Designer “Star”: Spacecraft Development of the Laser Guide Star for a Large Segmented Aperture Space Telescope

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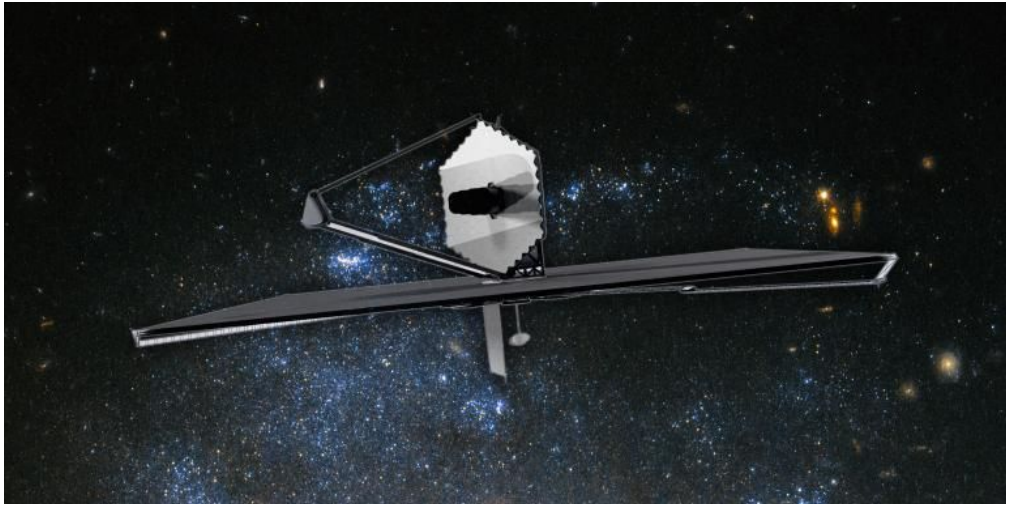
Motivation: Direct Image Earth-like Exoplanets

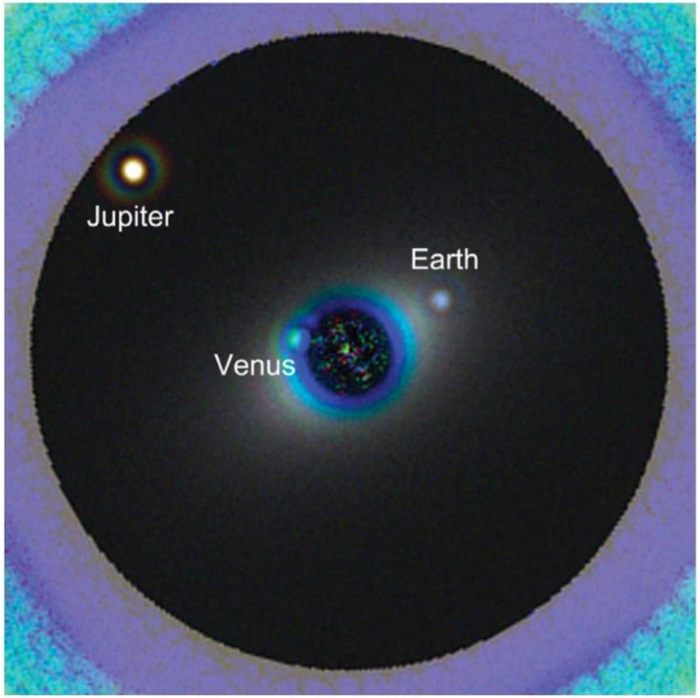
- 10^{-10} planet-star flux ratio
  → need to block star with high contrast
  → star shade or coronagraphy in space

- < 0.1 arcsecond planet-star separations
  → 4 meter to 16 m telescope



LUVOIR 9.2 m to 15 m segmented aperture concepts

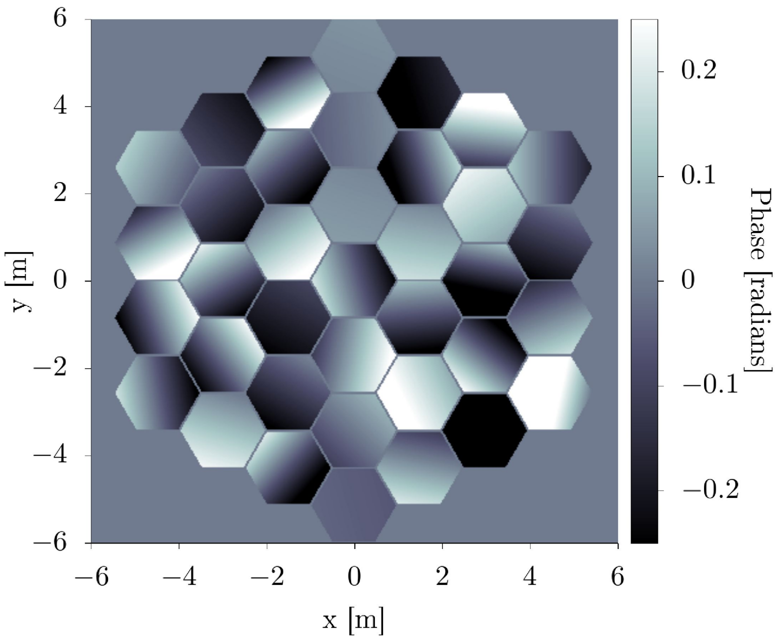
http://www.stsci.edu/scientific-community/community-missions/advanced-concepts



