Remote Occulter

An orbiting starshade working with Extremely large telescopes on the ground to study exoplanets and planetary systems.

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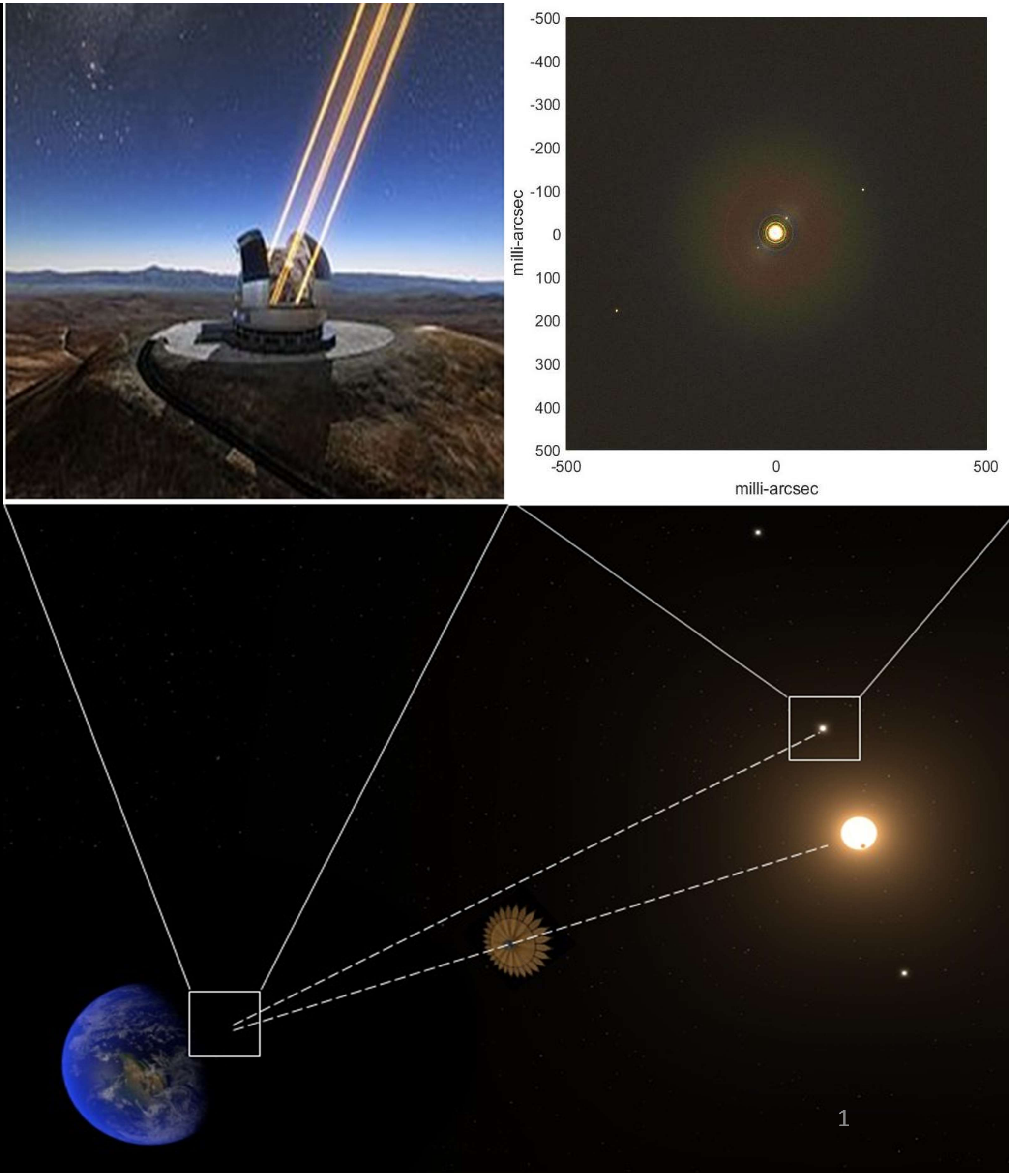
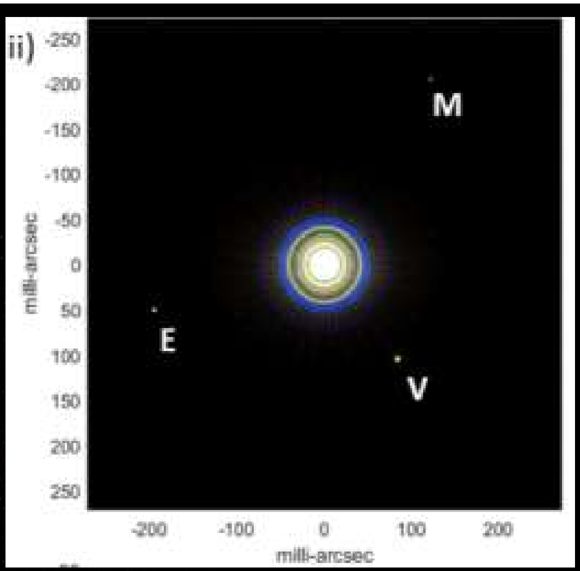
Feb. 7, 2020



Topics for Today

- Idea of orbiting starshade
- What we don't know: why this is interesting
- What we could see with an orbiting starshade: images and spectra
- Differences from other starshades
- Accomplishments and next steps
- Backup charts

98 Meter class Starshade
200,000 km altitude, 4-day orbit matches observatory v ~ 400 m/sec
Accelerate during observation
Laser beacon ensures AO performance



SISTER (JPL) - 2018

A few things we don’t know well: how hard is the problem?

- Frequency of “interesting” targets (→ sensitivity, contrast, resolution requirements)
- Exo-zodiacal light in Solar system analogs?
  - Sign of asteroids & comets
  - Limit to observations of faint planets (favors large telescopes)
- Is Solar System configuration necessary for life?
  - Small rocky inner planets, asteroid gap, gas giants, ice giants, …?
  - Large moon to stabilize Earth spin axis?
- Do we have to measure planet spin rates? (weather, ocean/continent)
- Signs of life through geological history? (what to look for?)
- How to raise the odds of looking at interesting systems?
  - Radial velocity, astrometry, detection of cool Jupiters, detection of exo-zodi, etc.?
- How well can ground-based equipment do? (unlimited ingenuity!)
  - Can we see Jupiters without a space mission?
- What’s the best efficiency of space coronagraphs? (the competing technology)
- What does Astro2020 want us to do?

Earth-Orbiting Starshades

- Highest angular resolution (39 m ELT)
- Highest instantaneous sensitivity (observing speed ~ D^4/Background)
- Highest resolution of exo-zodi light
- Achromatic high efficiency (all starshades)
- Wide separation of exoplanets from star/starshade
- Rejection of stray light from star and sun glint
- Terrestrial interference for strong molecular bands
- Short observing periods (~ 1 hour typical, every few days) limited by chemical fuel
- Slow and costly maneuvering to new targets (solar electric)
    - Really want to know there's something to see!

