NORTHROP GRUMMAN

NWO Trajectory and Alignment Control (TAC)

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NEW WORLDS OBSERVER

Seeking Earth-like Planets in Our Solar Neighborhood

The Big Picture

Two-Spacecraft System

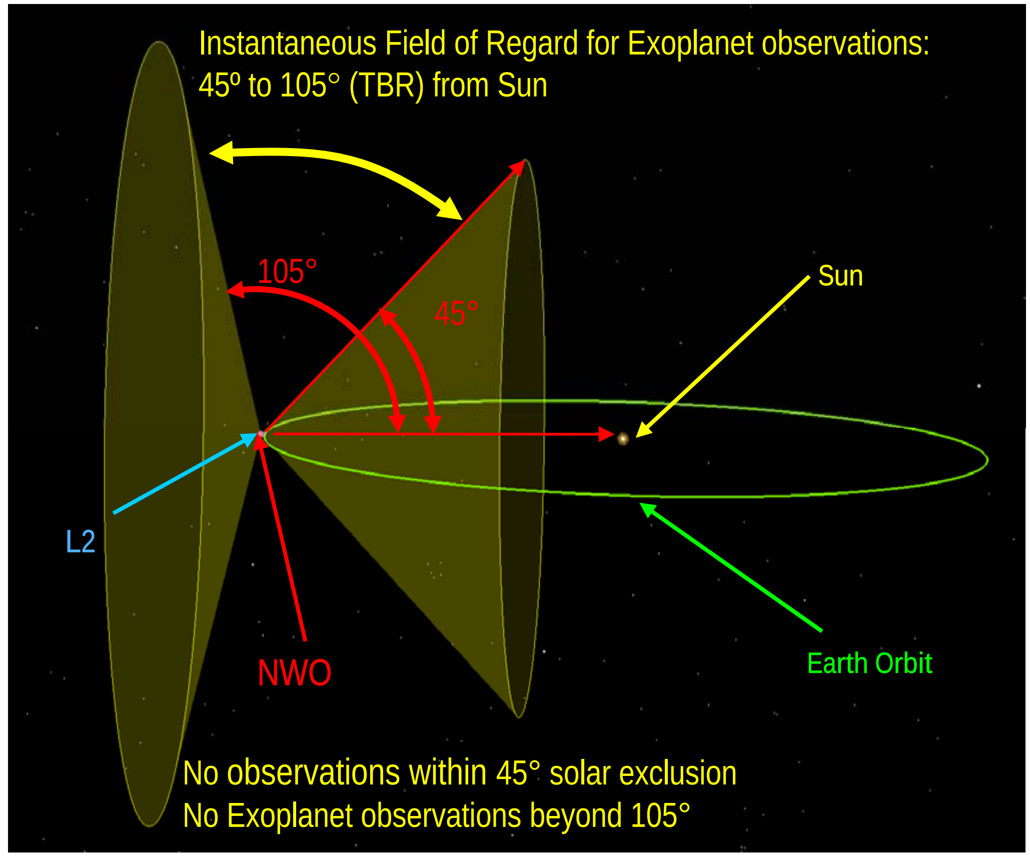
- **Telescope** in Sun-Earth L2 Libration Point Orbit
- **Starshade** in Quasi-L2 Orbit (near-constant thrust)

Two types of science:

- **Exo-Planet Observations:** new target ~ every 2 weeks
- **General Astrophysics:** Telescope observations while Starshade gets into position for next exo-planet target

Fields of regard:

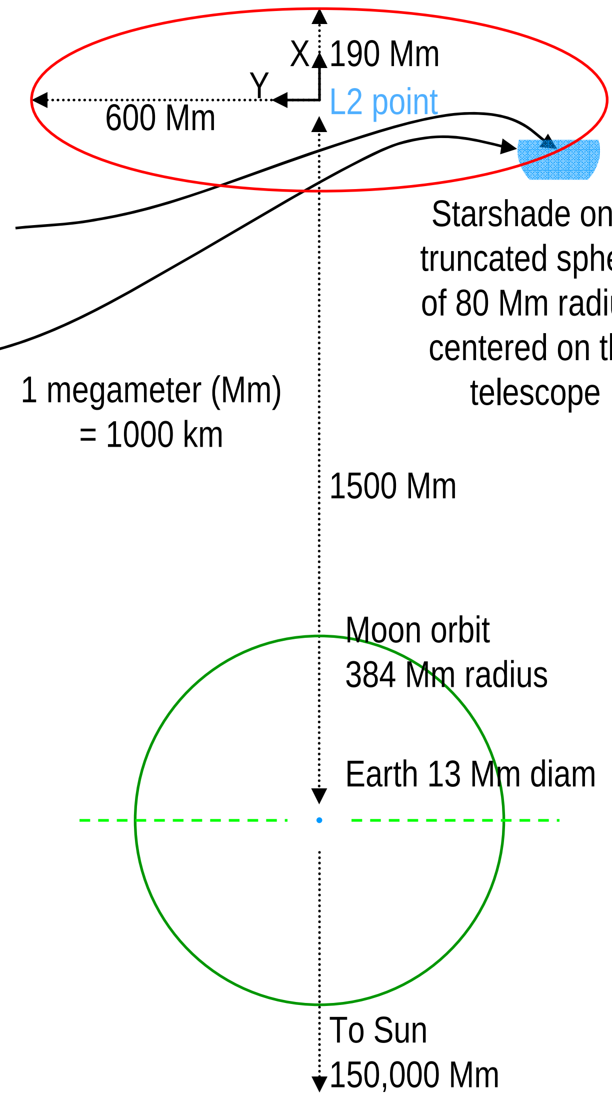
- Exoplanet observations 45°-105° from Sun-Earth-L2 line
- General astrophysics may be possible beyond 105°



The Big Picture

Zooming in on Earth and L2

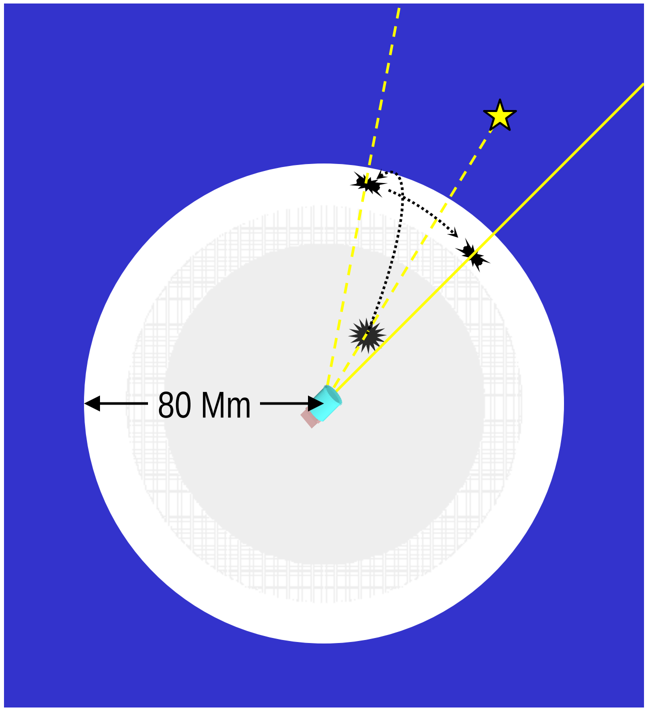
- Telescope in Sun-Earth L2 Libration Point Orbit
  - Orbit is similar to JWST
- Starshade Spacecraft in Quasi-L2 Orbit
  - Orbit is NOT like JWST — not a classic L2 orbit
  - Almost continuously thrusting
  - Positioned with reference to the Telescope



The Big Picture

Zooming in on the NWO system

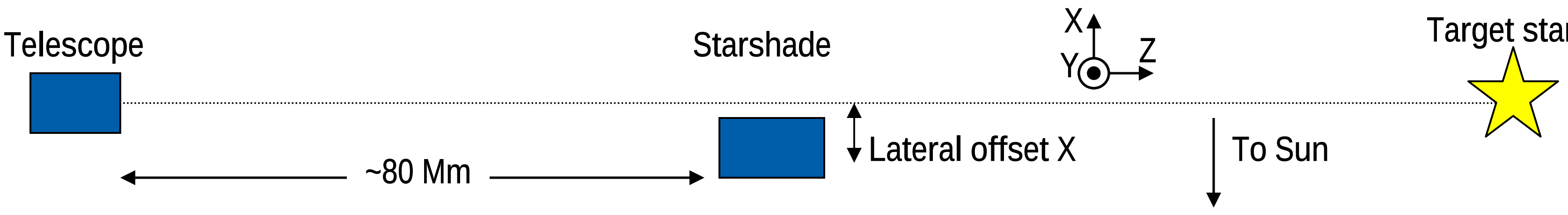
- Starshade moves on a sphere of ~80 Mm radius (TBR) centered on the Telescope
  - Starshade isn't exactly on same L2 orbit
  - Sphere is truncated by sun and anti-sun exclusions
- Starshade places itself between Telescope and a star → Telescope can see planets
- After detailed study of these planets, Starshade slews to the next star position
- Examine a series of stars in this way
- Sphere radius can be adjusted
- During the long periods between stellar alignments, both Telescope and Starshade can be engaged in other astronomical studies



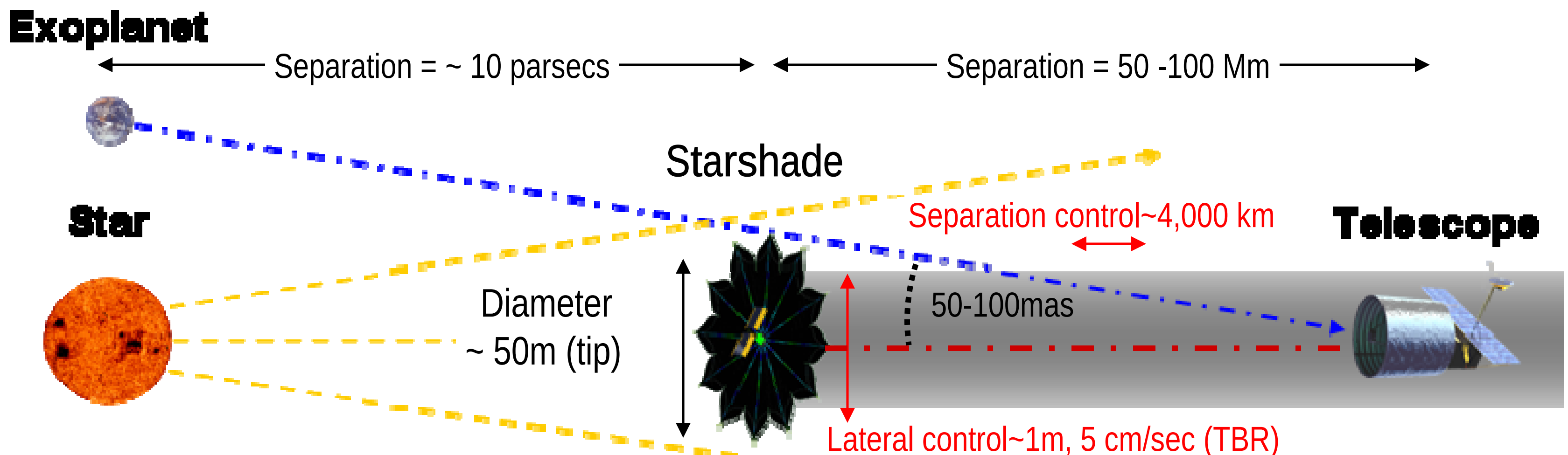
A single Starshade (black flower shape) moves around a sphere, blocking each star in turn. This shows 3 such positions: the 1st position blocks a star in this viewing window, while the 2nd and 3rd positions are for stars outside this view.

TAC Coordinate Systems

- Telescope in its L2 orbit is the Origin of the TAC coordinate system
  - Starshade is measured with respect to Telescope
- During the slews between exoplanet target stars (“trajectory”), <u>spherical</u> coordinates are most useful:
  - Range – Inter-spacecraft distance
  - Bearing – direction from Telescope to Starshade (celestial coords, e.g. RA/dec)
- When approaching or engaged in exoplanet observations (“alignment”), a <u>Line of Sight (LOS)</u> coordinate system becomes more useful
  - Z axis ≡ the line between Telescope and star
  - XY ≡ Starshade’s lateral offset (meters) from that line
  - Choose X in Sun-Telescope-Star plane
  - These axes often rotated widely from the traditional L2-based axes (p. 3)

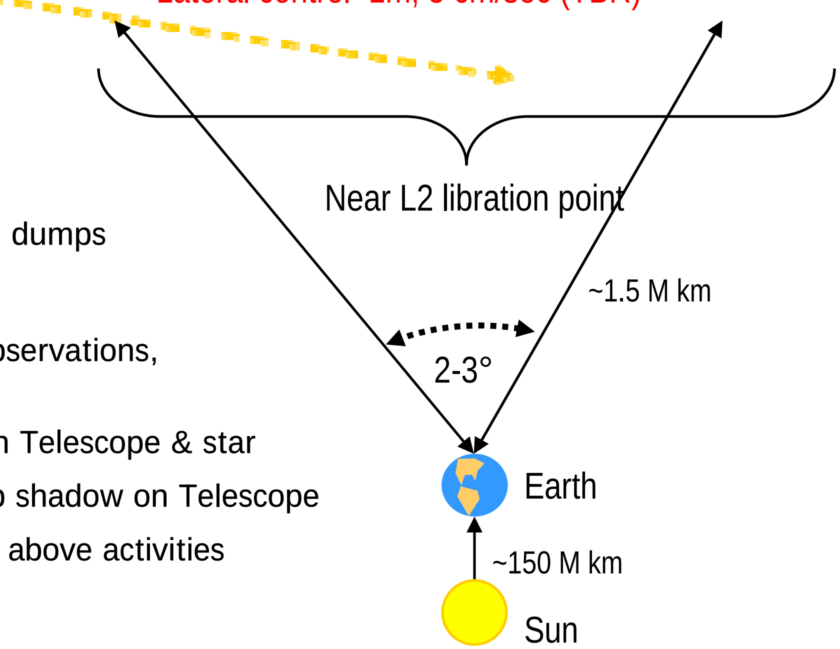


Preliminary TAC Requirements



Telescope

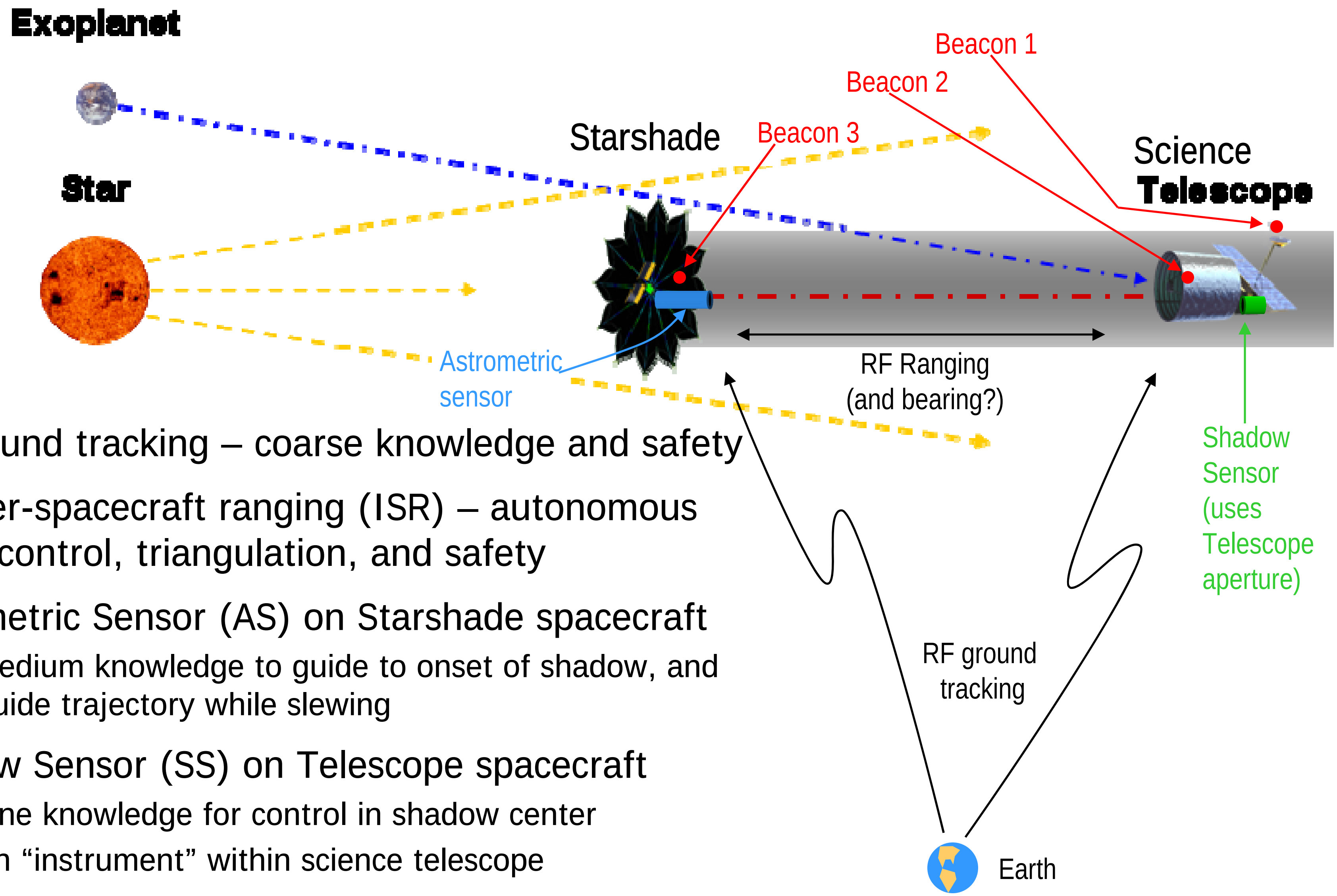
- Maintains L2 orbit, ≤4 orbit maintenance maneuvers/yr with chemical propulsion
- Reorients for exo-planet & general astrophysics observations
- RWAs control pointing to target, thrusters perform momentum dumps



