MagAO-X PDR

2.1 Optical Mechanical Design
Overview

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University of Arizona
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MagAO-X OptoMech Design Philosophy

The MagAO-X PDR design is based on our experiences with 5 years of high-contrast AO at Magellan and lessons learned from the current generation of ExAO systems (like SECxAO)

1. **MINIMIZE FLEXURE and NCP VIBRATIONS:** The design almost eliminates issues with NCP vibrations through use of a stiff floating optical table. It is gravity invariant. Our LOWFS should track and mitigate any NCP vibrations that are missed by the PWFS.

2. **MINIMIZE NCP WAVEFRONT ERRORS:** The design limits NCP errors by building the PWFS feed deep into the heart of the instrument. Also post-coronagraphic errors can be sensed with our flexible LOWFS concept which is common path with almost all the powered optics.

3. **MINIMIZE OPTICAL AND CHROMATIC ERRORS:** All reflective (silver) optics design with very tight polishing specs. Use an advanced triplet ADC design without on-axis ghosts.

4. **MINIMIZE MISALIGNMENT ERRORS:** Use all 2inch (or smaller) stainless steel mounts on Stainless table to minimize temperature effects (which are small at Magellan). Automatic pupil sensing and correction. Automatic re-alignment of masks and wheels.

5. **MINIMIZE DUST CONTAMINATION:** Use completely sealed instrument that doesn’t need to be opened during regular observations

6. **MINIMIZE INSTALLATION AND CALIBRATION COMPLEXITY:** Must be able to work with either the f/11 facility secondary or the MagAO f/16 ASM. Must be able to have internal interaction matrices that can be made in daytime at scope (internal, deployable fiber source).

7. **ALLOW DIFFERENT CORONAGRAPHs AND LOWFSs TO BE TESTED:** we have 2 focal plane wheels and 2 pupil plane wheels allowing a wide range of coronagraphs to be remotely deployed (From Simple vAPPs to PIAACMCs systems).

8. **ALLOW DIFFERENT SCIENCE CAMERAS AND SPECTROGRAPHS:** while the initial science camera is a pair of EMCCD SDI cameras there is room (post coronagraph) to deploy fiber fed spectrographs like RHEA or MKIDs cameras.

9. **SHIPPING SHOULD BE ROUTINE:** The instrument must be safe and easy to pack and unpack.
Conceptual design of f/11 MagAO-X optics with Coronagraph

MagAO-X Summary:

~80% Strehl at 0.65 microns + PIAACMC coronagraph with Contras of $10^{-5}$ @50 mas and $10^{-6}$ @150 mas on a 5th mag star in median conditions.
Also can feed MKID or RHEA IFS R=60,000 (PI Ireland)
9.6mm air gap between table and f/11 guider

Side view of MagAO-X Floating Table with upper Bench

127 mm (5 inch) beam height

787.4 mm (31 inch table Height)

Lower 6’x4’x1’ TMC research grade optical top

Upper 2’x6’x4” TMC research grade optical breadboard (aligned with Table)
Analytical concept of the f/11 feed to the Woofer and Tweeter on the upper bench.
Zemax design in Green – agrees with our analytical optical design, OAPs and pupils correct in ZEMAX.
Lower Table 6’x4’

Science Cam
Ultra 888
6 mas/pix

f/69 focal plane

To IR λ>1μm Science Cam (off table)

Zygo Verifier Interferometer

LOWFS
Ultra 887
(pupil viewer)

OAP5 #3 f/69
F=621
15 degree
2 inches

OAP5 #2 f/69
F=621
15 degree
2 inches

Footprint of upper fold flat

OCAM

f/69 focal plane PyWFS

f/57 focal plane

~45° lower fold flat for pupil alignment and folding beam onto lower table

PIAA

9.00x13.3 mm pupil
At 42.5 deg.

MCP DM for LOWFS

BS wheel

ADC

Future DM

OAP4 f/57
F=513
15 degree
2 inches

9mm pupil stop wheel

f/69 focal plane

Science Cam
Ultra 888
6 mas/pix

Cube turret

9mm pupil wheel
Selected Key MagAO-X Components

Based on our experiences with MagAO we could identify “tried and tested” sets of controllers/motors/gears/wheels/pinons that already perform well at Magellan for many years maintenance free.