We can see molecules through the atmosphere

SISTER (JPL) – 2019, Including atmosphere

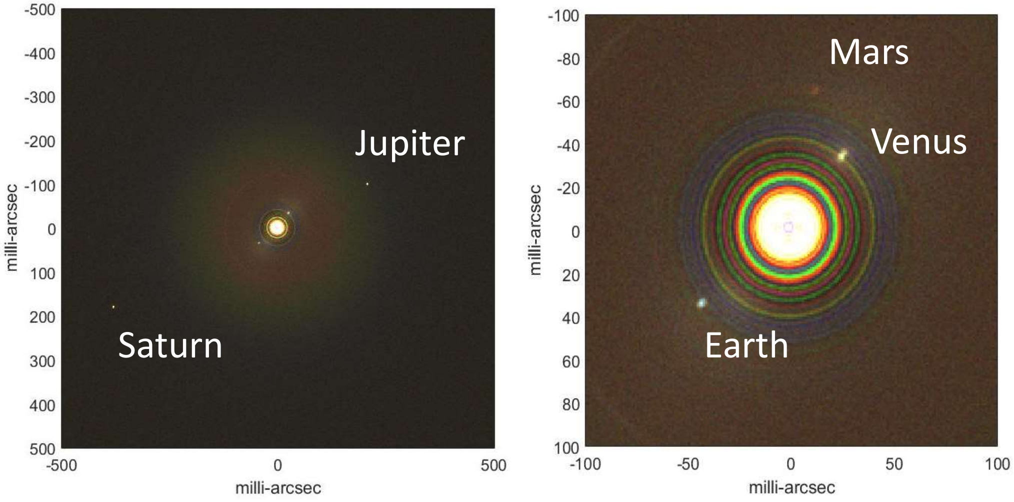
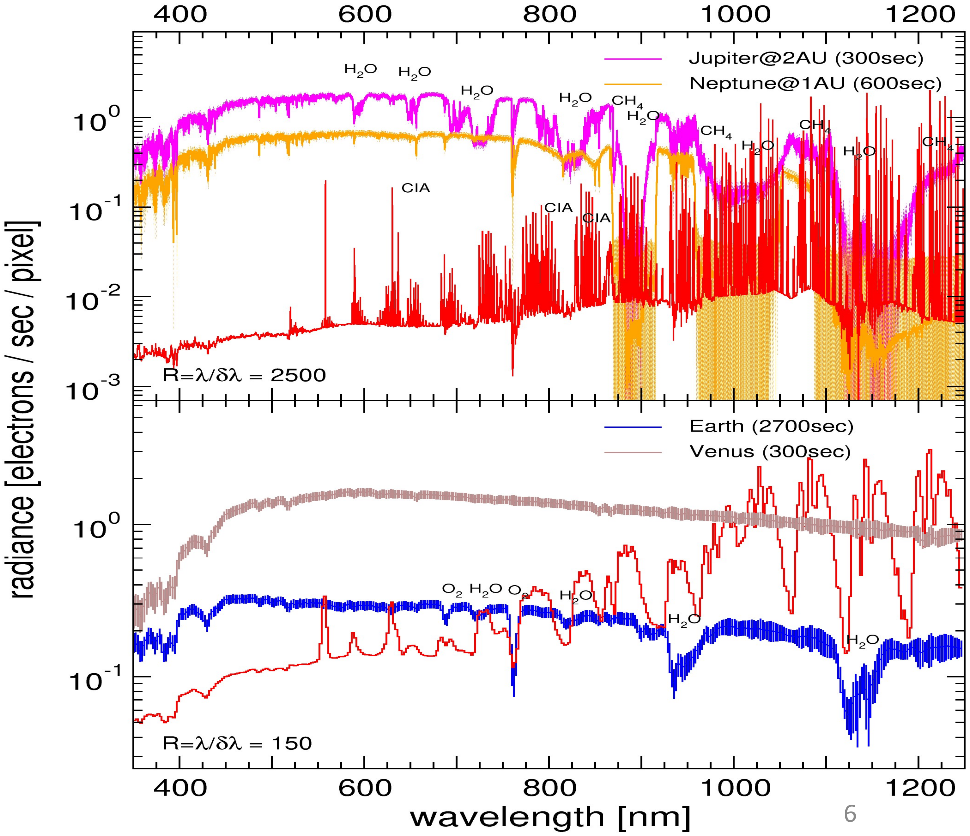


Figure 2. Left: Solar System with V=6 star at 17 pc, 20 min exposure, 400-700 nm, exozodi=5x solar system value, system inclined 60°, with Earthshine from starshade. Mars is at 1:00, Venus at 2:00, Earth at 7:30. Right: same with different angular scale. Jupiter and Saturn are at 2:00 and 8:00. Assumed Strehl 0.7, $\delta\vartheta$= 3 milliarcsec, seeing disk 0.5”. Venus is at IWA.

Figure 3. Simulated spectra for planets at 5 pc with Strehl = 0.5. Top panel $R = \lambda/\delta\lambda = 2500$, bottom $R=150$. 1 pixel = $\lambda_0/2R$ = 0.14 nm for R = 2000 and 2.34 nm for R = 150 at λ_0 = 700 nm. Red curves are sky brightness at the ELT in Chile. Widths of curves are ± 1σ. Water and oxygen are seen on exo-Earth and not on exo-Venus, and methane registers on a 2 AU Jupiter.

Ground team– 2019, Including atmosphere

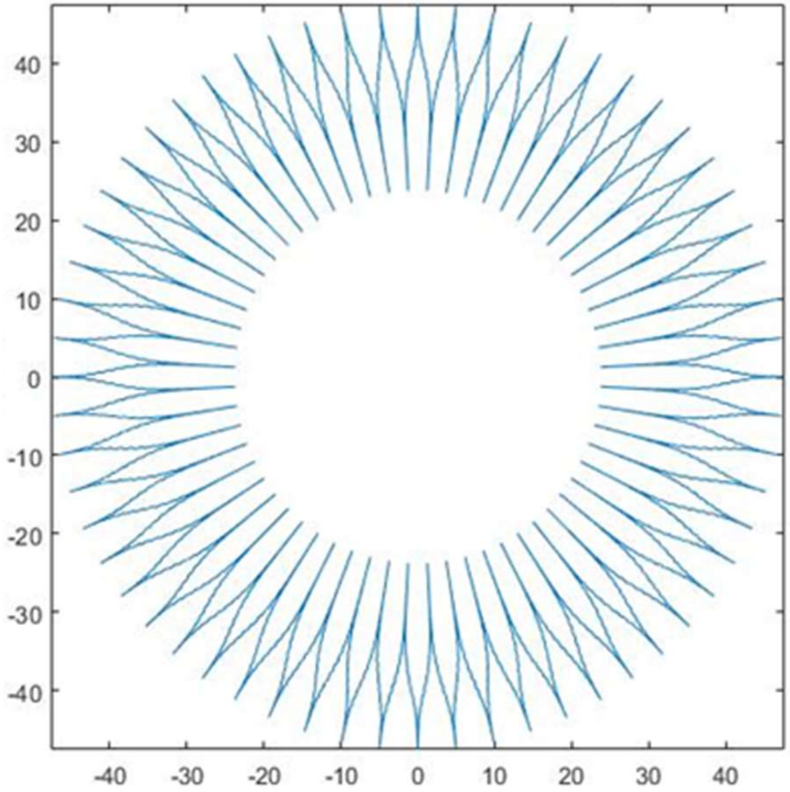


Key differences from other starshades

- ELT resolves starshade image (radius 50 mas, resolution 3 mas), AND is out of focus (40 mas diameter blur)
  - Telescope provides much of contrast
  - Greatly relaxed requirements for sun glints, holes, shape tolerances, stability
- Extreme angular resolution separates planets, increases contrast
  - Resolves exo-zodi dust
  - Resolves background galaxies
- More edge-on (within 1°) to Sun, to observe at meridian (not hard requirement)
- Up to 20° tilted from line of sight
- Too big to spin
- Fuel limited yield (shared with other starshades)
  - Need super-ultralight design, might be very different from WFIRST concept
  - Split starshade from propulsion during observation
  - Need refueling
- Propulsion during observation
  - Pulsed, due to plume brightness
  - Excitation of mechanical modes
- Earthshine important – black surface, not dusty
  - Super-black carbon nanotubes
  - Specular black coating

Starshade Tolerances – Moving from 1.5 to 20 $\left[\frac{\lambda}{D}\right]$ angular size – Resolved Observation

