CubeSat-Based
Laser Guide Stars

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Outline

- Background
- Motivation
- Approach
- Feasibility Analysis
- Summary and Acknowledgements

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- **Background**
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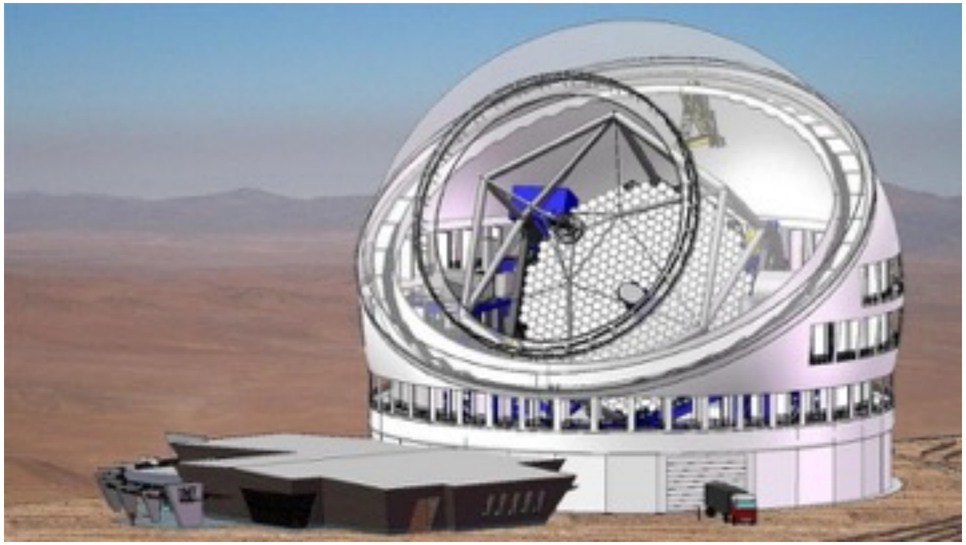
Previous Work

- **Greenaway (1991) proposed a satellite guide star system using highly elliptical orbits for astronomical imaging**[1]
  - **Intent to roughly match sidereal rates during a portion of the orbit**
  - **Enable fairly long integration times (~5000 seconds)**

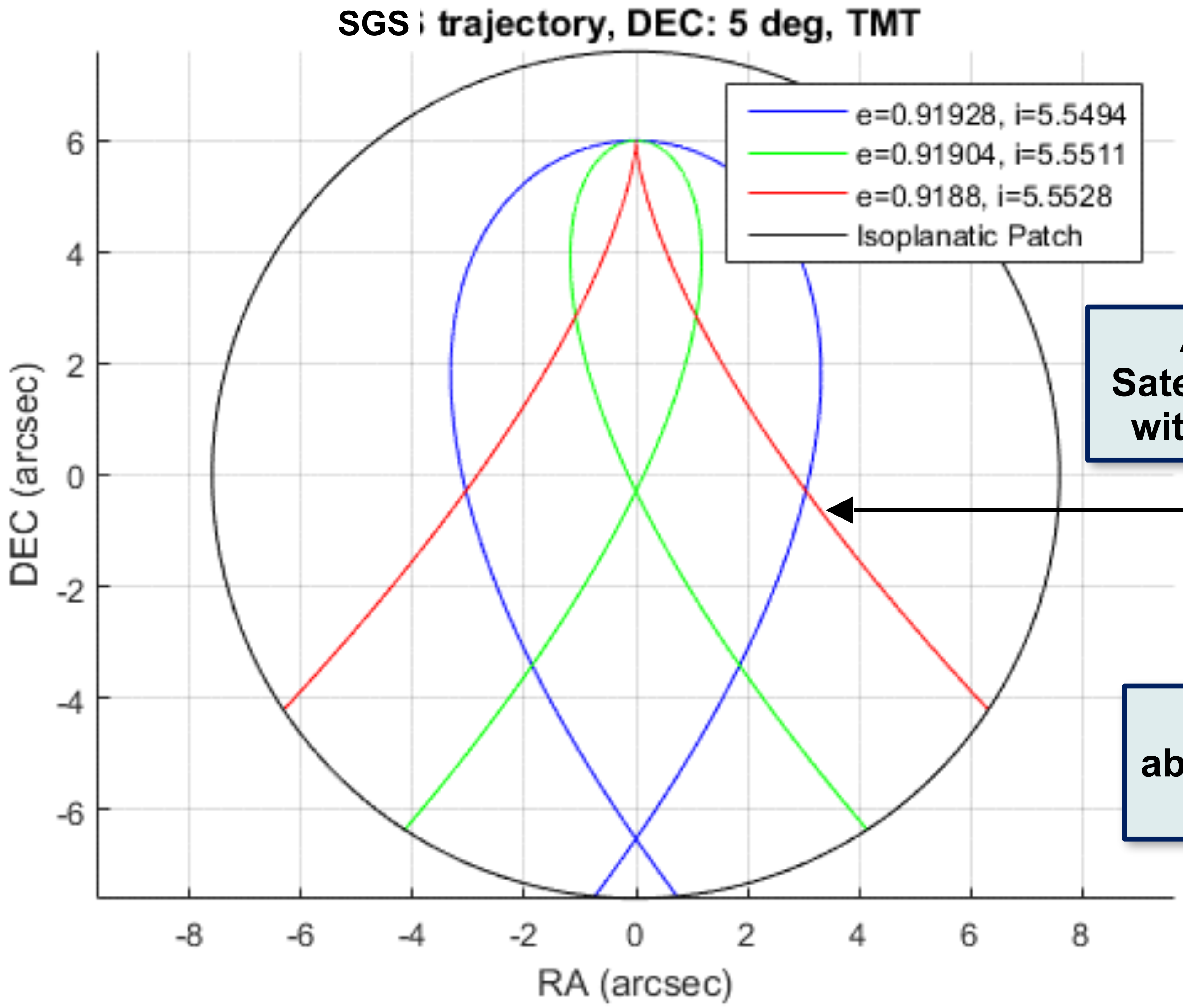
- **We revisit this work and analyze such a guide star system**
  - **Using the Thirty Meter Telescope (TMT) as the imaging system**
  - **Integration times are relative to the *Isoplanatic Patch* – patch of sky where adaptive optics (AO) corrects the wavefront**[3]



Rendering [2] of the
Thirty Meter Telescope
at Mauna Kea in Hawaii.

Proposed completion in 2022

Analysis of Previous Work



Apparent tracks of Satellite Guide Star (SGS) within isoplanatic patch

Best case shows about 5000 seconds of integration time

Image credit: H. Yoon, MIT

Tech Enablers

- The rise of CubeSats
  - CubeSat-class satellites and their proliferation
  - CubeSat propulsion system development [4]
  - Low size, weight, power commercial laser systems [5]
  - Low-cost launch opportunities [6]

- For manuscript in preparation on this topic, we consider GEO-located satellite guide star for imaging GEO satellites[7]
  - Allows for long integration times
  - Maneuverability within GEO
  - Delta-V requirements found to be consistent with expected CubeSat propulsion capabilities

Why not simply have a telescope in or near GEO to image targets directly?

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Space-based Imager

- **Diffraction limited optics** [8]

$$\boldsymbol{\theta = 1.22\frac{\lambda}{D}}$$

θ = angular resolution
λ = 550 nm (visible)
D = aperture diameter
space-based imager, no atmospheric effects

- **Satellite separation at GEO distance ~550 km, based on GEO population survey**[9]
- **To resolve features ~10 cm in diameter (CubeSat-size), angular diameter is thus:**

$$2\tan^{-1}\left(\frac{0.05\ m}{550 * 10^{3}\ m}\right) = \boldsymbol{0.18\ \mu rad}$$

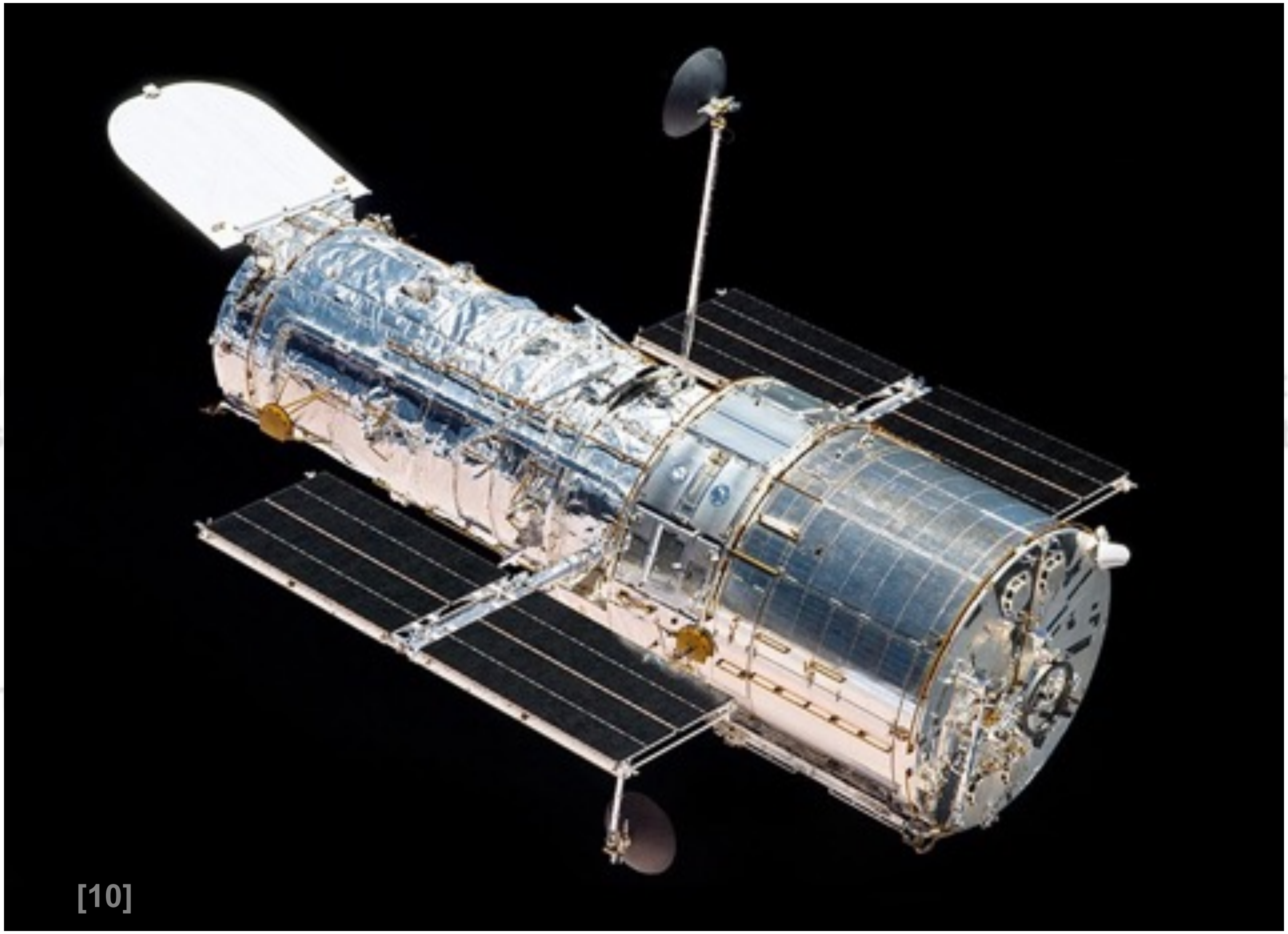
- **And the required aperture for such a system:**

$$D_{apt} = 1.22\left(\frac{550 * 10^{-9}\ m}{0.18 * 10^{-6}}\right) = \boldsymbol{3.7\ m}$$

Space-based Imager

- Diffra

That’s 150% larger than *Hubble* aperture



[10]

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- To res

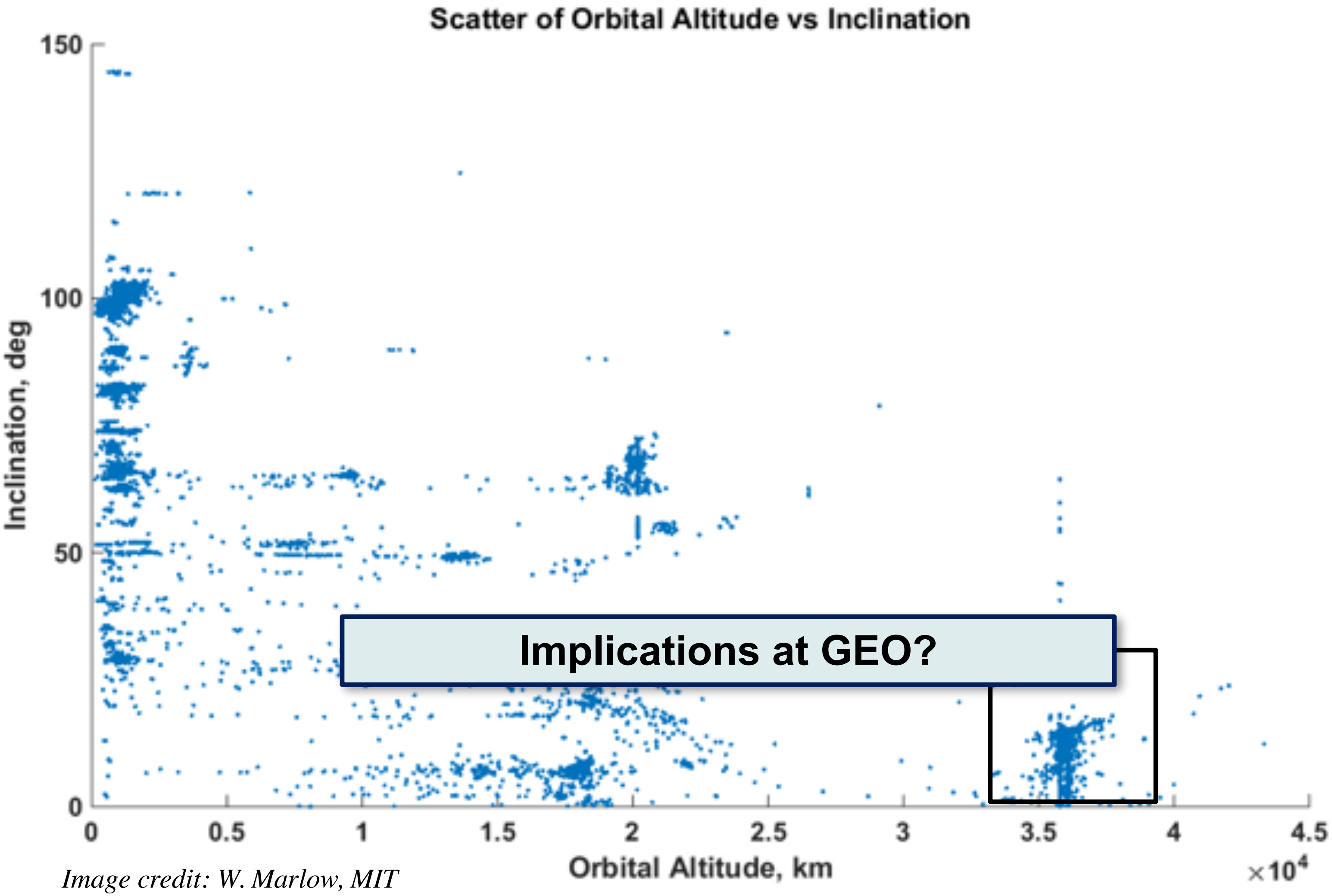
ion survey[9]

ter is thus:

- And th

Satellite Population

- **Survey of the space catalog out to GEO**



Implications at GEO?

