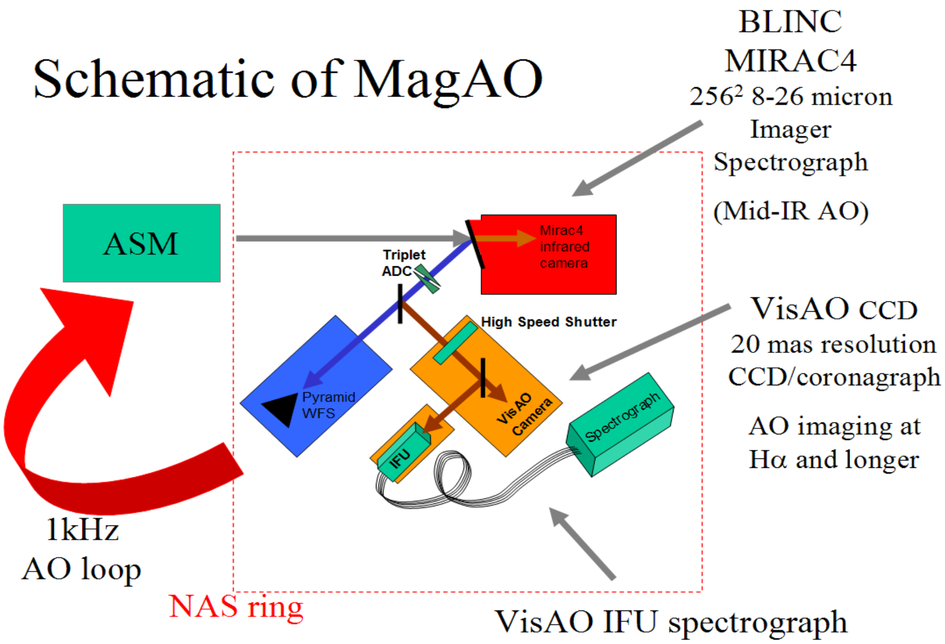
Figure 4. The Mid-IR AO image of AC Her (right) at Strehl 98% and S/N=3000. To the right we simply subtract a scaled image of the PSF star alpha Her. The residuals are less than 0.5% which is at the photon noise limit (Close et al. 2003b).

At Magellan we will complete the first low emissivity AO system in the southern hemisphere (Close et al. 2008). The south is very important for access to the most interesting galactic objects which are predominately located in the southern hemisphere; like the Galactic center itself, the nearest young stars in clusters like Sco Cen, TW Hya, Chamaeleon, p Oph, Upper Cen Lup, Lupus, Upper Sco, n Cha, Musca, Coalstack, Corona Australis, etc. As well as evolved stars like Eta Car, and those near the galactic center etc. To minimize risk and cost we have built a high performance 585 element version of the Large Binocular Telescope's (LBT) very successful adaptive secondary system customized for the 6.5m Magellan telescope. A brief technical description of the proposed ASM is presented in section 1.2.

TOP LEVEL SCIENCE REQUIREMENTS FOR MAGELLAN AO		Req#
MID IR AO MODE (3-25 µm)		
High Strehl & Super resolution (on-axis)	≥96% Strehls @ $\lambda \geq 8$ µm; $R \leq 13$	M1
Diffraction-limited Resolutions 3-20 µm	0.1” – 0.6”	M2
Wavelengths bands of interest	3-25 µm	M3
5σ detection of N=0.1 Jy point source	<60 sec	M4
Mid-IR spectra	8-13 µm Silicate features	M5
Circumstellar science	98% suppression of central star	M6
VISIBLE AO MODE (0.6-1.0 µm)		
Moderate Strehl (on-axis)	≥15% Strehl @ $\lambda \geq 0.85$ µm; $R \leq 8$	V1
Diffraction-limited Resolutions 0.6-1.0 µm	0.017 – 0.029”	V2
Wavelengths bands of interest	0.6 – 1.0 µm	V3
circumstellar science	<0.1”	V4
Faint & Bright star/binary science	$24<V\leq 4$ mag point sources	V5

DESIGN FOR COMPLIENT MAGELLAN AO SYSTEM		Meets Req#
Low emissivity AO system	chopping 585 actuator ASM	M1-M6
Scalable AO WFS with high order corr.	1kHz Pyramid WFS, 25 to 585 modes, 90x90” patrol field	V1-V2
MID IR AO MODE (3-25 µm)	256x265 array	
f/16 MIRAC4 platescales	50 – 100 mas/pix	M1-M2
f/16 MIRAC4 FOV	12.9 – 25.8” square	M1-M2
Filters	N,Q, 5 filter 10% silicate set	M3
Grism	R~80-120 over 7-14 µm at 0.1”/pix	M5
Nulling Interferometer (BLINC)	<2% nulls	M6
VISIBLE AO MODE (0.5-1.0 µm)	1k E2V “midband” CCD47-20	
VisAO CCD platescale (f/49)	8.5 mas/pix	V1-V2
VisAO CCD FOV	8.7” square	V1-V2
Filters	V,R,I,z,y, SDI(Hα, Hα_cont)	V3
Anti-blooming Coronagraph	0.1” – 3.0” ND3-ND6 spots	V4-V5
High Speed Mode (512x512x20 Hz)	Shutter Int. <3 ms (Full Frame; Readnoise <2e rms)	V5

