Space astronomy without barriers – synthesis of several papers written by many

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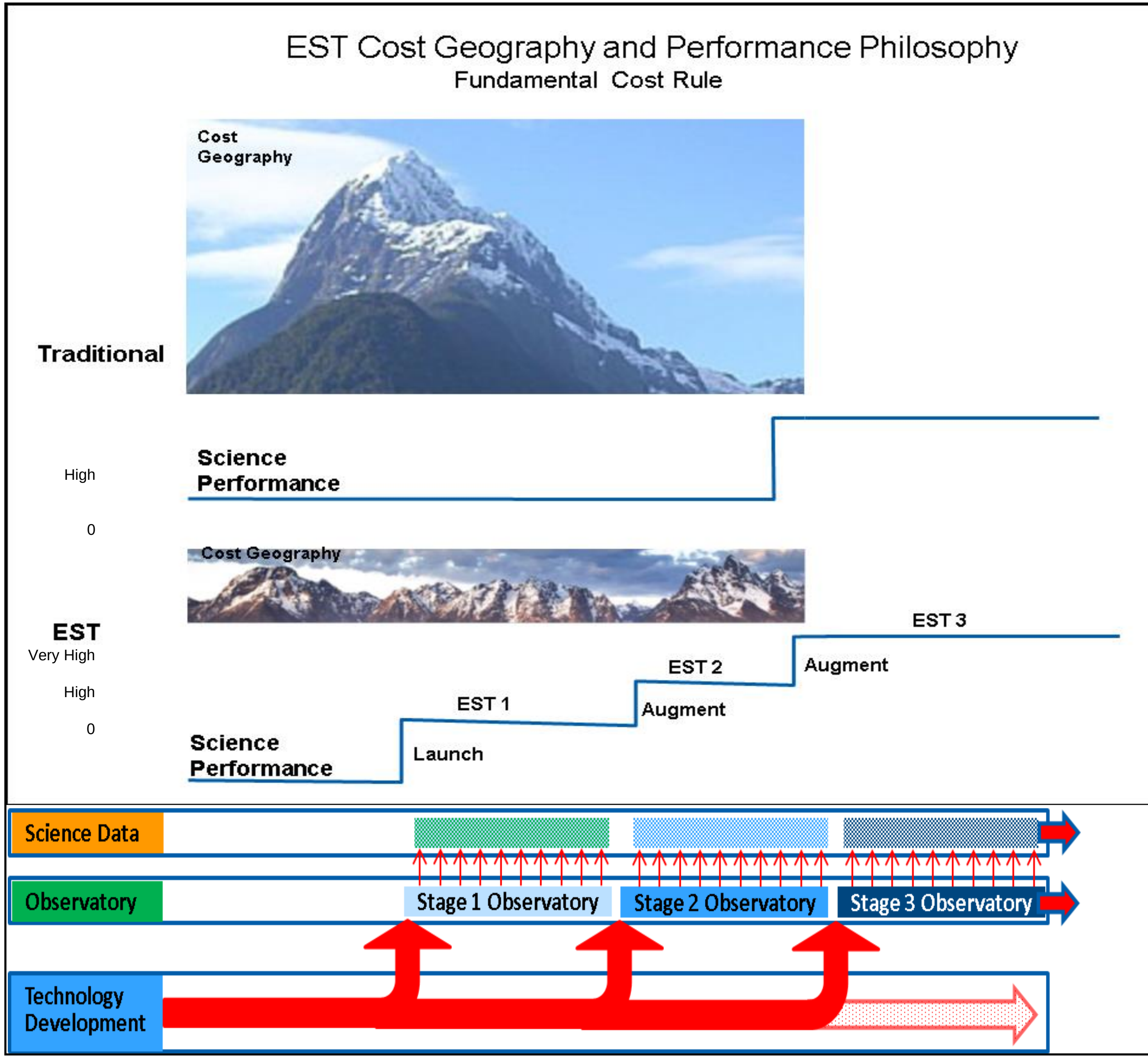
Space astronomy without barriers

- Larger aperture space telescopes & instruments are constrained by
  - Limited volume & mass => many complex mechanisms & large # of reflections & small FOV - One launch => risky & expensive
- **Tomorrow's science will require**
  - **Aperture >20 to 30-m & High transmittance telescopes & instruments**
- Cost awareness
  - No need to "throw-away" the investment in the telescope
  - Revisit observatory to upgrade instruments & telescope components
- **Need break the cost-curve to give more science per $**
  - **The 6.5-m JWST costs ~ $9B**
- **Never happen and "astronomy at the threshold of discovery" is dead!**

