Telescope Project Development Seminar

Session 3: Telescope Design

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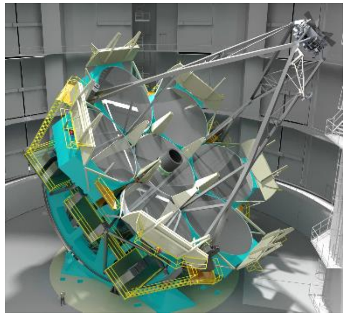
U. Tokyo

Telescope Introduction

- Telescope is the central structure in the observatory around which the rest of the facility is developed.
- Major subsystems are:
  - Mount structure
  - Bearings and drive systems
  - Optical systems (primary mirror, secondary mirror, tertiary mirror, correctors, etc.), their supports and controls
  - Instrument mounts and rotators
  - Auxiliary mechanisms (mirror covers, counterweights, etc.) and structure (ladders, service platforms, etc.)
  - Metrology and calibration systems
- Associated systems
  - Acquisition and guide systems
  - Active optics sensors and controls
  - Adaptive optics system
- Major Interfaces
  - Enclosure facility
  - Observatory control system
  - Science Instruments
  - Handling and service equipment
- A discussion of all of these topics is beyond the scope of this course but we will touch base on a couple of them.

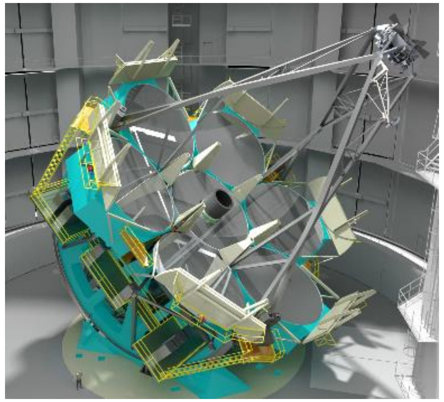
Telescope Basic Functional Requirements

- Support the optical components (mirrors, etc.) and science instruments in a dimensionally stabile mounting in the presence of gravitational, wind and thermal disturbances.
- Accurately acquire and track astronomical objects over the visible sky.
- Deliver a well-collimated and focused image to the science instruments.
- Minimize vibration and thermal effects that would otherwise degrade image quality.
- Provide for the service and maintenance of the telescope systems and instruments.
- Provide for the safety of personnel and equipment during all operations.



Telescope Performance Requirements

- Performance requirements are specified for well defined atmospheric conditions (temperature, humidity, wind speed, coherence time τ_0), and integration times, wavelength range, field-of-view.
- Requirements are captured in performance budgets:
  - Image quality
    - Image size (full-width half max (FWHM), RMS diameter, etc.)
    - Encircled energy (80% ee, etc.)
    - Wavefront error for diffraction limited (AO) operation
  - Throughput
    - Obstructions and vignetting through the system
    - Coating performance
  - Emissivity
    - Degrades the signal/noise for observations in the thermal IR ($\lambda \geq 1.5$ microns)
    - "Warm" structure that the instrument sees directly or by scattering.
    - IR emission from the coatings.

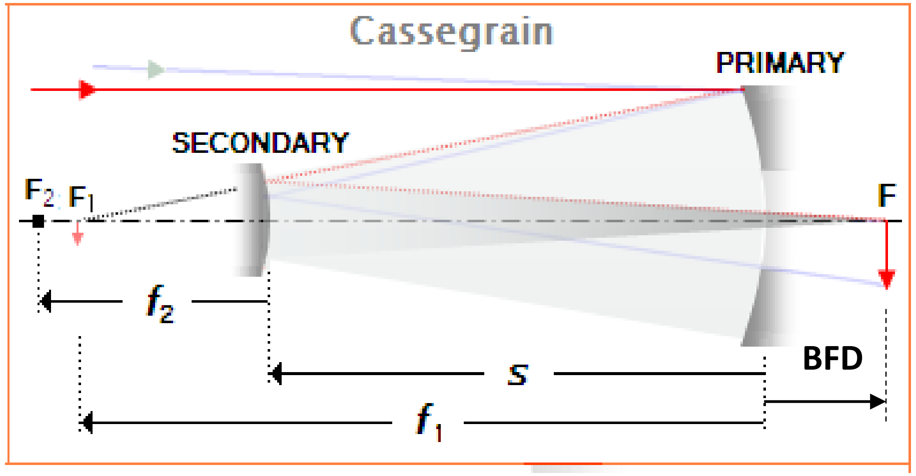


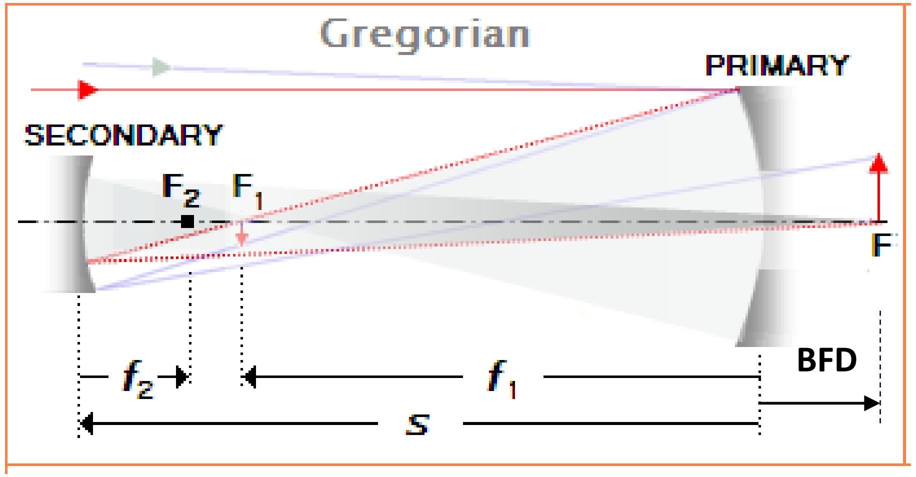
- Observing efficiency
    - Defined as the fraction of observing time spent accumulating science data ("shutter open").
    - Top-level requirements flow down to time to acquire targets, set-up times for the active and adaptive optics systems, detector readout and data handling, etc.

Design Principles

- "Fast" optical configuration to allow a compact structure.
- Stiff mount for high tracking performance and windshake rejection.
- Use thin cross section structural members to promote rapid thermal equilibration.
- Capitalize on existing experience, technology and expertise.
- Make maintenance and serviceably a priority.
- Design for ease of transport and assembly.
- Aim for low operating cost.
- Provide upgrade paths.
- Weigh system flexibility versus complexity.
- Prototype high technical risk components and assemblies.

Cassegrain & Gregorian Configurations





Definitions:

f1 : Primary mirror focal length

f2 : Secondary mirror focal length

f : Final focal length

D1 : Primary mirror diameter

BFD: Back focal distance below M1 vertex

F1 = *f1*/D1 primary focal ratio

m = *f/f1* transverse magnification

F = m * F1 Final focal ratio

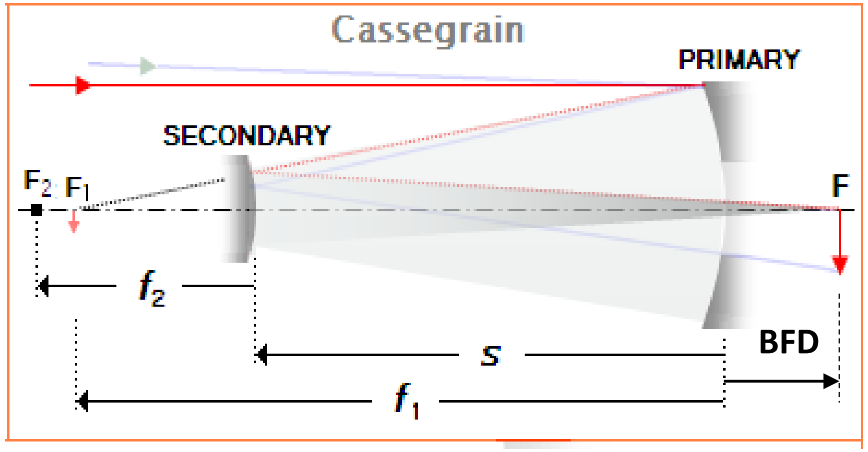
Plate scale = *f (mm)* / 206265 (mm / arcsec)

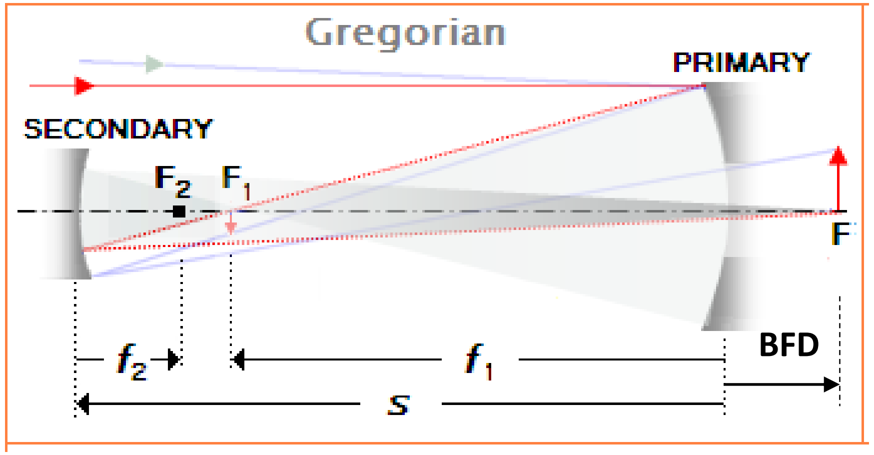
- The usable field-of-view in the Cassegrain and Gregorian configurations is limited by off-axis coma.
- The aplanatic “coma-free” designs provide a wider FOV limited by astigmatism. They are optimized for one combination of *f1*, *f2*, and BFD.
- Ref. “Astronomical Optics”, D. Schroeder (1987)).

Configuration	Primary	Secondary	Focal surface
Cassegrain	Parabolic	Hyperbolic	Concave
Ritchy-Chretien	Hyperbolic	Hyperbolic	Concave
Gregorian	Parabolic	Ellipsoidal	Convex
Aplanatic Gregorian	Ellipsoidal	Ellipsoidal	Convex

Cassegrain-Gregorian Discussion

- All else being equal, the Gregorian two-mirror configuration is longer than Cassegrain and M2 is larger. This impacts telescope and enclosure size. The relative disadvantage is lessened for short ("fast") primary mirror focal ratios.
- The Gregorian secondary mirror can be tested at its center of curvature with a relatively small null corrector and interferometer. The Cassegrain secondary requires expensive test optics or profilometers comparable in size or larger than the M2 diameter.
- The concave focal Cassegrain focal surface is well matched to reflective collimating optics in reimaging science instruments. The convex Gregorian focal surface is better suited to refractive collimators.
- The exit pupil in a Gregorian system is located between M1 and M2. Instrument calibration sources ("flat fields", spectral lamps) can conveniently be located in this position. The Cassegrain exit pupil is above M2 and not visible from the focal surface.

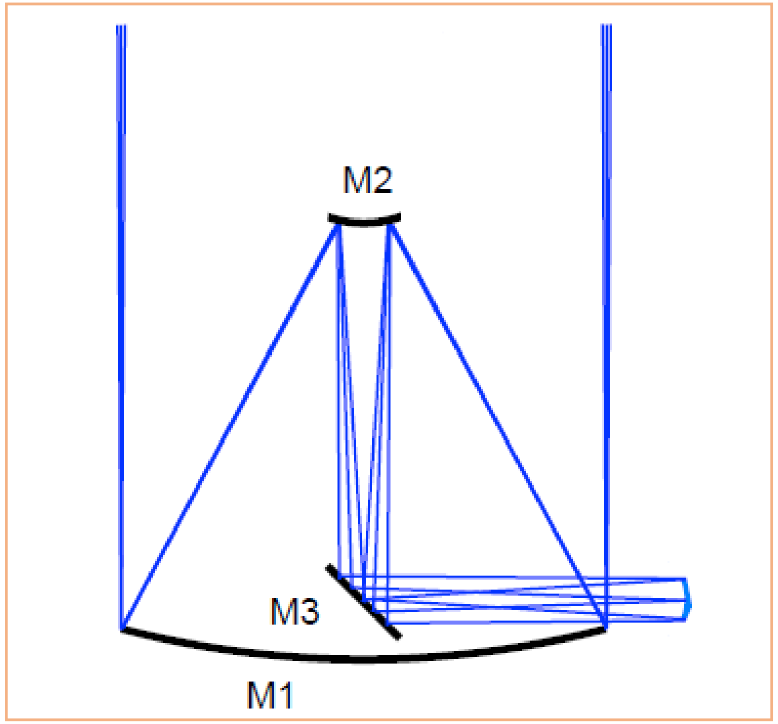




- M2 is conjugated by M1 several hundred meters above the telescope in the turbulent atmospheric ground layer in a Gregorian system. This is an advantage for AO systems with an adaptive M2. The conjugate is less advantageously placed below the Cassegrain telescope.

Nasmyth Configuration

- The addition of a planar tertiary mirror redirects the beam to a final focal position but does not otherwise change the imaging properties of the Cassegrain or Gregorian configurations.
- The Nasmyth beam is brought out along the elevation axis in an alt-az telescope, either above or below the primary mirror depending on the telescope elevation structure balance.
- Nasmyth has the advantage that it brings the beam out to a fixed focus on a gravity invariant platform.
- If the elevation axis is below the primary mirror, the back focal distance (BFD) is significantly longer than for a straight Cassegrain configuration and the secondary mirror is correspondingly larger for a given focal length.
- Fast final focal ratios are difficult to achieve at Nasmyth due to restricted clearances through the telescope structure for the beam.



Nasmyth or folded-Cass with elevation axis above M1.

Optical Prescription

- The telescope optical prescription (focal length, focal ratio, and field of view) follows from the need to efficiently couple to the proposed science instruments. This requires trade-off studies of the complete telescope-instrument system.
- The plate scale in the focal plane is determined by the telescope final focal length. For example, the plate scale on a 6.5m f/11 telescope is 0.35 mm/arcsec. This is not well matched to CCD detectors which have pixel sizes of order 15 microns. In order to get 2-pixel sampling in a reimaging instrument (e.g. a spectrograph) with 0.4 arcsec stellar images requires a reduction of around 5.8 which results in a f/1.5 focal ratio for the spectrograph camera. This is achievable but it becomes more demanding on larger telescopes with much longer focal lengths.
- The telescope focal ratio is determined by the focal length and entrance aperture (typically the primary mirror). Designing for small M1 and M2 focal ratios helps keep the overall size the telescope and plate scale manageable but fabricating such “fast” optics and aligning them in the telescope becomes very challenging.
- The physical diameter of the focal surface is set by the required field of view (FOV) and the plate scale. The maximum usable FOV of the bare (ie. no corrector) two mirror configurations is limited by off-axis aberrations.
  - Wider FOVs are achievable with the addition of a refractive corrector (e.g. Gascoigne, Wynne Triplet, etc.) (c.f. D. Schroeder, “Astronomical Optics”, 1987.

Student Assignment

Perform a trade-off study for the optical layout of a 30 meter telescope.

- Parameters
  - Primary mirror (M1) diameter: 30 meters
  - Primary mirror focal ratio: f/1.0
  - Telescope field of view : 10 arc-minutes
  - Straight Cassegrain or Gregorian focus: 4.0 meters below the M1 vertex.
  - Nasmyth focus: 2.0 meters beyond the edge of the primary mirror (ie. 15m + 2 m = 17m)
- Configurations: One case per student.
  - Case 1: f/15 classical Cassegrain versus f/15 folded Cass/Nasmyth
  - Case 2: f/7.5 classical Cassegrain versus f/7.5 folded Cass/Nasmyth
  - Case 3: f/15 classical Gregorian versus f/15 folded Gregorian/Nasmyth
  - Case 4: f/7.5 classical Gregorian versus f/7.5 folded Gregorian/Nasmyth
- **Calculate the layout and size of the optical elements (M1, M2, and M3) in the telescope.**

Student Assignment (instructions)

- For each folded configuration look at a layout with the beam coming out either just above or just below the primary mirror without vignetting by the M1 assembly.
  - Assume the top lip of M1 is the highest part of the M1 assembly and the assembly extends 2.0 meters below the M1 vertex and out to a radius of 30m/2 = 15m.
- This exercise can be performed with simple geometry and algebra using a few basic formulas:
  - Paraxial Equation for Reflection: $1/s1 + 1/s2 = 1/f$ where s1 and s2 are the object and image distances and f is the mirror focal length.
  - Relation between radius of curvature and focal length: $f = R_c/2$ where R_c is the mirror radius of curvature.
  - The relation between field of view, telescope focal length, and focal surface diameter.
  - Sagitta equation for getting the height of the M1 lip above its vertex.
- Assume the secondary mirror and tertiary mirror are sized such that they are just large enough to not vignette the beam for all field positions but no larger.
- In computing the size of M2 assume that it is a flat plate at the position of the mirror, ie. neglect its curvature.
- M3 is planar and elliptical in shape. Compute only the dimension of the minor axis. We'll assume the major axis is approximately $(2)^{1/2}$ larger.

Student Assignment (hints)

- Make the primary mirror vertex the origin with +Z along the optical axis in the direction of M2 and folded port at +X.
- Treat the pupils and mirror surfaces as planar and distortion-free for the purpose of computing diameters.
- The position of M2 can be determined using the paraxial formula for reflection in the straight Cassegrain configuration.
- The folded Cass/Gregorian geometries are a little more complicated by the requirement that the beam does not vignette the primary mirror assembly.
- All of the rays transmitted through the telescope to the focal surface pass through the stop defined by the primary mirror. This is the entrance pupil.
- The exit pupil is the conjugate of the entrance pupil formed by the secondary mirror. It and the diameter of the focal plane define the beam from the secondary mirror to the focus.
- Start off by locating the exit pupil using the paraxial formula for reflection. Calculate its size. Take into account that the exit pupil is the real-image of the entrance pupil for the Gregorian configuration and virtual image for Cassegrain.
- Reference source: “Astronomical Optics”, D. Schroeder, 1987.

While optical design software (e.g. Zemax) can be used to obtain these results, that is not the point of this exercise.

We’ll compare results in the last course session to see how the different configurations impact the overall telescope design.

Primary mirror technology

What makes a good mirror?

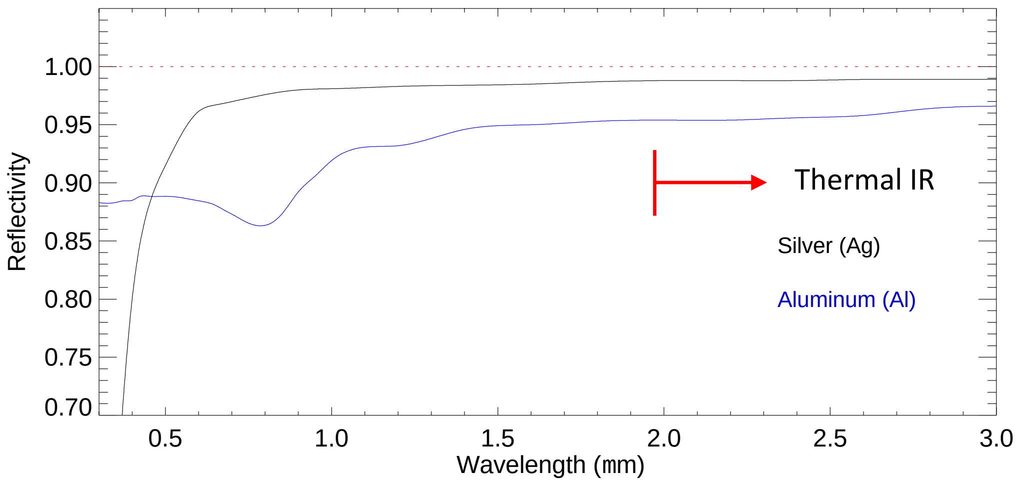
- Fundamental requirement is to deliver a good wavefront to focal plane in all specified conditions.
  - “Good” means mirror contributes less error than the atmosphere in the best seeing (~0.2 arcsecond).
  - Hold its shape to ~λ/5 rms on large scales
  - Be smooth to ~λ/50 rms on small scales
  - Contribute little to local seeing (temperature gradients in air)
- Stiffness against wind
  - implies thick mirror, aspect ratio ≤ 12:1
- Stiffness against gravity
  - implies low mass, ≤ 400 kg/m^2
- Thermal stability
  - Implies low coefficient of thermal expansion (CTE)
- Short thermal time constant
  - Mirror must equilibrate with air quickly to reduce thermo-elastic deflections and local seeing.
  - 1/e settling times less than 60 minutes implies thin glass sections, t ≤ 3 cm, with active ventilation

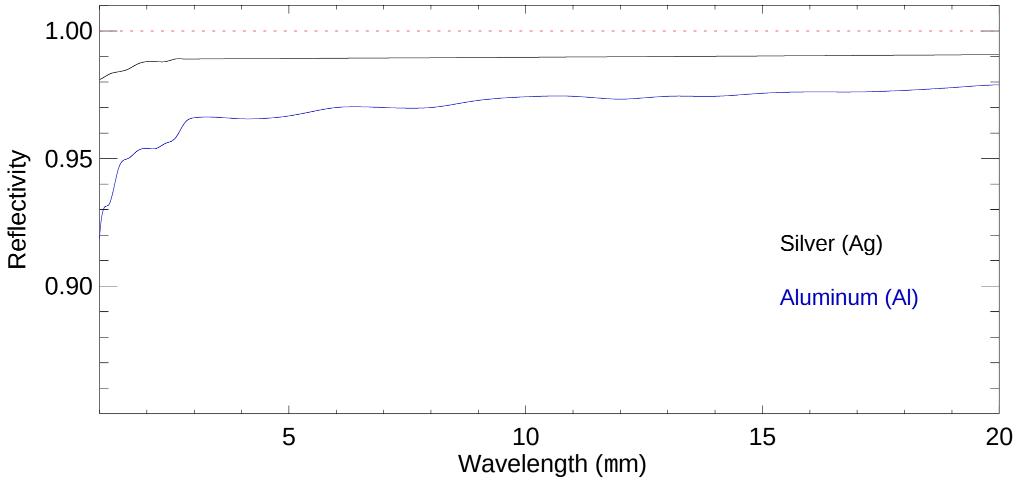
Telescope Mirror Materials

Type	Trade names	CTE (1) (x 10-7/C)	Pro	Con
Glass-ceramic	Schott Zerodur OHARA CLEARCERAM-Z Astro(Sitall)	0.2-1.5	Ultra-low CTE, Machinable	Large blanks no longer available, High material cost Not castable
Glass	Corning ULE	0.1-1.0	Ultra-low CTE, Can be fused, Machinable	Large blanks no longer available, High material cost Not castable
Borosilicate glass	OHARA E6 Pyrex	28	Low (but not zero) CTE, Machinable & castable Low material cost	Requires thermal system for figure control, Single-source (UA) for large blanks

- Note (1): Approximate. CTE depends on temperature range and expansion class grade.
- Metal (aluminum, beryllium), fused silica/quartz, and silicon carbide are used in small mirror applications.
- Mirror material choice must also take other physical properties such as CTE uniformity.

