Jet Propulsion Laboratory
California Institute of Technology

Micro-arcsecond Astrometry Small Satellite (MASS)

To Discover and Measure Masses of Nearby Earth-like Exoplanets

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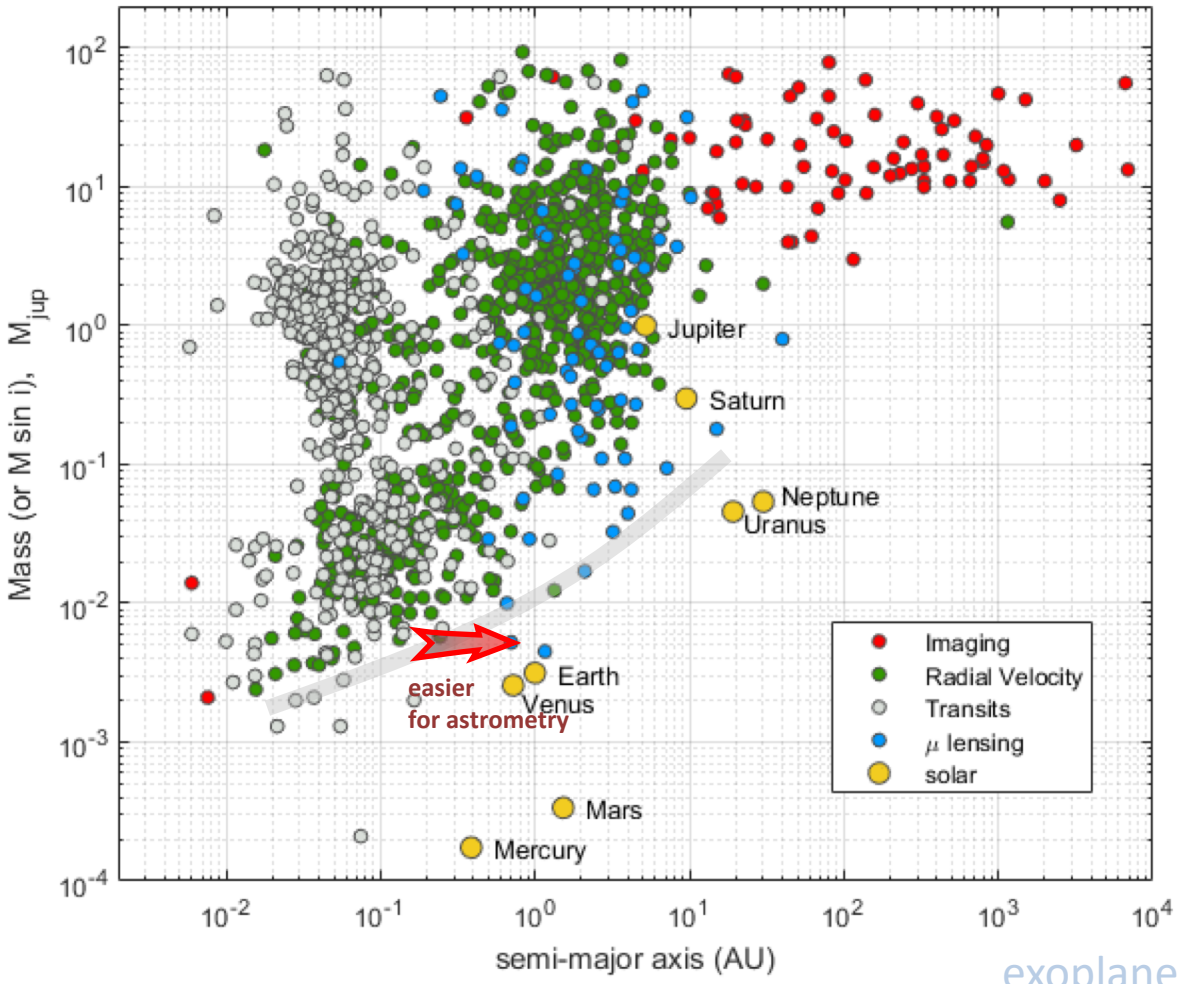
CL# 19-8215

How Can We Search for Exo-Earths around Nearby Stars?

- Radial Velocity Limitations:
  - Sensitive to small orbital radius
  - Also has $(M \cdot \sin i)$ ambiguity
- Transit technique Limitations:
  - Sensitive to smaller orbital radius
  - Favorable planet orbit inclination
- **Astrometry more sensitive to large orbital radius**



exoplanet.eu

MASS Overview

- Goal is ~4uas (1 hr) astrometric precision
- Would enable a search for Earth mass planets
  - around ~20 'nearest' FGK stars for
    - $\sim 5\times1\ M_{\oplus}$ and
    - $\sim 12\times2\ M_{\oplus}$
      planets in the mid Habitable Zone.
- Potential low cost possible taking advantage of low cost mass produced commercial Spacecraft.

HIP	Name	Depth, ME	V mag	Spect. Type	Dist., pc	signature µas	Ref Stars	hours to SNR=6	cumul. hours
71683	α Cen A	1	0.0	G2V	1.3	2.42	1228	59	59
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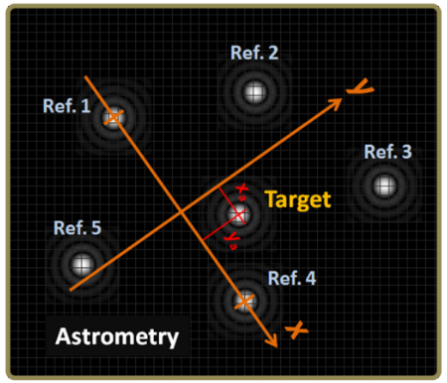
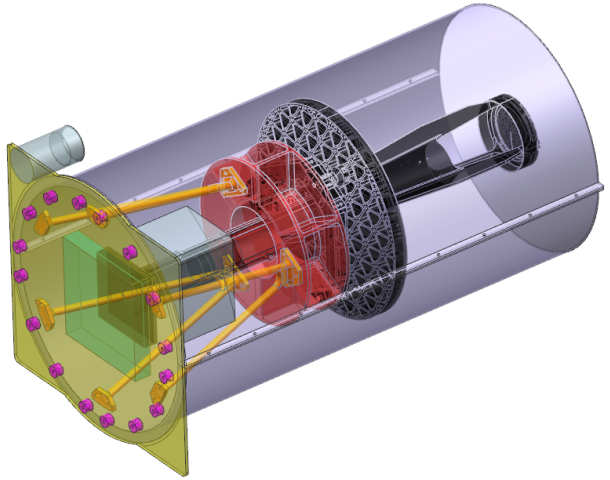
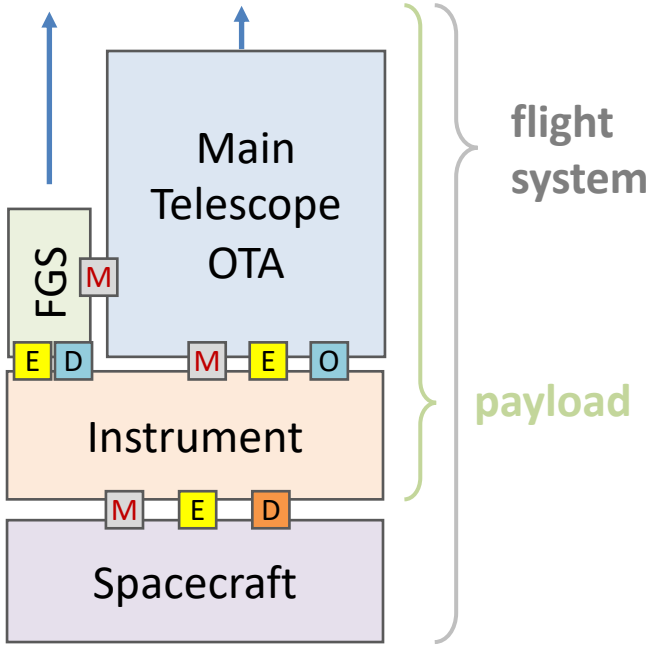
64394	β Com	3	4.2	G0V	9.2	1.06	31	3419	28763