Starshade SC

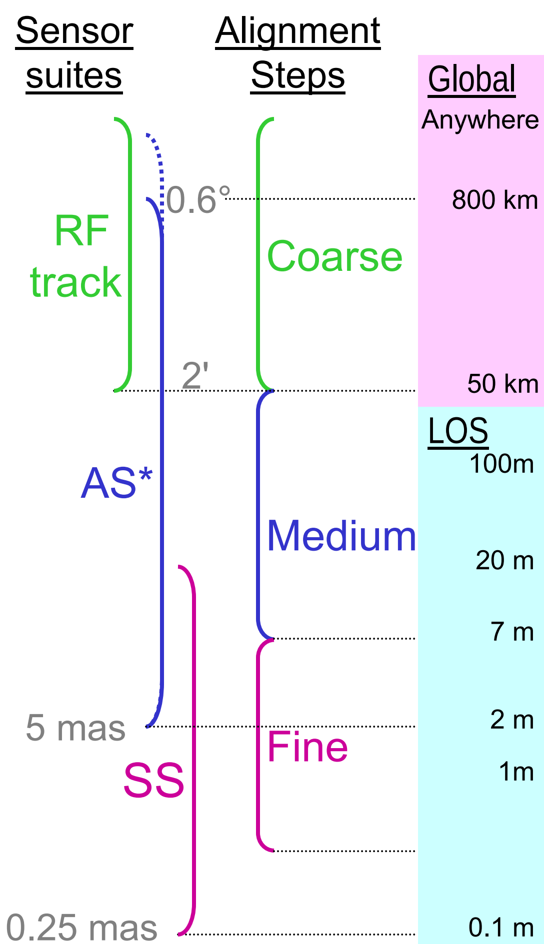
- Using SEP thrusters, follows a trajectory between exoplanet observations, moves into position to block next target star
- Reorients and repositions spacecraft to align with LOS between Telescope & star
- RWA, chemical propulsion control position and attitude to keep shadow on Telescope
- L2 location maintenance & momentum dumps concurrent with above activities

TAC Sensor Overview



- RF ground tracking – coarse knowledge and safety
- RF inter-spacecraft ranging (ISR) – autonomous range control, triangulation, and safety
- Astrometric Sensor (AS) on Starshade spacecraft
  - Medium knowledge to guide to onset of shadow, and guide trajectory while slewing
- Shadow Sensor (SS) on Telescope spacecraft
  - Fine knowledge for control in shadow center
  - An “instrument” within science telescope

TAC System Summary

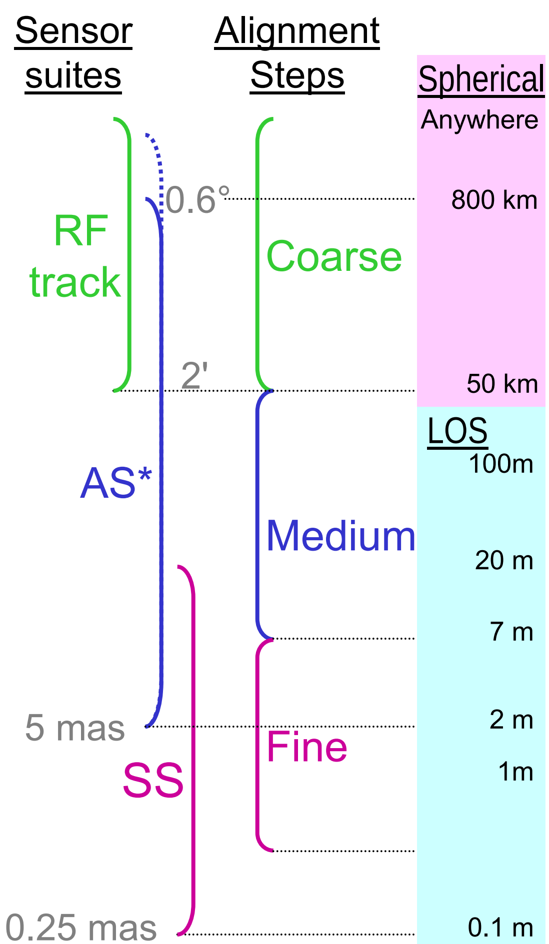


Phase	Time	SSS thrusters	RF track	AS	SS	Science Instruments
AS initialization	5-15 days	Off	DSN, ISR	Turns on	Off	GA or off
Slew	5 – 15 days	EP	ISR, DSN (maybe)	Periodic Looks	Off	GA
Transition	~ hours	EP → chemical	ISR	On, then hand off to SS	Turns on	GA, or pointed at target star
Science Observation	~ days	chemical	ISR	Off	On	ExoCam, ExoSpec

SSS: StarShade Spacecraft AS: Astrometric Sensor SS: Shadow Sensor GA: General Astrophysics ISR: inter-spacecraft range

* After AS has initialized (found Telescope on sky), it gives full accuracy for any bearing value in the truncated sphere.

TAC System Margin



- Sensors have comfortably overlapping ranges of applicability
  - Factor 16 margin for handoff from RF track to AS
    - Room for degradation of RF tracking due to thrusting
    - AS can also manage Coarse step, after initialization
  - Factor 10 margin for handoff from AS to SS
- Alignment steps have margin within them too
  - Beacons enable Coarse to Medium handoff (AS acquisition) even beyond 800km/ 0.6° uncertainty with modulation and a spiral search
  - Medium to Fine handoff at σ=7m gives 99.7% confidence that offset$\leq$20m (shadow onset)
  - Fine requirement of 3σ < 1m gives high confidence of remaining in deepest shadow
    - SS performance ~0.1m → 10σ < 1m

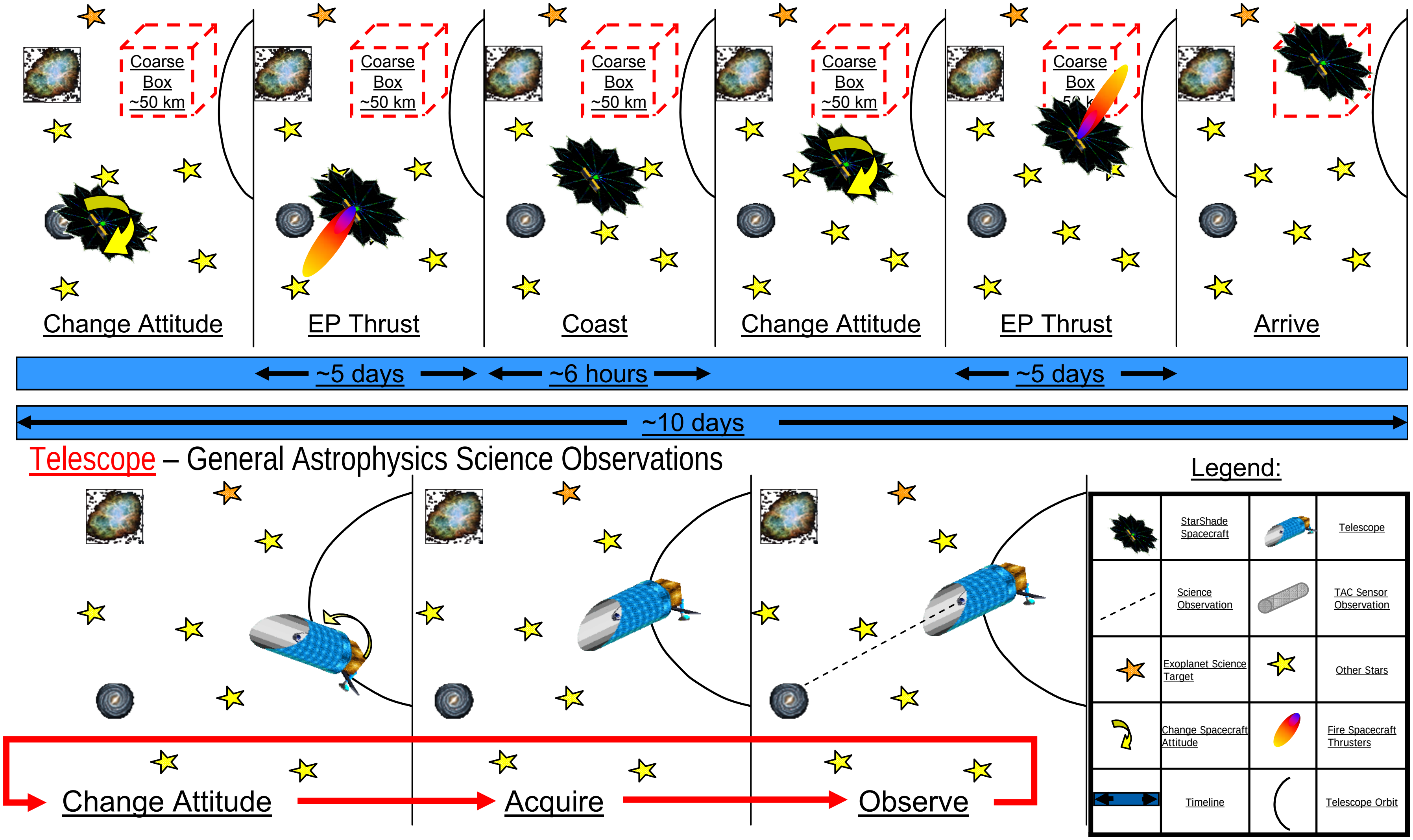
Sensor Requirements

Sensor	Objective	Allowable range	Accuracy	Sensitivity
RF ground tracking	Enable AS to find Telescope	Any place near L2	<800 km	<800 km
	Guide slew to new star			
ISR	Monitor distance between s/c	Within 200 Mm	150 km	15 km
Astrometric sensor (AS)	Guide slew to new star	Within FOV (~1°)	~100mas	~100 mas
	Guide to onset of shadow		50 mas (3σ)	5 mas
Shadow sensor (SS)	Guide to shadow center	Within shadow (radius ~ 20m)	~1 m (3σ)	~0.1 m

- All values TBR
- Reference: 2m / 80 Mm = 5 mas = 25 nrad

Coarse Alignment

Starshade Spacecraft – Coarse Alignment, using AS and RF tracking



TAC System Requirements for Coarse Alignment

Trajectory from one star to the next

- For initialization of the Medium Sensor (=AS), the Starshade and Telescope Spacecraft positions shall be measured to a 3-D accuracy of ±800 km (3σ) (TBR) at a separation of 80 Mm
  - Capability ~50 km 1σ after ~2 weeks coasting
- For nominal slew operations, the Starshade spacecraft shall be positioned by ground command to align with the target star with a 3-D accuracy of ±50 km (1σ) (TBR)
  - Allow slew trajectories governed by DSN or AS, with handoff at 50km
  - AS could cover entire slew up to onset of shadow; 50km boundary disappears
- The Starshade spacecraft relative velocity shall be <1 m/s (1σ) (TBR)
  - 1 m/s is comparable to the Δv needed to guide from 50 km offset to 0 in <12 hr
- Requires appropriate access to sky for S-band and/or AS during slew

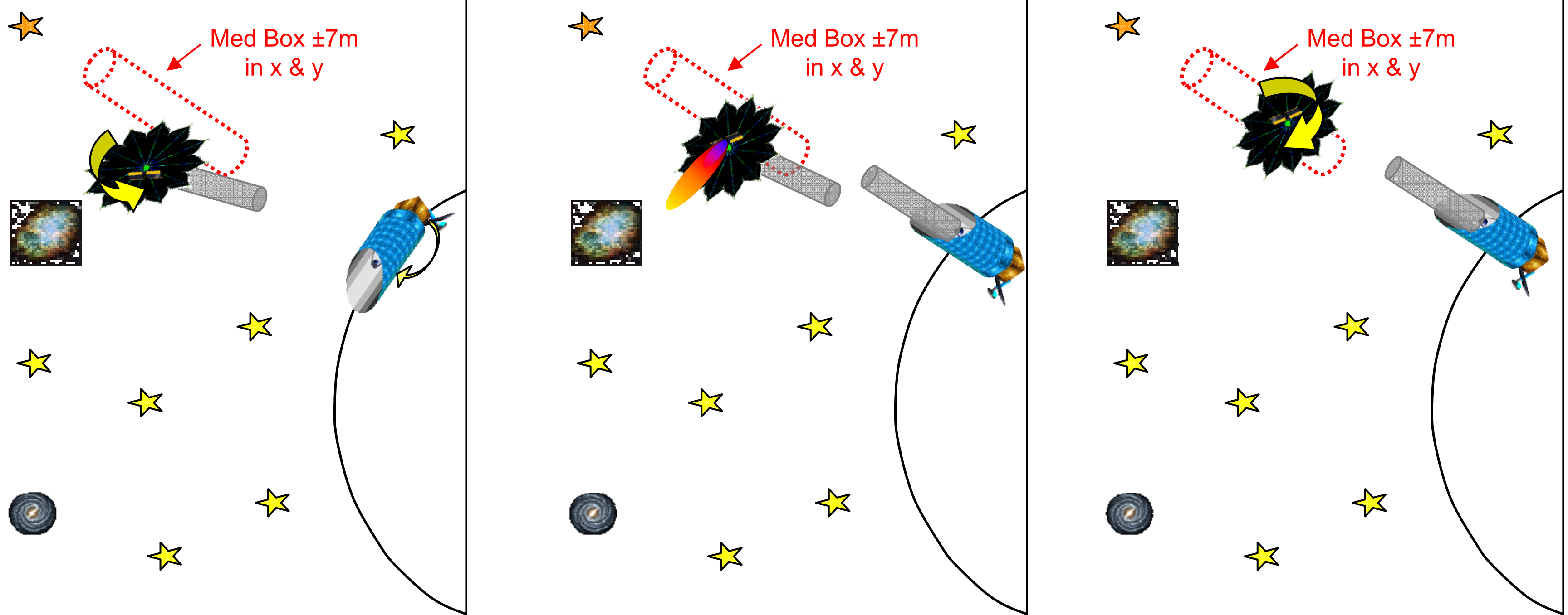
RF tracking

- Measure 2-way range and Doppler during ~daily DSN contacts with Starshade and Telescope
- Estimation algorithms to solve for orbit
- Tracking data during ~2 week coasting periods can yield orbital solutions with 3D uncertainties of ~50km for positions near L2
  - Enables initialization of Astrometric Sensor (pg. 16):
    - Pointing beacon toward Starshade, with <1° uncertainty
    - Pointing AS toward Telescope, with <1° uncertainty
- Useful for routine operations and emergencies (recovery from anomaly)
- Orbit solution uncertainty is expected to degrade if coasting is interrupted by thruster firings, e.g. during slew to next star
- ISR by S-band time-of-flight measurement: $\sigma \sim 15$ km
- AS concept allows repeated observations during slew to track progress across the sky
  - Baseline is to take and use this data, even if RF tracking is available also
  - Can rely on AS during normal slews if needed

Medium Alignment

Starshade Spacecraft – find onset of shadow using AS

Point AS at Telescope	Use AS & Chemical Thrust	Arrive & Change to Science Attitude



Telescope – detect onset of shadow using SS

Point to Target Star and Starshade	Use Shadow Sensor	Use Shadow Sensor

← few hours →

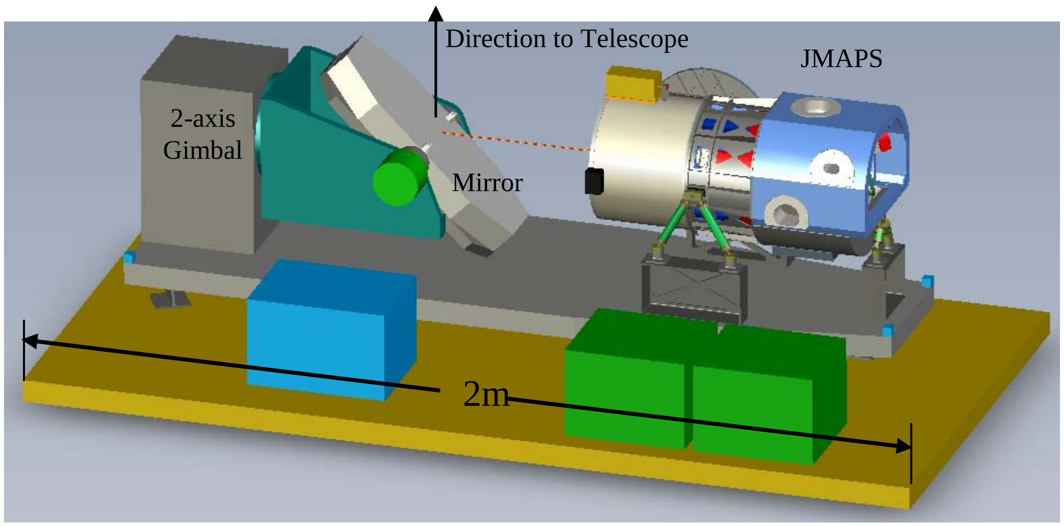
TAC System Requirements for Medium Alignment

