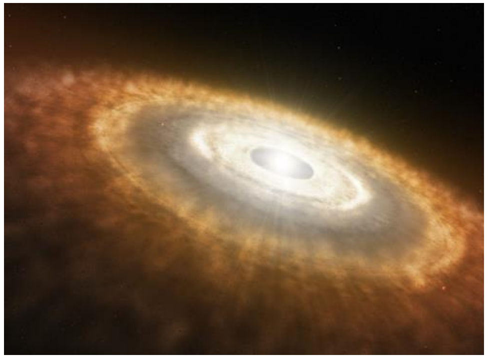
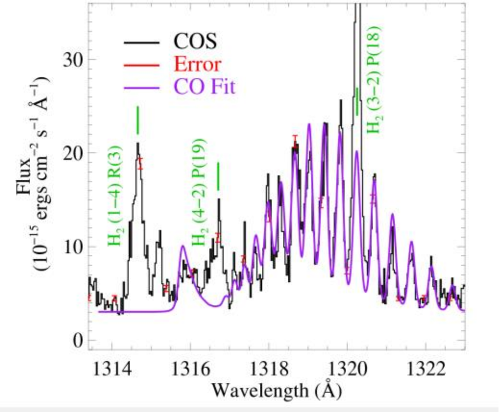
Notional Telescope Design for 10meter LUVOIR Mission

J. Scott Knight
Ball Aerospace
Mission Systems Engineering

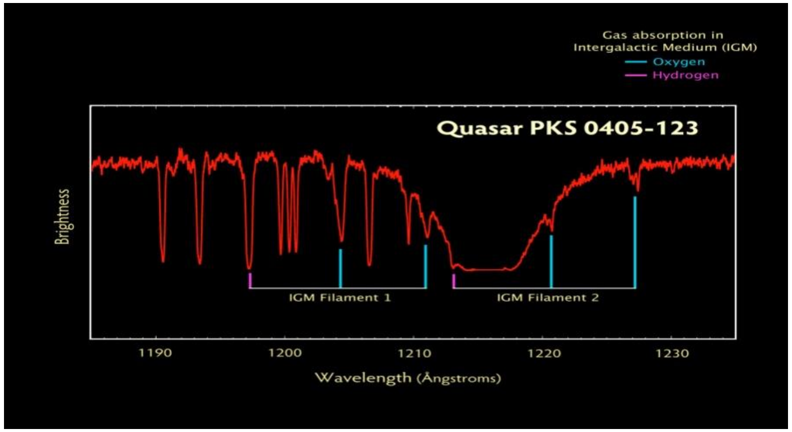
A UV-Optical flagship will address major science themes for NASA's Astrophysics Division

Exoplanets and circumstellar disks

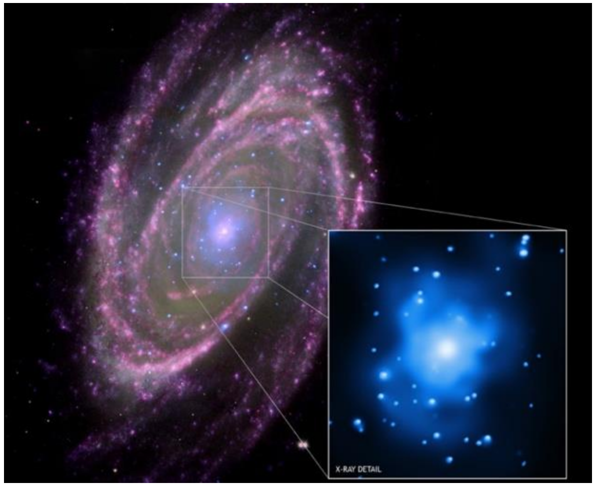




Structure and composition of the Intergalactic and Circum-Galactic Medium



Gravitationally lensed high redshift galaxies



Stellar populations, Galaxies, AGN, Quasars, black holes

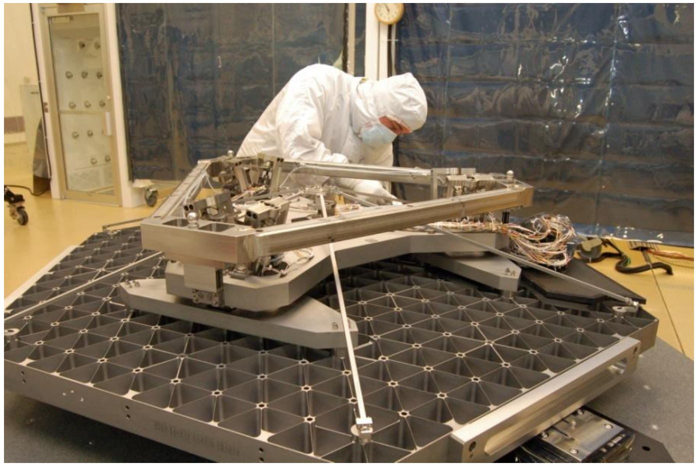
Images Credit: NASA

A large primary aperture enables both high sensitivity and fine spatial resolution

- If larger than practical for a monolith it requires segmentation
- If larger than launch vehicle fairing it requires deployment or assembly
- The full benefits of large size also require stability, precise alignment, precise pointing control
- These issues were resolved for JWST operating in IR. UV-optical solutions may need different approaches, or at least higher precision performance.
- High-contrast Imaging will drive many of the requirements.

Segments should be a net simplification to the system

- Size & shape
- Total number
- Materials
- Manufacturing flow
- Test approach
- Facilities
- Schedule
- Cost