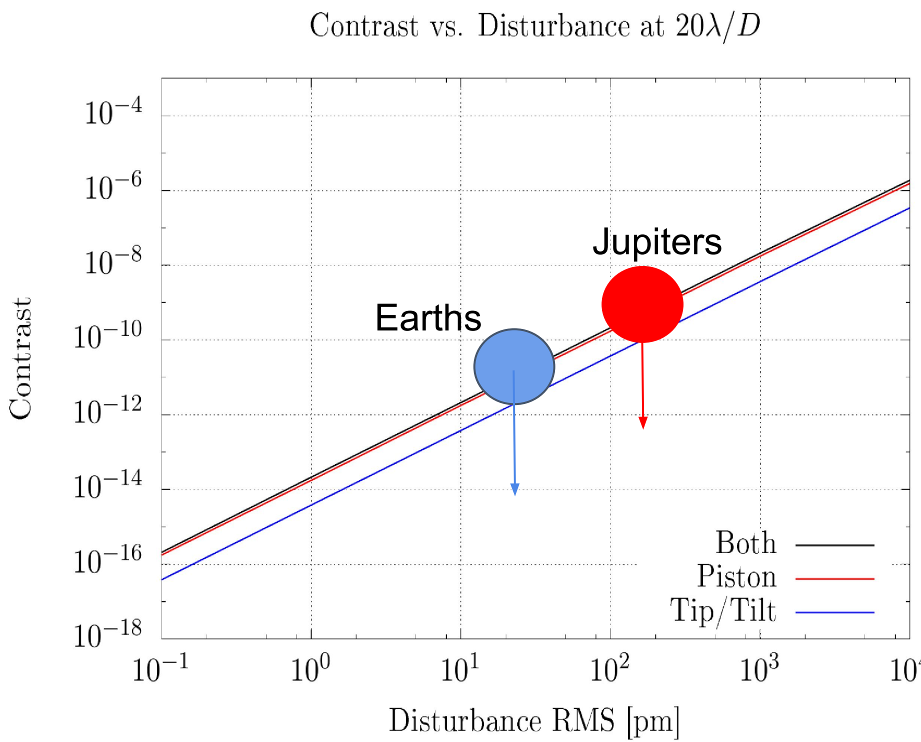
Roberge *et al.*, "Finding the Needles in the Haystacks: High-fidelity Models of the Modern and Archean Solar System for Simulating Exoplanet Observations," *Publications of the Astronomical Society of the Pacific*, vol. 129, 2017, p. 124401.