We have also identified long lead time optics (such as the pyramid optic for the PWFS) and have that fabricated ahead of time.

We also identified a series of low thermal drift stainless steel optical mounts, that were also low stress for our flats and OAPs.

Also we have identified a vendor with excellent coatings for our SDI differential Hα camera. Moreover we will feed the 2 SDI cameras at 90 degrees through a dichroic beamsplitter cube. Hence we should be able to image at Ha and the continuum simultaneously with around ~95% transmission of the Ha photons (this is a large improvement over MagAO’s ~20% transmission of its current SDI optics).
Pyramid Optics for PWFS: In Hand

Very high quality tip
All powered Optics are OAPs

Aperture Optical Sciences (AOS) OAP

<table>
<thead>
<tr>
<th>Main Parameters of AO Design</th>
<th><strong>AO ASM f/ratio</strong></th>
<th>dia. of 48 act tweeter to have 47 act dia.</th>
<th>Second f/#</th>
<th>dia. of Coron beam</th>
<th>Final f/#</th>
<th>f11 f/#</th>
<th>dia. of Woofer</th>
<th>Ang. Inc. on woofer</th>
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<td>16.16</td>
<td>19.2</td>
<td>11.716</td>
<td>57</td>
<td>9</td>
<td>69</td>
<td>11.02</td>
<td>13.5</td>
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FS (vertex focus) mm | theta (deg) | FP (parent focus) mm | Off Axis Dist. OAD | OAD to inner edge of 2in | effective f/ | optic size | name |
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<td>2inch</td>
<td>OAP5 x3 for Corona</td>
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2inch OAP & Fold Mirror Mounts

--Monolithic and Spring Flexure Arms Provide Highly Stable Mirror Retention
--Matched Actuator Threading Minimizes Drift and Backlash
--Heat Treating Stainless Steel Minimizes Temperature-Dependent Hysteresis
--Sapphire Seats Ensure Long-Term Stability

HOW MUCH TILT DUE TO TEMP CHANGES?
--in one MagAOX night only expect 5C change hence only 4μrad of tilt
-- 4μrad/night of tilt is 57μm over the whole 8.2m pathlength which is just over a pixel/night of drift (open loop)
-- with the loop closed it is only 0.6m of NCP path -and so just 4 μm / night.
-- This very slow motion can easily be completely corrected by stacking the SDI images post-detection.
Wheels & Motors -- versions of our current VisAO wheels

Use slightly larger version with spring loaded pinon and Faulhaber motors with 1:66 gear reducers
ADC (modified version of MagAO ADC)

- Very Compact
- Well understood optomech design
- Same motors
Linear Stages

PI M-406 Precision Linear Stage
Cost-Effective With High Guiding Accuracy – high load crossed bearings
Can Drive the LOWFS and Main Utra 888 EMCCDs 150 mm for phase diversity and focus uses

PI N-565 Linear Positioner with the Highest Precision
NEXACT® Piezo Stepping Drive with Subnanometer Encoder Resolution
will drive all the Pupil & mask wheels by up to 13mm with no vibration or heat when powered off.
SDI Beamsplitter (Hα, also r’ & i’ SDI)

In-coming f/69 beam, 15x15mm

Transmitted “continuum” Beam:
666-670nm
Greater than 90% of original beam transmitted

Reflected “H-alpha” Beam:
654.3-658.3nm
Greater than 90% of original beam reflected

Narrowband 666-700 nm single substrate filter

Narrowband 654.3-658.3nm single substrate filter
Halpna SDI design with ~95% Throughput
SDI Hα (656nm) and (668 nm) Continuum Cube Filters