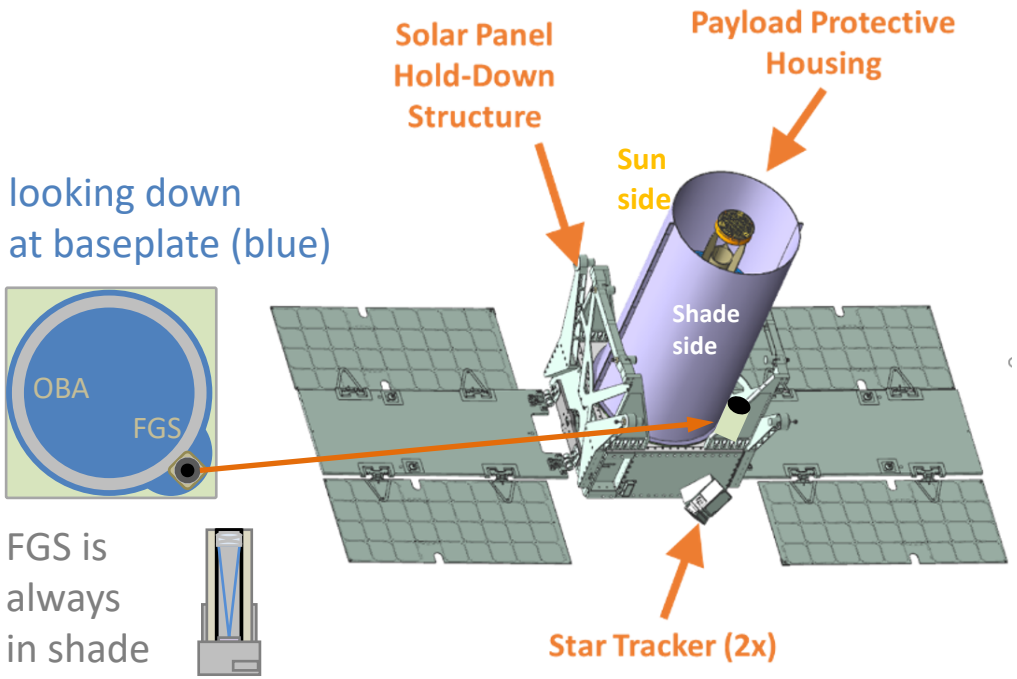


MASS Flight System Basic Elements

MASS Flight System Context



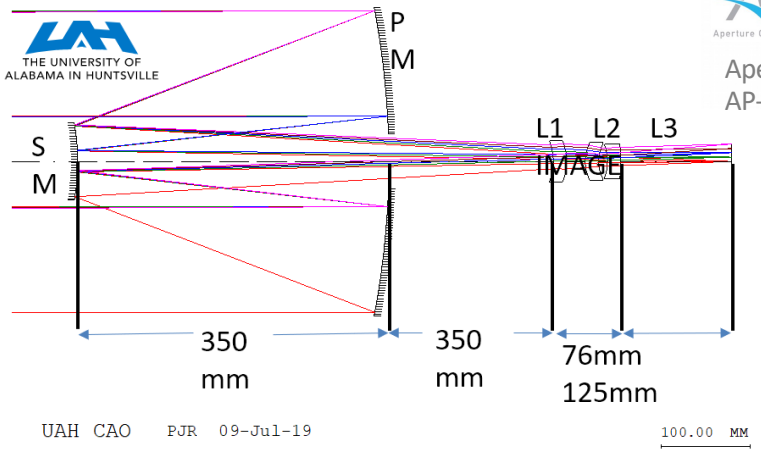
MASS Flight System Preliminary Design



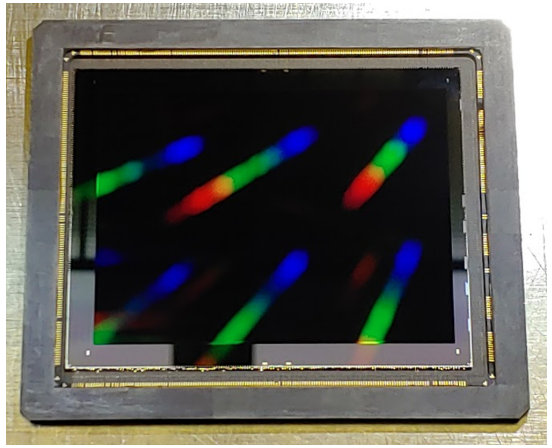
MASS Telescope & Focal Plane

- **Telescope**: corrected RC
  - Modified version of the AOS AP-35
    - 35cm Telescope
    - > 0.5 deg FOV
    - Nyquist-sampled Focal Plane
    - SiC OTA

UAH design meets MASS specs
while compatible with the AP-35 OTA



- **Focal Plane**: next gen sCMOS
  - SONY IMX 411 large format sensor
    - 150 Mpix (14,208 x 10,656 pixels)
      - Pixel size 3.76 um
    - Backside illuminated
      - cover glass removed
    - ~90% peak QE
    - 1.5 e- Read noise
    - 40 ke- full well, 2 Hz full frame rate