From Coarse Alignment to onset of shadowing

- Starshade spacecraft shall be able to identify, locate, and track the Telescope spacecraft on the sky, using celestial coordinates with initial uncertainty <0.6°(3σ)
  - Handoff from RF tracking to AS
- Starshade spacecraft shall position itself to (X,Y) < 20 m (3σ) (TBR), and Z=80±4 Mm (1σ), in the LOS coordinate frame
  - <52 mas (3σ) with respect to LOS to star
  - This offset guarantees the onset of shadow
  - Calibration of spherical to LOS coordinates (AS angles to XY origin) is a challenge; contributes to uncertainty in X,Y
  - ISR (S-band) is used to monitor Z; usually no correction of Z errors during exoplanet observation
- Starshade's final relative velocity shall be <0.5 mm/s (1σ)
  - Comparable to typical velocities during observation (1m / 30min)

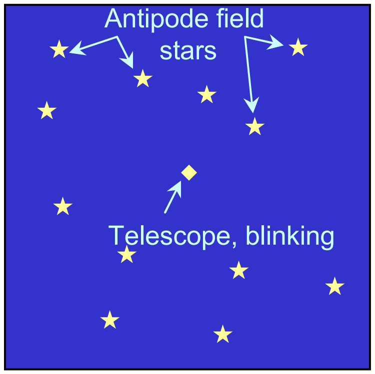
Astrometric Sensor (AS)

- Determines Starshade-to-Telescope direction referenced to stars
- Differential angular measurements using a "super-star-tracker"
  - Baseline uses JMAPS instrument
- AS mounted on Starshade, looking toward Telescope



Astrometric Sensor assembly concept from GSFC's IDL

- Laser beacon(s) on Telescope → modulated, bright
- Differential astrometry of the beacon vs. stars with ~5 mas accuracy → bearing, e.g. in RA/dec
- After some work, this achieves shadow onset → transition from spherical to LOS coordinates

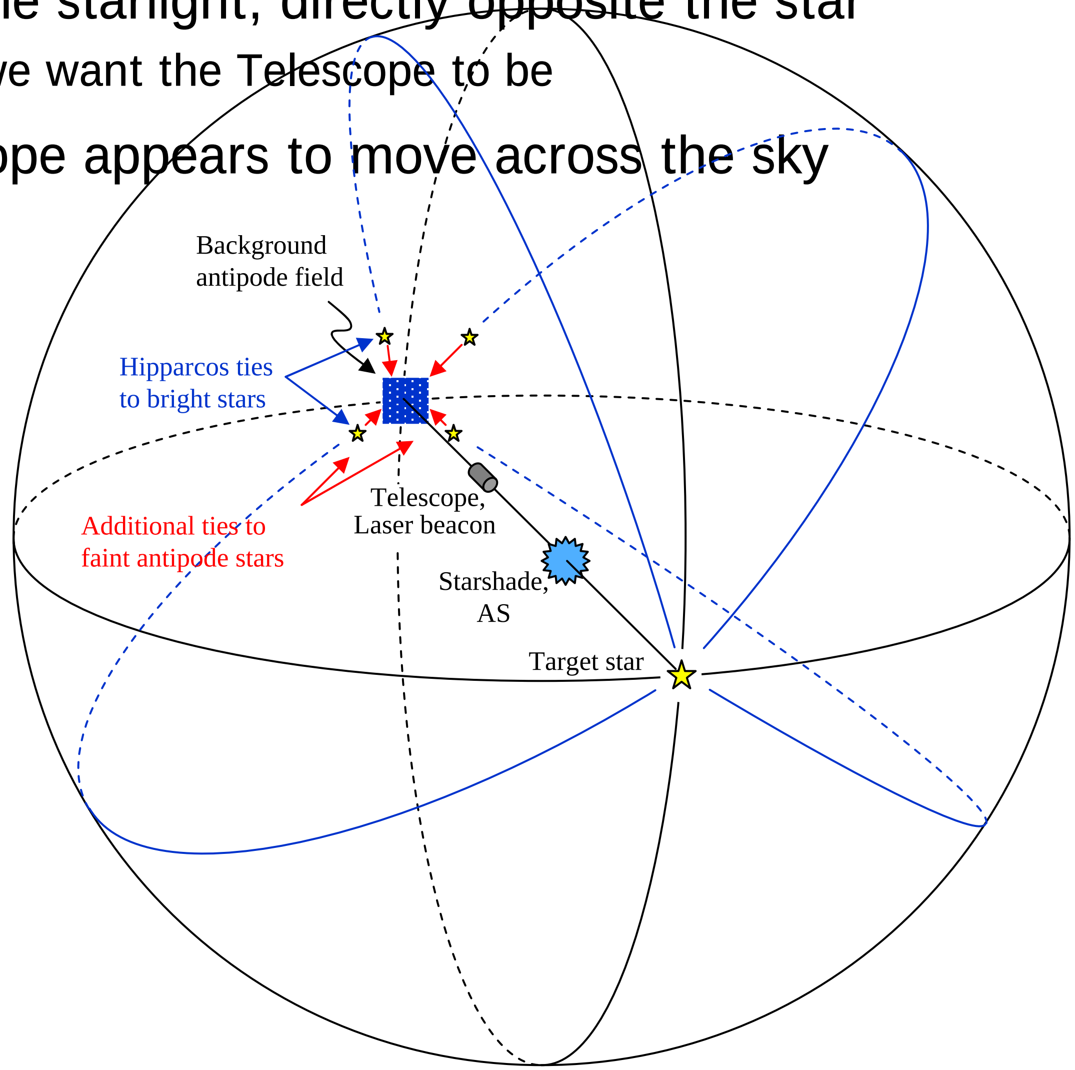


Astrometric Sensor's view toward Telescope

- Gimbal → flexibility on Starshade attitude while AS watches Telescope

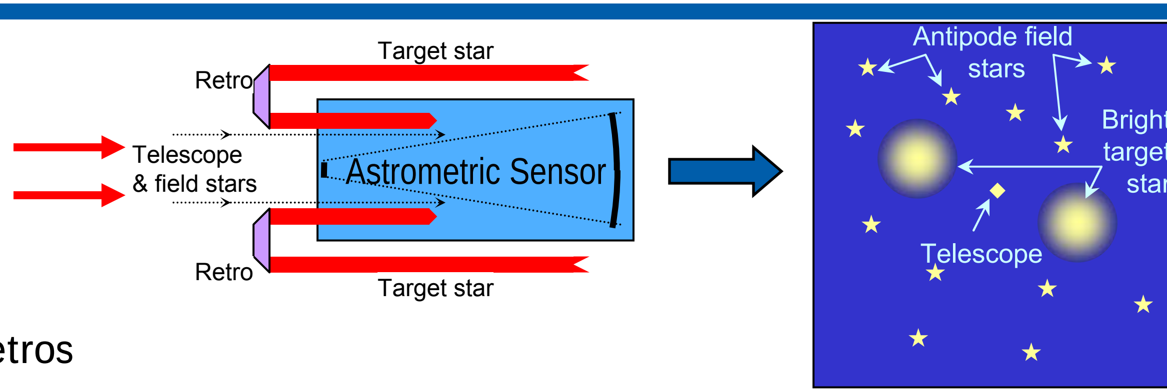
Finding the shadow using the AS

- Starshade casts a shadow in the starlight, directly opposite the star
  - The star's "antipode" – where we want the Telescope to be
- Move the Starshade → Telescope appears to move across the sky
- Use Hipparcos grid, with expected improvements, to calculate antipode location w.r.t. field stars
  - One estimate of calibration between spherical and LOS coordinates
- Maneuver Starshade until Telescope appears at antipode
- Repeat for every target star
  - Some astrometric uncertainty in the transfer via catalog data
  - Worst case up to ~40 mas



Cubecorner retros make AS into a sextant

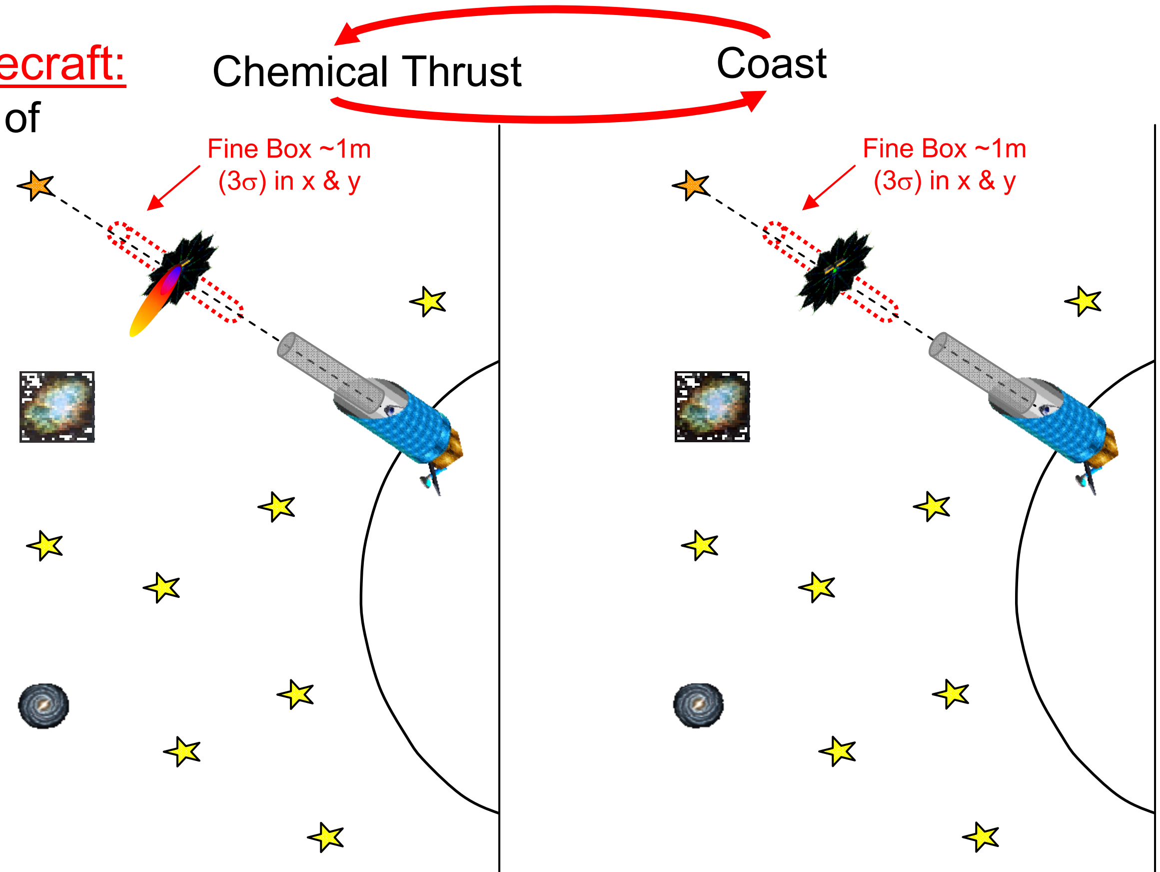
- Retros inject 1-2 copies of the target star into the antipode field
  - Fatter images because of small aperture through the retros



- Those fat images of the target star are "synthetic astrometric references" at a fixed offset from the antipode (location of the target star's shadow)
  - In the illustration above, the shadow would lie on the "Telescope"
  - Misalignment of retros is tuned to give chosen non-zero offsets
- Relative position of science telescope with respect to those copies is a direct measure of telescope-starshade-star collinearity
  - Integration times of order 10 sec each for Telescope, synthetic and real reference stars
- Before on-orbit calibration, knowledge is good enough to initiate first occultation
- Once calibrated, accuracy ≈ sensitivity, not limited by catalog uncertainty
  - Another estimate of calibration between spherical and LOS coordinates
- This gives a portable reference that works on every target star

Fine Alignment

StarShade Spacecraft:
Maintain centering of shadow using SS



Telescope: Report SS readings to Starshade for alignment maintenance,
Observe Exoplanet target with science instruments

1-14 days

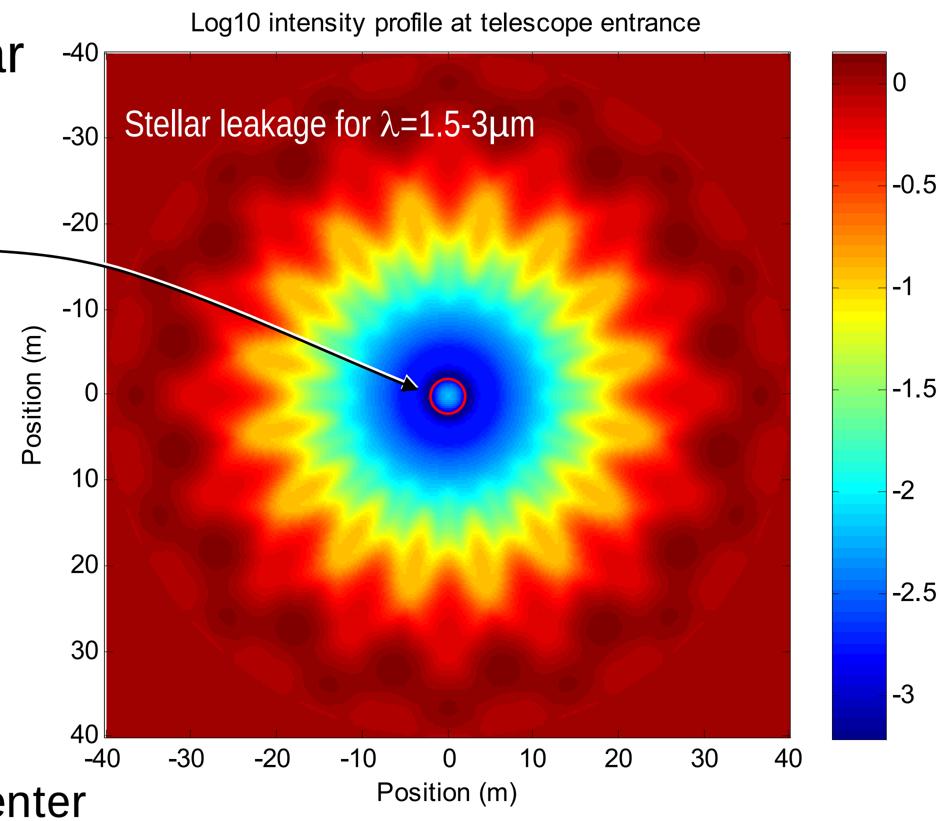
TAC System Requirements for Fine Alignment

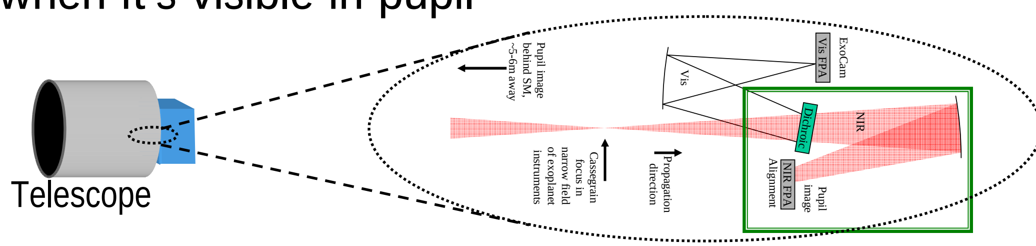
In shadow, finding and keeping the true center

- The Telescope shall be able to measure the X,Y position of the shadow for (X,Y) < 3m to an accuracy of ±10 cm (1σ)(TBR)
- The TAC system shall be able to measure the Starshade's Z position to an accuracy of ±100 km (1σ)(TBR)
  - Inter-spacecraft ranging (ISR) using S-band transponders: σ<15 km
- Starshade spacecraft shall be able to maintain its position with respect to the Telescope to within (X,Y)= ±1 m (3σ) and Z = ±4000 km (1σ) during an observation
- For fine alignment, the Starshade spacecraft relative velocity shall be <0.5 mm / sec
  - Roughly 1m / 30 min, typical control system performance

Shadow Sensor for fine alignment in shadow

- For $\lambda >> 1\mu m$, central peak in stellar leakage returns
  - Poisson's/Arago's spot again
  - 4m telescope covers most of it
- Measure profile of NIR flux in pupil, locate this peak
  - Extract NIR light from science passband using a dichroic mirror
  - Reimage telescope pupil and sample NIR on ~10 cm grid
- Algorithms are a minor challenge:
  - Guide reliably from shadow edge to center
  - Accurately locate center when it's visible in pupil