Perturbation	Random or Bias	Magnitude		Contrast	Notes
PETAL POSITION IN PLANE					
Petal Radial position	Random	125	mm	5.00E-12	Random radial positionof petals relative to nominal. Magnitude is 3
Petal Radial position	Bias	50	mm	2.50E-12	All petals are shifted radially by 50 mm.
Petal Tangential position	Random	5	mm	1.20E-12	Random shift of petals in plane, perpendicular to petal spine. 3 sigma.
Petal clocking angle	Random	0.005	rad	2.90E-12	Random in-plane tilt of petals about their base. 3 sigma.
PETAL POSITION OUT OF PLANE					
Petal tilt about base	Random	0.004	rad	6.50E-16	Random tilt of petal about base, out of plane. 3 sigma. Tip is 25 m * 0.004 = 150 mm out of plane
Petal tilt about base	Bias	0.004	rad	6.50E-16	All petals tilted same amount.
Petal Rotation about spine	Random	0.015	rad	3.00E-15	Petal rotates about spine, so half is above and half is below plane.
Petal Rotation about spine	Bias	0.015	rad	1.00E-13	All petlas rotated about spine by the same amount.
PETAL SHAPE IN PLANE					
1 cycles/meter amplitude	Random	1	mm	3.50E-12	Sine wave with amp=1 mm running along side of petal. Each edge has a different phase and amplitude. 3 sigma amplitude.
1 cycles/meter amplitude	Bias	1	mm	6.50E-12	All petal edges have the same in-plane sine-wave deformation.
Edge segment displacement	Random	2.5	mm	2.12E-12	Edges are made of 4-m long segments. Segments are randomly displaced in plane by 2.5 mm 3 sigma.
Edge segment displacement	Bias	2.5	mm	3.75E-12	All edge segments are similarly displaced.
Petal 1 cycle shape error	Random	150	mm	3.74E-12	Petal in-plane shape take on a sine wave deformation (1 cycle/petal), width preserving. All petals have different phase and amplitude.
Petal Cantilever bend	Random	300	mm	4.20E-13	Petal spine is deviated quadratically along it's length. Petal follows, width preserving. All petals have different ampliude.
PETAL OUT OF PLANE SHAPE					
Cantilever bend	Random	125	mm	2.00E-17	Quadratic out-of-plane bend, zero at the base, increasing to the tip. Specified as distance of tip out of plane.
Cantilever bend	Bias	125	mm	1.66E-17	Same as above, same bend on all petals.
Petal Twist bout spine	Random	0.5	rad	4.00E-14	Petal twists about spine from base to tip, increasing linearly with radius. Specified as rotation value at the tip.



UH 47 Design

It is not going the be built the same way..

Need to better understand the mass drivers for existing designs

Next Steps (as of Sept. 2019) were:

- NIAC proposal for orbiting guide star, submitted
- Report to HQ, October, done with JPL
- Servicing architecture study for starshades in general – initiated conversations.
- Yield calculation with refueling – improved orbit calculations including Simone, planning a paper. Mather found general solution: $dV/d\varphi = L / b$ for small tilt changes, where L is specific angular momentum, b is semiminor axis
- Mechanical concept for lower mass, loose tolerances – on hold, need more resources to pursue
- Memo update to Decadal Survey – no significant changes to report
- SmallSat proposal for orbiting guide star, Dec. 20, submitted
- Review error budget spreadsheet and document from WFIRST, HabEx, and make equivalent for Orbiting Starshade – on hold
- Speak to Decadal Survey – awaiting interest

Planned Orbiting Starshade Activities (Feb 2020)

- Additional orbit studies & documentation - publish
- Respond to editor comments on scientific manuscript
- Prepare workshop on hybrid space-ground instrumentation (not just starshades, also guide stars, photometric calibrators, space VLBI, space Event Horizon Telescope, etc.)
- Start SmallSat proposal to NASA (due 2021) for ORCAS (orbiting guide star for adaptive optics) – key necessary technology, could be ready in few years

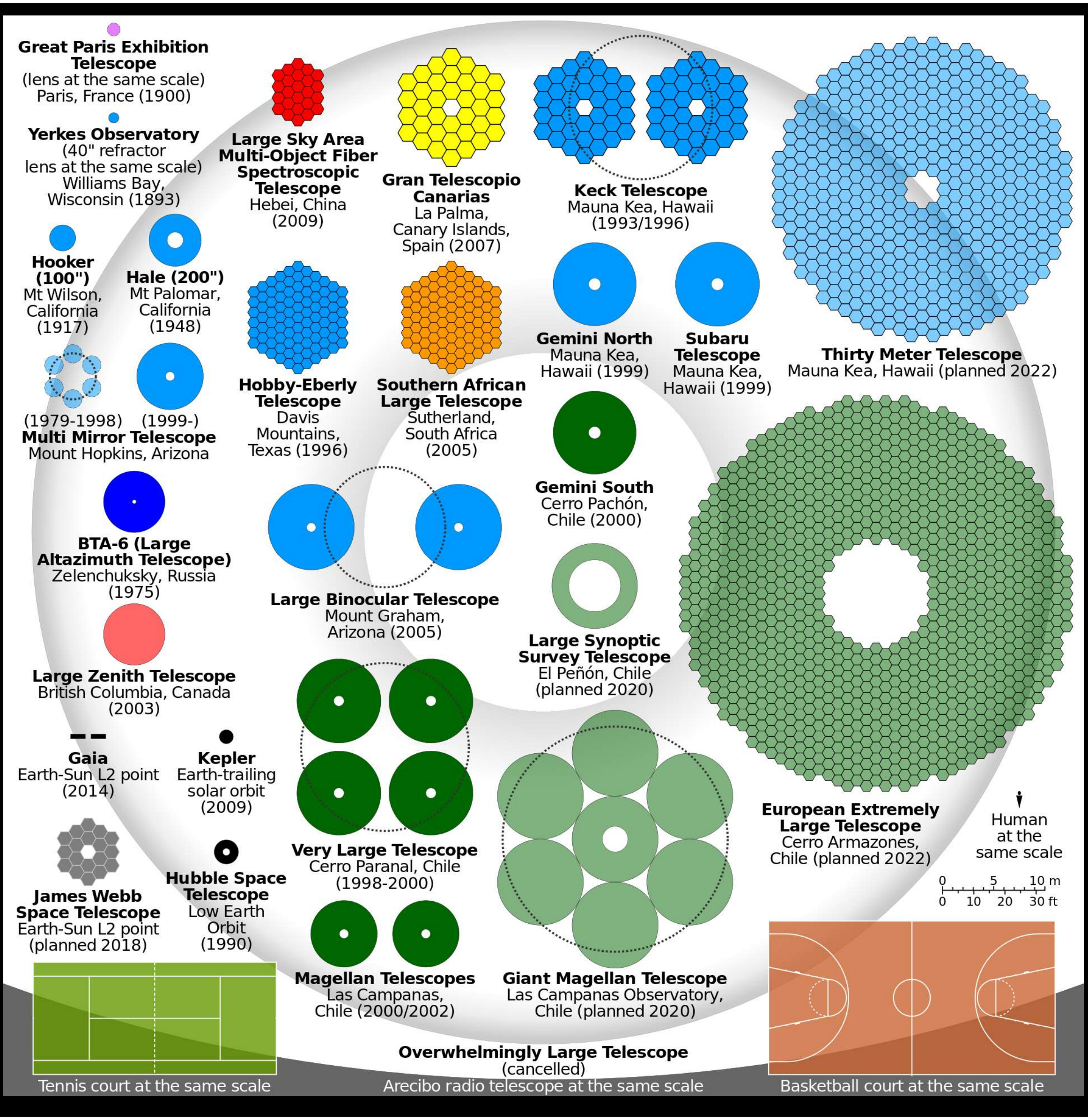
Backup slides from Sept. 2019

Why work on the orbiting starshade?