An Evolvable Space Telescope Requires a Culture Change

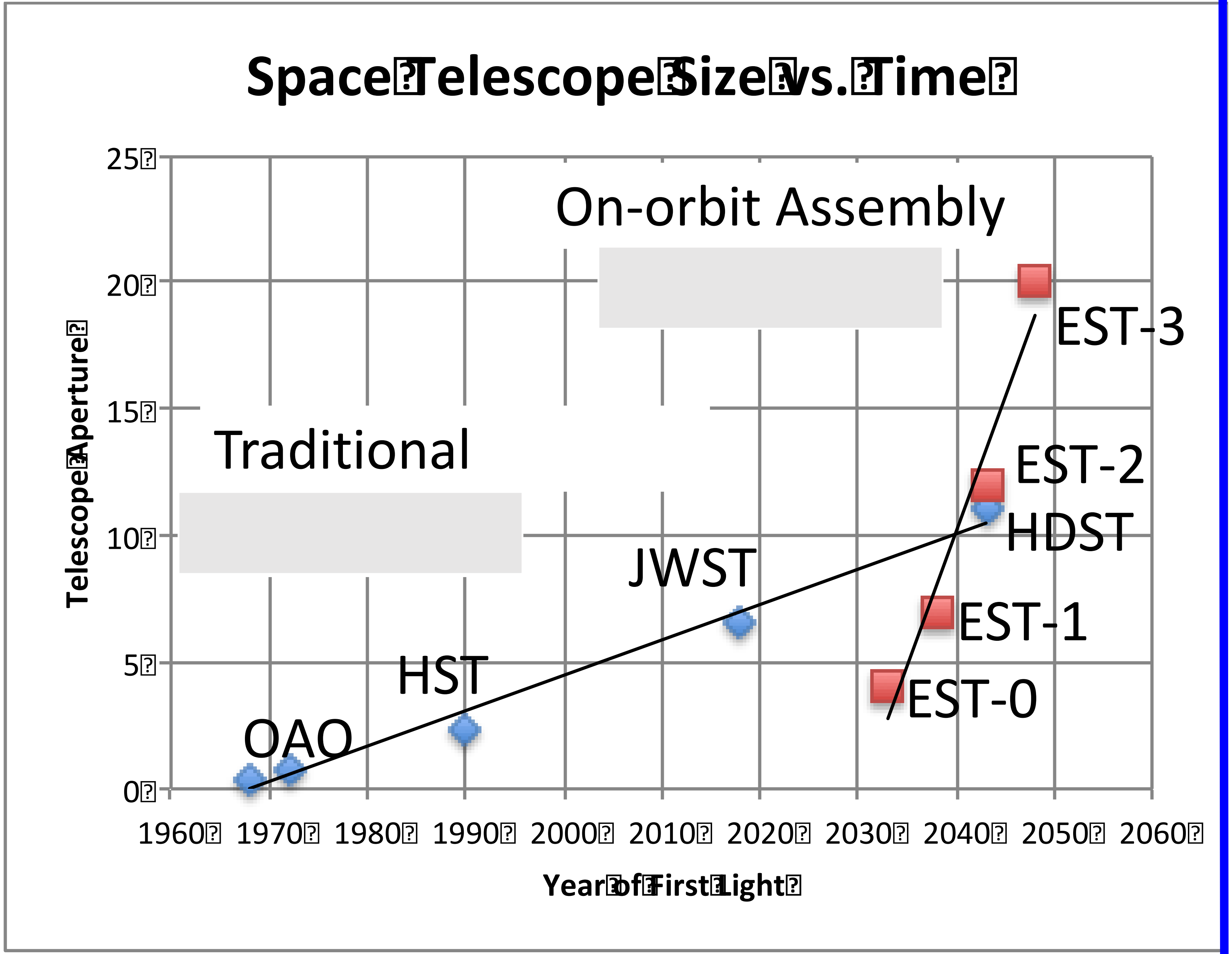
- Commit to a long term program to modulate the large cost/year fluctuations
  - Schedule is dictated by budget realities (can accelerate or decelerate)
- **Grow the in-space performance over time**
  - **Design for aperture, resolution, science scope to evolve with time**
  - **Improve/advance instruments with on-orbit replacement**
- Benefits:
  - – Much earlier science return
  - – On-orbit replacement of instruments and support hardware to adapt to evolving science and technology



Mountain Images from open source public domain.

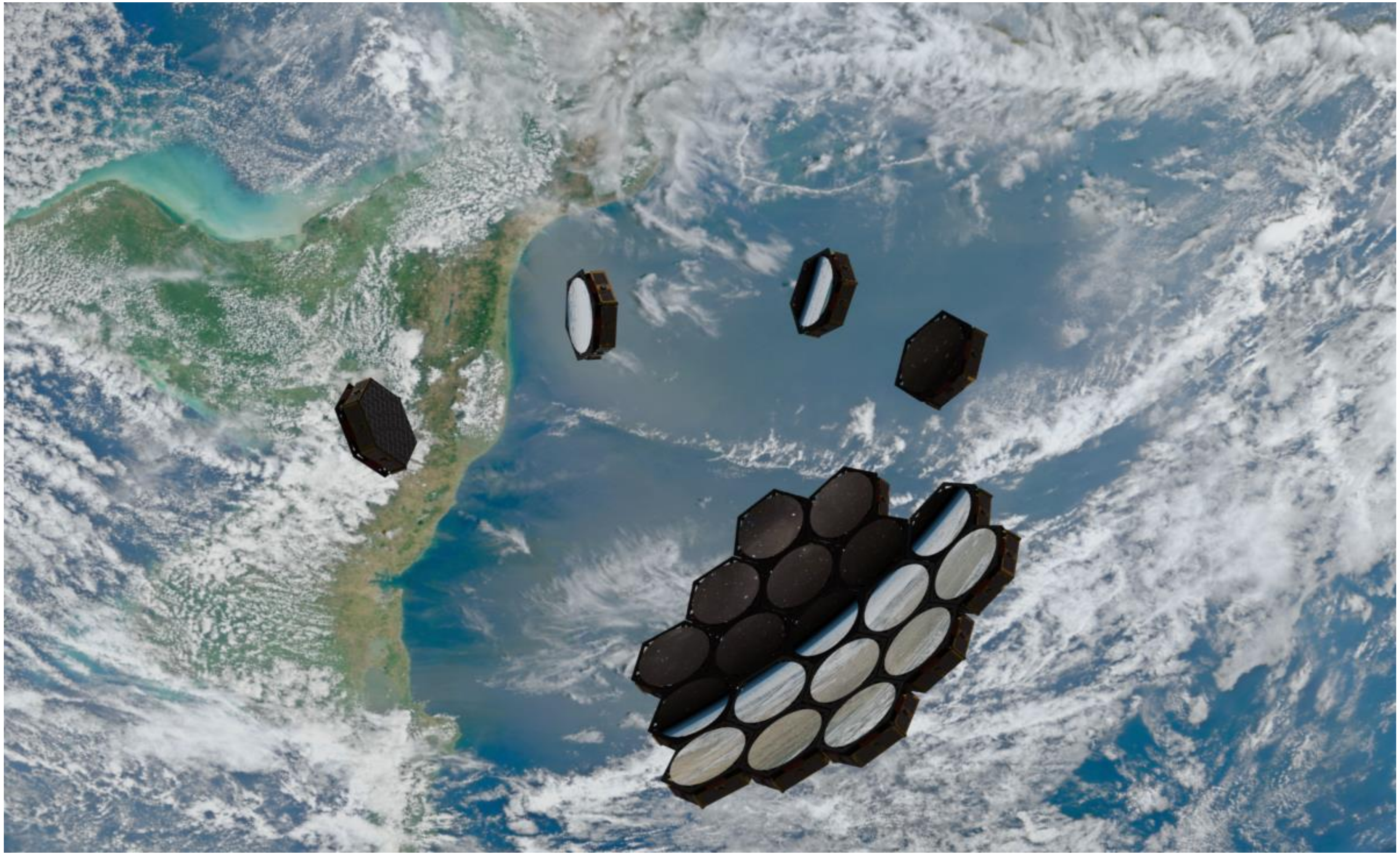
In-space assembly of telescope and instruments