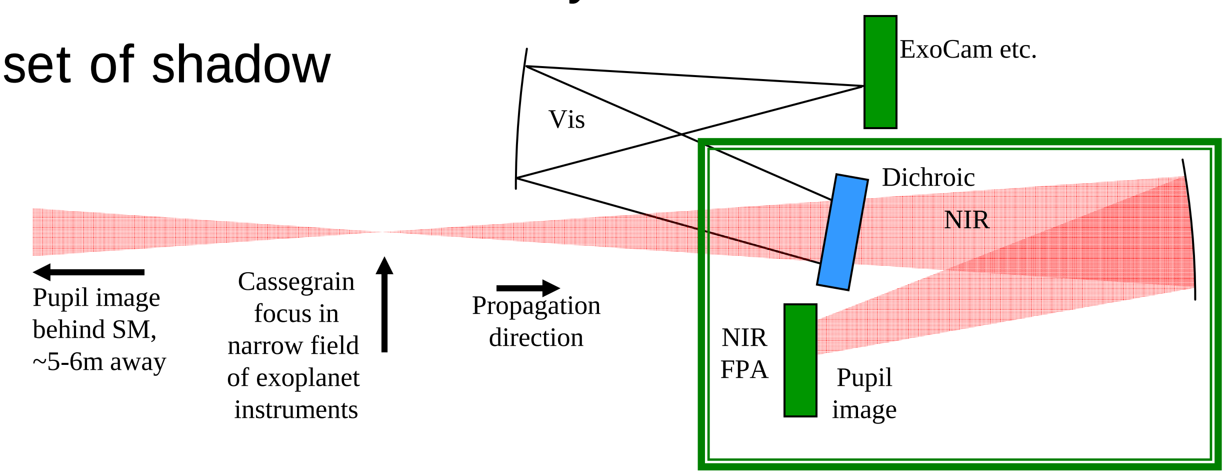




See next page

Telescope NIR pupil imager concept for Shadow Sensor

- Dichroic beamsplitter transmits the NIR light to a mirror & detector
  - Images the entrance aperture (a pupil image)
  - Must preserve diffraction-limited PSF in visible wavelength science instruments
- Imaging detector e.g. MCT
  - One shown, but recommend 2 for redundancy
  - λ ~ 1.7–2.3 µm (TBR)
  - 4-6mm wide, pixel size ~100 µm (TBR)
- Integration time < 0.9 sec for 10cm uncertainty
- Acquisition requires onset of shadow



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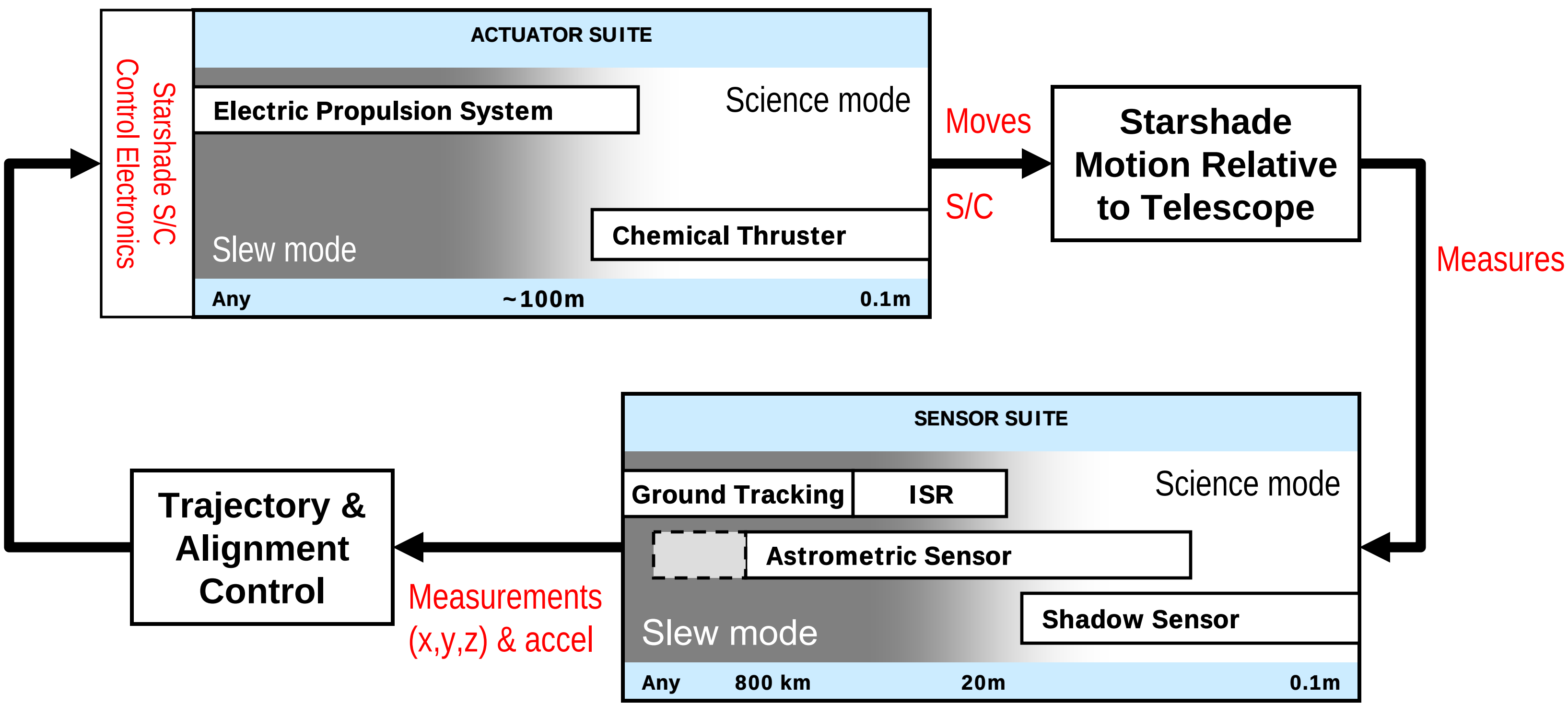
System Aspects of NWO TAC

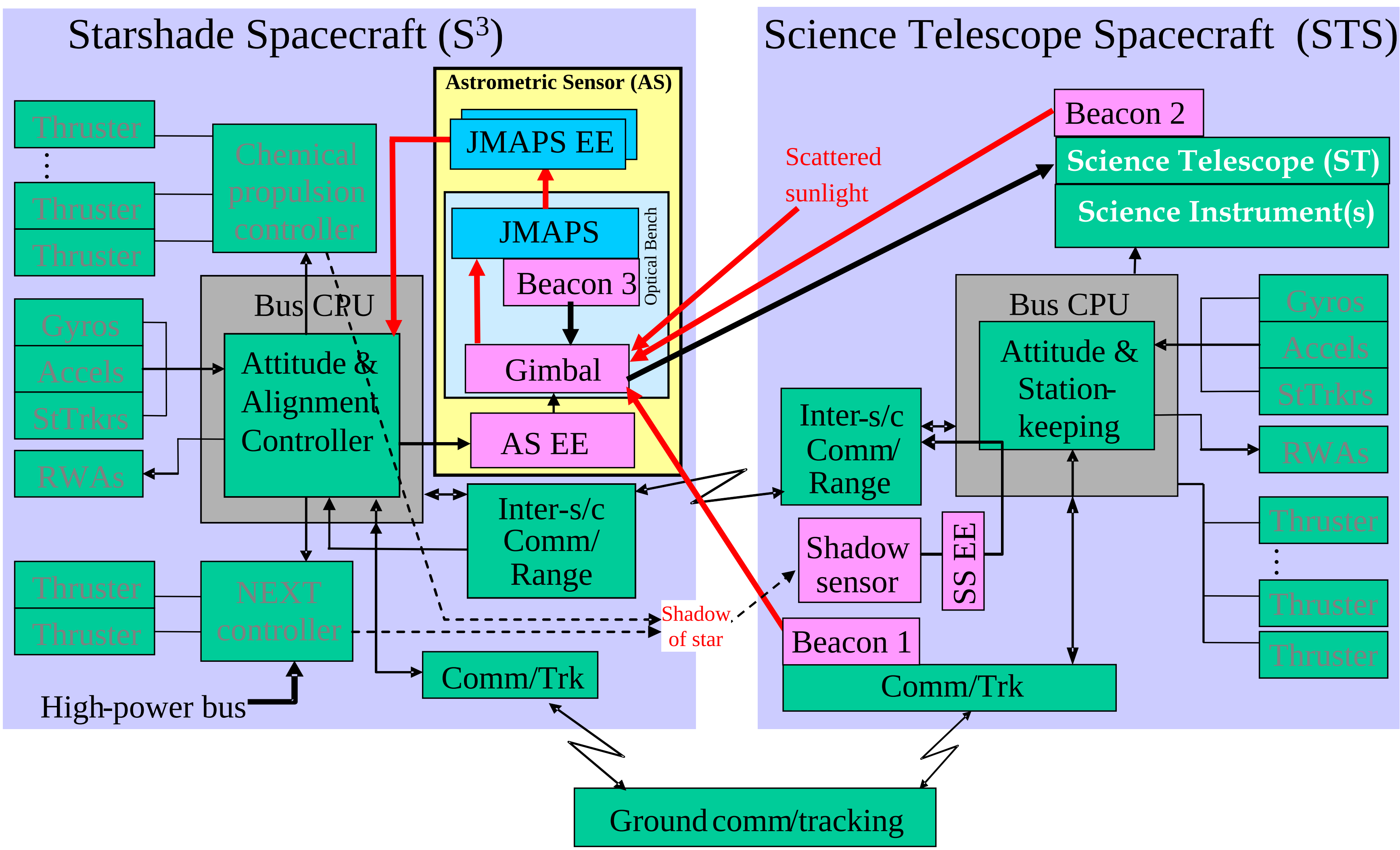
NEW WORLDS OBSERVER

Seeking Earth-like Planets in Our Solar Neighborhood

Trajectory & Alignment Control Architecture



TAC functional block diagram



Systems used during each step

Telescope	Starshade
Coarse alignment	
• Ground based RF tracking (2-way Doppler & range) • ISR using S-band transponders • Chemical propulsion (maintain L2 orbit)	• Ground based RF tracking (mission start only) – Degraded by Starshade thrusting for normal slew • ISR using S-band transponders • Bearing by Astrometric Sensor (AS) • Solar-electric propulsion (repositioning)
Medium alignment	
• Shadow Sensor (detect onset and guide to center) • ISR using S-band transponders	• Chemical propulsion to maneuver into shadow • Astrometric Sensor (until onset of shadow)
Fine Alignment	
• Shadow Sensor (measure offset within shadow) • ISR using S-band transponders	• Chemical propulsion to maintain shadow centering • Shadow Sensor measurements from Telescope

TAC Control Modes

Mode	Sensors active				Propulsion		Control Accuracy (3σ)		Knowledge (1σ)	
	GT	ISR	AS	SS	EP	CP	Range	Bearing or offset	Range	Bearing or offset
Independent safe/cruise*	X				X		Any		50 km sphere/cube	
Formation safe/cruise*	X	X	/		X		Any		100 km	0.1°
Formation coarse	X	X	X		X		Any		100 km	<100 mas
Cooperative transition (medium alignment)		X	X	X		X	4 Mm	120→20 m	100 km	7 m
Cooperative fine		X		X		X	4 Mm	1 m	100 km	0.1 m

* Cruise is the same as Safe w.r.t. TAC

GT Ground tracking
ISR Inter-spacecraft range sensor
AS Astrometric sensor
SS Shadow sensor

TAC Communications/Tracking Overview

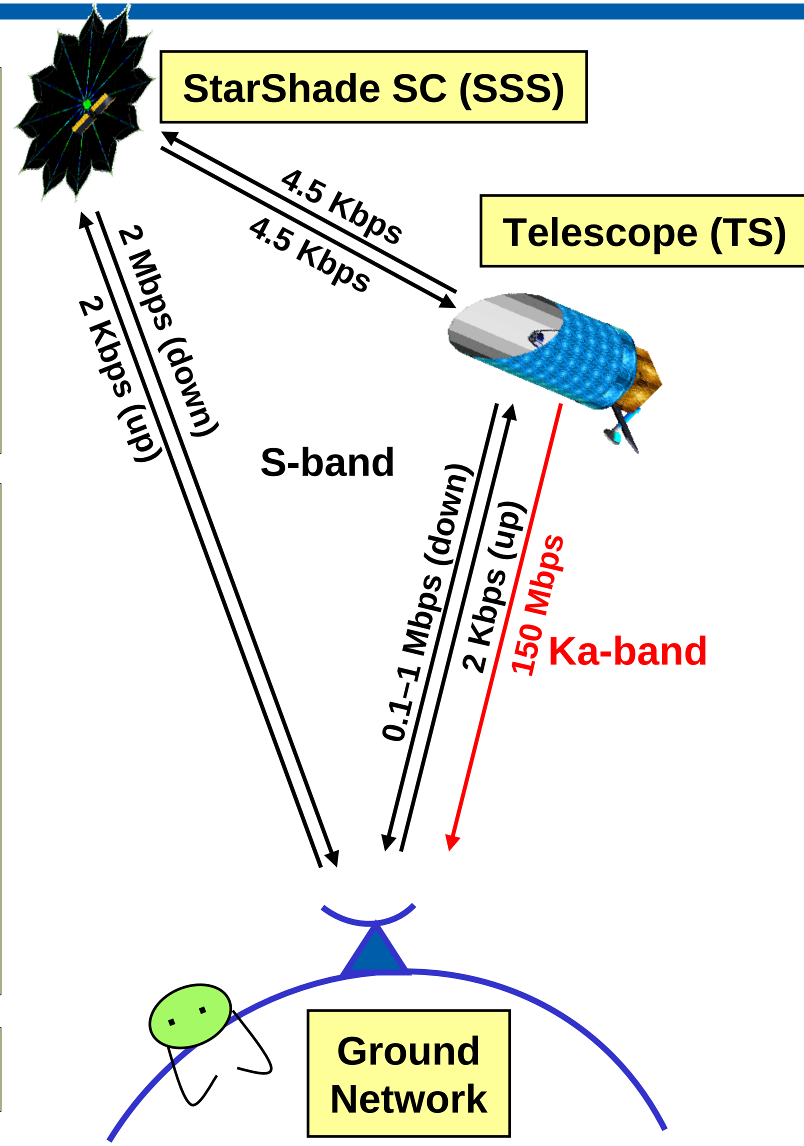
StarShade Spacecraft (SSS)

- S-band 2-way for T&C, coherent for 2-way Doppler & range
- S-band ISR link with TS
- Same electronics & antenna to communicate with GN & TS; thus cannot communicate with GN & TS simultaneously
- SSS can receive commands from GN or TS

Telescope Spacecraft (TS)

- Ka-band downlink for high volume of science data
- Simultaneous Ka-band & S-band coherent to GN required
- S-band 2-way for T&C, coherent for 2-way Doppler & range
- S-band ISR link with SSS
- Separate electronics for all 3 services/links; can communicate with GN & SSS simultaneously or separately
- TS can autonomously send uploaded commands to SSS

Ground Network – DSN (prime), USN, WS 18-m



Concept of Operations overview

- Launch to L2
  - Two launch vehicles
  - Two spacecraft inject into near-identical L2 libration point orbit
  - ~6 months apart (TBD)
- Formation acquisition (“first day”)
  - RF ground tracking to acquire AS; beacon blinking for identification
  - Medium alignment: Antipode star astrometry to acquire first shadow
  - Calibrate AS while SS holds it centered on shadow
- In-shadow formation control
  - Shadow sensor finds the shadow and guides to the best place in it
- Slew to next target
  - Guided by ground tracking and AS
- Re-acquisition after anomalies (lost-in-space)
  - Same as “first day”, with some calibrations and prior position knowledge

2 Week Cycle in the Life of the NWO Starshade

Sensor	Actuator	Activity
AS, ISR, RF tracking	SEP	Slew to 50km coarse box
AS, ISR	SEP or chem	Move to 7m medium box
Telescope: acquires target star & guide stars		
SS, AS, ISR	Chem	Locate center of starlight shadow <1m
SS, ISR	Chem	Maintain centering in shadow while telescope observes planets
Telescope: Send data to ground promptly, commands back up ASAP Optionally continue observing for deep planet spectrum		
AS, ISR, RF tracking	SEP	Begin slew to next star

Acquisition and calibration sequence

	New Worlds Observer			
	Entrance conditions	During	Exit conditions	Exit mode
Launch	Launch pad	LV control, 1st and 2nd stage separation, 3rd stage firing	solar arrays deployed, 3rd stage firing complete	Launch 2
Trans-L2	3rd stage firing complete	Starshade & telescope separate, arrays on sun, HGA on earth; Periodic RF tracking, small orbit corrections including delta-V between spacecraft	Arrival at L2	Independent cruise
L2 injection	Arrival at L2	Lissajous orbit injection (2 spacecraft, few days apart)	In L2 lissajous orbit, 80 Mm separation, transverse relative velocity >~1m/s and <~30 m/s (TBR)	Independent safe
Range acquisition	In L2 lissajous, SS ~80 Mm from ST	Inter-spacecraft (ISC) range transponders turn on and find each other.	In L2 lissajous, SS ~80 Mm from ST; inter-spacecraft range acquired	Formation safe
Formation acquisition	In L2 lissajous, SS ~80 Mm from ST	Locate partner spacecraft by optical sensors – Options 1-4	Optical detection of ST by AS	Formation coarse
Orbit knowledge refinement	Optical detection by AS	Ground analysis of AS and other data	Coarse knowledge: Bearing ~0.1" Range ~1 km (TBR)	Formation coarse
Slew to first star	Coarse knowledge	SEP thrusters engage. AS conducts astrometric observations, and intermittently checks ST position on sky. ST conducts general astrophysics observations.	Coarse knowledge, approaching star, SEP disengaged, switch to chemical thrusters.	Cooperative transition

Star acquisition and planet science

	New Worlds Observer			
	Entrance conditions	During	Exit conditions	Exit mode
Star acquisition	Coarse knowledge	ST observes target star and nearby field. Guide starshade to begin occultation, options 1-3	ST sees change in star brightness	Cooperative transition
Star shadow optimization	ST sees change in star brightness	Engage shadow sensor; measure profile and depth of stellar shadow; locate shadow's center. Calibrate AS to that alignment.	Shadow sensor is ~centered. AS is calibrated.	Cooperative fine
Star-planet observation	Shadow sensor is centered	ExoCam and ExoSpec take images and spectra of planets surrounding target star; data download and then observations resume; commands for any additional exoplanet science observations are received.	Shadow sensor is centered.	Cooperative fine
Slew to next star	Shadow sensor is centered; slew command received	SEP thrusters engage. AS conducts astrometric observations, and intermittently checks ST position on sky. ST conducts general astrophysics observations.	Coarse knowledge, approaching star, SEP disengaged, switch to chemical thrusters.	Cooperative transition
Return to Star Acquisition				

Options for Formation Acquisition on "first day"

- These are alternatives to aid initialization of the Astrometric Sensor (AS)
  - Identifying and locating the Telescope in the AS FOV
  - Need ~1° *a priori* bearing knowledge to point beacon and AS toward each other

Formation acquisition at BOL **Remarks**

NB: Beacons cannot be aimed until after formation acquisition, so it cannot easily help with formation acquisition. Therefore all the following options rely on solar illumination of ST instead.