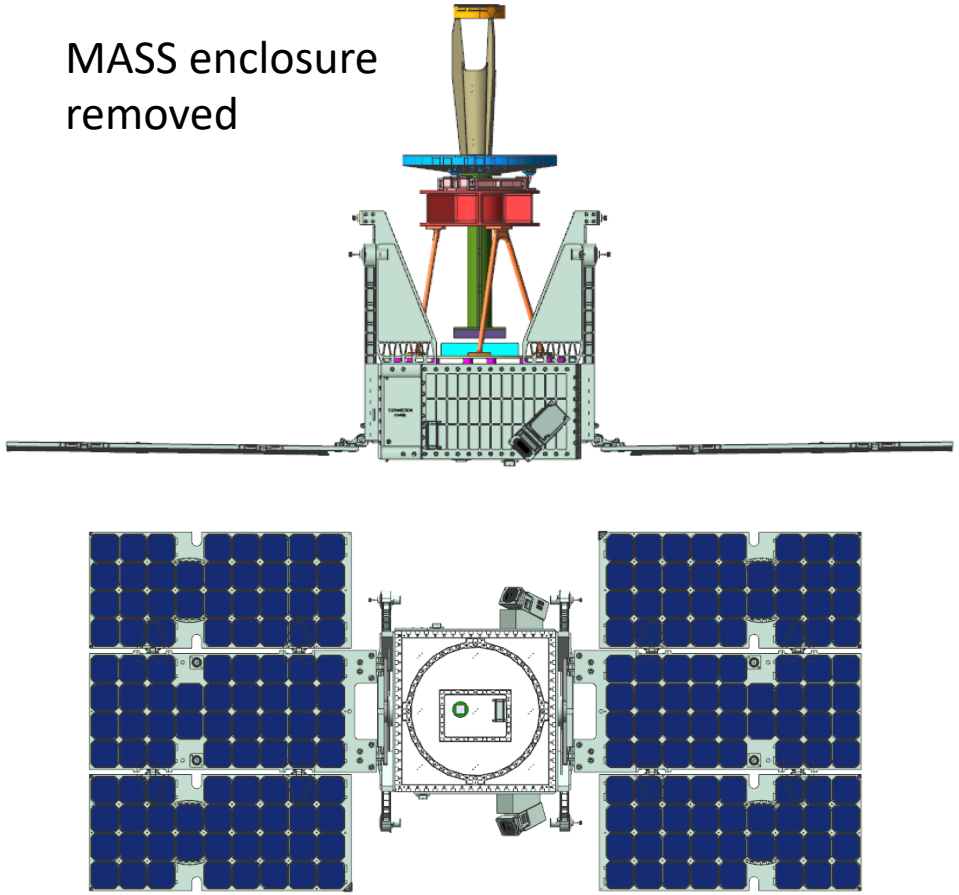


Spacecraft

- Commercial ESPA class spacecraft from Blue Canyon

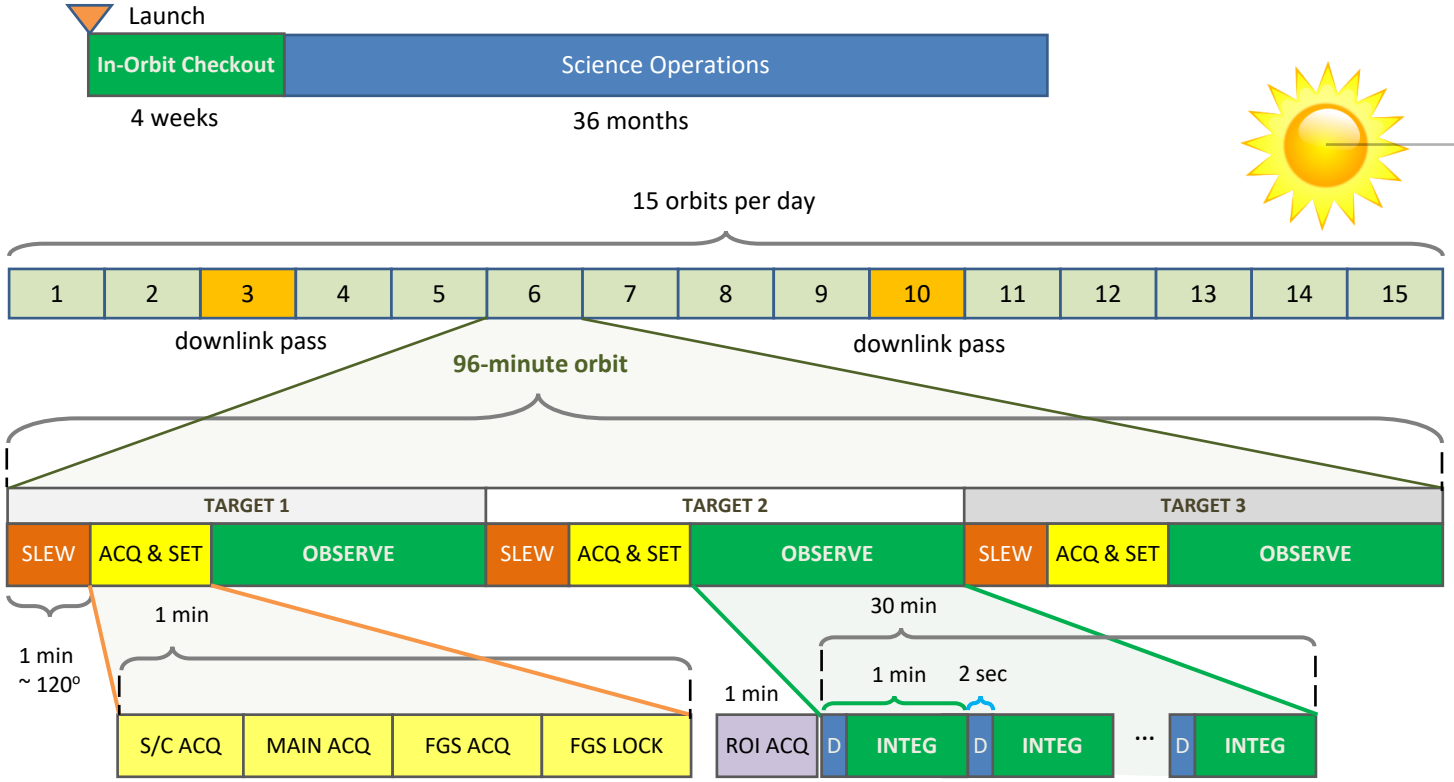
Similar to the S5 mission:
ESPA using cubesat parts

