TRW Space & Electronics Group

Occulter

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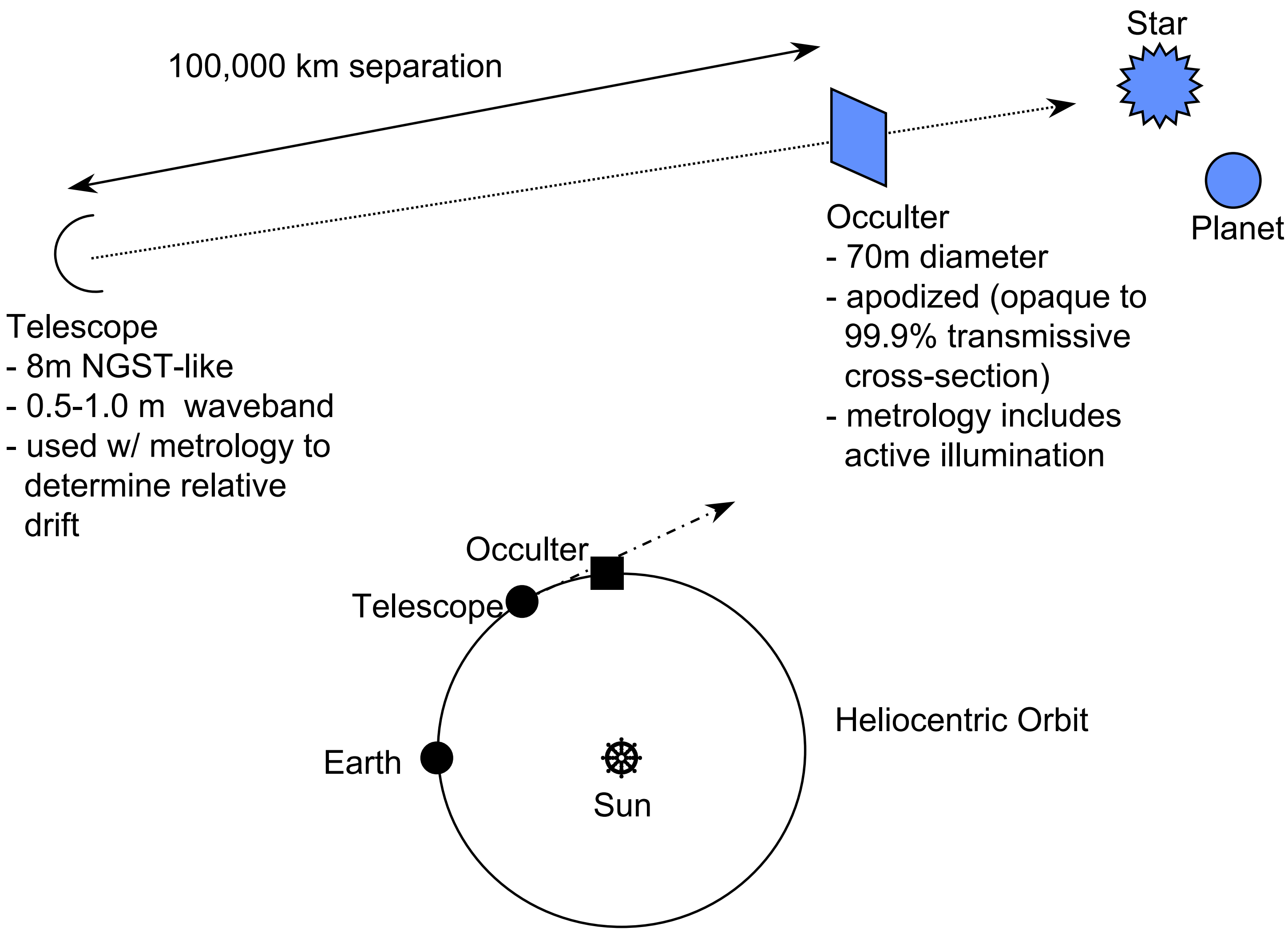
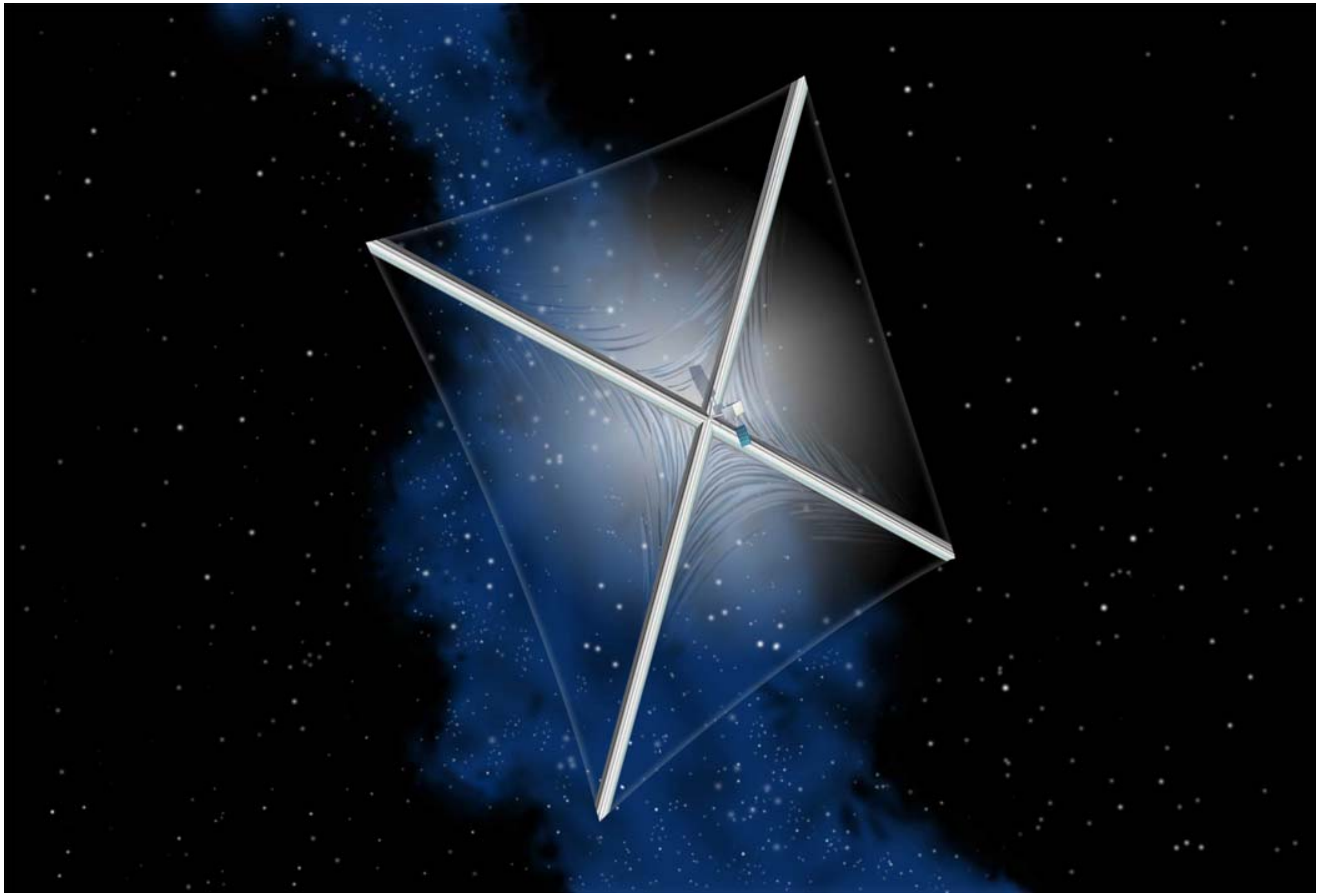
Occulter Concept