Option 1	No-thrust period (1-15 days) to allow orbit determination. Use result to narrow a sky search using AS to find ST spacecraft optically	Patience. Sure to work.
Option 2	Use prior orbit estimate, propagated through L2 injection, to narrow search region. Then do a very broad sky search using AS, looking for high proper motion object – the ST (due to its residual relative velocity).	Residual lateral motion of 1 m/s gives 0.7 arcsec/hr; do two quick successive sky scans with AS, looking for motion
Option 3	Use parallax of Mars seen by SS and ST to estimate inter-s/c bearing relative to Mars. (Aim the L2 injection to place ST and SS ~collinear with Mars). Not so broad sky search using AS, looking for high proper motion object.	More orbit constraints than Option 2: time of launch vs. Mars, and aiming injection. Is this worth the trouble?
Option 4	Scanning ST boresight back and forth across the sky, with integration times lasting 10s of seconds. Look for dashed line in WFcam images due to a blinking SS beacon (#3). Quickly narrow the scans on the beacon.	Assumes beacon #3 is wide-angle and takes advantage of high-sensitivity ST and instruments

First stellar occultation – options

- These are alternatives to aid in calibrating the AS angle offset needed to begin the onset of shadowing

Find first stellar occultation		**Remarks**
Option 1	AS with retros finds target star in FOV; use ground calibration to come within 0.1" (TBR) of collinearity.	Optional spiral search if calibration is worse than 0.1"
Option 2	AS images ST and antipode field. Ground estimates position of shadow based on astrometric catalogs. AS guides SS to put that shadow onto ST.	Optional spiral search if AS calibration is worse than 0.1"
Option 3	ST observes beacon #3 on SS next to target star; guides SS to align with target star	High brightness ratio; might lose beacon in stellar glare

Procedures allow quick recovery from anomaly

- Each spacecraft safes itself
- Re-establish RF inter-spacecraft ranging and communication
- For quick recovery, use last known bearing and rates to estimate current bearing; otherwise use RF ground tracking
  - Aim beacon from science telescope, blinking slowly with sync via RF comm
  - Aim AS and find beacon among stars
- Resume previous operations

- The only time-critical concern is gravity gradients near L2
  - Because of distance, collisions are never an issue
  - Time scale is weeks for full recovery or interim orbit adjustments (to buy time)

Fallback methods in case of equipment failures

Several options can be exercised to restore mission capability after a mishap:

- Celestial navigation (e.g. parallax of Moon or Mars) to help formation acquisition
- Use of HGA on science telescope (ST)
  - Peaking RF received power to find bearing, aid formation acquisition (AS init)
- Beacon on Starshade, observed by Telescope
  - Search for a blinking and fast-moving object in sky
  - Formation acquisition, slewing guidance, and onset of shadow
- Use of antipode stars seen in AS to find shadow
- Use of AS for fine sensing (<1m) in shadow

Conclusions

- RF ground tracking is sufficient for safety and for AS acquisition
- Sensor suite is robust, allowing many autonomous and commanded scenarios
  - RF inter-spacecraft range transponders enable range determination without DSN
  - AS can guide slew travel for many degrees on the sky, to onset of shadowing
    - Allows acquisition of SS with high confidence
  - SS can guide alignment from the edge to the center of the shadow
- Beacons improve confidence in identifying the partner spacecraft against a background star field

Shadow Sensor for NWO

Charley Noecker

GSFC IDL Team

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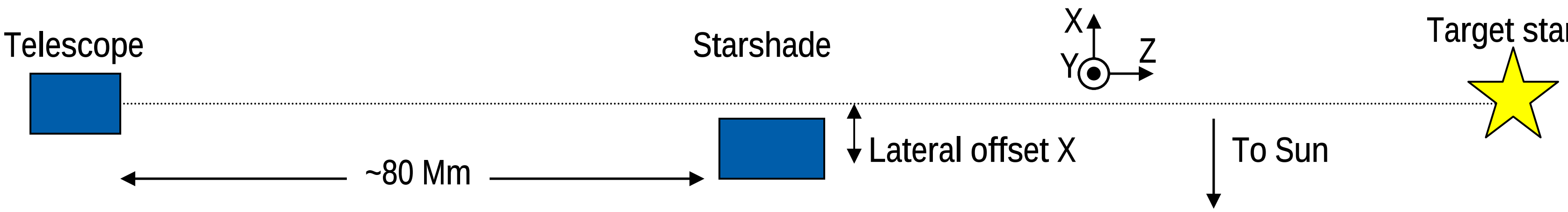
Shadow Sensor measures alignment in shadow

- Alignment sensing in shadow is a special challenge
  - Telescope can see Starshade, but the star is gone – no reference point
  - By the time the Starshade offset is visible, science observation is already degraded
  - Controlling this alignment using astrometric sensor from the Starshade would require a very good sensor — 0.5 mas uncertainty including calibration
- Solution: look at longer wavelengths
  - Starshade is designed to produce adequate stellar suppression out to ~1µm
  - Well beyond that (>1.5µm), stellar suppression degrades sharply
  - Spot of Arago returns also, forming a strong peak exactly in the shadow's center
  - Measuring that spot profile is the basis for the Shadow Sensor concept

TAC System Requirements for Fine Alignment

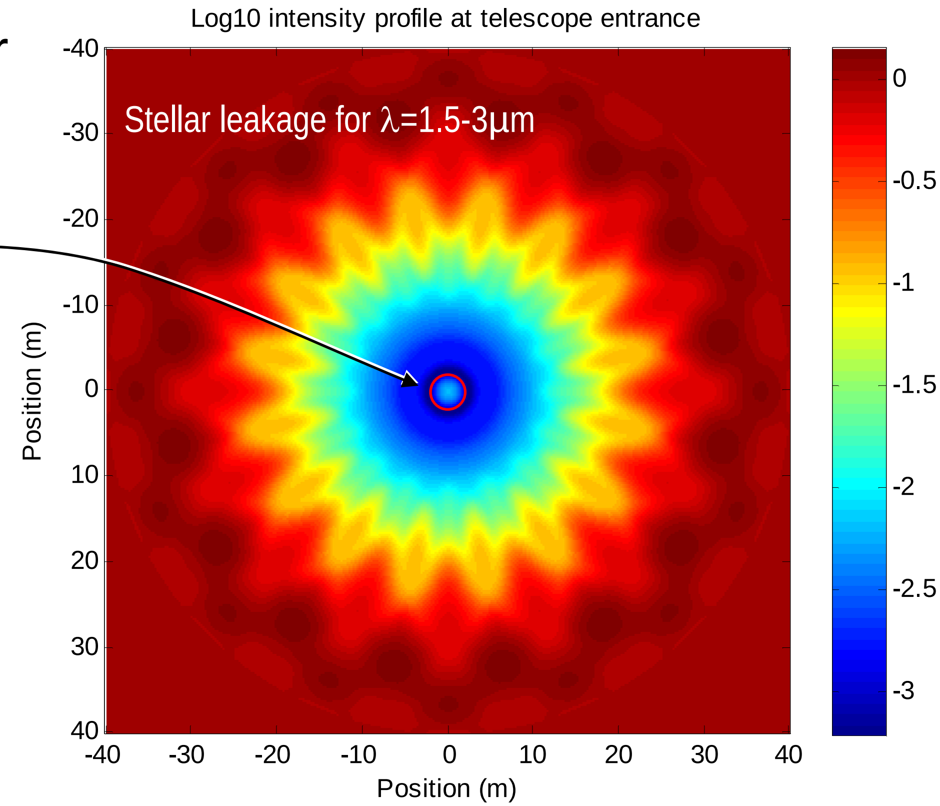
In shadow, finding and keeping the true center

- The Telescope shall be able to measure the X,Y position of the shadow for (X,Y) < 3m to an accuracy of ±10 cm (1σ)(TBR)
- The TAC system shall be able to measure the Starshade's Z position to an accuracy of ±100 km (1σ)(TBR)
  - Inter-spacecraft ranging (ISR) using S-band transponders
- Starshade spacecraft shall be able to maintain its position with respect to the Telescope to within (X,Y)= ±1 m (3σ) and Z = ±4000 km (1σ) during an observation
- For fine alignment, the Starshade spacecraft relative velocity shall be <0.5 mm / sec
  - Roughly 1m / 30 min, typical control system performance

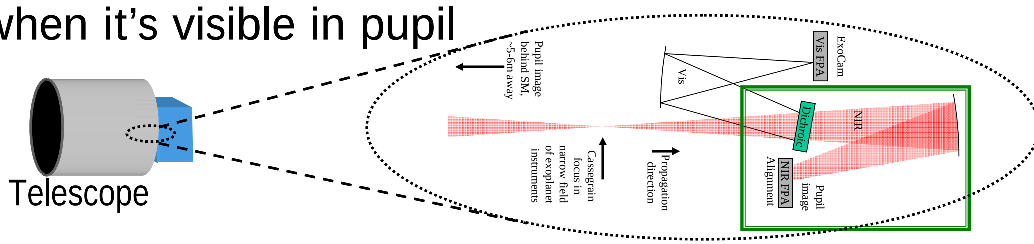


Shadow Sensor for fine alignment in shadow

- For $\lambda >> 1\mu m$, central peak in stellar leakage returns
  - Poisson's/Arago's spot again
  - 4m telescope covers most of it



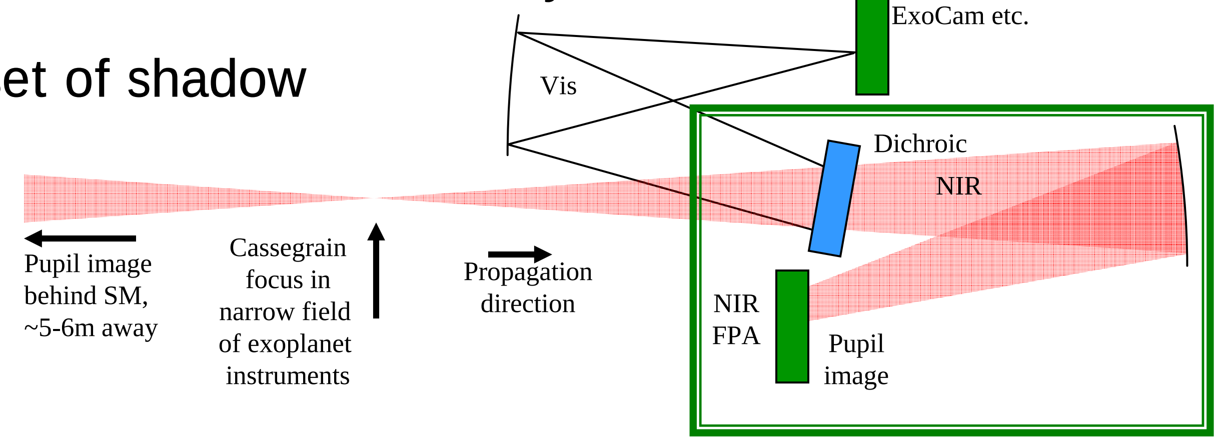
- Measure profile of NIR flux in pupil, locate this peak
  - Extract NIR light from science passband using a dichroic mirror
  - Reimage telescope pupil and sample NIR on ~10 cm grid
- Algorithms are a minor challenge:
  - Guide reliably from shadow edge to center
  - Accurately locate center when it's visible in pupil



See next page

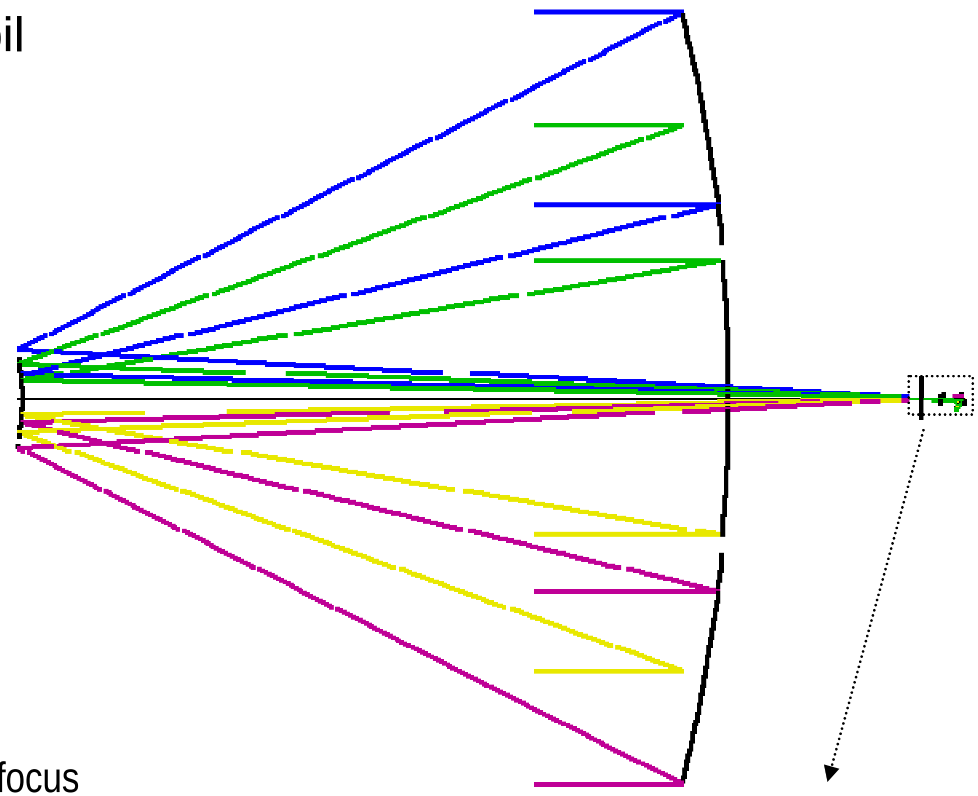
Telescope NIR pupil imager concept for Shadow Sensor

- Dichroic beamsplitter transmits the NIR light to a mirror & detector
  - Images the entrance aperture (a pupil image)
  - Must preserve diffraction-limited PSF in visible wavelength science instruments
- Imaging detector e.g. MCT
  - One shown, but recommend 2 for redundancy
  - λ ~ 1.7–2.3 µm (TBR)
  - 4-6mm wide, pixel size ~100 µm (TBR)
- Integration time < 0.9 sec for 10cm uncertainty
- Acquisition requires onset of shadow

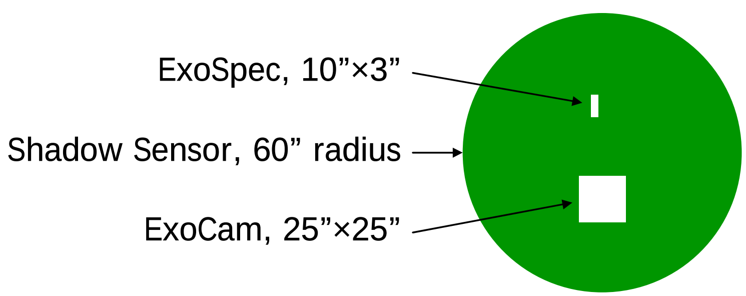


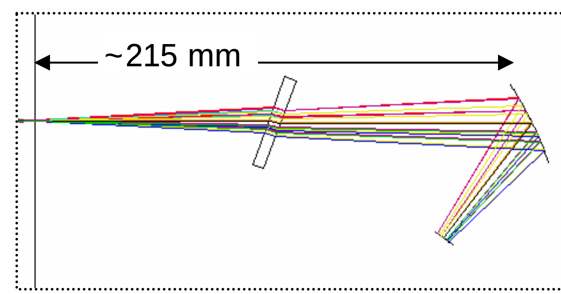
NWO Shadow Sensor in the Telescope

- Shadow Sensor instrument images pupil of Telescope
  - Brightness profile of Spot of Arago
- Located among science instruments, picked off at Cassegrain focus
  - Dichroic mirror transmits $\lambda > \sim 1.6 \mu m$
- Must operate at same field angles as ExoCam and ExoSpec
  - Separated by dichroic
- Vignetting restricts FOV on sky
  - Sources within ~1’ of ExoCam FOV