On good nights (<0.65" seeing, which are frequent (>50%) at Magellan) we should be able to make diffraction-limited (20 mas FWHM) optical AO images with the system as designed (this is because 585 elements on a 6.5m pupil is twice as high density as the Keck AO system, for example). Hence, in addition to Mid-IR AO we will bring visible AO (Vis AO) to the southern sky, with Strehls of ~10-30% and resolutions of ~25 mas at I band on nights of median seeing. Detailed analytical simulations are presented in Males et al. (2010; these proceedings paper 7736-105).



The VisAO IFU is an optional mode of the system where either a 92 mas platescale or 20 mas platescale is produced on an lenslet array that feeds a 26x26 fiber bundle. The fiber bundle is than re-directed to the LDSS3 spectrograph (another possible options is the new fiber fed M2FS spectrograph) which can be parked near the Nasmyth port. In the 20 mas mode this is the highest spatial resolution IFU spectrograph yet planned. For more details on the VisAO IFS please see Follette et al. (2010).

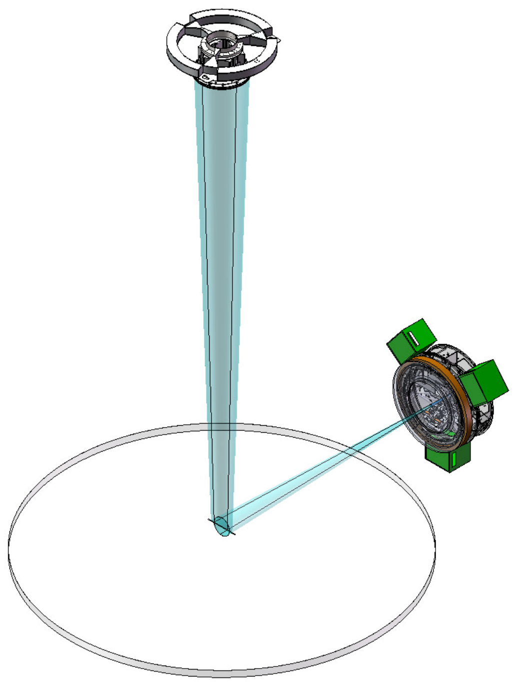


Figure 5: Magellan adaptive secondary mounted on the Magellan telescope as an Gregorian secondary. Note that an LBT secondary of size 0.851m will produce an f/16 beam that focuses just 9 inches past the nominal Nasmyth focal ports for all current Magellan instruments. To the right we show the normal Nasmyth focus where all "first-light" AO instruments (BLINC/MIRAC4, and the Vis AO CCD), and the WFS will be mounted on the so called NAS unit. This NAS ring also contains the pyramid WFS and the active optics probe needed to keep Magellan collimated..

2. THE MAGELLAN AO SYSTEM OVERVIEW

To address the unique gains of Mid-IR AO in southern skies the Magellan AO system received a TSIP 2007 award, which in addition to our previous (now expired) support from the NSF MRI program enables the construction phase of this ambitious project to be finished in late 2011 with first light in 2012. However the VisAO CCD and IFU portions of the project are only funded up to the prototype phase.