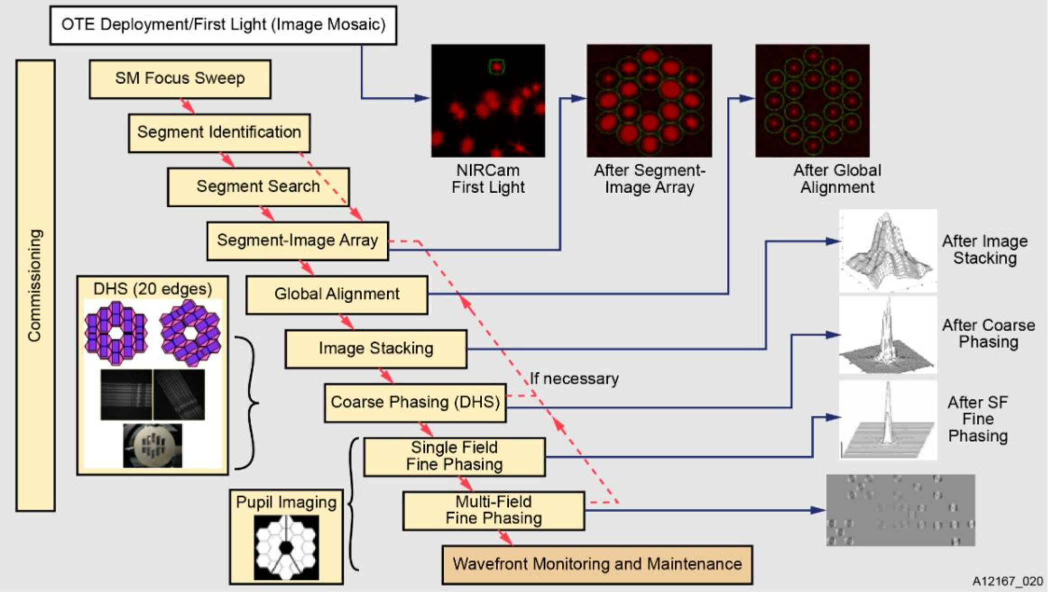


- Control authority
- Sensors
- Actuators
- Structures
- Complexity, reliability

Segmented architecture and control systems make verification and I&T easier/possible

Wavefront Sensing and Control enables precise image quality and Phasing of Primary

JWST Sequence

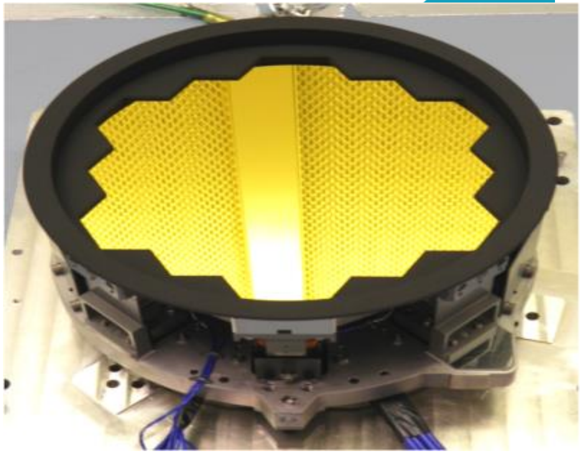


- Angular resolution of large diameter telescope
- Stability for coronagraph
- Symmetry for gravitational lensing
- Uniformity of PSF over FOV

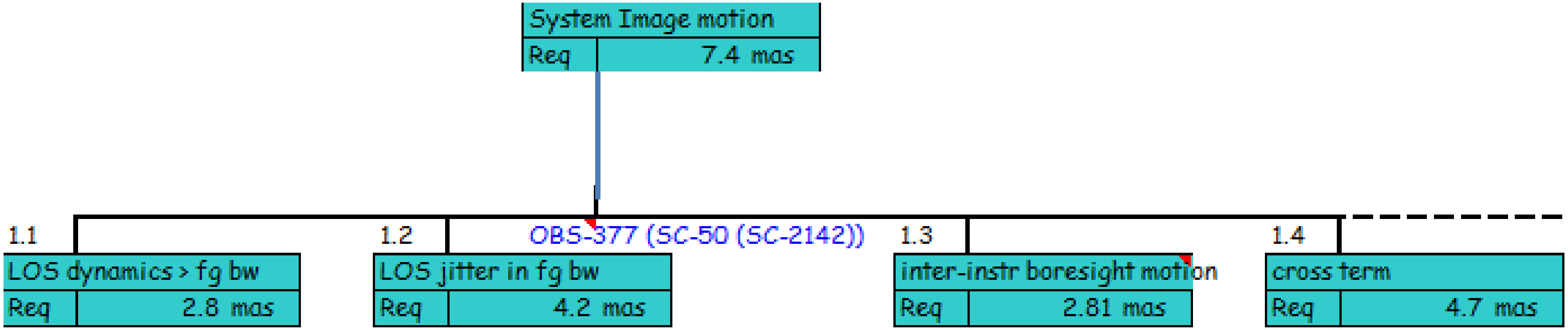
- System architecture
- WF Sensing instrumentation
- Signal processing algorithms
- **Actuators**
- **Range and resolution**
- **Update Rate**
- **Real time & autonomous**
- Interaction with thermal, pointing etc.

Fine guidance and jitter control prevents smearing of the images

- For D=10m and λ=500nm, λ/D=10mas
- Drift & Jitter must be a small fraction of this
- Separate Guidance Sensors, HST, JWST, WFIRST Coronagraph
- Or, Guide signal on science focal plane, Kepler,
- Body-point entire observatory, or payload
- and use a Fine Steering Mirror
- Interactions with structural, thermal, pointing and WFC subsystems



JWST Fine Steering Mirror with 24 Hz bandwidth and 16 mas resolution. UV-VIS FSM will need ~< 0.1mas resolution, higher bandwidth and wider range.



System Image motion
Req 7.4 mas

OBS-377 (SC-50 (SC-2142))