Free Flying Occulter Conceptual Drawing



Occulter Implementation Trades

Waveband	Occulter Quantity*	Telescope Size	Orbit
Visible IR	Appodized Single Occulter Bottlebrush	8m Primary 16m Primary	L2 Orbits Heliocentric Orbits
• Reduced occulter size and separation • Reduced telescope size • Eliminate thermal cooling of occulter • Reduce thermal cooling of telescope	• Reduced system complexity • Improved nulling performance	• Reduced system cost	• Reduced target reposition delta V

*Occulter quantity along LOS to target

Occulter Size Vs Telescope/Occulter Separation

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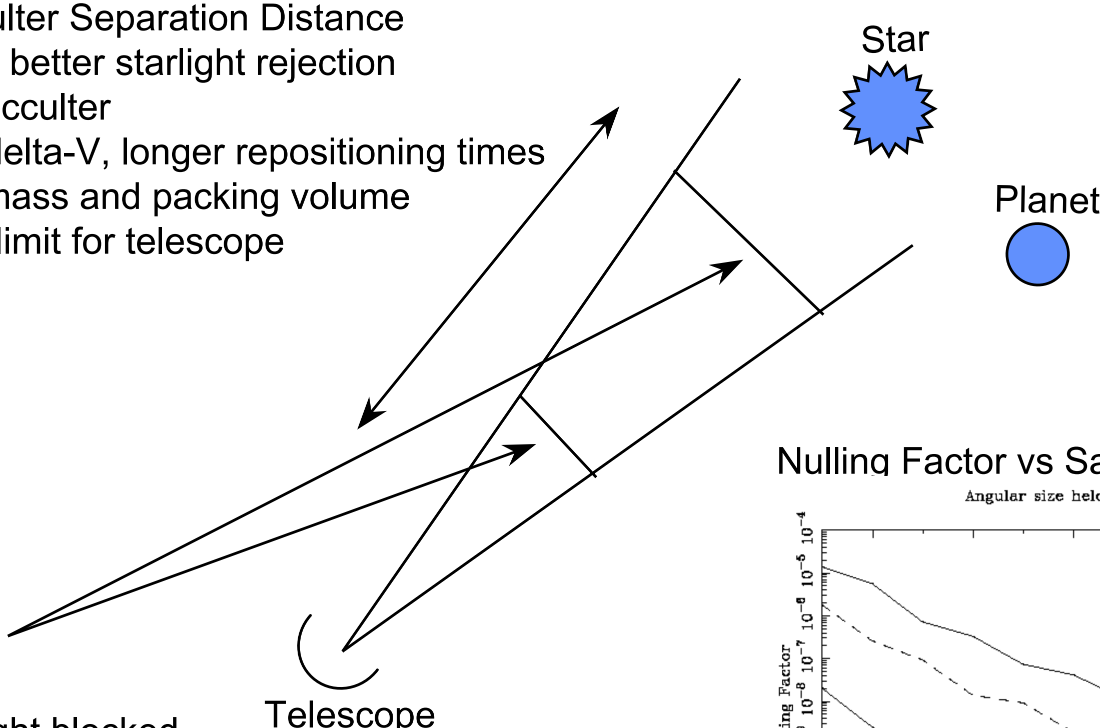
Telescope-Occulter Separation Distance

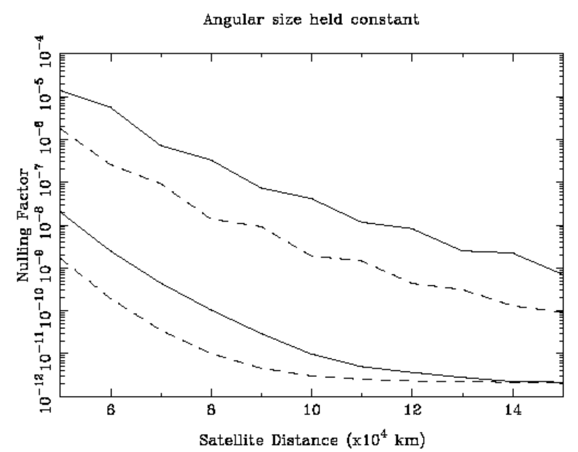
- Increase gives better starlight rejection
    - Larger occulter
    - Higher delta-V, longer repositioning times
    - Larger mass and packing volume
    - 50 mas limit for telescope



Occulter Size

- Larger size
    - more light blocked
    - larger separation

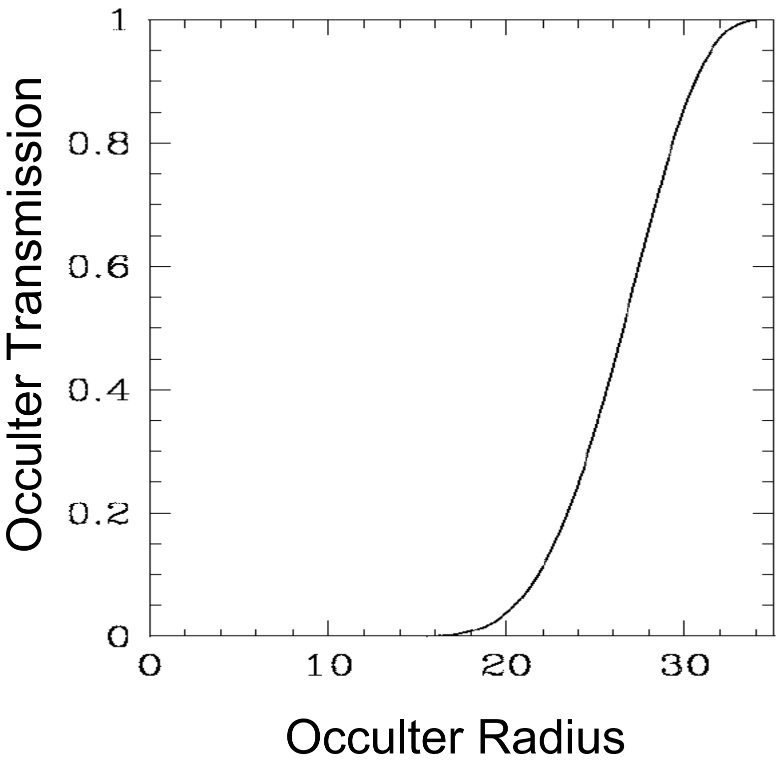
Nulling Factor vs Satellite Distance



For Feasibility Assessment Used Separation Distance 100,000 km and Occulter Radius 35m

Occulter Transmission Function

- Minimizes on-axis intensity
  - advantages: 1- independent, analytic
  - disadvantage: not optimized (especially for large telescopes)
- Stringent Occulter requirements limited to outer ~ 2 meters



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Performance Model Summary

- Star
  - unresolved, at infinity
  - black body at T_{eff}
- Planet
  - unresolved, at infinity
  - unnocculted (placed beyond occulter edge)
  - Spectrum - reflected stellar black body plus lines
- Telescope
  - 100% transparent hole in 100% opaque aperture plane
  - no scattered light
  - 100% efficiency detectors
- Occulter
  - no scattered light, no thermal emission in visible
- Waveband
  - 0.5 - 0.7 mm for detection
  - 0.5 - 1.0 mm for characterization

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Occulter System Parameters

- Telescope
  - Diameter: 8m (NGST configuration)
  - Waveband: diffraction-limited over 0.5 - 1.0 μm (NGST at 2.0 μm)
    - Kodak has technology path for making NGST diffraction-limited in visible
  - Properties: non-cryogenic (simplified shielding)
  - Low risk CCD technology for instrument
- Occulter
  - Radius: 35m
  - Maximum Transmissivity: 99.9%
  - Thickness: ~10 μm
  - Supporting Struts: 2 cm
- System
  - Location: heliocentric, earth trailing
  - Separation: 50,000 - 100,000 km

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Scene Model Summary

- Numerical computation of intensity of double-diffracted starlight (star-occulter-telescope-image plane) & single-diffracted reflected planet-light (planet-telescope-image plane) at each pixel in field-of-view
- Diffraction-limited beam sub-pixelated by 3^2
- Fluxes in waveband assigned using black body spectrum for T_{eff} of star
- Waveband sampled by 4 wavelengths, boxcar filter assumed, intensities averaged
- Integration times, are times to S/N=5