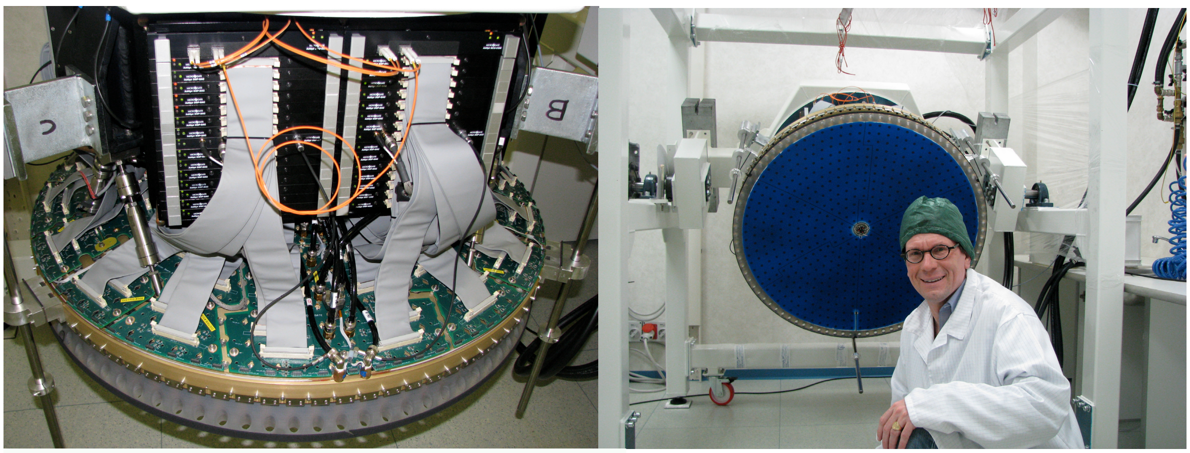
While the operating principles of the MMT deformable secondary are straightforward, the electromechanical system for many fast and high precision actuators is inevitably highly complex. The design balance for the present mirror was obtained by development with Arcetri Observatory over years of a number of prototypes of progressively increasing sophistication. The process is continuing through new the manufacture of two 91 cm deformable secondaries for the two 8.4 m telescopes of the LBT (the first of these LBT units has achieved amazing on-sky performance (SR>85% at 1.6μm) in 0.7" seeing at first light; see these proceedings for more on the LBT AO systems; Esposito et al. 2010; paper 7736-12).

The Magellan secondary AO system embodies all of the MMT and LBT experiences so far, and add the advanced features and robustness desired for Magellan while strictly adopting core LBT standard hardware and software for the ASM (Riccardi et al. these proceedings) and WFS (Esposito et al. these proceedings, paper 7736-12). An LBT standard design will ensure that lab testing and telescope commissioning will occur with maximum robustness and efficiency. Moreover, maintenance and upgrading the system will be become much simpler if all ASM systems on Magellan and both LBTs are almost identical.

The Magellan AO design is lead by UA in collaboration with Lorenzo Busoni (PWFS) and Armando Riccardi (ASM testing) at Arcetri Observatory. The Magellan shell (fig 6,7) is identical to the LBT shell except that it is 85.1 cm in dia instead of the 91.1 cm used at the LBT. This is significantly larger than the 65cm MMT shell. At this size it will be critically sized for the Magellan pupil.

Our system will use the more advanced “LBT” 2nd gen. electronics to allow improved servo control (electronic damping with position control at 70 kHz) for faster response time, (<1 ms compared to the MMT’s ~2ms). This will allow a larger gap, to accommodate the larger stroke needed for Magellan and for improved chop angle (~4” P-P) for the thermal infrared. It will also use higher precision encoders for the capacitive sensors to give <5nm rms noise per actuator for very high accuracy control of low and intermediate order aberrations needed for VisAO.

The mirror is a concave ellipsoid (to be used as a Gregorian secondary at Magellan) so it can be easily tested in the test tower with artificial aberrated starlight. It will have a deployable artificial source, so it can be tested subsequently on-telescope as a Gregorian mirror at the Magellan II (Clay) telescope. The larger size allows the use of larger, more efficient magnets in the actuators than in the MMT. The power per actuator and per unit area to correct turbulence is reduced despite the larger scale.



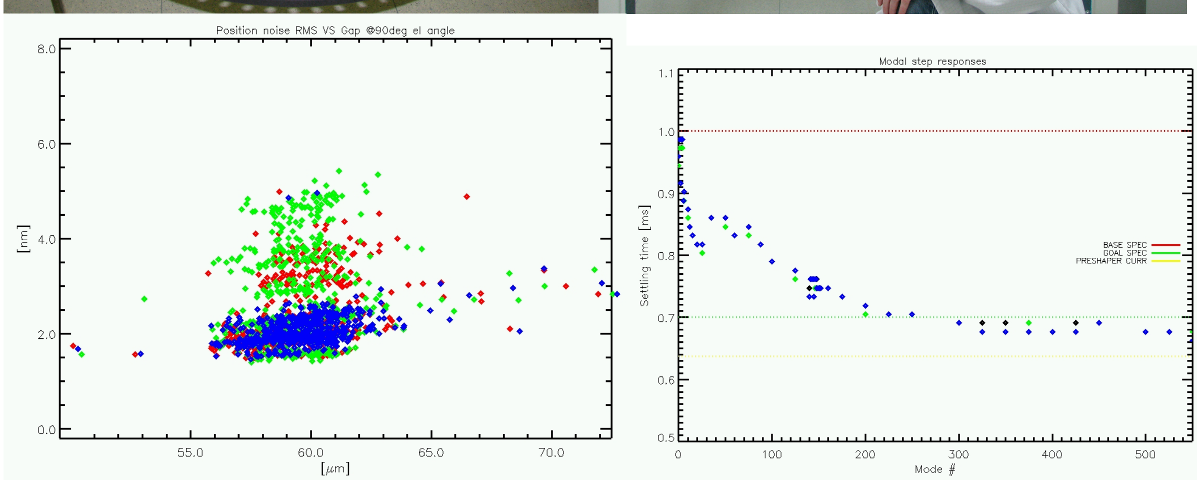


Figure 6 (top). The fully integrated figured and polished 1.6mm thick aspheric Magellan Adaptive Secondary Shell mated to its reference body (in Microgate’s lab in Bolzano Italy). Our Shell is only Al coated on the back face at this time, the front face is protected with a thin layer of blue opti-coat (see right hand photo). The regularly spaced dots are areas that have been masked during coating and are where the 585 magnets are glued. The size of the Magellan shell is 85.1 cm dia.