1.1 LOS dynamics > fg bw
Req 2.8 mas

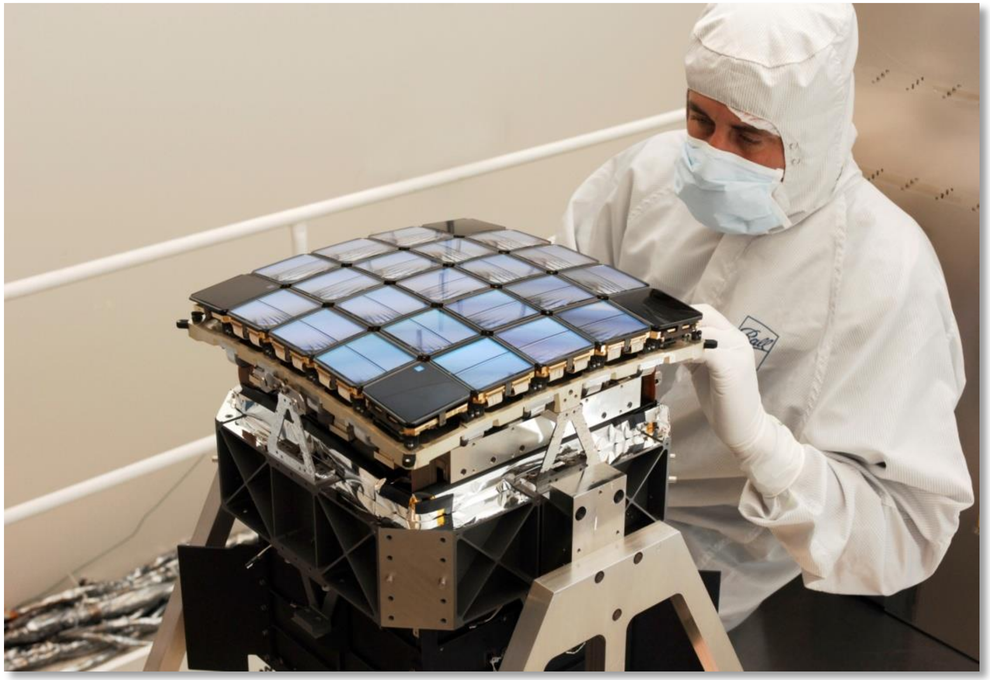
1.2 LOS jitter in fg bw
Req 4.2 mas

1.3 inter-instr boresight motion
Req 2.81 mas

1.4 cross term
Req 4.7 mas

Large Focal Plane Arrays will be needed for resolution and FOV

- If 10 mas pixels
  - 1 Gpx = 32K x 32K
  - 5.3 arcmin FOV
- Detector technologies
  - Modules
  - FPA architecture
- Alignment
  - Electronics, Cables
  - Mass, Volume, Power
  - Thermal
- Data rate and volume
- Serviceability, replacement



The Kepler Focal Plane Array
42 1K x 2K CCDs in 21 modules
4 CCDs for fine guidance
Curved Schmidt focal surface

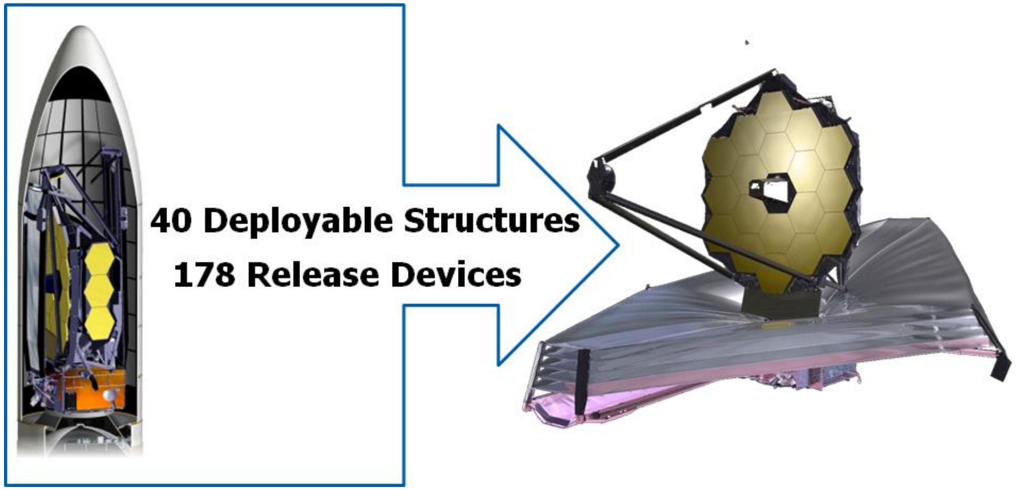
There are good reasons to consider in-space servicing

- Replacement of limited-lifetime items
- Replenishment of expendables
- Restoration of degraded or failed components
- Infusion of advanced technologies
- New generations of instruments, capabilities
- Extension of mission lifetime

DARPA's Orbital Express mission demonstrated proximity operations, autonomous rendezvous & soft capture, removal and installation of ORUs, fluid transfer.

We want a much longer lifetime
Is it better to design for 30 years or Service every 5?

JWST Observatory Launch



40 Deployable Structures

178 Release Devices

- To fit into the Ariane V launch vehicle, JWST must be folded into a smaller package and then deployed after launch.
- Several major subsystems deploy during the 30-day transit to orbit
  - Solar Arrays
  - High-gain Antenna
  - Sunshield
  - Deployable Tower
  - Secondary Mirror
  - Primary Mirror Wings
- Advances in Deployable technology should be considered for larger, complex missions.

JWST is the closest Space Telescope Analog for Segmented LUVOIR

- JWST has design heritage to Keck and ground based-segmented telescopes
- LUVOIR would utilize JWST and ground-based (GMTO, TMT, ELT) segmented technologies

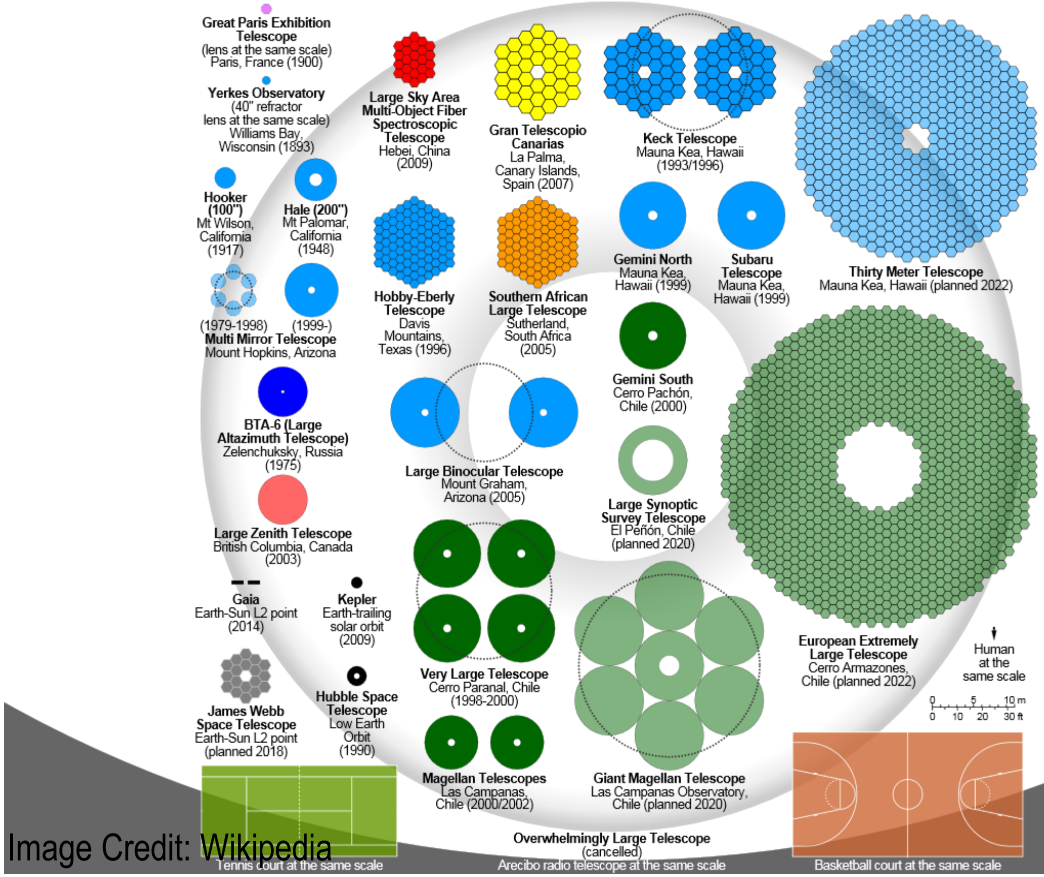
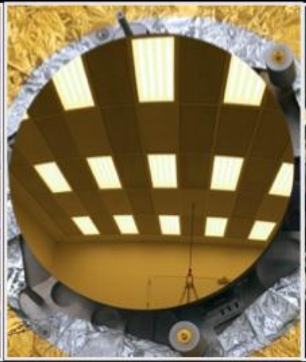