Transmission

Blocking <0.01% leak at Hα

Hα at 656.3 nm at >95% Transmission

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OPTICAL DESIGN

• Zemax design by Oli Durney (Senior Optical Engineer Steward Observatory) from initial analytical design
• The design is all reflective (save the ADCs)
• All the powered optics are OAPs (eliminates ghosts and chromaticity)
• The ADC design is diffraction-limited from 1-2 airmasses and from 0.6 to 1.8 microns. The ADC is commonpath with the PWFS and the science cameras.
• The design was first analytically done by Laird Close and then done with zemax by Oli Durney. Both designs are in excellent agreement.
• The true aperture stop (the primary mirror) is relayed to the Woofer pupil to the Tweeter pupil to the first coronographic pupil to the Lyot stop.
• The first coronagraphic focal plane is f/67 and is the location of the coronagraphic mask
• The final focal plane is after the Lyot stop and is also f/67 yielding a 6mas/pixel platescale on the Ultra 888 science camera.
• The optical quality of the on-axis beam has a Strehl 100% (with perfect optics) over any broad band astronomical filter that we would use (such as r’,i’,z’,J, H).
Upper Bench Optical Design (on-axis)

Greg. f/11.02 Focal Plane from Magellan

(f/16.16) focal plane (can be also used with MagAO’s ASM if not used in f/11 mode)

K- Mirror

Woofer DM Pupil Plane (image of primary)

OAP 0

OAP 1

Fold Mirror 1

Periscope Mirror 1

Periscope Mirror 2

OAP 2

Tweeter DM Pupil Plane

Bench Fold Mirror 1

OAP 3

500 mm
Upper Bench Optical Design (10” FOV)

Full Field
(FOV=10 arcsec)
Lower Table Optical Design On-Axis

- OAP 5 #2
- Int. Focal Plane (f/69)
- 9mm Lyot Stop Pupil Plane
- OAP 5 #3
- Fold Mirror 2
- Ultra 888 Focal Plane
- Fold Mirror 4
- Fold Mirror 3
- PI S-331 Pupil Plane
- Fold Mirror 2
- Future DM
- Breadboard Fold Mirror 2
- Int. Focal Plane (f/57)
- ADC
- Zemax File: Tele2.1 Relay1.0 Peri2.0 ADC1.1a OFD7.1.zmx
- 500 mm
Lower Table Optical Design with PWFS

Lauren’s PWFS optics here

Input PWFS (f/69) focal plane

OAP 5 #1

53°

PWFS fold mirror

Breadboard Fold Mirror 2

Int. Focal Plane (f/57)

Future DM

PI S-331 Pupil Plane

ADC

Zemax Pupil Tele2.1 Relay1.0 Peri2.0 ADC1.1a OFD7.1.zmx

OAP 4

500 mm
Lower Table Science Full FOV

1st Coronagraph Focal Plane (f/69) – possible LOWFS feed

9mm Lyot Stop 2nd Pupil Plane – possible LOWFS feed

OAP 5 #3 (only powered NCP optic but after coronagraph)

Full Science Field (FOV=10 arcsec square)

Fold Mirror 2

Breadboard Fold Mirror 2

9mm Coronagraph 1st Pupil plane

NCP LOWFS DM

ADC

Ultra 888 Science Camera Focal Plane

Fold Mirror 3

Fold Mirror 4

Beamsplitter to pick off science light away from PWFS path

500 mm
Bench to Table Periscope

- Compound angles for both BBFM1 & 2 result in an exit beam that is parallel with the input beam plane but shifted 550.6 mm lower, 161 mm out-of-the-page, and rotated in its output direction vector.

- The output beam is also rotated about the optical axis with respect to the input beam by ~63° in the clockwise direction.
Spot Diagrams for Zenith Z=40° w/ ADC

No ADC Correction

ADC Correction (Current Design)
ADC Prism Design Layouts

**Current ADC Design**
- $\phi = 14$ mm
- S-PHM53, S-TIM8, N-KZFS4
- $CT = 5.0, 3.0, 4.0$ mm
- $\theta = 57.785^\circ$, 65.474°

**New ADC Design**
- $\phi = 18$ mm
- S-PHM53, S-TIM8, N-KZFS4
- $CT = 5.0, 3.5, 3.5$ mm
- $\theta = 73.687^\circ$, 0.260°
Spot Diagrams at Focal Planes
Spot Diagrams at Pupil Planes
PSF at Focal Planes