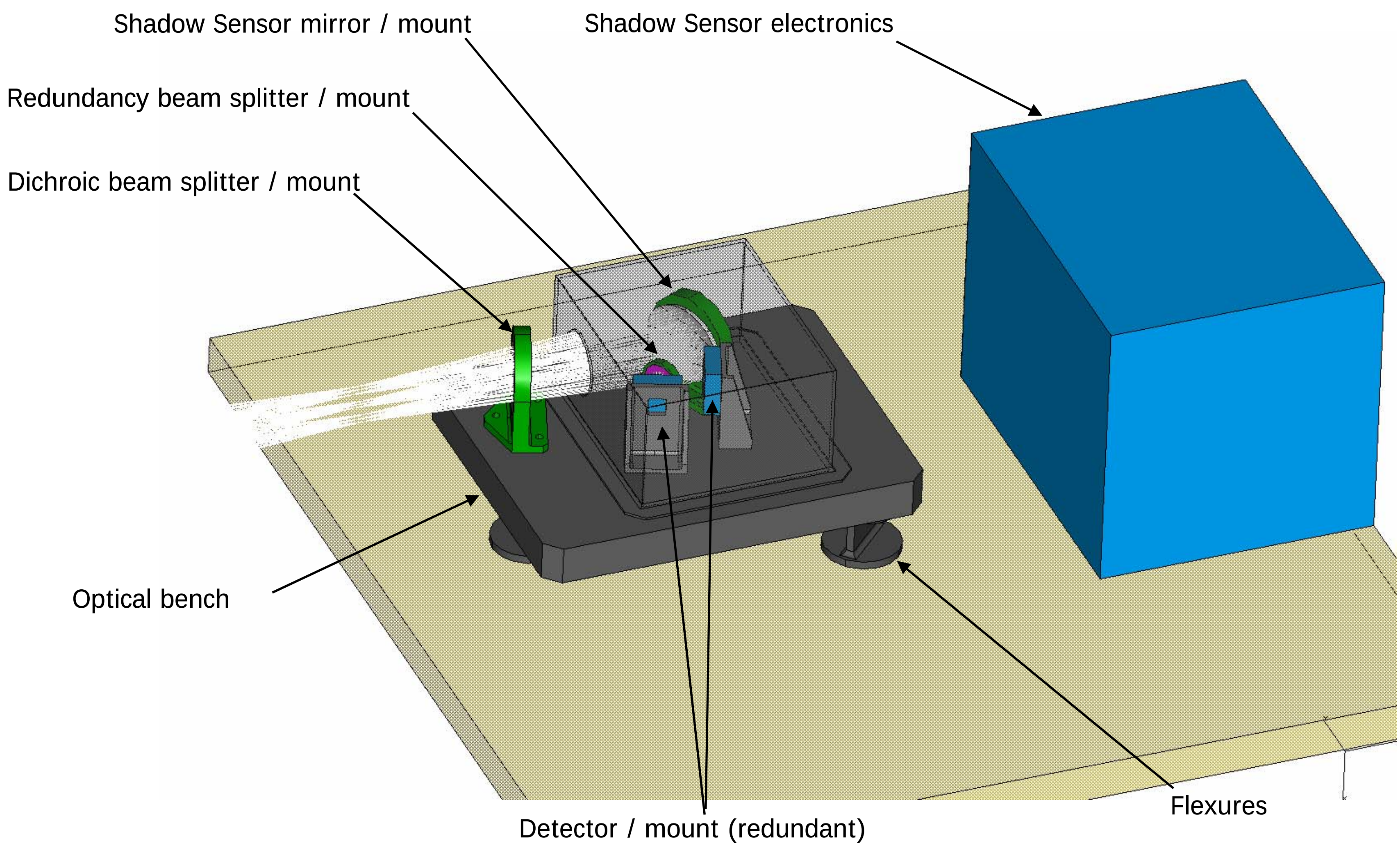


<u>Instrument fields of view at Cassegrain focus</u>



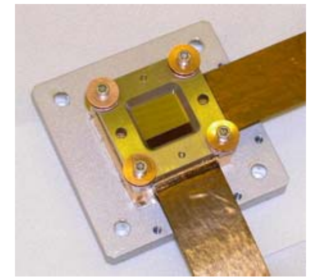


Shadow Sensor preliminary mechanical layout



Teledyne MCT Array & PICNIC ROIC

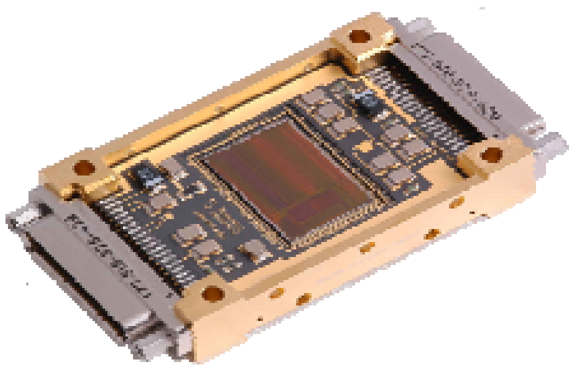
- Teledyne has made many flight qualified MCT arrays at various cutoff wavelengths
  - **256 X 256 PICNIC with 2.5um cutoff for New Horizons - Pluto**
  - Hawaii 1R (1k x 1k) array with 1.7um cutoff for HST-WFC 3
  - Hawaii 2RG (2k x 2k) 5.0um cutoff for JWST



New Horizons SCA

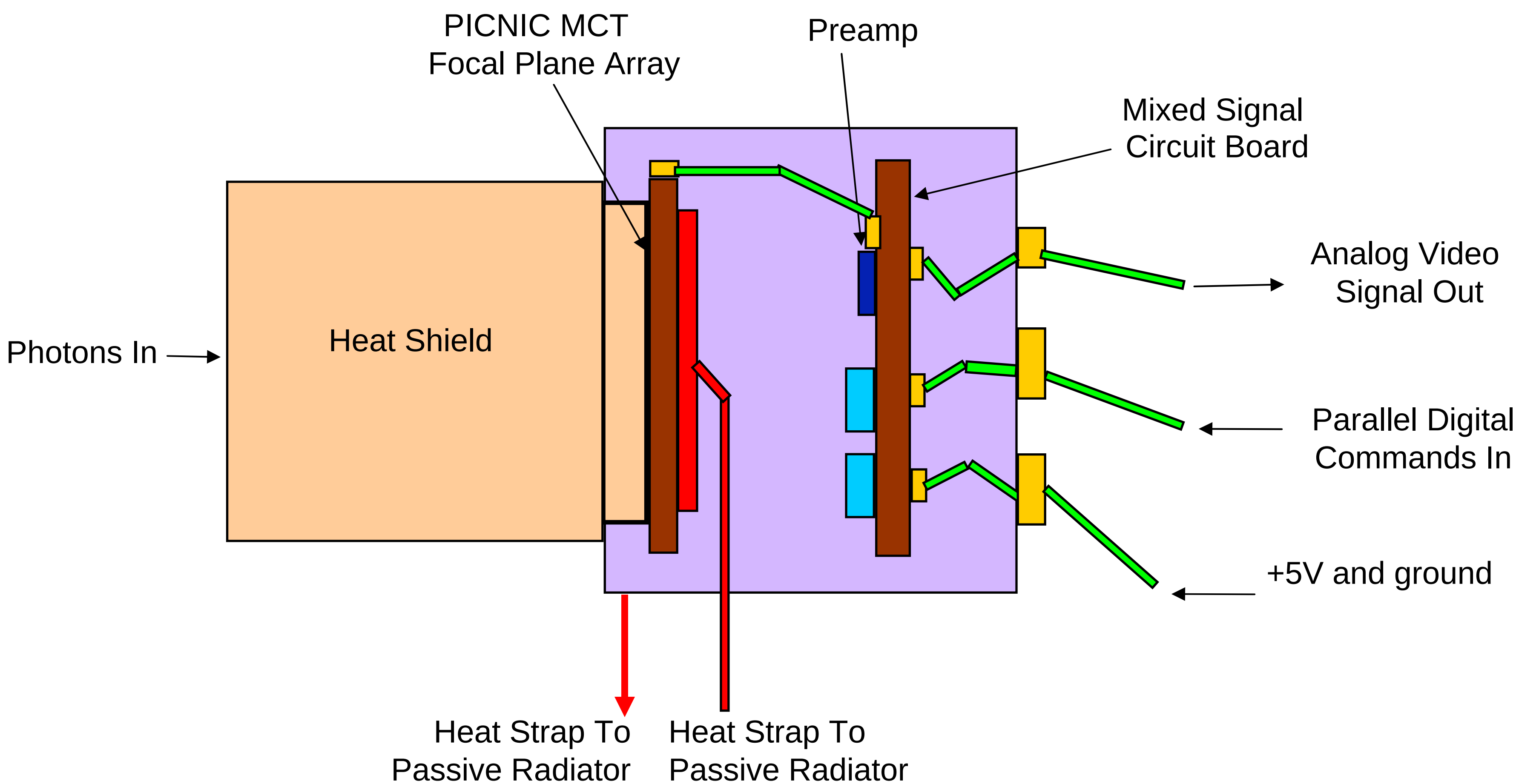
- The PICNIC ROIC is mature technology
  - 256 X 256 array of 40um pixels
  - 10.24mm active area matches the Shadow Sensor requirement

- The SIDECAR* ASIC designed to drive the Hawaii series of ROICs



JWST SIDECAR Implementation

Focal Plane Module Notional Diagram



NORTHROP GRUMMAN

Astrometric Sensor

Charley Noecker

USNO JMAPS Team

GSFC IDL Team

NEW WORLDS OBSERVER

Seeking Earth-like Planets in Our Solar Neighborhood

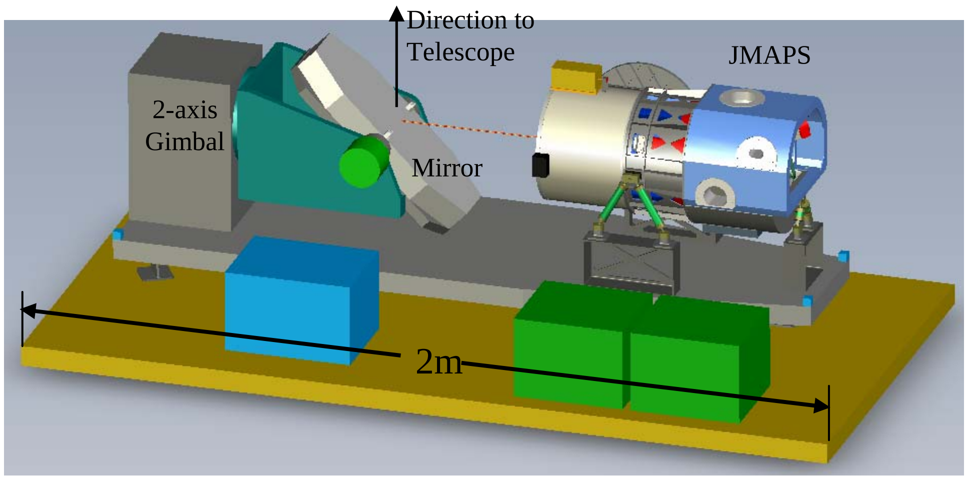
Astrometric Sensor's Purpose:

Guide the Starshade maneuvers until the onset of shadow

- Span the gap between RF ground tracking (DSN) and Shadow Sensor
  - RF tracking accuracy is limited (~50km), insufficient to put shadow on Telescope
  - Shadow Sensor cannot provide a useful signal until shadowing has begun
- Maybe the main sensor during routine large-scale maneuvers
  - RF tracking typically comes with restrictions: e.g., no thrusting for ~2 weeks (TBR) to allow unperturbed measurements of curved trajectories near L2
  - If this restriction applies during the near-continuous weeks of slewing between targets, then RF tracking is not viable – uncertainty too high
  - Then we'd need an instantaneous measure of position, independent of thrusting
- Provide the calibration from spherical coordinates (bearing angles on sky) to LOS coordinates (XY offset from the Telescope-to-star LOS)
  - Minimize the time spent hunting for the shadow
  - Minimize the need for Telescope time to support that search
  - Maintain a "portable" calibration from star to star

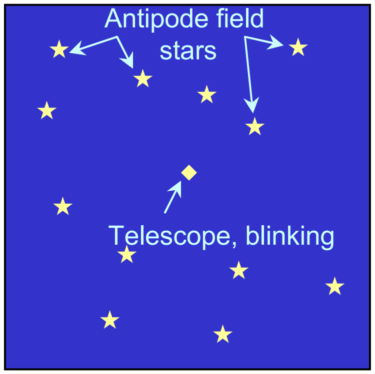
Astrometric Sensor (AS)

- Determines Starshade-to-Telescope direction referenced to stars
- Differential angular measurements of Telescope vs. background stars
- Comprises an astrometric instrument ("super-star-tracker") and a gimbal
  - Baseline uses JMAPS instrument



Astrometric Sensor assembly concept from GSFC's IDL

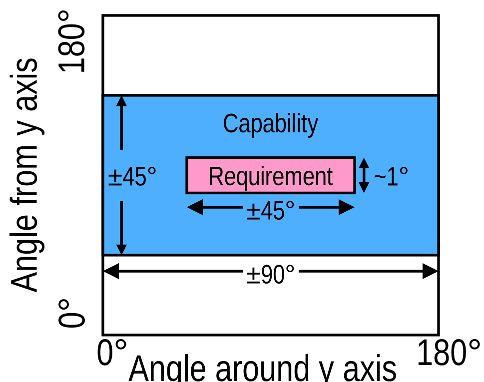
- AS is on Starshade, looking toward Telescope
- Laser beacon(s) on Telescope → modulated, bright
- Differential astrometry of the beacon vs. stars with ~5 mas accuracy → bearing, e.g. in RA/dec
- After some work, this achieves shadow onset → transition from spherical to LOS coordinates
- Gimbal → flexibility on Starshade attitude while AS watches Telescope

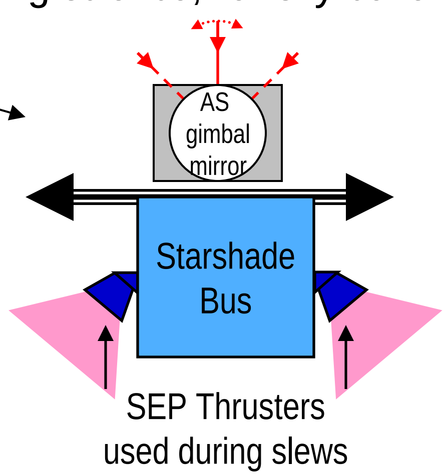


Astrometric Sensor's view toward Telescope

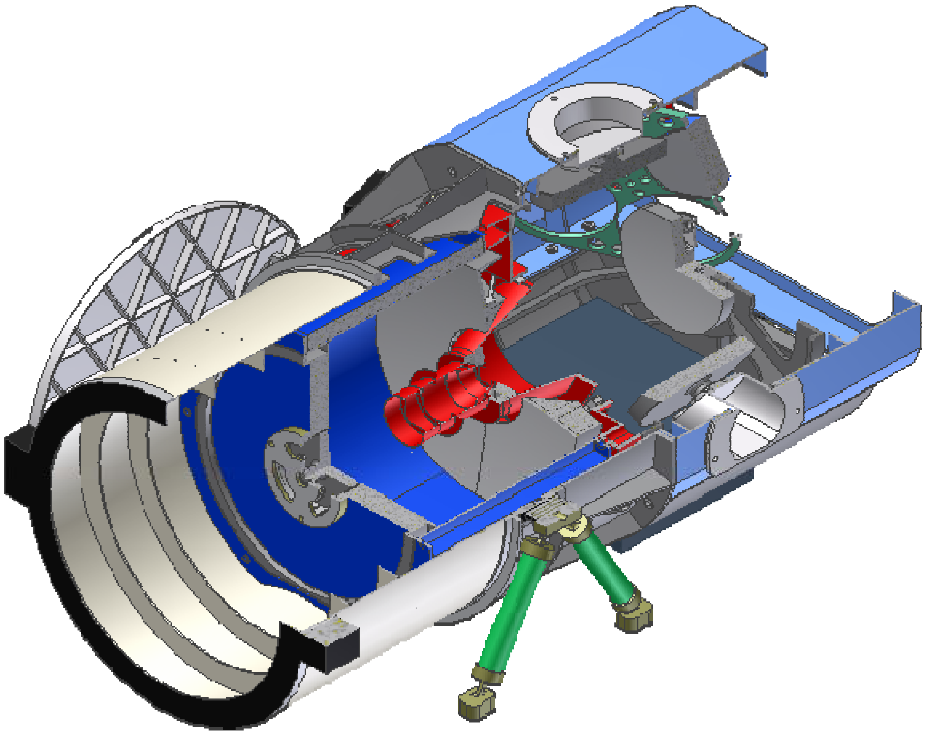
Dynamic range challenge

- The Astrometric Sensor (AS) must have enough resolution and accuracy to guide the Starshade (~50-70mas radius) to cover the target star
  - The AS must have small pixel size (arcsec scale) to permit $3\sigma < 50\text{-}70$ mas
- The AS must have a large FOV to find its partner spacecraft with *a priori* knowledge uncertainty as loose as 1° (TBR)
  - The AS must be bootstrapped (initialized) by finding and identifying the partner spacecraft (Telescope) in its FOV
  - Blinking beacon technique can be very helpful for confident identification
  - The RF tracking accuracy must be good enough to guide a brief search of the sky by the AS to find the beacon
    - RF tracking can provide ~50km/80,000km ≈ 0.04° accuracy
- The AS field of regard (including gimbal motions) must be several steradians to accommodate a range of Starshade spacecraft attitudes
  - Attitude control residual (fine motion)
  - Off-normal tilt during science, for sky coverage
  - Observe Telescope during slews (SEP thrust angles)