Figure 7 (bottom): The Magellan ASM passed Electro-Mechanical tests in July 2010. No actuator has more than 5 nm rms noise from 1-3 airmasses. Also all mirror modes are quicker than 0.9 ms 10-90 go to time. This ASM is as good (if not slightly better) than the LBTa unit currently running on-sky at the LBT telescope.

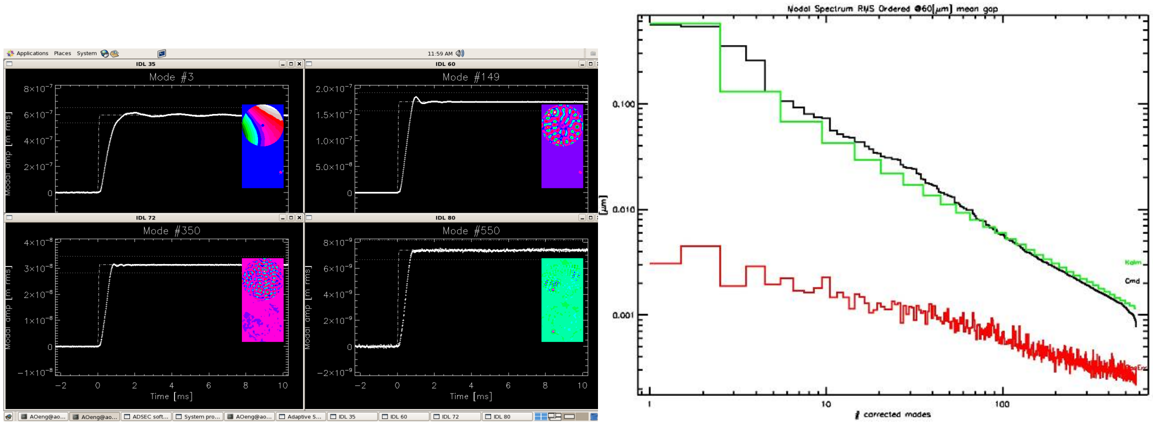


Figure 8: Left: A selection of 4 of the 585 modes and step responses of the ASM. They are all excellent and will allow 1 KHz response at the telescope with a standard 60 micron gap. Right: Here we see how well the ASM can track real turbulence phase screens. The MagAO system can follow 1100 nm rms (typical 0.65" seeing) of turbulence injected at 1 kHz to within just 33 nm rms residual at 1.4 airmasses – excellent dynamic behavior. Also The total >30microns stroke of the mirror is more than enough to obtain an excellent optical "flat" without using a significant amount of system stroke.