Reflective Mirror Coatings





Ref. M. Boccas, et. al., Coating the 8-m Gemini telescopes with protected silver", SPIE 5494

Throughput

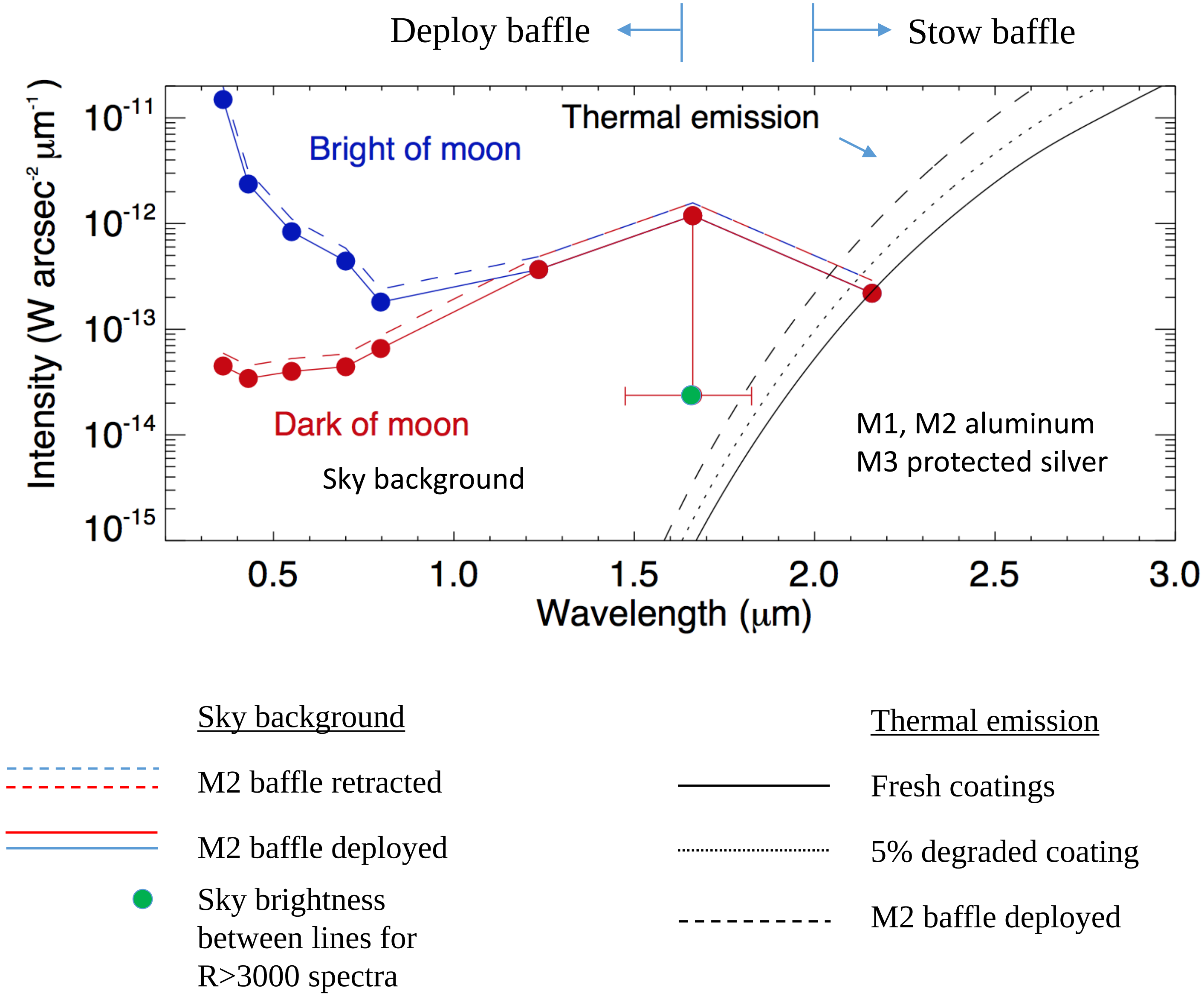
$$R_{total}(\lambda) = R_{M1} \cdot R_{M2} \cdot R_{M3} \cdots$$

where
M1 = Primary mirror
M2 = secondary mirror
M3 = tertiary mirror, etc.

Three-mirror throughput

λ	Alu		Protected Ag	
µm	Fresh	5% degraded	Fresh	5% degraded
0.37	0.69	0.59	0.34	0.29
0.40	0.69	0.59	0.53	0.45
0.60	0.69	0.59	0.89	0.76
0.80	0.64	0.55	0.93	0.80
1.20	0.80	0.69	0.94	0.81
1.50	0.86	0.74	0.96	0.82

Background emission



- Background emission compared with telescope emission
- Telescope emission is dominated by mirror coatings
  - Mirror Emissivity = ($1 - R_{total}$)
- Other sources include warm telescope structure and radiation scattering into the beam.

Mirror Coating Maintenance

- The reflective coatings on telescope mirrors degrade with time and require periodic cleaning and occasional replacement.
- Typical practice includes:
  - Weekly dust removal with CO2 snow.
  - Regular yearly washing with detergents and deionized water.
  - Stripping and re-coating in a vacuum chamber every couple of years.
- Cleaning frequency depends on coating type, dust conditions at the site, operating procedures, and system optical throughput requirements.
- Re-coating of the large telescope optics is typically done on site.
  - For small segments the coating plant can be relatively small (~2m).
  - Large segments require proportionately bigger vacuum tanks.
- The type of coating system depends on the coating type.
  - Aluminum can be applied by thermal evaporation with filaments.
  - Sputtering systems using magnetrons are required for multi-layer dielectric coatings and may also be used for aluminum.

VLT re-coating

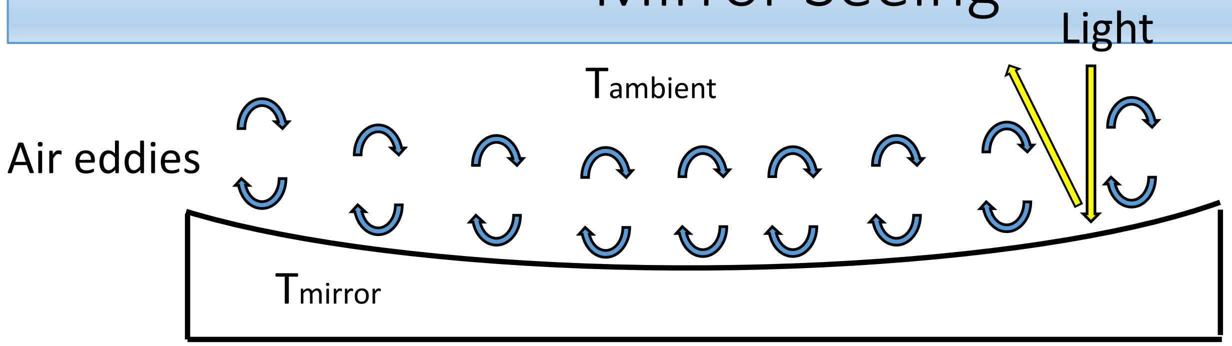
This video shows the re-coating of a VLT primary mirror:

https://www.youtube.com/watch?v=goNtYKB0ecg

Mirror Cleaning with CO^2 Snow

Regularly (weekly) spraying the telescope mirrors with CO^2 removes accumulated dust and extends the intervals between mirror cleaning and re-coatings.

Mirror Seeing



$\Delta T = T_{mirror} - T_{ambient}$

- Mirror seeing results from unstable air turbulence that forms when the upward facing mirror surface is warmer than ambient.
- Analytical calculations, lab measurements, and measurements on existing telescopes confirm the effect.
- While there is general agreement the effect is real, estimates of the magnitude and its dependence on temperature difference (ΔT) vary between investigators.
- Comparison is complicated by different metrics and results highly dependent on environment, mirror configuration and operating conditions.
- The estimated image size (50% ee) contribution for $\Delta T = +1^{\circ}C$ ranges between 0.1 – 0.4 arc-sec.
- Controlling mirror seeing is important to meet image quality requirements for a good seeing site.

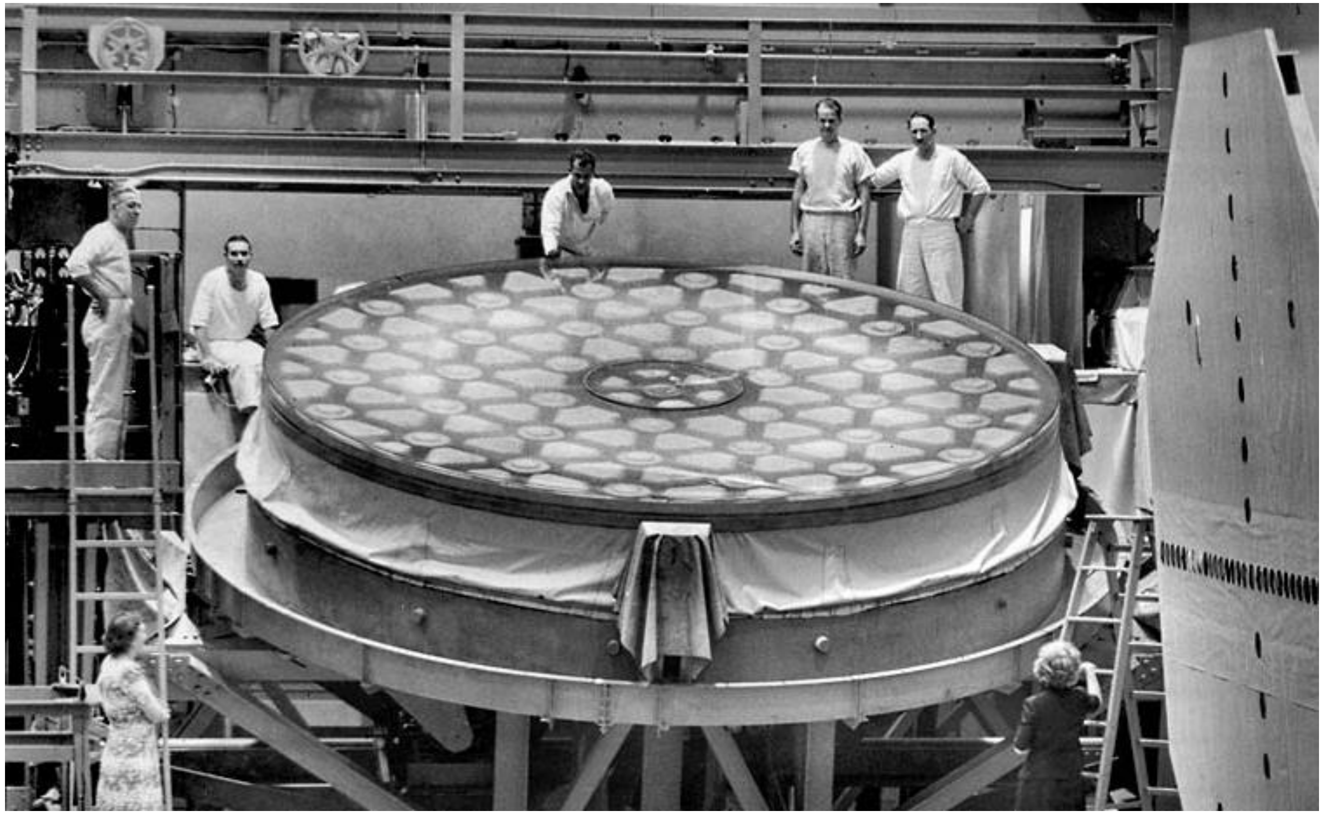
References:

- Bridgeland M. T., Jenkins C. R., 1997, MNRAS 287 and op. cit.
- Iye M., Noguchi T., Toril Y. Mikami Y., Ando H., 1991 PASP 103
- Racine R. Salmon D., Crowley D., Sovka J., 1991 PASP 103

See also: En-Peng Zhang *et al.*, "Preliminary numerical simulation of mirror seeing for the Chinese Future Giant Telescope ", 2016 *Res. Astron. Astrophys.* **16** 098

Primary Mirror Evolution

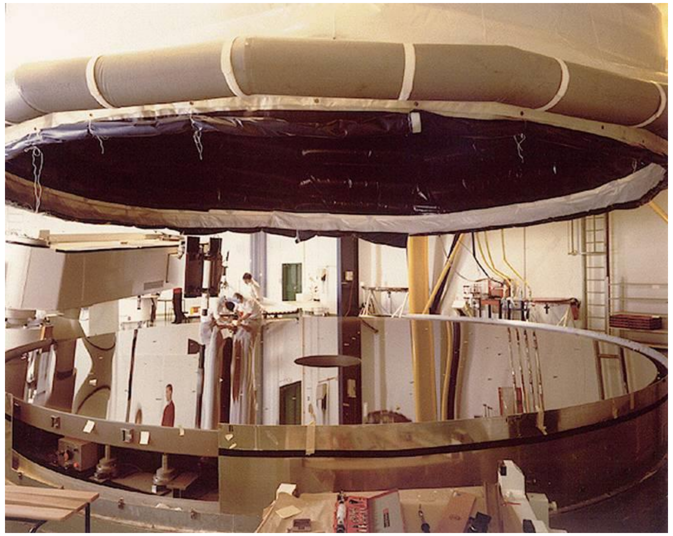
- Traditional monolithic primary mirrors had a thickness to diameter ratio of ~1:8 for stiffness
  - Heavy
  - Difficult to produce for increasingly large sizes
  - Thermal time constants were too long to follow nightly ambient air temperature
    - → mirror seeing
- Palomar 5 m primary was an early attempt to lightweight a mirror with cast-in pockets & open back plate
- New large primary mirror technologies emerged after the 1970s:
  - Thin, solid "meniscus" mirrors
  - Segmented mirrors
  - Honeycomb mirrors
- These three types are the basis for almost all modern-day large optical telescopes



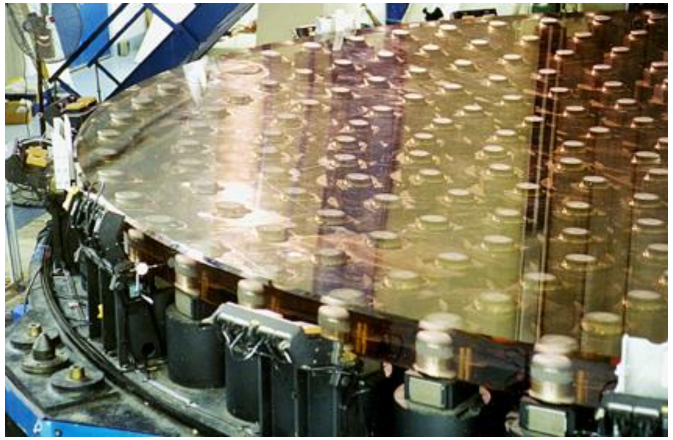
Palomar 5m Primary Mirror

1. Meniscus Primary Mirrors

- Thin, solid mirrors whose shape is controlled by active optics
- Active optics concept by Ray Wilson and colleagues in Europe (e.g. NTT)
  - Replace stiffness by active control of shape
  - Reduces mass and thermal inertia with ~175 mm thick mirror compared to traditional (1:10) mirrors
- Technology:
  - Zerodur glass ceramic and ULE glass, both with near zero thermal expansion
  - Precise active mirror supports (~1N accuracy)
  - Wavefront sensors similar to those used for adaptive optics
- Examples: ESO VLTs, Gemini Telescopes, Subaru Telescope



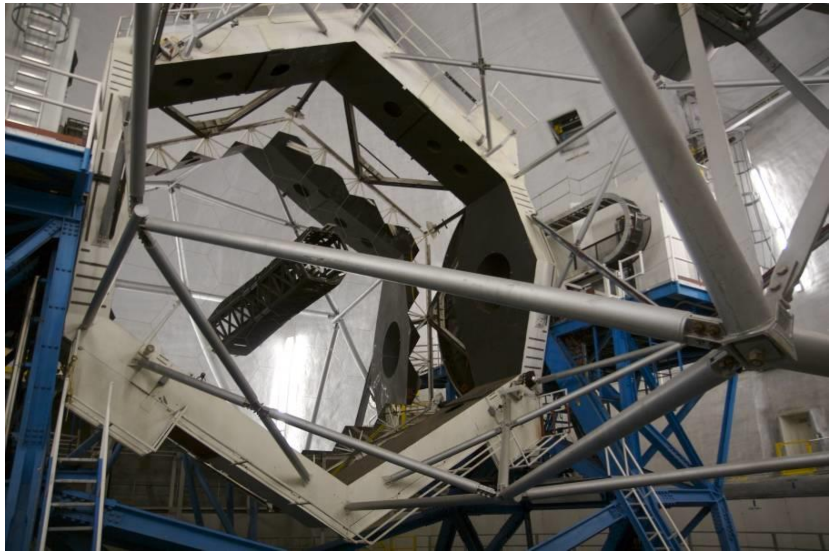
VLT 8m Primary Mirror



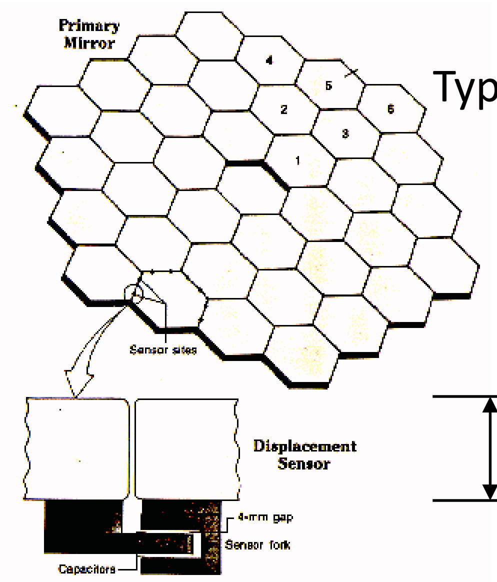
Subaru 8m primary mirror & supports

2. Small Segment Mirrors

- Concept developed by Jerry Nelson and colleagues at UC
  - Achieve continuous optical surface by active control of position of small segments.
  - Reduces mass and thermal inertia even more than thin solid mirror (75 mm vs 175 mm)
  - Warping harness to facilitate figuring the aspheric segments
- Technology
  - Precise segment positioning actuators (~10 nm resolution)
  - Precise segment-segment displacement sensors
  - Controller continuously updates piston actuators to maintain phasing
  - Occasional wavefront measurement of segment phasing
- Used for Keck, HET, GTC, SALT
  - To be used for TMT (30 m), ESO ELT (39 m)