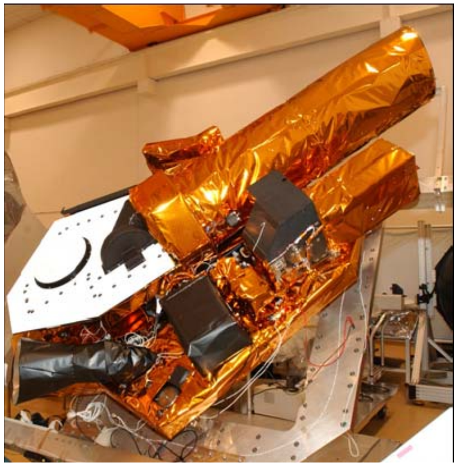


Several candidates for this instrument



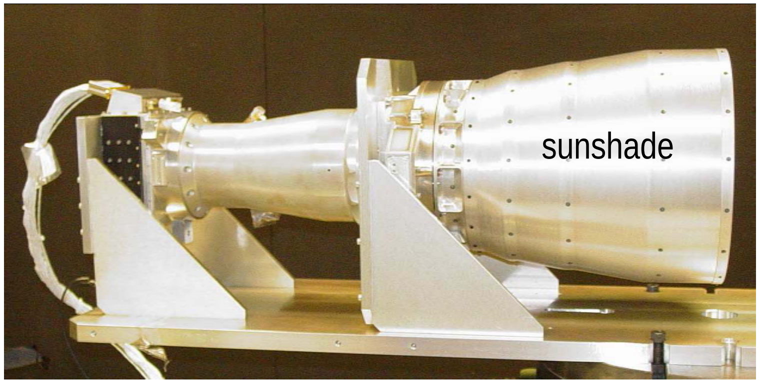
Deep Impact High Resolution Imager

- Flight heritage
- 2 μrad pixels
- 10.5m focal length
- 30 cm dia aperture
- Volume ~40cm diam 200 cm long
- Differential astrometry performance unknown



High Accuracy Star Tracker (HAST)

- Flight heritage
- Tracking up to 1°/sec
- Demonstrated boresight bias correction <40 mas
- Differential astrometry performance unknown



Joint Milli-Arcsecond Pathfinder Survey (JMAPS) mission & instrument

- Designed for differential astrometry
- Performance prediction ~5 mas (systematic floor)
- 19 cm diam, 3.8m focal length
- FOV 1.2°

United States Naval Observatory
Joint Milli-Arcsecond Pathfinder Survey

Instrument Parameters:
- 7.5”, f/20 ultra-low-distortion optical/NIR astrograph telescope
- SiC optics, metering structure
- Advanced, large format CMOS Hybrid FPA
- Gratings for color sensing
- Mass ~ 40kg
- Power ~ 85W

Objectives and Description:
- Fully funded mission, December 2011 launch
- Dedicated, high-accuracy astrometric instrument
  - Single measurement precisions (narrow field) of 5 milli-arcseconds from 0-16 mag
  - 1 milli-arcsecond global accuracy over 3 year mission life

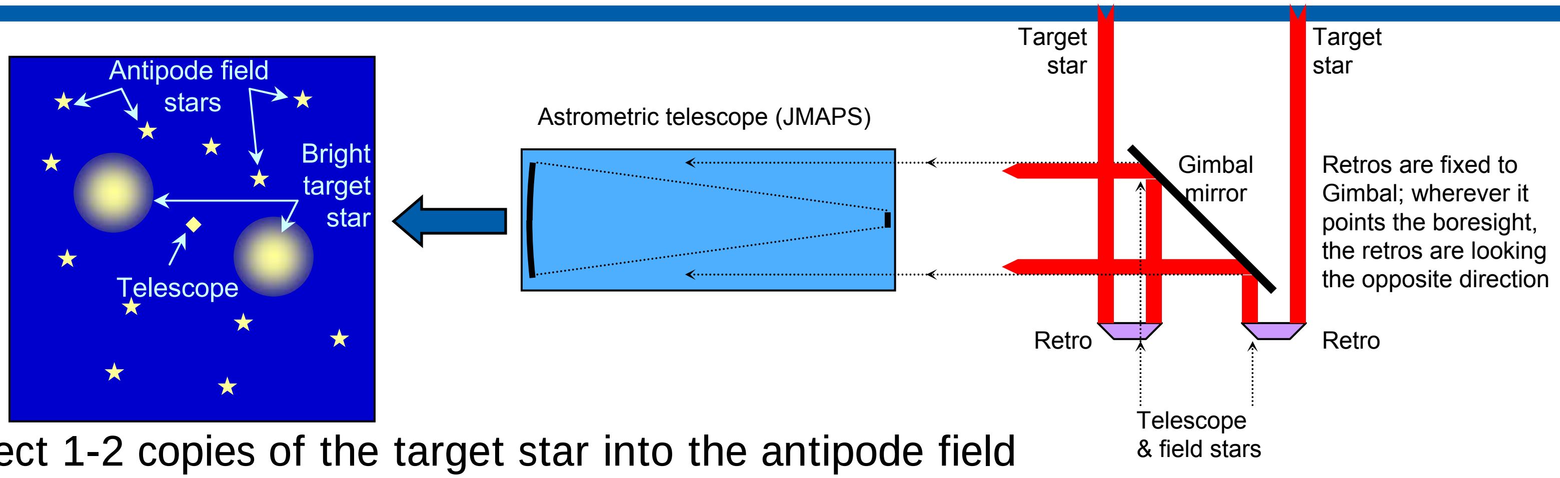
JMAPS Mission Goals:
- Update star catalogs, viable for decades
- Demonstrate 10mas attitude determination on-orbit
- Mature the critical optical and FPA technology

NWO Trajectory & Alignment Control (TAC):
- State of the art optics and detector technology permits high accuracy astrometry—critical for NWO TAC
- Updated stellar catalog in time for NWO

See supporting JMAPS document

Authority to Proceed **October 2008** → System Req. Review **June 2009** System Design Review → **December 2009** Preliminary Design Review → Critical Design Review **June 2010** → Launch **December 2011** → **FY 2011-2014** Operations → **December 2015** Release of Final Catalog in time for NWO

Cubecorner retros for improved calibration

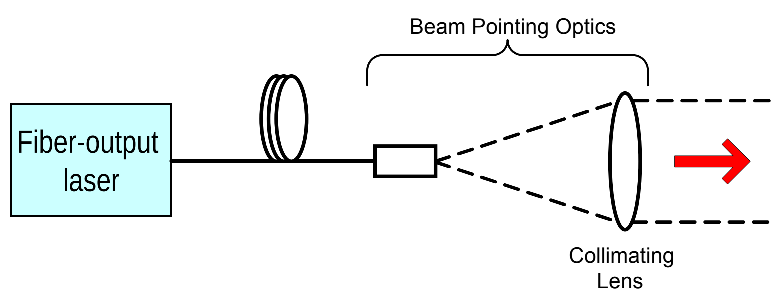


- Retros inject 1-2 copies of the target star into the antipode field
  - Fatter because of small aperture through the retros
- Those fat images of the target star are "synthetic astrometric references" at a fixed offset from the location of the target star's shadow
  - In the illustration above, the shadow would lie on the "Telescope"
  - Misalignment of retros is tuned to give chosen non-zero offsets
- Relative position of science telescope with respect to those copies is a direct measure of telescope-starshade-star collinearity
  - Integration times of order 10 sec each for Telescope, synthetic and real reference stars
- Ground calibration knowledge is good enough to initiate first occultation
- After on-orbit calibration, knowledge improves to ~5 mas, and gives an accurate portable reference that is available on every target star

Beacons on Science Telescope

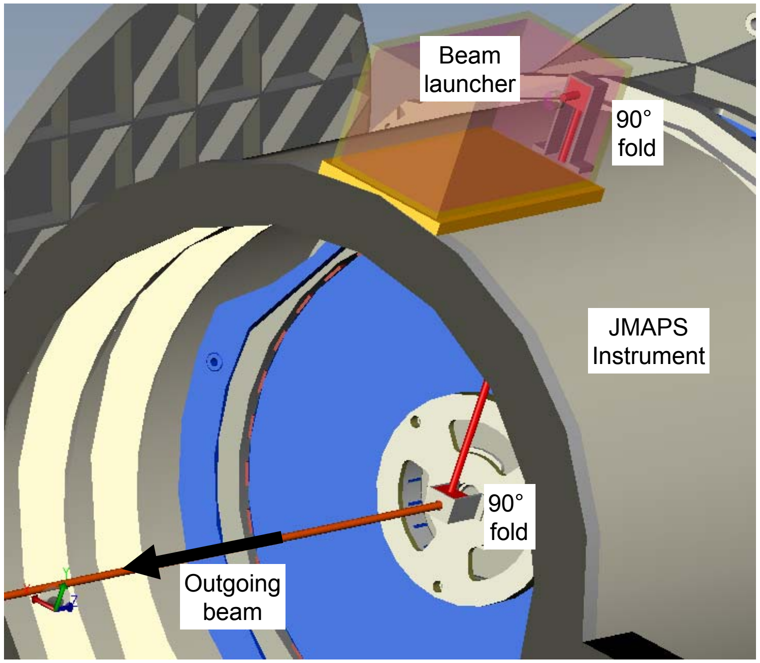
- AS can detect objects as faint as m_I=15-16
- Sunlight scattered from Science Telescope at 80 Mm is at least that bright – but unmodulated
  - Possible confusion between Telescope & other stars
- Laser beacons on Telescope provide brighter, modulated signal
  - With inter-spacecraft sync signal, very confident indentification
- Common fiber-pigtailed laser sources in NIR (700-900 nm)
  - Matches JMAPS detection band
- Beacon must be aimed at AS on Starshade → need *a priori* bearing
- 1 beacon co-boresighted on Telescope
- 1 beacon on HGA (to be steerable)

Shot noise	0.005	arcsec
Wavelength	780	nm
Operating distance	80	Mm
Cone full-angle	0.36	deg
Laser output power	28.1	mW



Beacon on the Starshade (AS assembly)

- A similar beacon is mounted on AS, pointing out along JMAPS boresight
  - Gimbal allows this beacon to be steered also
- In case of AS failure, this beacon enables a fallback alignment procedure
  - Beacon is observed by Telescope (with optional laser line filter)
  - Guidance to the onset of shadow
  - Tracking the slew position and velocity



- Places much heavier operational burdens on the Telescope

AAS 09-181

THE JOINT MILLI-ARCSECOND PATHFINDER SURVEY (JMAPS): MISSION OVERVIEW AND ATTITUDE SENSING APPLICATIONS

Bryan N. Dorland,[*] Rachel P. Dudik,[†] ,[‡] and Gregory S. Hennessy[§]

The Joint Milliarcsecond Pathfinder Survey (JMAPS) is a Department of Navy bright star astrometric all-sky survey scheduled for launch in the 2012 time-frame. Mission objectives include a complete update of star positions for the 2015 epoch to accuracy levels of 1 milliarcsecond (5 nano-radians) for bright stars, as well as demonstration of 10 milliarcsecond attitude determination capability and 50 milli-arcsecond attitude control on-orbit. In the following paper, we describe the general instrument design and expected performance. We also discuss the new mission capabilities enabled by the unprecedented attitude determination accuracy of such an instrument, and focus specifically on the application to long distance (50,000-100,00 km) formation flying and solar system navigation.

INTRODUCTION

The Joint Milli-Arcsecond Pathfinder Survey (JMAPS) is a Department of the Navy (DoN) space astrometry mission, approved for flight, with a 2012 launch date. JMAPS is an all-sky, bright-star astrometric and spectrophotometric survey. The primary goal of the mission is to completely update the bright star catalogs currently used by Department of Defense (DoD), NASA and civilian sensors for purposes of attitude determination. Secondary goals include the development and flight of cutting-edge hardware that will benefit future attitude sensing and imaging applications. In addition, the instrumentation developed to collect stellar catalog data will also demonstrate unprecedented attitude determination capabilities, useful to future advanced applications.

JMAPS is currently under development, with the program office at the Office of Naval Research (ONR), the Principal Investigator and ground data processing activity at the US Naval Observatory (USNO), and the space, downlink and mission operations, and launch segment activity at the Naval Research Laboratory (NRL). The current concept, shown in Figure 1, is of a single-aperture instrument hosted on a microsat spacecraft bus. The instrument is similar in concept and size to a star tracker, but with significantly higher accuracy.

The instrument observes the sky in a step-stare mode, spending approximately thirty seconds (includes integration, slew and settle) on each star field. Target stars within the magnitude range

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of 0.5—14 will be observed 50 to 75 times over the course of three years. These data are returned to the ground, where they are processed together with instrument state parameters, thereby yielding a "global solution" for each star; i.e., a solution for the five primary astrometric parameters (position in Right Ascension [RA] and declination [DEC], proper motion in RA and DEC, and parallax). The baseline orbit for the satellite is a 900 km Sun Synchronous Orbit (SSO).

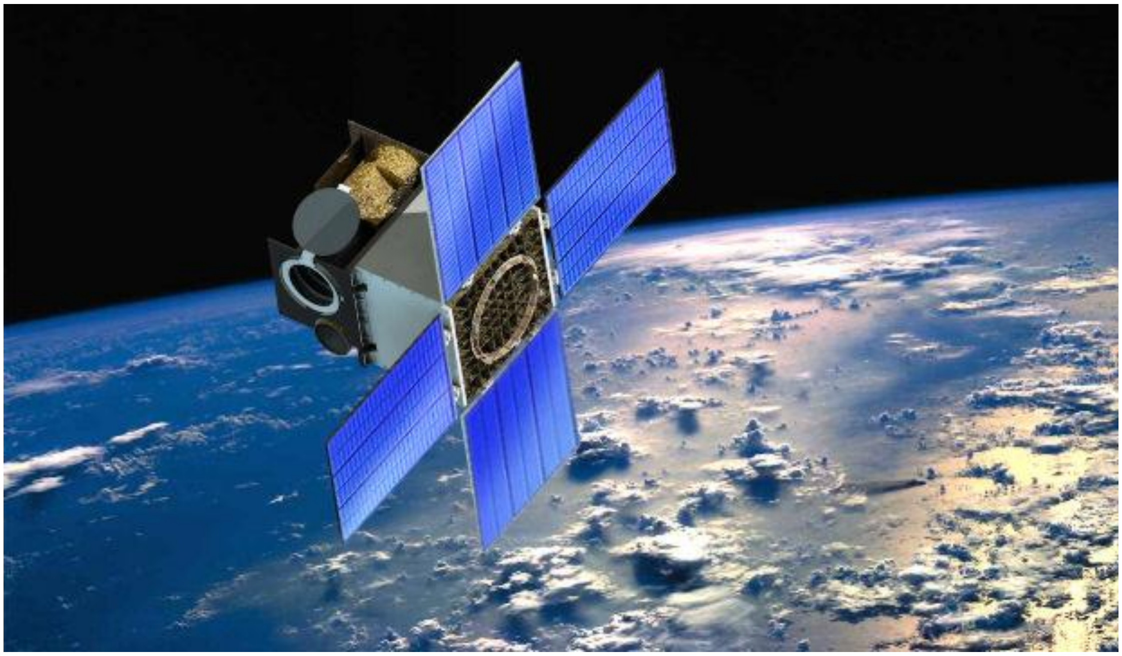

Figure 1. Current JMAPS spacecraft concept. Primary instrument is an 8" visible/near IR telescope. Spacecraft is microsat-class.

The mission will produce a final catalog by the end of 2016 that will include stars within the target magnitude range at mission accuracies of 1 milli-arcsecond (mas)* /1 mas $year^{-1}$/1 mas for position/proper motion/parallax. In addition, the catalog will include photometric and spectral data that will support extending high-accuracy astrometric and photometric results across the visible/near IR spectral range.

In this paper, we will first describe the on-orbit instrument and the attitude sensing capabilities of the JMAPS telescope. We will then provide illustrations of how these new capabilities can be used to support future missions by discussing two specific applications: (1) long distance formation flying, and (2) solar system navigation.

THE JMAPS INSTRUMENT

The heart of the JMAPS program is the astrometric instrument. The instrument consists of a single-aperture† optical telescope assembly (OTA), the Focal Plane Assembly (FPA) and the

* 1 mas is approximately equal to 5 nano-radians.

† The basis for the single-aperture, step-stare imager for global astrometry, a significant departure from the two-aperture approach adopted by other space astrometry missions such as Hipparcos and Gaia, was established by Zacharias & Dorland (reference 1).

supporting electronics. The telescope is an 8”, on-axis astrograph design, implemented using silicon carbide and designed to be highly stable over the on-orbit conditions. The focal plane consists of an 8k x 8k, 10 um pixel CMOS-Hybrid FPA. The FPA is controlled by the instrument electronics, which also digitizes, processes and stores the output data from the FPA for periodic download to the ground station. The total instrumental spectral response in the astrometric passband is approximately aligned with the astronomical photometric Cousin’s I-band*. The instrument is deployed on a “deck” as shown in Figure 2. In the figure, the OTA, the camera electronics and the coarse star tracker (used during acquisition and lost-in-space modes) are shown. The instrument deck is mounted to the spacecraft during integration.