- **Relieves constraints on mass, volume & structures to improve**
  - **Pointing & control stability**
  - **Optical performance - transmittance (increases threshold science)**
  - **Very high angular resolution**
- **Investigate architectures for in-space robotic assembly of telescope and instruments**
  - **Innovative optical designs**
  - **High transmittance, low polarization, exoplanet science compatible**
  - **FOV wide & narrow AND spectrometers**
- **New architecture concepts are needed**
  - **Telescopes & Instruments**

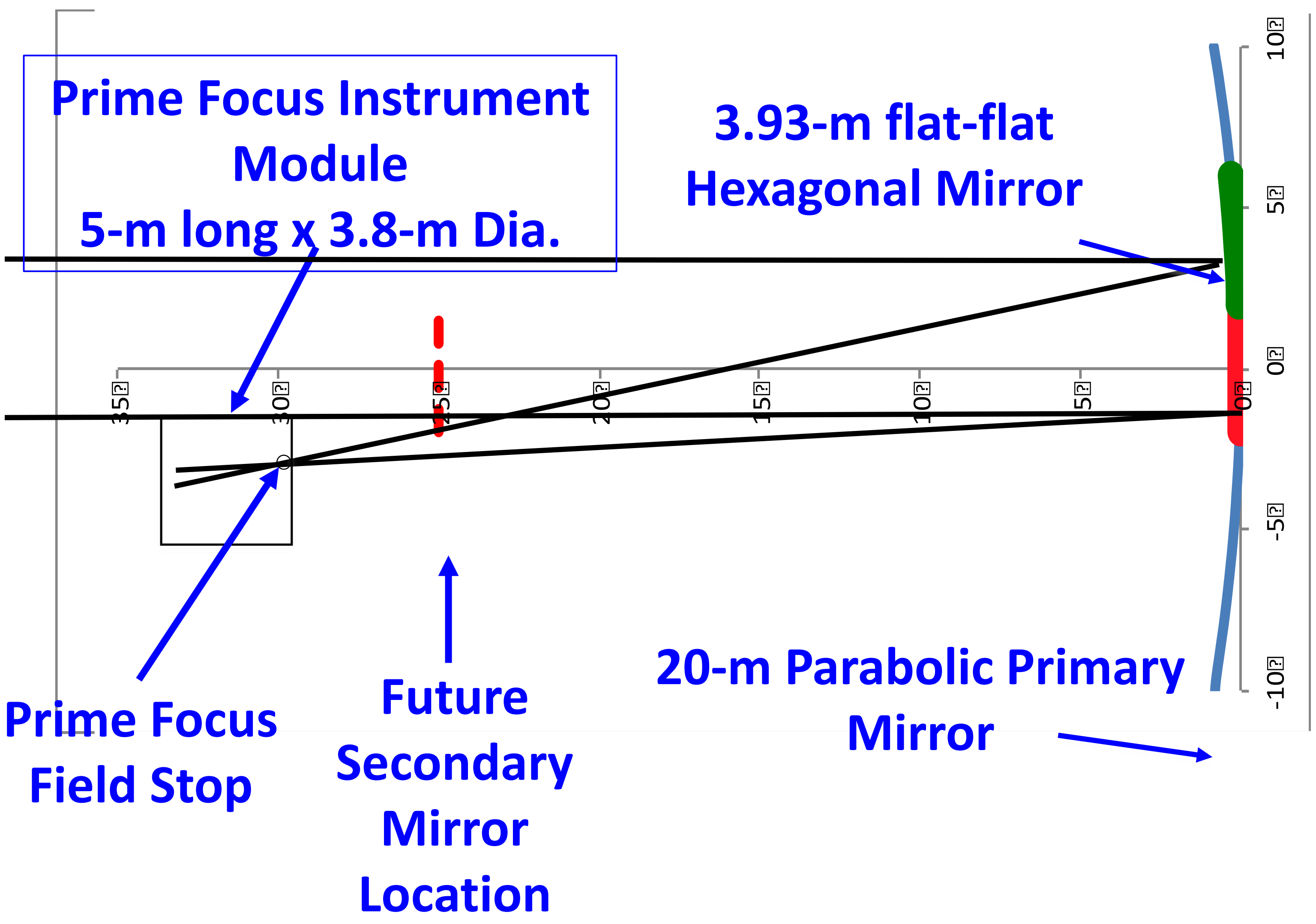


To afford new large aperture space telescopes, we as a community need to discover a way to break the cost-aperture curve