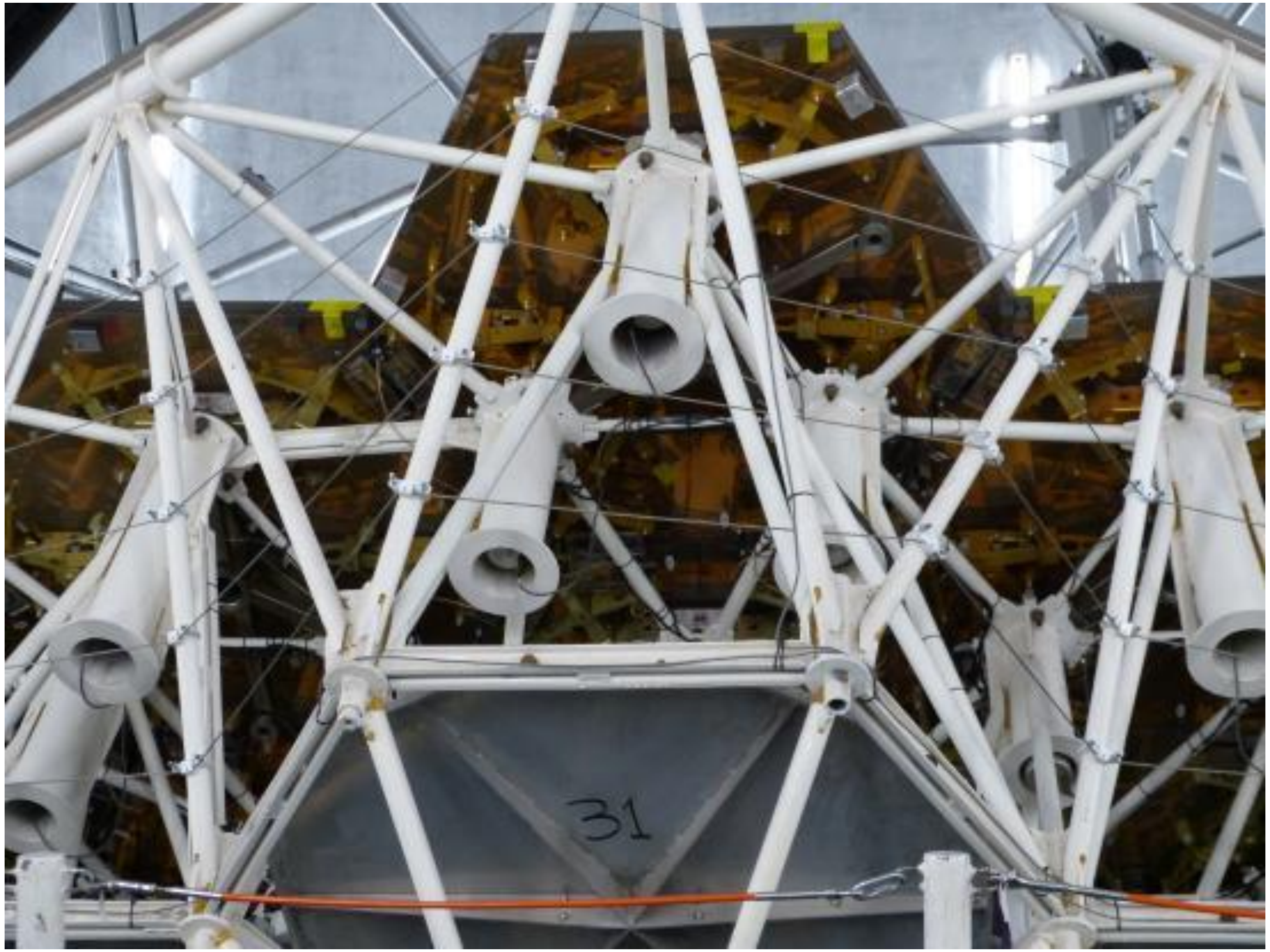
Keck 8m



Typical segment size 1.0m – 1.8m

75 mm

Small Segment Supports



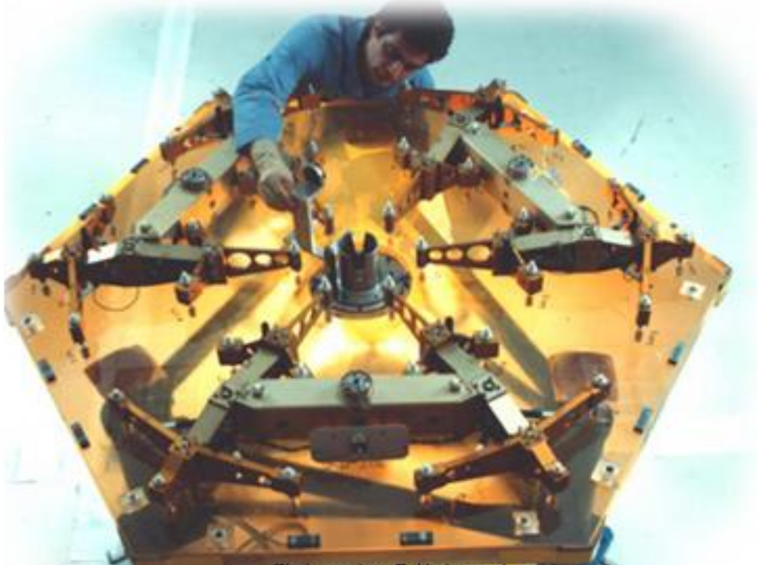
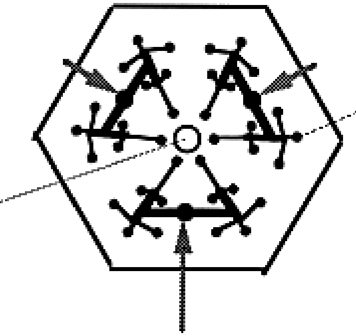


Photo courtesy R. Underwood

About the markings on the back of the mirror segments:

Three Whiffletrees and one Flex Disk are illustrated on the back of each mirror segment.

MIRROR SEGMENT BACK



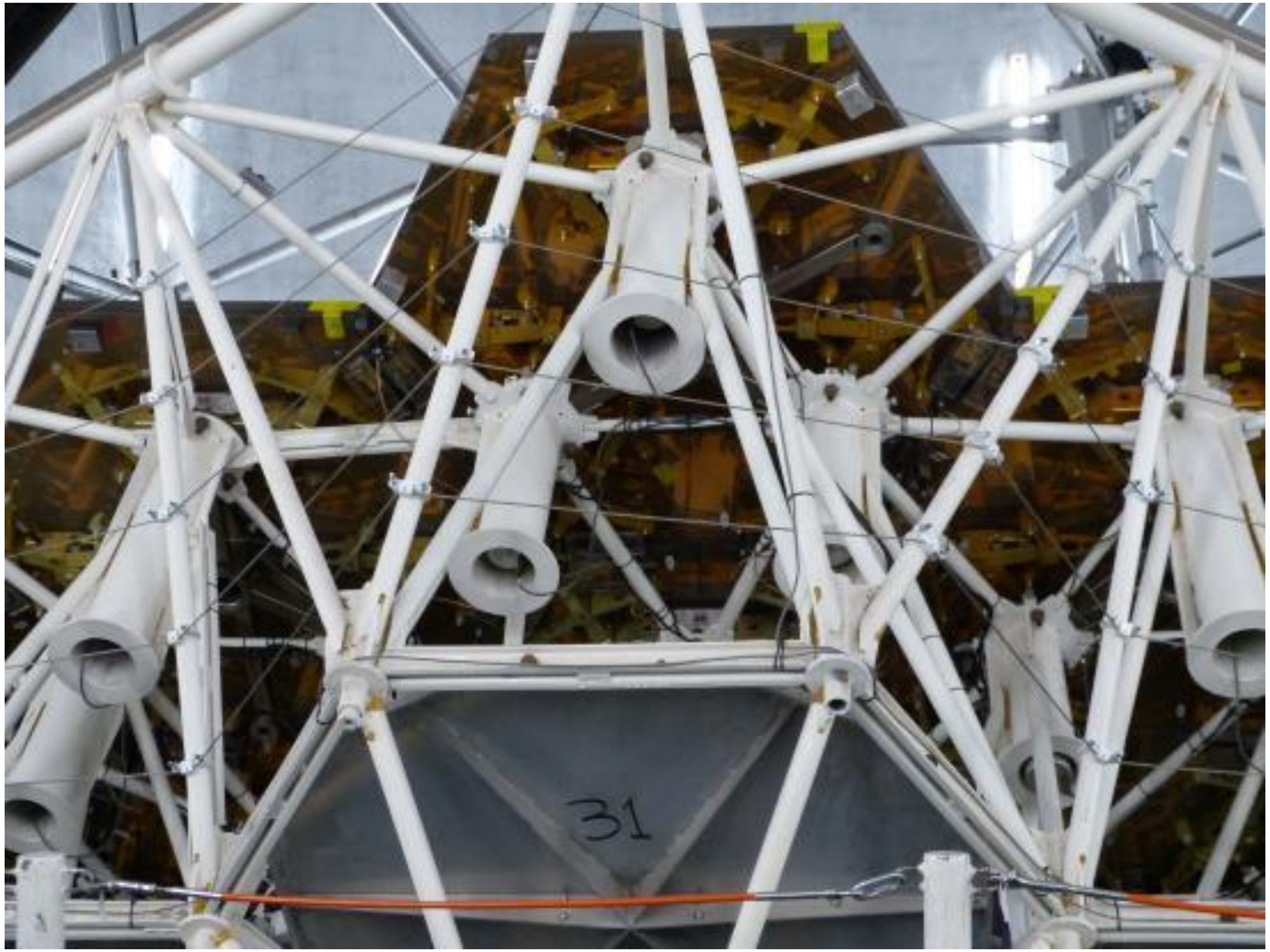
A FLEXIBLE METAL DISK, WHICH IS ANCHORED TO THE MIRROR CELL TRUSSWORK, FITS UP INTO A CENTRAL CIRCULAR DEPRESSION IN THE BACK OF EACH MIRROR SEGMENT TO PROVIDE LATERAL STABILITY, YET PERMIT THE MIRROR TO TILT AND MOVE IN AND OUT UNDER ACTUATOR CONTROL.

THESE DOTS, TWELVE PER WHIFFLETREE, SHOW MIRROR ATTACH POINTS. THE MIRROR SEGMENT BACK IS EPOXIED TO THE WHIFFLE TREE AT THESE POINTS.

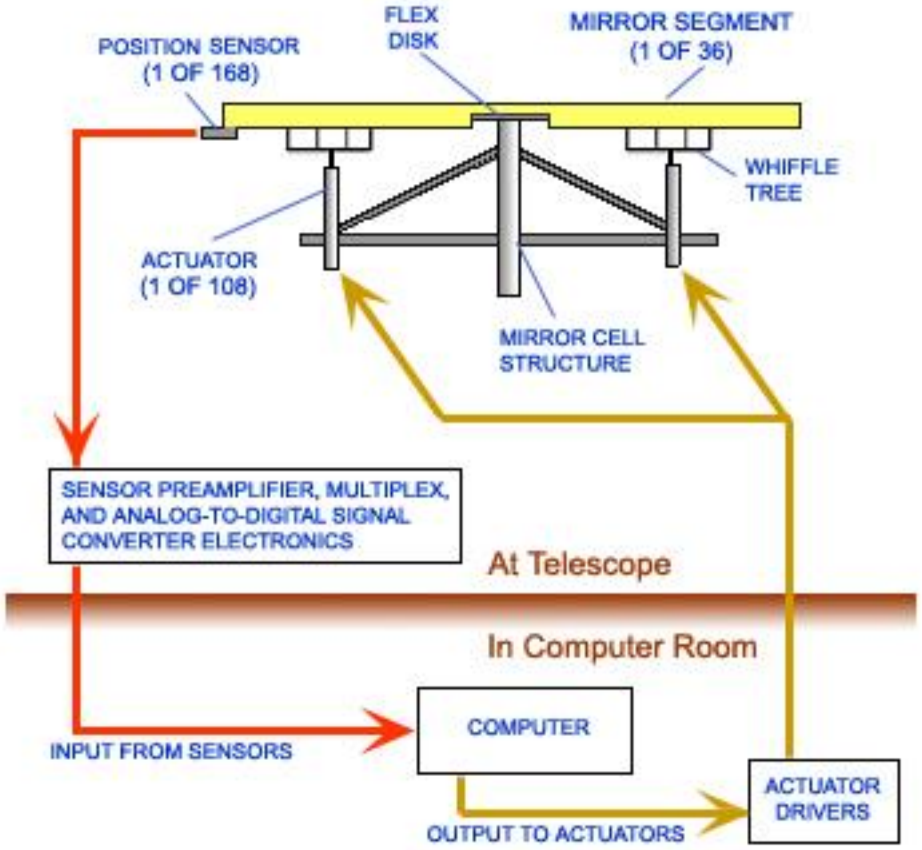
ARROWS ILLUSTRATE ACTUATOR ATTACH POINTS. ONE ACTUATOR DRIVES EACH OF THE THREE WHIFFLETREES.

THE YELLOW COLOR OF THE BACK OF THE MIRROR SEGMENTS REPRESENTS THE APPEARANCE OF THE GLASS/CERAMIC MATERIAL, "ZERODUR", WHICH THE MIRROR SEGMENTS ARE MADE OF.

Small Segment Supports



Keck primary mirror support structure

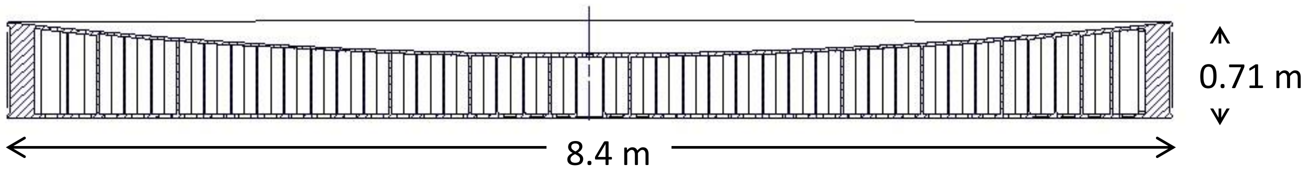


Simplified Control System Diagram

See the TMT prototype in the TMT visitor's gallery at NOAJ, Mitaka Japan

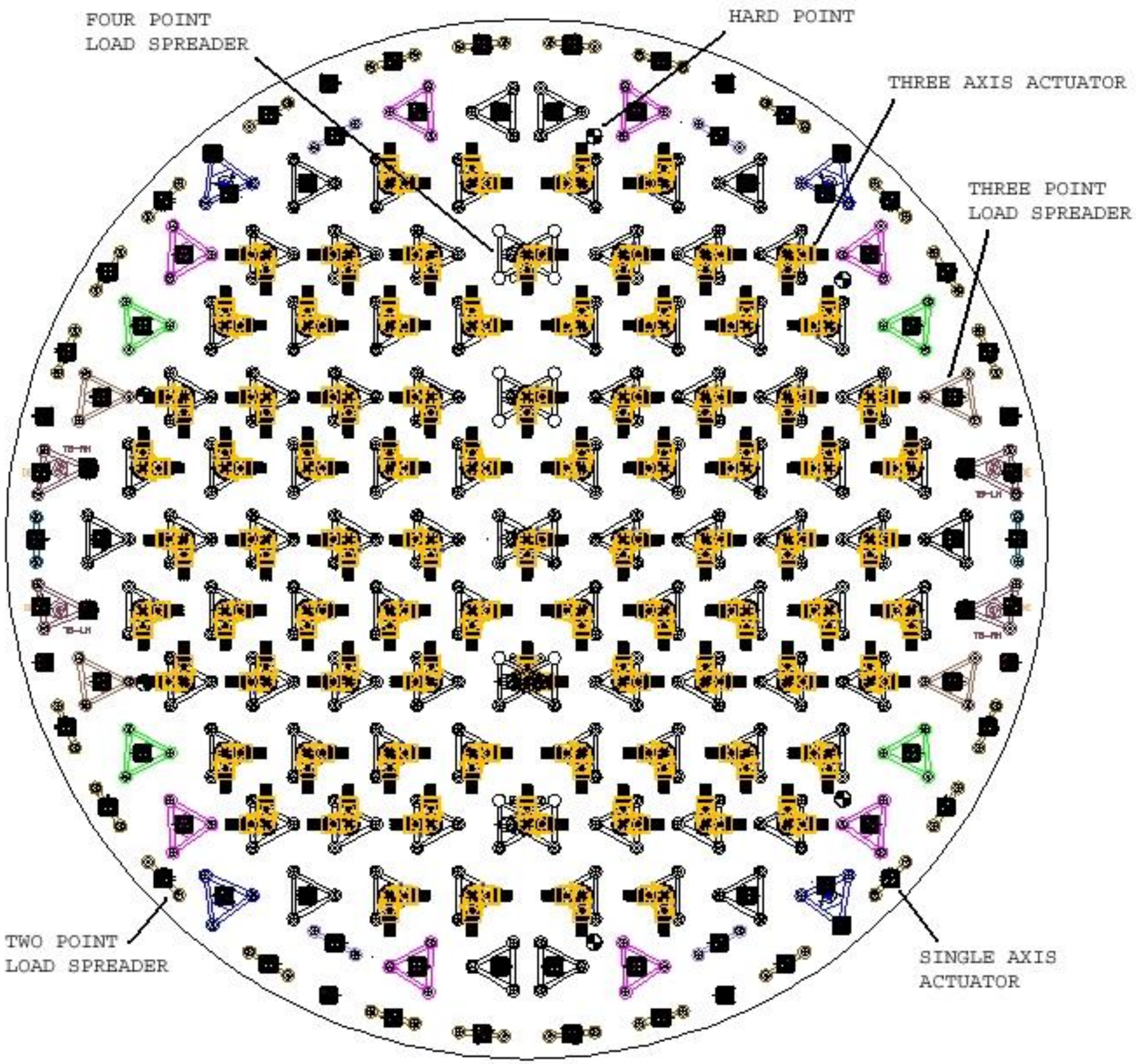
3. Honeycomb mirrors

- Concept developed by Roger Angel and colleagues at UA
  - Extend Palomar technology to 8 m with more extreme lightweighting and a bottom plate
  - Maintain stiffness of traditional mirrors, reducing dependence on active control & relaxed actuator accuracy (~10N)
  - Achieve very short thermal time constant with thin glass sections & active ventilation
- Technology
  - One-piece spin-casting of honeycomb structure with 80% lightweighting
  - Polishing and measuring very fast mirrors (short focal length, f/0.7 - f/1.25)
- Used for MMT, 2 Magellan telescopes, LBT, LSST
- To be used for GMT 25 m, TAO 6.5 m, TSPM 6.5m



LBT 8m

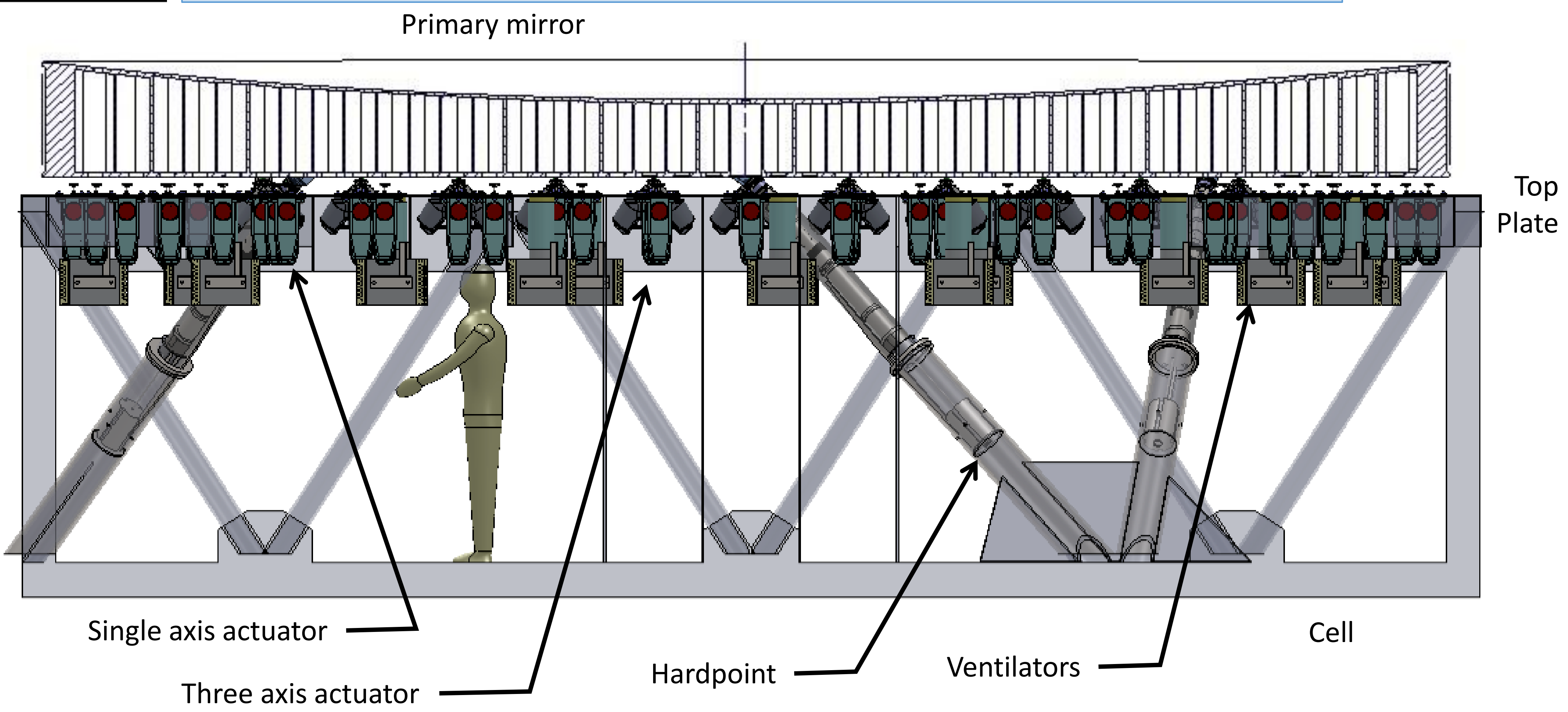
GMT mirror support layout



<u>8.4 m M1 Supports</u>

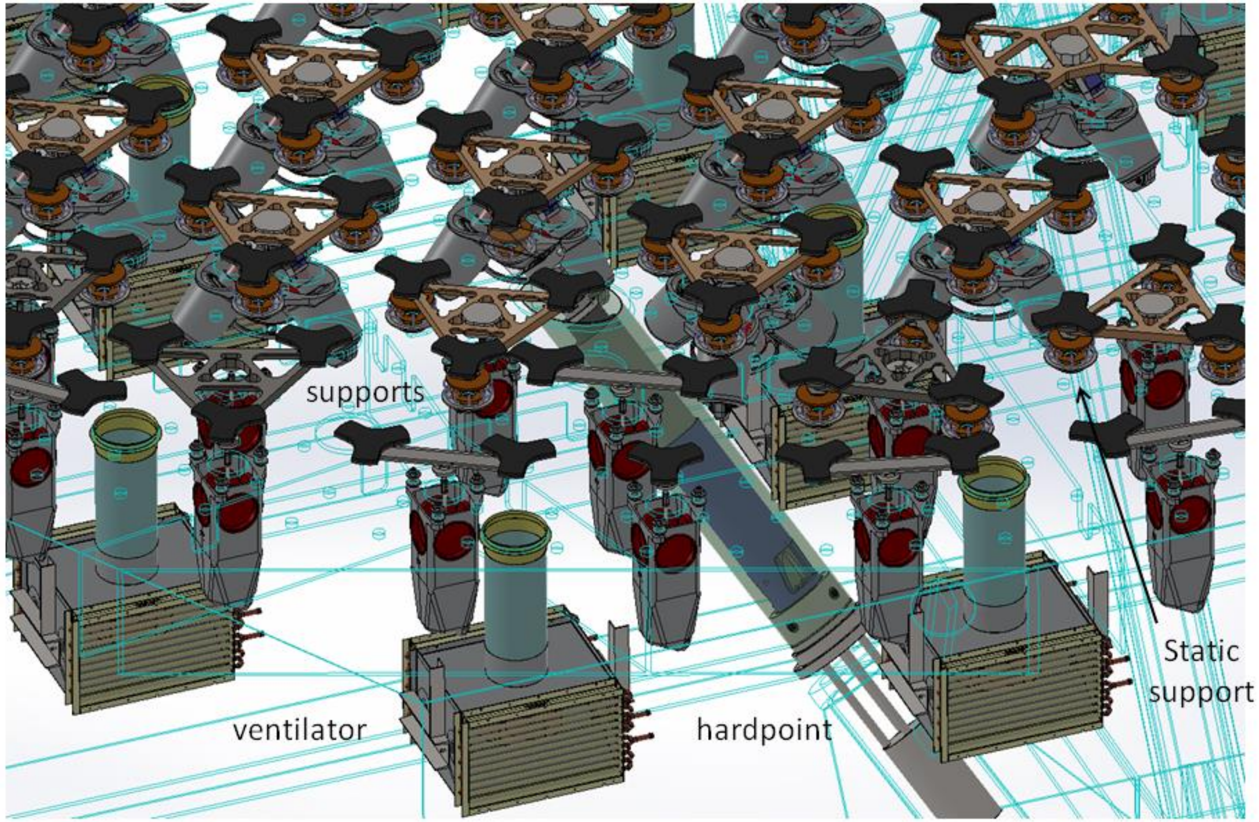
- 160 astatic support actuators
  - Mix of 1- and 3-axis actuators
- Attach to loadspreaders on the bottom plate and provide both axial and lateral support
- Active M1 figure control is provided by adjusting the axial forces
- Mirror position is controlled by a 6 hexapod motorized struts (“hardpoints”)