Image Credit: Wikipedia

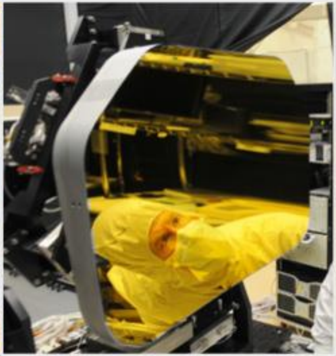
JWST Telescope Mirrors

Primary Mirror Segment

Secondary Mirror

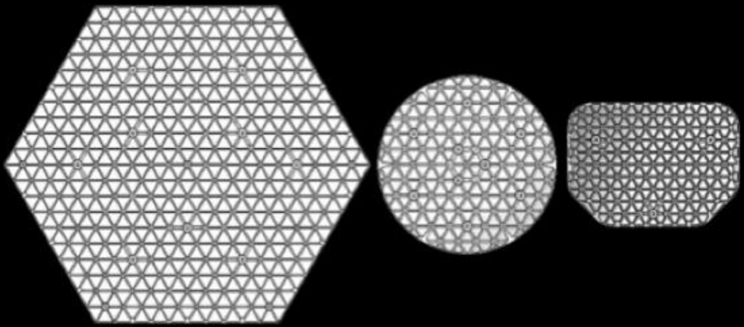


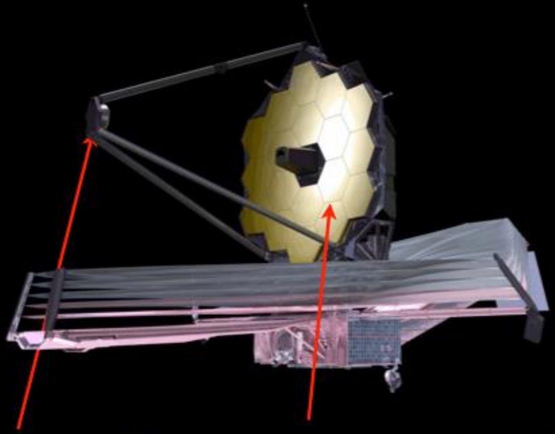
Tertiary Mirror



Fine Steering Mirror

Rear side view of mirrors showing relative size

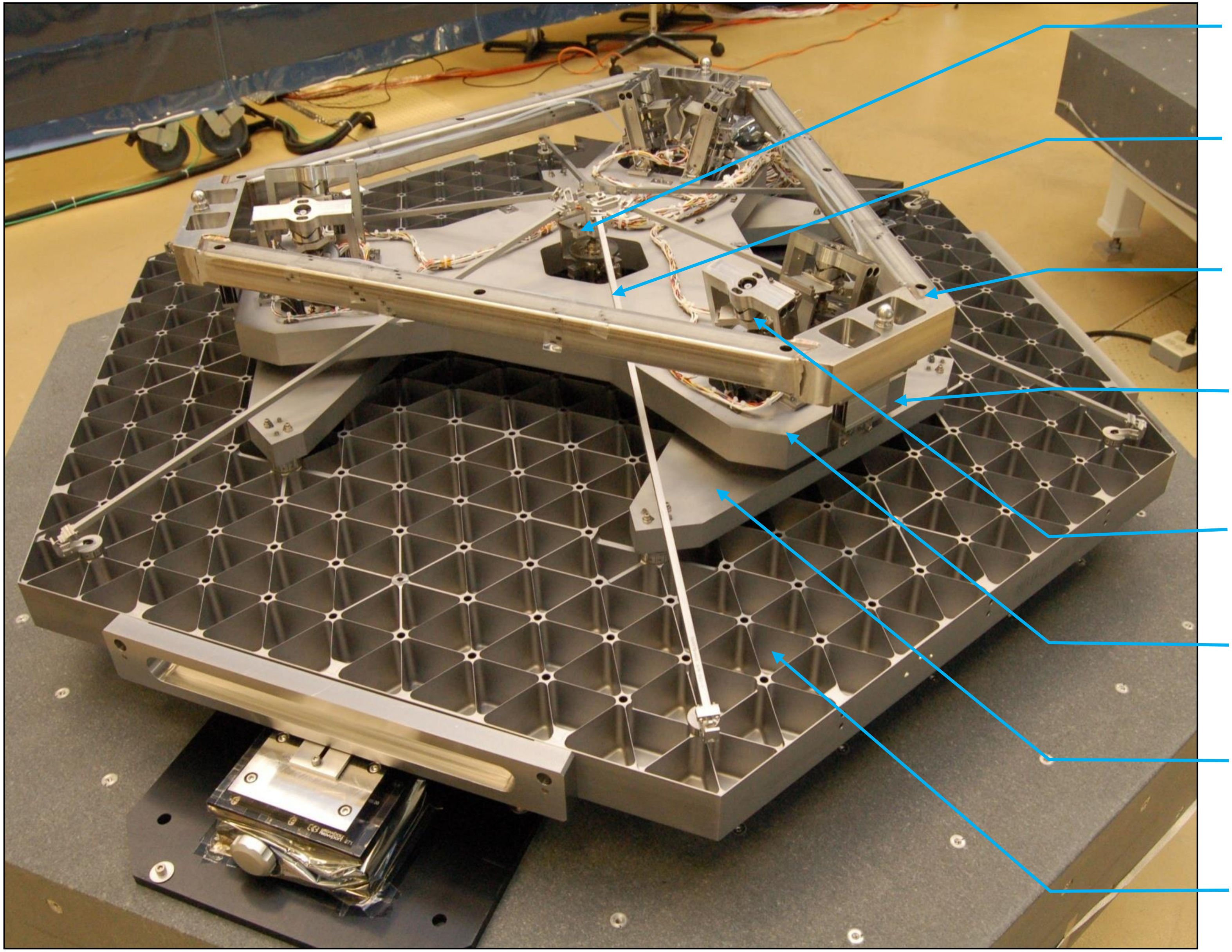




Secondary Mirror

18 segment Primary Mirror

Anatomy of a JWST Primary Mirror Assembly



ROC Actuator

Beryllium ROC Strut (6 pl)