Image credit: W. Marlow, MIT

GEO Belt Detail

- **Survey of the space catalog out to GEO**

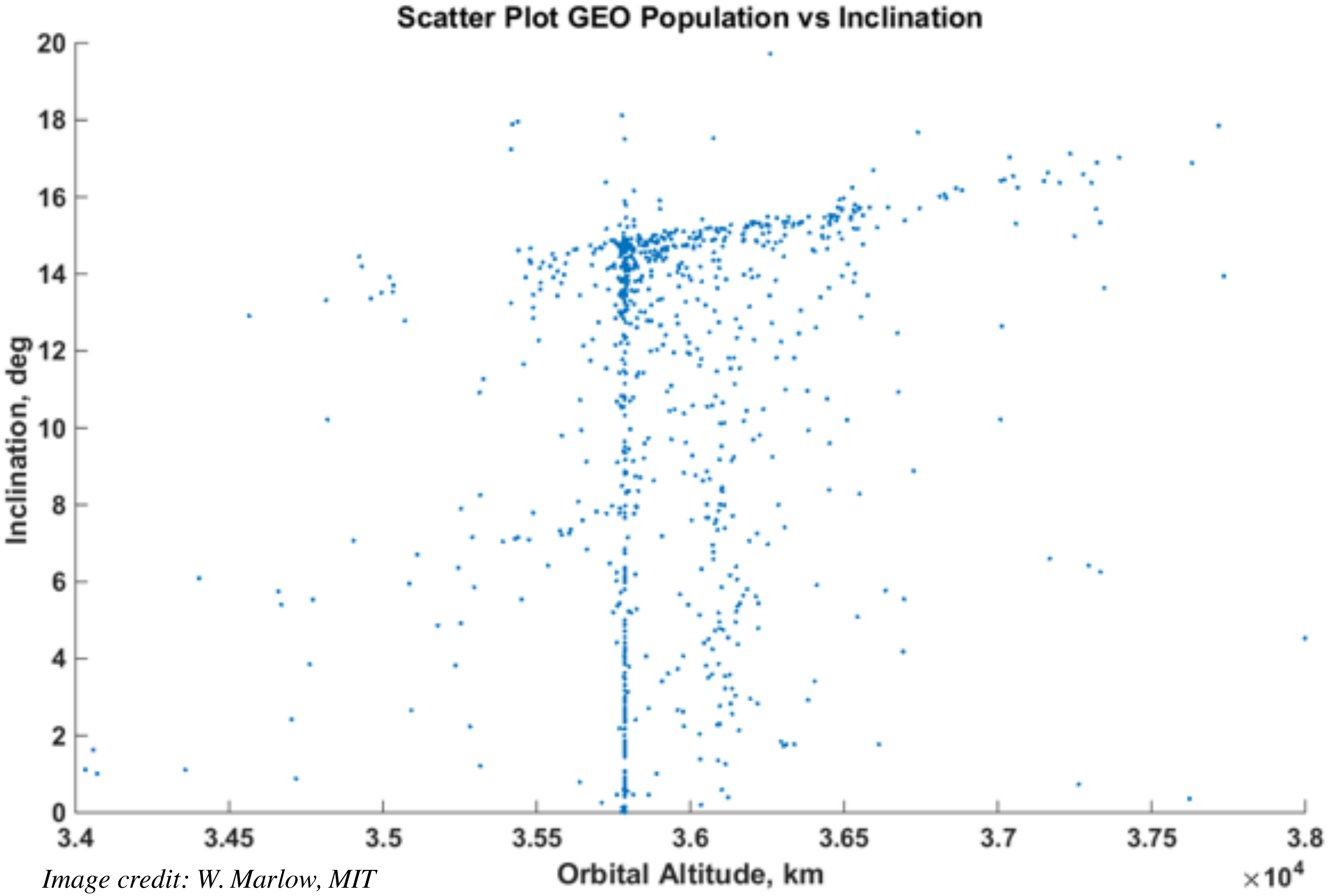
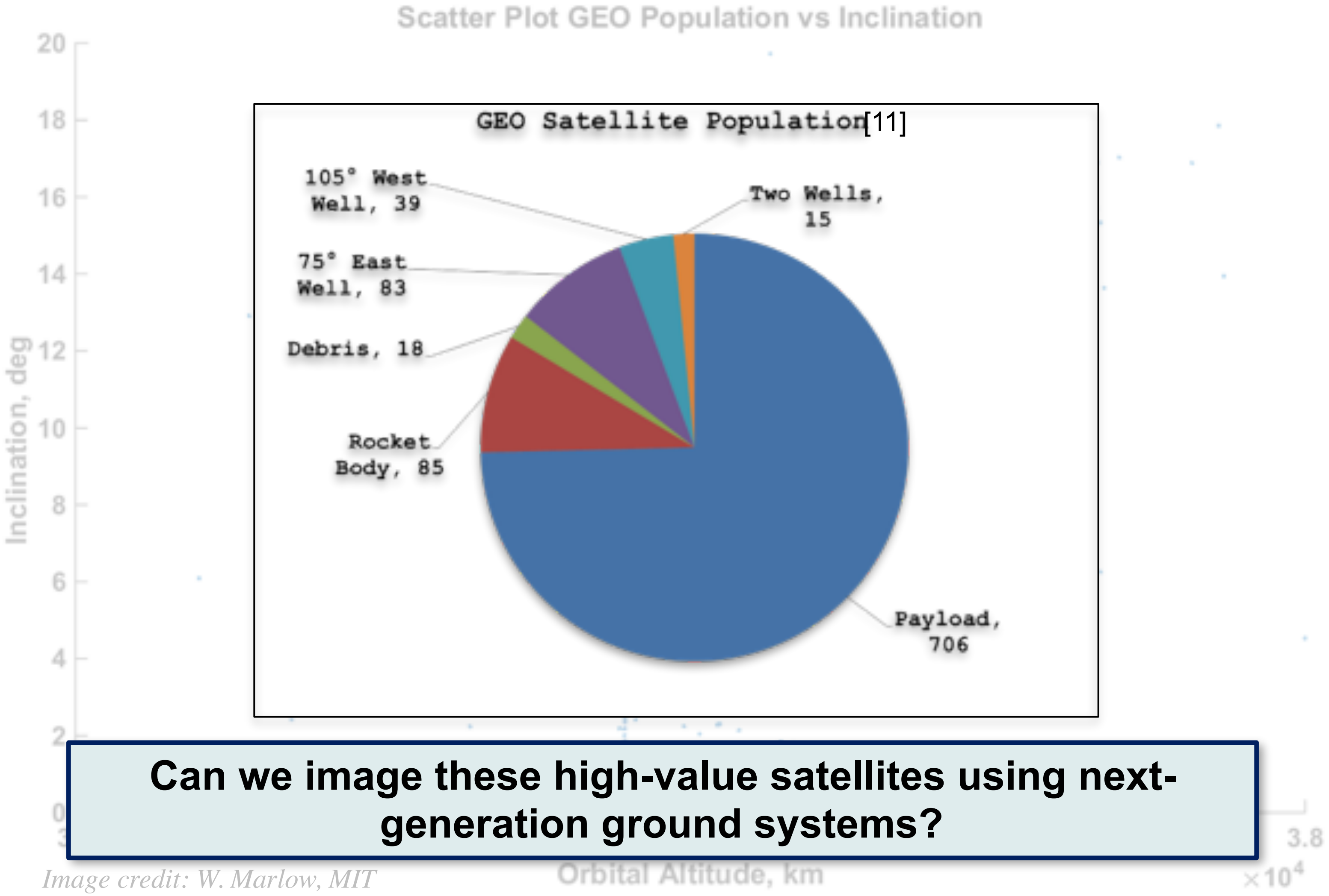


Image credit: W. Marlow, MIT

GEO Belt Detail

- Survey of the space catalog out to GEO



Can we image these high-value satellites using next-generation ground systems?

Image credit: W. Marlow, MIT

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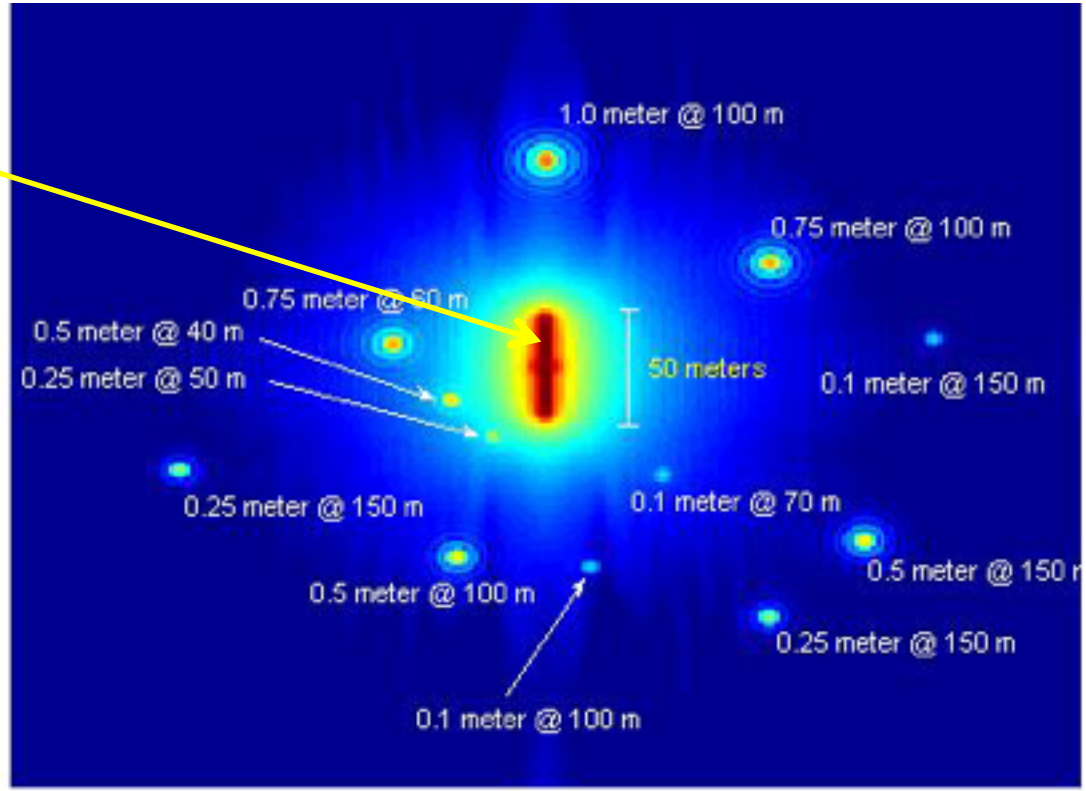
Ground-based AO Imaging[12]

- Image CubeSat-sized neighboring objects around high-value systems with ground AO stations
  - Simulated with 3.65 m AO telescope
  - Boeing Model 702 GEO satellite
  - 3 seconds of total integration time



High-value Asset

[12]

Ground-based AO Imaging[12]

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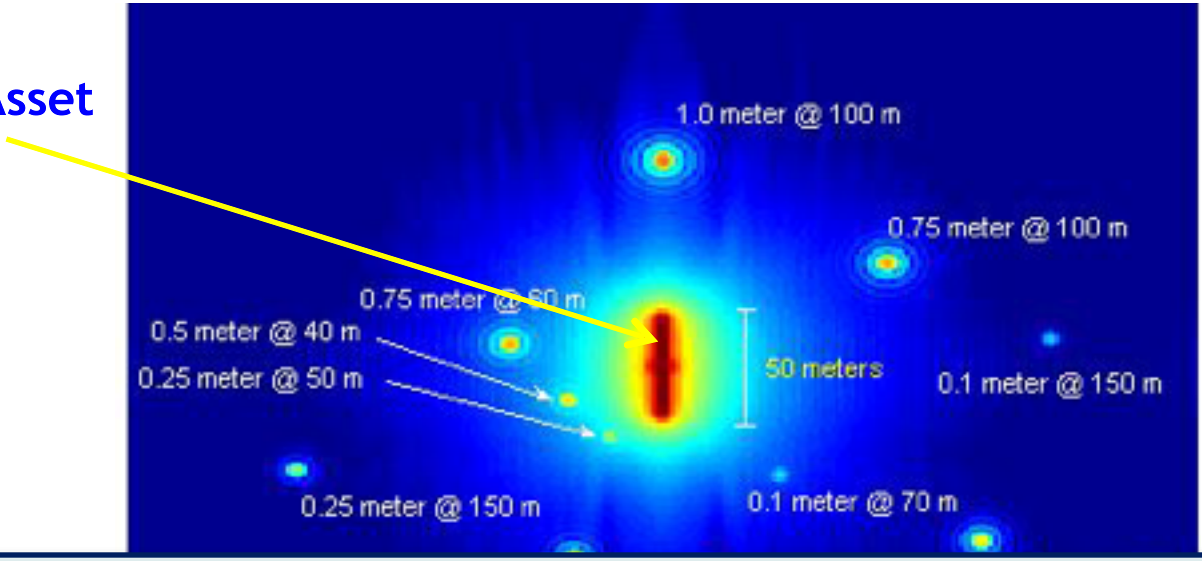