GMT M1 Cell Assembly

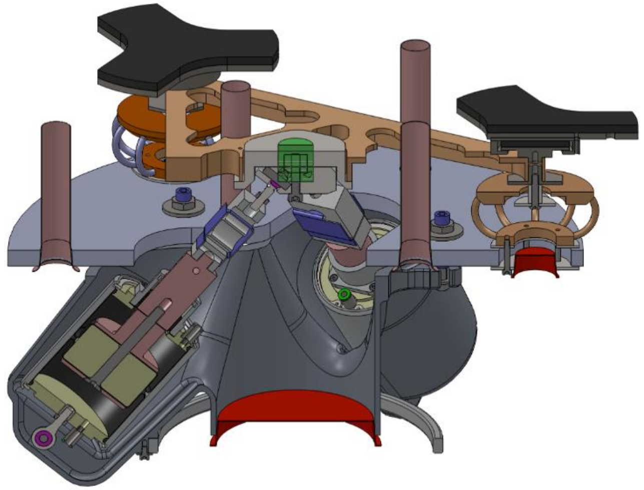


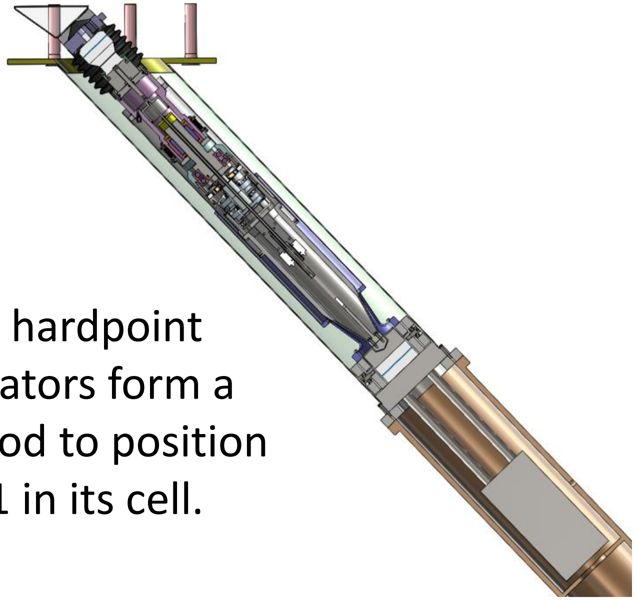
- Astatic actuators provide gravity support and figure control
- Six hardpoints ("hexapod") control mirror position
- Ventilators thermally condition the mirror

Mirror supports



3-axis astatic force actuators



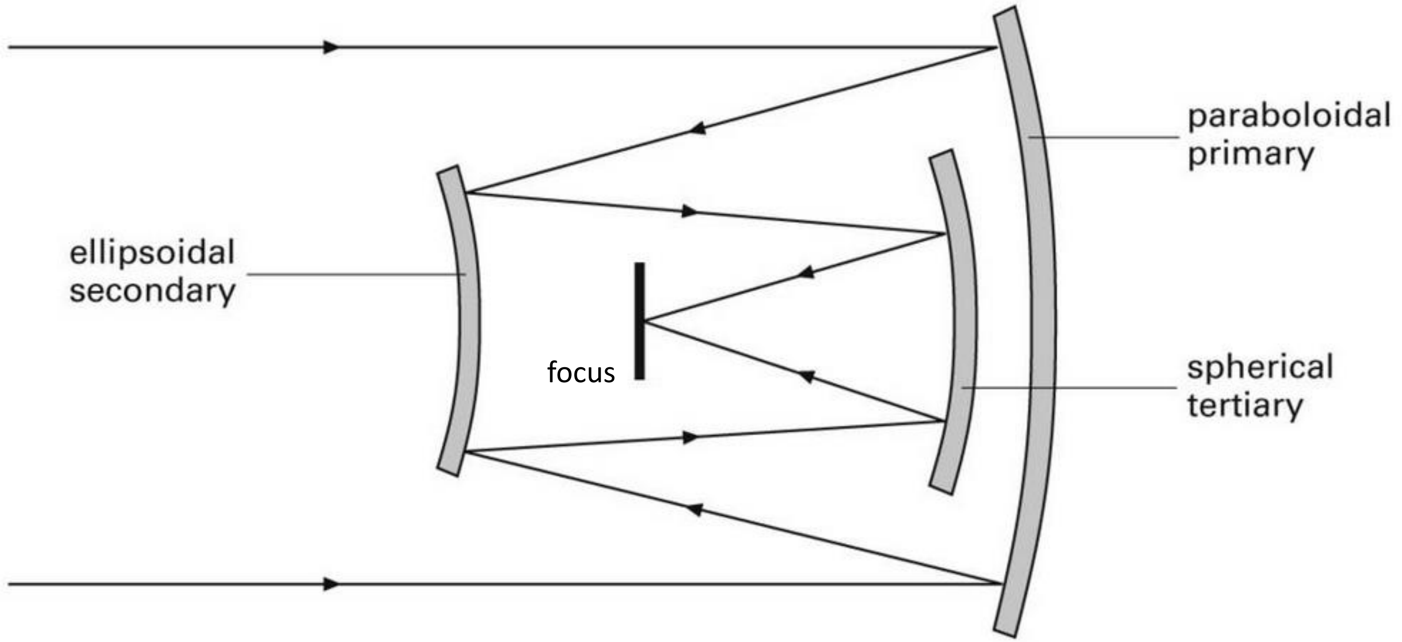


Six hardpoint actuators form a hexapod to position M1 in its cell.

- Support actuators, hardpoints, ventilators derived from heritage designs (MMT, Magellan, LBT)
- Two-axis actuators are required for single mirror telescopes
- Three-axis operation required for GMT

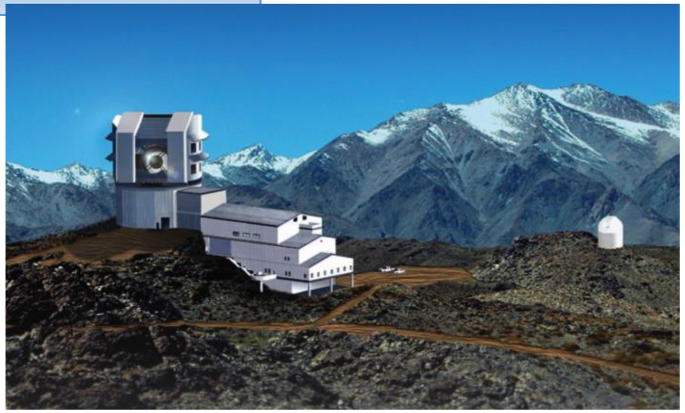
Three –mirror Telescopes

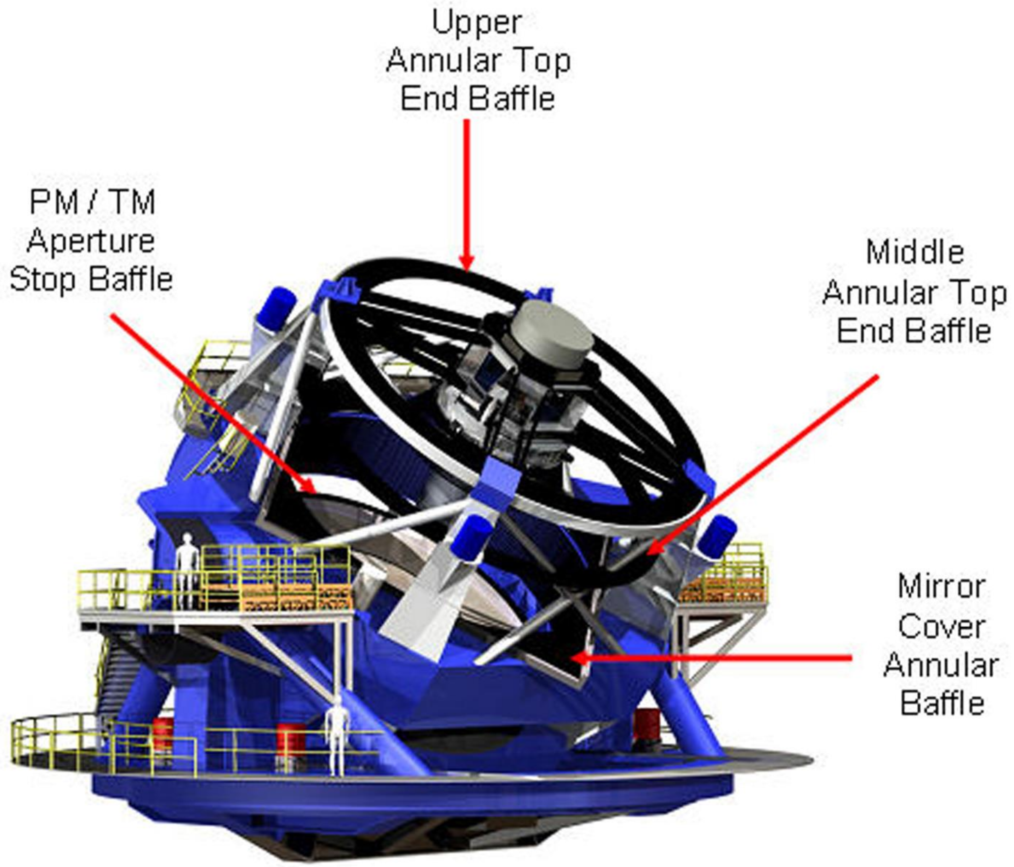
- A two-mirror telescope with a corrector can deliver FOVs up to around 1 degree.
- A three-mirror Paul-Baker type telescope provides additional control over optical aberrations and the possibility of wider FOVs at the cost of throughput loss due to additional reflections and greater internal obscuration and a less flexible instrument mounting location.

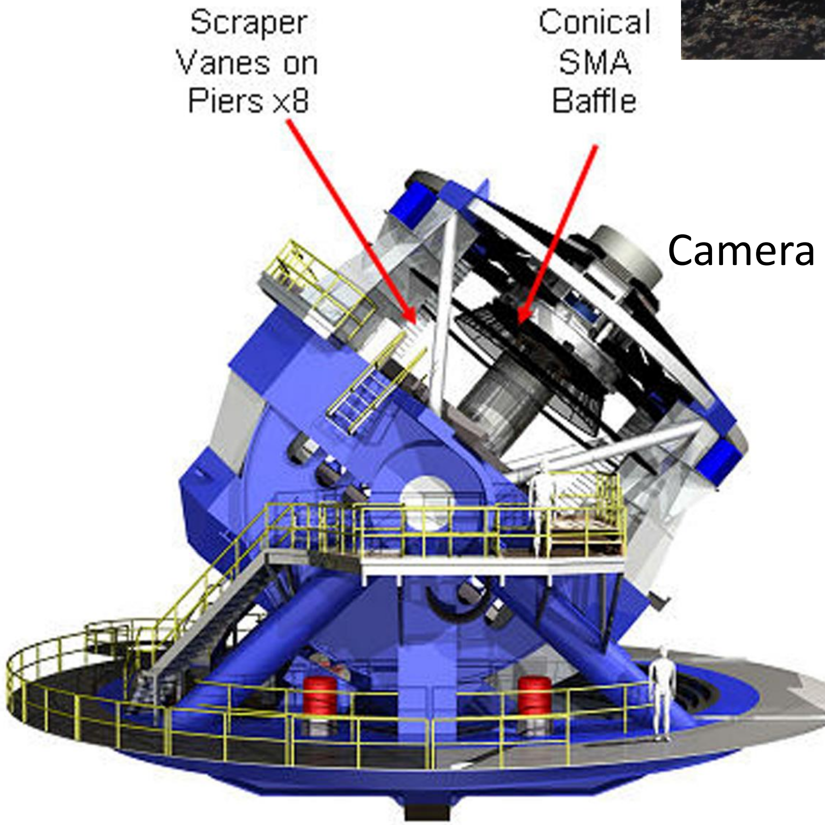


Paul–Baker telescope

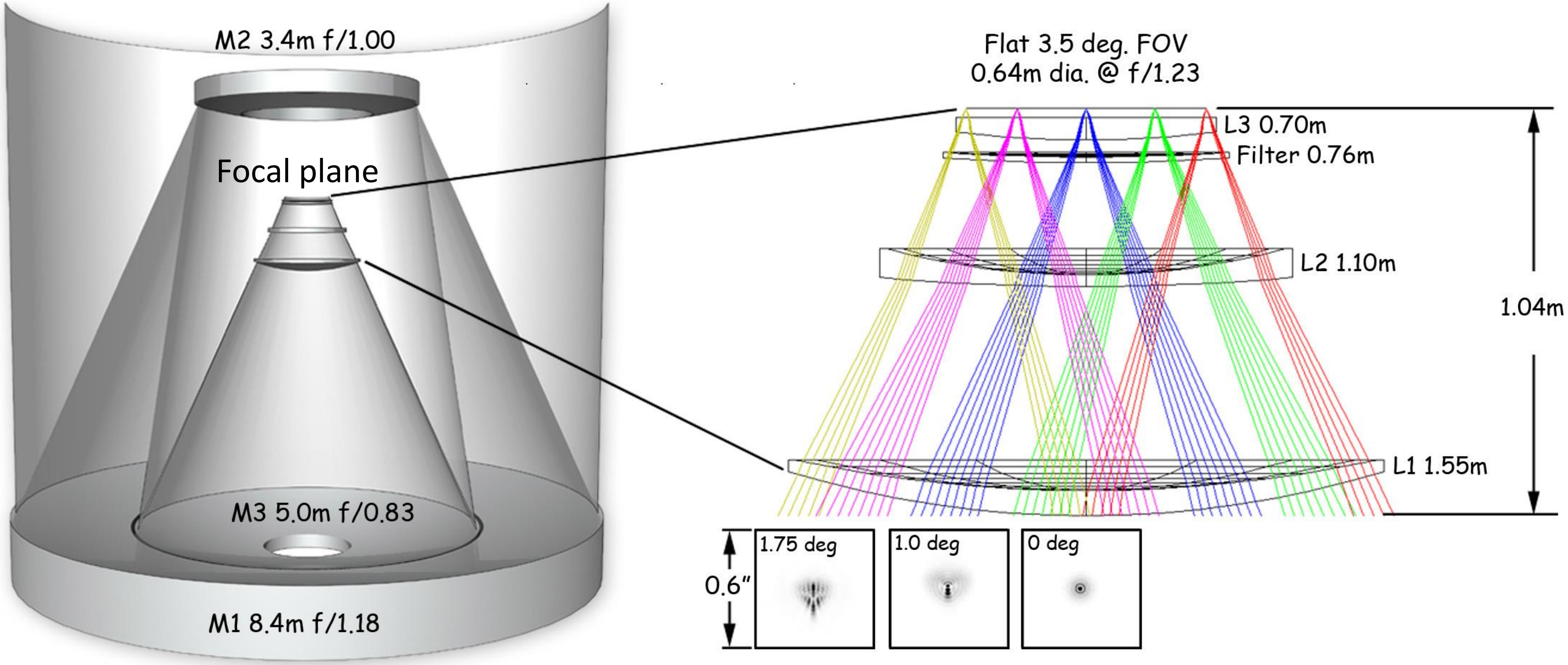
8m LSST modified Paul-Baker







LSST modified Paul-Baker Optical Layout



- Large Synoptic Survey Telescope (LSST) telescope optical design with 3.5 degree FOV.
- Wide-field survey camera is mounted above the focal plane.

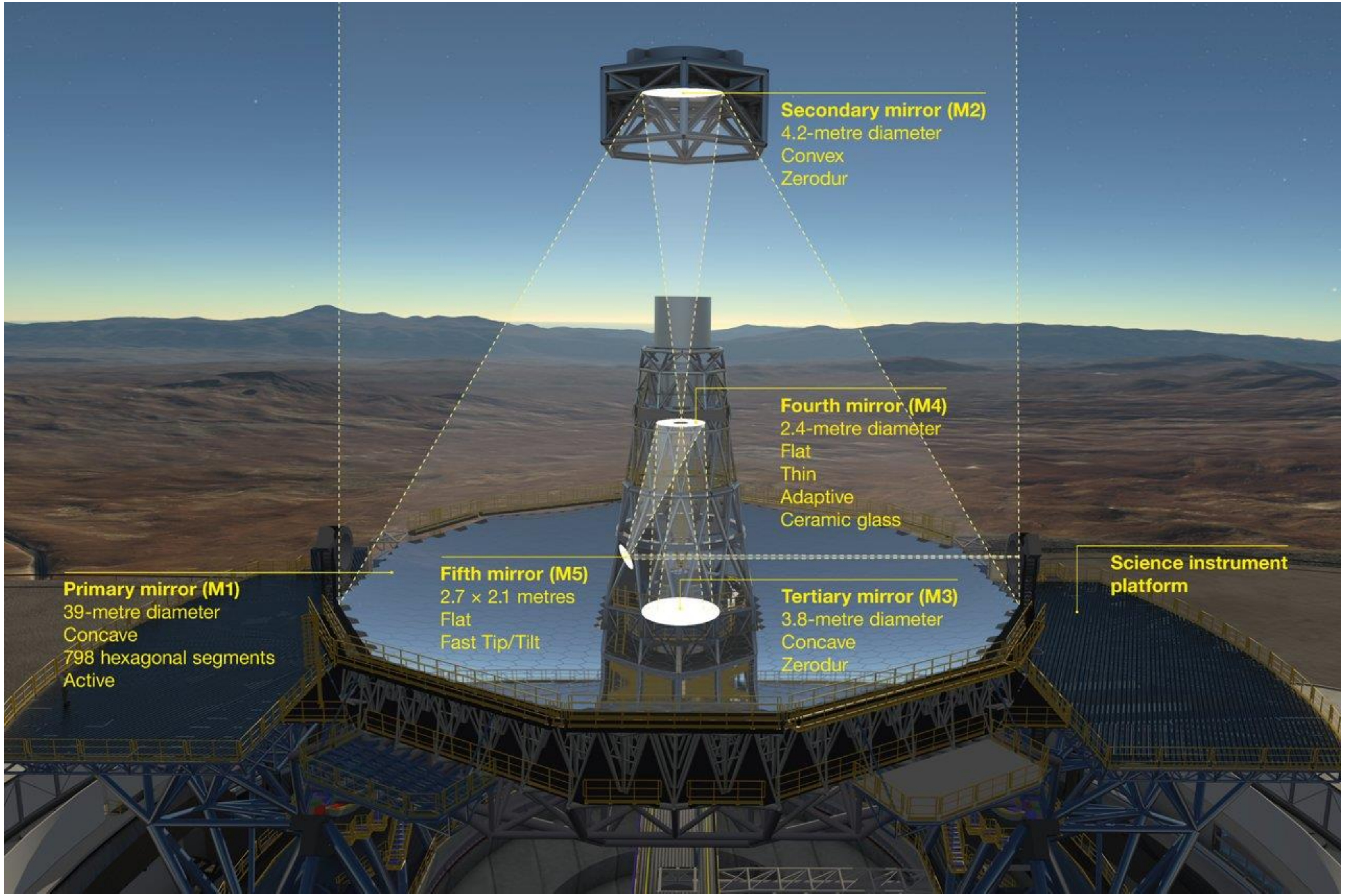
LSST Primary Mirror

- Primary Mirror (M1) and Tertiary Mirror (M3) are generated and polishing in the same 8.4 m cast borosilicate blank.
- This requires the test tower to have two separate metrology set-ups with well determined relative positions.