Solar System at 10 pc with 8m telescope, Δt = 25,000s

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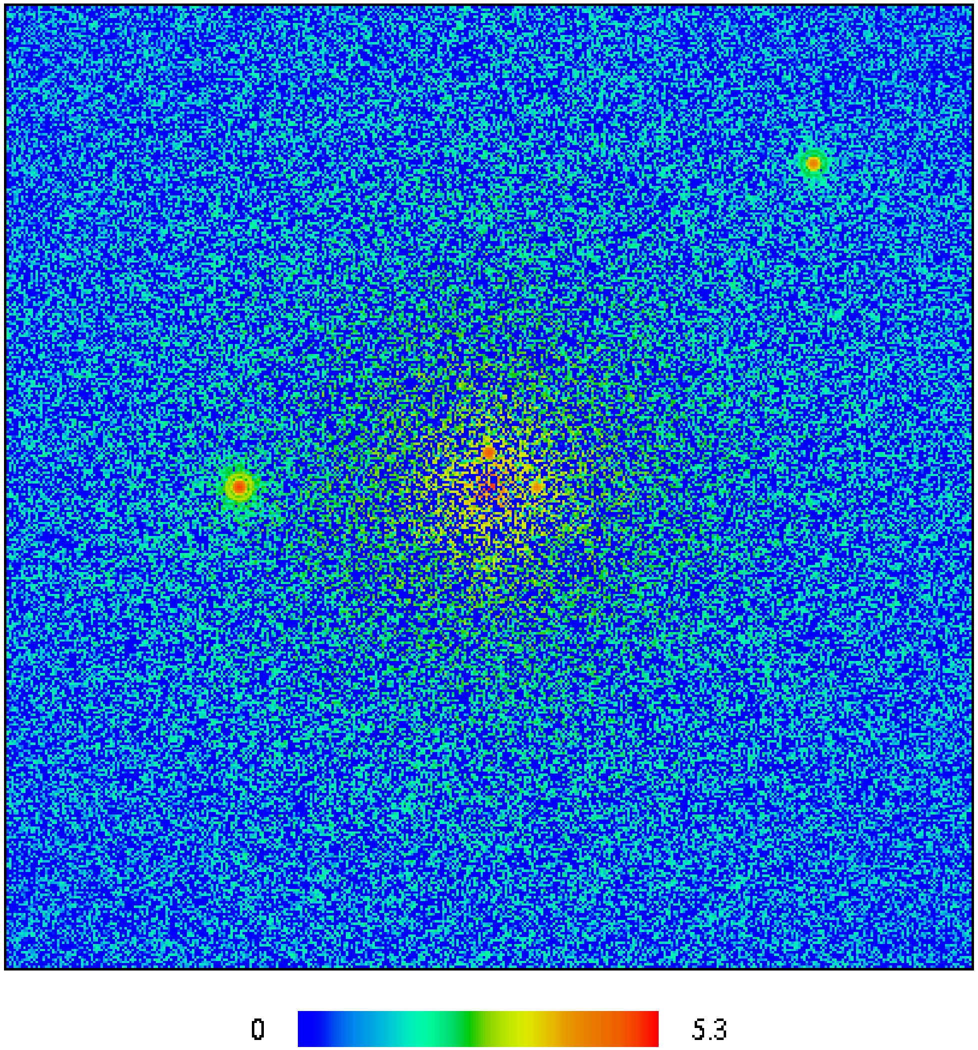

Planet	S/N
Mercury[a]	N/A
Venus	38
Earth	18
Mars[b]	3
Jupiter	1308
Saturn	722
Uranus[c]	39
Neptune[c]	15

a occulted
b marginally visible
c outside fov--projected S/N

Target Star with Planet at 83mas, 8m telescope, Δt=25,000s

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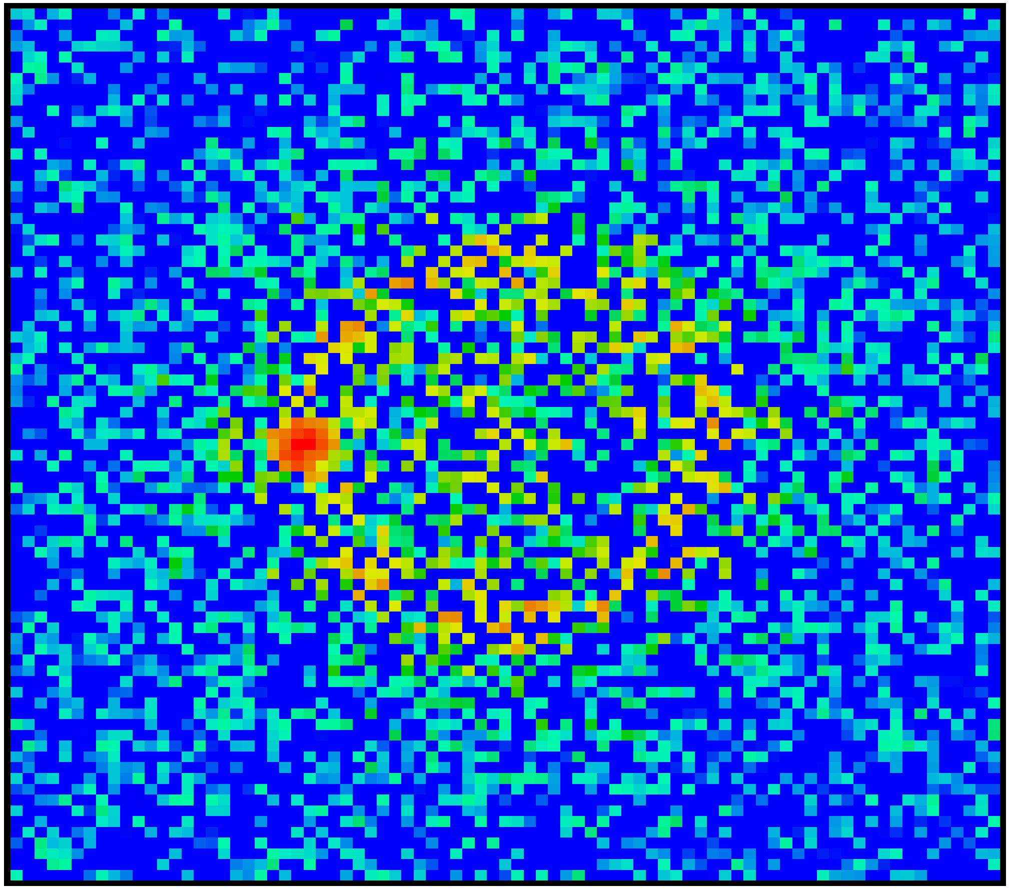

Possible Improved Detection Strategies

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- Polarization: reflected planet light is partially polarized
  - starlight is unpolarized
- Time dependence: planet moves on orbits, noise does not
- Wavelength dependence: λ dependence of nulling
  - modifies occulted stellar spectrum
  - but not unocculted planetary spectrum

Characterization Model Summary

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- Star
  - Sun at 10 pc
  - Blackbody spectrum at 5770K (as per SWG)
- Planet
  - Earth at 1 A.U. and 100 mas
  - Reflected solar continuum (as per SWG)
  - SWG-supplied spectrum
- Waveband
  - 0.5-1.0 μm with R=20 and R=50
  - Raw spectrum sampled at R $\approx$ 1500
  - Nulling computed at R $\approx$5, linearly interpolate log(nulling) in λ
- Approach
  - Earth spectrum+ occulted Solar continuum -- Poisson sampled
  - Fit to Earth continuum + occulted Solar continuum
- Spectral Feature Detection Criterion
  - 5σ inconsistency with continuum over feature width