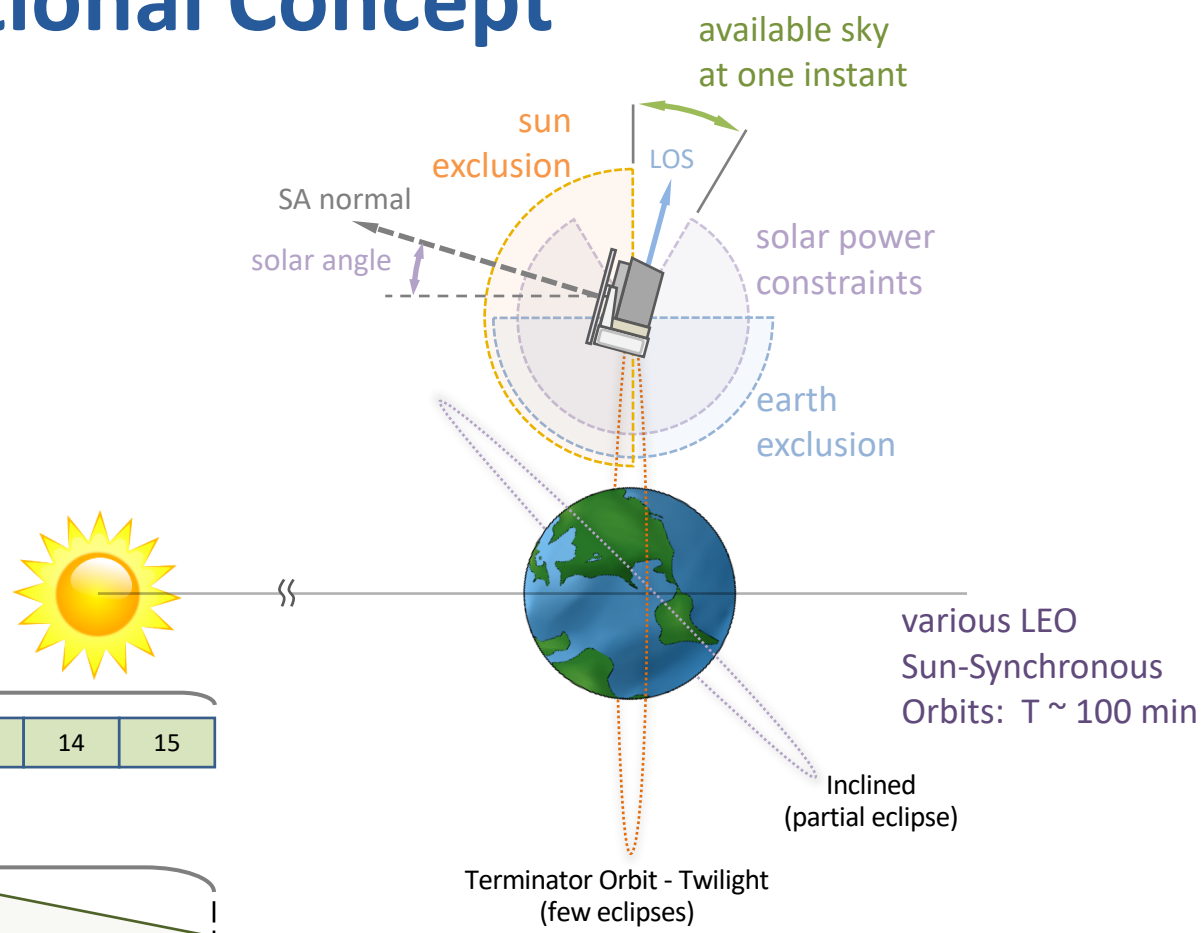
MASS enclosure removed



Sun-Synchronous Orbit Operational Concept

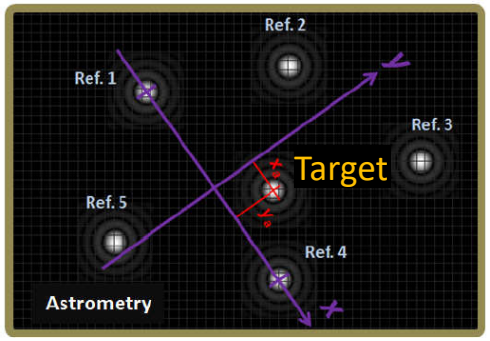
- Nominal design:
  - SSO 583 km orbit, 96 minute period





Single-Digit μas Astrometry

- λ/D for a 35cm telescope ~ 0.35 arcsec
- 10uas → centroiding to
  1 part in 30,000.
- 3 major noise/error sources
  1. Photon noise (of ref stars)
     - Use wide FOV
  2. Optical distortion
     - Use crowded field of stars to calibrate
       - High degree of thermal stability so distortion calibration needed < 1/day
       - Prefer GEO or HEO altitude
  3. Detector imperfections
     - Use laser fringes to calibrate Pixel positions