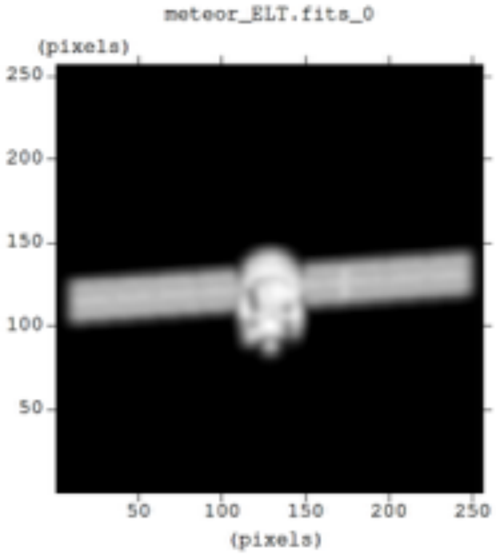
High-value Asset

At this resolution or better:

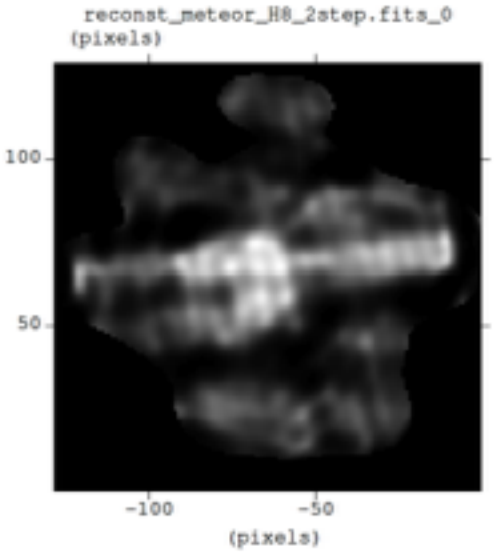
- **Monitor deployments or maneuvers in real-time**
- **Discriminate resident space objects near GEO assets**

Interferometric Imaging[13]

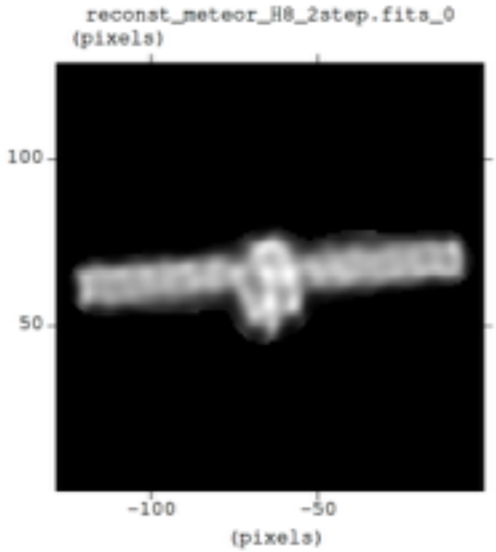
- **Interferometric imaging simulation results show promise**
  - **Magdalena Ridge Observatory Interferometer (MROI)**
  - **Visual magnitude 8 GEO target, 27 m longest dimension**



Original target



MROI only



8 m class non-redundantly masked telescope added

Image from Young, *et al.*
“Interferometric imaging of geo-synchronous satellites with ground-based telescopes”
Aerospace Conference, 2013 IEEE

Interferometric Imaging[13]

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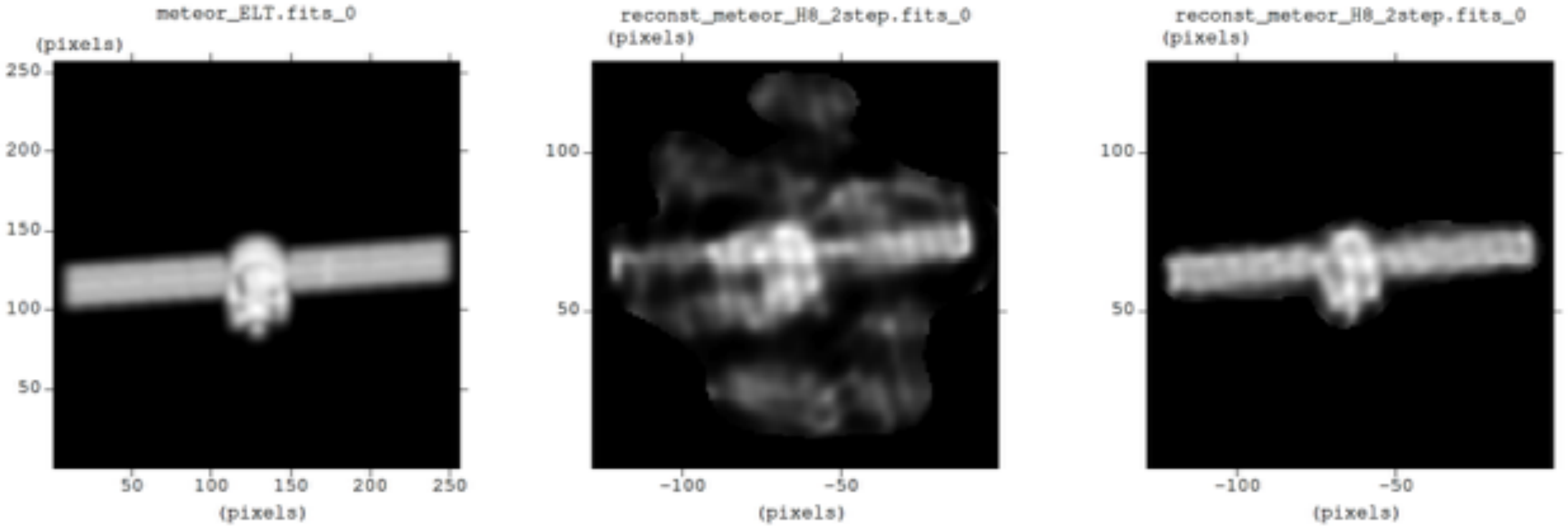

Original target

MROI

8 m class non-redundantly

These systems would benefit from a calibration source that is spatially stationary but repositionable

Aerospace Conference, 2013 IEEE

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Notional 6U Design

1. **Power**
   - 6U Main deployable & body panels
   - >50 W nominal
2. **Communications**
   - S, C, or X band patch antenna
3. **ADCS**[14]
   - All-in-one (reaction wheels, mag torquers, star tracker)
   - Stand alone star tracker
4. **Laser Transmitter**
   - 1-W 850 nm output (10 W input)
   - MOPA configuration with fine steering mirror
5. **Command & Data Handling**
   - Custom and COTS heritage HW
   - Custom flight software
6. **Propulsion**
   - Monopropellant system shown[15]
   - 4 x 0.5 N thrusters
7. **Launch Opportunities**
   - Requires ride-share with GEO launch
   - Comprised 24 out of 73 launches in 2014[16]

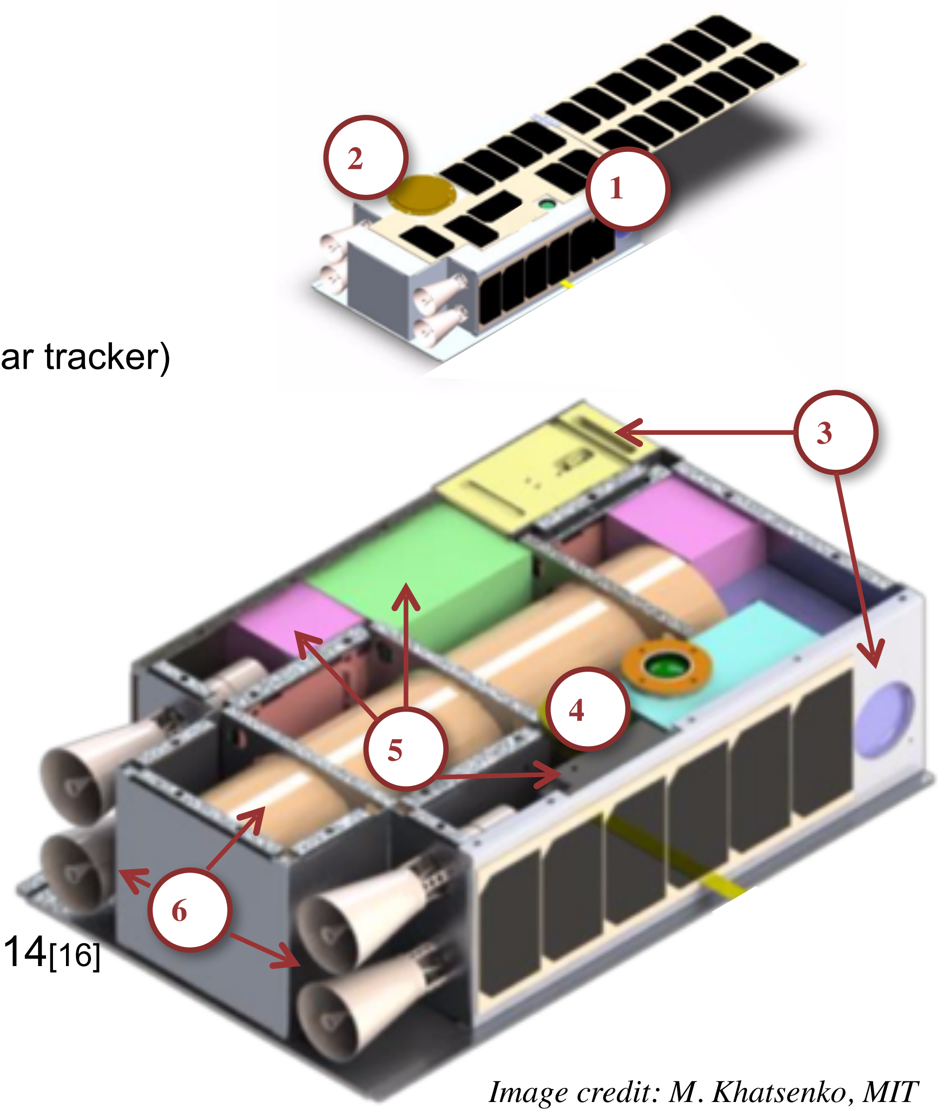

Image credit: M. Khatsenko, MIT

Required Laser Power

- Pointing ability directly affects required laser power
  - Two-stage pointing approach is most appropriate[17]
- Current MIT STAR Lab projects exploring precision laser pointing
  - Nanosatellite optical downlink experiment (NODE)
  - Free-space lasercomm and radiation experiment (FLARE)
  - KitCube, lunar distance lasercomm downlink