Very High Resolution Energy Spectrum (per SWG)

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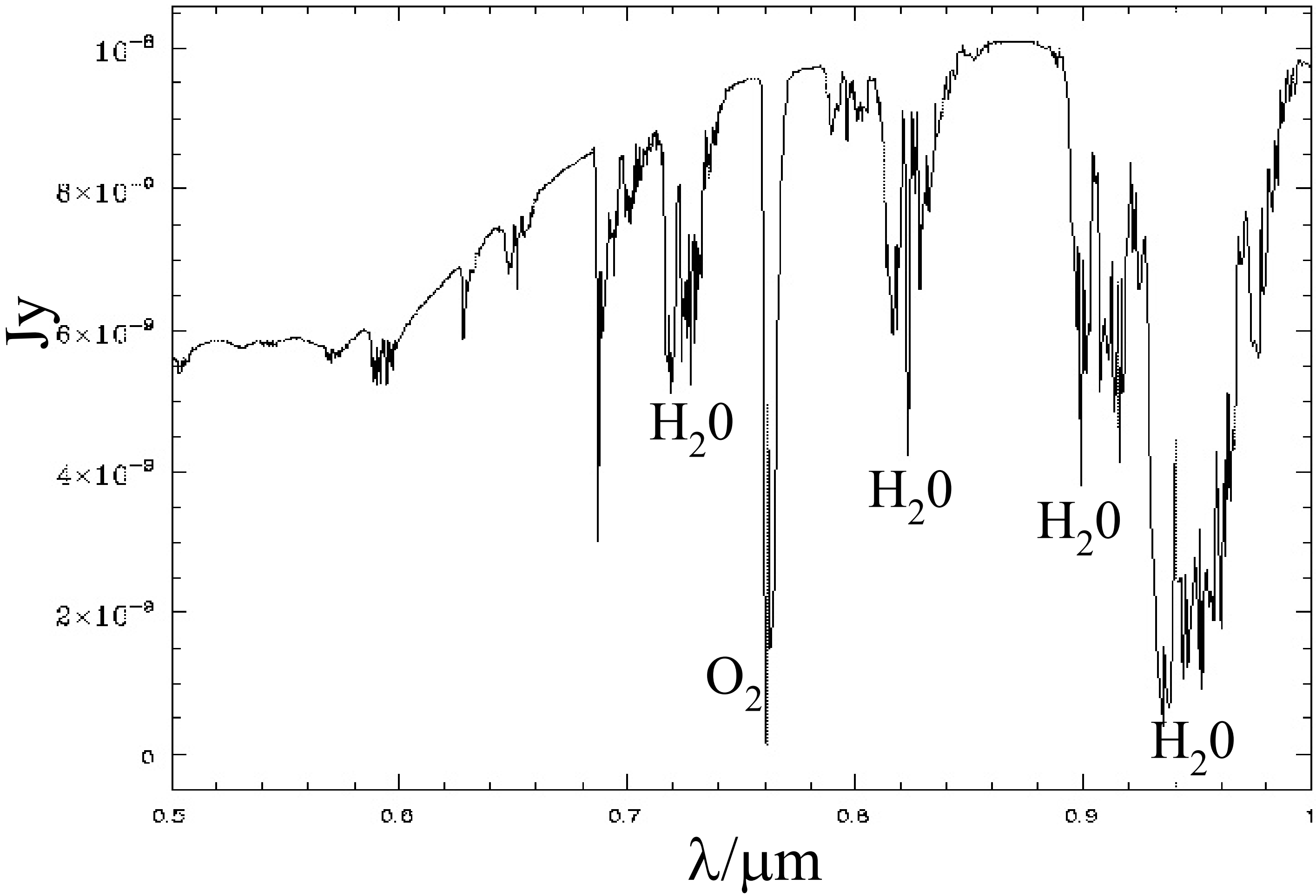

Target Spectral Features 0.5-1μm

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- SWG spectrum contains no specification of underlying chemical species
- Clearly present in SWG spectrum:
- H_2O - multiple bands including 0.74μm, 0.82μm, 0.91μm, 0.95μm
- O_2 - $(b'\Sigma_g^+ - X^3\Sigma_g^-)$ O-O band at 0.76μm
- Also in target waveband:
- CH_4 - 0.49μm,0.540μm,0.62μm,0.73μm,0.87μm 0.90μm, 1.0μm, …
- NH_3 - 0.55μm,0.65μm,0.79μm
- H_2 - 0.64μm,0.82μm
- Resolution for detection unknown

Times to 5σ Detection of Lines

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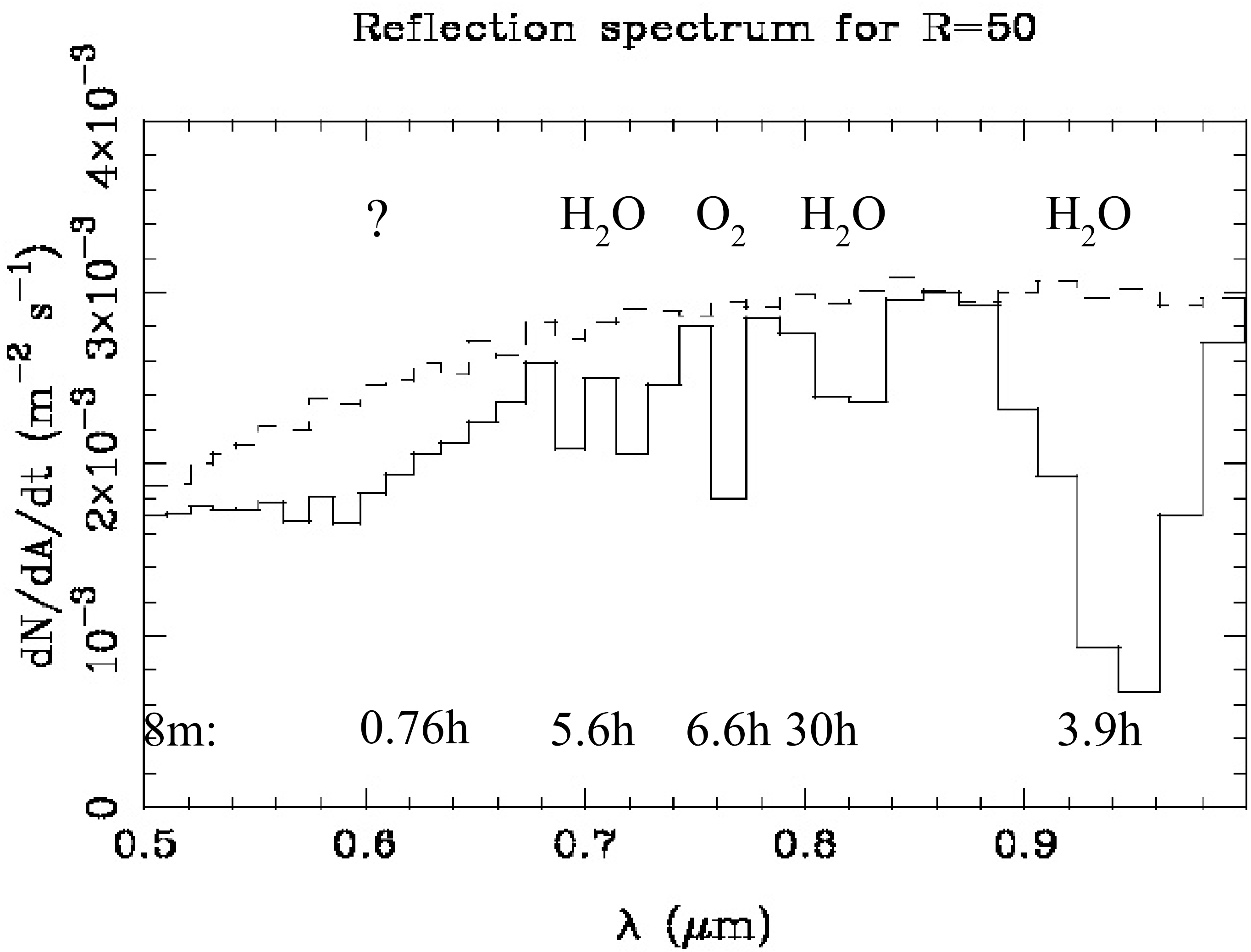