- Reflected light spectroscopy of Exo-Earths is top recommendation of the Exoplanet Science Strategy report
- Only alternative to space telescopes, with/without starshades
- Opportunity for ELTs and ground-based community to contribute

$(10^{-7}\ Maybe, 10^{-8}\ optimistic)$

- Possibility that orbiting starshade could fly sooner than HabEx/LUVOIR
- Possibility that HabEx/LUVOIR might not meet stability or contrast requirements



Ideal Angular resolution @550 nm:

EELT - ~3.5 mas

TMT - ~4.5 mas

GMT – ~5.6 mas

AO Performances:

MagAO-X: project status and first laboratory results

Proceedings Volume 10703, Adaptive Optics Systems VI; 70309

80% @ 656 nm

90% @ 900 nm

EELT – (PCS):

V-band [0.55um] = 40%

R-band [0.64um] = 65%

I-band [0.79um] = 80%

J-band [1.25um] = 90%

H-band [1.6um] = 90%

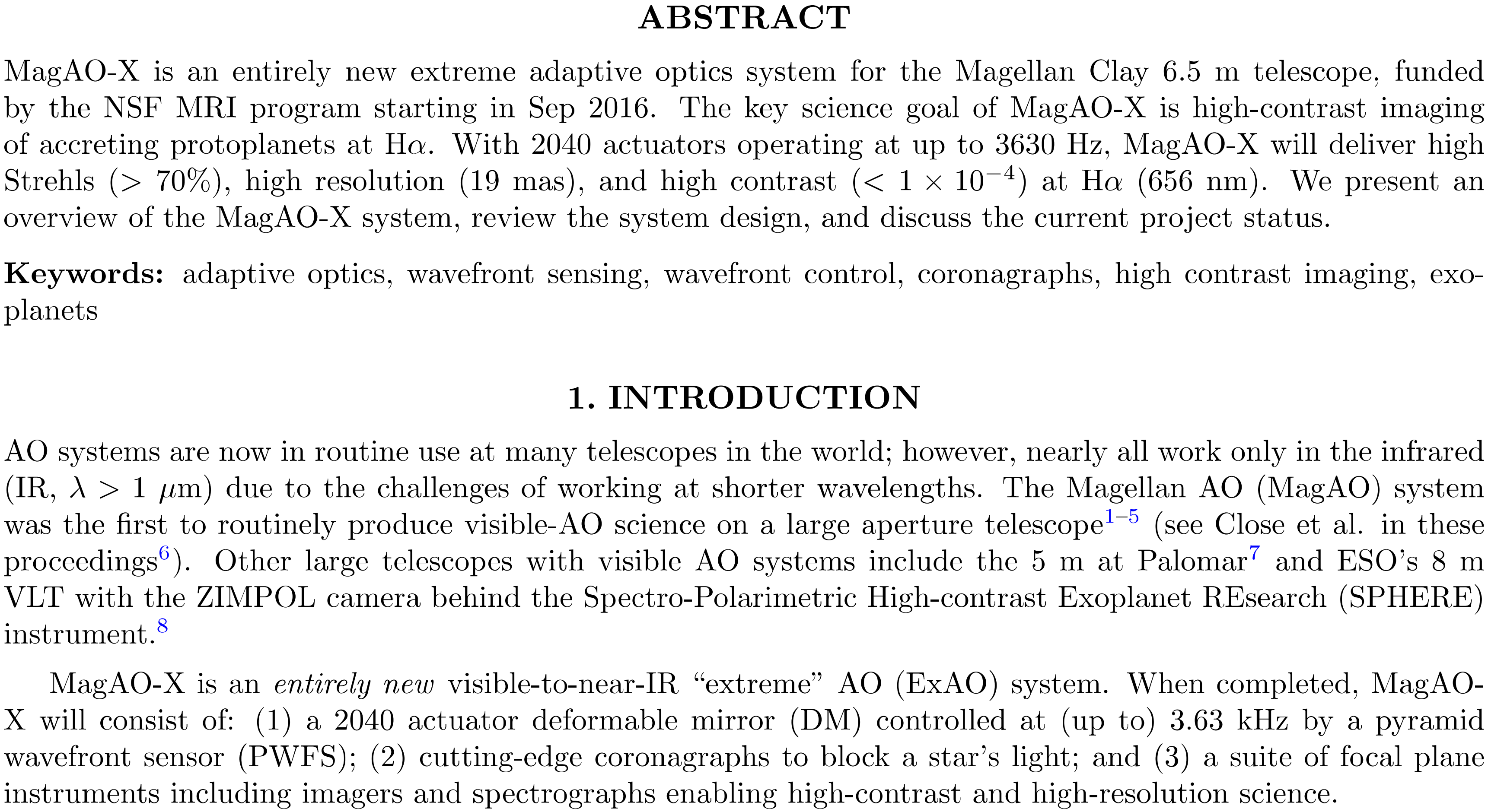
K-band [2.2um] = 90%

Key Science Programs NOAO

https://www.noao.edu/us-elt-program/astro2020swp.php

The real challenge However for ground based telescopes is **light suppression**.

MagAO-X, Males et al., Proc SPIE 2018



ABSTRACT

MagAO-X is an entirely new extreme adaptive optics system for the Magellan Clay 6.5 m telescope, funded by the NSF MRI program starting in Sep 2016. The key science goal of MagAO-X is high-contrast imaging of accreting protoplanets at Hα. With 2040 actuators operating at up to 3630 Hz, MagAO-X will deliver high Strehls ($> 70\%$), high resolution (19 mas), and high contrast ($< 1 \times 10^{-4}$) at Hα (656 nm). We present an overview of the MagAO-X system, review the system design, and discuss the current project status.

Keywords: adaptive optics, wavefront sensing, wavefront control, coronagraphs, high contrast imaging, exoplanets

1. INTRODUCTION

AO systems are now in routine use at many telescopes in the world; however, nearly all work only in the infrared (IR, $\lambda > 1$ μm) due to the challenges of working at shorter wavelengths. The Magellan AO (MagAO) system was the first to routinely produce visible-AO science on a large aperture telescope[1–5] (see Close et al. in these proceedings[6]). Other large telescopes with visible AO systems include the 5 m at Palomar[7] and ESO's 8 m VLT with the ZIMPOL camera behind the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) instrument.[8]

MagAO-X is an *entirely new* visible-to-near-IR "extreme" AO (ExAO) system. When completed, MagAO-X will consist of: (1) a 2040 actuator deformable mirror (DM) controlled at (up to) 3.63 kHz by a pyramid wavefront sensor (PWFS); (2) cutting-edge coronagraphs to block a star's light; and (3) a suite of focal plane instruments including imagers and spectrographs enabling high-contrast and high-resolution science.

Orbiting Starshade Teams

Study Team Leads:

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Keith Warfield (ExEP)

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Norbert Przybilla (Innsbruck)
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Robert Pritchett (GSFC)
Cassandra Webster (GSFC)
Donald Dichmann (GSFC)
Daniel Solomon (GSFC)
Sun-Hur Diaz (GSFC)
Rizwan Qureshi (GSFC)

Activities:

Begun - Feb 2018
IRAD Study -2018 (GSFC)
Team A Study – Aug 2018 (JPL)
IRAD Study -2019 (GSFC)
APD Mission Study -2019 (HQ/ExEP)
Science Workshop – May 2019 (GSFC)
Team-X Study – June 2019 (JPL)
Engineering Workshop - July 2019 (GSFC)
Astro 2020 – Remote Occulter APC white Paper
Astro 2020 – ORCAS APC white Paper
SPIE San Diego 2019 – paper on observable sky

IRAD Study -2018 (GSFC), Team A Study (JPL) : [study initiation]

1. What can be seen through the atmosphere?
2. How much of the sky can be seen?
3. What is the required size and shape?
4. Sky coverage and estimates on fuel budget?

IRAD Study -2019 (GSFC), APD Mission Study -2019 (HQ/ExEP), Science Workshop 2019 (GSFC)

1. Establishing Architecture A science goals
2. Deriving initial engineering requirements

Team-X Study – June 2019 (JPL)

1. Establishing a single closed design point of reference
2. First cost and yield estimates

Engineering Workshop - July 2019 (GSFC)

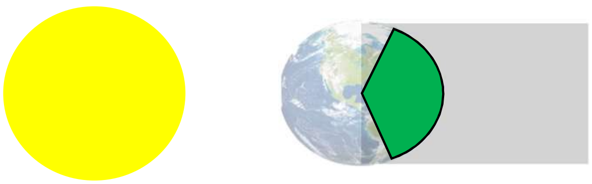
1. Starshade mechanical structure
2. Mission Operation Concept

Current work: High Fidelity imaging and spectra simulations, Starshade Architecture trade, Detailed Mission Operation Concept. Value of split system – separating propulsion module from starshade during observations.