GSE Handling Ring

Backplane Interface Flexure (3 pl)

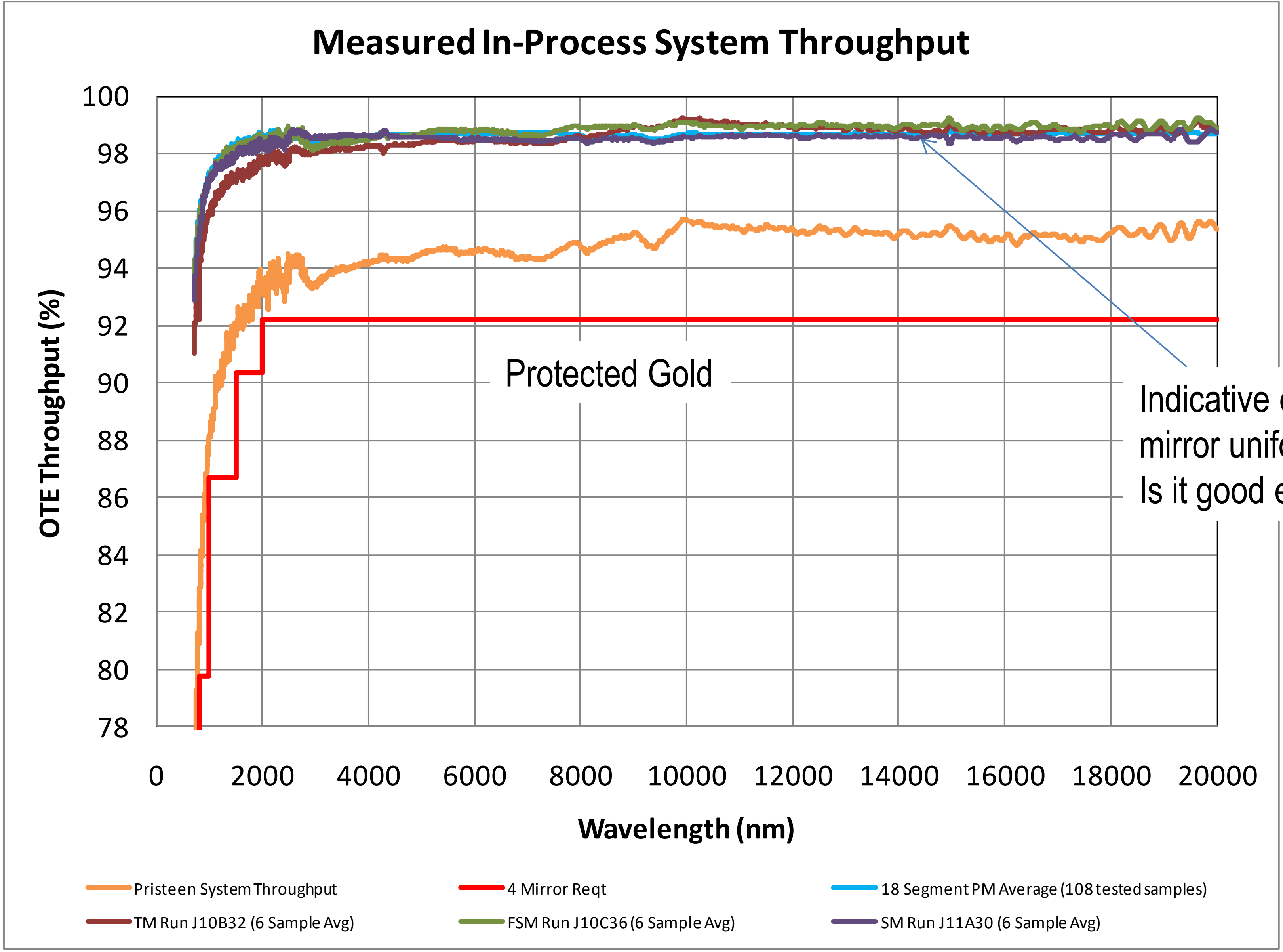
6 DOF Actuators (3 bipods)

Beryllium Delta Frame

Beryllium Whiffle (3 pl)

Beryllium Mirror Substrate

JWST OTE Reflectivity Performance



Indicative of mirror to mirror uniformity

Is it good enough?

JWST Final Segment Surface Requirements certified at Cryo temperatures

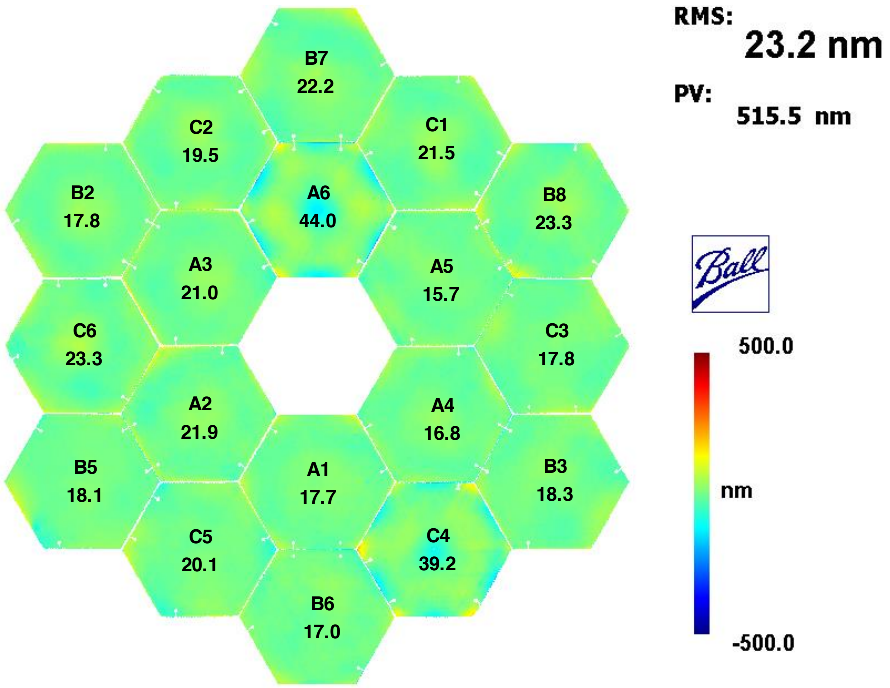
Parameter	Specification	Tolerance	Units	Comments
Requirements for final acceptance testing				
Clear Aperture	*	Minimum	mm^2	*Different for 3 segment types (approx 5 mm from edge)
Conic Constant	-0.99666	+/- 0.0005		
Global Radius of Curvature		+/- 1	mm	
Radius of Curvature Segment to Segment Matching	*	+/- 0.15	mm	*All segments are matched to a single radius value within the global RoC
Prescription Alignment				
Decenter	*	≤ 0.80	mm	* Different for 3 segment types
Clocking	0	≤ 0.65	mrad	
Total Surface Figure Error:				
Total Surface (≥0.08 mm/cycle)	25.8	Maximum	nm rms	Relative to cryo-target map
High Frequency (222 to 0.08mm/cycle)	13	Maximum	nm rms	Relative to cryo-target map
PSD Spike Requirement	3	Maximum	nm rms	Single Frequency Contribution

- These Specs would have to be tightened up considerably for System WFE.
    - Material choice and polishing time
    - Ambient operation is much easier
- Segmentation does allow correction and compensation of many system AI&T, Launch, etc. issues.