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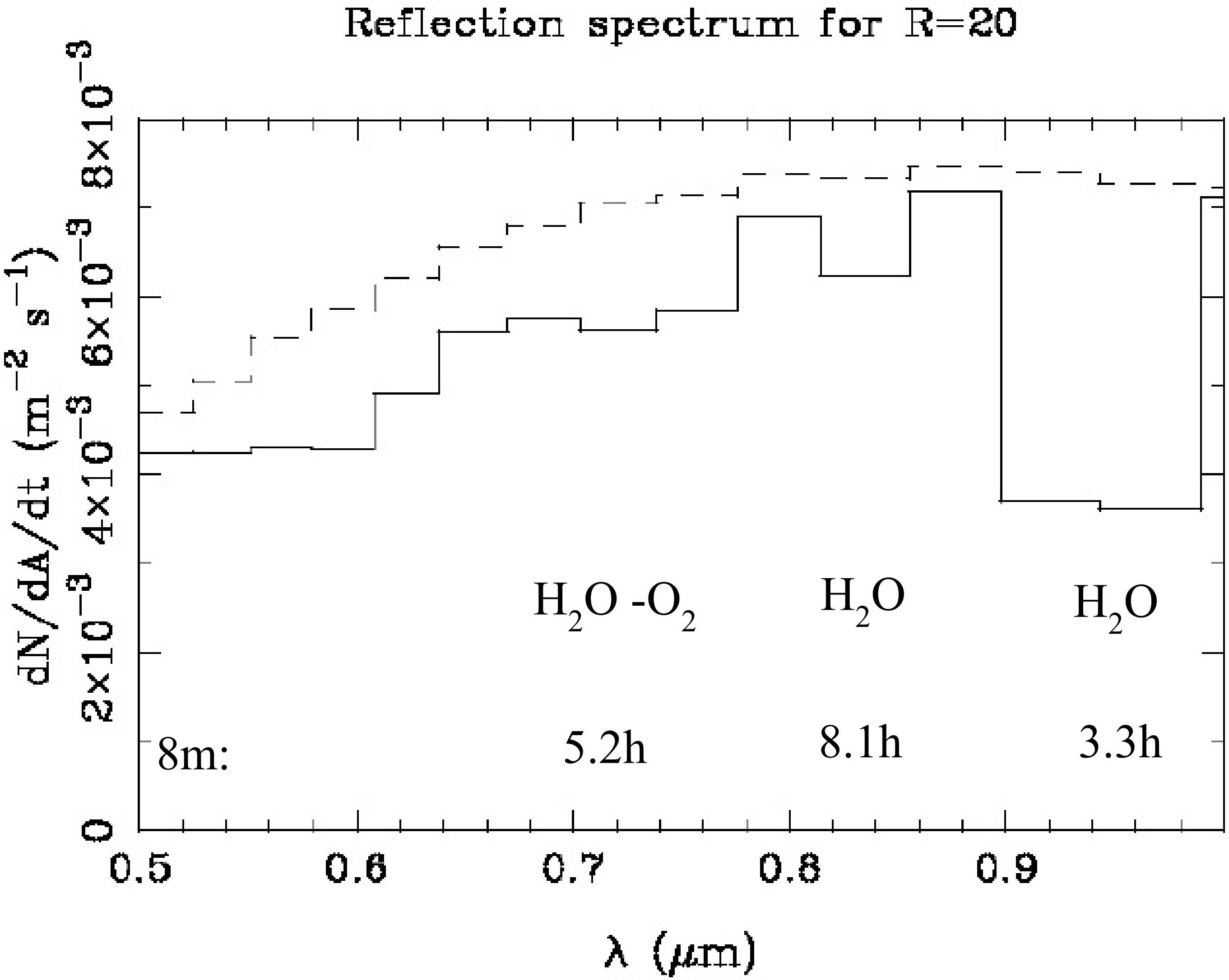
Times to 5σ Detection of Lines



Observed spectrum with best fit occulted stellar continuum + unocculted planetary continuum

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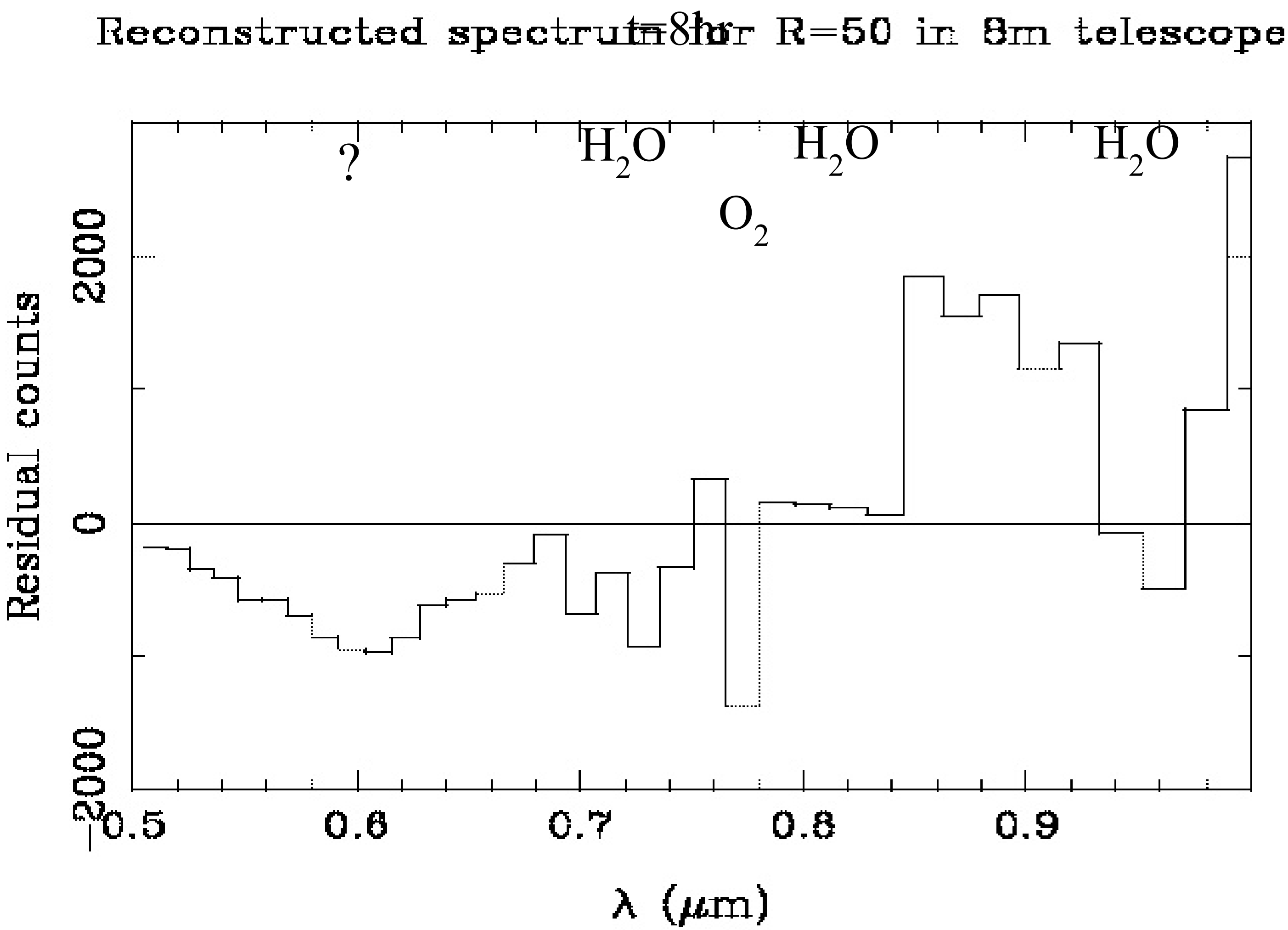