Evolvable space telescopes and Instruments use previous investments to evolve into new capabilities



Evolvable space telescope optics concept

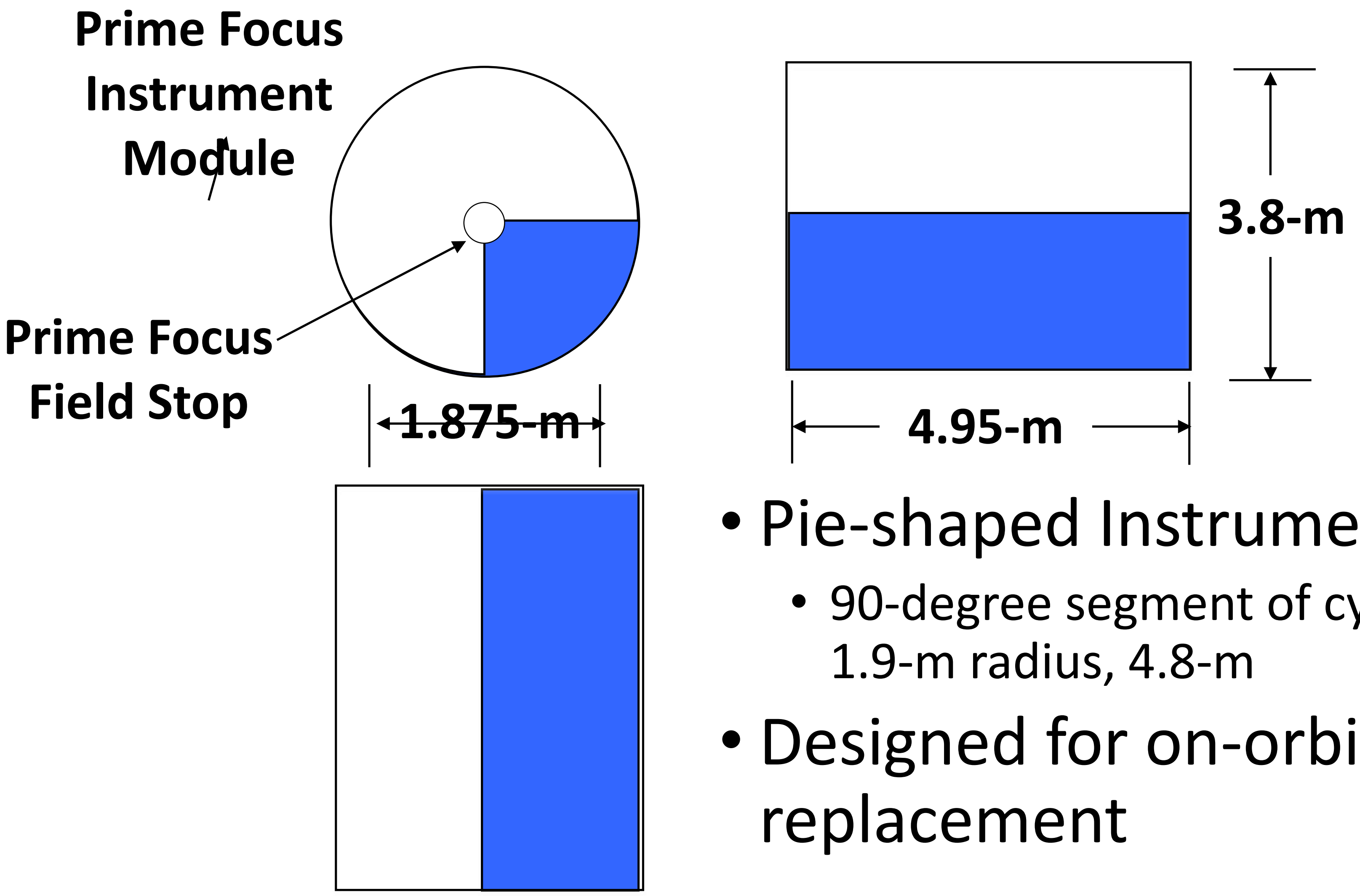


Primary mirror structure stays in space

Segments replaced

New science Measurements => replace instrument module

Instrument Enclosure Dimensions



- Pie-shaped Instrument Enclosure
  - 90-degree segment of cylindrical module with 1.9-m radius, 4.8-m
- Designed for on-orbit removal and replacement
- Kinematic mount
- Linear removal/replacement

Advantages to prime focus

- **Prime focus architectures for large space telescopes: reduce surfaces to save cost – Breckinridge & Lillie SPIE - 9904-173**
- **Reduce # of surfaces**
  - **Less surface scatter & absorption**
  - **Increases SNR in UV & visible**
  - **Decreases cost: fewer mechanical parts to design, build, align and hold to optical tolerances**
  - **Baffle architectures simpler – reduce mass**
  - **Lower cumulative polarization aberrations**
- **Off axis prime focus**
  - **Improved image quality over wide FOV**

Assume a 10 meter telescope can be built for $3B. What is the cost to recover the losses caused by reflections ?

