TRW Space & Electronics Group

Large Aperture Mirror With Coronagraph

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TPF Terrestrial Planet Finder

Large Aperture Imager Is Natural Extrapolation of NGST

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- Direct imager is most straight forward way to image planets around other stars
  - Key difficulty is separating photons from the planet from photons from the central star
  - With very high resolution imaging, planet is separated from the star at the detector $\Rightarrow$ very large aperture to overcome diffraction
  - If star light can be blocked, need less resolution to see the planet
- Coronagraph techniques allow imaging very close to a bright point source by blocking the light from the point source
  - Very good control of PSF needed
  - Still need relatively large aperture to see planet on the diffraction spike of the stellar source

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Trades For Implementation Driven By Phenomenology

- The aperture size is driven by the wavelength observed
  - Thermal IR observations require aperture of 30 - 40 m in diameter
  - Visible observations require aperture of 8 - 10 m in diameter
  - Precision of the mirror is also a function of wavelength
- A key trade between filled and partially filled apertures will be done during phase 2 of the study
  - Initial indications are that the endo-zody background drives to require as near full aperture as technically possible in the thermal IR
  - Believe that optimizations may be made to reduce fill factor to some extent to minimize launch mass and volume
  - For a visible observatory, heritage to NGST would permit a fully filled aperture of order 10 m
- Baseline performance modeling has only been performed on the nearly filled aperture
  - Thermal and dynamical analysis on IR system were done for the partially filled aperture (potentially a worst case)
  - Packaging is best case of partially filled aperture for IR system