Observational requirements

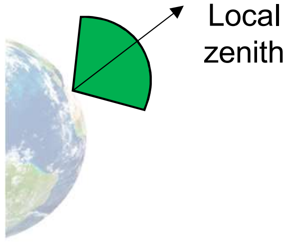
Requirement driver	Observational requirement	Logic
1. Ground based Telescope	**The pointing vector to the sun shall be at least 18 degrees below the horizon as seen by the telescope**	Make sure the sky is dark enough
2. Ground Based Telescope	**The telescope shall be pointed within 60 deg of its local zenith direction.**	Work within ground instruments air-mass constraints

1.



Compliant telescope locations during observations (7:15PM-4:45AM local solar time)

2.

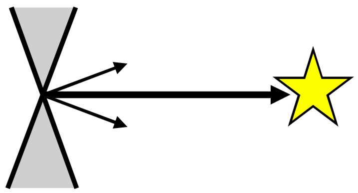


Compliant telescope pointing directions during observations

Observational requirements

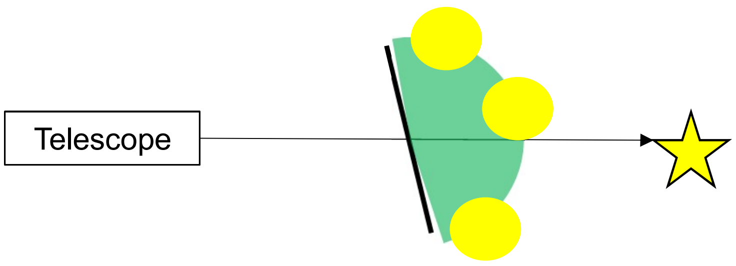
Requirement driver	Observational requirement	Logic
3. Starshade Optical Performance	**The normal vector to the starshade plane shall be within 20 deg of parallel to the line of sight from the telescope to the target star.**	Shadow cast on the ground telescope is deep enough; cosine loss of projected starshade size
4. Starshade Optical requirement	**The target-facing normal vector to the starshade plane shall be within 89 deg of the pointing vector to the sun.**	Starshade telescope facing side is not illuminated by the sun during an observation.

3.



Compliant starshade plane orientations w.r.t. target star

4.

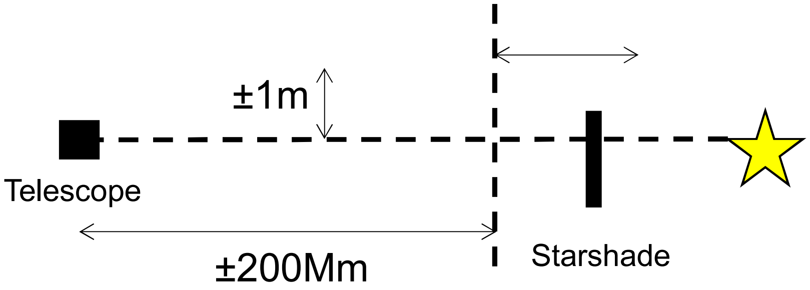


Compliant sun locations w.r.t starshade

Orbital requirements

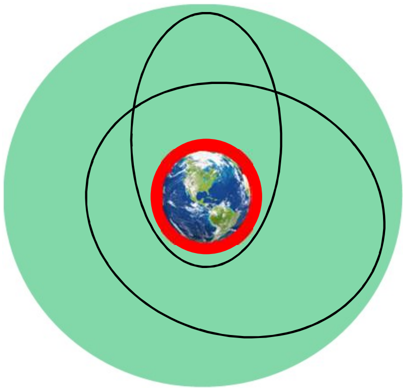
Requirement driver	Observational requirement	Logic
5. Starshade Optical performance	**The center of the starshade shall remain within ±1m of the line of sight from the telescope to the target star.**	Shadow cast on the ground telescope is deep enough
6. Starshade Safety	**The orbit perigee shall have an altitude of at least 1000 km.**	Safety Consideration
7. Operational consideration	**The starshade orbit shall be commensurable to the sidereal day. (?)**	Ensures recurring observations at the right time.

5.



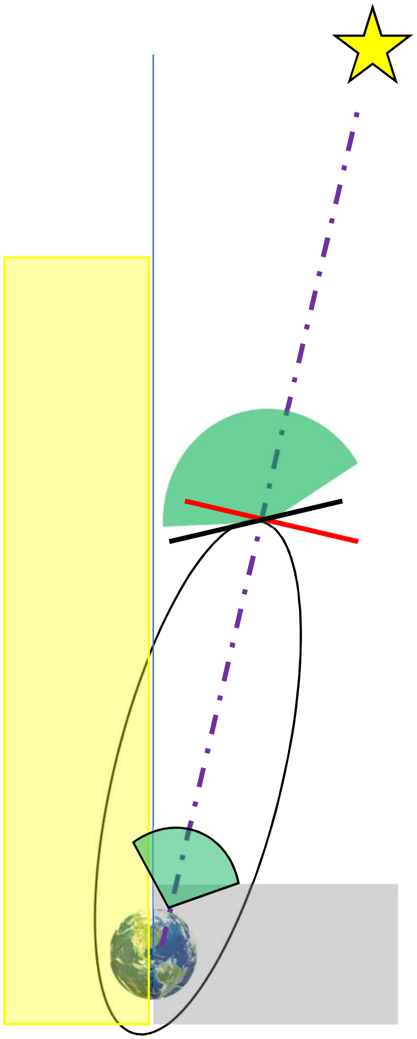
Compliant relative position envelope during observations

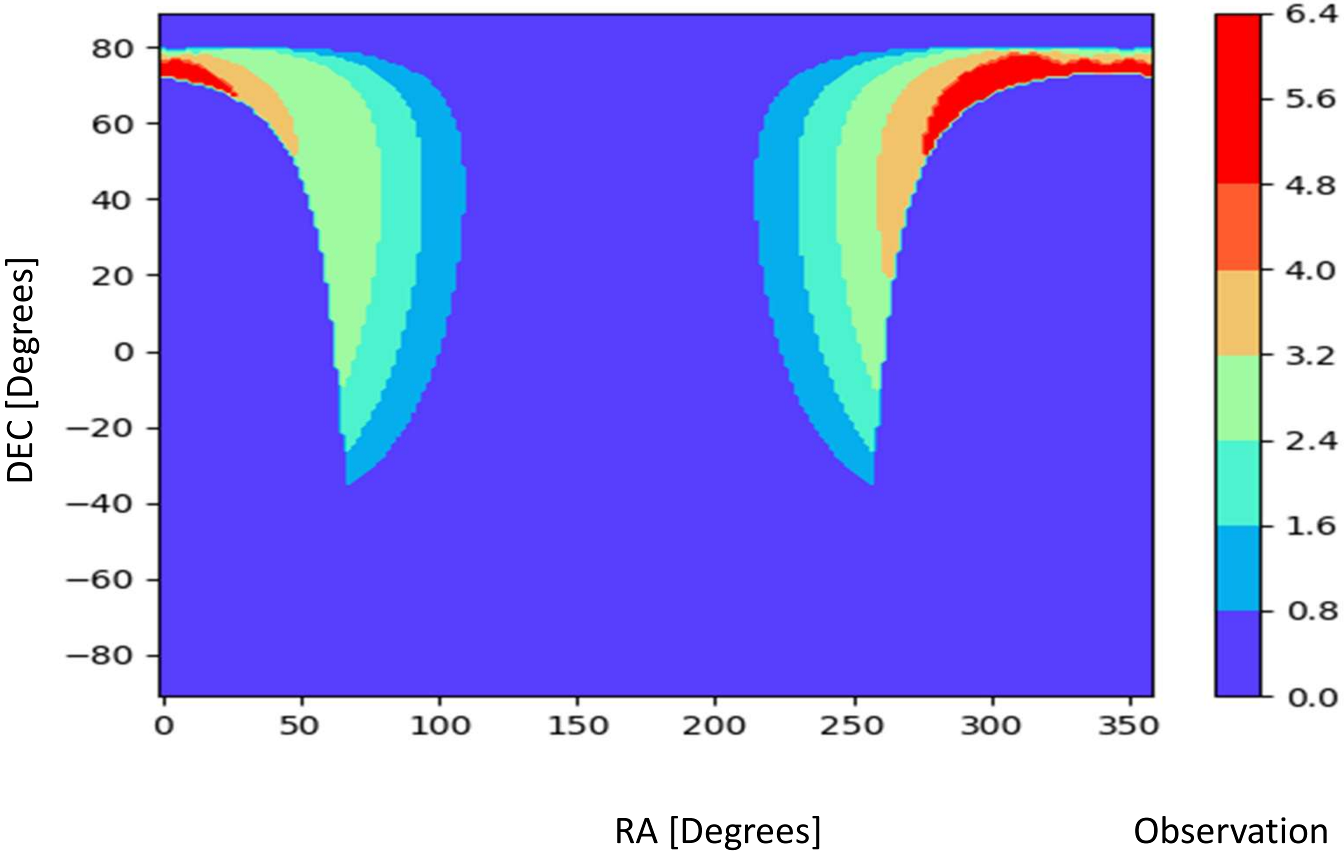
6,7.