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Observed spectrum with best fit occulted stellar continuum + unocculted planetary continuum

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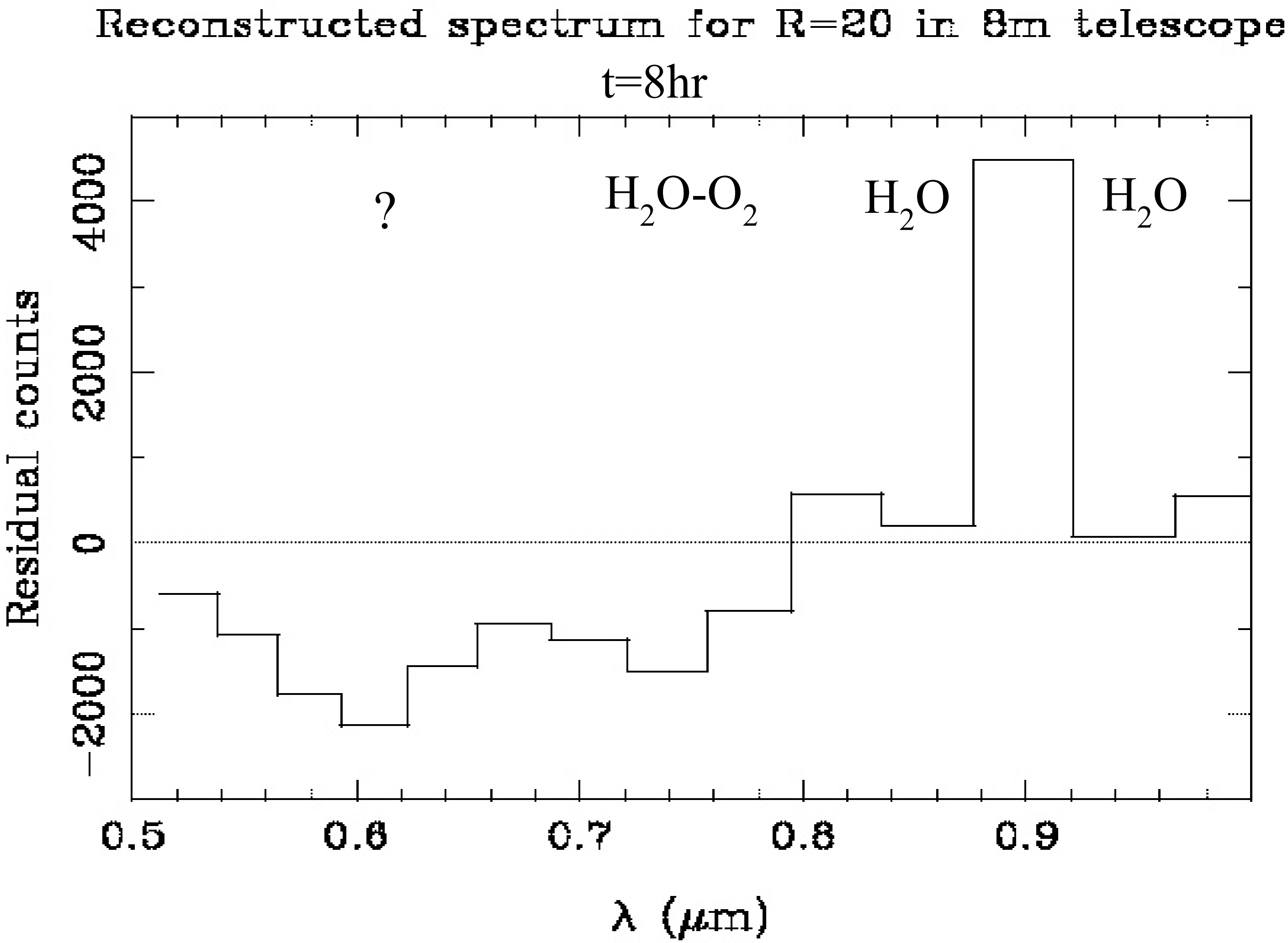
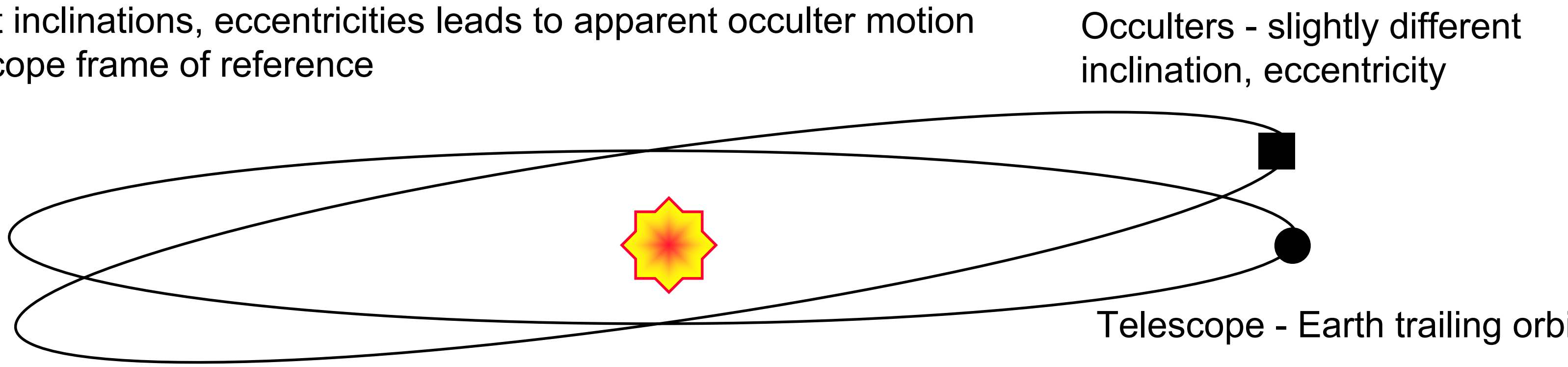
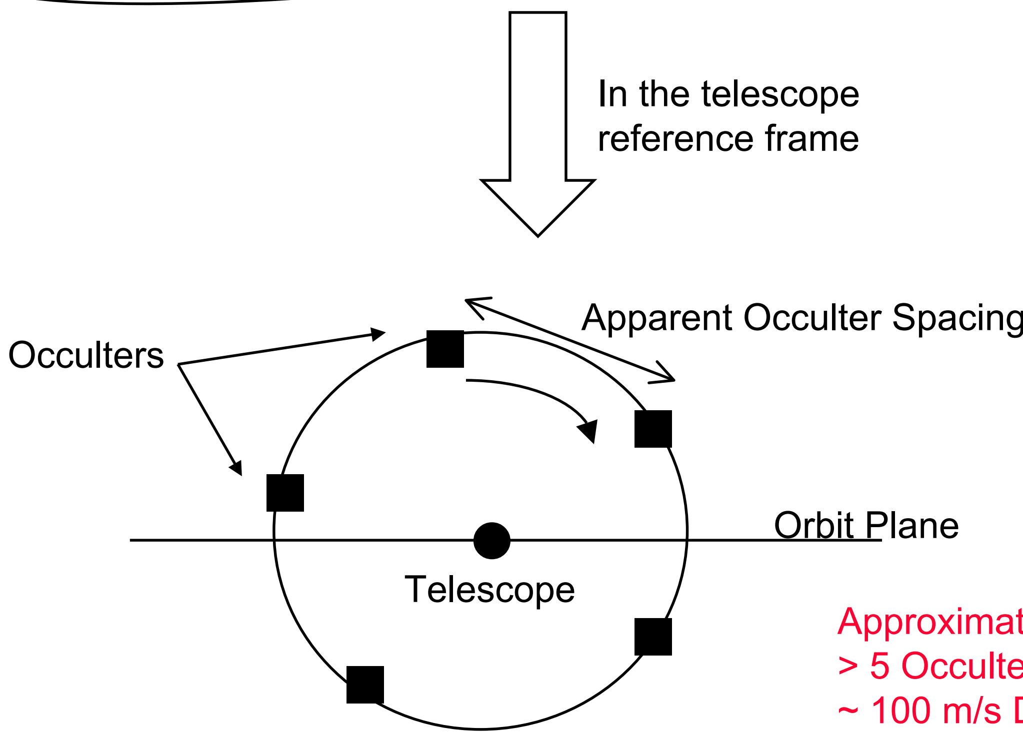