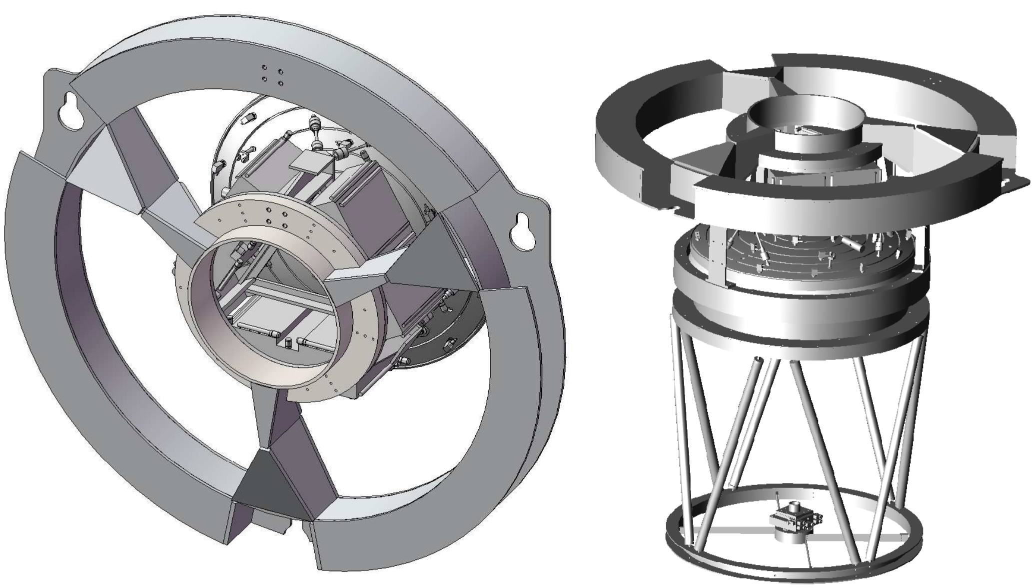


Fig 9: LEFT: The ASM mounted on its interface ring for the Magellan Telescope top end (cage). Right: The ASM with its wind screen attached. Also the calibration retroreflector (CRO) unit is shown installed with our struts below the windscreen ring. This CRO unit will only be needed during daytime calibration of the loop with an artificial source that mimics a real NGS star.

An important goal for this secondary is a robust software control system for the highest reliability and least maintenance. We have much experience through on-telescope use of the MMT and LBT secondary, fixing practical problems and developing safe operating procedures. All of these have been incorporated into the new AOsup and ADsec control systems. Software and hardware elements have been included to keep mirror position and actuator forces within safe margins. This control system will form a solid basis for future ELT deformable secondaries like that planned for GMT. In fig 7,8 we show the successful electro-mechanical tests of the Magellan shell with the full Magellan ASM hardware and electronics.

CAOS Simulations of VisAO

r_o=14cm (0.7" seeing) , L_o=25m, τ_o=2ms: (at LCO 75% of the time seeing is better)

VisAO $0.7\mu m$ Error Budget for an R=7 G2 Guide Star			
Error Term	**Est. (nm)**	**Sim. (nm)**	**notes**
Fitting	77.2	···	Estimates from standard thumb-rules.[16] These are added in quadrature for loop total.
Servo	47.4	···	
Recon.	47.0	···	
Loop Total	102.1	102.4	CAOS simulations as described in the text.
Static.	30	30	Based on LBT design specifications.
Non-Com. Path	30	30	Based on VisAO design specifications.
Resid. T/T	52.6	52.6	For 5 mas residual.[17]
Total	122.4	122.7	Sum in quadrature.
$0.7\mu m$ **Strehl**	0.3	0.3	Using extended Marechal approximation.

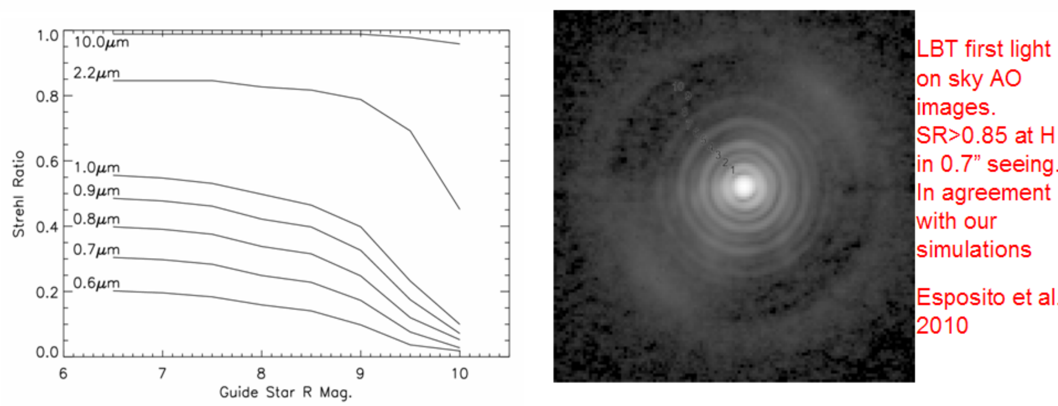


Figure 10: Here we have our detailed numerical simulations of the MagAO system's error budget with a bright guide star. In the plot below it is clear that the VisAO system will have moderate SR with bright guide stars. This is due to the excellent combination of a next generation ASM combined with a PWFS which can increase its Strehl with a diffraction-limited spot on the tip of the pyramid (photo: note the excellent results of a near clone of our system has achieved on the 8.4m LBT during first light). See Males et al. 2010 for more details on these CAOS simulations.

3. New Science Enabled with the Magellan ASM

Several new science fields will be opened up in the south with our new ASM. Mid-IR AO (low emissivity 8-25 μm imaging and 8-14 μm spectra) will be immediately available in the southern hemisphere for the first time. We will use the mid-IR AO camera MIRAC4 for the first facility mid-IR AO camera in the south. As well we will use the BLINC nulling interferometer for unique nulling of host stars (to reveal new debris disks) in the south. In addition the very high number of actuators (585) on a 6.5m telescope will enable some modest correction in the visible 0.5-1.0μm (Vis AO). See our detailed numerical error budget derived with the CAOS AO simulation package in figure 10.