Problem: Segment motion swamps exoplanet signal

Segmented Primary Aperture

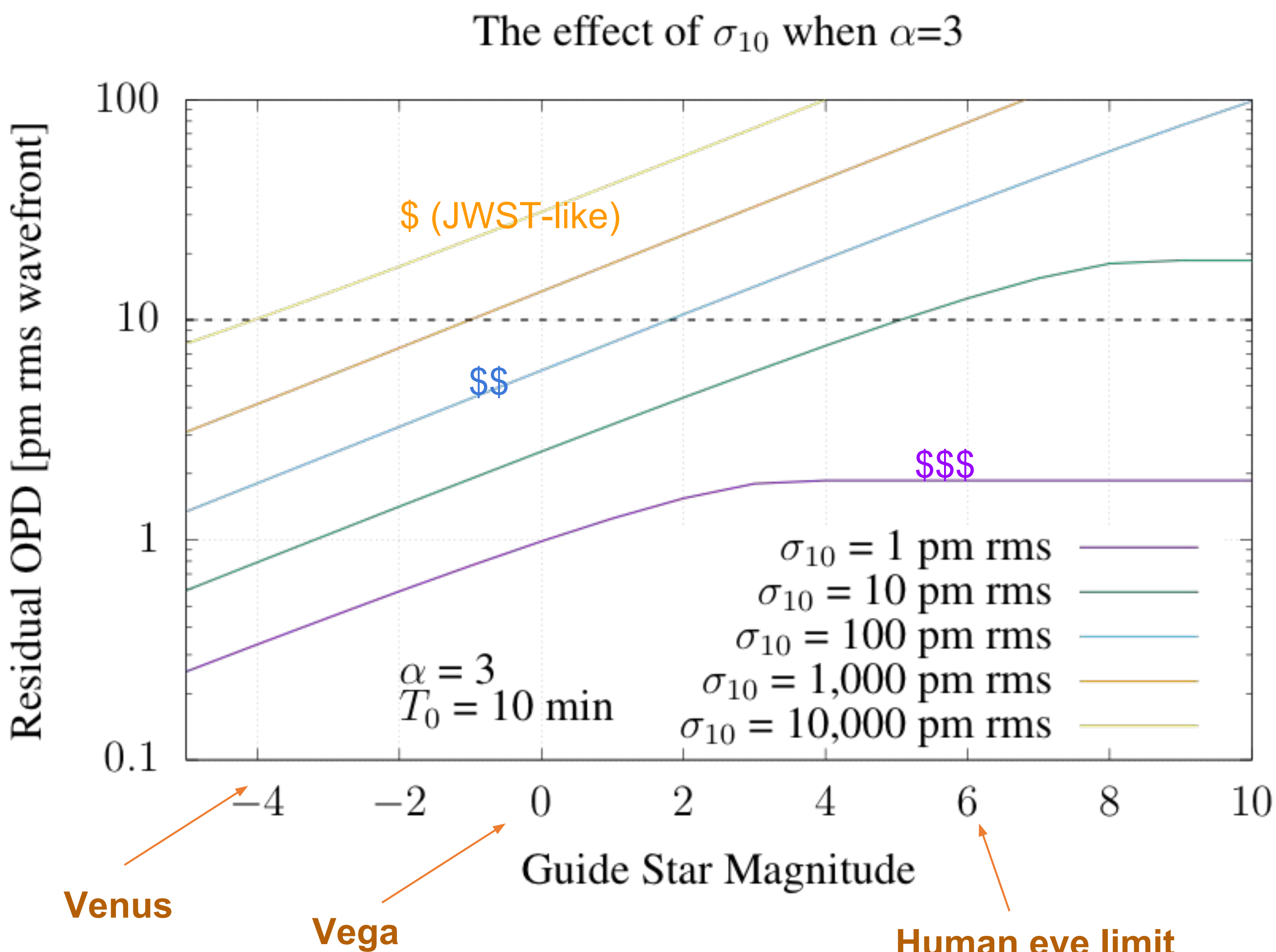


Contrast vs. Disturbance at $20\lambda/D$

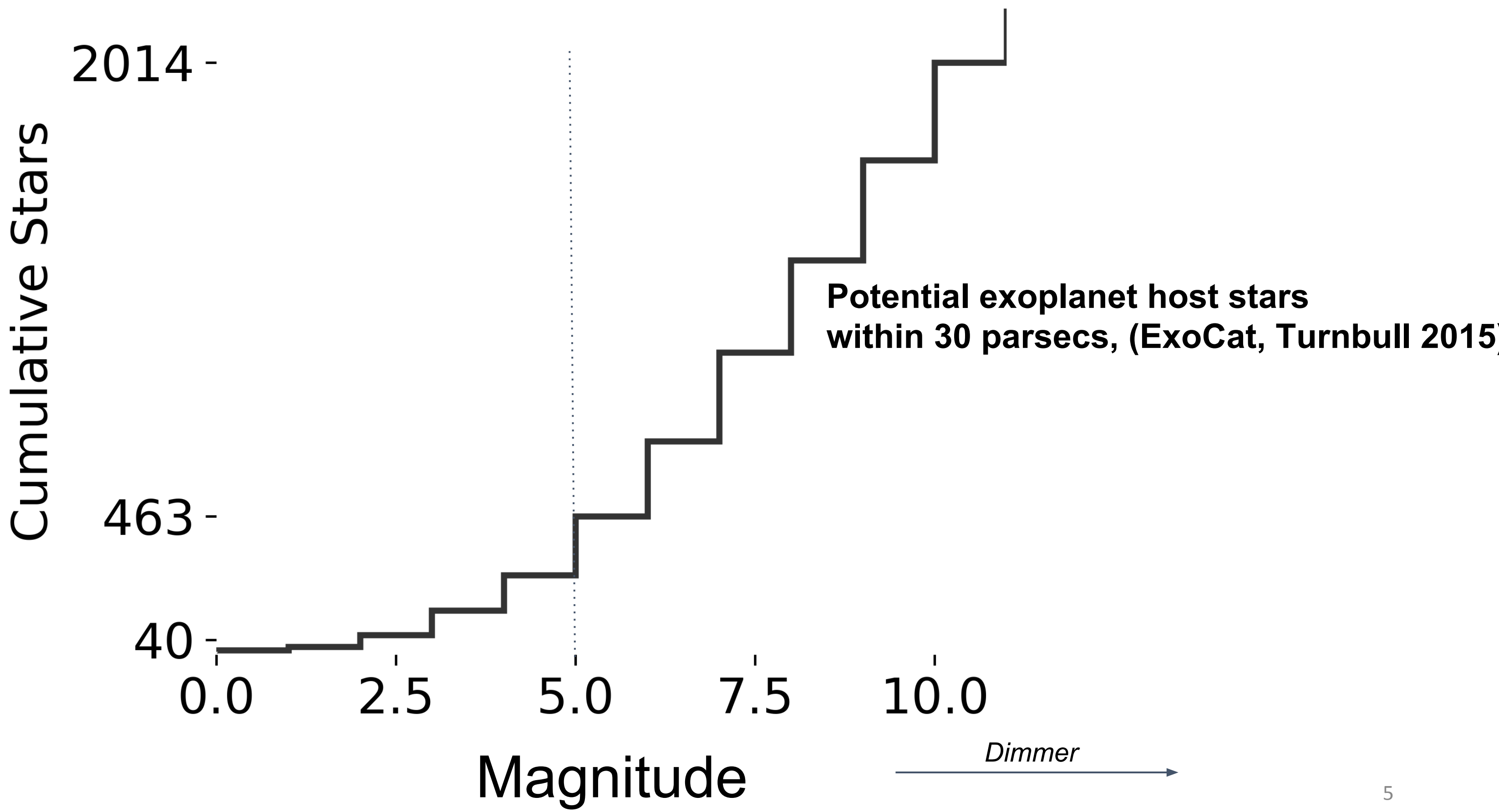


J. Males (U. of Arizona).

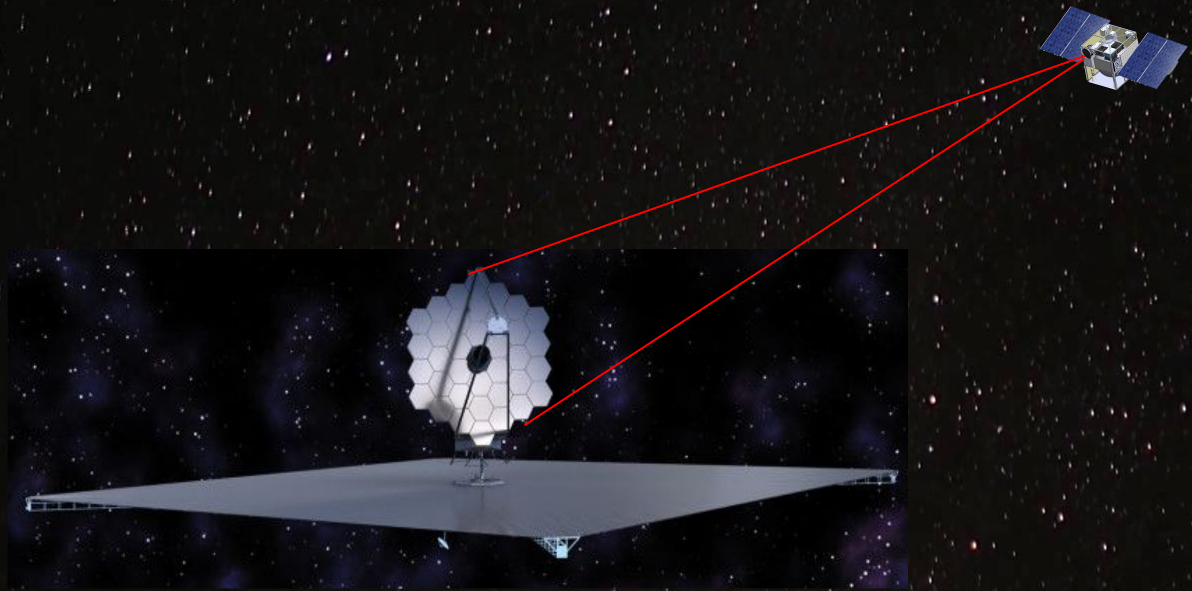
Bright guide stars improve closed loop wavefront sensing & control