Strawman Design of A Large Annular Reflector + Coronagraph

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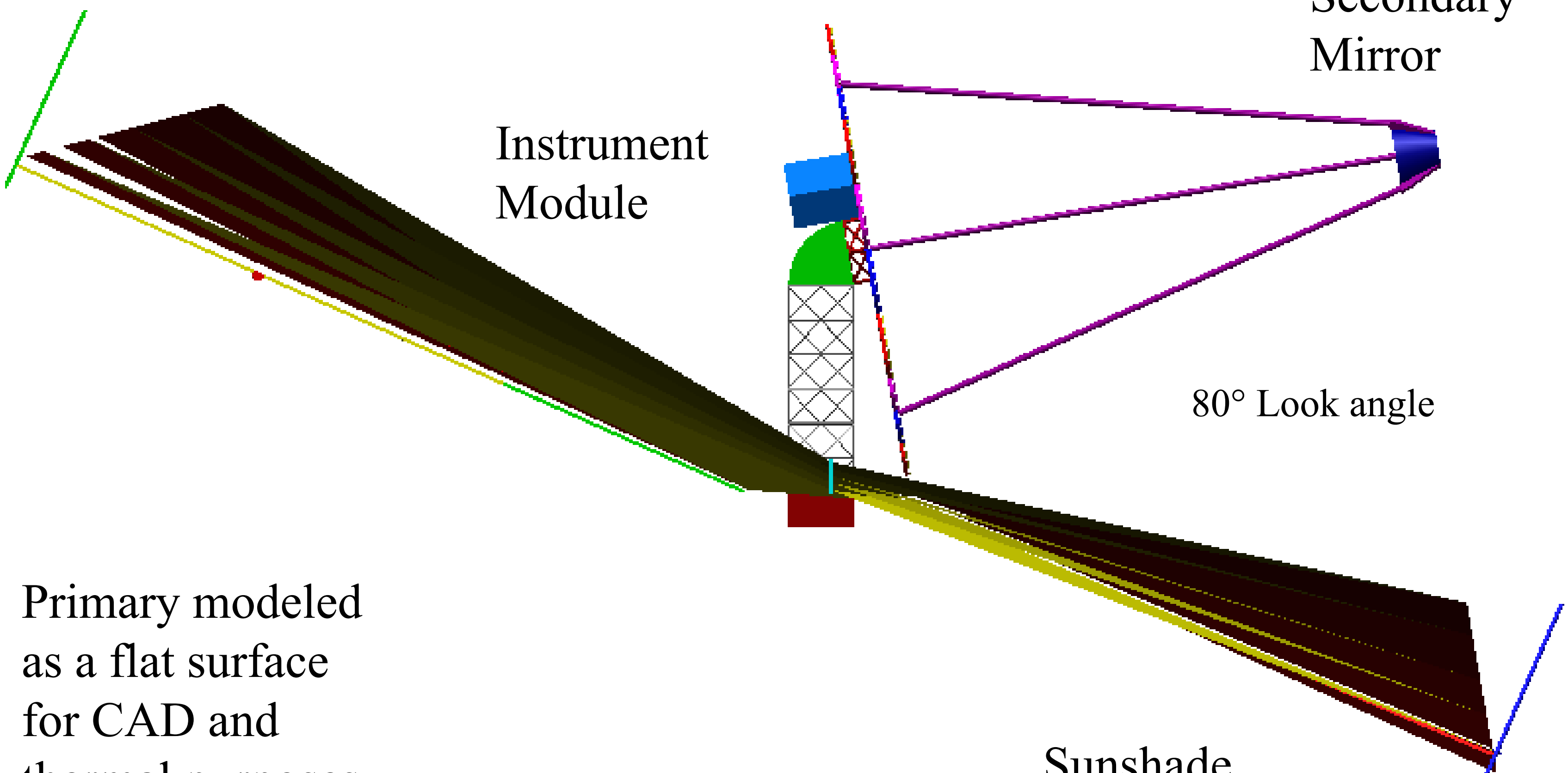
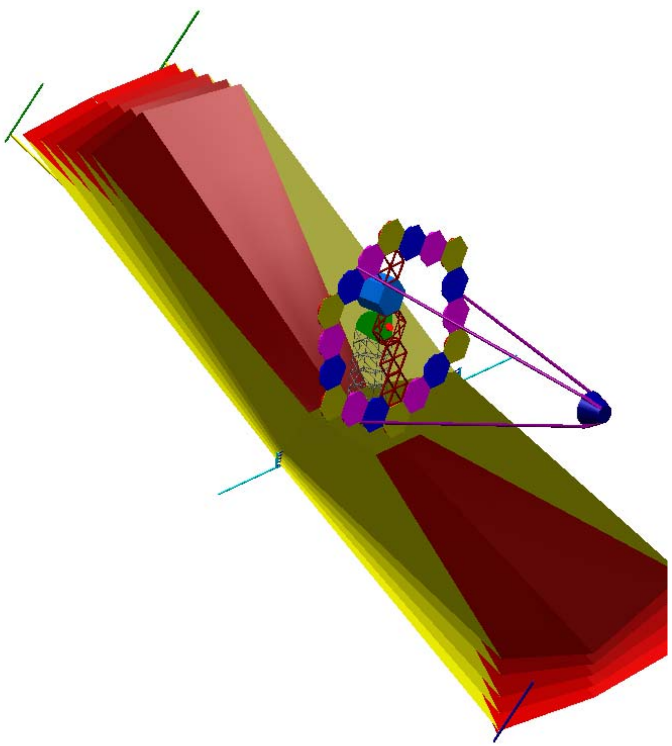
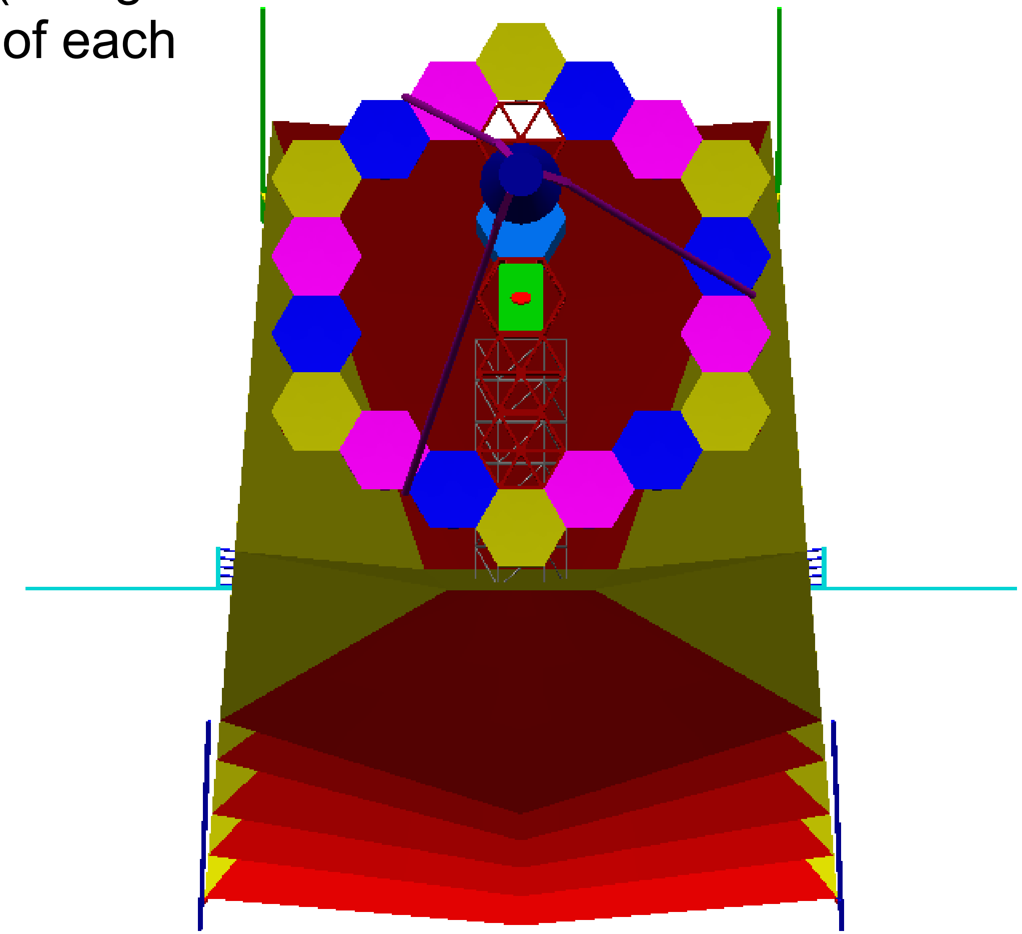