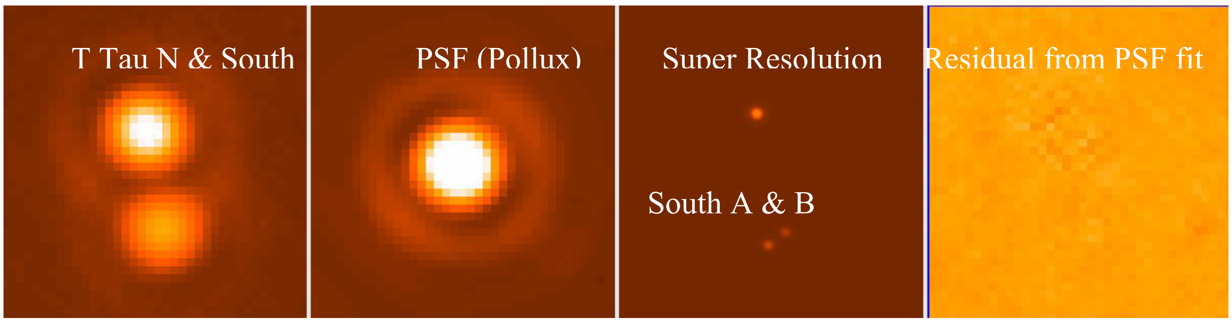


Figure 11: Images of the prototype young triple T Tauri. These images were made at first light of the Magellan Facility instrument MIRAC4 (at the MMT with our existing ASM). Here we see how ~100% Strehl Mid-IR AO can be used to probe structures at ≤0.3λ/D. Here we are able to use super-resolution to resolve T Tau into a triple system for the first time in the Mid-IR. In particular, we have split T Tau South A from South B which are only 0.11" apart. Moreover, we find that South A has deep Silicate absorption proving the existence of an edge-on disk. While South B has no such absorption, implying that South A and South B do not have aligned disks (Skemer et al. 2008). This result was only possible with the use of Mid-IR AO. Many more exciting discoveries will be possible with Magellan and this MIRAC4 camera combined with observing the young southern clusters.

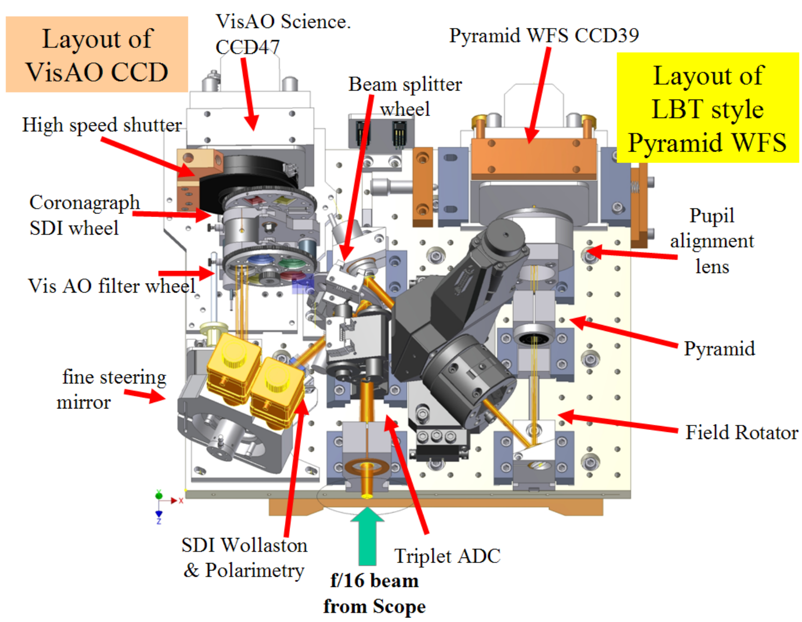


Figure 12: The Vis AO camera (left half) of the WFS optical table (which itself patrols ±90" for guide stars) for more detail on the Vis AO camera see Kopon et al. 2010, Males et al. 2010 these proceedings.

3.1 *Thermal Mid-IR AO Science Enabled in the Southern Hemisphere*

Science with adaptive optics in the thermal infrared will be possible with the Magellan adaptive secondary with a concurrently developed Thermal-IR camera, the Mid-Infrared Array Camera (MIRAC4) and associated nulling interferometer, the Bracewell Infrared Nulling Cryostat (BLINC; See fig 11).

