Overview of External Occulter concepts

ExoPAG 2 – SAG 5 progress report

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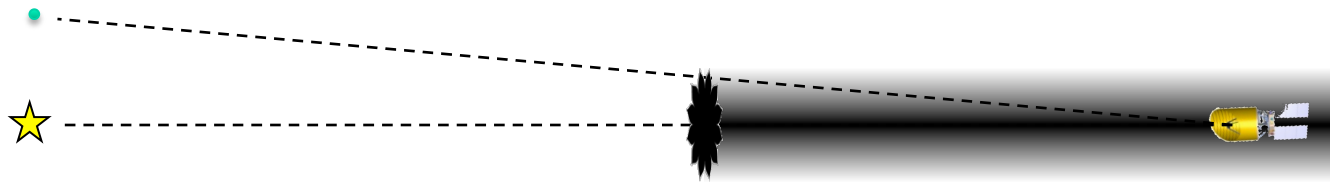
SAG 5 - State of External Occulter Concepts and Technology

- Introduction
- Summary of current mission concepts
  - Flagship class (ASMCS)
  - Probe class (JWST)
  - Other
- Requirements overview
- Technology status

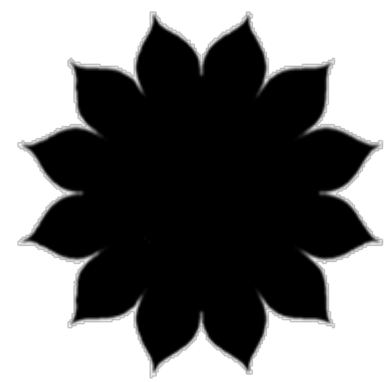
Introduction

- **Objectives:**
  - Describe the features of external occulter concepts for direct detection imaging of exoplanets
  - Summarize the various estimates of potential scientific harvest
  - List the technology tall poles and assess the prospects
  - Provide information to JWST on the state of occulter technology
- **Participants:** members of the principal advocacy teams for external occulters
- **Product:** report on challenges and potential benefits of external occulter missions
  - Top-level instrument concepts (summarizing ASMCS studies and other sources)
  - Published estimates of exoplanet science harvest
  - Known technology challenges and plans for addressing them
- This is a preliminary sketch of a response to that charge

Features of starshade mission concepts



- Two spacecraft instead of one
  - "Flat space" orbits: L2 or drift-away
- Inner working angle is decoupled from telescope diameter
- Star suppression tolerances fall on starshade, not telescope
  - Tolerances of microns to meters
  - Any diffraction limited telescope
  - High optical throughput
- Few visits → Make each one count
  - High throughput – short integration
  - Choose tough requirements on "systematic floor"
  - Spectroscopy on the first visit



Starshade sizing

- Define Fresnel number $F = R^2/\lambda Z$
  - Starshade radius = R
  - Distance to telescope = Z
  - Optical wavelength λ
- Design requirements:
  - Deep shadow at the telescope (10^{-9}–10^{-10}) ➔ F>~10
  - IWA (inner working angle) α ~ 50-100 mas
  - Longest science λ ~ 0.5–1.0µm
- Then $R = F\lambda/\alpha$ ~ 30-60 m
  and $Z = R/\alpha$ ~ 30,000 – 80,000 km (=30-80 Mm)

Telescope sizing

- IWA is defined by R and Z, ~independent of telescope size
  - Width of shadow at telescope depends weakly on R, Z
- Could in principle operate with IWA << λ/D

  (D: Telescope diameter)

- But telescope angular resolution is needed
  - Isolate pointlike exoplanets from exozodiacal dust profile
- Typically want IWA >~ 2 λ/D to resolve ambiguity in image
  - Rough estimate – TBD
  - This rule of thumb is broadly applicable for exoplanet direct detection
- If λ_{max}=1μm, α=100 mas, we want D > 4m – as usual!

Starshade Engineering Tallest Poles

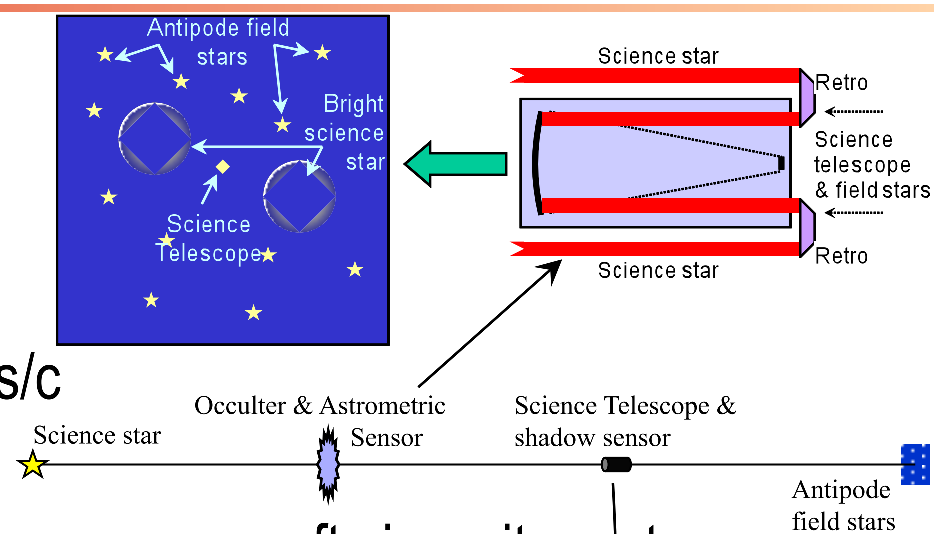
- Starshade manufacturing, testing, and deployment
- Starshade-Telescope alignment
- Large thruster systems