Occulter System Configuration

Maintaining several occulters in heliocentric orbits with slightly different inclinations, eccentricities leads to apparent occulter motion in telescope frame of reference





Approximate System Sizing:
> 5 Occulters
~ 100 m/s Delta V each Occulter

Telescope Space Vehicle Functions

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Telescope/ Instrument Functions

- Primary/Figure Control/Deployment
- Fine Point Control
- Starlight Sensing
- Data Management
- Occulter Position Sensing
- Shade/Deployment

Telescope Spacecraft Functions

- Orbit Position Control
- Attitude Control
- Communications
- Data Management
- Power Generation/Control
- Thermal Control
- Propulsion

Terrestrial Planet Finder

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Occulter Space Vehicle Functions

Occulter Functions

- Shade Beacon
- Shade/Deployment

Occulter Spacecraft Functions

- Orbit Position Control
- Attitude Control
- Communications
- Data Management
- Power Generation/Control
- Thermal Control
- Propulsion

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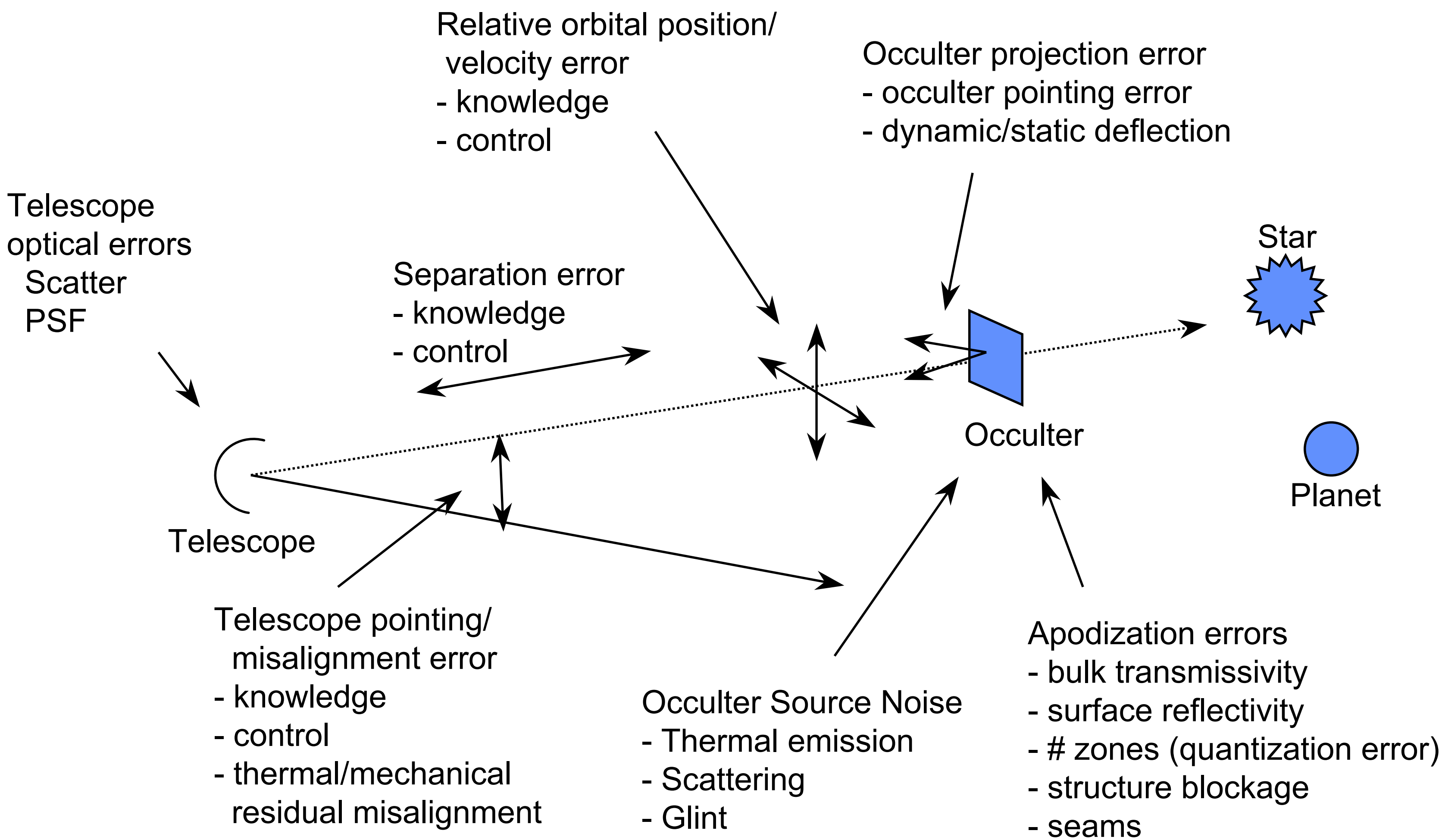
Occulter Error Sources



Terrestrial Planet Finder

Occulter Error Budget

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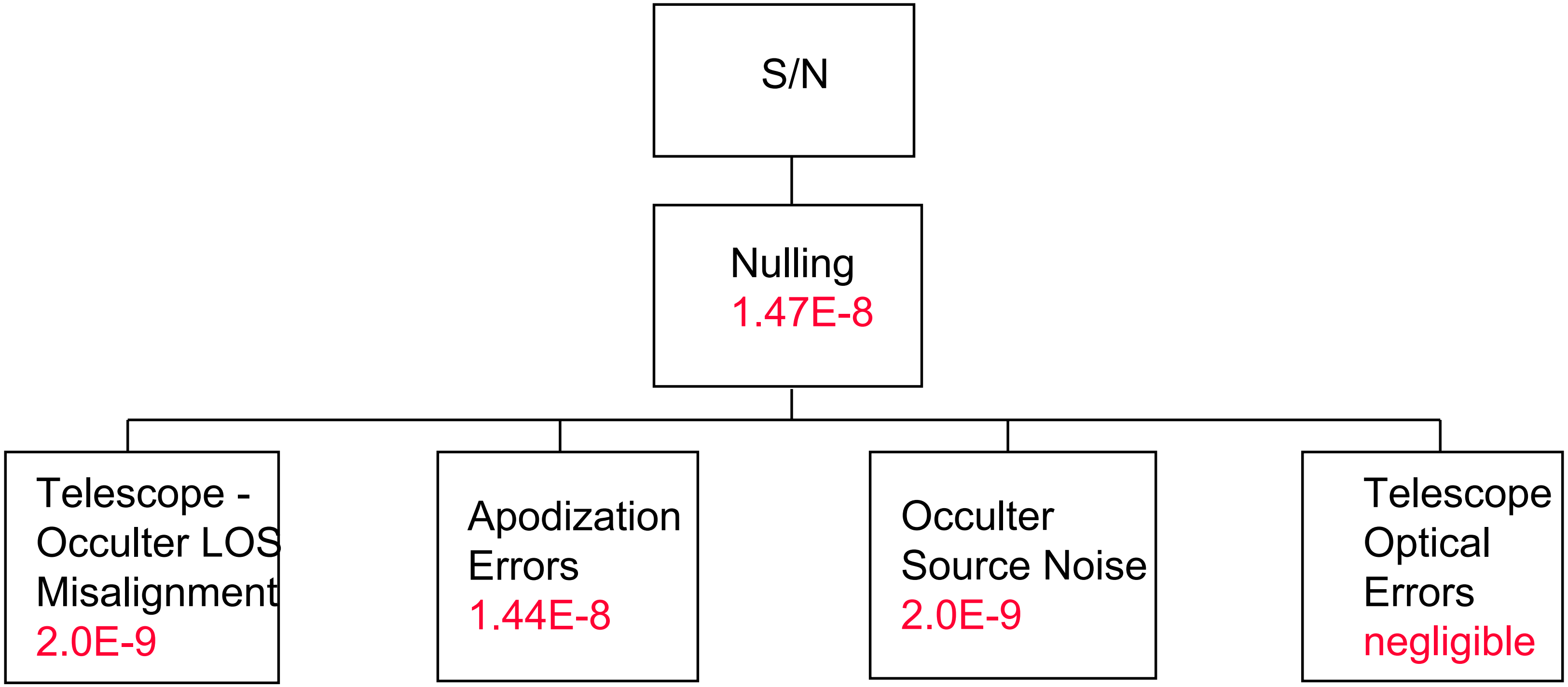