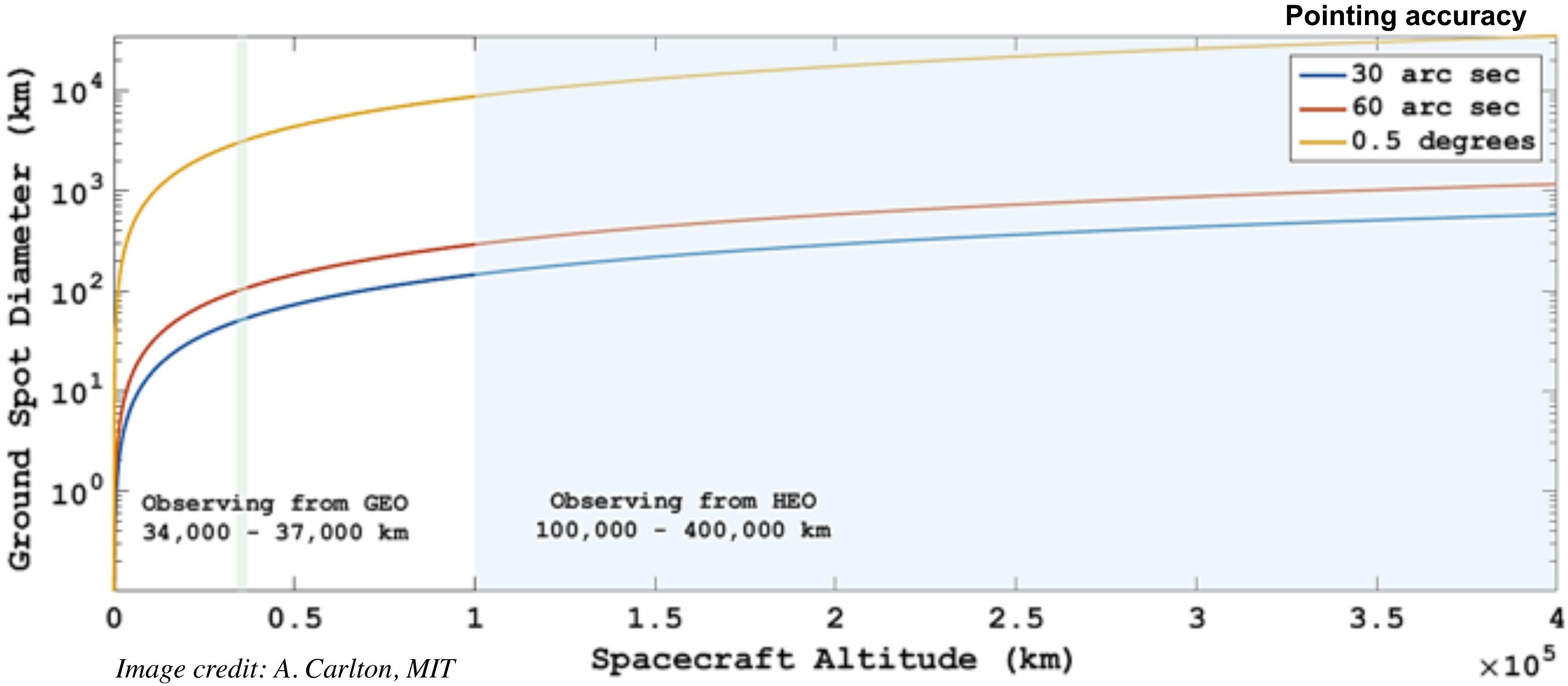

Image credit: A. Carlton, MIT

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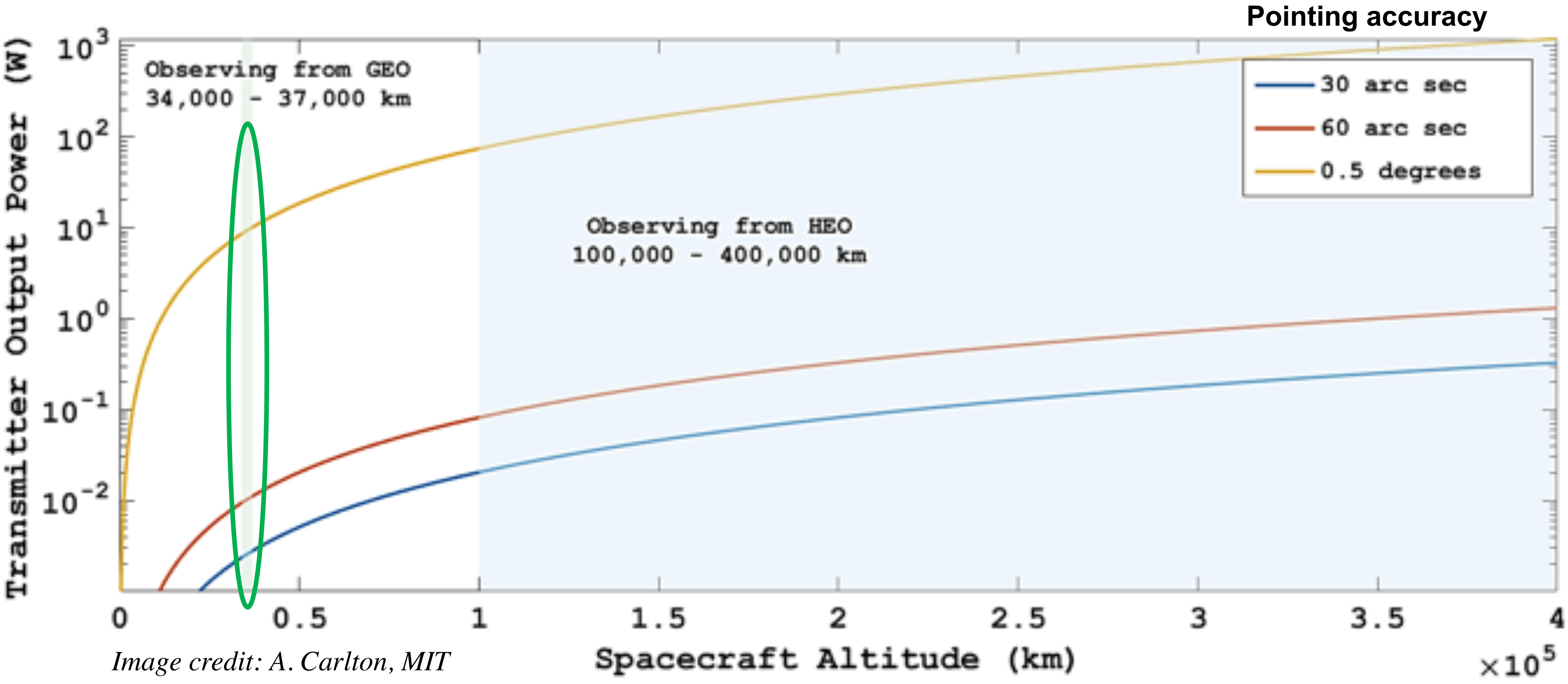

Image credit: A. Carlton, MIT

Delta-V and Integration Time

- GEO CubeSat guide star maneuvering slightly out of GEO belt
  - Acts as a passing reference source
  - “Integration time” refers to time within isoplanatic patch
  - Monopropellant system can deliver 500-600 m/s delta-v
  - Propulsion in development with >5 km/s delta-v (electrospray)[4]

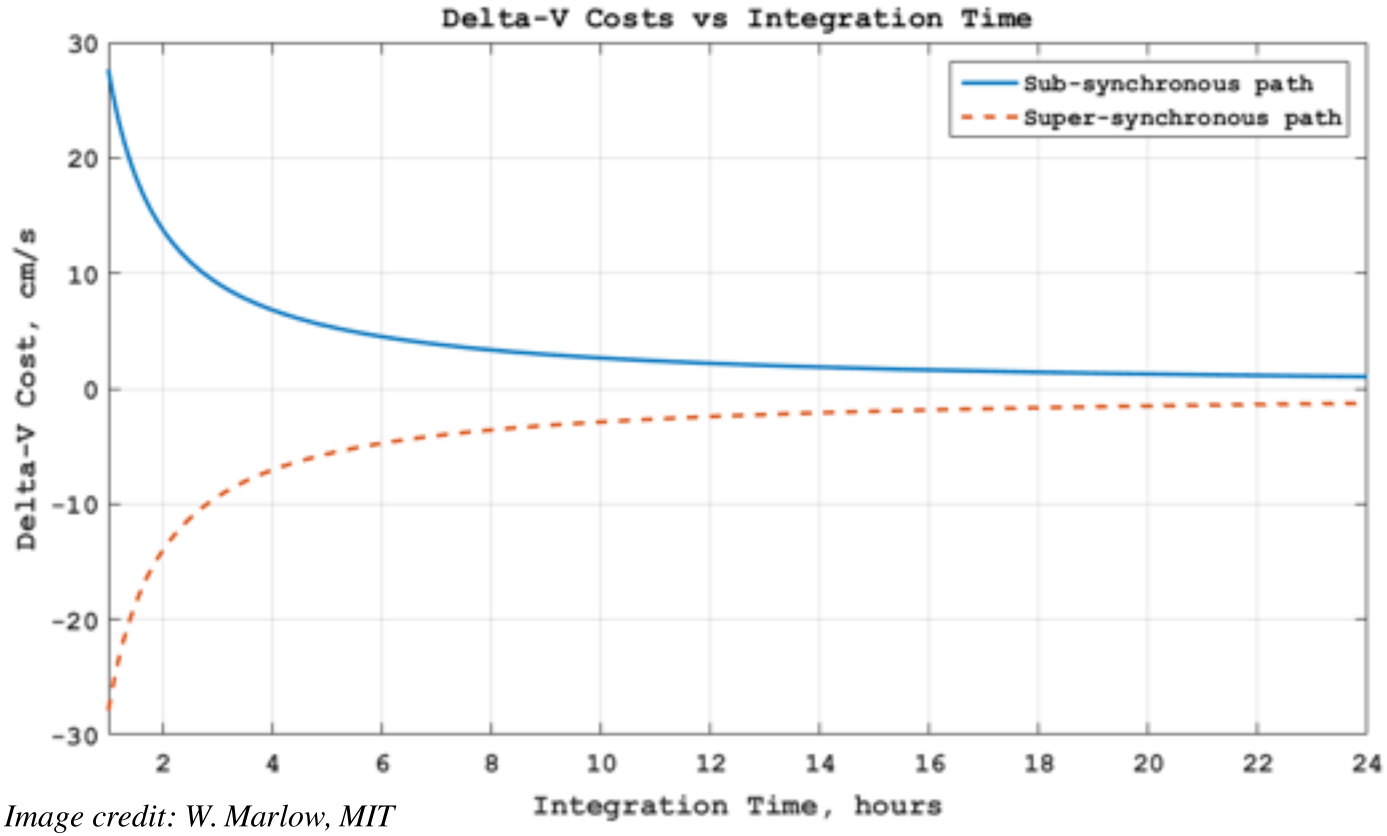

Image credit: W. Marlow, MIT

Maneuvering Around GEO

- Maneuvering via subsynchronous or supersynchronous Hohmann transfers
  - Maneuver to imaging target and remain stationary during imaging
  - Demonstration mission with monoprop. could have >10 maneuvers
  - With electrospray propulsion could have >100 maneuvers

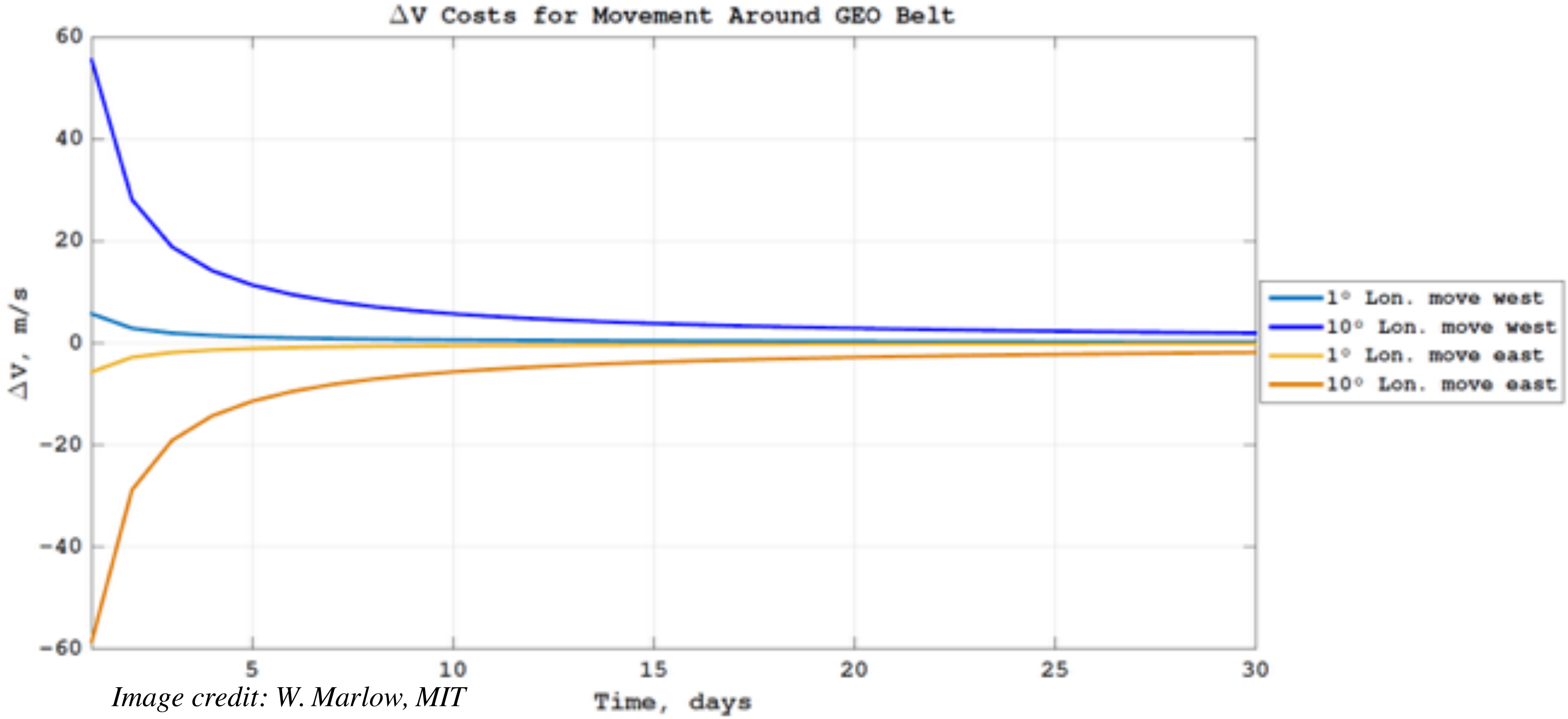

Image credit: W. Marlow, MIT

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Summary

- **CubeSat technology is a key enabler for revisiting the concept proposed by Greenaway (1991)**

- **CubeSat guide stars for AO ground systems**
  - **Increase capability for astronomical observations**
  - **Allow for high-quality GEO belt imaging from ground**

- **High flexibility in integration times and low delta-v maneuver costs make these attractive systems**

- **Upcoming (2018) launch service for 6U CubeSats to GEO**[6] **make these highly feasible**

Funding in the near future would allow for a demonstration mission to align with GEO CubeSat launch service

Authors

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  - PhD candidate, MIT Space Systems Lab, STAR Lab
- **Hyosang Yoon**
  - PhD candidate, MIT Space Systems Lab, STAR Lab
- **Christian Haughwout**
  - Master’s student, MIT Space Systems Lab, STAR Lab

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Questions?