THE UNIVERSITY OF TOKYO

EELT 5-mirror optical system

Visiting Professor Lecture



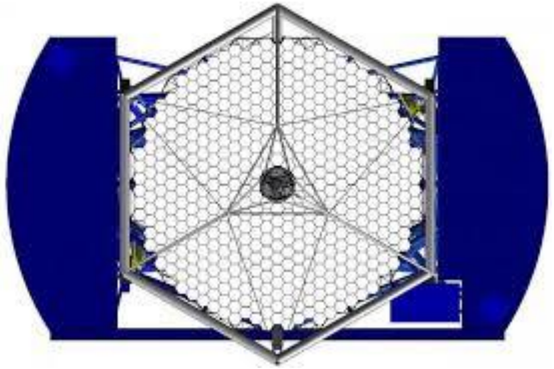
Five-mirror optical system of ESO's Extremely Large Telescope (ELT). In-coming light is first reflected from the telescope's concave 39-metre segmented primary mirror (M1), it then bounces off two further 4-metre-class mirrors, one convex (M2) and one concave (M3). The final two mirrors (M4 and M5) form a built-in adaptive optics system to allow extremely sharp images to be formed at the focal plane on the science instrument platform.

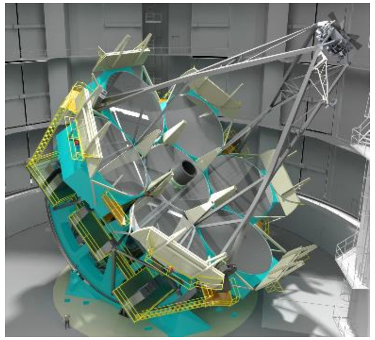
- Aperture: 39 meters
- Focal length: 683 meters
- Focal ratios: f/17.5
- FOV: 10 arc-minutes
- Plate scale: 3.3 mm/arc-sec

Segmented Mirror Systems

- **Monolithic mirrors larger than ~8 meters are too risky to fabricate & transport.**
- **The largest telescopes have segmented primary mirrors to get around this problem.**

Small segment
TMT





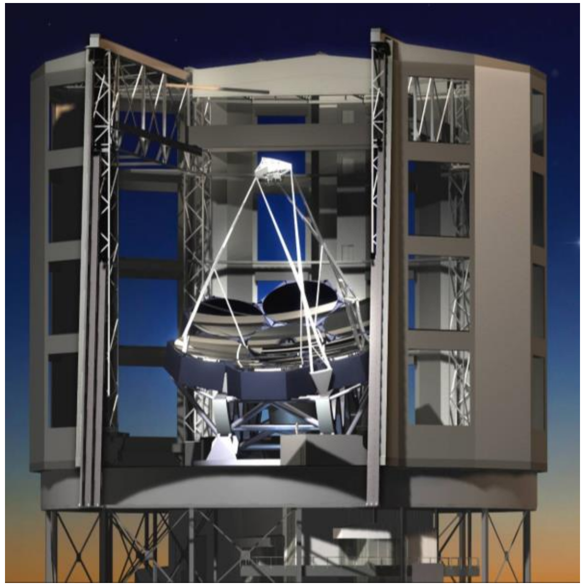
Large segment
GMT

Telescope	Aperture (m)	Segments	Segment size (m)	Collecting area (m^2)	M1 Focal ratio
Keck Telescope	10	36	1.8	76	1.75
Large Binocular Telescope (LBT)	22.8	2	8.4	111	1.14
*Giant Magellan Telescope (GMT) **	*25.4*	*7*	*8.4*	*368*	*0.71*
*Thirty Meter Telescope (TMT) **	*30*	*492*	*1.4*	*655*	*1.0*
*European Extremely Large Telescope (EELT) **	*39*	*798*	*1.4*	*978*	*0.93*

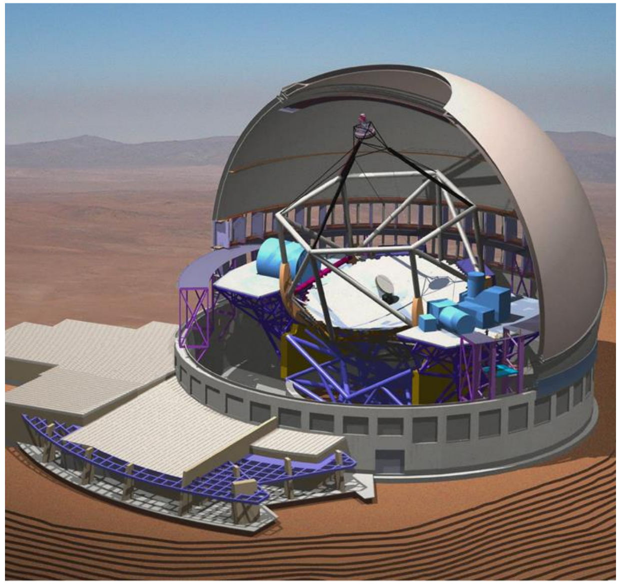
** Under development*

Comparing the ELTs

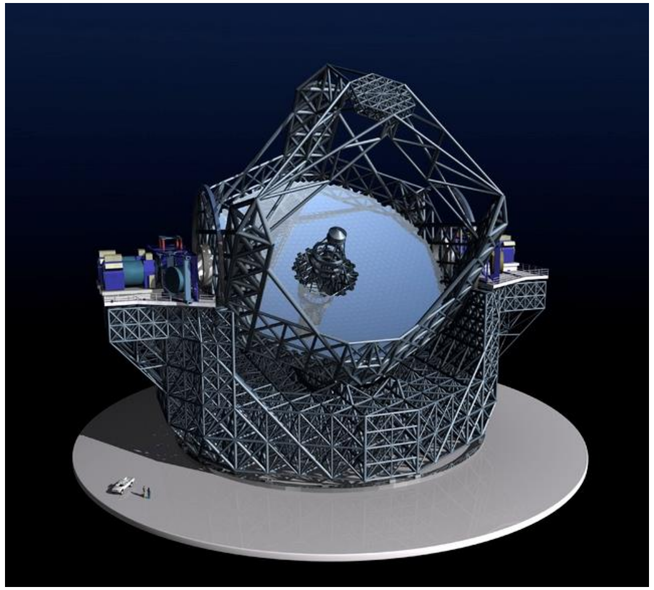
Increasing collecting area & angular resolution



GMT 25m
2 reflections
f/8
20 arc-min FOV
Focal surface: 1.2 m Φ
1.0mm/arcsec
Diff. limit 11.8 mas



TMT 30m
3 reflections
f/15
20 arc-min FOV
Focal surface: 2.6 m Φ
2.2mm/arcsec
Diff. limit 8.4 mas



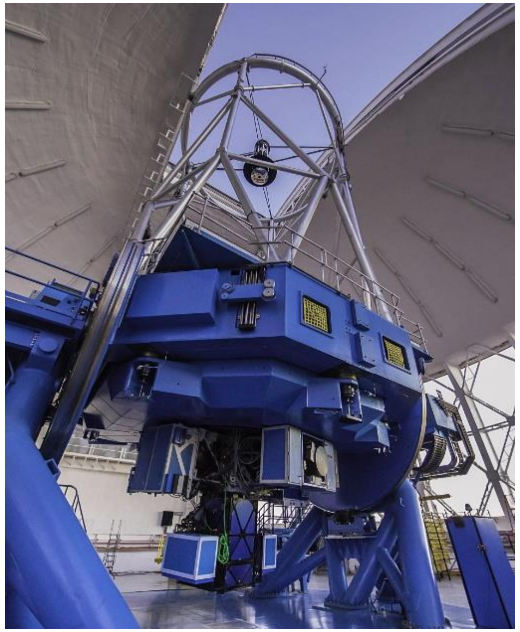
EELT 39m
5 reflections
f/17.5
10 arc-min FOV
Focal surface: 2.0 m Φ
3.3 mm/arcsec
Diff. limit 6.4 mas

mas: milliarcsecs @ λ= 1.0 μm

Mount Design

Large Telescope Structures

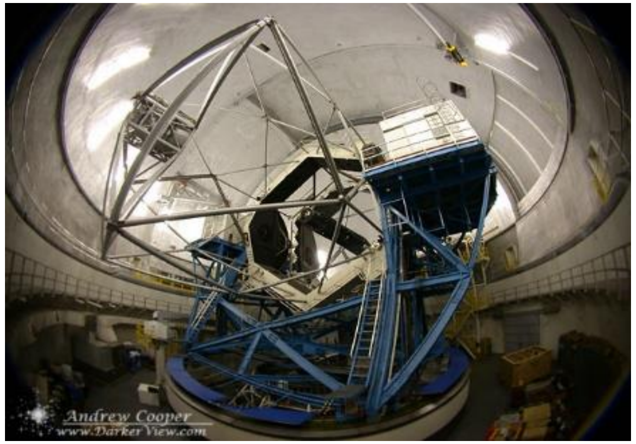
Subaru



Gemini

MMT

Magellan

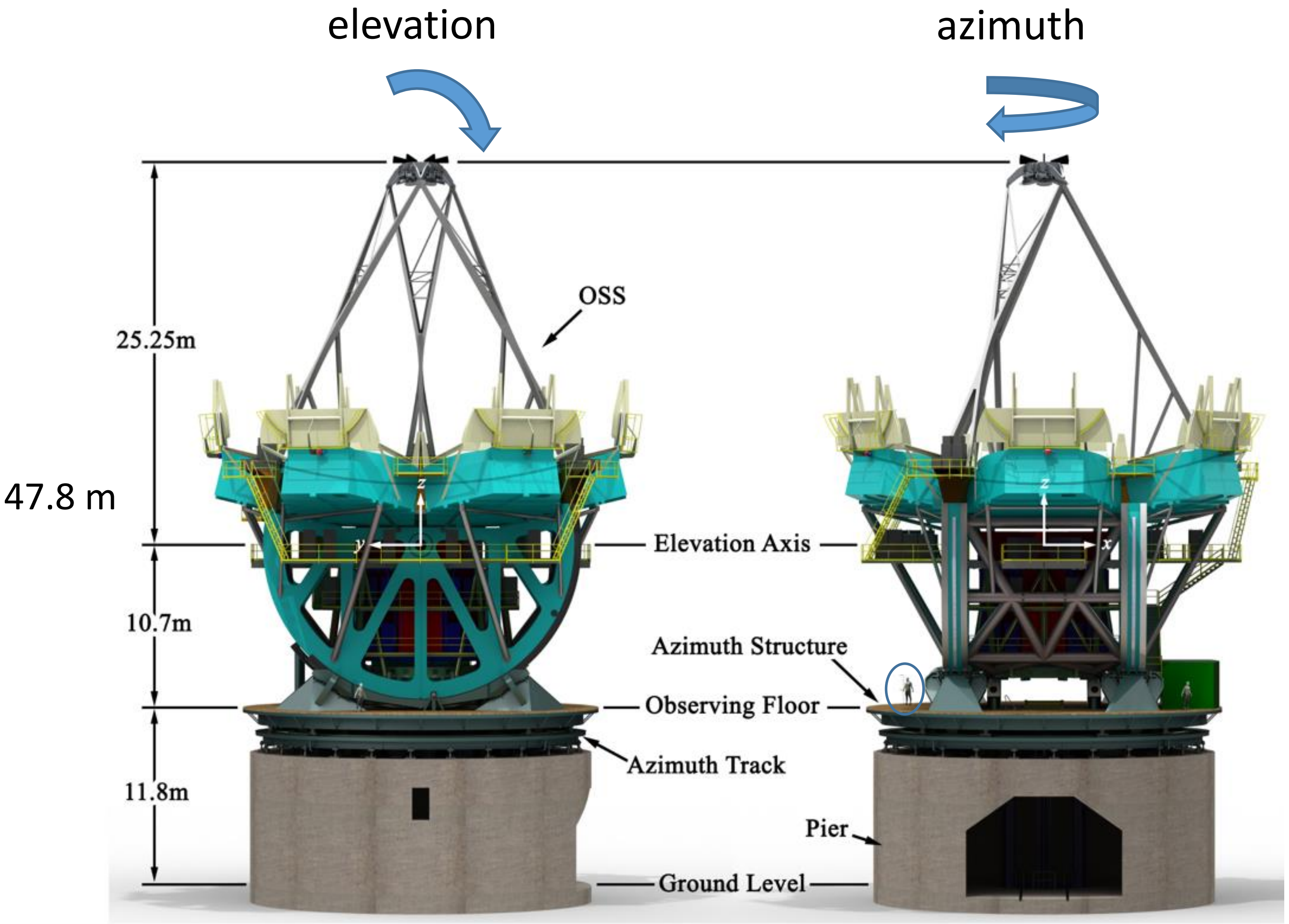


Keck

Altitude-Azimuth Mounts are the standard for large telescopes.

Alt-az structure

- The altitude-azimuth (alt-az) configuration is the most common modern-day telescope structure.
- It consists of a 2-axis gimbal that allows the mount to point in all directions above the horizon.
- It is stiffer and more compact than the traditional equatorial mount but does require both axes to be tracked to follow astronomical targets and includes a circular “zone of avoidance” at the zenith where the azimuth track rate becomes infinite.
- Objects in the field of view rotate about the optical axis as the telescope tracks requiring an instrument de-rotator.



GMT

Moving mass (azimuth + elevation) = 1,261 metric tons

Fixed mass (track) = 168 metric tons

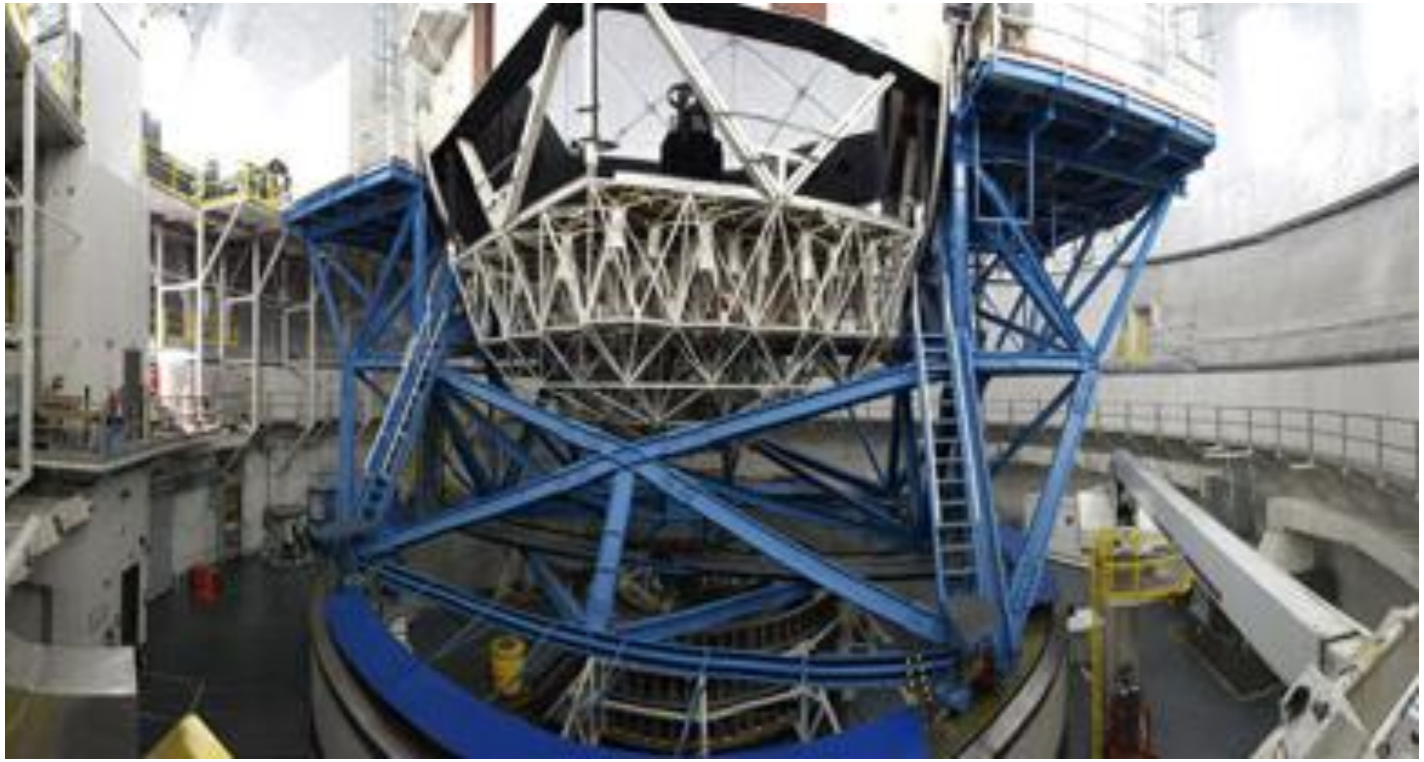
Mount Configurations

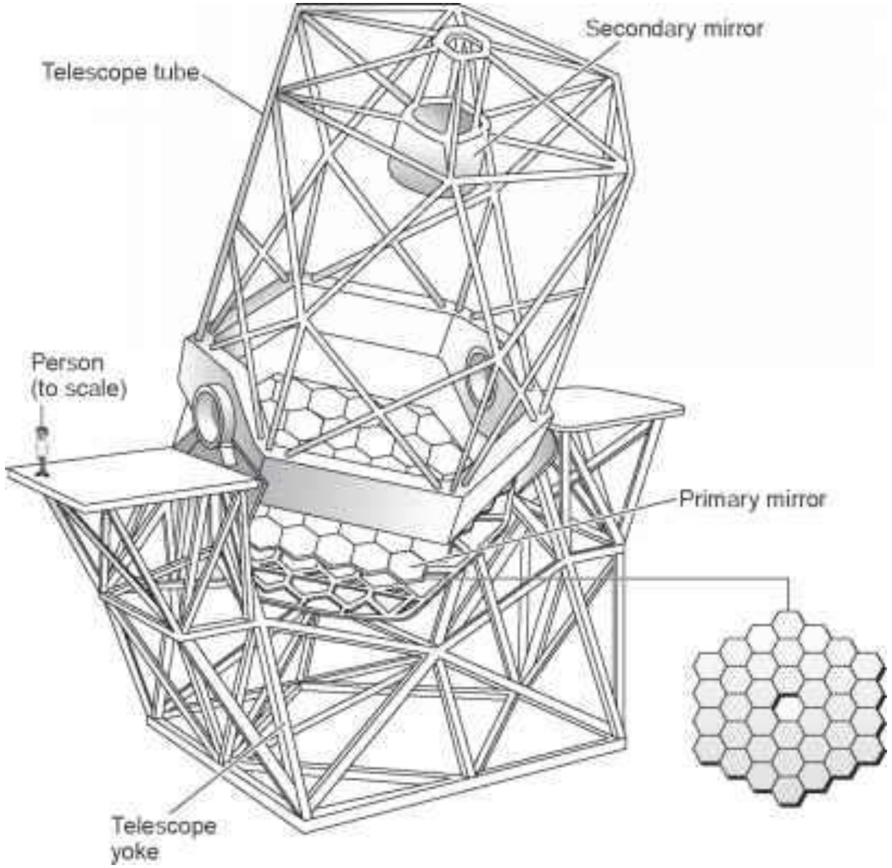
Large telescopes have some distinguishing features:

- Elevation structure – truss versus steel weldments
- Primary mirror support within the mount.
  - The primary mirror is supported within the telescope on actuators that connect the mirror to the mount structure. On multi-segments telescopes each segment has its own separate set of supports. The optimal method for attaching the mirror(s) to the structure differ for large mirror segments compared with multiple small segments.
- Mounting of secondary (secondary, tertiary, etc.) optics within the structure.
- Instrument mounting
  - Nasmyth or folded Cass Platform
  - Cassegrain/Gregorian
  - Prime focus
- Bearings – Hydrostatic versus rolling element
- Drives- gears, friction, direct