Compliant orbit geometries

Observable Sky, Dec 3rd, 2031, Mauna Kea





Evolving Field: 1 (Deg/Day) + Geometrical constraints.

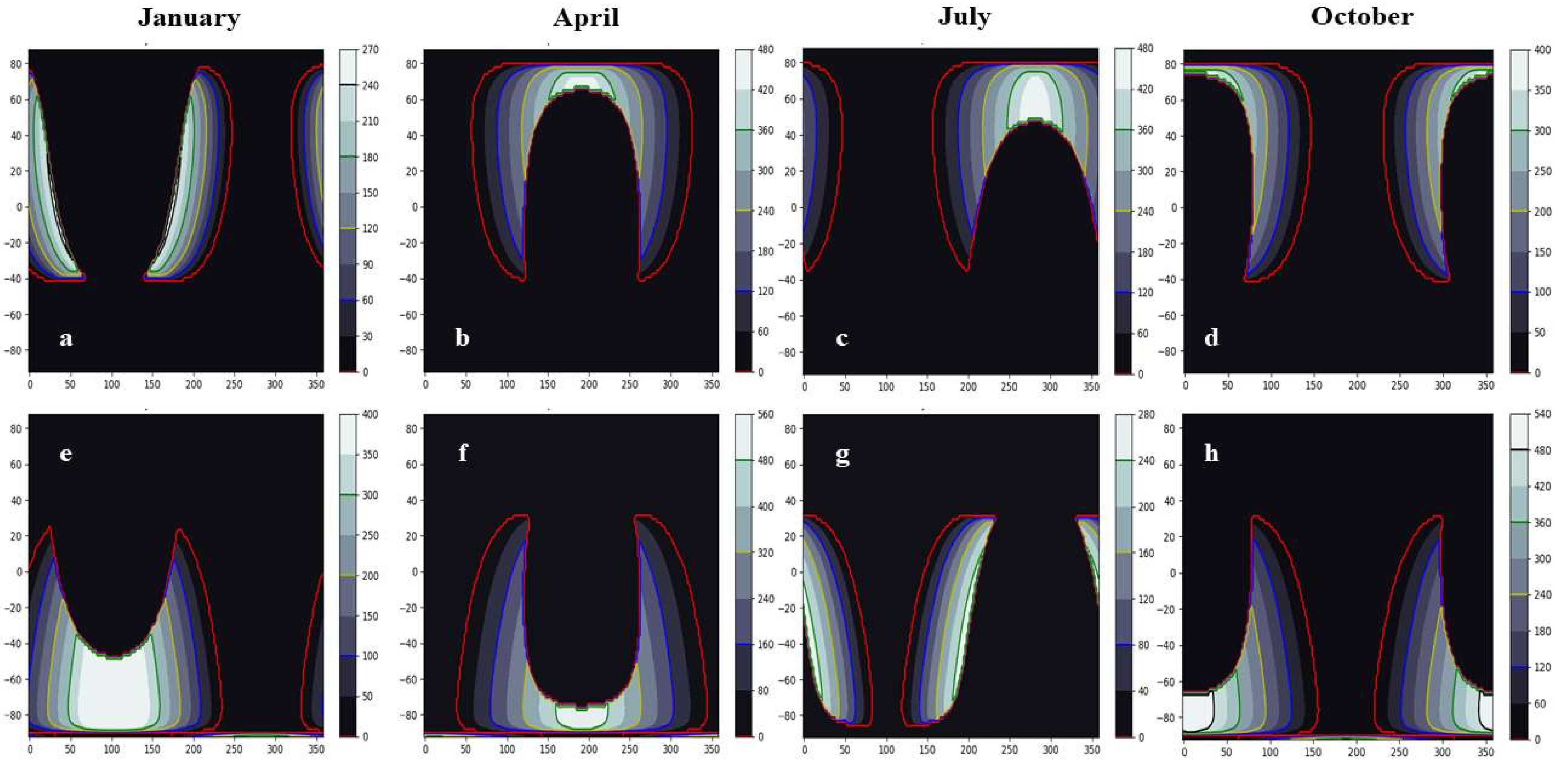
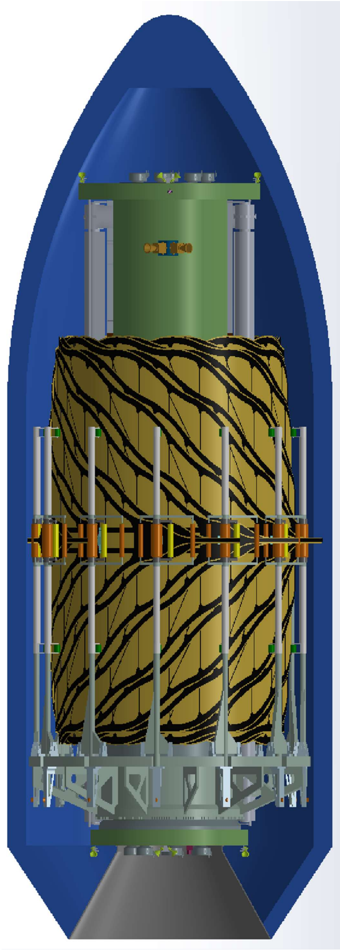


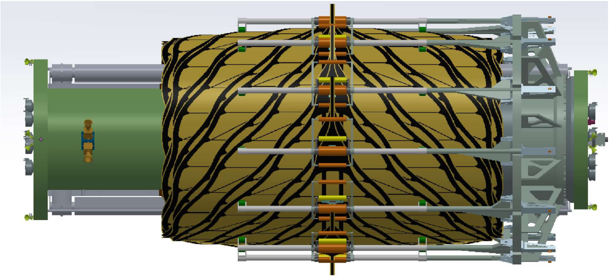
Figure 6. Observable night sky, showing minutes available for observation each night as indicated by the color bar. Range of each image is 0-360° right ascension and -90° to +90° for declination. Upper set is for Mauna Kea, lower set for Las Campanas. Dates are the first of each month, 2035.