BACKUP

Telescope Zenith Angle Effects

- **Higher zenith angle decreases effective isoplanatic angle**

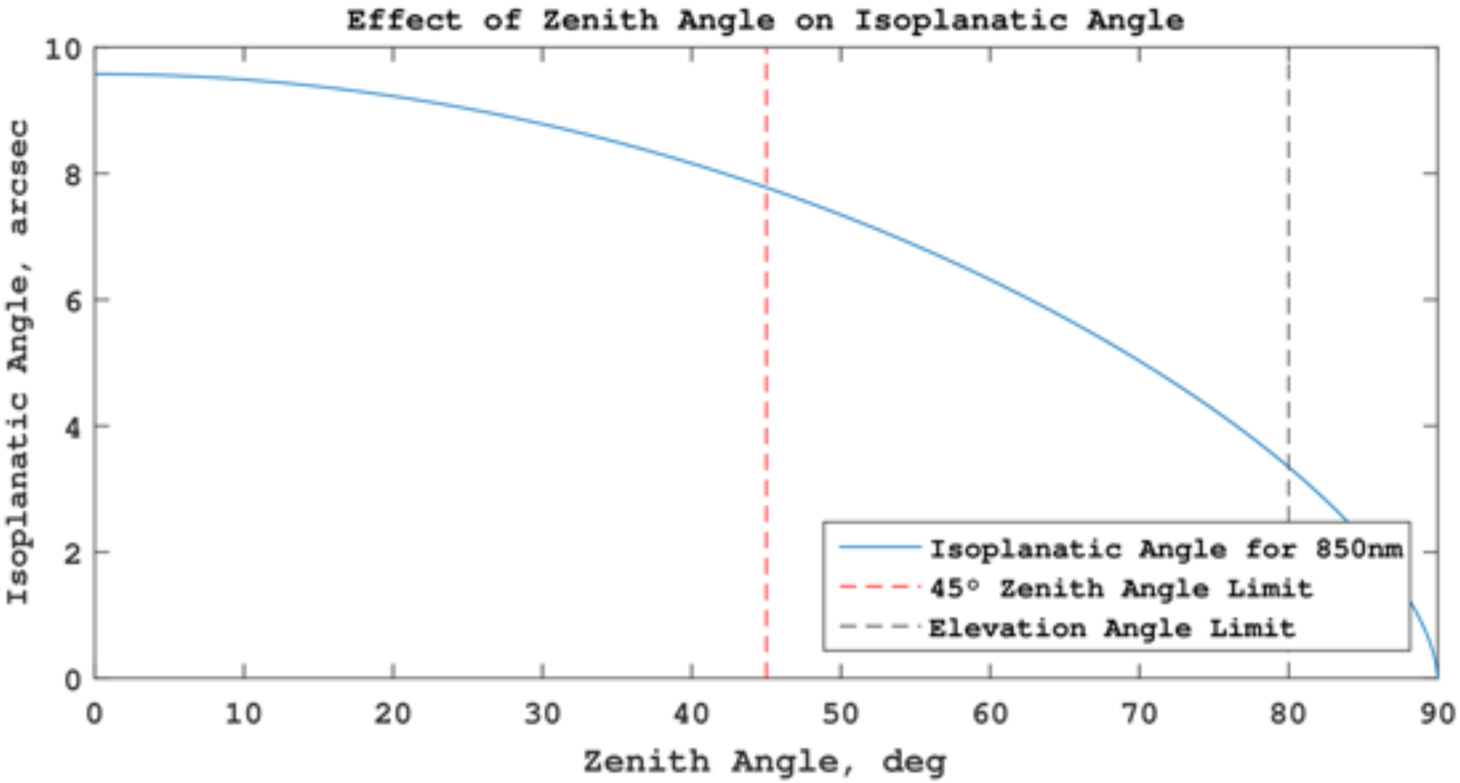
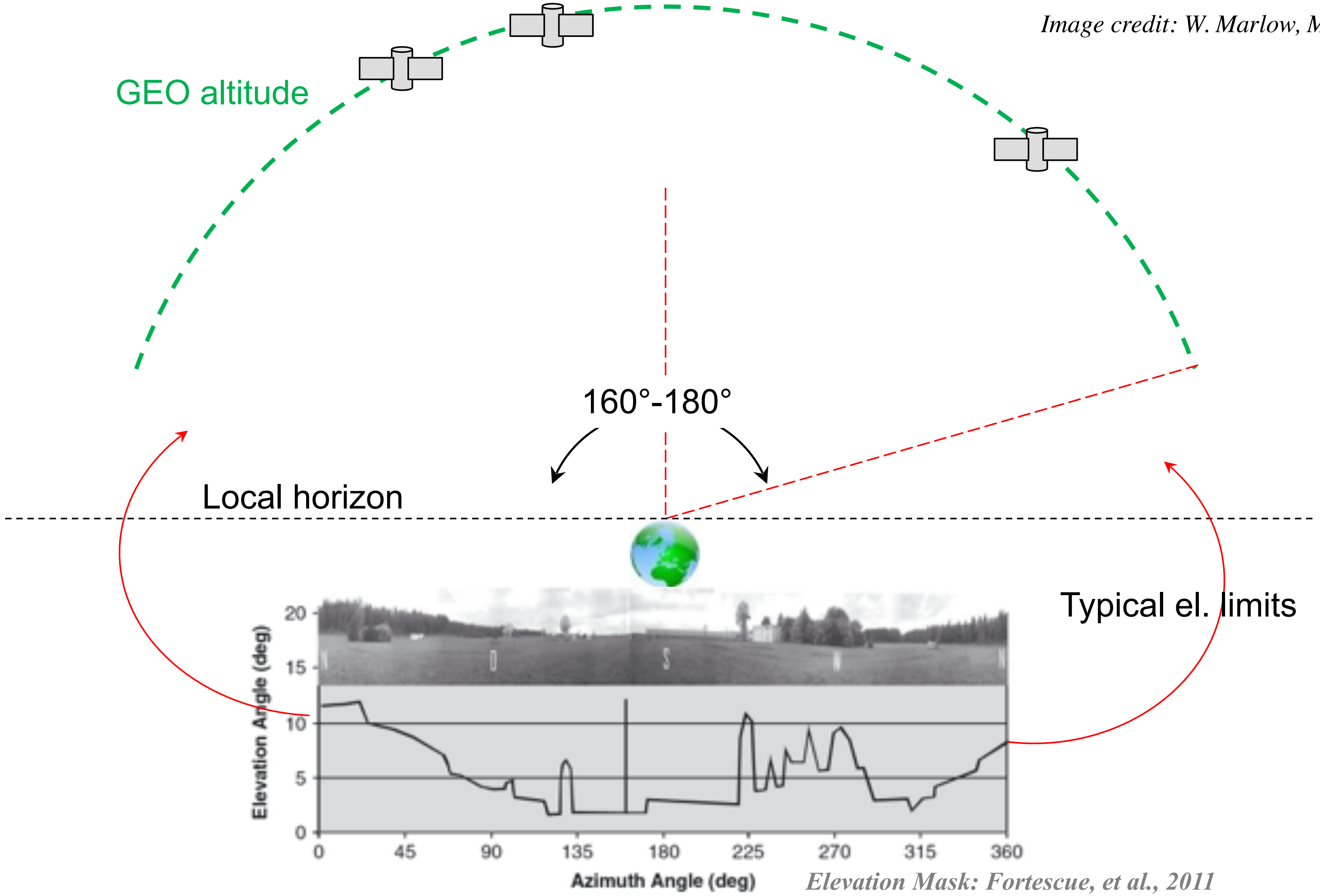


Image credit: W. Marlow, MIT

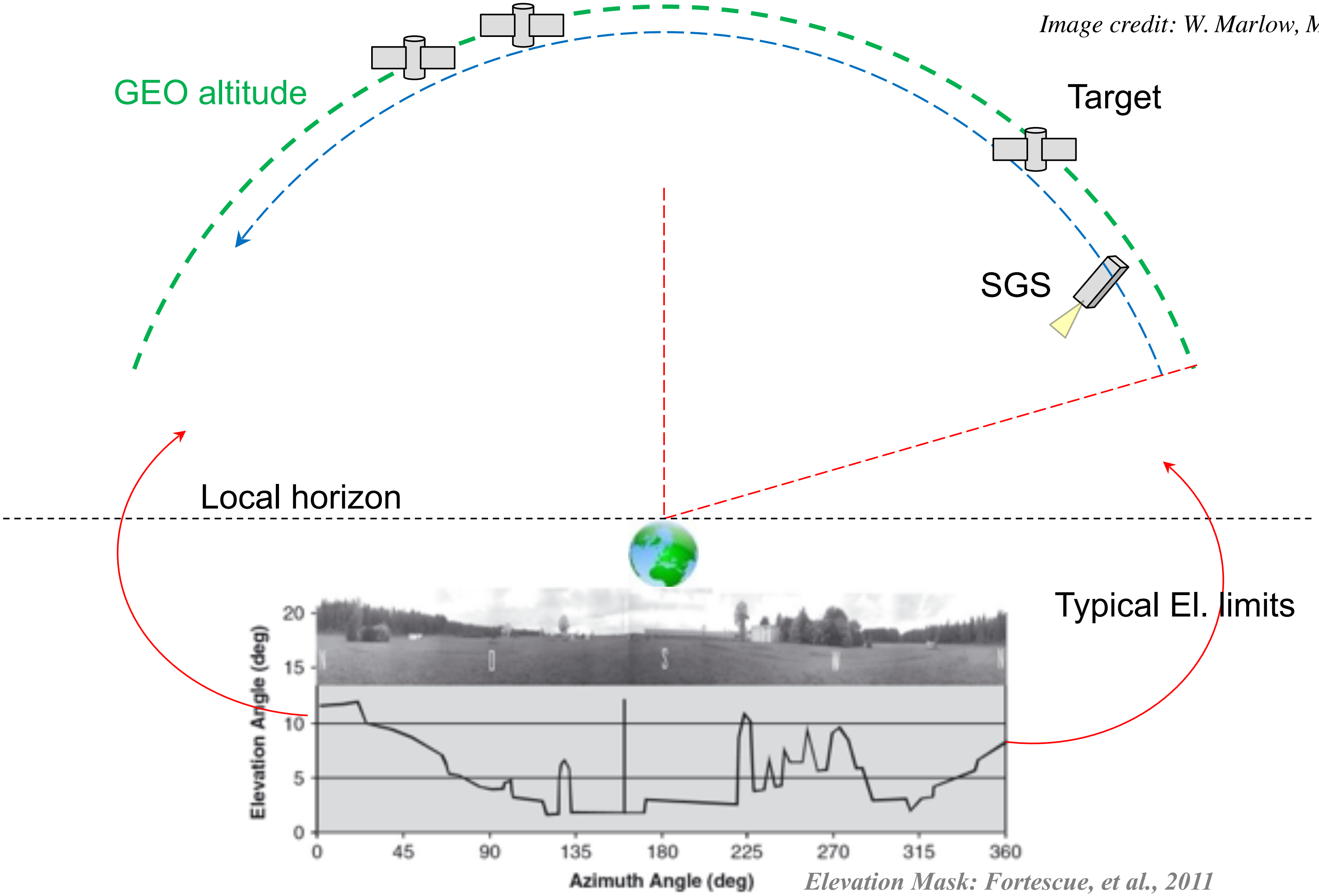
Ground System FOV

Image credit: *W. Marlow, MIT*



Elevation Mask: Fortescue, et al., 2011

Ground System FOV



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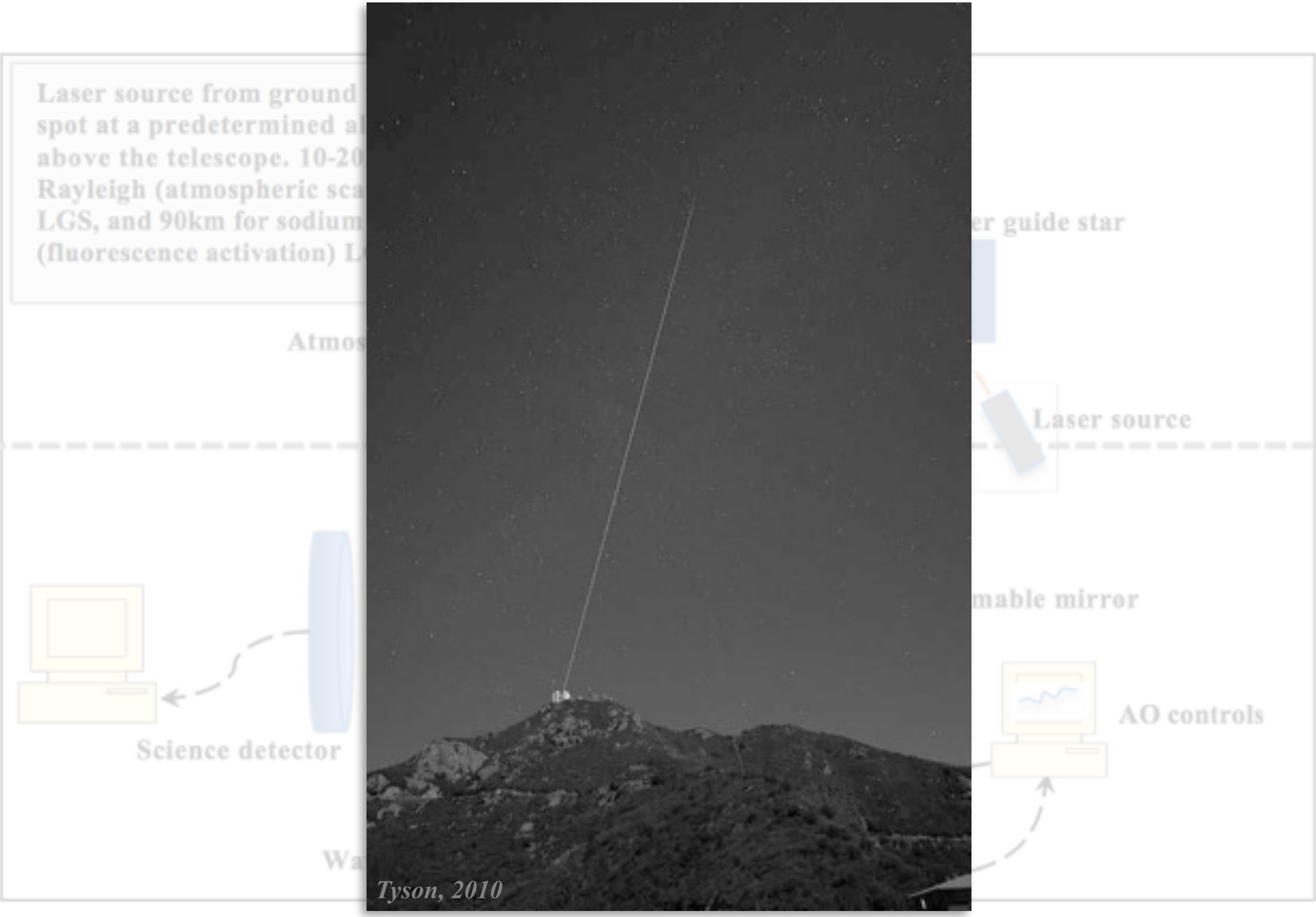
Elevation Mask: Fortescue, et al., 2011