Telescope attitude
Telescope residual misalignment
Relative orbital position/ velocity
Separation
Occulter projection error

Transmissivity curve mismatch
- Max transmissivity 1.2E-8
- Structure blockage 8.0E-9

Thermal Emission
Scattering: 2.0E-9
Glint

Scatter
PSF

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Error Budget to Requirements Flow

Nulling
1.47E-8

Telescope - Occulter LOS Misalignment
2.0E-9 = 8m ∅

- Telescope attitude
- Telescope residual misalignment
- Relative orbital position/ velocity
- Separation distance
- Occulter projection error

Apodization Errors
1.44E-8

- Transmissivity curve mismatch

Occulter Source Noise
2.0E-9

- Thermal Emission
- Scattering
- Glint

Telescope Optical Errors
negligible

- Scatter
- PSF

Telescope Pointing
-knowledge,control
Telescope Position/Velocity
-knowledge, control
Thermal/mechanical residual misalignment
Occulter Pointing
Static/dynamic deflections

Occulter physical characteristics
- bulk transmissivity: 99.9%
- surface reflectivity
- scatter coefficient
- surface roughness/waviness
- # zones (quantization error)
- structure blockage: 2 cm struts
- seams
- temperature
- absorptivity
- emissivity

Nulling Factor Vs Telescope Size

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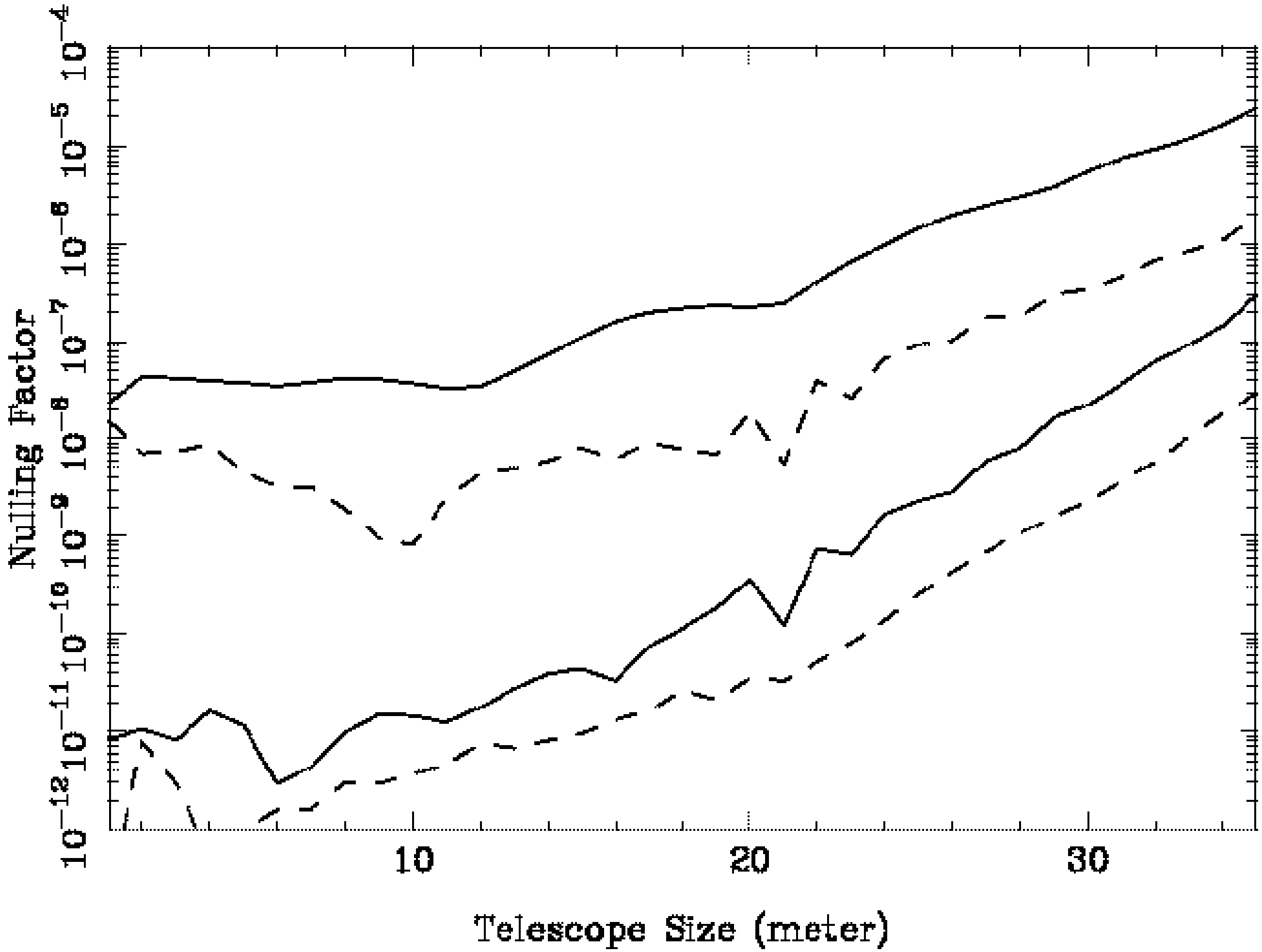

Occulter Parametric Sensitivity To Increased Telescope Size

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- Relaxation of critical parameters for 16m telescope vs 8m telescope
  - Telescope-Occulter LOS misalignment: 6m radial vs 4m
  - Transmissivity: 99% vs 99.9%
  - Structure Blockage: 7 cm struts vs 2 cm
- The occulter parameters for the 16m telescope have not been tuned to correspond in S/N to the equivalent parameters for the 8m telescope. The 16m scenes (in backup material) and associated characterization times are therefore often less attractive than for 8m
- A full trade study would be needed to more completely explore these tradeoffs

Occulter Technical Challenges

- Occulter shade material
  - state of art < 98% transmissive (CP1, CP2 polyimide films; optical adhesive films, carbon fiber weaves)
  - meshes vs films for high transmissivity
  - low scattering, surface reflectivity
  - uv/cosmic ray degradation
  - micrometeoroid damage
  - large shield size vs maximum fab capability (1 - 1.5 m wide), leads to large number of zones and associated seams

Occulter Technical Challenges (Cont'd)

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- Occulter configuration
  - strength, stiffness vs mass, volume
  - deployment of large thin films (tearing, etc)
  - control of shield orientation during spacecraft attitude control
- System operability
  - Controlling relative drift of 4m radial over 100,000 km separation
  - Metrology w/ beacon from shield for relative drift knowledge (using telescope)
  - Orbit position knowledge accuracy
  - Optimal repositioning scheme to minimize delta V vs number of required occulters