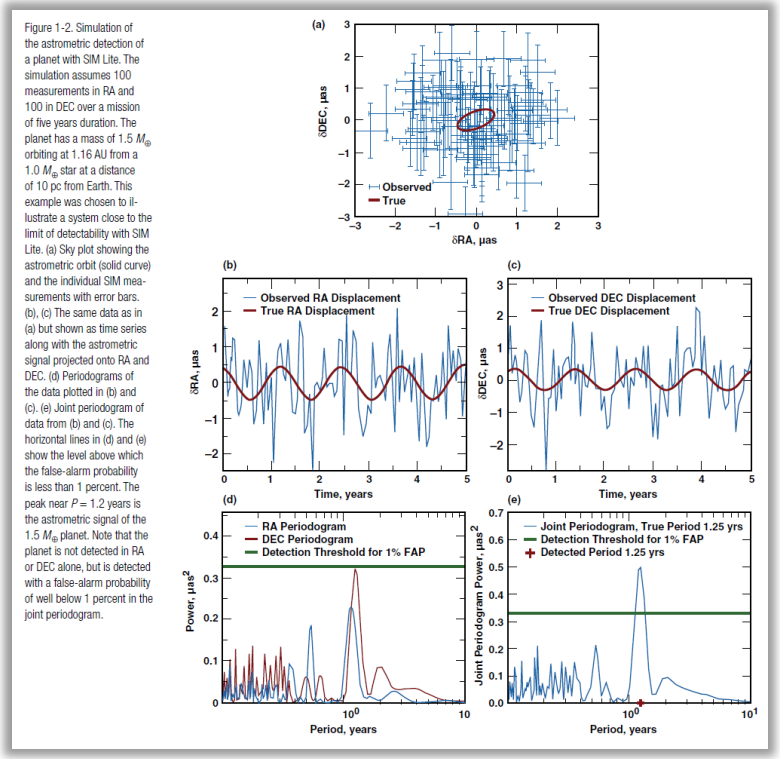
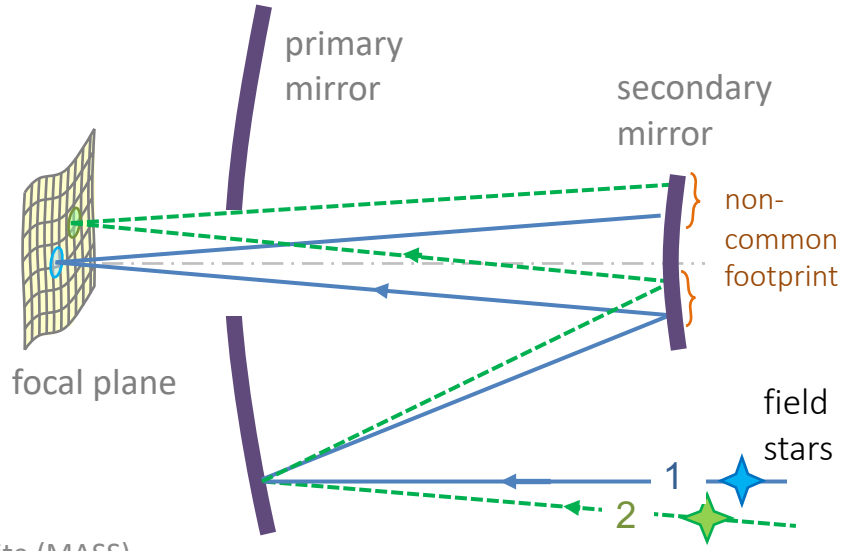
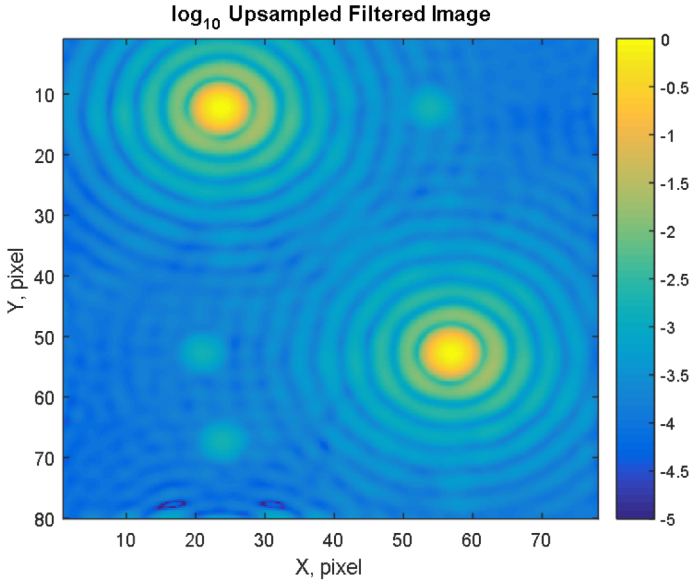
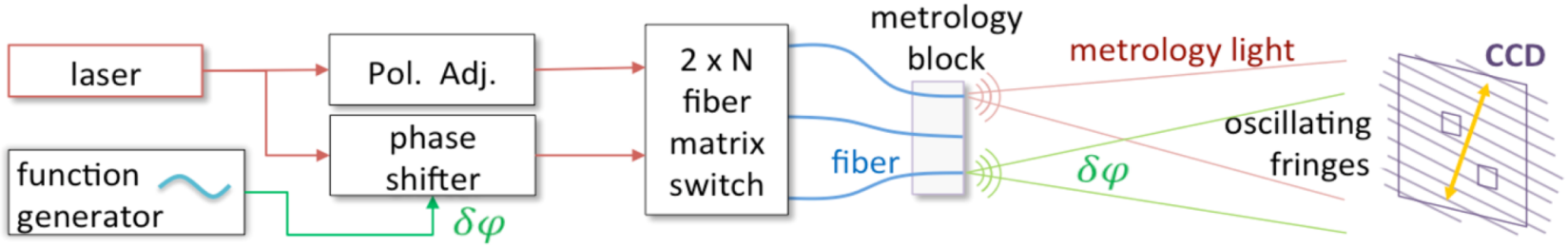


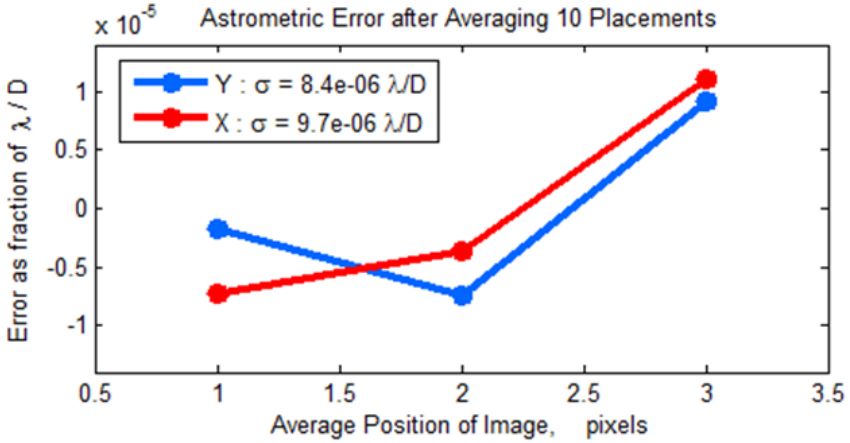
Figure 1-2. Simulation of the astrometric detection of a planet with SIM Lite. The simulation assumes 100 measurements in RA and 100 in DEC over a mission of five years duration. The planet has a mass of 1.5 $M_{\oplus}$ orbiting at 1.16 AU from a 1.0 $M_{\odot}$ star at a distance of 10 pc from Earth. This example was chosen to illustrate a system close to the limit of detectability with SIM Lite. (a) Sky plot showing the astrometric orbit (solid curve) and the individual SIM measurements with error bars. (b), (c) The same data as in (a) but shown as time series along with the astrometric signal projected onto RA and DEC. (d) Periodograms of the data plotted in (b) and (c). (e) Joint periodogram of data from (b) and (c). The horizontal lines in (d) and (e) show the level above which the false-alarm probability is less than 1 percent. The peak near $P = 1.2$ years is the astrometric signal of the 1.5 $M_{\oplus}$ planet. Note that the planet is not detected in RA or DEC alone, but is detected with a false-alarm probability of well below 1 percent in the joint periodogram.