Sodium-layer Guide Stars



Laser source from ground
spot at a predetermined al
above the telescope. 10-20
Rayleigh (atmospheric sca
LGS, and 90km for sodium
(fluorescence activation) L

Tyson, 2010

The Greenaway Orbit

- **Explored ‘Greenaway’ orbit**
  - **Difficult with highly elliptical orbits**
  - **Very short integration times (orbits are designed for sidereal rate matching)**
  - **Sparse imaging opportunities**
- **Leads to the need for a GEO-specific orbit for GEO imaging**

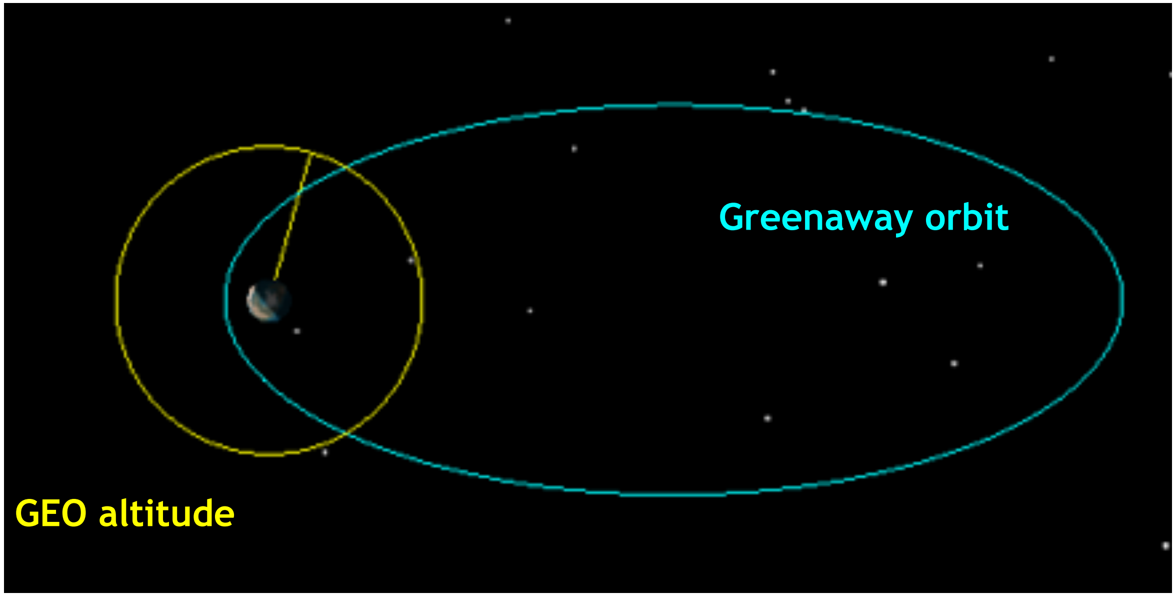
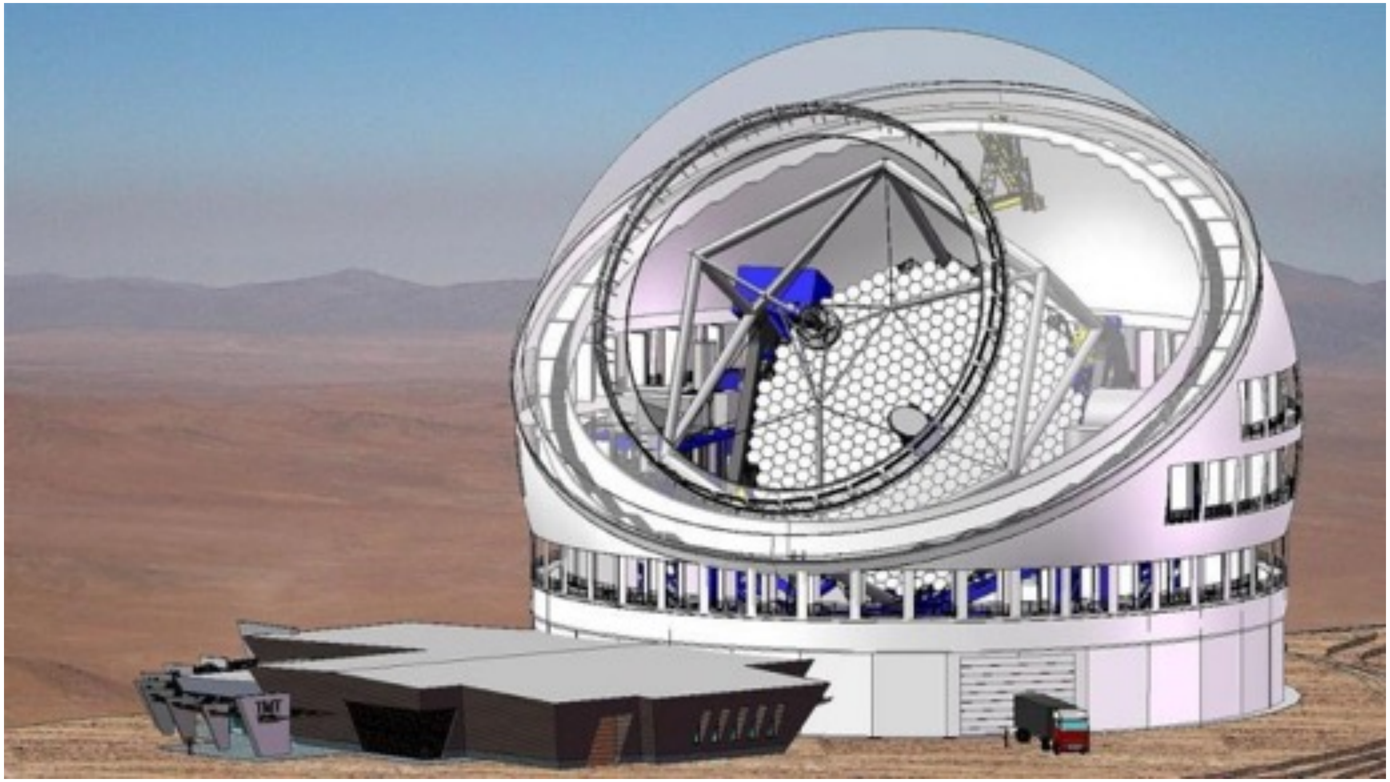


Image credit: W. Marlow, MIT

Next Generation Optics



http://www.tmt.org/gallery/renderings

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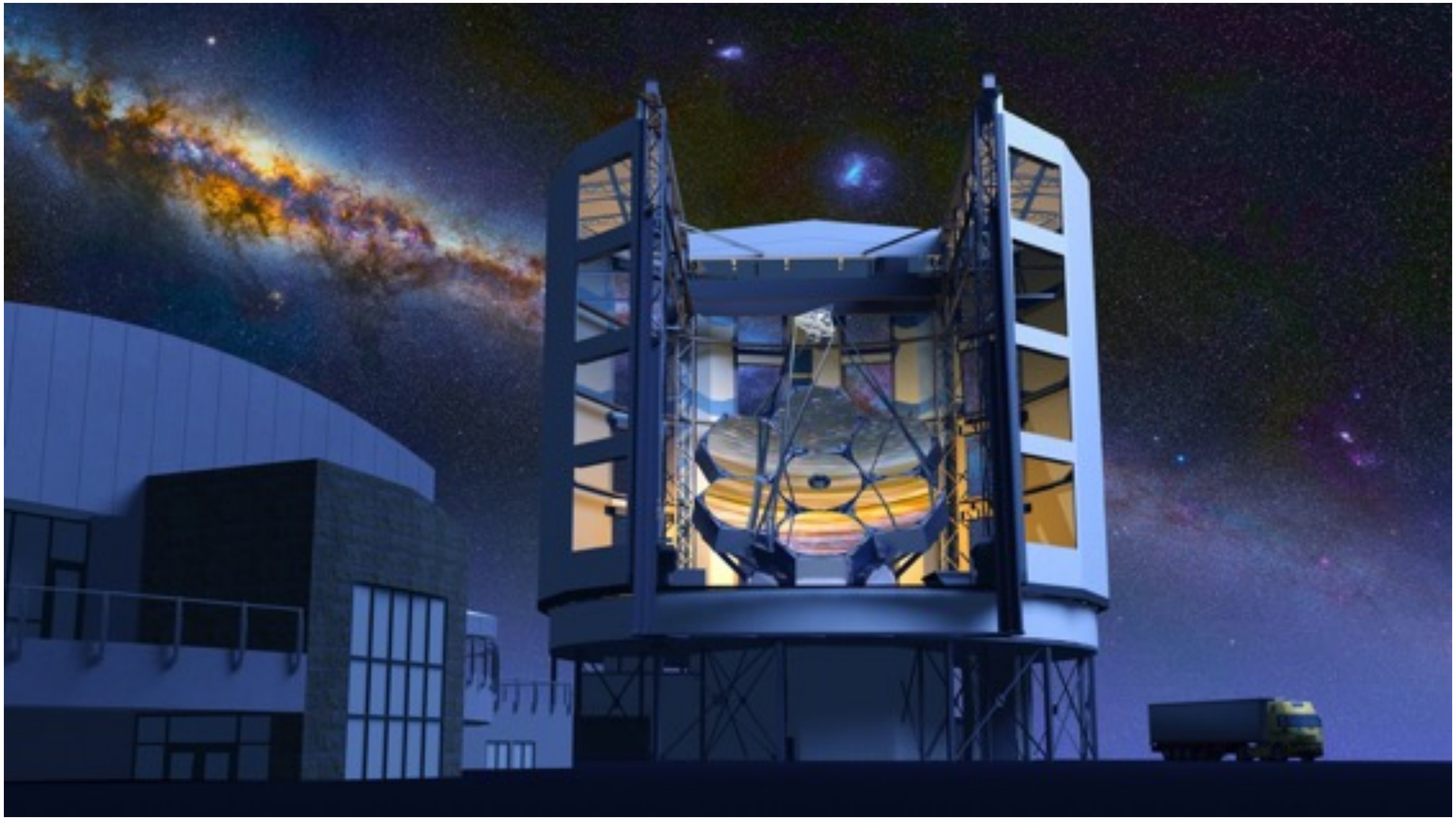
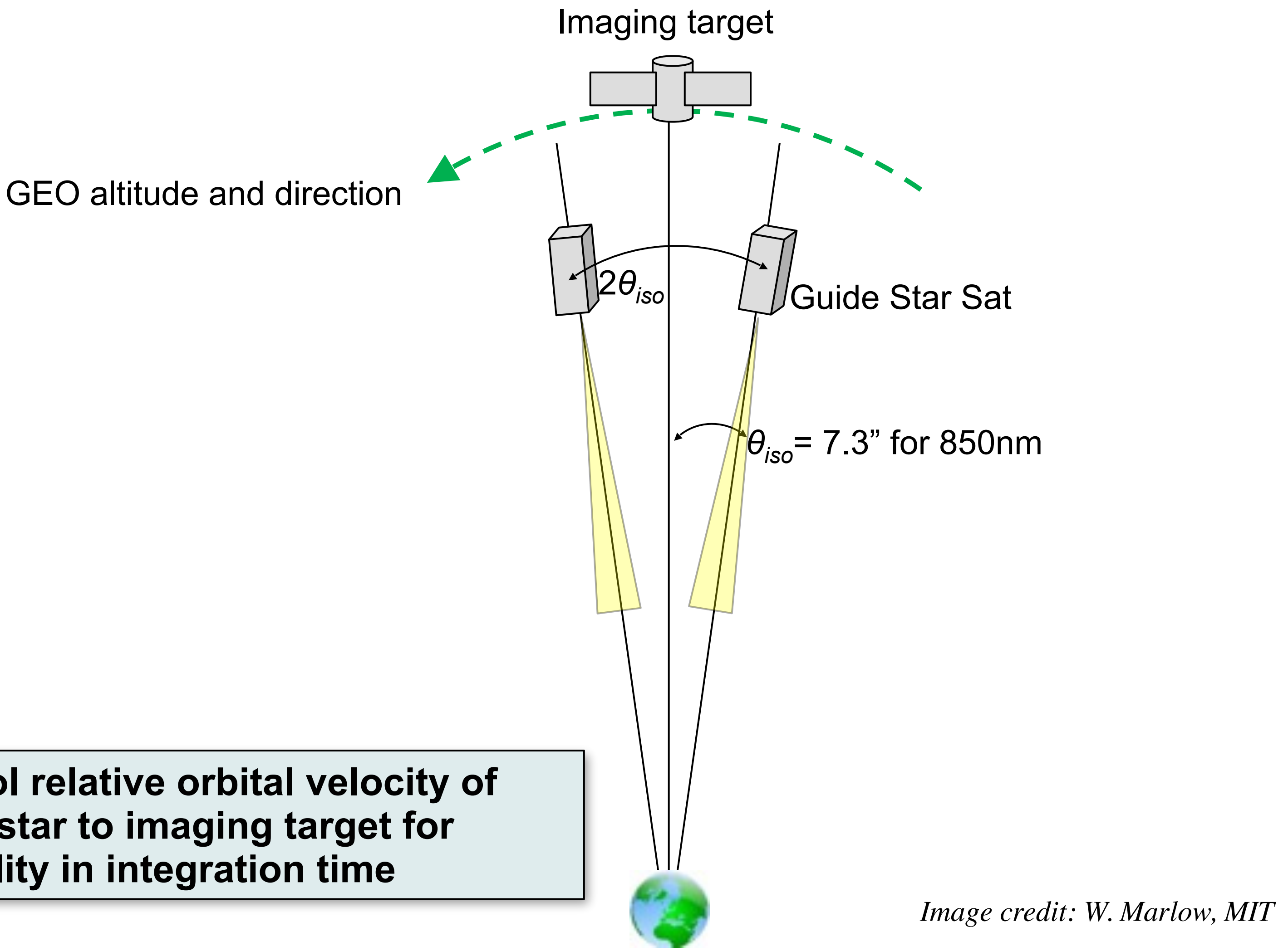


http://www.gmto.org/Resources/Still-GMT-S21-hi-res.jpg

Imaging Within Isoplanatic Patch

Diagram of guide star traversal during imaging of GEO object



Control relative orbital velocity of guide star to imaging target for flexibility in integration time