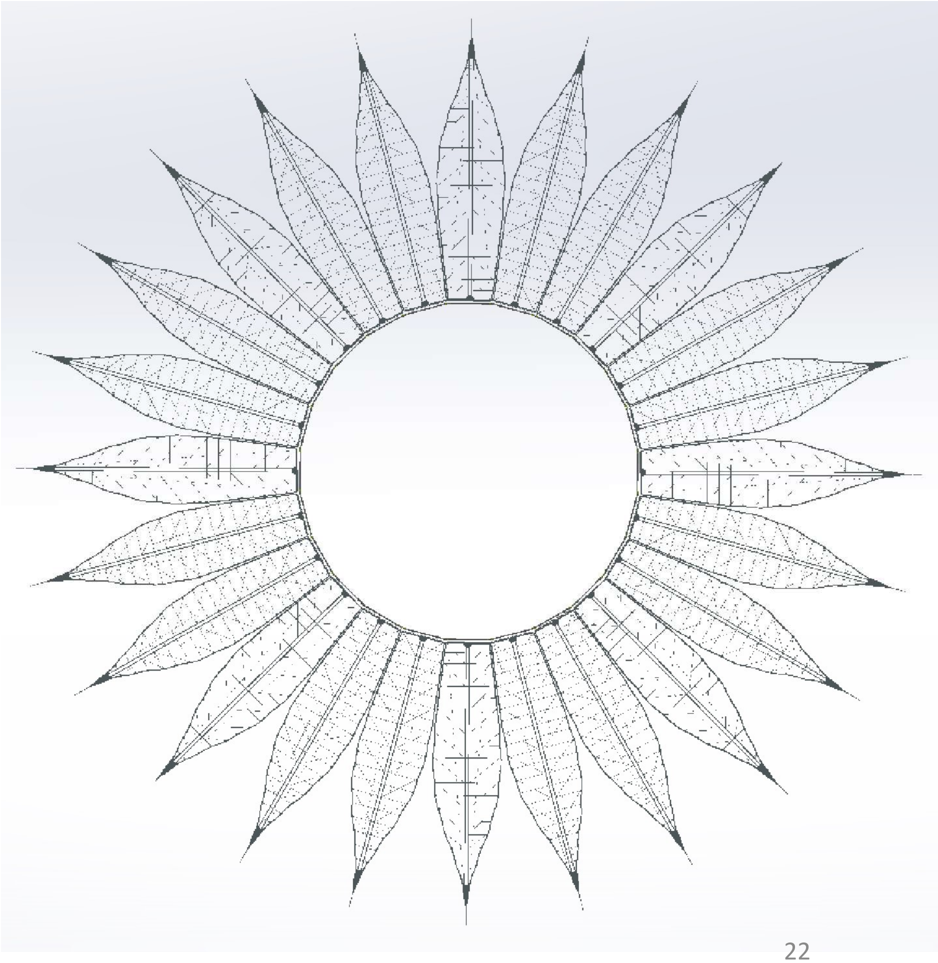
Team X Concept.



This potentially could be achieved in reality.

Need to reduce mass, enable refueling; fuel limited.



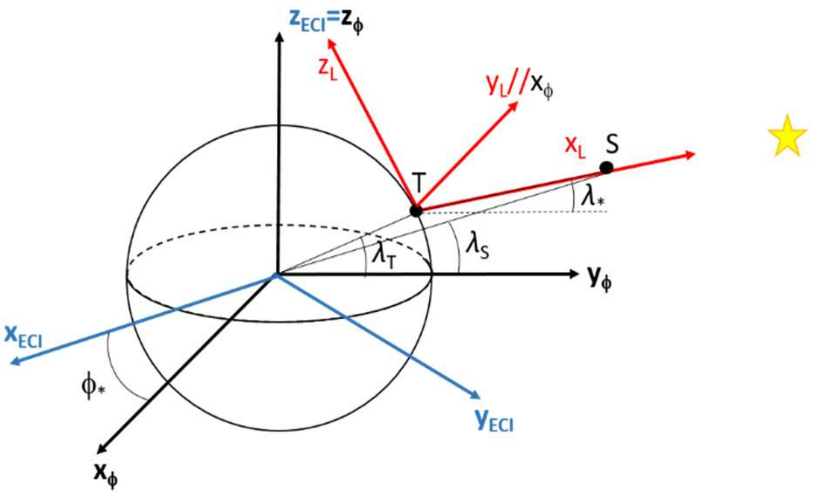


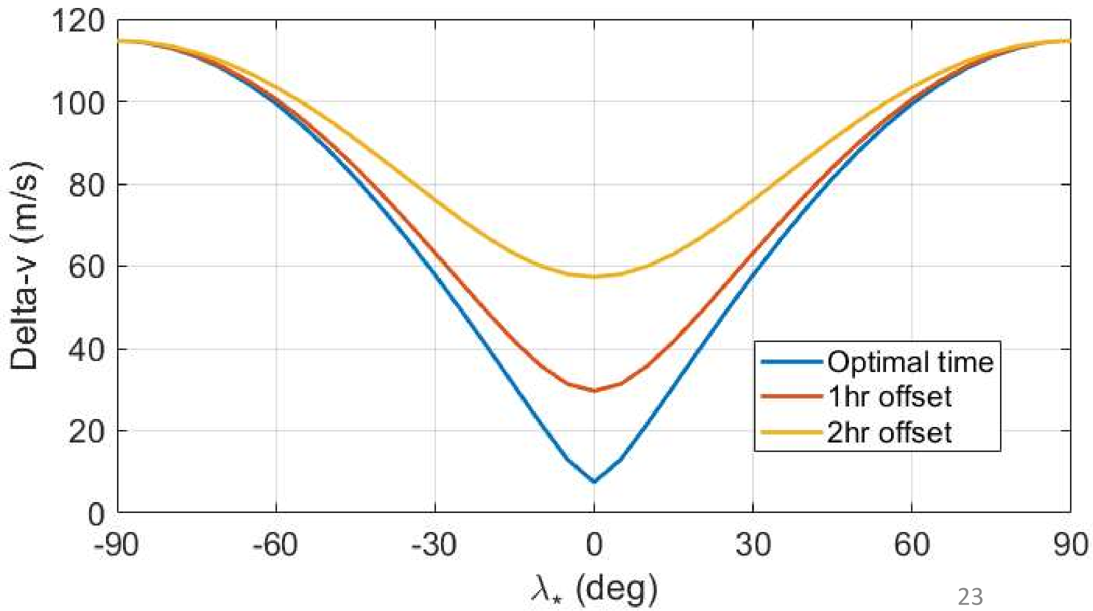
Observation Delta - V

$$\boldsymbol{a}_S = -\mu\frac{\boldsymbol{r}_\mathrm{S}}{r_\mathrm{S}^3}$$

$$\boldsymbol{a}_{\mathrm{T_L}} = \omega^2 r_\mathrm{T}\cos\lambda_\mathrm{T}\begin{bmatrix}-\cos\lambda_*\cos\omega t\\ -\sin\omega t\\ \sin\lambda_*\cos\omega t\end{bmatrix}$$

$$\Delta v = \omega^2 r_\mathrm{T}\cos\lambda_\mathrm{T}\int_{t_0}^{t_0+\Delta T}\sqrt{\sin^2\omega t + \cos^2\omega t\,\sin^2\lambda_*}\,dt$$