Examples of Truss Structure telescopes
Keck and TMT

Keck Truss-style Design

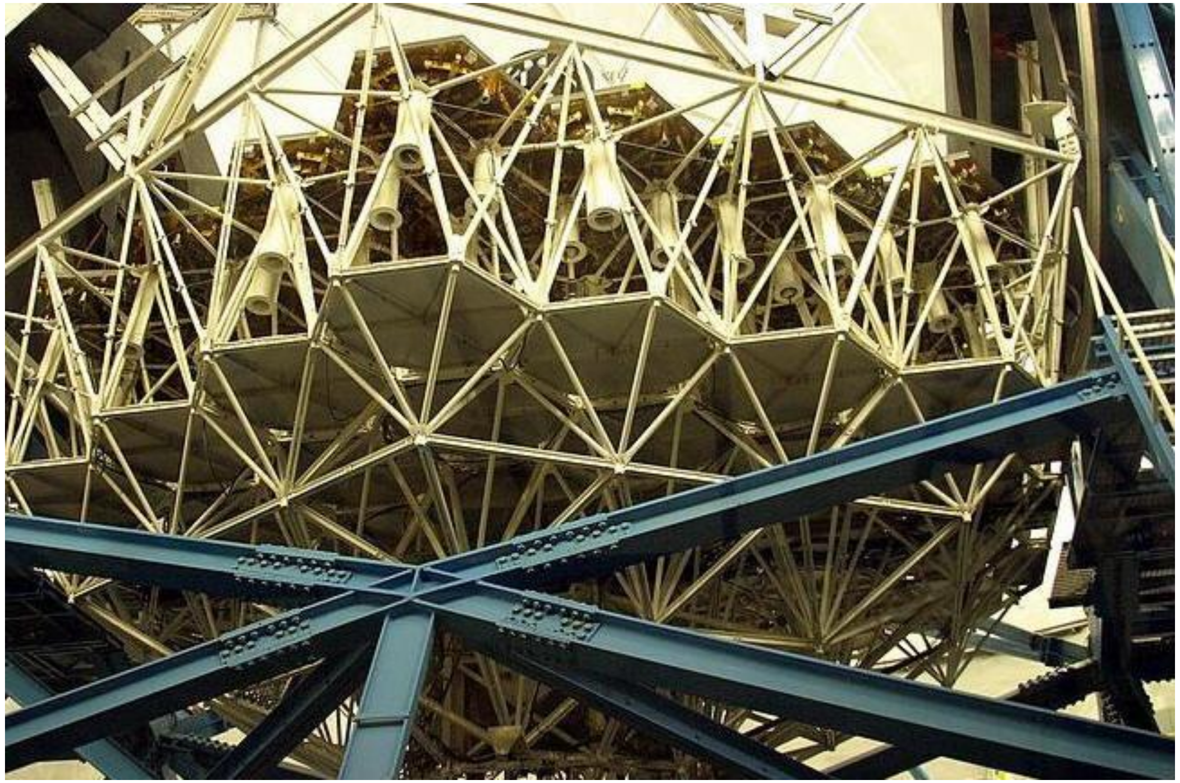




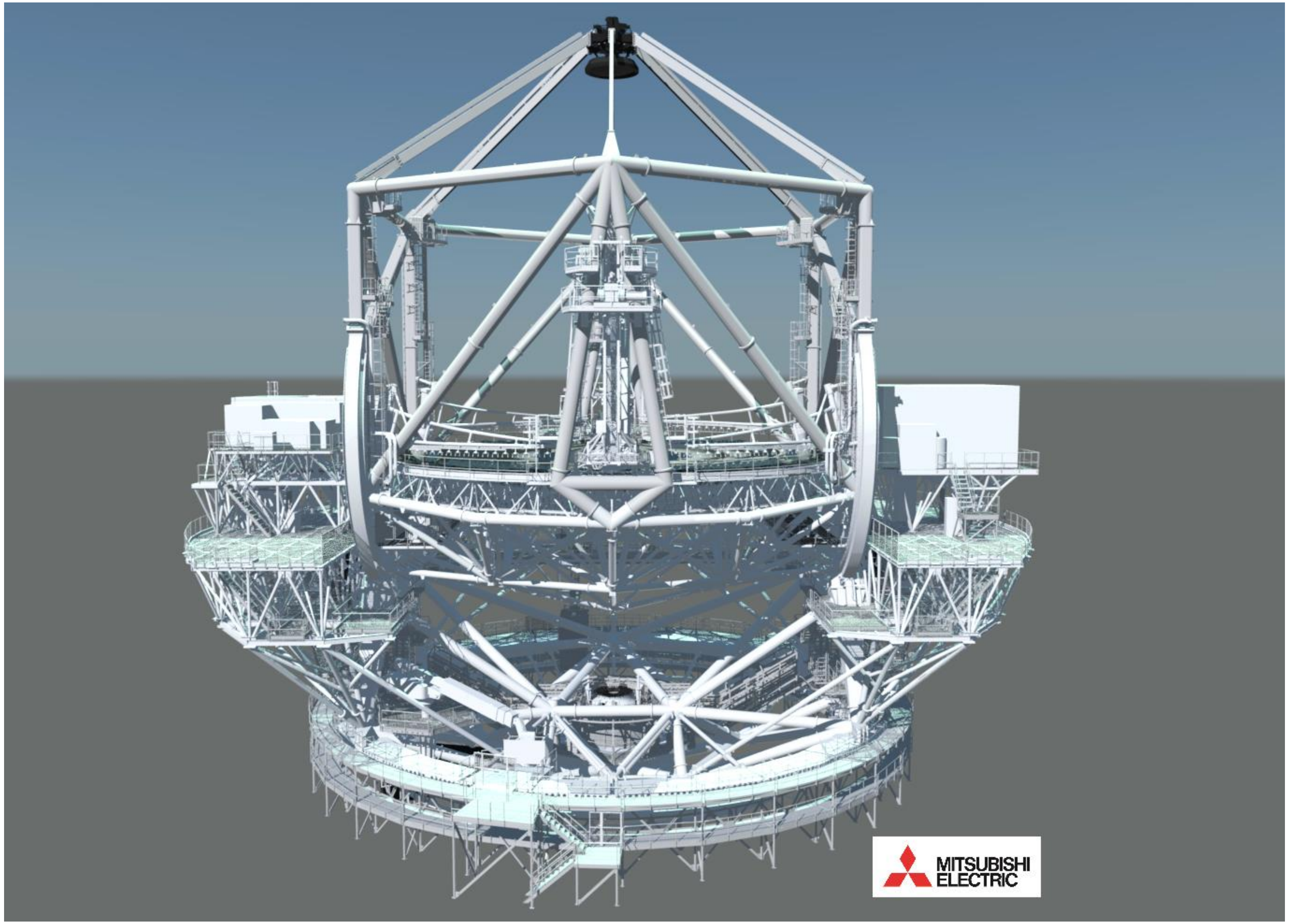
- Truss structure used for both the elevation pedestals.
- Two layer truss for the primary mirror.
- Gravity invariant Nasmyth platforms for instruments
- Proportionately small elevation bearings.
- Two tier secondary support truss.

Keck Truss Design

- On small segment telescopes such as Keck M1 supports are attached to a truss that spans across the mount below the mirror. The truss provides the stiffness for holding the segments in fixed relation to each other and the mount.
- Segment supports can be serviced from below.
- Segments are lifted out of the telescope individually or in rafts and for re-coating depending on the telescope.



Future TMT Mount



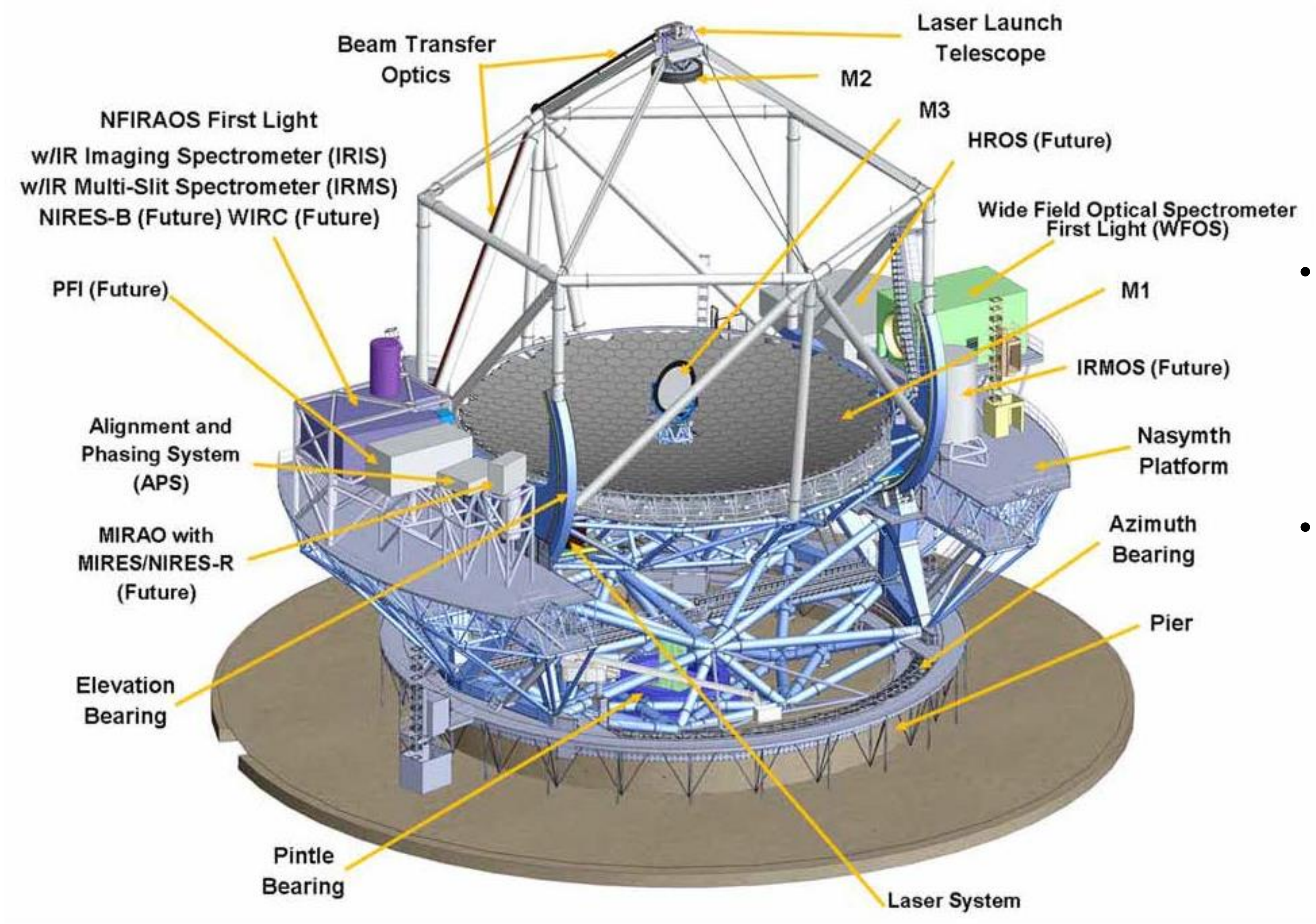
The TMT Mount scales up the design features of Keck:

- Alt-az configuration.
- 30 meter segmented primary mirror.
- Trusses used throughout for the structural members.
- Nasmyth platforms for science instruments.

Size:

- 56 m W. x 51 m H.
- Moving mass: 1,430 mt

TMT Instrument & AO Systems Mounting

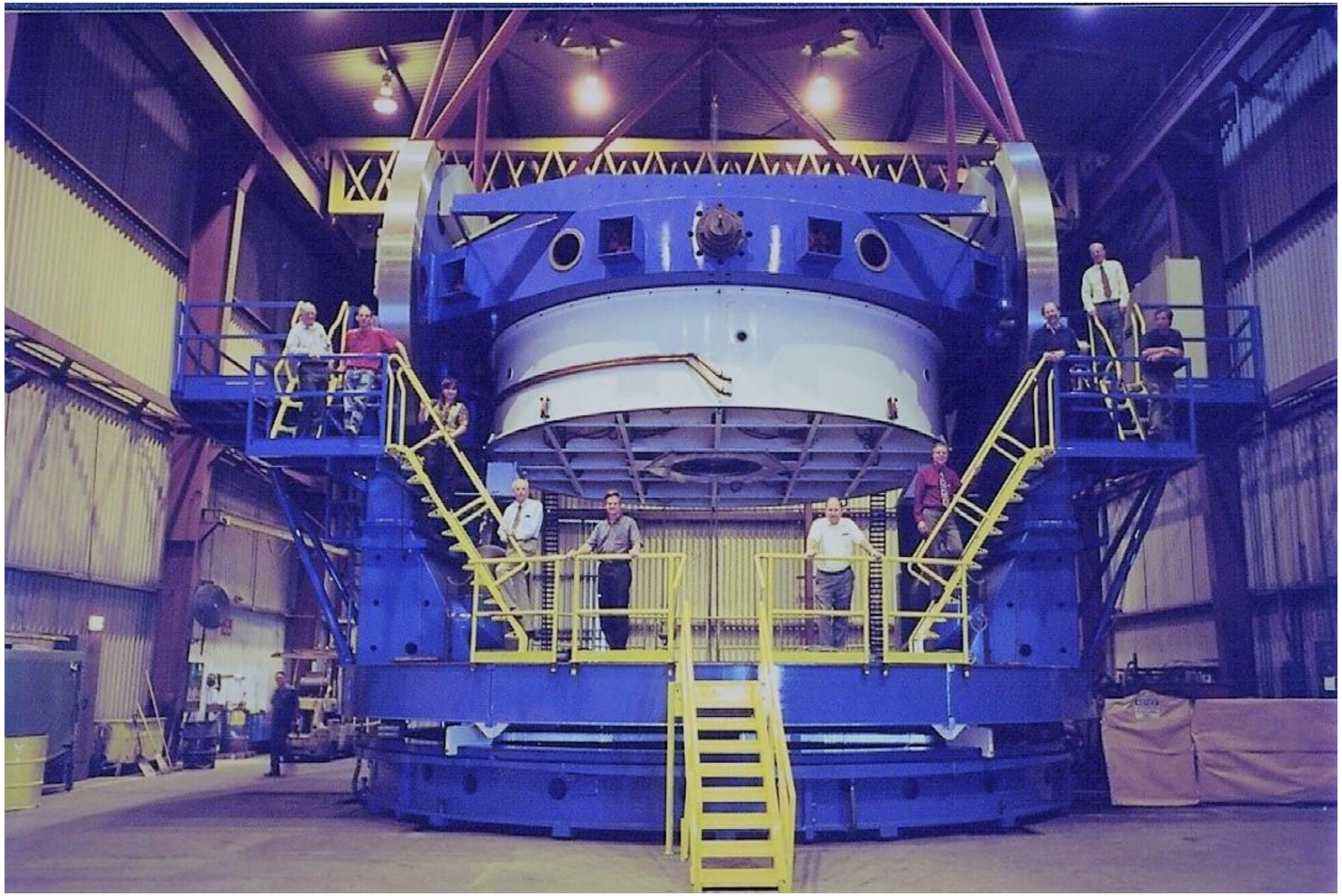


- Instruments are mounted on a gravity invariant Nasmyth platform that enables service access with the telescope at off-zenith elevation angles.
- Fold mirrors direct the beam to instruments not directly mounted on the elevation axis.

Examples of Weldment Structure telescopes - Magellan and GMT

Magellan Mount

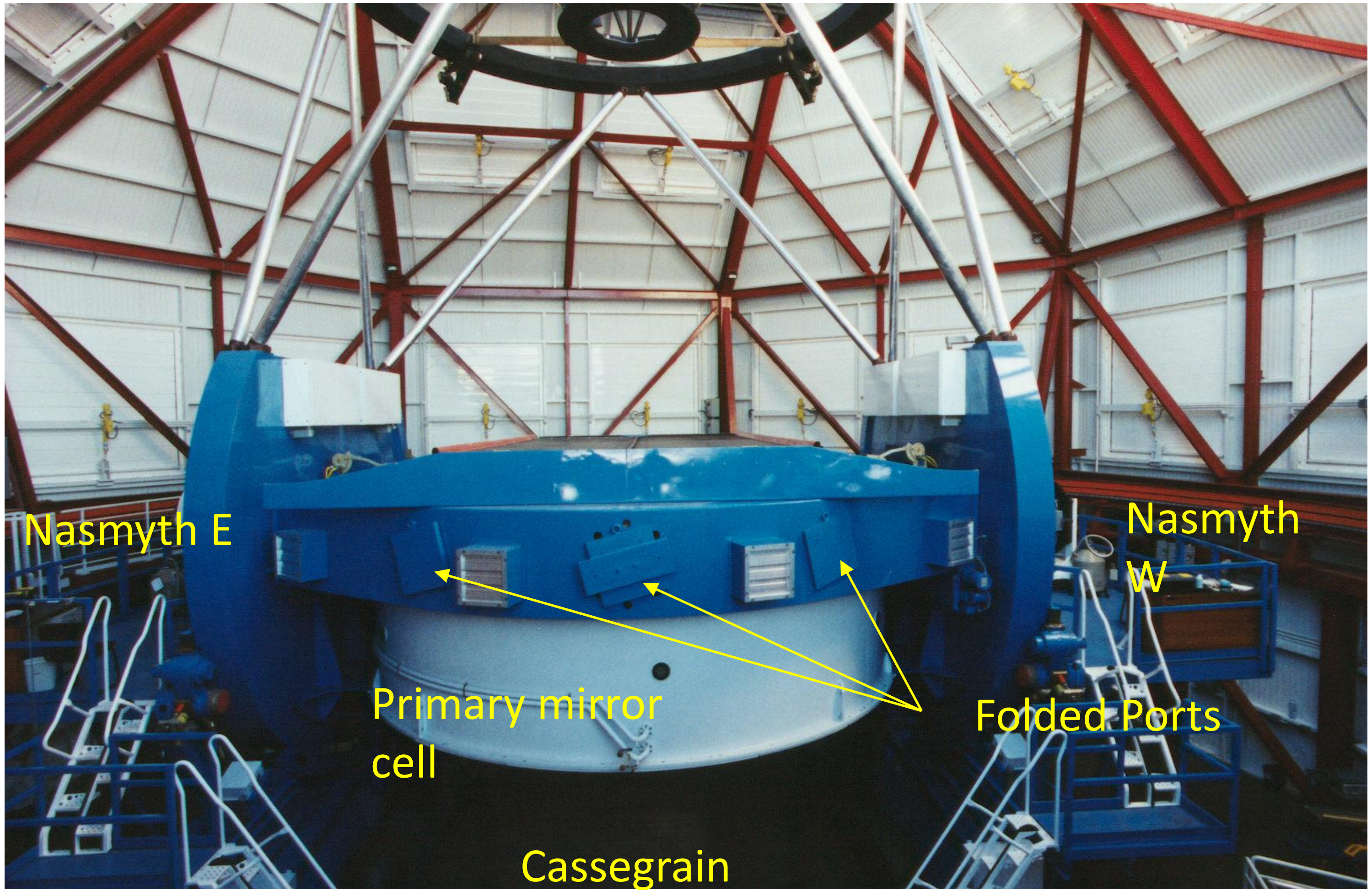
- Elevation structure consists of bolted together steel weldments.
- Large diameter elevation hydrostatic bearing journals (tracks).
- Primary mirror cell spans the width between elevation disks.
- Instruments are mounted on Nasmyth platforms, folded-Cass ports, and Cassegrain.



Shop assembly at L&F Industries

Magellan Mount

- Elevation structure consists of bolted together steel weldments.
- Large diameter elevation hydrostatic bearing journals (tracks).
- Primary mirror cell spans the width between elevation disks.
- Instruments are mounted on Nasmyth platforms, folded-Cass ports, and Cassegrain.



Magellan 1 (Baade) at LCO

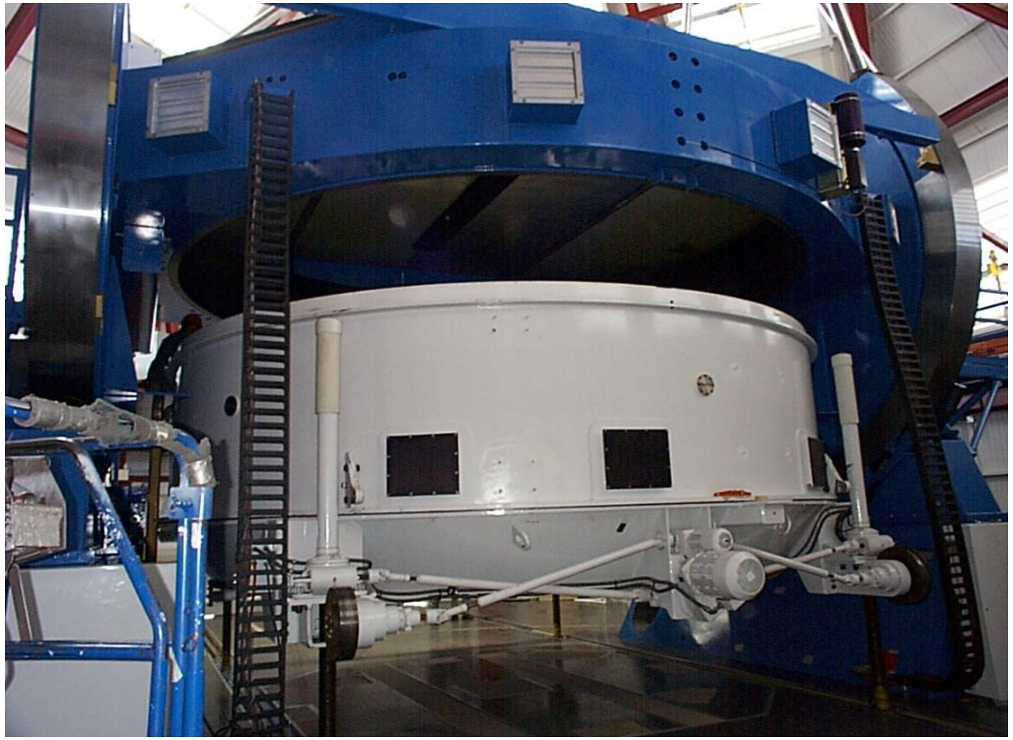
Top-end Assembly & Vane Actuator

Top-end view of Magellan showing the secondary truss, elevation structure, azimuth disk and track, mirror covers, and Nasmyth Platform.

A novel feature of Magellan is that the secondary mirrors and cage are positioned by four vane actuators mounted on the top ring of the secondary truss. M2 mirrors bolt onto the cage and do not have to provide additional focus or alignment motions.