Image credit: W. Marlow, MIT

Orbit Assignment

Diagram of guide star traversal during imaging of GEO object

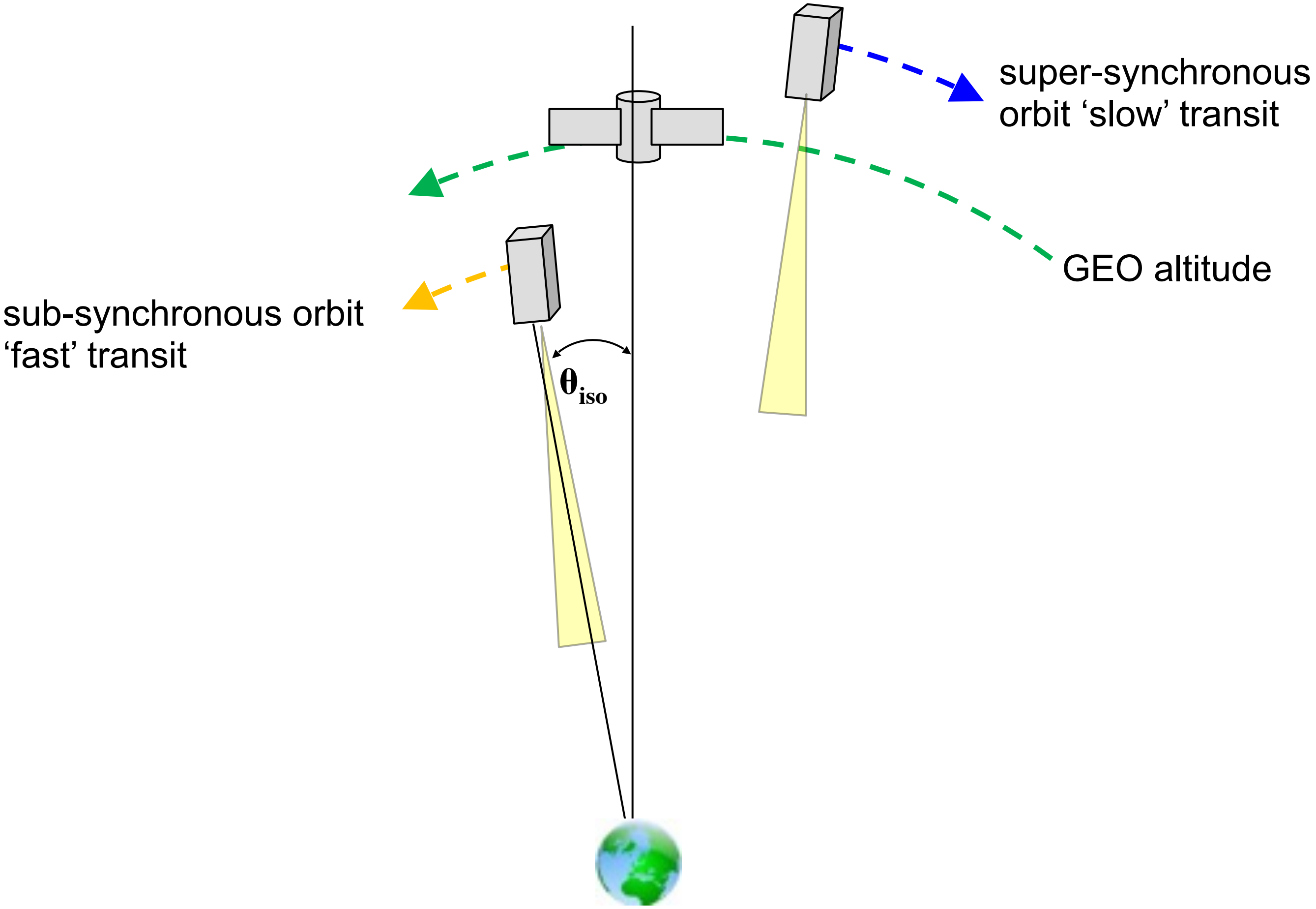


Image credit: W. Marlow, MIT

Orbit Assignment

Diagram of slow vs fast transits relative to imaging target

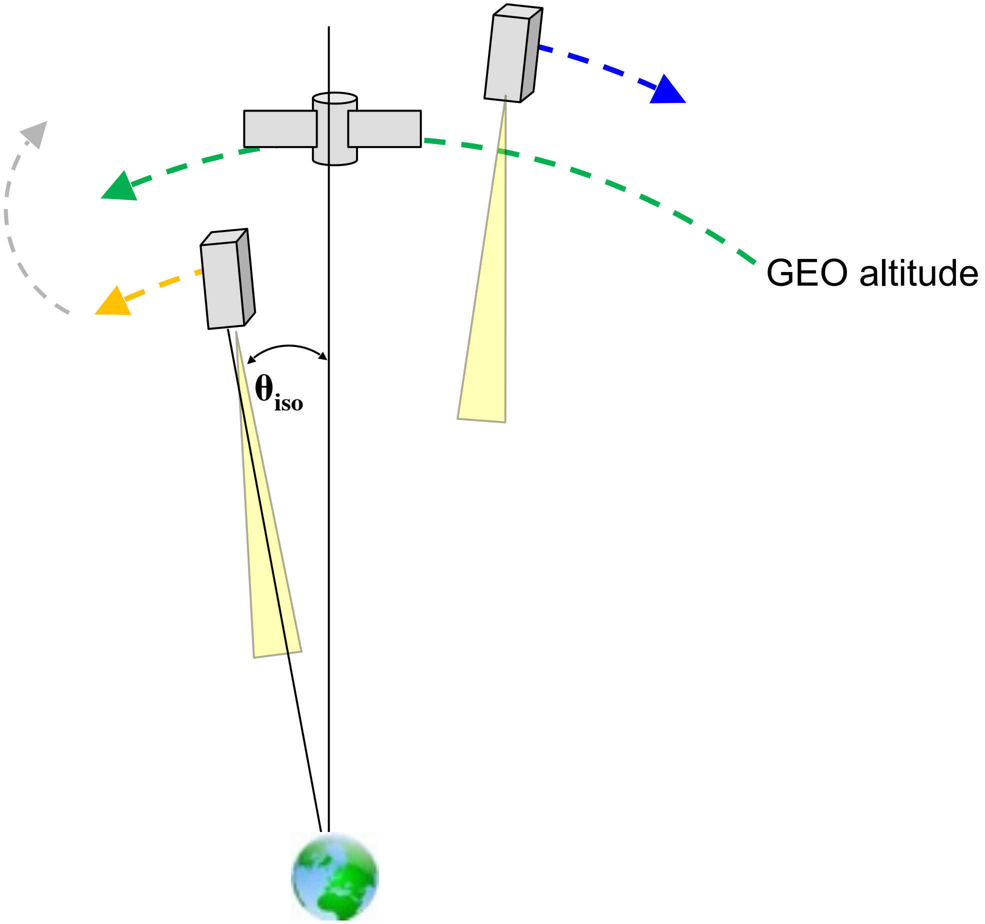


Image credit: W. Marlow, MIT

Optics Basics

- For optical systems, angular resolution is limited by diffraction
  - For circular apertures, it is defined as the Rayleigh criterion:

$$\theta = 1.22\frac{\lambda}{D}$$

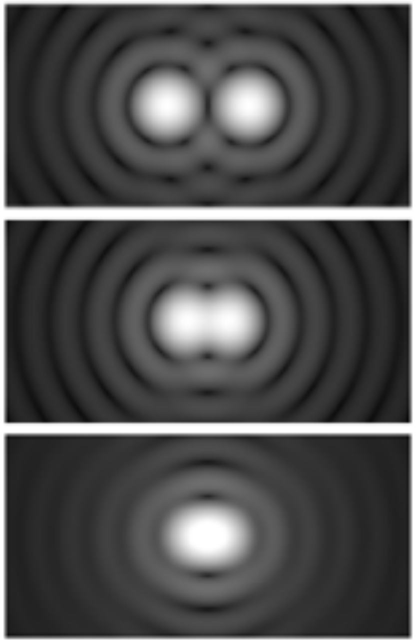
θ = angular resolution
λ = wavelength (*500nm or 850nm for this talk*)
D = aperture diameter

- Fried's parameter and FWHM Criteria
  - Optical systems viewing through the atmosphere are limited by effects of turbulence

$$FWHM \cong \frac{\lambda}{r_0}$$

$FWHM$ = Full width at half-max
r_0 = Fried's parameter, captures turbulence effects

Results in resolution 30-90 times worse than diffraction limit



Airy disk patterns
https://en.wikipedia.org/wiki/Airy_disk

Optics Basics

- **Fried's parameter**
  - Captures atmospheric effects:

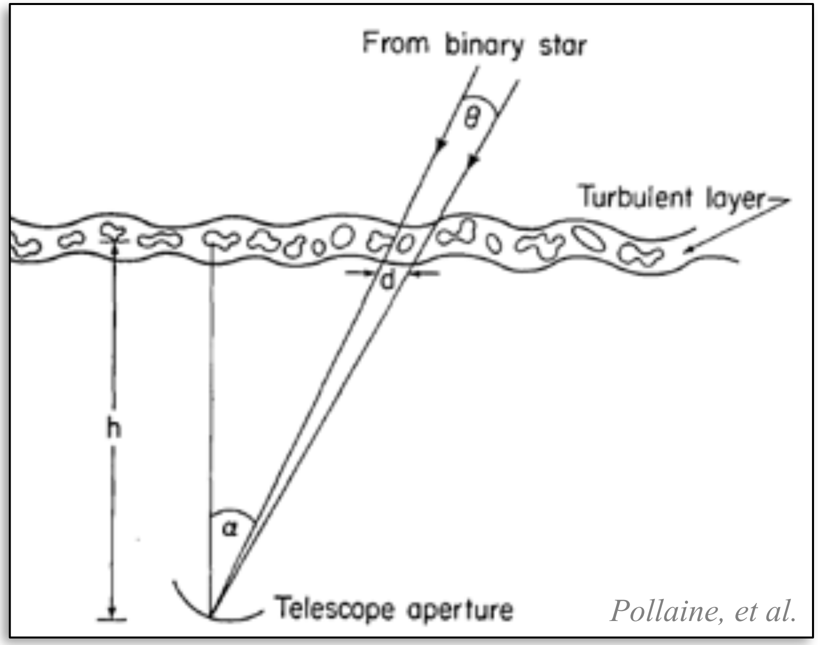
$$r_0 \cong 0.98 * 0.206265 \left(\frac{\lambda_{LCO}}{FWHM_{500nm}}\right)\left(\frac{\lambda_{desired}}{\lambda_{LCO}}\right)^{\frac{6}{5}} sec(\beta)^{-\frac{3}{5}}$$

$\lambda_{Las\ Campanas\ Observatory(LCO)}$ = 500nm
$\lambda_{desired}$ = 850nm
$Full\ width\ at\ half\ max$(FWHM)= aperture diameter
β = zenith angle, 0° for best-case

- **Leads to Isoplanatic Patch**
  - Patch where disturbance qualities assumed to be temporally coherent
  - Key metric for talk

$$\theta_{iso} \cong 0.314 \frac{r_0}{h}$$

h = altitude of characteristic turb. layer



Pollaine, et al.