# of normal incidence reflections to detector	Tau for R=0.95	Increase the d = 10m diameter to maintain SNR in m	New $ cost assuming cost=d^2.0
1	0.95	10.3	3.2
4	0.81	11.1	3.7
8	0.66	12.3	4.5
12	0.54	13.6	5.6
16	0.44	15.1	6.8
20	0.36	16.7	8.4
24	0.29	18.5	10.3
28	0.24	20.5	12.6

Package today's instruments => > 8 reflections

Eight reflections cost > $1B

Minimize reflections & Maximize reflectivity

Minimize internal polarization aberrations

EST Draft top Level Requirements

Parameter	Requirement	Goal	Notes
Telescope Aperture	> 10 m	> 16 m	~HDST concept
Stage 1	3 segment	~ 4 x 12 m	Three hexagonal segments
Stage 2	Filled Aperture	12 m	Twelve hexagonal segments
Stage 3	Filled Aperture	20 m	Eighteen hexagonal segments
Wavelength	100-2400 nm	90-8000 nm	UVOIR, MIR under evaluation
Field of View	5 to 8 arcmin	30 arcmin	Wide field VNIR imaging
Diffraction Limit	500 nm	250 nm	Enhanced UV/Optical
Primary Segment Size	2.4 m	3.93 m	flat to flat
Primary Mirror Temp	< 200 K	150 K	Minimize heater power
Design Lifetime	15 years	>30 years	On-orbit assembly and servicing

The primary mirror

Nicolas Lee, Paul Backes,
Joel Burdick, Sergio Pellegrino et. al.
Architecture for in-space robotic assembly of a modular space telescope,
JATIS (2) 2016

Launch the mirror structure separately and assemble in space

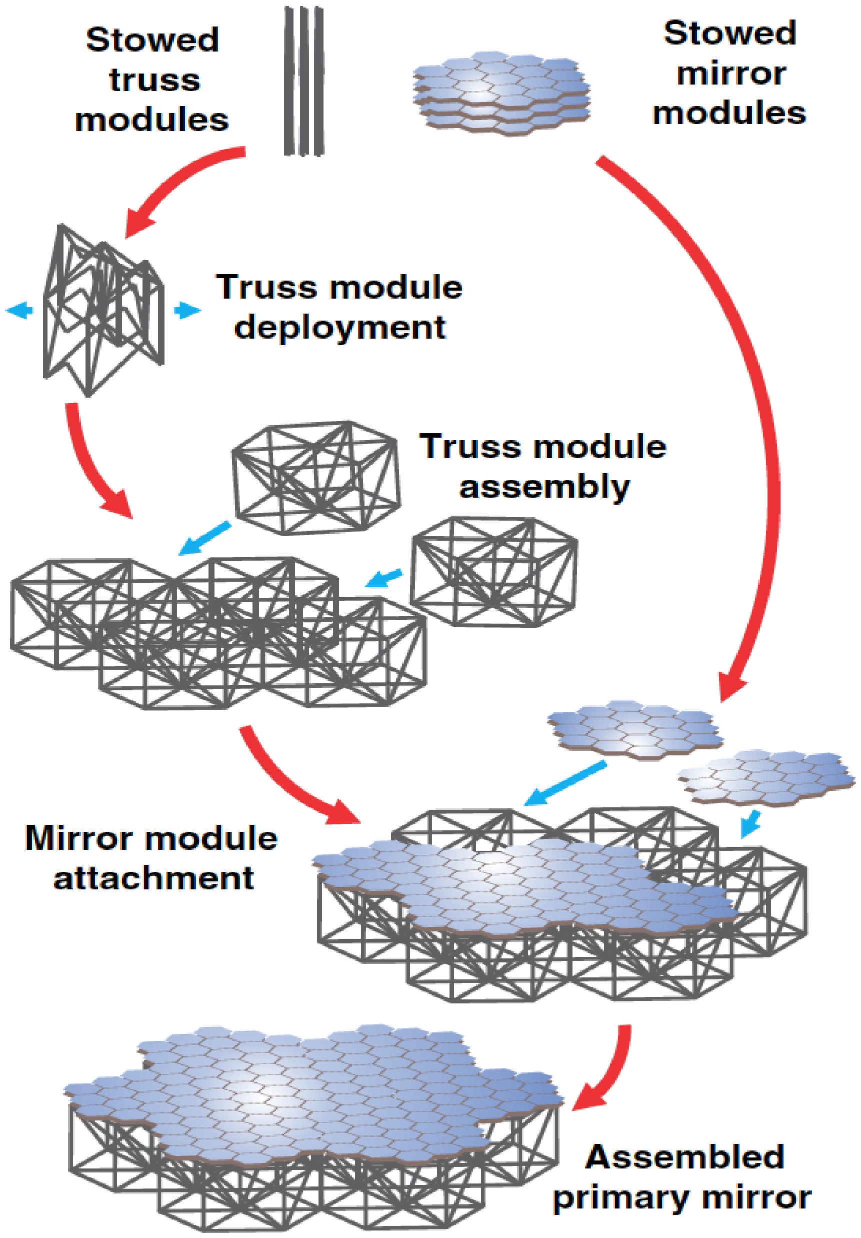
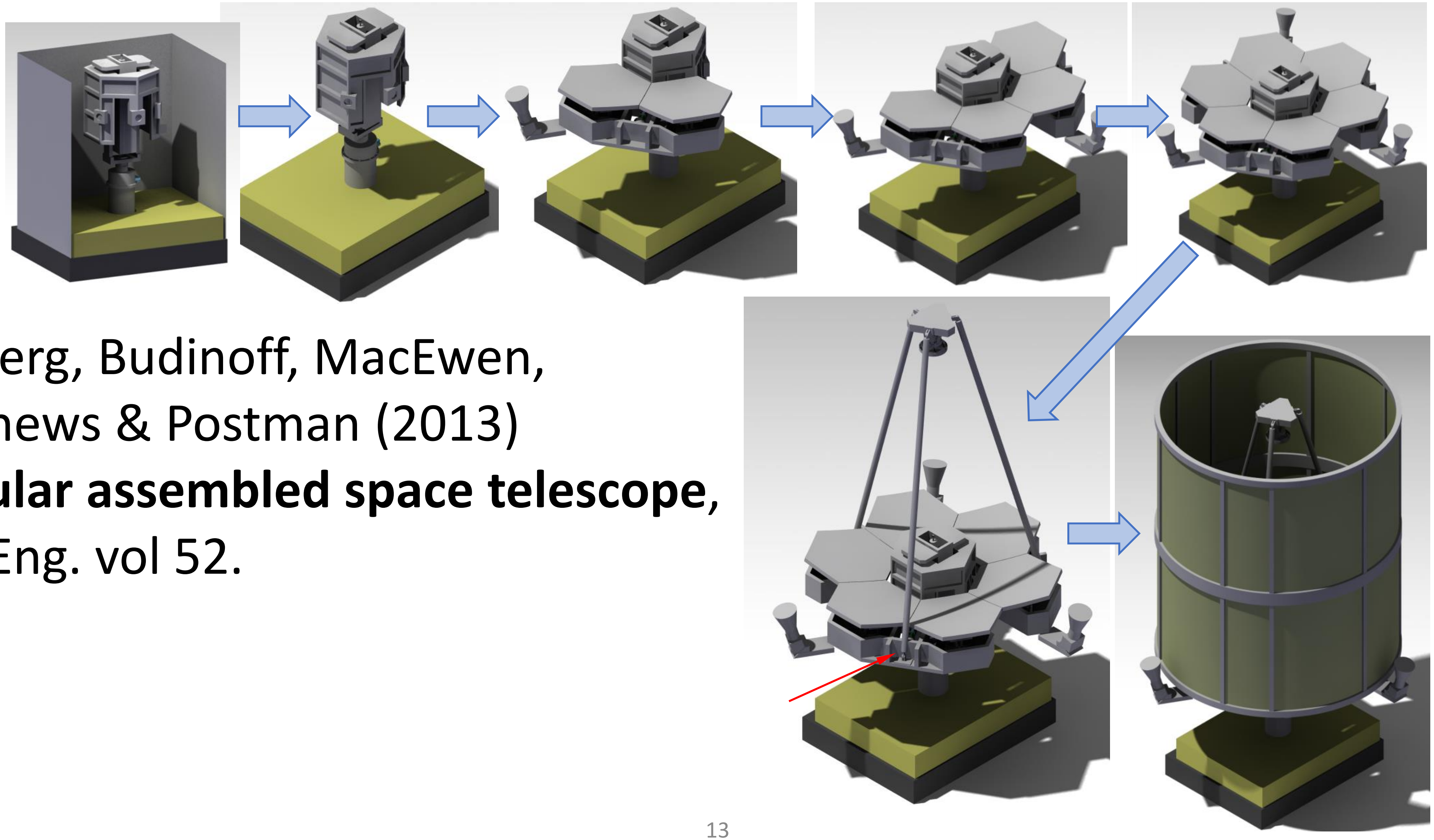