Primary modeled as a flat surface for CAD and thermal purposes

Detail of Mirror and Structure

Three families of mirrors (though two are simply opposites of each other)





Mirror Utilizes Kodak AMSD Mirror Technology

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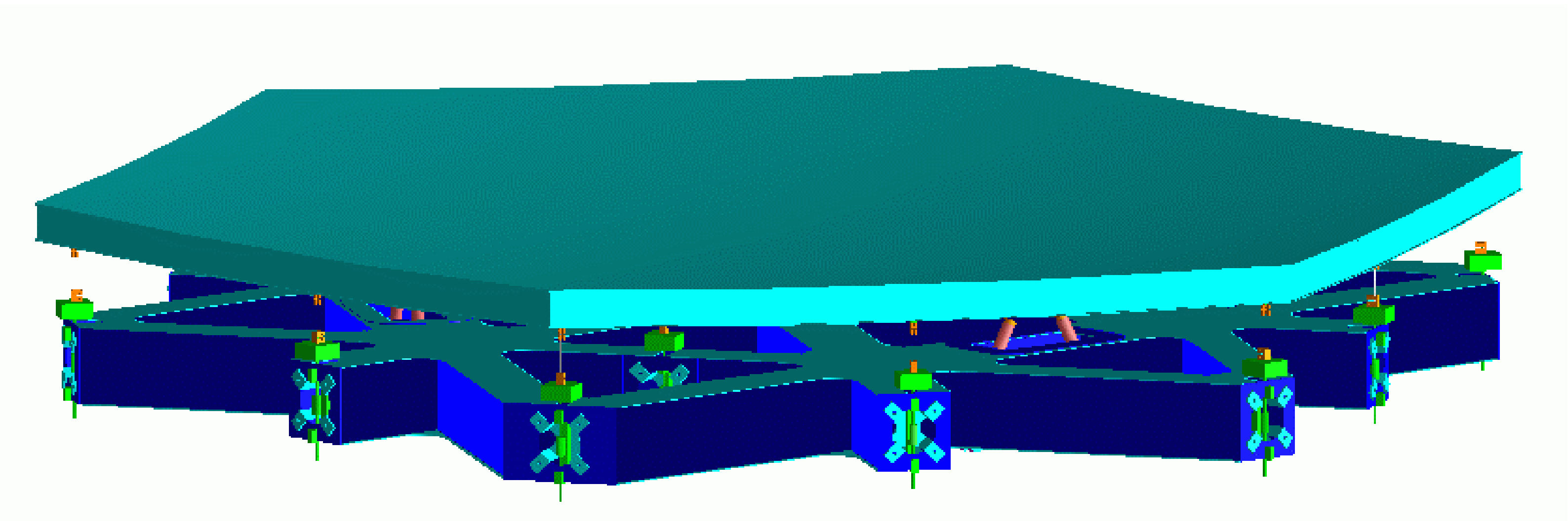
- Kodak AMSD < 15 Kg/m^2 **(includes mirror and all reaction hardware)**
- Lightweight stiff mirror (sandwich construction)
- Composite reaction structure
  - Low expansion cyanate siloxane
  - Minimizes radial expansion delta between structure and mirror