Adaptive Optics

Goal is to achieve $\theta \cong \frac{\lambda}{D}$ for well-performing AO systems

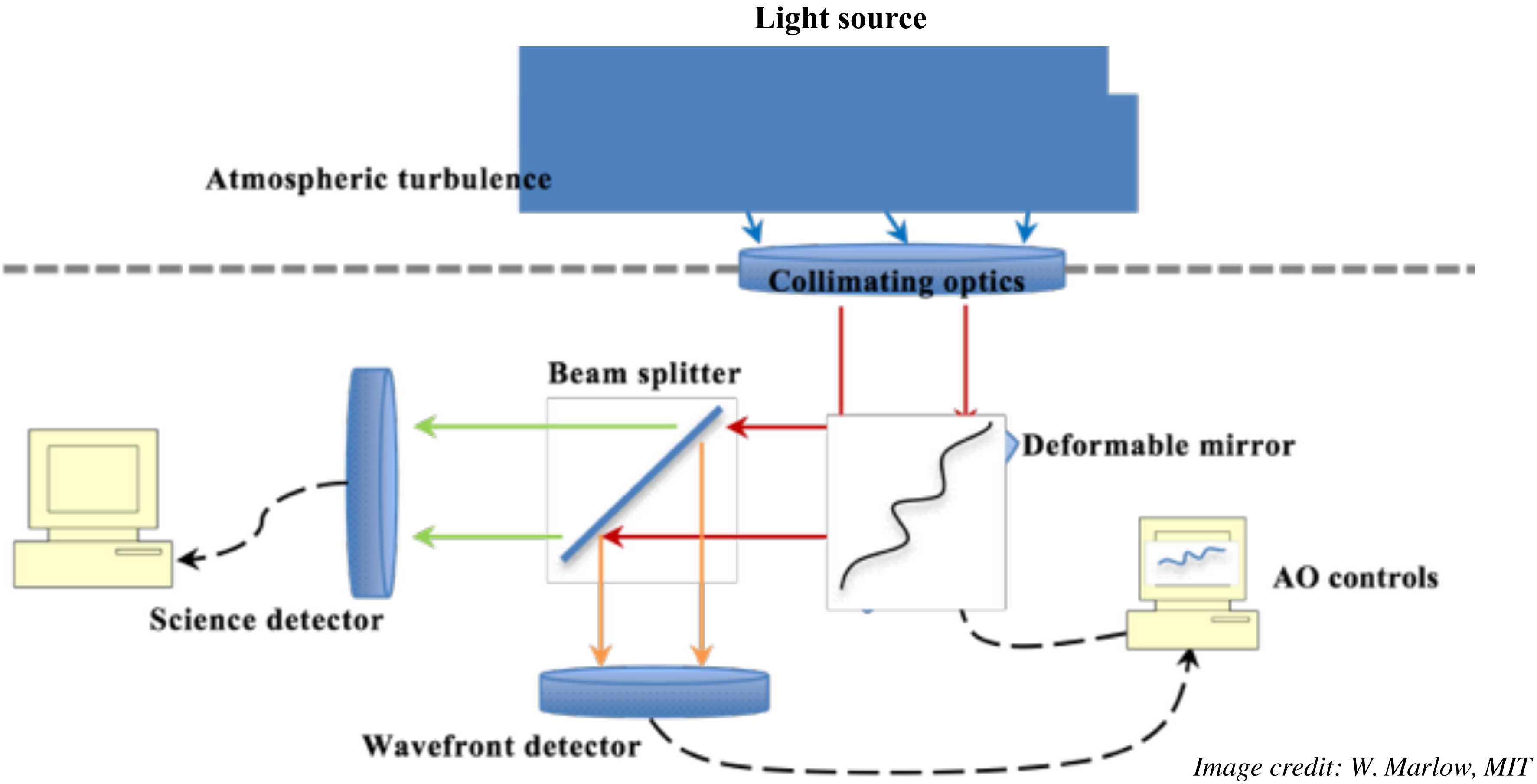


Image credit: W. Marlow, MIT

Natural Guide Stars

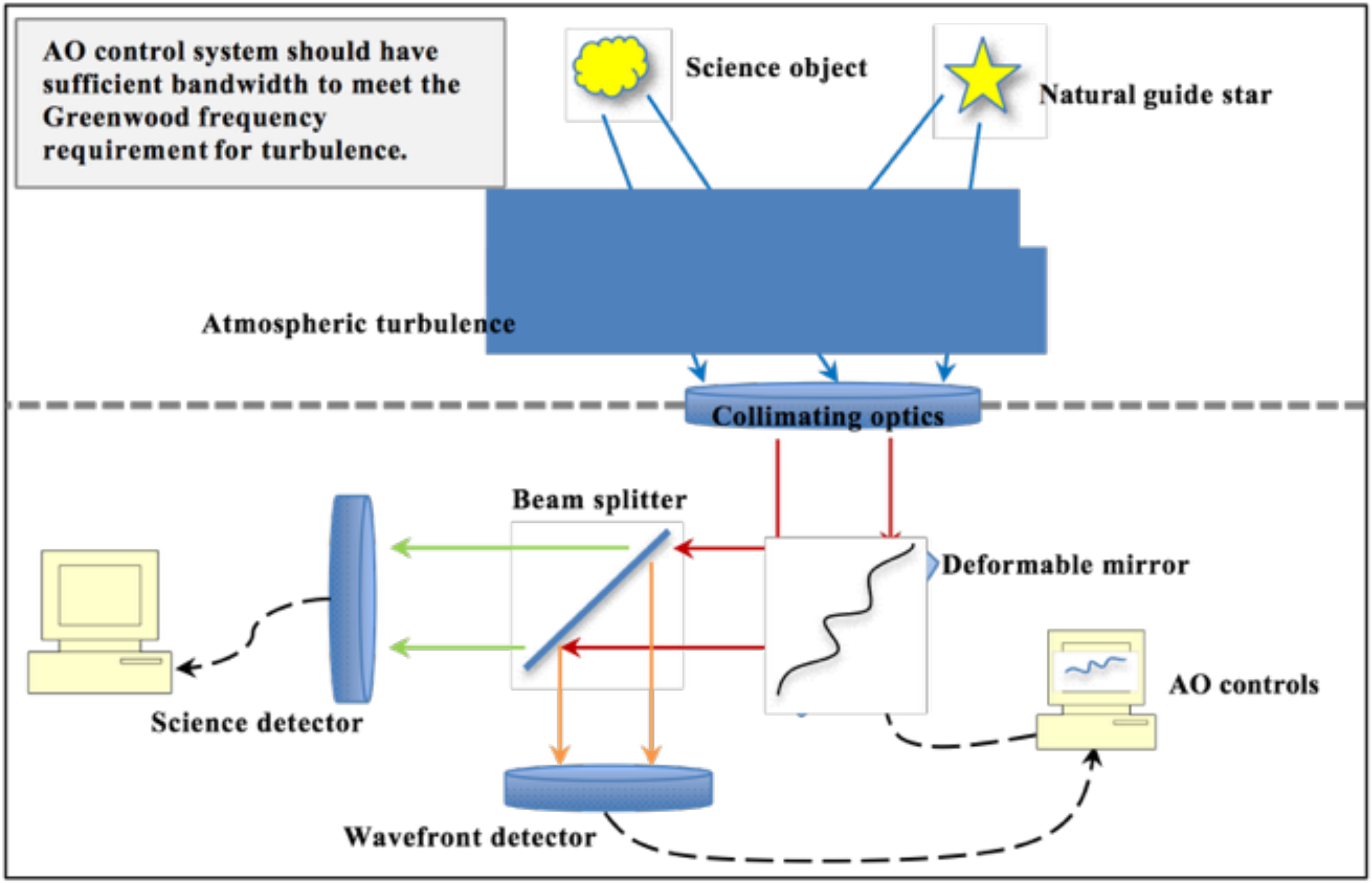
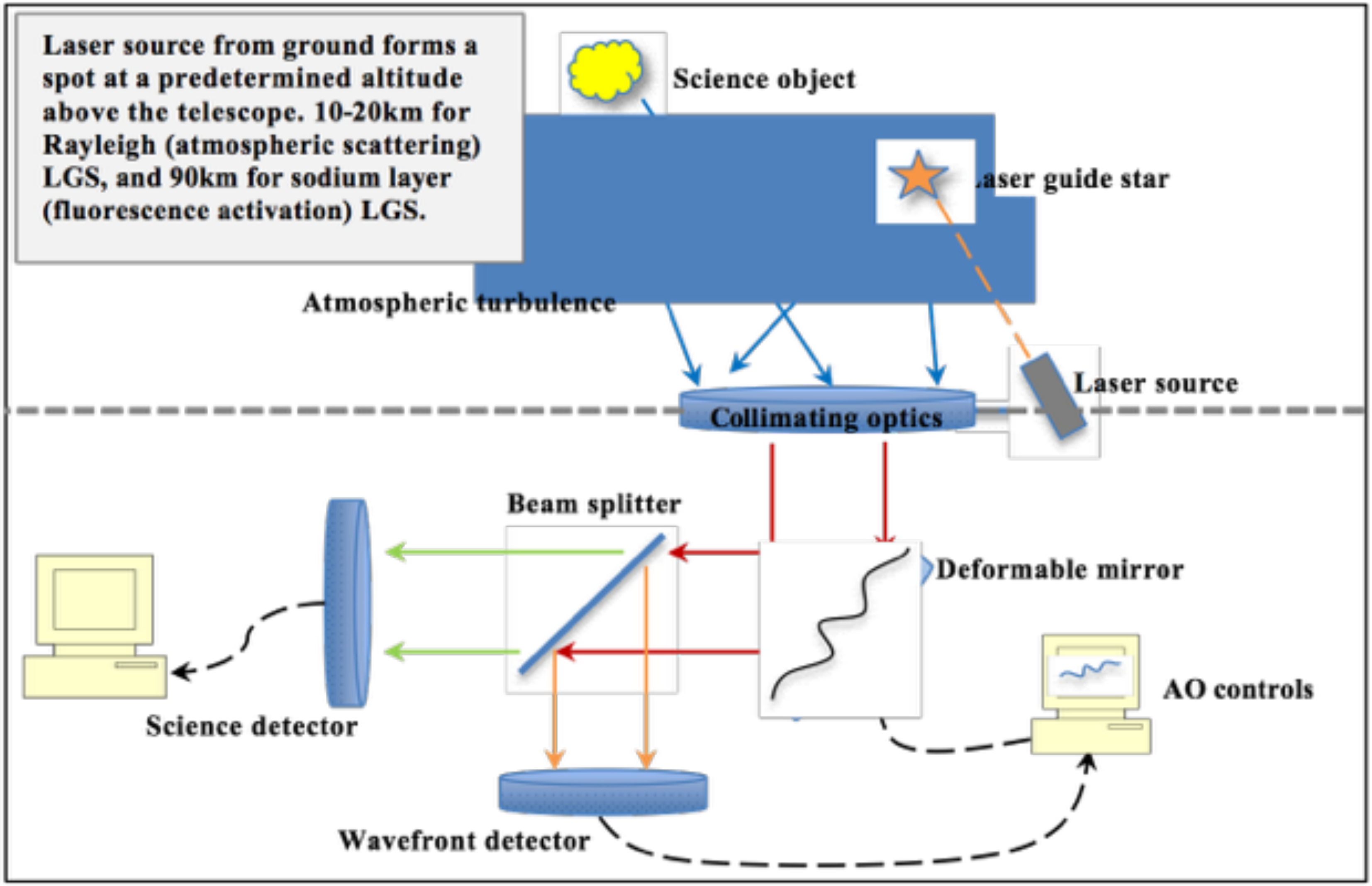


Image credit: W. Marlow, MIT

Sodium-layer Guide Stars



Laser source from ground forms a spot at a predetermined altitude above the telescope. 10-20km for Rayleigh (atmospheric scattering) LGS, and 90km for sodium layer (fluorescence activation) LGS.

Image credit: W. Marlow, MIT

Proposed CubeSat Guide Stars

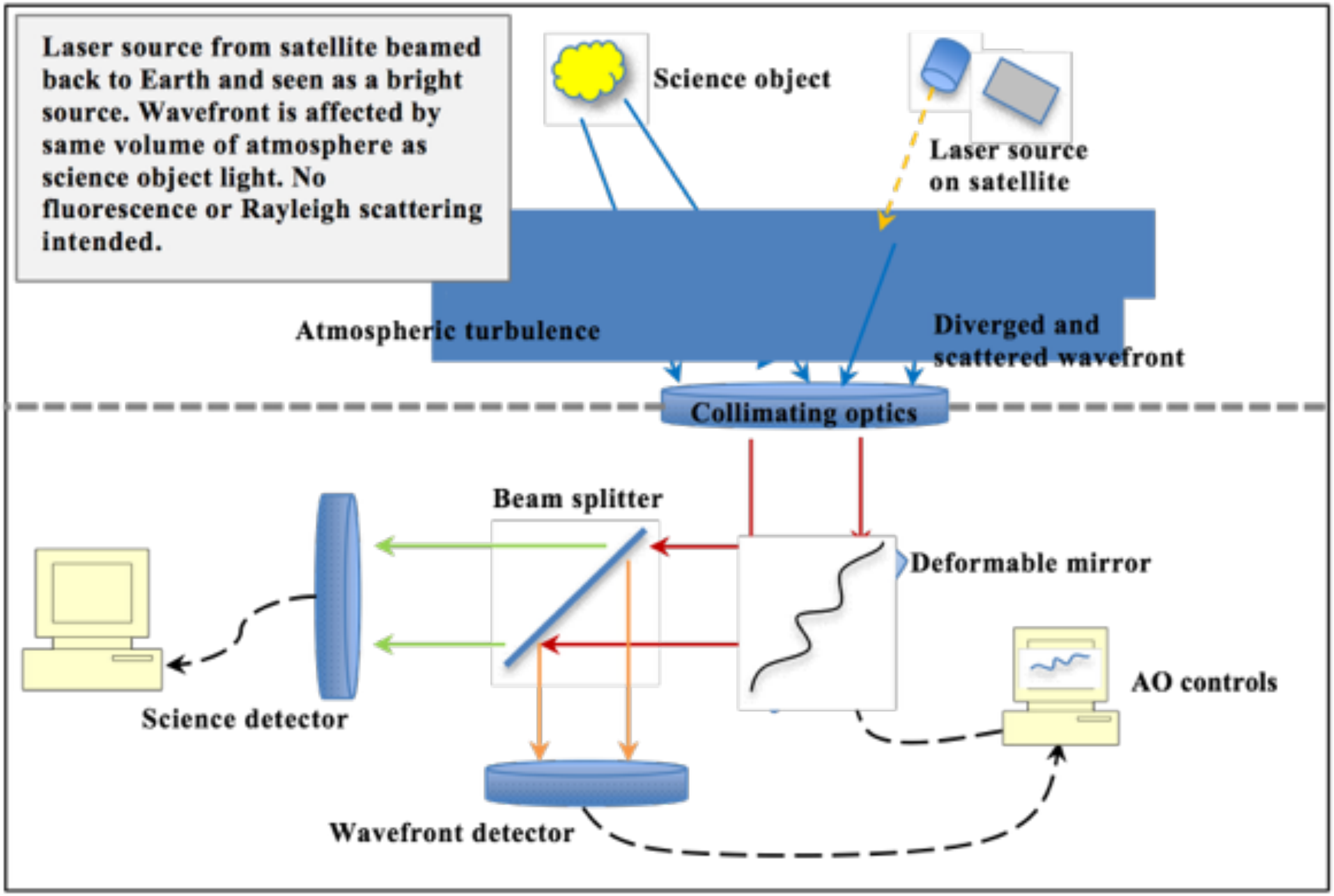


Image credit: W. Marlow, MIT