Fig. 2 Primary mirror assembly concept and module nomenclature.

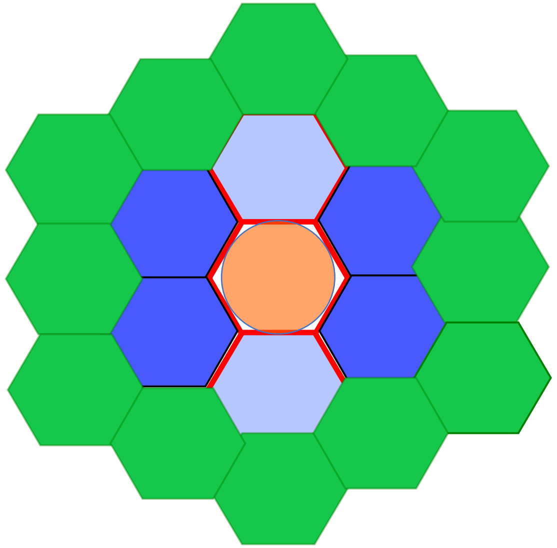
Modular Demonstration of an Evolvable Space Telescope (MoDEST)

Feinberg, Budinoff, MacEwen, Matthews & Postman (2013) **Modular assembled space telescope**, Opt. Eng. vol 52.



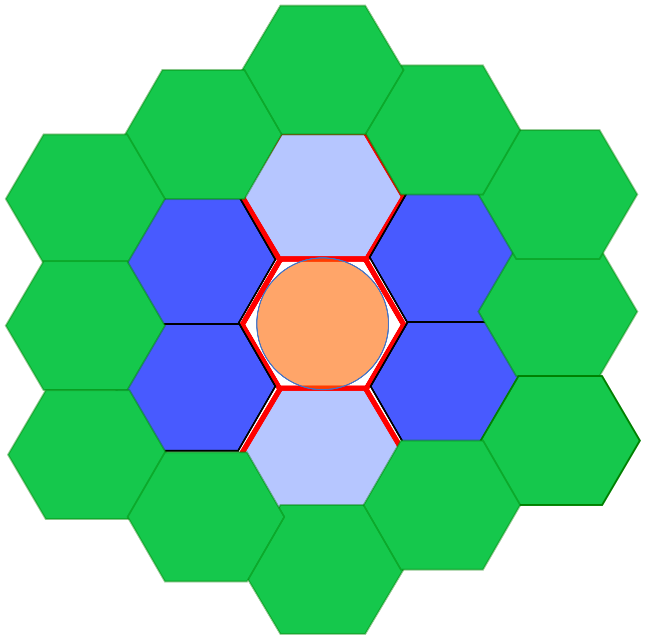
The Evolvable Space Telescope

- This Northrop Grumman Evolvable Space Telescope (EST) concept study was initiated in 2014
- **Concept science goals were taken from various community studies (e.g. AURA HDST Report)**
- Architecture is a staged, in-space assembled, concept that began small and grew in stages to achieve a > 14 meter segmented telescope