Backplane Structure of Kodak AMSD Mirror

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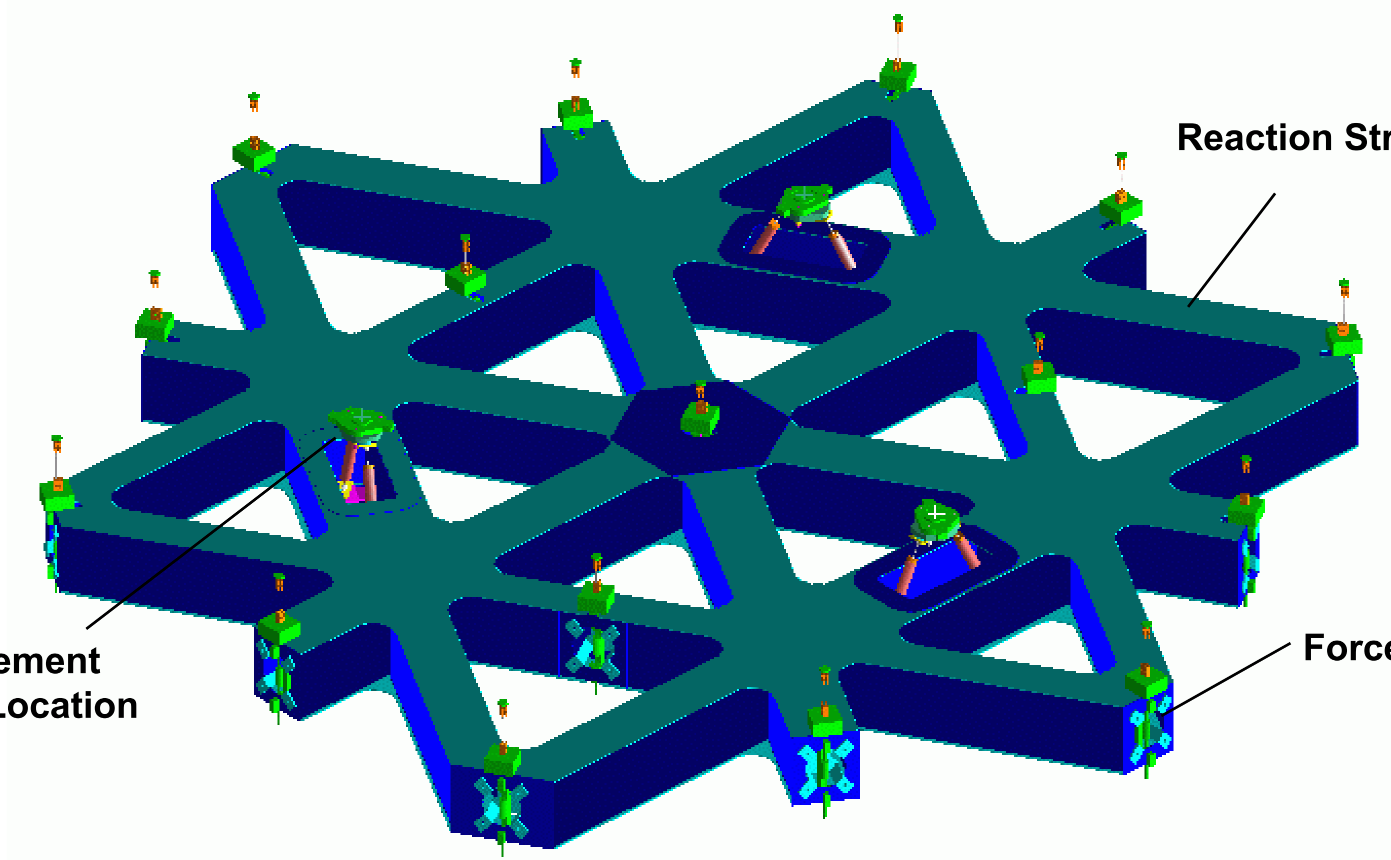
- 3 stiff displacement actuators
  - kinematic mirror mount
  - 3 DOF mirror rigid body control
- 16 soft force actuators
  - mirror radius & figure control