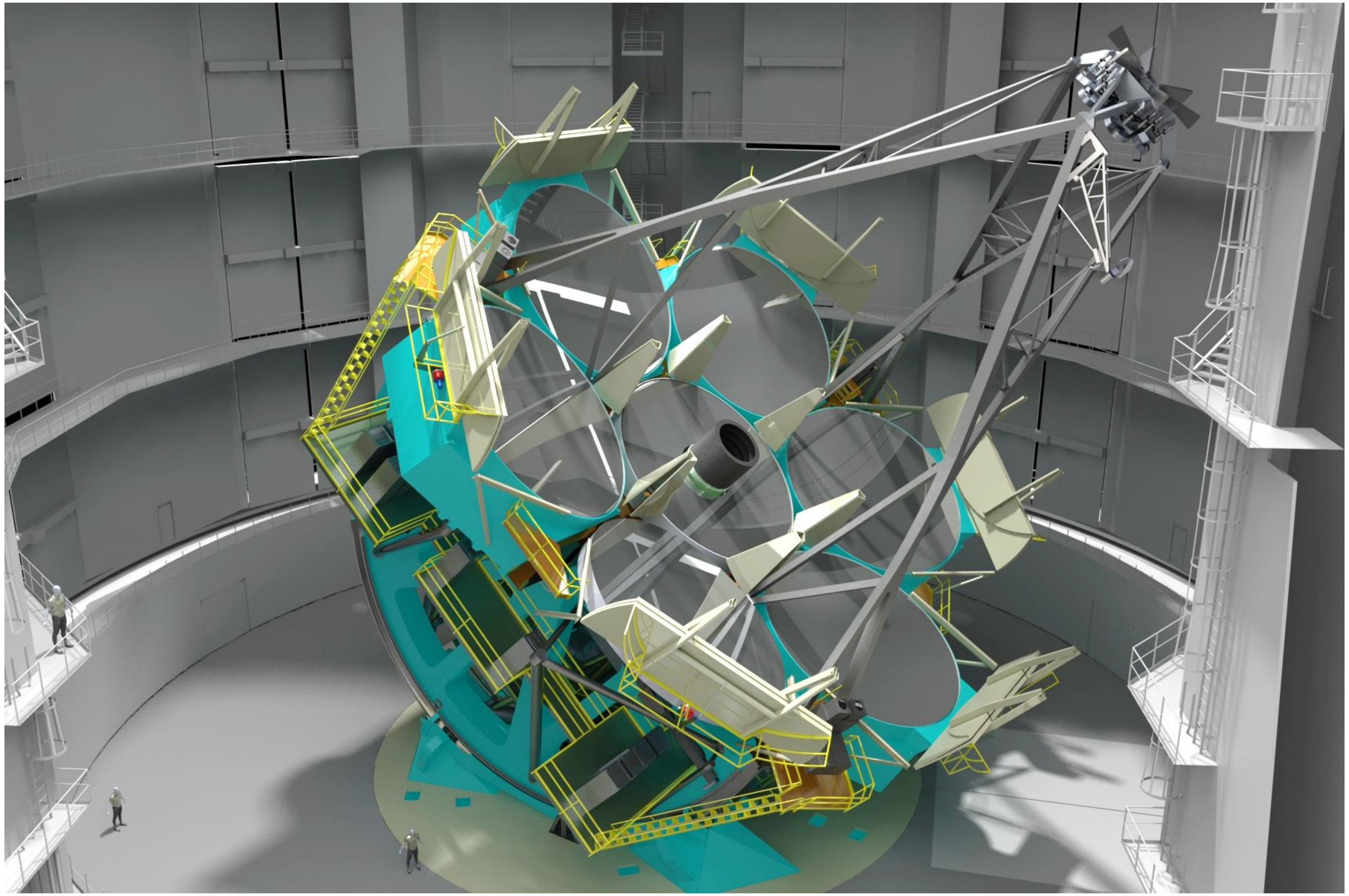
Primary Mirror Cell

- On single segment or multi- large segment telescopes the primary mirror is installed in a cell on its supports. The cell in turn is installed in the telescope as an assembly.
- Different procedures are used for re-coating the mirror.
  - The MMT primary mirror is coated in its cell on the telescope.
  - On VLT the primary mirror assembly is removed from the telescope, moved to the coating plant where the mirror is removed from its cell and coated in the vacuum chamber.
  - The Magellan primary mirror and cell are removed from the telescope and moved into to the coating chamber where the mirror is coated on its supports in the cell.



Removing the Magellan Primary Mirror from the telescope for coating.

Future GMT



GMT scales up many of the design concepts from Magellan.

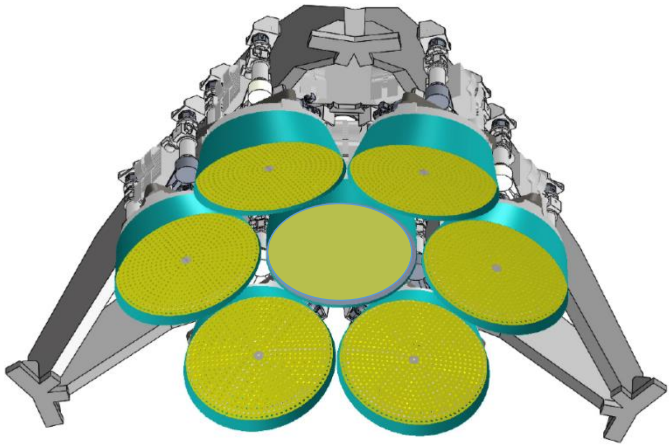
- Fabricated steel alt-azimuth structure
- Hydrostatic bearings and friction drives
- Multi-instrument (broad science) capability

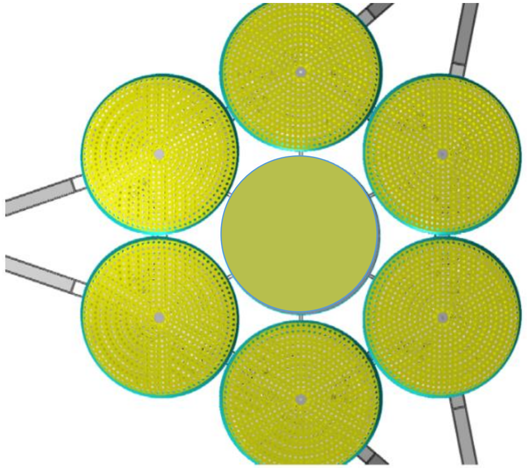
Differences include:

- 25 m segmented primary mirror
- Segmented secondary mirror
- Primary mirror assemblies are removed for recoating using the overhead bridge crane.

Dimensions: 26 m W. x 48 m H. including 12 m pier.

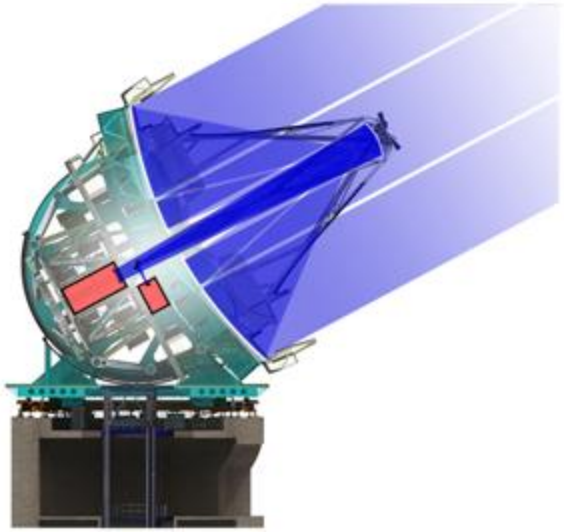
GMT Secondary Mirrors

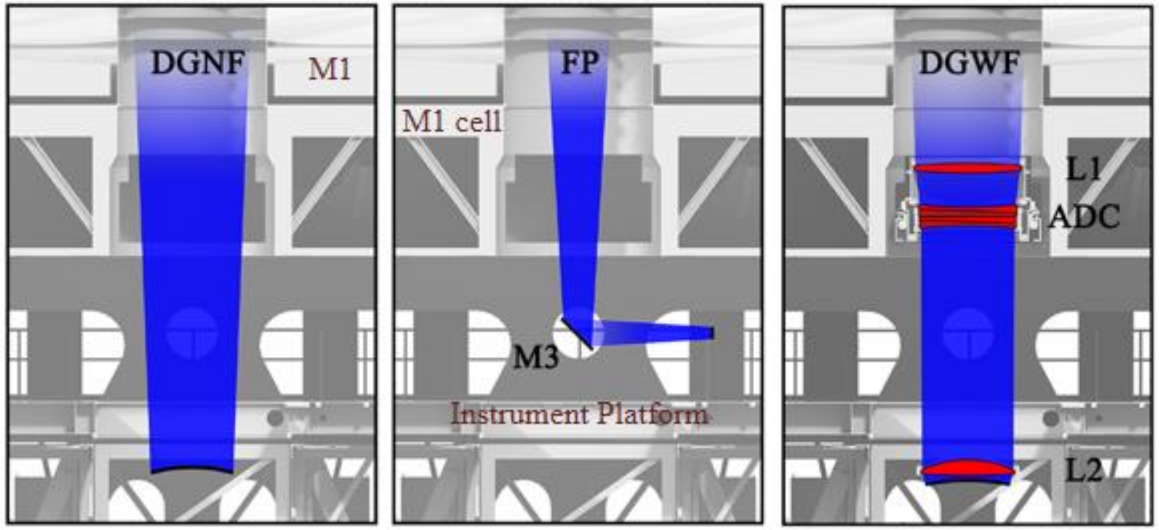




- Secondary mirror segments are conjugated 1:1 with the M1 segmens.
- Mean circular aperture (1.04 mm) defined by M1 conjugation ratio.
- Segments have independent translation, tip/tilt, and piston (focus) motions.
- Two interchangeable secondary mirrors top assemblies:
  - FSM: Fast-steering Secondary Mirror
  - ASM Adaptive Secondary Mirror

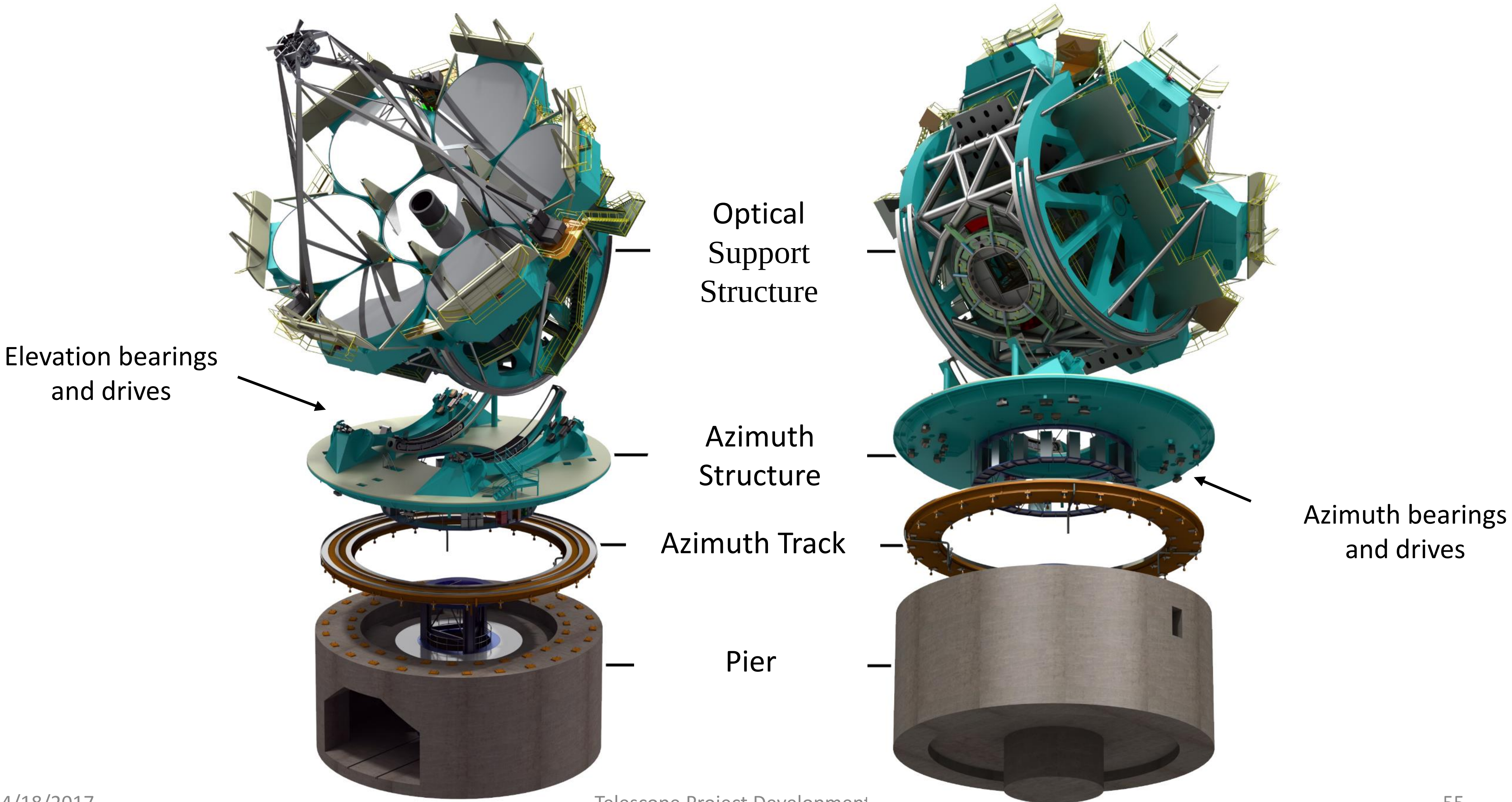
GMT Optical configurations



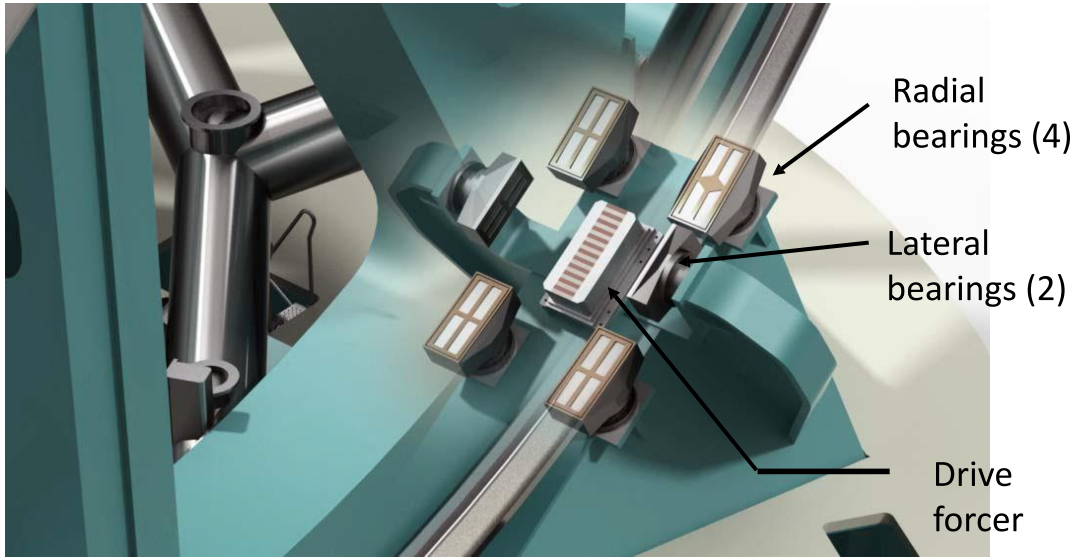


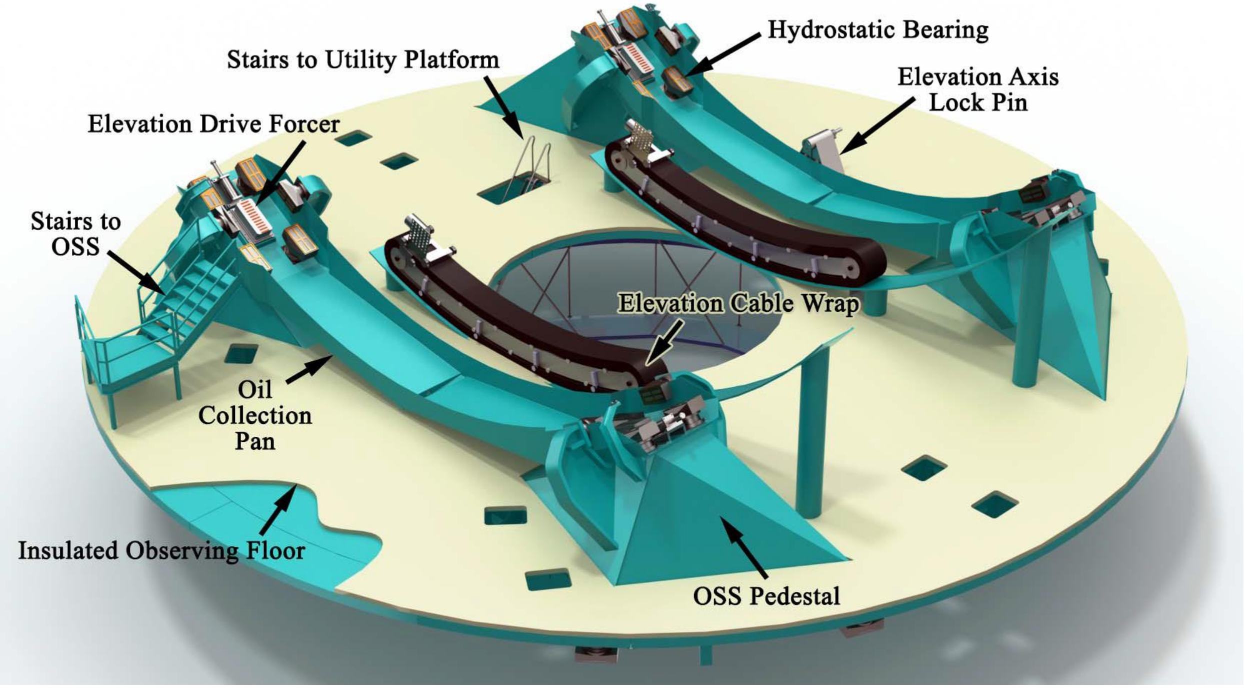
Config	Unvignetted field of view	Instrument ports/stations
DGNF	20 arcmin, ~10 arcmin well corrected	Direct Gregorian narrow-field focus
FP	3 arcmin	Folded ports Feed to auxiliary ports, instrument platform stations
DGWF	20 arcmin	Direct Gregorian wide-field focus