3.2 VisAO: A Visible AO facility for Magellan

Our dense actuator grid has an effective actuator spacing of 23 cm when the pyramid sensor is “28x28” and fully sampled (i.e. when the WFS CCD39 is used in unbinned mode; this is higher resolution sampling than any other large telescope AO system in operation today for science- save the LBT). So that implies that we are well sampling the turbulence at a lambda where r_o=46 cm. At the excellent Magellan site where often r_o=20 cm at 0.55 μm it is clear that at λ~ 0.9 μm there will be AO correction on bright stars. Hence moderate Strehls will be possible in the red on good nights on bright stars (see fig 10 for more details). The resulting angular resolutions of such CCD images will be a spectacular 20-30 mas (although the corrected FOV will be limited by the isoplanatic angle to less than the CCD’s 8.5” FOV typically). To maximize this VisAO science without impacting our Mid-IR AO mode we have designed an AO science CCD with an ADC ready at first light to capitalize on these amazing resolutions (2.7x better then the best HST ACS images). For more on our Vis AO science camera and advanced ADC see fig 12,13 and the paper by Derek Kopon (Kopon et al. 2008; 2009; Kopon et al. 2010; 7736-105).

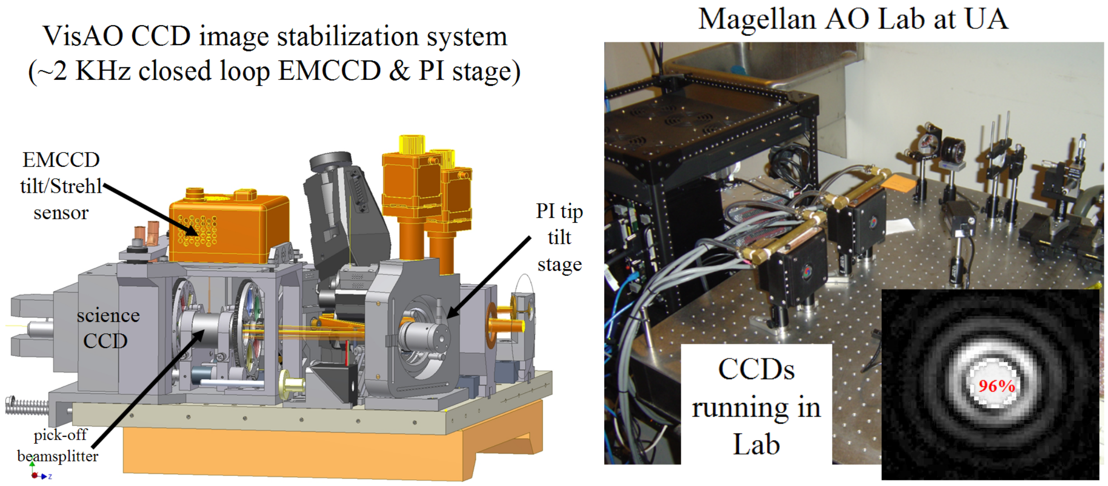


Figure 13: LEFT to eliminate residual vibrations from the PWFS we have designed a secondary independent 2KHz tilt loop with a EMCCD, The EMCCD is fed by reflected light off the beamsplitter spot that acts as an anti-saturation device for the VisAO CCD. Up to 99.9% of the PSF core light is sent into the EMCCD camera from the inner 0.25”. The rest of the core light passes through the pick off and is imaged by the CCD47 with out saturation. In this manner we can obtain long 10s exposures of R=6 mag stars at 40% Strehl without saturation of the PSF core. RIGHT: here we see the UA Magellan AO lab, with working CCD39 and CCD47 cameras and electronics and software. All the VisAO optics have been tested and yield SR>96% at 0.53 μm.

One might question if adaptive optics in the visible is even possible with 585 modes. The Pyramid WFS optical Strehl achieved by Esposito et al. (2010) for the LBT scaled to our system suggests that at R band we will have ~30% Strehls assuming residual tip-tilt jitter is less than 5 mas rms (see fig 10 for our full error budget). While these Strehls are low compared to what will be achieved at 10 μm, there is still a large body of science that can be done at lower Strehl. Indeed most current ~200 actuator 8-10m AO systems do not achieve Strehls much higher than 2-5% in the I band (0.85 μm).

To take full advantage of the periods in a night when the seeing is <0.7” requires the VisAO camera to “always be ready”. Our design is convenient in that the VisAO camera is integrated into the WFS stage. Hence at “a click of a button” we can select a beamsplitter to steer 10-90% of the WFS visible light into the E2V CCD 47 (with 8.5 mas pixels) to make VisAO science images. As well we have designed an apochromatic triple ADC to allow wide band (0.5-1.0 μm) Vis AO at up to 3 airmasses (Kopon et al. 2010).