Not enough bright stars near Earth-like system targets

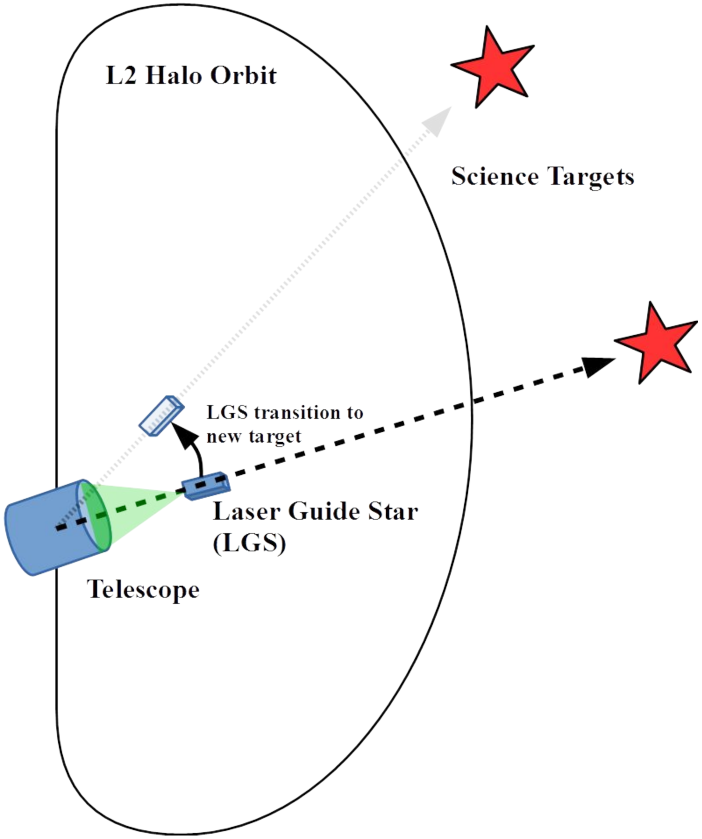


Solution? Build your own bright star.



Approach: Formation flying ConOps at L2

- Large segmented space telescope stays on periodic halo orbit
- Small satellite companion(s) fly in front of target star.
- Range: 10,000 km to 100,000 km
  - Sets wavefront curvature (near-field focus) and fuel usage
- Station keeping
  - Sets accuracy, keeps guide-star behind coronagraph
- Pointing
  - Sets power budget and beam divergence



J. Clark (MIT)

Primary Segment Motion Compensation

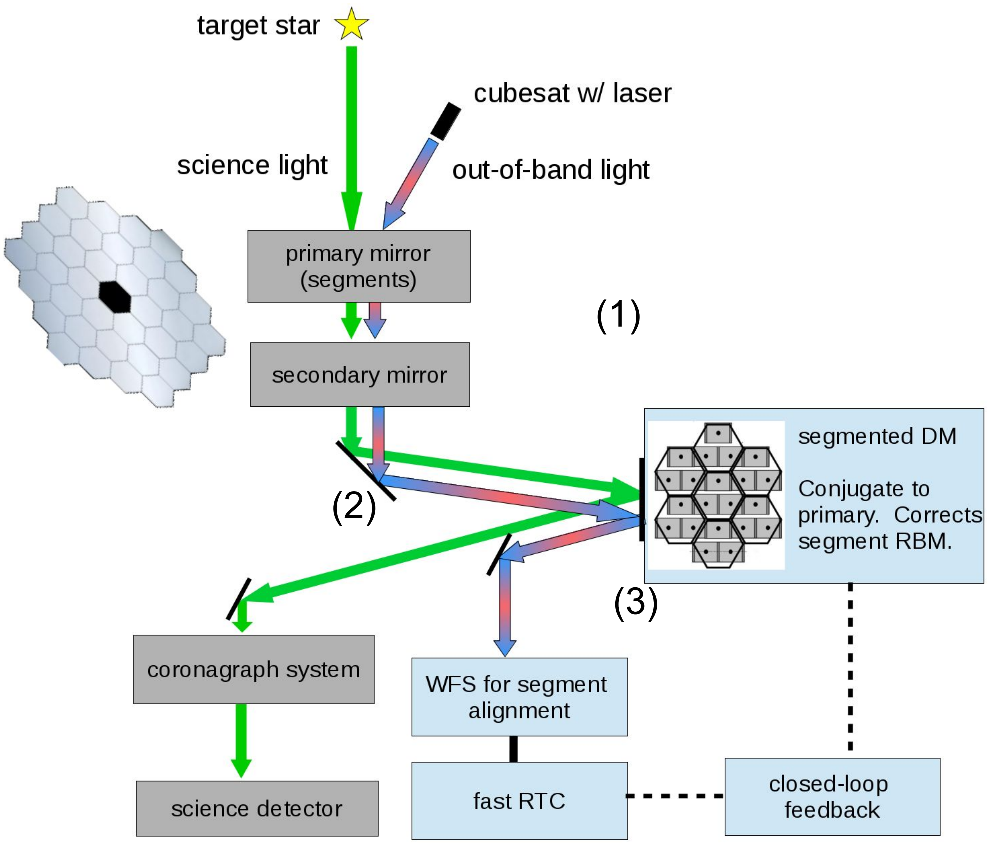
Goal: Relax stability requirements

Segment rigid-body motion compensation

1) Primary is re-imaged on fast segmented Deformable Mirror

2) LGS light is split to a WFS, science light goes to coronagraph.