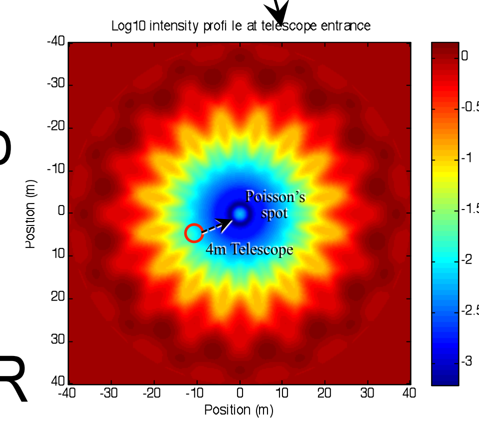
Starshade manufacturing, testing, and deployment

- Large deployable "optic"
  - Binary & paraxial, not a mirror/lens
- Diameter ~30-60m
  - Lightweight materials
  - Folded into 5m launch fairing
  - More than 12 petals, and each *must* deploy reliably
- Perimeter edge sharpness
  - To limit solar stray light in telescope
- Position tolerances ~ mm to m
  Shape tolerances ~ µm to mm
  - Later presentation
- Full-scale pre-launch testing of diffraction is impossible
  - Propagation distance ~6-12 $R_{\oplus}$
  - Instead use precision shape measurements in the lab, and optical diffraction modeling

Starshade-Telescope alignment

- Typical 3σ tolerance ~5 mas = 1m lateral / 40,000 km
  - Looser (5%) along LOS
- Coarse sensor: RF ranging
  - Between s/c, and DSN-to-s/c
- Medium sensor: Astrometric
  - Astrometric telescope on one space-craft views its partner spacecraft against a background of stars
  - Measures angles precisely to acquire alignment with science star
- Fine: Shadow sensor
  - For λ > science passband, star diffraction into shadow increases, as Poisson spot returns
  - Center that spot in telescope pupil
  - Direct lateral-position measurement, high SNR





Alignment sensing for two mission concepts

With dedicated telescope (**Flagship** mission concept)

- Medium: Astrometric sensor
  - 100 mas quality is off the shelf
  - Guide slew to onset of shadowing: starshade between science star and telescope
- Fine: Shadow sensor
  - Straightforward instrument build
  - Excellent SNR, accuracy for alignment

Starshade with JWST (**Probe** mission concept)

- Medium: Astrometric sensor
- Fine: Astrometric sensor

  → Starshade must autonomously maintain alignment
    - No new instruments on JWST
    - No telecom modifications either
  - Astrometric sensor on starshade observes JWST and science star
- This puts harder requirements on astrometric sensor
  - There is no real alternative

"Fuel Is Science"

- Science is limited by number of stellar visits in a mission
  - Initial detection, characterization
  - Return for more characterization
- Visits limited by fuel
  - Typical 1 star/2 weeks for 5 years requires total $\Delta v \sim 10{,}000$ m/s
    - High I_{sp} thrusters needed → fuel mass ~900-1200 kg Xenon
  - Fuel consumed on <u>each slew</u> ∝ 1/(slew time T):

SEP: (50 Mm)(20°) in 12 day
→ 67m/s stop-to-stop
150 stars → 10 km/sec

$$\Delta m_{fuel} = 4 \cdot \frac{D}{T} \cdot \frac{M_{wet}}{g \cdot I_{sp}}$$

- Number of stars observed in entire mission depends directly on fuel mass

$$N \cong \sqrt{\frac{g \cdot I_{sp} \cdot T_M}{4 \cdot D} \cdot \frac{m_{fuel}}{m_{dry}}}$$

Mission duration (T_M)

Typical slew distance between stars (D)

External occulter mission concepts

- Flagship class (NWO, THEIA/XPC)
  - 4m telescope – “HST2”
  - Starshade radius ~30m
  - 50-70 mas IWA
  - ~30 HZs for Earth-size planets
- Probe class – NWP
  - JWST or another diffraction-limited visible-NIR telescope in flat space
  - Jovian planets & few Earths
- Probe class – O3
  - 1.1m dedicated UV-vis telescope
  - 30m diam starshade
  - Jovian planets & few Earths
- Others with small telescope and small starshade

Your Favorite Concept Here

- Concept description including cost category
- Summary of expected science harvest
- Technology tall poles

- Examples:
  - THEIA/XPC
  - O3
  - NWO
  - NWP
  - And others

Current status

- Soummer et. al. have studied a filter change on JWST that would enhance it as an exoplanet hunter with a starshade
- Kasdin et.al. have studied a mission concept (O3) with a small dedicated UV telescope and starshade
- A team including members of JPL, Northrop Grumman, Ball, and Princeton have worked successfully to reconcile differences in tolerance allocations and performance
  - A full budget incorporating multiple simultaneous errors is within reach
  - Likely two separate budgets, due to design differences

Next steps

After error budgets have settled

- Revisit design trades
- Reassess technology readiness levels
- Technology Development Funding
- External review of designs and TRLs
  - Independent validation of advocate claims
  - Support robust technology roadmaps

References

- Incomplete…
- Astro2010 white papers
- ASMCS final reports
  - http://newworlds.colorado.edu/documents/ASMCS/asmcs_documents.htm
- High-level journal or conference papers

Shaklan tolerance paper