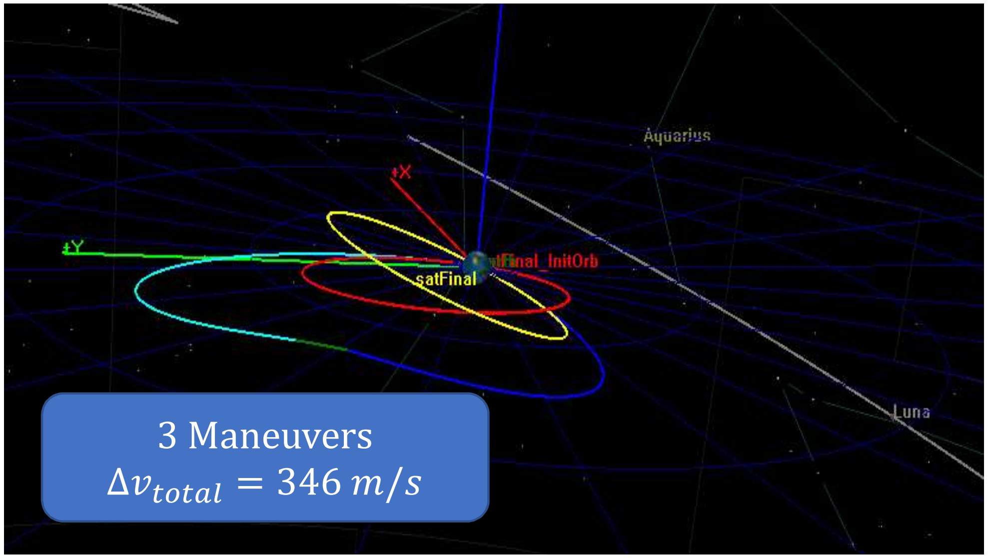


Large maneuvers – SEP

1. TESS, Moon Flyby.

- **Change from initial orbit:**
- ΔRAAN $\approx 55°$
- ΔINC $\approx 11°$
- ΔTime $\approx$ 10 Days

Initial Target Orbit
Lunar Flyby
Midcourse Correction
Transfer to Final
Final Target Orbit



3 Maneuvers
$\Delta v_{total} = 346\ m/s$

2. Deep Space Maneuvers

Small maneuvers – SEP (<12 degrees)

Test #	Delta [Deg]	Total Coast Time [Days]	Total Burn Time [Days]	Total time of Orbit Transfer	Total DV [m/s]
1	1	1.99	1.00	2.99	29.21
1(b)	1	4.84	1.14	5.98	28.03
2	1.5	4.67	1.32	5.98	42.49
3	2.5	3.72	2.26	5.98	73.14
4	3	3.28	2.70	5.98	90.23
5	4	5.45	3.52	8.98	119.06
6	5	4.42	4.55	8.98	154.03

The Δv required to change orbital parameters is dependent on the initial orbit. Some orbits require closer to 20 m/s in Δv per degree. However, others will require more. Best to assume an average of 30 m/s.

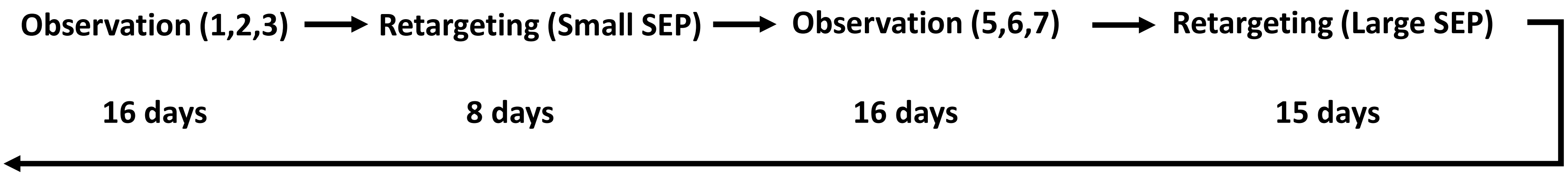
Operation Concepts:

7 (metric) Ton SS -> 4.5
Ton SS
5.8 ton Chem
1.7 ton SEP
7.5 Ton Spacecraft
22 total wet

Chemical propulsion Only: $\Delta v \sim$ 1241 m/sec

Hybrid propulsion : $\Delta v_{Chem} \sim$ 841 m/sec , $\Delta v_{SEP} \sim$ 2571 m/sec

Hybrid propulsion, Separated : $\Delta v_{Chem} \sim$ 2127 m/sec , $\Delta v_{SEP} \sim$ 3000 m/sec, $\Delta v_{Chem} \sim$ 3183 m/sec


Observation (1,2,3) → Retargeting (Small SEP) → Observation (5,6,7) → Retargeting (Large SEP)

16 days
8 days
16 days
15 days

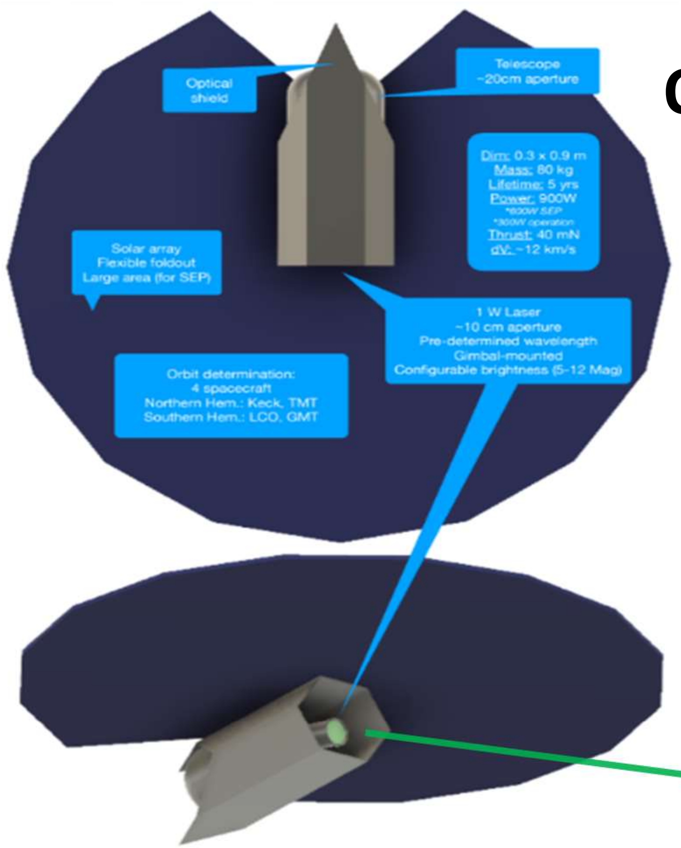
Chemical	SEP	Chemical	SEP
~390 m/sec	~300 m/sec	~390 m/sec	~400 m/sec

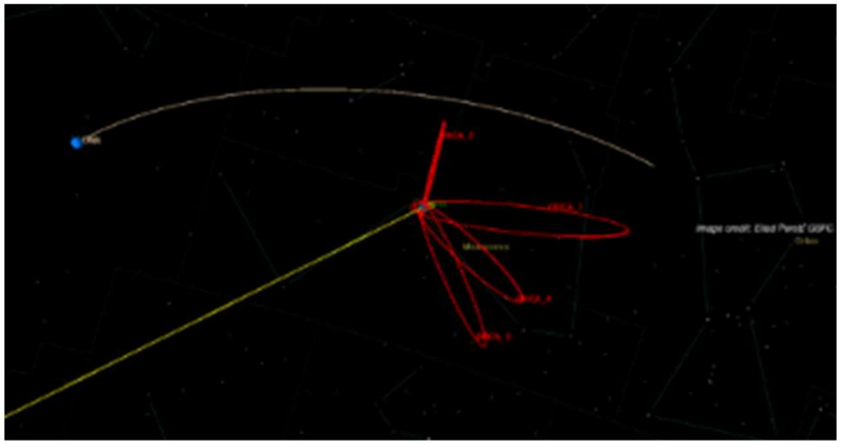
~5 targets (15 observations every) ~150 days, ~8 targets (40 observations every) ~220 days

Refueling will be required

This is still work in progress

ORCAS: Orbiting Configurable Artificial Star





Orbiting Configurable Artificial Star (ORCAS) for Visible Adaptive Optics from the Ground: Astro2020 white paper

http://surveygizmoresponseuploads.s3.amazonaws.com/fileuploads/623127/5043187/66-c09d3c8e99db32fab95d6d3139c2540c_ORCAS_EP_07102019.pdf

A remote Occulter could work with ground based telescopes to measure the reflected light spectra of temperate planets around sun like stars.

Much work is needed to better understand how many targets can be seen.