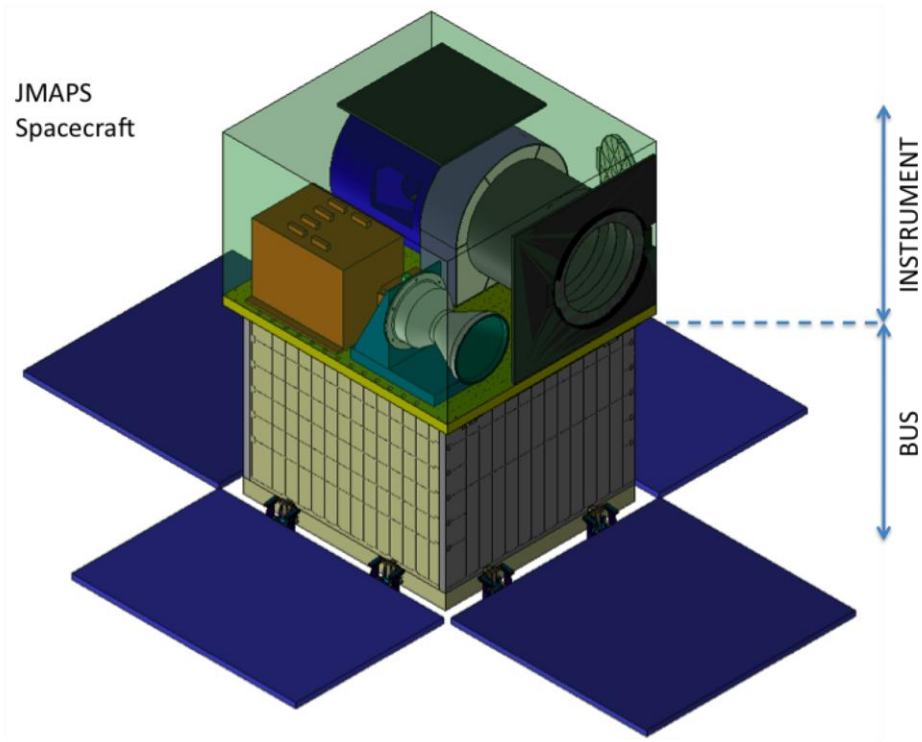

Figure 2. JMAPS spacecraft concept showing separation of bus and instrument sections. On the instrument deck, the primary telescope is shown, along with the electronics (orange box) and the secondary, coarse star tracker. The flat plate at the aperture is the dedicated FPA radiator.

The total single-measurement systematic floor of the instrument (i.e., residual FPA, electronics and optical effects) has been designed to not exceed 5 mas. For a 12^{th} magnitude star in the primary astrometric band, combining the signal-to-noise centroiding accuracy with the predicted systematic floor yields a single measurement precision of at least 7 mas for a twenty-second inte-

* Approximately 700—900 nm

gration time, the longest integration time routinely used for the survey. By combining multiple observations over the three-year mission lifetime, final catalog accuracies of 1 mas or better will be achieved.

ATTITUDE SENSING AND POINTING CONTROL

During science data collection, the spacecraft is required to maintain very stable pointing. In order to achieve the single-axis pointing requirement of 50 mas (1-σ), the spacecraft Attitude Determination and Control System (ADCS) will use the astrometric instrument as the fine guidance sensor. The astrometric instrument will observe approximately 12 bright stars per field of view, and read out star images every 200 msec. The instrument will then calculate individual centroids for these twelve guide stars, combine them into a single solution for the boresight, and generate a boresight quaterion at a 5 Hz rate.

Using these individual star position measurements, how well can the instrument boresight pointing be determined? Analysis of USNO's NOMAD catalog statistics (Reference 2) suggests that the mean guide star will have an I-band magnitude of 8—9. Adopting the more conservative value of 9th magnitude, the current instrument model predicts a single measurement precision (including both random and systematic error) of less than 13 mas. Combining all twelve of these measurements to determine the overall boresight orientation of the instrument, pointing accuracies of well under 10 mas are feasible with significant margin. Sparse fields, such as those near the galactic poles, yield the worst-case results. In these cases, NOMAD statistics suggest that the guide star population can be as faint at 11th magnitude. This translates to single measurement precisions of approximately 32 mas per star per 200 msec integration time. Here too, total boresight accuracies of under 10 mas are feasible, though with significantly less margin than the average case. This analysis is consistent with more detailed analyses conducted by mission ADCS personnel as part of ongoing assessment and design activities.

TWO APPLICATIONS: LONG-DISTANCE FORMATION FLYING AND SOLAR SYSTEM NAVIGATION

In order to illustrate the value of this level of attitude determination for future space missions, in the following sections we provide two illustrations of how a JMAPS-like instrument could be used to enable new in-flight capabilities for advanced missions. In the first section, we examine whether a JMAPS-like instrument can be used to enable long-distance formation flying and what accuracies can be achieved. In the second section, we look at the ability of a JMAPS-class instrument to determine position in the solar system, for support in spacecraft navigation when outside the Earth orbital environment.

Long-distance formation flying

One potential future application for this class of instrument is to help in the alignment of components of formation flying systems. In Figure 3, we consider the alignment of two components (marked "A" and "B") that are separated by 50,000 km. In this particular example, the alignment tolerances are extremely tight in the transverse direction, but relatively loose in the radial direction.

In order to accomplish this alignment, a JMAPS-derived astrometric instrument is deployed onto A and pointed at B. On B, an I-band beacon is included, so that A can assume a steady level of illumination from B rather than counting on reflectance of solar illumination, which can fluctuate with the varying solar zenith angle. We assume that the beacon has sufficient power to appear 12th magnitude when viewed from A. This assumption will be discussed in more detail later in the paper.

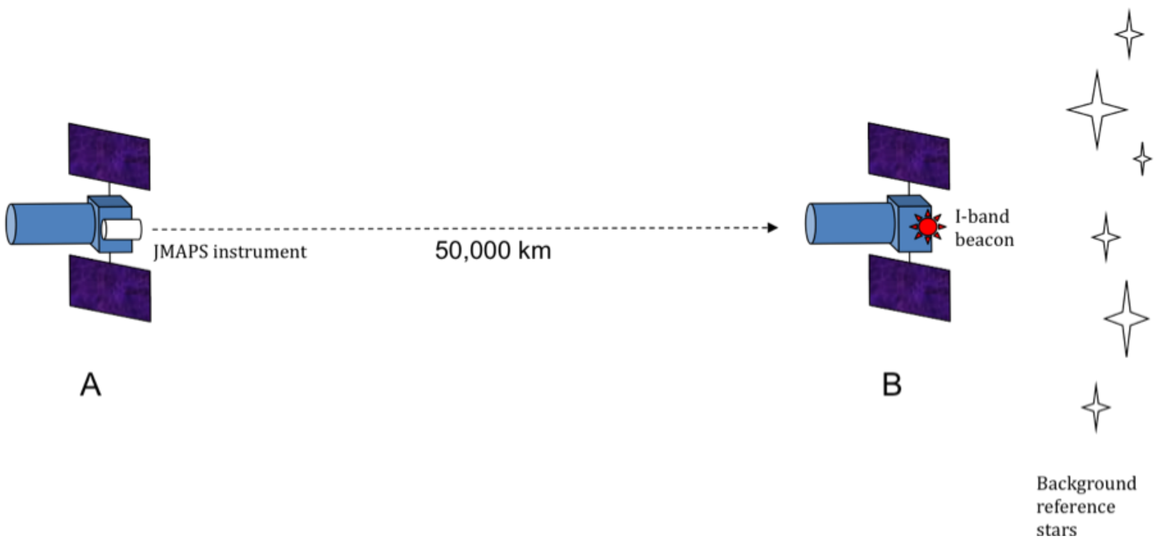

Figure 3. Formation flying alignment problem. Two spacecraft, marked "A" and "B" in diagram, must be aligned to very small tolerances in the transverse direction. An astrometric instrument is deployed on A and a beacon on B. Alignment is effected using the instrument to guide A into alignment with B. Based on analysis described in the text, alignment accuracies of 2 meters in the transverse direction are feasible.

The JMAPS instrument will be able to determine its boresight orientation to better than 10 mas every 200 msec. For a 10 second integration time, a 12th magnitude I-band beacon can be detected and measured to approximately 8 mas accuracy. Ten seconds is equivalent to 50 measurement cycles for guide stars. By combining guide star observations over ten seconds, the instrument can reduce boresight orientation error to under 1 mas. The combined accuracy of the observations of the beacon against the background reference grid is approximately 8 mas, which translates to 2 m at 50,000 km. This means that using a JMAPS-class instrument and a beacon, at a minimum, the two spacecraft can be aligned to within 2 meters at a distance of 50,000 km.

Is the beacon requirement feasible? Analysis of the flux at the instrument aperture indicates that a 4.5 kW source is needed on B to produce a 12th magnitude source at A if the beacon uniformly illuminates 4π sr. On the other hand, a unidirectional beacon reduces the power requirement on the source significantly. A directional beam of width[*] of approximately 11° from B towards A would reduce power requirements to a feasible 10 W power level. Such a beam width corresponds to approximately 10,000 km at 50,000 km distance, well within the navigational capabilities of A and B even without using the JMAPS-class instrument. Thus we conclude that 2m

[*] i.e., beam diameter

precision in formation flying can be achieved at 50,000 km given a 10 W beacon directed toward a JMAPS-class instrument.

Solar system navigation

In this application we consider solar system navigation. Around the Earth, spacecraft typically use Global Positioning System (GPS) signals to locate their positions and orbits with high accuracy. However, outside of low Earth orbit, such positioning is impossible to any accuracy. For spacecraft deployed to Sun-Earth L2—an increasingly popular destination for astronomical missions—accurate position determination can be an extremely challenging problem. Figure 4 illustrates the way in which an astrometric instrument can solve this problem.

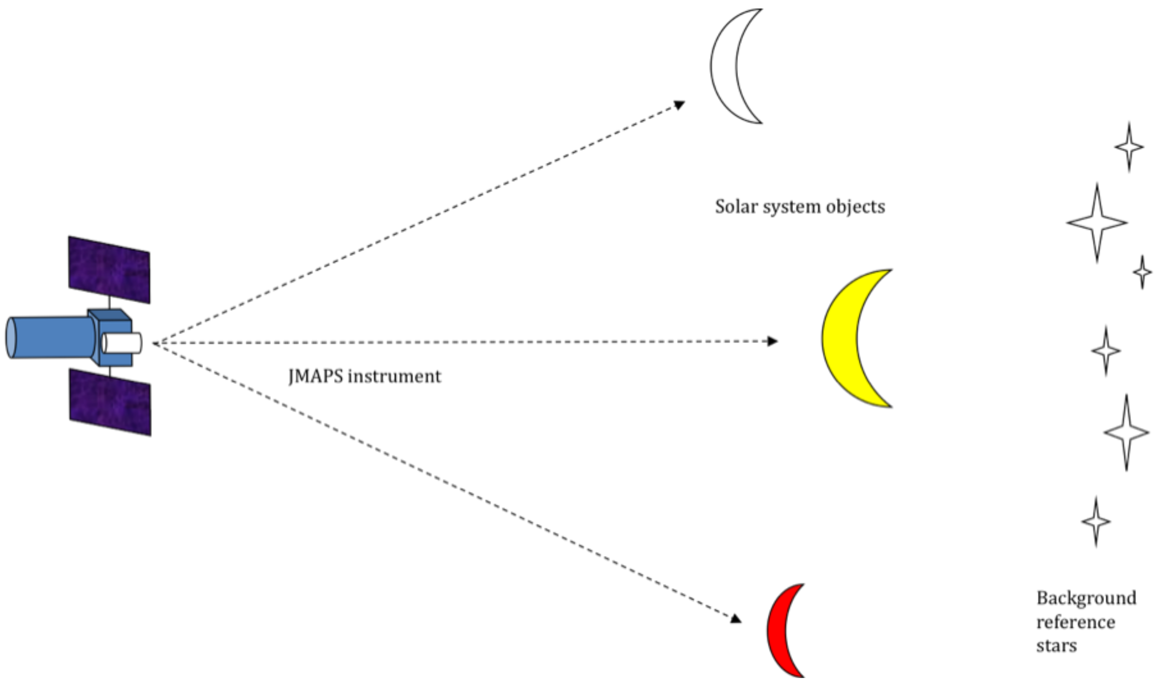

Figure 4. Solar system navigation problem. 6 DOF Spacecraft position and velocity needs to be determined with some accuracy. Spacecraft uses JMAPS-like astrometric instrument to determine solar system position.

Given solar system reference objects with accurately known positions, Figure 4 illustrates how observations from a JMAPS-class instrument can be used to find the position of the spacecraft within the solar system. The astrometric instrument takes bearings on these objects against the background reference grid, and calculates the position of the observer using the known positions and motions of the solar system reference objects.

Choosing the appropriate set of reference objects is crucial to this approach. On the one hand, giant planets are bright and have well defined orbits. However these objects also present a number of obstacles including: (1) their paucity—in this case position determination accuracy becomes highly dependent on the geometry of the scenario, and (2) they are resolved—for a JMAPS-class instrument, the definition of centroid and center of mass are problematic for such objects. In addition, for resolved objects such as Jupiter and Saturn, the photocenter will a function of solar zenith angle (i.e., the illumination conditions) at the levels of accuracy we are concerned with.

A better solution employs a set of reference targets such as asteroids that are relatively numerous, more or less uniformly distributed around the Sun, and relatively point source-like. Just such a population exists—90 km-class asteroids. There are about 100 of these objects with relatively well-know orbits. These are main belt objects that are approximately evenly distributed around the sun. They are large enough to be quasi-spherical in nature, and as a result, photocenters fluctuations due to rotation are estimated to be at the 5 mas level (Reference 3). This is small enough to support the navigation accuracy needs.

Our method involves observing approximately 8 of these asteroids near opposition, approximately 8 positioned about a month ahead of the Earth's orbit and approximately 8 that are about a month behind for a total of 24 objects. The eight asteroids at opposition will have apparent magnitudes around 12 in the I-band, while the leading and trailing 16 will have apparent magnitudes of approximately 13 due to distance and illumination effects. For a ten-second integration time (as with the formation flying scenario above), these objects can be observed with sub-10 mas precision. By combining the accuracies over these 24 objects, we have derived the resultant error ellipsoid for our solar system position measurements. The error ellipsoids are shown in Figure 5.

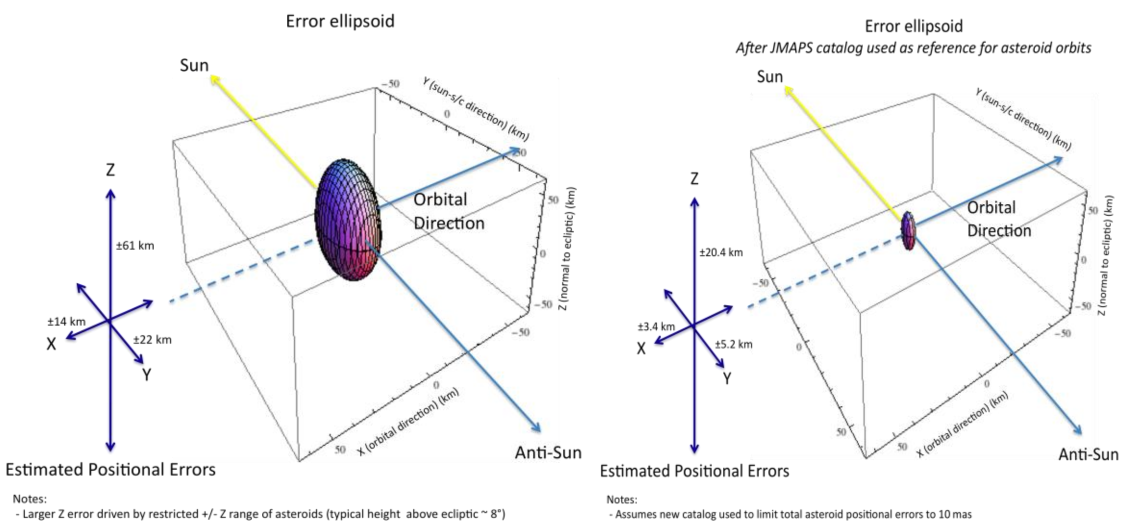

Figure 5. Solar system navigation results. (Left) results assuming no improvements to background reference catalogs, and (right) results assuming updated background catalogs. The Z directed error is much larger than Z or Y because the asteroids typically orbit ~8° or less out of plane, so not much information is collected in the Z direction.

In the first plot (left figure), the error ellipsoid associated with using the astrometric instrument and the current generation of catalogs is shown. Errors of order a couple dozen km are obtained in-plane, while the out-of-plane error is over 60 km. These errors are dominated by errors in positions of the asteroids caused by the zonal errors in the star catalogs. Significant improvement is obtained by using JMAPS-updated catalogs (right figure), which drive the star position errors down to 1 mas. Resultant observer platform position errors are reduced to a few kms in-plane, and approximately 20 kms out-of-plane.

CONCLUSION

JMAPS is a DoN mission, scheduled for launch in 2012, that will update the bright star astrometry catalog. The mission will demonstrate new technological capabilities, including the capacity for an astrometric instrument to obtain very high precision pointing knowledge.

A JMAPS-class instrument can be used in advanced applications for complex missions as a star-tracker capable of unparalleled accuracy. We have discussed two examples of applications for this new and significantly improved attitude determination capability: long-distance formation flying and solar system navigation. We have shown that, using JMAPS-class astrometric instruments, alignment tolerances of 2 m at 50,000 km distances are feasible. We have also shown that, using the astrometric instrument to observe solar system reference objects—specifically, asteroids—one can determine position to a few km in-plane and a few tens of km out-of-plane.

ACKNOWLEDGMENTS

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REFERENCES

[1] N. Zacharias and B.N. Dorland, "The Concept of a Stare-Mode Astrometric Space Mission." *The Publications of the Astronomical Society of the Pacific*. Vol. 118, Issue 848, 2006, pp. 1419–1427.

[2] N. Zacharias, D.G. Monet, S.E. Levine, S.E. Urban, R. Gaume, and G.L. Wycoff, "The Naval Observatory Merged Astrometric Dataset (NOMAD)." *Bulletin of the American Astronomical Society*, Vol. 36, 2004, pp.1418

[3] H. Harris. Private Communication, 2008