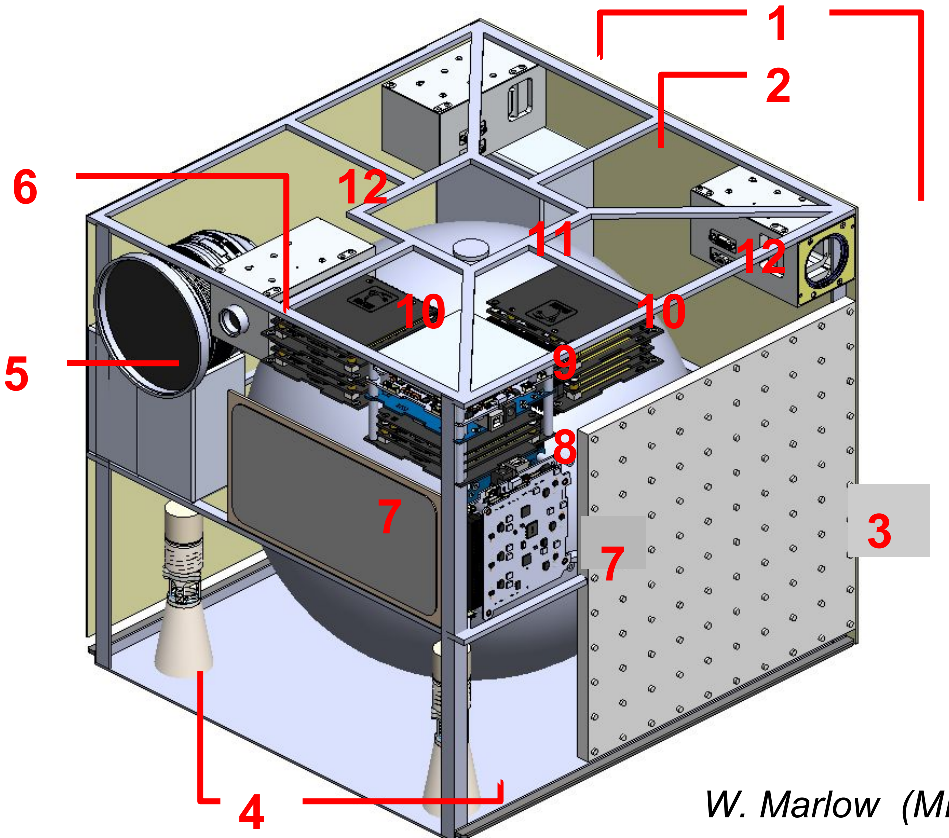
3) WFS feedback in closed-loop to segmented DM, which corrects piston & tip/tilt



segment RBM correction in closed-loop with a fast segmented DM

J. Males (U. of A.)

27U Preliminary Spacecraft Design



W. Marlow (MIT)

	Idle Flight	Formation Flight	Propulsion Full	Laser Ops
Power Draw	22 W	67 W	87 W	175 W

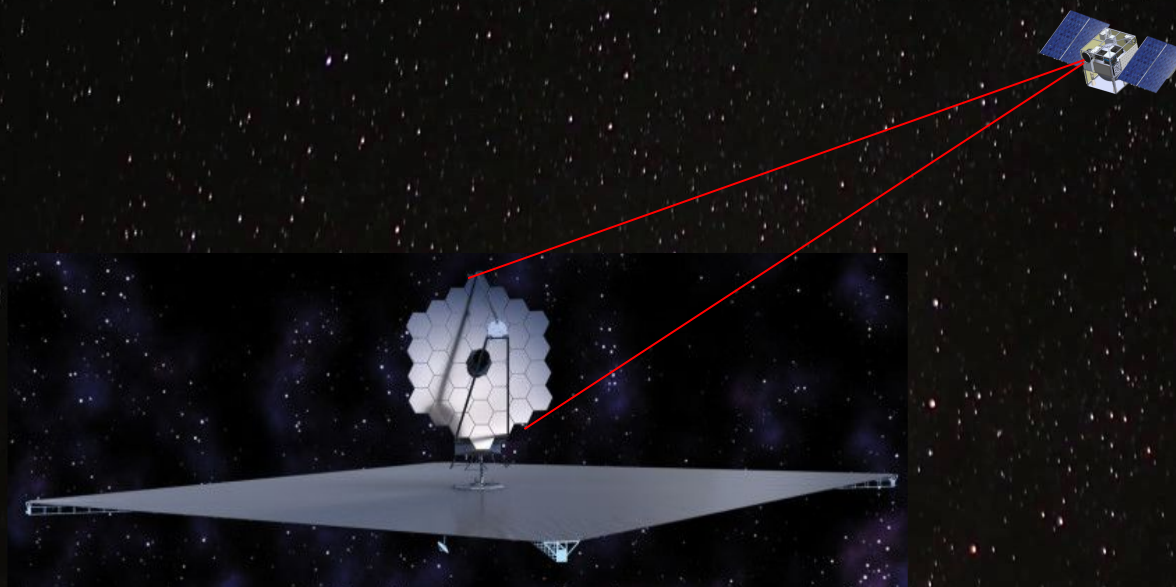
Shown:

1. **Star trackers**
2. **ADCS**
3. **LED beacon**
4. **Thrusters (2 of 4 shown)**
5. **Main laser system**
6. **Beacon laser**
7. **RF ranging and comm**
8. **Electrical power system**
9. **Avionics system**
10. **Batteries**
11. **Fuel tank**
12. **Radiator panels**

Not shown:

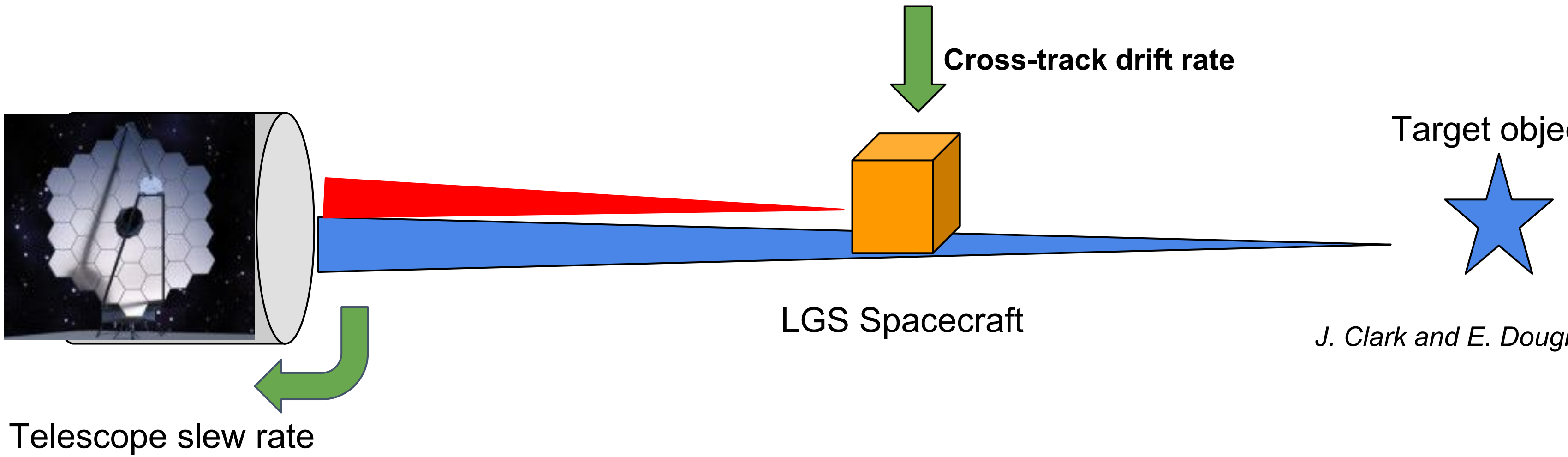
- **Solar arrays**
- **Full thruster plumbing**
- **Full thermal management**

But how to test (not at L2)?



Earth Orbit Demo Performance Factors

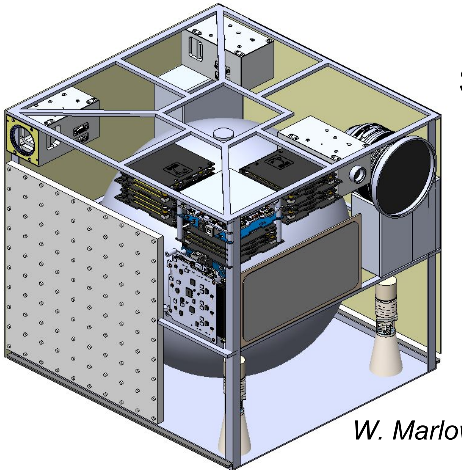
- Two important angle rates
  - The **slew rate** of telescope tracking the target
  - The guide star **drift rate** across the telescope-target vector
    - This is related to the thrust that the LGS would have to use to fight the dynamics of the system to stay on the target vector.
  - We consider these factors in order to **design a propulsion system** for the LGS
    - And assess how long the LGS can formation fly with a target



J. Clark and E. Douglas (MIT)

Earth-Orbit Demonstration Feasibility

Telescope Location	LGS Location	Target	Telescope-LGS Range	Telescope Slew Rate	LGS Drift Rate	LGS Thrust Requirement
L2	*L2*	*Star*	*10,000 km to 100,000 km*	*“0”*	*~1 deg/day (0.2 urad/sec)*	*< 0.1 mN cross-track*
LEO	GEO + 300 km *(graveyard)*	GEO ComSat	35,000 km to 45,000 km	~0.1 mrad/sec (0.3’/sec)	~0.8 urad/sec	0.01-0.1 N radial in
Ground	**GEO + 300 km** *(GEO graveyard)*	**GEO ComSat**	**32,000 km to 39,000 km**	**“0”**	**~0.3 urad/sec**	**0.01-0.1 N radial in**



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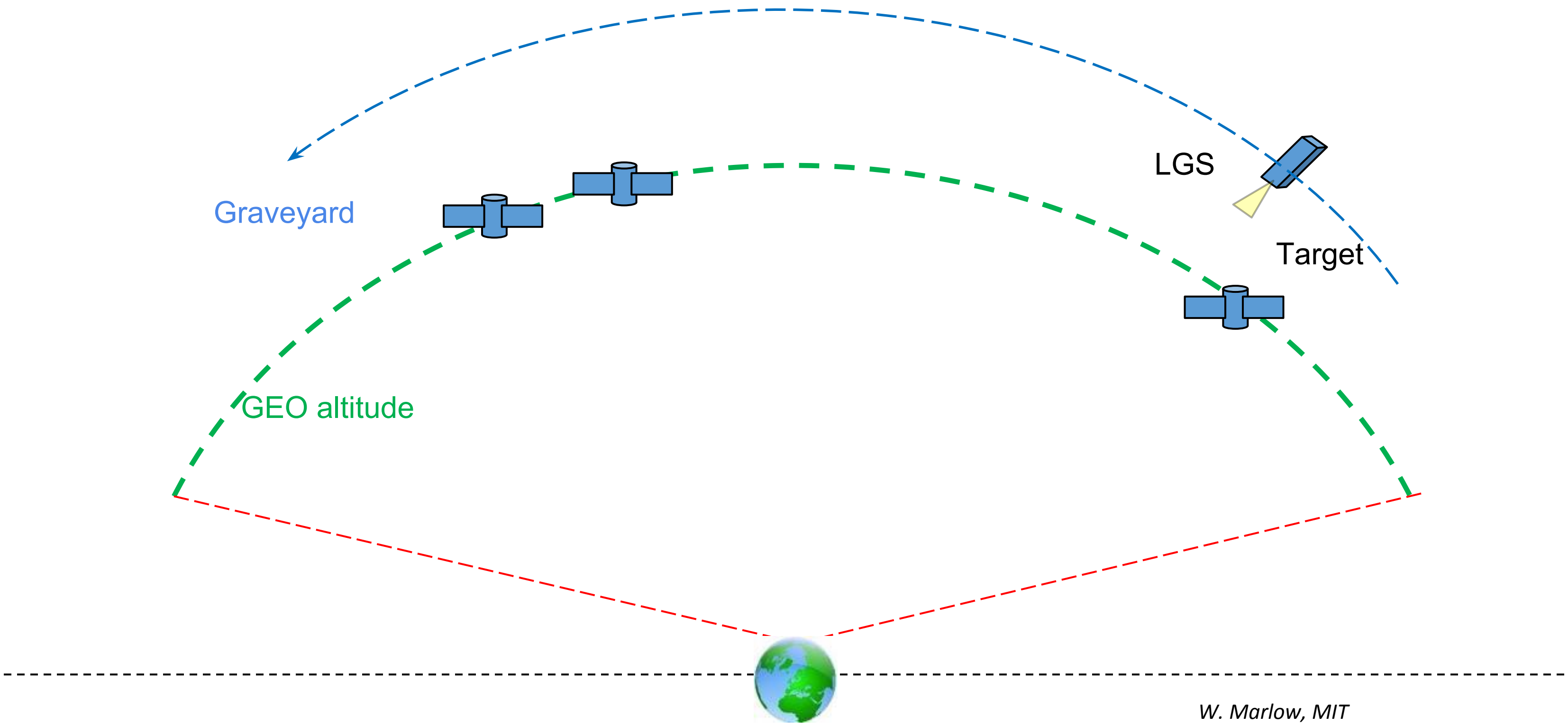
27U LGS Spacecraft at GEO