Active Architectures allow "Mechanical alignment tolerance on the ground, optical alignment on orbit".

JWST Composite PM Cryogenic Total Surface Figure

Requirement = 25.8 nm rms
Total Measurement + Uncertainty = 25.0 nm rms



Photograph Credit: NASA

- These numbers represent mirrors meeting spec, not necessarily state-of-the-art.
- There are limits to Beryllium Mirrors but mostly polishing time
- Edge polishing requirement not significant for JWST ~5 mm avg specified.
- Mirror Gap is ~7 mm.

1st order LUVOIR Telescope Design Parameters

- Package: TBD (overall Volume)
- General Class Observatory
  - Narrow FOV = UV/Coronagraph
  - Wide FOV = General UV, Visible,IR Imaging and Spectroscopy
- Design 1:
  - Traditional TMA
  - Circular FOV capability vs. complexity
  - Obscuration ≤ 15% linear
- Design 2:
  - Spherical primary, investigate feasibility of slower net FNO using microscope objective for stage 2 (similar to Hobby-Eberly)
- Design 3:
  - Traditional TMA, relax obscuration constraint
  - Evaluate RMSWFE vs. FOV and optics complexity

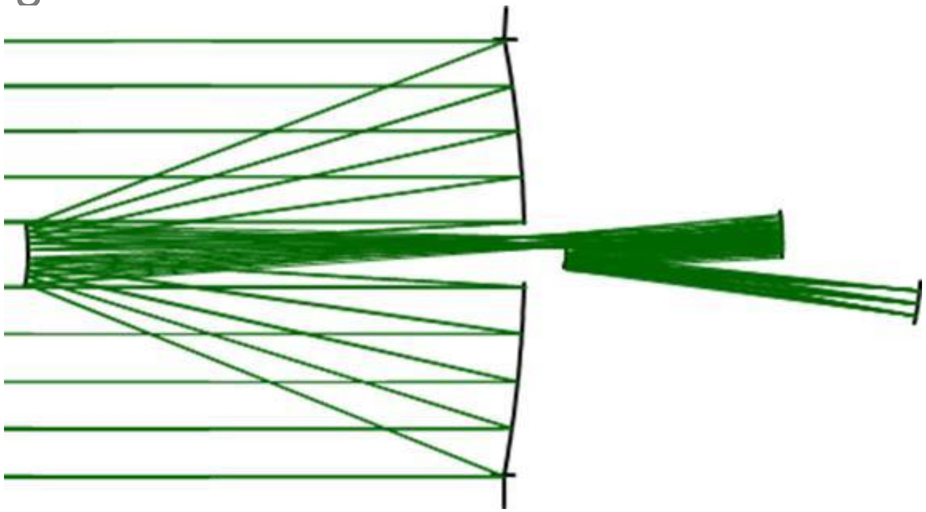
LUVOIR Telescope Notional Design

Assume 10 m, on-axis aperture

- Minimize central obscuration
  - Coronagraph and throughput considerations
- Create large FOV with small design residual
  - 10-20 arcmin
  - Maximize Instrument Packaging and Science
- Have accessible intermediate focus
  - UV/Coronagraph Throughput
- Pupil /Field Distortion and Pupil Wander not yet know or constrained
  - JWST Design Driver
- Telescope Final F#/Effective Focal Length not yet chosen
  - Assume desired is 10<F#<24
  - Impacts instrument design complexity
- Primary Mirror ~F# 1.5
  - Polarization effects for faster Primary Mirror
- Overall WFE
  - Diffraction limited at 500 nm (35 nm rms)
- Try to hold design residual to 16 nm rms
  - This is a large fraction of total WFE 20% of budget
  - JWST is 1.5%

Design 1A: Traditional TMA, 15% obscuration

- PM-SM conic only
- PM ~F/1.3, PM-SM length ~11m
- No distortion constraint, curved image
- Holding F/20 (prefers slower)
- FOV results
  - Simple Design: ~8arcmin
  - Complex Design 1: ~10arcmin
  - Complex Design 2: ~10.5arcmin