Structural assemblies

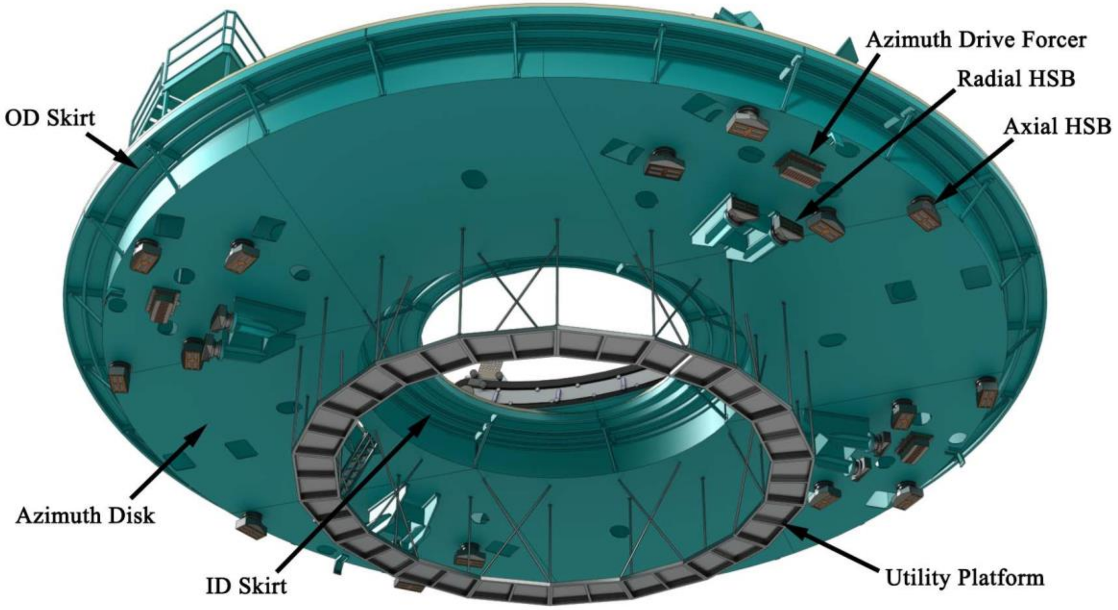


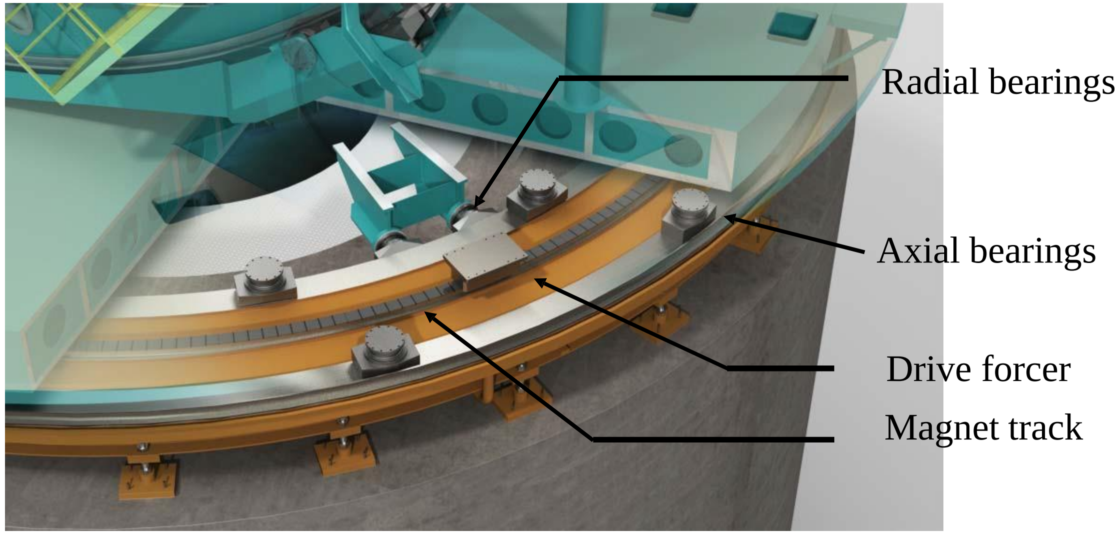
Elevation Bearings & Drives



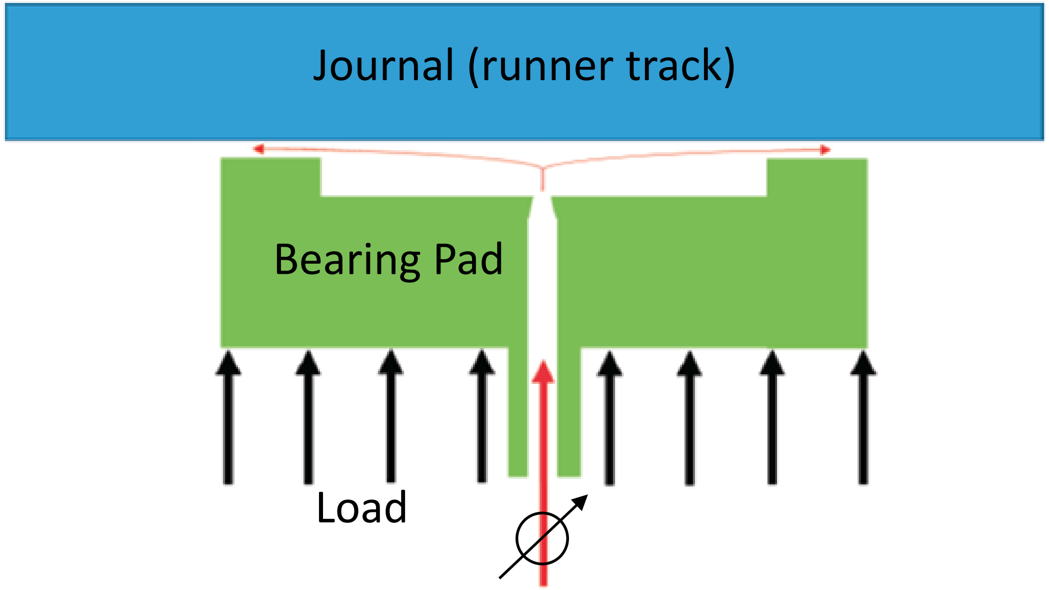


Azimuth Bearings and Drives

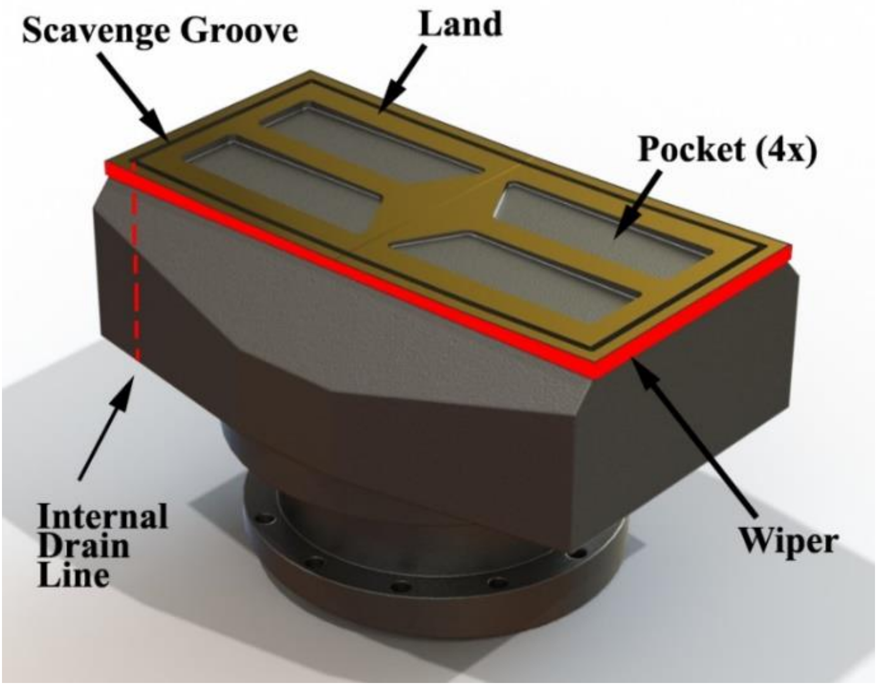




Hyrdrostatic Bearing Concept



High-pressure Oil



Articulating Four-pocket hydrostatic bearing

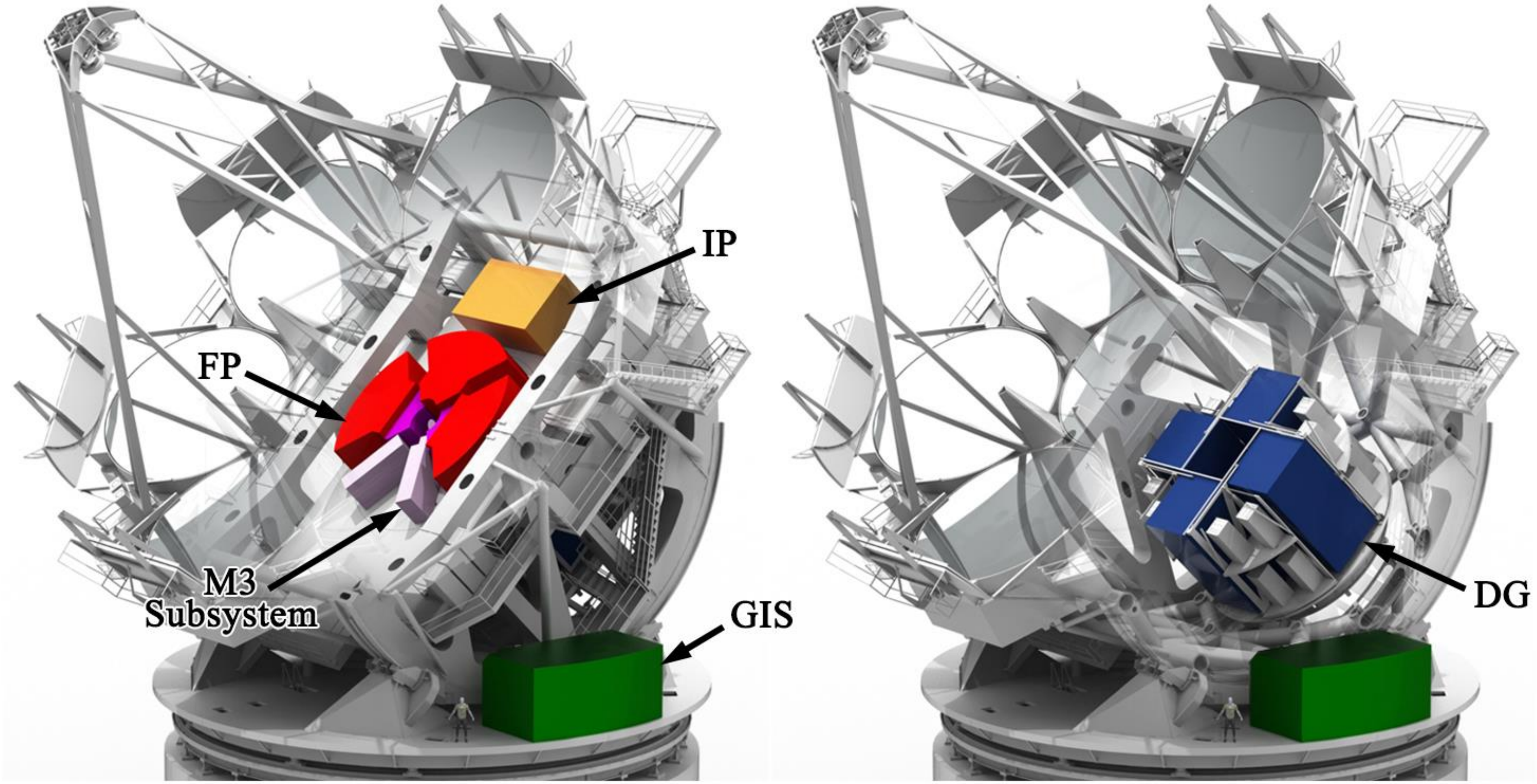
High pressure oil is injected into the pocket at a **fixed flow** rate set by a flow control valve, capillary, or orifice.

Pressure in the pocket lifts the structure until increased flow in the gap between the bearing pad and runner reduces the pocket pressure to just what is needed to support the weight.

The bearing can then slide frictionlessly on the oil film.

Multiple pockets provide stability against tilt.

GMT Instrument mounting



- Most GMT instruments will mount below the primary mirror at the Gregorian or Folded Gregorian Ports.
- The ports are mounted on an internal rotator that compensates for field rotation.
- Direct Gregorian instruments are shuttled into position on-axis avoiding the need for an additional fold mirror.
- Service platforms are fixed to the elevation structure. Access to the instruments is restricted with the telescope pointed off-zenith.
- A gravity invariant instrument mounting location is provided on the azimuth turntable for a fiber fed spectrograph.
- A Nasmyth platform is not provided.

FP : Gregorian Folded Port

IP : FP Instrument access Platform

DG: Direct Gregorian instrument carousel

GIS: Gravity Invariant Station on Azimuth Disk

Discussion

- Fast optical systems reduce the telescope size with gains in structure performance and reduced cost.
- Gregorian vs Cassegrain
  - "Coma-free" aplanatic optical configurations provide wider fields of view compared with parabolic primary mirror configurations.
  - Three mirror configurations can provide wider fields of view at the cost of additional reflections.
- Telescopes larger than ~8 m require a segmented primary mirror.
  - Large-segment primaries are probably not practical above ~25 m.
- Small segments (1.5m) have a 0.4 arc-sec diffraction limit at 1 µm. Segments must be phased to deliver images that take advantage of the best seeing.
  - Subaperture image stacking is sufficient for seeing-limited operation with large segments.

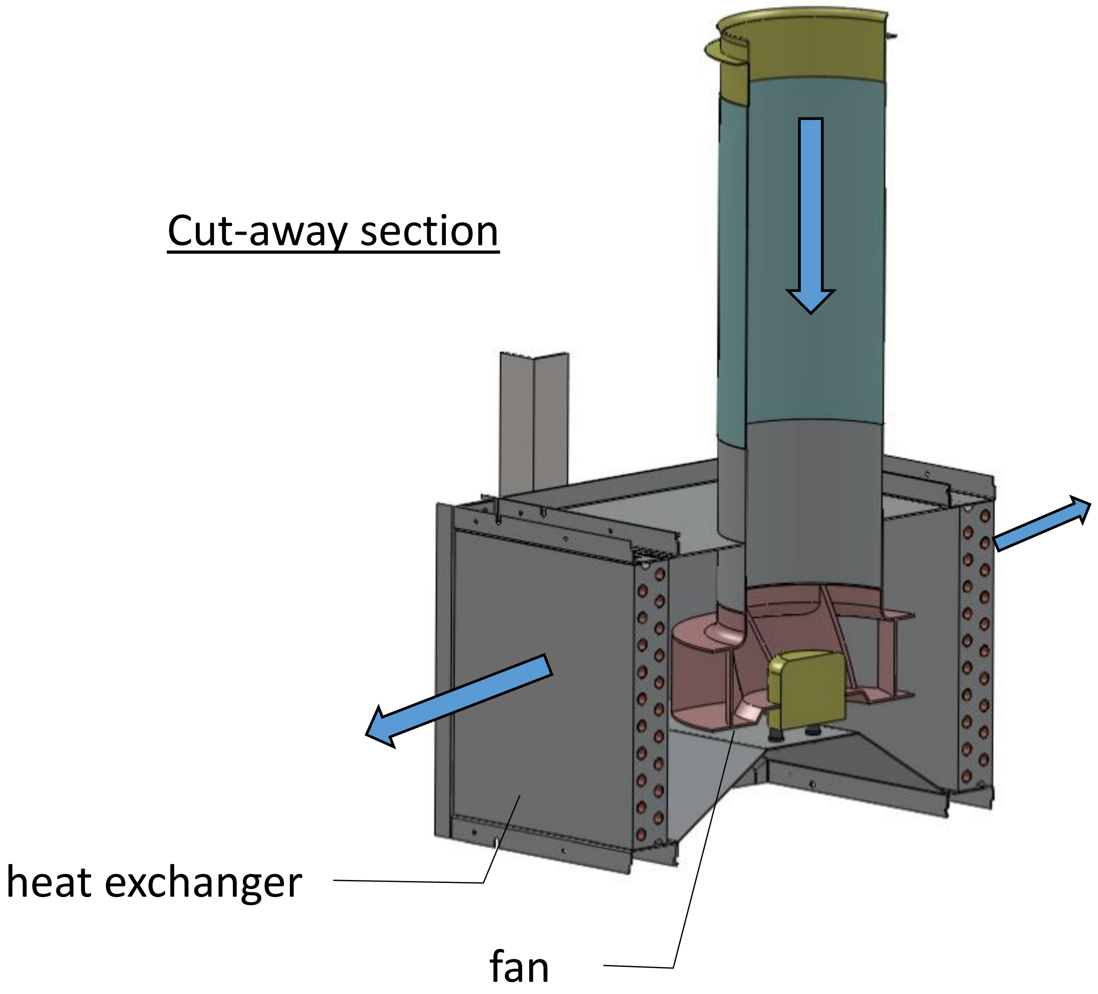
Discussion

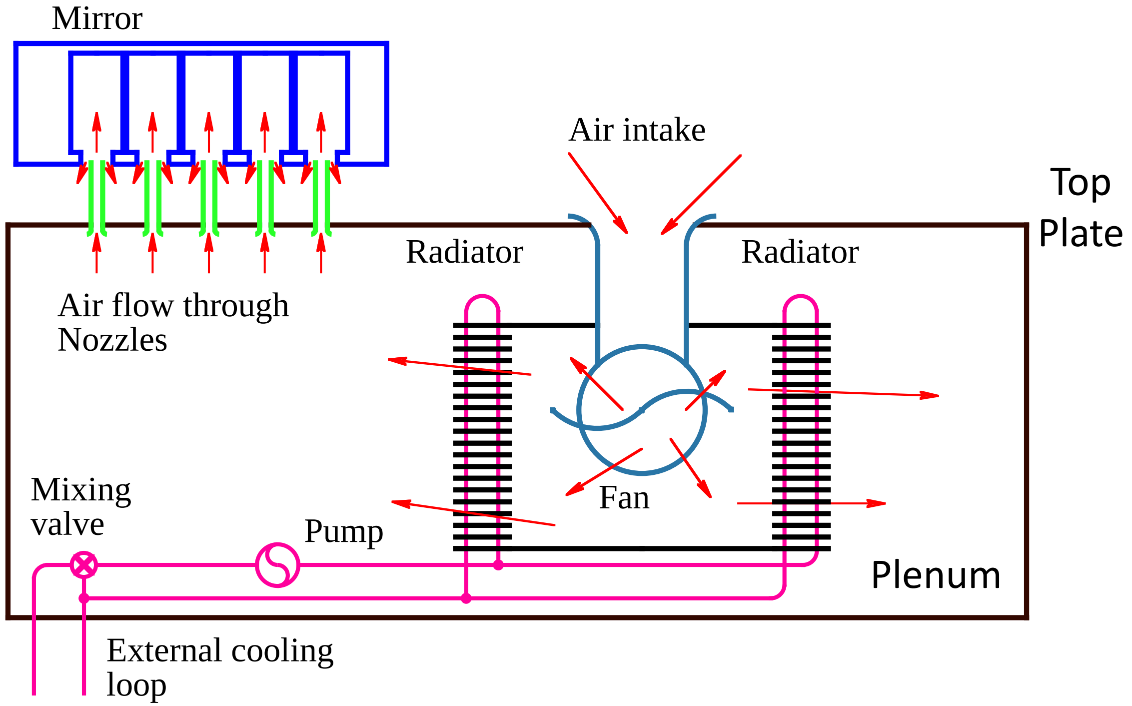
- Meniscus and small segment mirrors can be made of ultra-low expansion material (ULE, Zerodur, Clear-Z). Cast borosilicate mirrors are subject to thermal distortion requiring ventilation and active supports to compensate.
- Ventilated honeycomb mirrors are better at controlling mirror seeing due to thinner cross sections and thermal control.
- Honeycomb mirrors are stiffer than meniscus types and require less precise supports for figure control and resistance to wind disturbance.
- Mirror coating type affects both telescope optical throughput and emissivity.
- More reflections mean lower throughput.
- Well-developed equipment and procedures are required for maintaining the coatings. This is significant part of telescope operations.
- Nasmyth provides a flexible and gravity stable instrument platform but results in a significantly wider telescope structure and puts constraints on the optical design as we'll see when we discuss the results of the student optical design exercise.
- Instruments mounted within the telescope structure such as on GMT will have limited service access with the telescope pointed off-zenith.

End of session 3

Backup slides

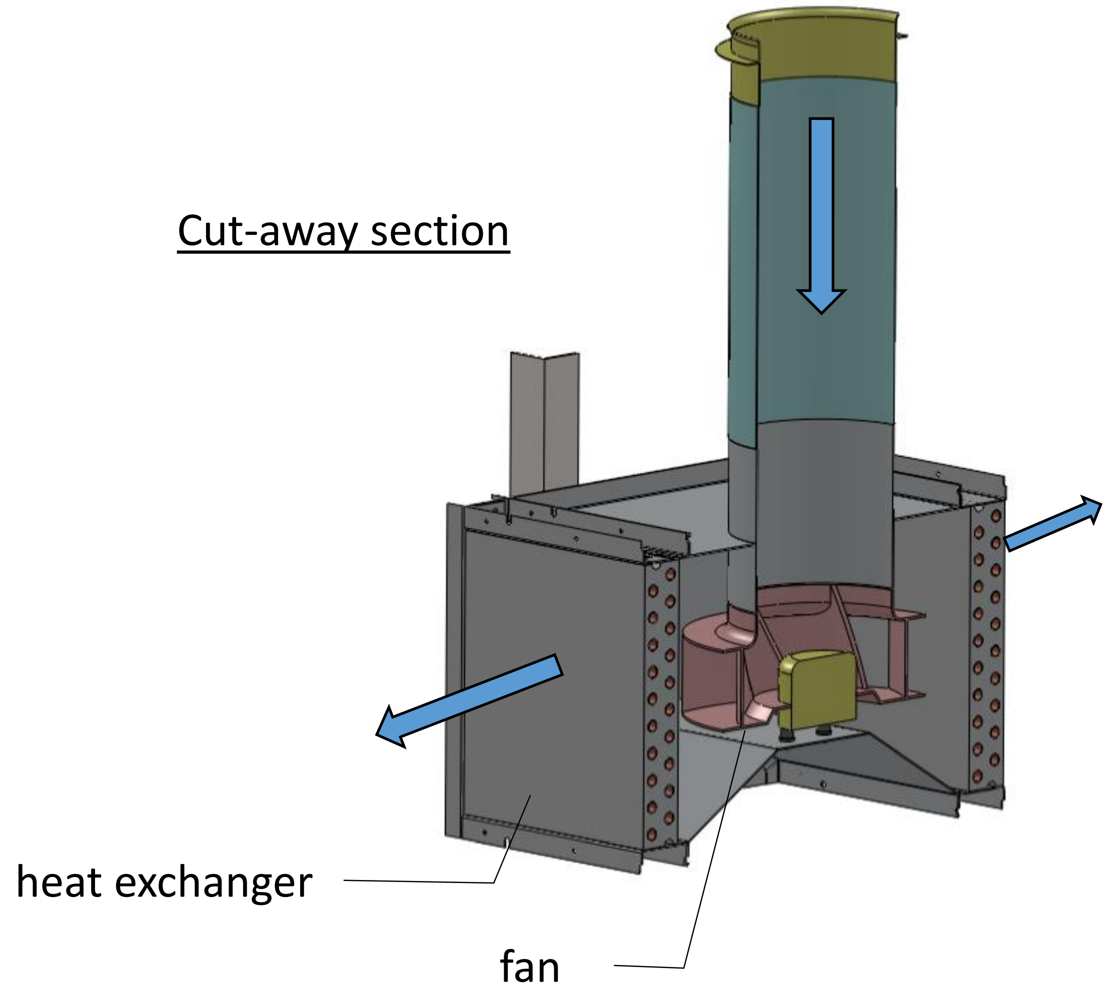
GMT M1 Thermal Control





- Ventilators draw air down from above the top plate pressurizing the lower plenum.
- Air temperature is controlled by passing it through a liquid cooled heat exchanger box.
- High-velocity air is injected into the honeycomb cells in the mirror by nozzles in the top plate at 8 l/s/cell.

Thermal Performance



- Steady state thermal primary mirror equilibrium: $dT_{m1} = \tau_{M1} \times dT_{ambient}/dt$ where τ_{M1} is the 1/e mirror thermal settling time.
- For conventional non-ventilated mirrors τ_{M1} is long compared with the rate of nightly temperature variations on typical sites.
- Actively ventilated structured mirrors:
  - Magellan τ_{M1} = 60 minutes
  - GMT (design) τ_{M1} = 40 minutes