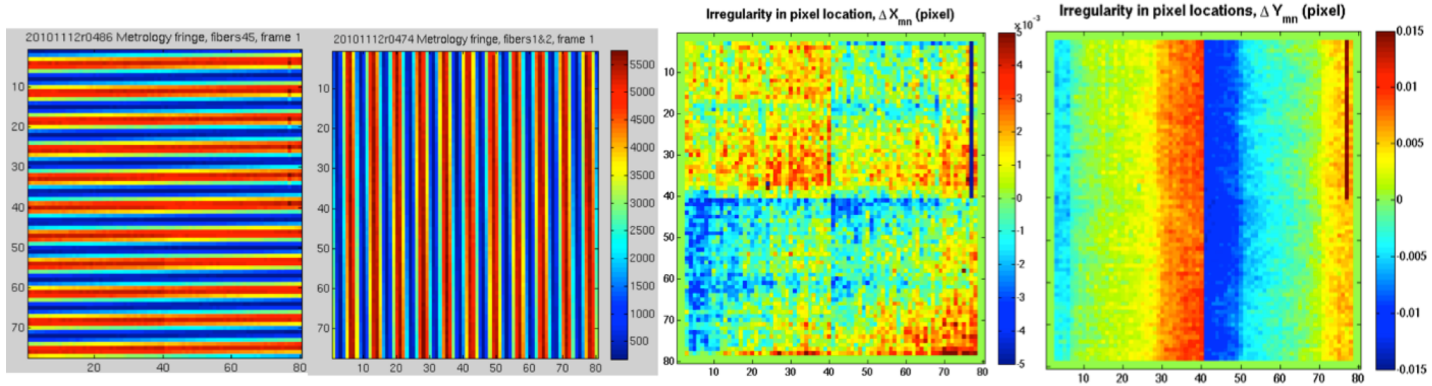


SubPixel detector calibration, centroid to $10^{-5}\lambda/D$





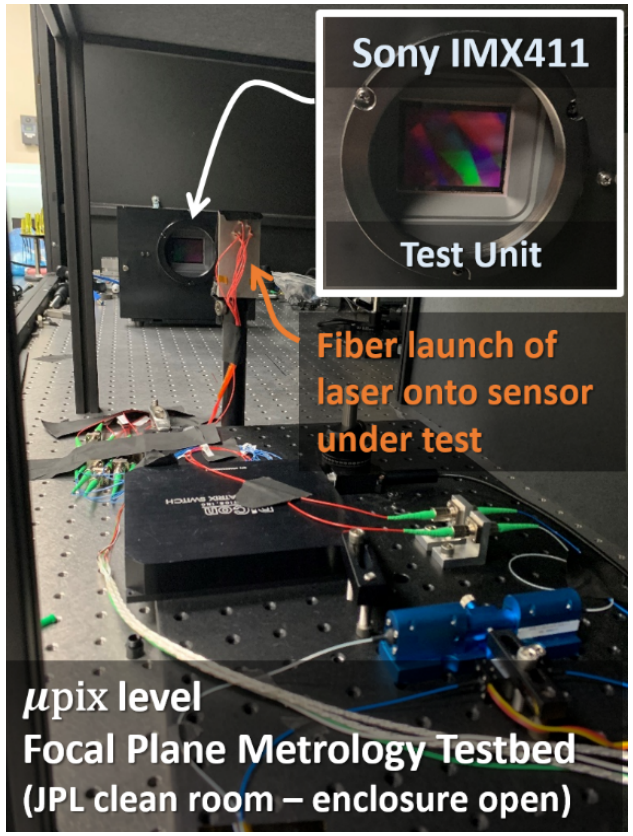




Preliminary tests on a Larger sCMOS detector

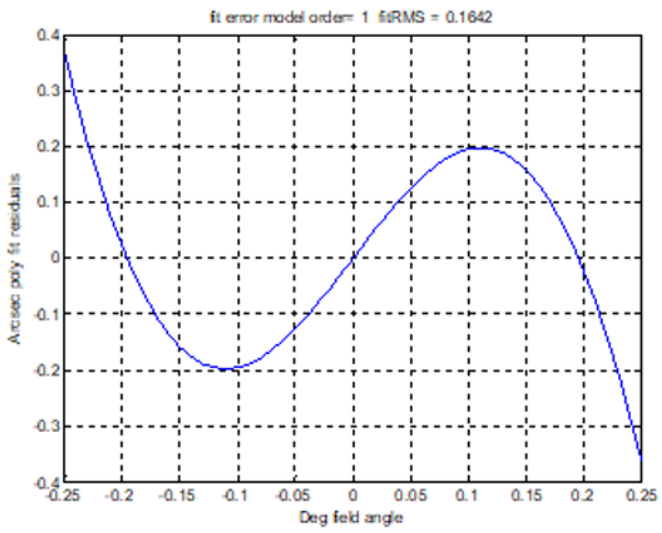
- Last fiscal year we did conduct some tests on a larger format backside sCMOS detector.
  - The sensor was a 2K*2K backside sCMOS with 11um pixels.
- We found two issues
  - Like many sCMOS sensors it had two A/D converters (one with a high gain amplifier for low level signals, one with low gain that provide a large full well)
  - In this case the two 11 bit A/D were blended in the camera electronics to produce a 16 bit output. There were photometric errors >> 0.1% in the blended output. Fortunately the very large format 150Mpix sCMOS sensor we plan to use for MASS has a single 16 bit A/D. (the 1st sCMOS to feature a 16bit A/D)
  - We also saw geometric errors in the pixel positions, the left/right halves of the sensor had slightly different pixel spacing. (diff by ~0.2% (11um vs 11.02um) This was a discontinuity in the slope (not the position) and even at 1/1000 pixel would be modeled with a low order polynomial (as field distortion)
  - But at 1e-4 pixel this has to be measured and explicitely.