Other scenarios assessed, found less suitable; details in backup

Imaging GEO: Super/Sub synch maneuvers

- Space-based Laser Guide Star for ground-based imaging of Geostationary (GEO) objects (Marlow et al. 2017)



W. Marlow, MIT

27U GEO LGS Demo thruster design trade

Propulsion option	Max Thrust (mN)	Power Required (W)	Delta-V Cap. (m/s)	Max offset from GEO (km)	Max formation flight duration (hours)	TRL (Est.)
6U, Accion TILE 5000 (x2)	3	60	860	47	950	7
6U, Busek BIT-3	1.24	80	2900	16	9,000	5+
27U, Aerojet MR-111C (x4)	21,200	54.56	1060	300	184	9
27U Microsat, Enpulsion IFM micro (x4)	16	1600	6840	30	12,000	5

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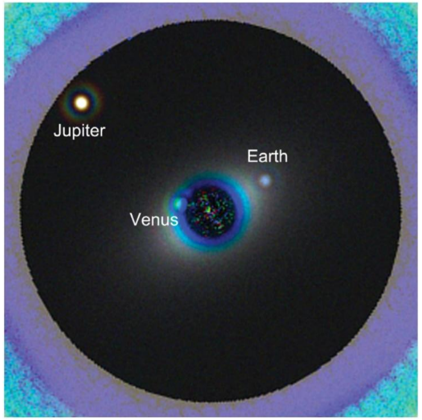
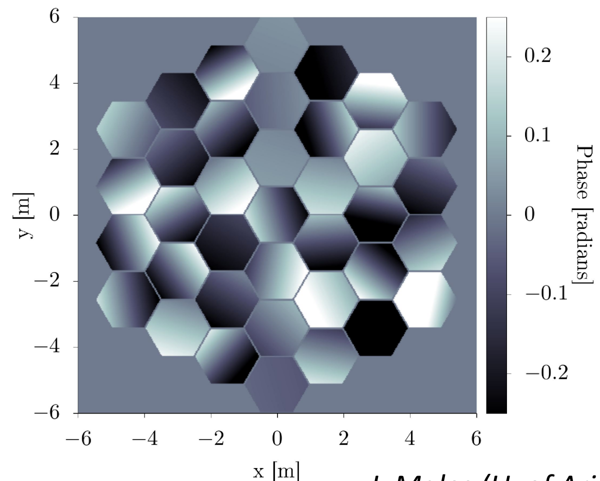
- Max formation flight duration does not include costs of stationkeeping or matching speeds with the target satellite.

Summary



Roberge et al.



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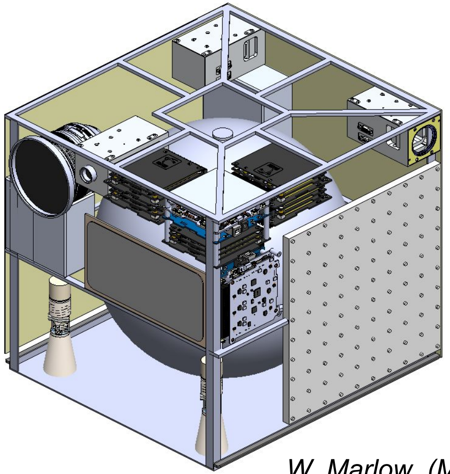

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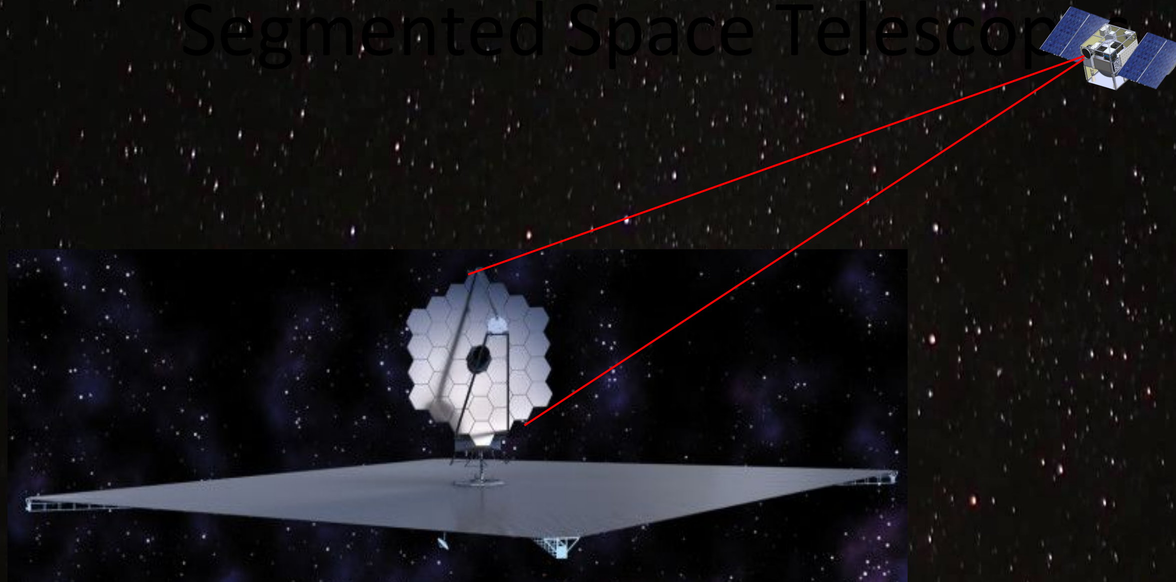
- We have developed a baseline laser guide star spacecraft concept which increases discovery space while relaxing requirements on segmented aperture telescope stability by several orders of magnitude