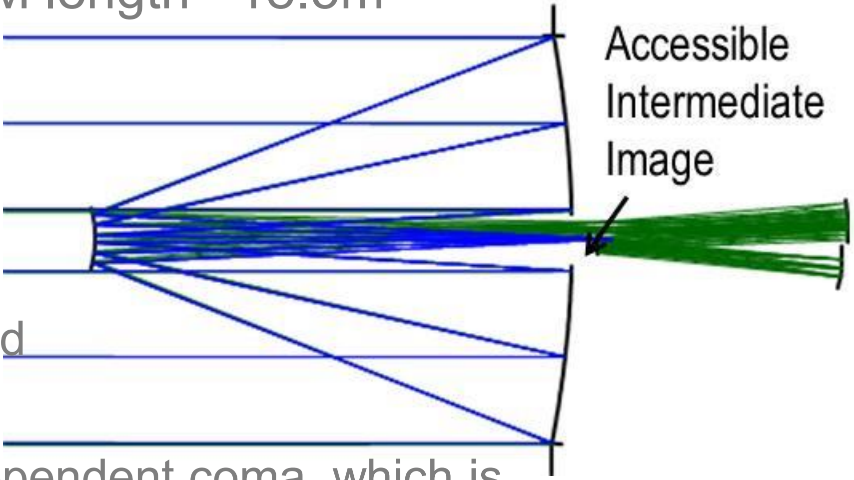


Aspheric TM, 10’ FOV, with fold/FSM

Small Central Obscuration limits WFOV with small design residual

Design 1B: Traditional TMA, 15% obscuration, intermediate image constrained

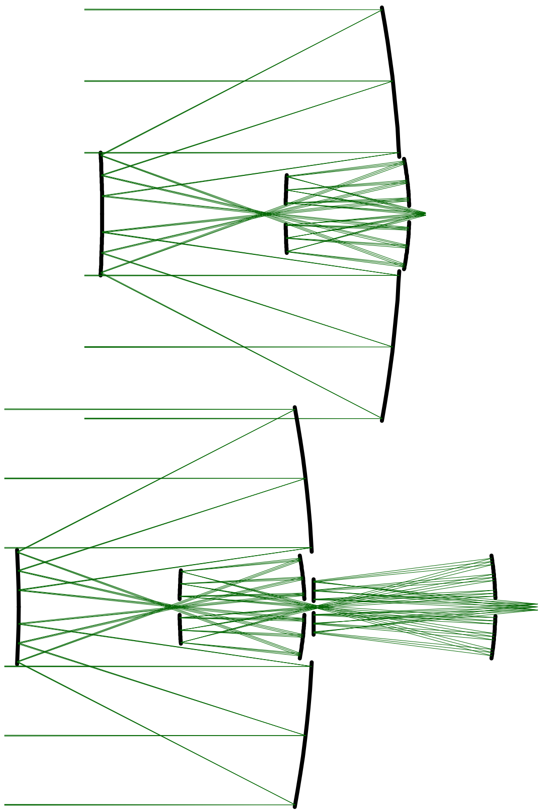
- Traditional TMA, Constrain intermediate image quality
- PM ~F/1.33, PM-SM length ~11.7m, SM-TM length ~18.5m
- No distortion constraint, curved image
- 8arcmin circular WFOV, F/18
  - RMSWFE ≤ 14nm (~16% total budget)
- Intermediate FOV, 10arcsec circular
  - RMSWFE 1.3nm on-axis, 17nm edge of field
  - RMSSPD 0.5μm on-axis, 5μm edge of field
  - Limiting aberration is predominantly field dependent coma, which is predictable and correctable with single lens or as part of coronagraph design
  - UV/Coronagraph FOV is on-axis to PM-SM, outside of WFOV
- Results are roughly consistent with 12m ATLAST design.



Constraining Intermediate Image reduces FOV.
With a small obscuration, a traditional TMA is long.

Design 2: Spherical PM

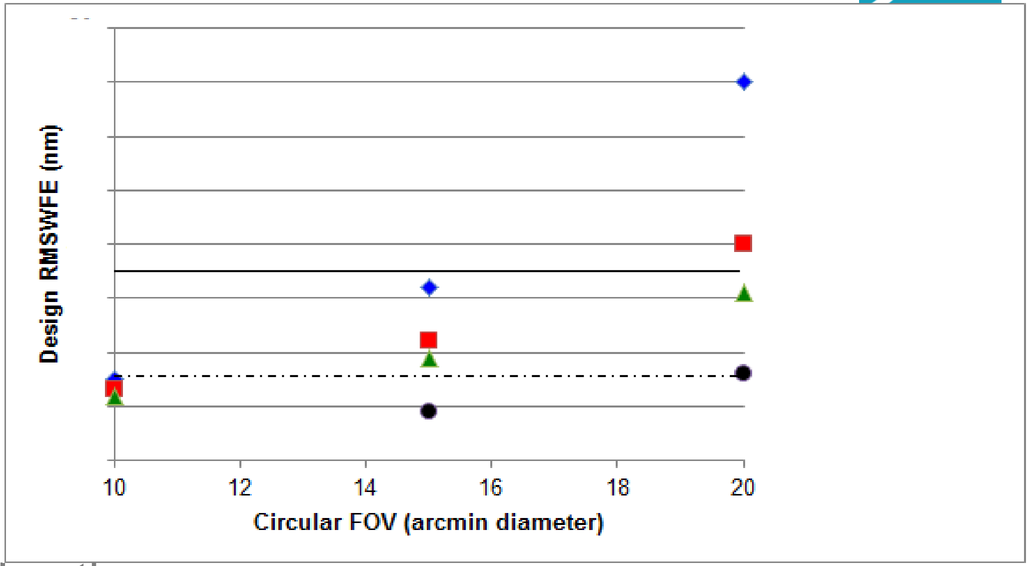
- Includes SM to enable space vehicle packaging
- 10m, 10arcmin circular FOV, 30% linear obscuration
- Aspheric SM
- PM F/1.2, PM-SM length 8.5m
- 2 aspheric mirror concave cavity relay, final F# F/2.2
- Design RMSWFE 10nm, curved image

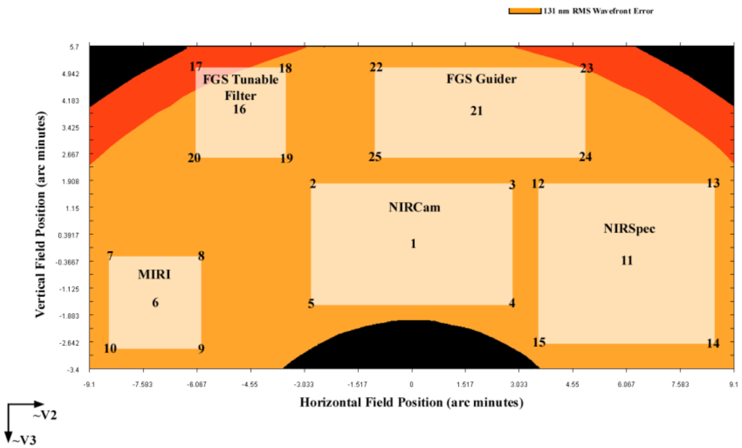


Hard to get a Spherical Primary to Work with small obscuration and slow system.

Design 3: Relax obscuration, FOV/Complexity

- Constraint set
  - No slower than F/20
  - No distortion or pupil constraints
- Aft optics complexity options
  - 1) Conics
  - 2) More complex
- Conclusions
  - 10-12arcmin FOV with traditional optics
  - 20arcmin FOV possible with complex optics
  - Obscuration ends up ~21% linear
- How big is the needed FOV?