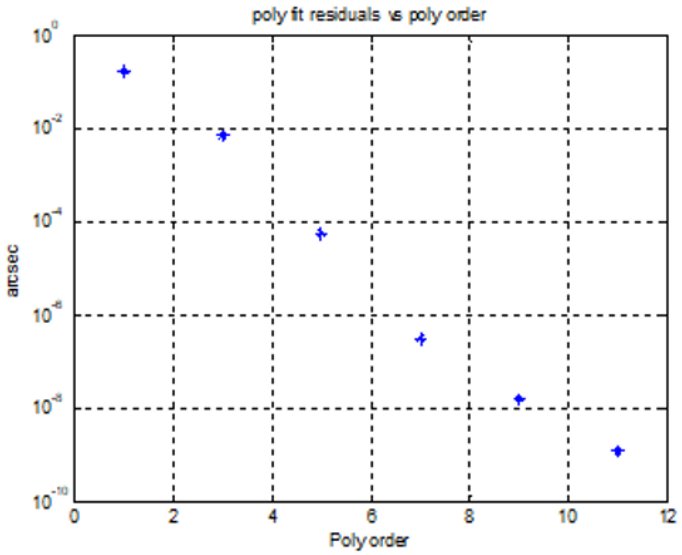
New setup with MASS sensor

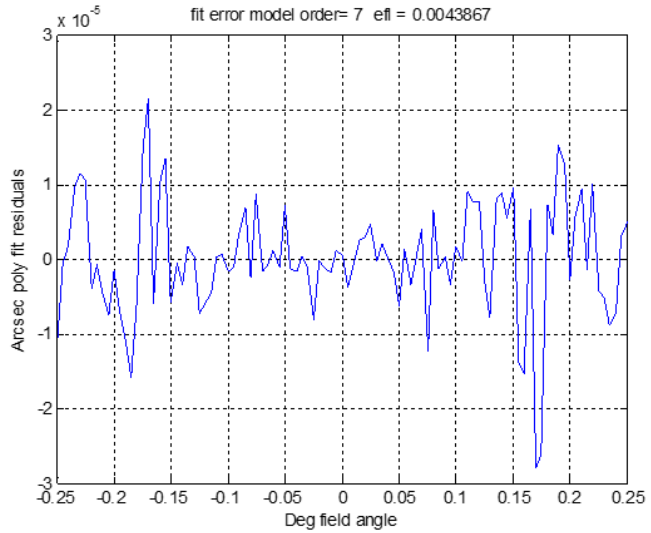


Optics Field Distortion

- Optics field distortion has several sources
  - Perfectly fabricated optics will have distortion. (part of design)
  - Optics are not perfectly manufactured. (l/20 errors 1/f3) to be expected
  - Possible chromatic errors when lenses are used.
- All in modeling, found distortion of the design can be modeled to < 5uas with 9th order poly.
- Also we found that $\lambda/20$ optical figure errors are also well modeld by the 9th order poly. (optic closes to focal has the most beam walk)
  - Made errors ~2X worse with l/20
- Chromatic errors were dealt with by limiting spectrum to 500~750nm. And designing the system accordingly.
  - What matters is shift in position when star's temperature changes. (offsets don't matter because we're looking for periodic motion)

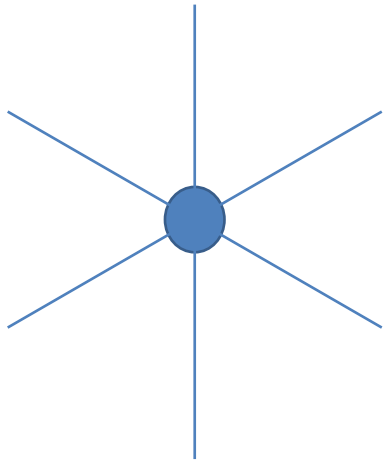


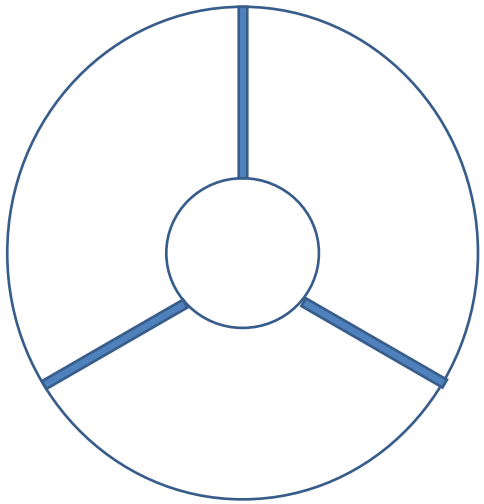




Bright Stars (and detector saturation)

- The closest stars are very bright. (Alp Cen is ~0 mag) and even though the CMOS detectors have much higher frame rates than CCDs, saturation is an issue.
- Our approach is to use a technique that has been used on HST and planned for WFIRST (WFI) perform astrometry on the diff spikes of very bright stars.
- The diffracting aperture is on the primary mirror (oversized from the physical spider suppport)
  - The % of light diffracted was increased to ensure that the its photon noise was smaller than photon noise from reference stars, for the dimest target star whose central peak was saturated.
- This will be simulated and tested in the lab.





All diff apertures (spider and secondary) on primary mirror slightly enlarged so there is no beam walk over the ~0.5 deg FOV

Astrometric Error Budget

- 4 uas astrometry of a bright target star against 11~16 mag reference stars
  - 100~200 ref stars

Target Star	*η Cas*	
Visual Magnitude	3.46	*mag*
1 ME signature	0.53	*uas*
Reference Stars	9-15	*mag*
Tel Diam.	35	*cm*
FOV diam	0.51	*deg*
Wavelength	575	*nm*
Bandwidth	250	*nm*
Dithers/obs.	60	*dithers*
PSF sampling	0.51	*lam/D*
Integ. time /obs.	29	*min*

Astrometric Signature
η Cas @ 1.0ME
V=3.5, G0V, 6.0 pc
0.53 uas

Required SNR
for 1% FAP **6.0**

Integration Time
1 obs. 29 *min*

Observations Needed
To Reach SNR *hrs*
REQ 4138 *obs* *2000*
CBE 3255 *obs* *1573*