- A GEO to ground demo is feasible first step, demonstrating comparable vehicle rates

Laser Guide Star for Large Aperture Segmented Space Telescop

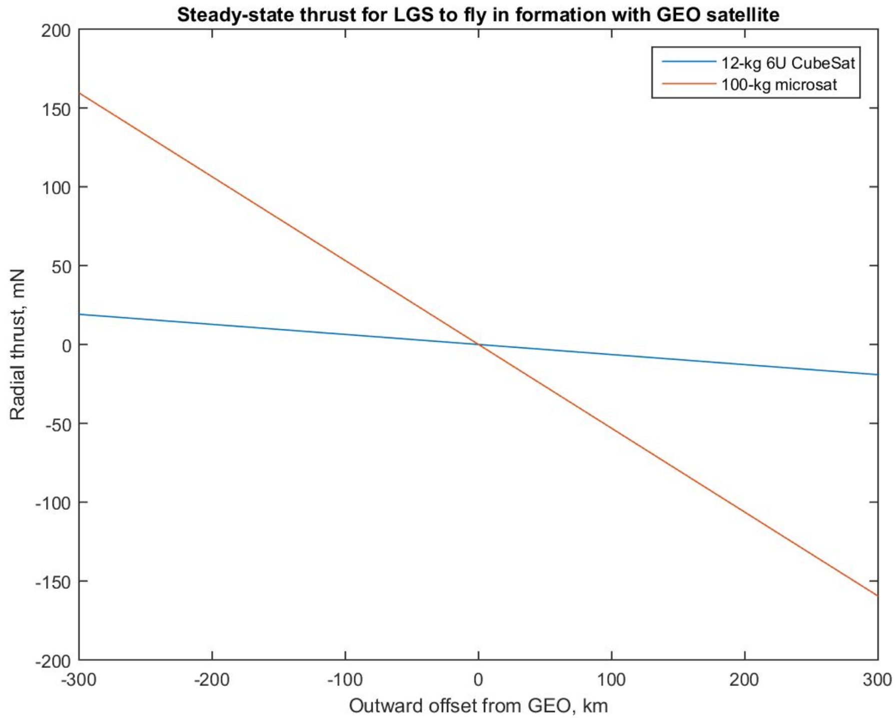


Questions?

Backup

Demonstrate with GEO target and quasi-GEO Guide Star

- To fly in steady formation with a GEO communication satellite, the LGS must either fly at a lower altitude and (after slowing down to match the 1-revolution-per-sidereal-day orbit period) thrust upwards against gravity, or fly at a higher altitude, speed up, and then thrust downwards against centrifugal acceleration. The required thrust is approximately linear with the offset. At 300 km (the typical offset above the GEO belt used for graveyard orbits) a 12-kg 6U CubeSat would need to produce 20 mN of thrust, and a 100 kg microsat would need to produce 160 mN.



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Formation Flight Scenarios

Scope Location	LGS Location	Target	Scope-LGS Range	Scope Slew Rate	LGS Drift Rate	LGS Thrust Req.	Notes
L2	*L2*	*Star*	*10,000-100,000 km*	*"0"*	*~1 deg/day (0.2 urad/sec)*	*< 0.1 mN cross-track*	*Reference scenario*
LEO	GEO	Star	35,000-45,000 km	"0"	~0.1 mrad/sec (0.3'/sec)	10-100 N radial in	"Hubble/ISS + LGS"…very different from L2 ops.
LEO	GEO + 300 km	GEO-Com	35,000-45,000 km	~0.1 mrad/sec (0.3'/sec)	~0.8 urad/sec	0.01-0.1 N radial in	Useful for SSA
LEO	GEO	Imaginary ref. in GEO	35,000-45,000 km	~0.1 mrad/sec (0.3'/sec)	~1 deg/day (0.2 urad/sec)	< 0.1 mN	The LGS performance metrics match, but do we get anything for it?
Ground	GEO	Star	32,000-39,000 km	0.25 deg/min (70 urad/sec)	~0.1 mrad/sec (0.3'/sec)	1-10 N radial out	Sort of like Greenaway and Clark 1994, but it won't work (they proposed HEO)
Ground	GEO + 300 km	GEO-Com	32,000-39,000 km	"0"	~0.3 urad/sec	0.01-0.1 N radial in	Marlow et al. 2017, useful for SSA
Ground	GEO	Imaginary ref. in GEO	35,000-45,000 km	"0"	~1 deg/day (0.2 urad/sec)	< 0.1 mN	The LGS performance metrics match, but do we get anything for it?

J. Clark (MIT)

PSD definition

Wavefront error power spectrum defined as

$$\beta_{OPD}^2 = \frac{\sigma_{10}^2}{\int_{1/600}^{\infty} \left(f_o^2 + f^2\right)^{-\alpha/2} df}.$$

c.f. Males and Guyon. 2018.:
https://www.spiedigitallibrary.org/journals/Journal-of-Astronomical-Telescopes-Instruments-and-Systems/volume-4/issue-1/019001/Ground-based-adaptive-optics-coronagraphic-performance-under-closed-loop-predictive/10.1117/1.JATIS.4.1.019001.pdf

Example Transmitters

Case	Laser Power	λ_{tx}	Range	Throughput	θ	tx jitter	m	band
	W	nm	km		$''$	$''$	s	
I	50.0	980	49000	0.05	1.93	0.005	-7.5	z’
II	10.0	980.0	43184.0	0.05	12.49	0.1	-2.0	z’
III	50.0	532	90263	0.05	1.93	0.005	-5.3	V
IV	0.02	980	49000	0.05	1.93	0.005	1.0	z’
V	0.02	532	90263	0.05	1.93	0.005	3.2	V