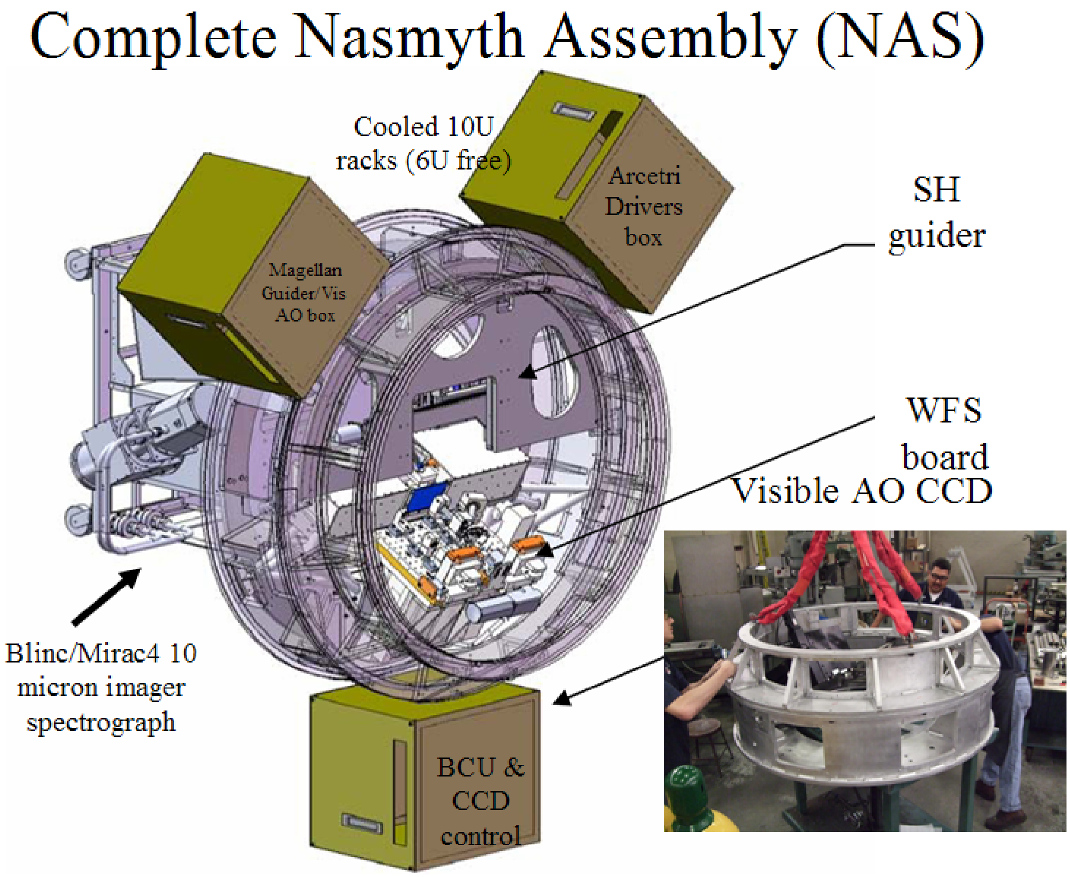


Figure 14: The current design for the AO WFS & Shack Hartmann (SH) off-axis active optics guider for the Nasmyth port Assembly (shown with the MIRAC4 camera mounted). For Mechanical design see Gasho et al. (2009). The WFS can patrol ±90". Inset at bottom shows the fabricated system in the UA shop before anodizing with the WFS 3-axis stage mounted inside. Note the NAS ring and inner crab mount allow the WFS to be <1mm in X and Y and +3 mm in Z. In angle the WFS is at 30 degrees to within 5 arcmin (mechanical). Overall the NAS unit is well within spec. Note there is an extra VisAO electronics box beside the CCD box that is not shown here.

4. OVERVIEW OF THE COLD STOP

At a diameter of 0.851 m the Magellan secondary just fits the pupil size for an on-axis star. Thus this critically sized secondary mirror forms the entrance stop of the telescope optical system. Some scattering (by diffraction) of the warm slightly oversized reference body will illuminate the edge of the pupil. A slightly (<5%) undersized cold pupil inside the Mid-IR camera will eliminate most of this diffracted thermal light, leading to <1% increase in system emissivity at 13 μm (P. Hinz, GMT internal study).

5. MAGELLAN AO MAJOR FUTURE MILESTONES

Despite the complexities of the system we have made good progress since CDR in June 2009. At this point most of the hardware has been fabricated and delivered. We are now in the integration phase. The future major milestones are:

- July 2010 – final electromech ASM acceptance tests at Microgate (done)
- March 2011 – start optical calibration of the integrated system
- Dec 2011 – finish “end-to-end” closed loop tests at Arcetri Obs.
- Jan 2011 – Ship Magellan ASM and MIRAC4 to Magellan. Day time Tests.
- March 2012 – First Light of Magellan AO (ASM & WFS)

Acknowledgments

This project could not be possible without help from our partners and collaborators. The ASM and WFS could not have been possible without the design work of Microgate and ADS in Italy as well as Arcetri Obs. (A. Riccardi and S. Esposito, L. Busoni et al) and the LBT observatory. We would also like to thank the NSF MRI and TSIP programs for generous support of this project.

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