**ASM Focal Plane (f/16)**
- Relative Irradiance
- X-Position (um) vs Y-Position (um)
- Polychromatic Hygoms PSF
- Center coordinates: 0.00000000E+00, 0.00000000E+00 Millimeters

**Int. Focal Plane (f/57)**
- Relative Irradiance
- X-Position (um) vs Y-Position (um)
- Polychromatic Hygoms PSF
- Center coordinates: 0.00000000E+00, 0.00000000E+00 Millimeters

**Int. Focal Plane (f/69)**
- Relative Irradiance
- X-Position (um) vs Y-Position (um)
- Polychromatic Hygoms PSF
- Center coordinates: 0.00000000E+00, 0.00000000E+00 Millimeters

**Ultra 888 Focal Plane**
- Relative Irradiance
- X-Position (um) vs Y-Position (um)
- Polychromatic Hygoms PSF
- Center coordinates: 0.00000000E+00, 0.00000000E+00 Millimeters
Mechanical Solid Model

Solid works design by Corwynn (Cork) Sauve, Steward Observatory
Mechanical Solid Model With TMC Table

All gray components (bench, table, and legs) are a single custom build, of our design, offered by TMC.

Bench

Table

Legs with leveling pads

Earthquake restraints
Full Science FOV (10”) Rays
10” Rays

All the optics, mounts, and cables fit on the bench and Table

5 inch b. height through
With PWFS

NCP rays for PWFS in blue
With PWFS

NCP rays for PWFS in blue
The Closed-loop Air Damped Table

- Top bench
- Air
- Table Top

- 21.67” (550.6 mm)
- 12” (304.8 mm)
- 19”
- 6’ (1828.8 mm)

Each leg has a 2-way variable-orifice proportional servo valves.

TMC’s PEPS II
100 Hz - 2.0 KHz closed loop capacitive positions sensors stabilize position of floating table w.r.t. table legs.
±50μm Long term Stability w.r.t. Telescope with PEPS® II – Specifications

±50μm Variation of height

±47μm with ±50 μradians of tilt variation

21.67” (550.6 mm)

12” (304.8 mm)

0.957m

Beam center

Top bench

Air

Table Top

19”

6’ (1828.8 mm)

Long term (~1-2 seconds after slew) stability is ±50μm in height and ±50μrads in tilt
Completed Design At Magellan
MagAO-X fits on the NASE

- Guider
- Electronics rack
- Facility glycol, power, air, fibers/internet
- MagAO-X in f/11 position
- 9.6mm air gap
- PFS plate (1 of 3)
- NASE platform (lots of room)

Elevator
Unpacking and Alignment at Telescope

START: Use the Isuzu truck to move the shipping box to the lift gate at summit, then hand truck to elevator, then:

1) hand truck shipping box to telescope observing floor off of the elevator
2) Independently, position our legs (on their casters) to the correct X position of the legs w.r.t. the guider center of the NASE platform. So all that is needed is a straight push (in Y) towards the guider, rotate the casters in the Y direction.
   (Note: we could use a simple piece of angle bar bolted to the hatch to guarantee the casters motion in Y only once the Table is attached- TBD)
3) lift up the 5 sided top of the shipping box -- rotate dome and place beside Table.
4) pull bench out of shipping box base with overhead jib crane and lifting triangle
5) lower the Table onto the legs with crane, remove Triangle.
   (NOTE: the Table/Legs alignment is guaranteed with alignment pins (that slide into the tiebars on legs) that are bolted onto in the tapped holes for earthquake brackets -- these pins are already attached when we are shipping the bench)
6) Now slowly push the whole assembly on the casters towards the guider until the air gap is 9.6mm then stop.
7) Carefully engage all 16 leveling pads (disengaging the casters)
8) remove alignment pins and add the missing 2 upper earthquake brackets.
9) Add the lower earthquake brackets
10) cable up the system, etc.
Unpacking and Alignment at Telescope

CASTERS ALLOW TABLE TO BE FINELY ALIGNED EVEN UNDER FULL LOAD
Wind/dust screen

This “backside” of panels is proud by ~5mm past edge of the current table, hence final air gap is 4.6 mm.
Wind/dust screen

MagAO-X as it will appear for observing (or shipping) with dust covers attached