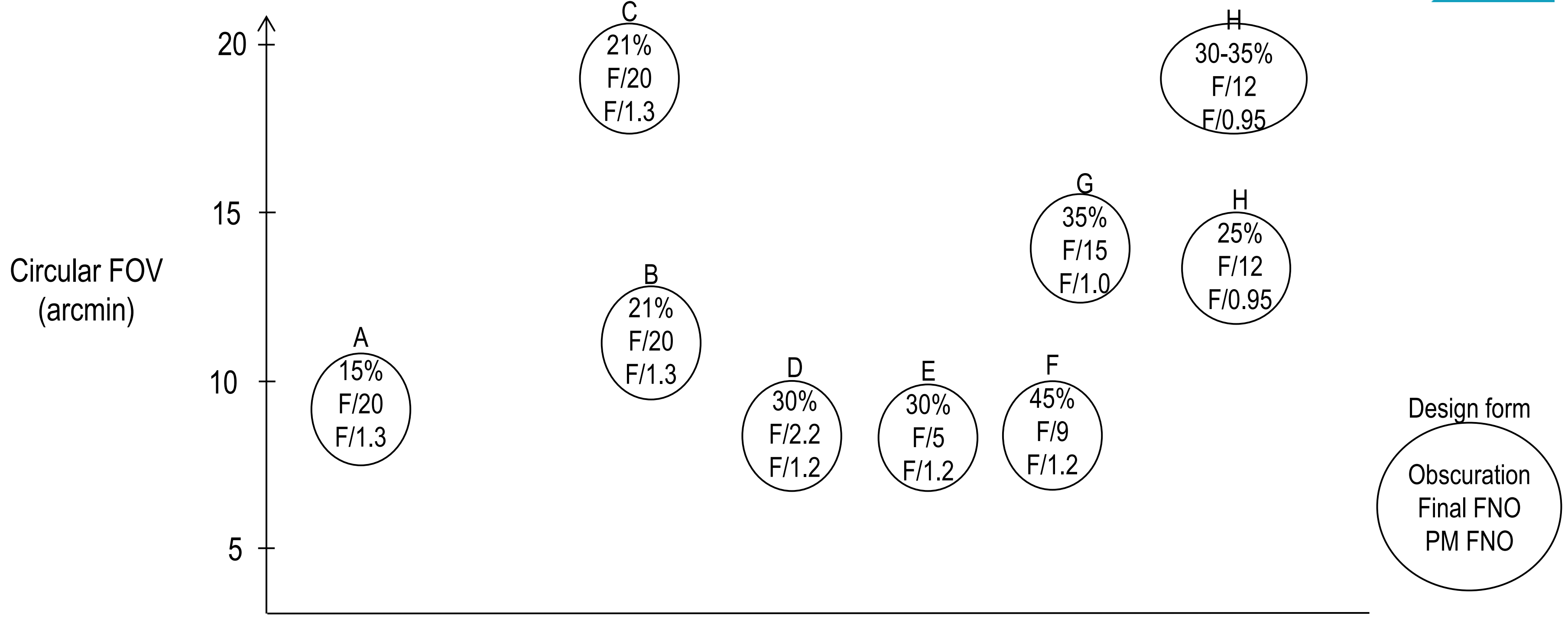




18arcminx9 arcmin

Opening up Central Obscuration opens up design space.

FOV-Obscuration-FNO with design residual constrained



A: Traditional TMA, 8-10.5arcmin
B: Complex 1 TMA, 10-12arcmin
C: Complex 2TMA , 20 arcmin
D: Spherical PM, Corrector 1
E: Spherical PM & SM, Corrector 2
F: Spherical PM & SM, Corrector 3
G: Alternative Design1
H: Alternative Design 2

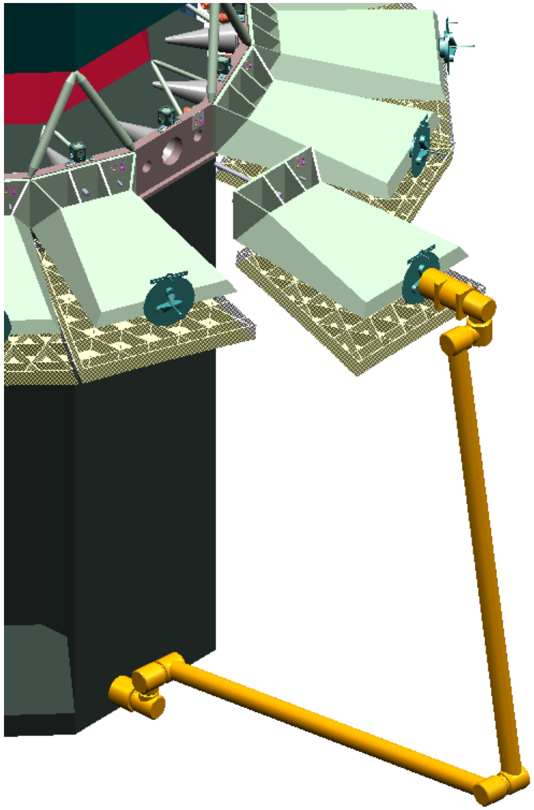
- Most designs that have a large FOV, require a TMA.
- TMA designs prefer faster PM than F#1.5.
- Larger central obscuration and more complex optics allow a larger FOV.

Summary

- A flagship-class UV-optical observatory will be scientifically compelling.
- Scientifically interesting size will require modularity, segmentation, deployment, assembly etc.
- Technologies will be applicable to systems and missions beyond astrophysics.
- JWST has solved many of the basic issues, but UV optical requirements will be more challenging.
  - Stability, Diffraction-limited WFE, Throughput, Polarization, etc.
- Telescope Design is not a given or fully defined for General Purpose and more work is needed.
  - Small Central Obscuration significantly limits design choices and FOV.
  - Is there a pupil constraint?
  - Is there a field distortion constraint?
  - Is there a desired telescope F#?
- There is also an architecture decision between telescope complexity and instrument complexity.
  - TMT has AO systems in each instrument.
  - WFIRST has correcting optic in each instrument.
  - High Contrast Instrument will have control surfaces.

In-space assembly may have advantages for a large(r) system

- Geometry that provides the most efficient packaging for launch is independent of arrangement of components in the assembled telescope
- Service module that provides launch accommodation does not need to be a precise optical bench. It is a rack for storage & transportation
- Structures and mechanisms that provide precise optical alignments in space **do not have to bear launch loads**
- Requirements for deployment of components are allocated to robotic arms instead of distributed to multiple subsystems with hinges, actuators, sensors, latches, etc.



These capabilities have wider applicability

- Other users of large aperture visible light imaging could participate in technology development
  - Earth Science & Solar System science
  - Defense & intelligence applications

- Robotic assembly and servicing
  - Applicable to many large systems, not just telescopes
  - Could assist or be supervised by astronauts

- Modularity allows partnerships with many stakeholders, including other nations

A few other things

- Science instruments and components
  - High Contrast Imaging
  - High resolution imaging (UV/VIS)
  - Integral Field and Multi-object spectroscopy

- Management and transmission of high data volumes
  - High bandwidth Communication (Lasercom?) will be of interest to many future applications
  - Avoid limitations faced by HiRISE, Kepler etc.

- Precise, Formation flying to enable consideration of an external starshade