The Evolvable Space Telescope

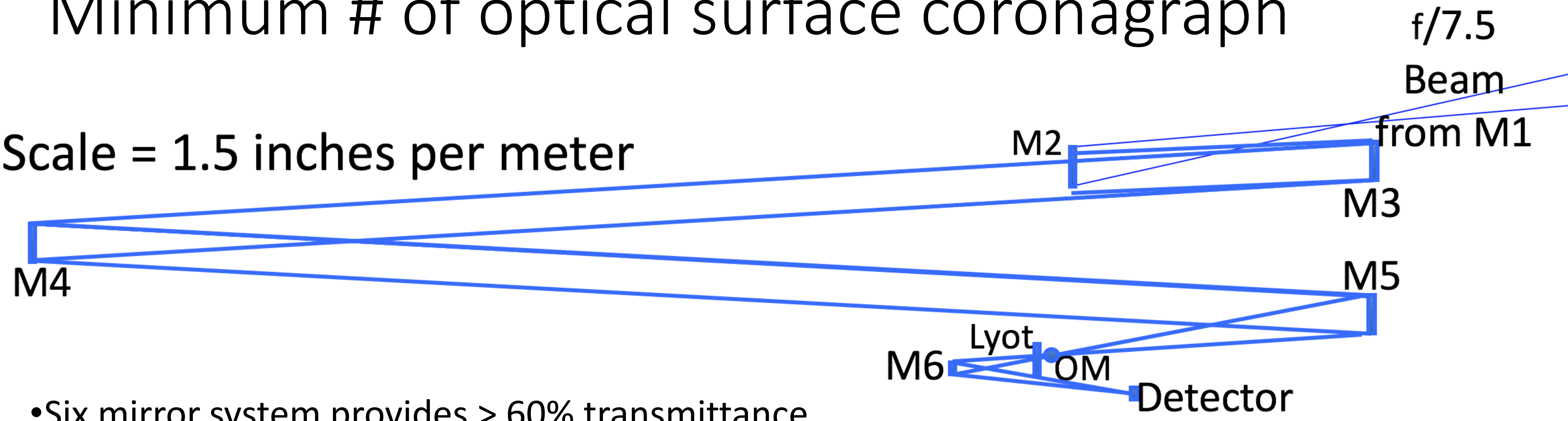
- **Stage 1** is a medium sized (equivalent to a 4 or 6 m telescope) partially filled aperture, launched as a fully functional astronomical telescope complete with instruments.
- **Stage 2** is launched some years later and augmented the Stage 1 telescope with additional mirror segments, instruments, and additional support systems, growing the Stage 1 telescope into a larger (8 – 12 meter) filled aperture.
- **Stage 3** Augment the existing Stage 2 telescope with more mirror segments to achieve a 14 – 20 meter aperture with new, enhanced, instruments and additional support systems.
- **Stage 4 is** a sustained Stage 3, refurbishing or enhancing the now existing large Space Observatory as needed to enable a multi-decade useful lifetime.



Instrument volume barriers gone!

- Minimize # of reflections
  - Maximum power to the focal plane
- Threshold science @ minimum cost
  - Each optical mirror absorbs 3%
  - **To hold the threshold science constant => Increase aperture to collect more light to compensate for absorption**
  - For a $3B space telescope each instrument mirror costs about $100M+
- New way to think about instruments
  - Minimize mirror count
  - Think of deploying instrument optics

Minimum # of optical surface coronagraph



- Six mirror system provides > 60% transmittance
- M3 and M4 are 128 x 128 actuator Xinetics DMs
- 512 x 512 pixel EMCCD photon counting detector with 16 μ pixels
- Inner Working angle of 83 mas and Outer Working Angle of 1320 mas at 400 nm
- Enhanced Silver or Al MgF2 mirror coatings for 400 to 950 or 250 to 950 nm bandpass
- 10 arc second Field of View for Exoplanets, 106 arc second FOV for general Astrophysics
- Focal Ratios ≥ 4 minimize polarization effects to maximize image quality for $>10^{-9}$ contrast