Single Observation
Differential Astrometry
REQ 5.66 uas 1 obs
CBE 5.02 uas 1 obs

End of Mission Error
after REQ Integration Time
REQ 0.09 uas
CBE 0.08 uas

Performance Margin
in observations
21 %

uas ≡ μas

signal source: SPI
Ref. Star Count Basis: GAIA DR2 R15

Pointing Jitter
Line of sight jitter
REQ 2.50 uas
CBE 1.75 uas

Photon & Detector Noise
Differential Astrometry
REQ 3.11 uas
CBE 2.97 uas

Focal Plane Errors
Pixel Location Knowledge
REQ 3.14 uas
CBE 2.97 uas

Field Distortion Errors
Telescope and OTA
REQ 2.12 uas
CBE 1.98 uas

Astrophysical Errors
ref and target
REQ 1.30 uas
CBE 0.73 uas

Target Star
Photon & Detector Noise
REQ 2.20 uas
CBE 2.15 uas

Reference Stars
Photon & Detector noise
REQ 2.20 uas
CBE 2.05 uas

Pixel Cal. & Centroiding
Ground calibration of FPA
REQ 2.89 uas
CBE 2.81 uas

Detector Thermal Change
since focal plane metrology
REQ 1.22 uas
CBE 0.95 uas

Field Distortion Calibration
Error after on-sky Cal.
REQ 2.00 uas
CBE 1.91 uas

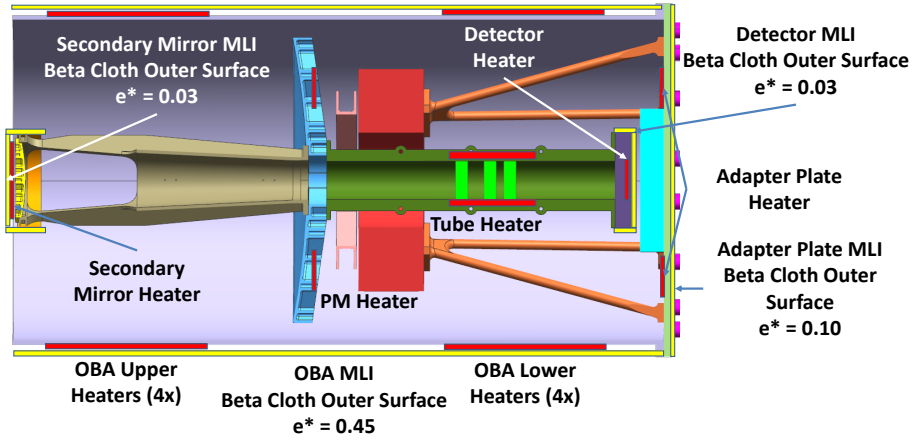
Telescope Thermal Change
since FD calibration
REQ 0.70 uas
CBE 0.50 uas

Target Star Astrphys. Noise
brightness centroid motion
REQ 0.51 uas
CBE 0.13 uas

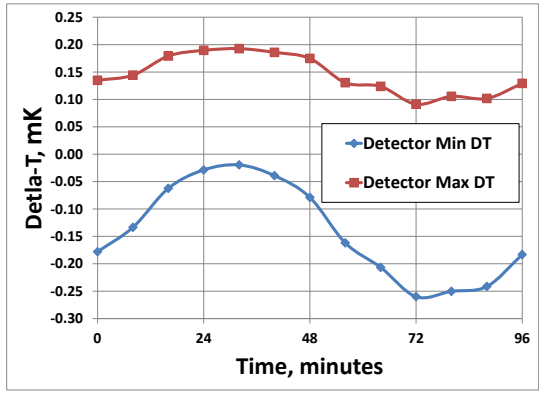
Ref. Star Astrophys. Noise
spectral chg. x chromaticity
REQ 1.20 uas
CBE 0.72 uas

Thermal Control

- We simulated a thermal control system (for flight)
  - turned out to be very capable.
- SSO orbit was chosen
  - few eclipses
- Examined 1 orbit in SSO
  - heating by Earth changed
- Detector stable to < 0.5 mK
- Telescope optics and structure stable to ~ 10mK.
  - SiC structure
- Detector stable to < 5uas (over field)
- Distortion stable to < 5uas (over field)



Temperatures in °C	PM	SM	Optics 1	Optics 2	Optics 3	Detector
Mean Temp	-10.5174	-10.5011	-6.9487	-6.5735	-6.3522	-4.9996
Maximum Temp	-10.3406	-10.4907	-6.9462	-6.5717	-6.3409	-4.9993
Minimum Temp	-10.6589	-10.5059	-6.9617	-6.5832	-6.3542	-5.0000
ΔT overall	0.3183	0.0152	0.0155	0.0115	0.0133	0.0007



Spacecraft capabilities needed/Orbit etc

- The focal plane can be read out quickly (compared to CCDs) but because its so large, it does take time. (3 hz). The spacecraft attitude has to be stable to < l/D on the time scale to read the array. (ideally 0.25~ 0.5 l/D)
- JPL's Asteria achieved (on a cubesat budget) the type of pointing stability we want.
  - This may require a separate ~6cm telescope with sCMOS focal plane as a fine guidance camera.
- Default SSO orbit. Thermal design to aim for 1 digit mK sensor stability and < 10 mK telescope thermal stability. (SiC telescope thermal stability is slightly better at low Temp (<200K), reducing heater power needed to maintain thermal stabilty.
  - Sufficient battery energy to maintain thermal control during eclipse of S/C in SSO orbit for part of the year.

Commercial Space Industry has dramatically lowered the cost of ESPA class spacecraft

- Dozens of ESPA class S/C now orbit the earth providing Earth sensing data for Business/Industry. Many of these are "mass produced" in quantities ~10. Mostly they use cubesat parts. (some eg reaction wheels, scaled up for microsats)
  - Mass produced satellites with 30~35cm telescopes and CMOS focal planes can be below $10M/each.
  - One of a kind science missions will be more expensive, but affordable
- Unlike traditional NASA and DoD missions, the spacecraft bus for commercial satellites are bid "fixed price". Major components such as small (30~35cm telescopes and CCD/CMOS focal planes are also bid fixed price).
  - Reducing the mission cost risk.
- Life time (on their website) advertised as ~5 yrs. (very different from "student cubesat" projects of 10yrs ago)
  - The very low cost of cubesat components, lets one think of redundant components (eg reaction wheels, star trackers, solar panels) to ensure 3~5 yr mission life.
- BUT the cost of these commercial missions are NOT in the NASA/DoD data base. (in some cases historical costs are proprietary, (bid fixed price), NASA Centers and NASA costing may or may not accept these low costs.

Exoplanet Science /Mission Cost

- 5 nearby stars down to 1 Mearth in 1 AU equiv orbit
- ~20 stars down to 2 Mearth in 1 AU equiv orbit
- JPL Team X costing exercise
  - ~3 cost numbers
    - Grass roots (based on ROM quotes)
      - ~ $24M (all costs include 30% reserve)
    - 50% cost (based on historical data)
      - ~ $40M
    - 70% cost
      - ~ $44M: 70% prob mission will be completed within this cost

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64924	61 Vir	3	4.7	G7V	8.5	0.97	121	1661	23383
15510	e Eri	3	4.3	G6V	6.1	1.28	51	1961	25344
64394	β Com	3	4.2	G0V	9.2	1.06	31	3419	28763