- FROM: Lillie

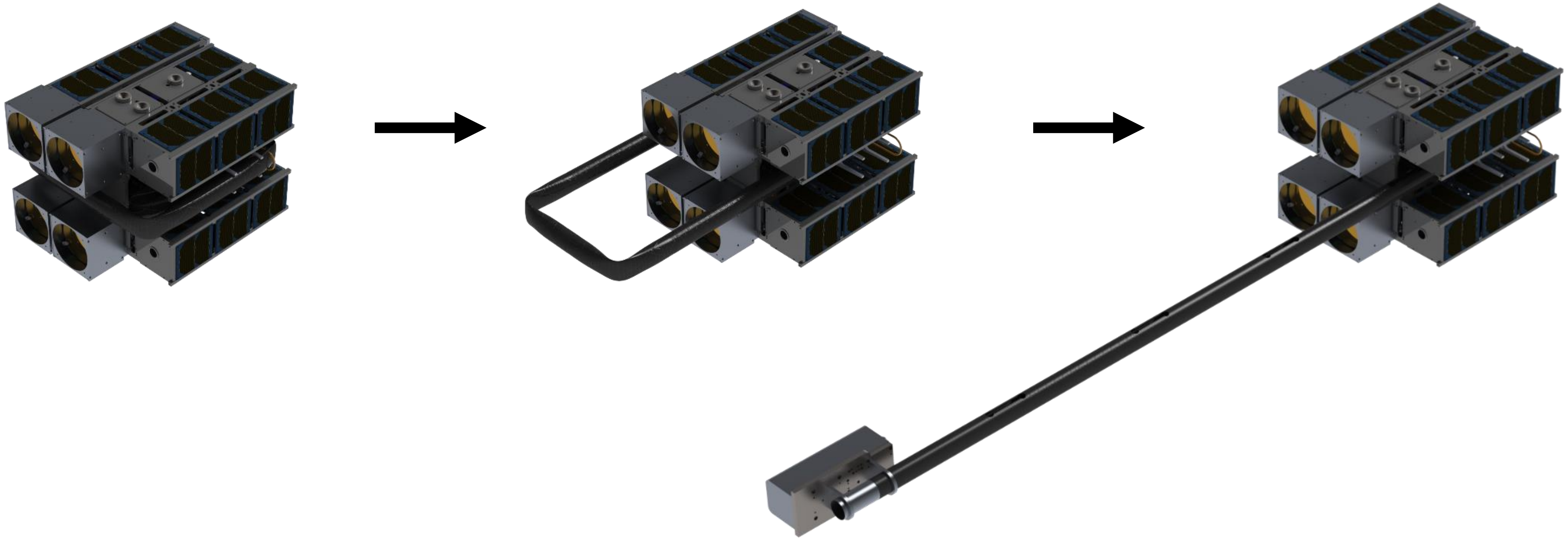
Autonomous Adaptive Reconfigurable Space Telescope (AAReST)

- Caltech student driven small sat based on cubesat technology
- **Space technologies**
  - **Wafer mirror adaptive optics**
  - **Formation flying reconfigurable telescope pupil**
- Demonstrate technology that is focused on assembling a segmented primary mirrors in space

Concept of Operations for Caltech AAReST
Team lead: Professor Pellegrino, Caltech Aero

- Turn on, verify satellite components
- Stabilize attitude, temperature

- Deploy boom in two stages:
  1. Boom segments unfold
  2. Camera is released
- Uncage deformable mirrors

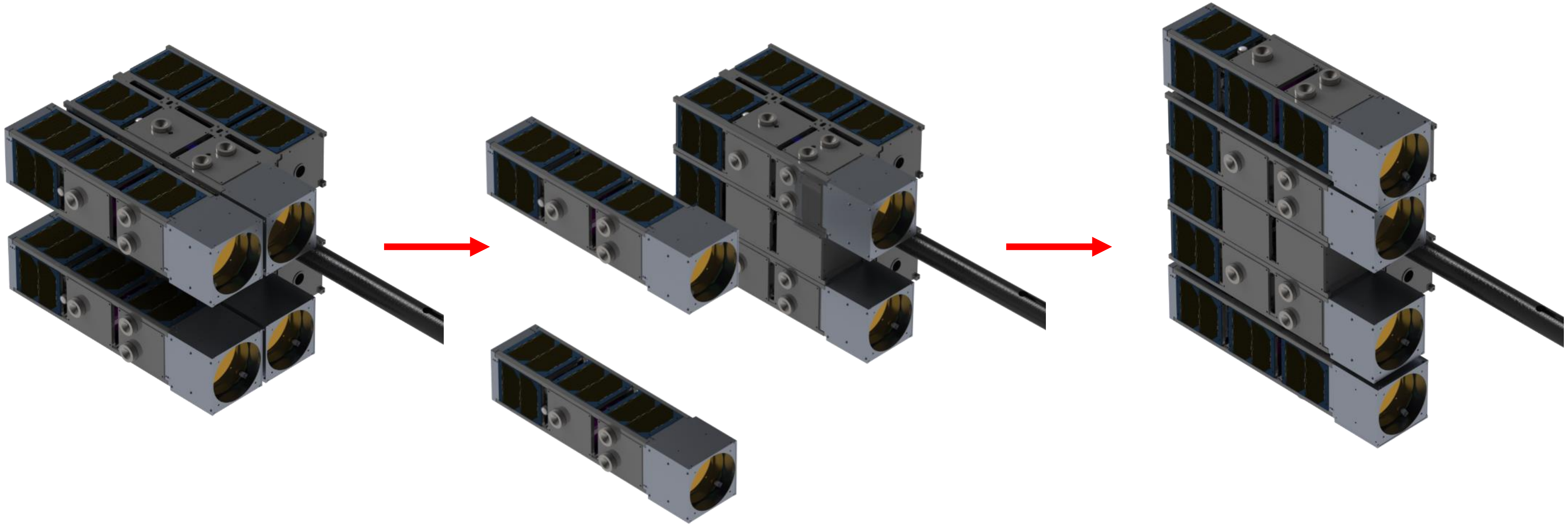


AAReST Concept of Operations

- Telescope points to a bright reference star
- Calibrate:
  - Segment tip/tilt/piston
  - Deformable mirror surface figure
- Camera provides feedback for segment calibration

Concept of Operations

- MirrorSats release from CoreSat (one at a time)
- Fly out ~1 m
- Re-dock into "wide" configuration



Conclusion

- Many studies on servicing and assembly in space
- Many applications to next large aperture telescopes & instruments
- No resources being expended to study how these technologies will benefit astrophysics and exoplanet science
- What can we do to change that?

Back-up