Simple Tools Used to Scale Required System Size

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- Simple IDL model by C. Bennett used to calculate relative SNR of the system with the following assumptions
  - Annular aperture in entrance pupil
  - Gaussian occulting spot at prime focus
  - Graded Lyot stop
  - Solar system at 10 pc used as input scene
  - Occulting spot and Lyot stop optimized for the given aperture
- Ring thickness drives SNR if diameter is large enough to allow detection at small separations
- Noise dominated by the Endo-zody background

Sizing Model Results Imply Fill Factor Is Critical For Sizing System

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Outer Diameter	Ring Width	SNR (Earth)
35 m	5 m	3
35 m	10 m	44
35 m	17.5 m (filled)	120

Model is for a 12 hour integration time

System optimization will be necessary to achieve maximum performance at a reasonable cost

Detailed model to determine best primary mirror geometry still to be done

These results indicate that partial fill is possible but must be greater than 50%

Thermal IR System: Performance Model Assumptions

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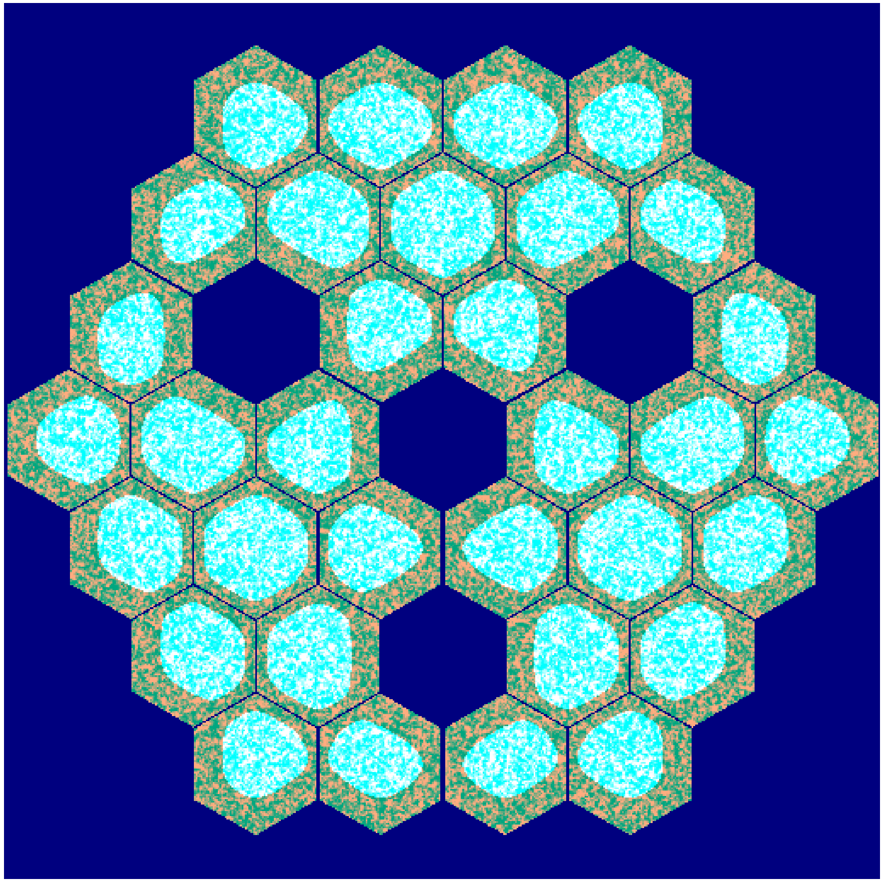
- Detailed system modeled by John Trauger using code developed for specialized coronagraph designs
- Input is Solar System at 10 pc
- Mirror is 36 segment hexagonal design in 3 rings around a center gap with segments 4.57 meters flat to flat, giving a full aperture of 32 m
- Mirror figure errors are based on analysis by Kodak
- Coronagraph spot and Lyot stop have been optimized for this system
- Overall system efficiency is 50%
- Simulations use a 20% bandpass filter at 10 microns
- Pixel Scale is 0.0161 arcseconds / pixel
- Have used 24 hour integration times (not needed given the high SNR that were achieved)

Thermal IR System: Primary Mirror As Modeled



- Primary mirror shown with assumed figure error of 100 Å rms
- No active mirror correction is assumed in model
- Occulting spot is gaussian-graded with 0.5 transmittance at a radius of 0.8 arcseconds
- Lyot mask superimposed as shaded area and transmits 50% of the incident light
- Missing hexes are due to support struts bisecting them (leaving little usable glass so easier to leave out)

Thermal IR System: PSF Produces Good Stellar Rejection

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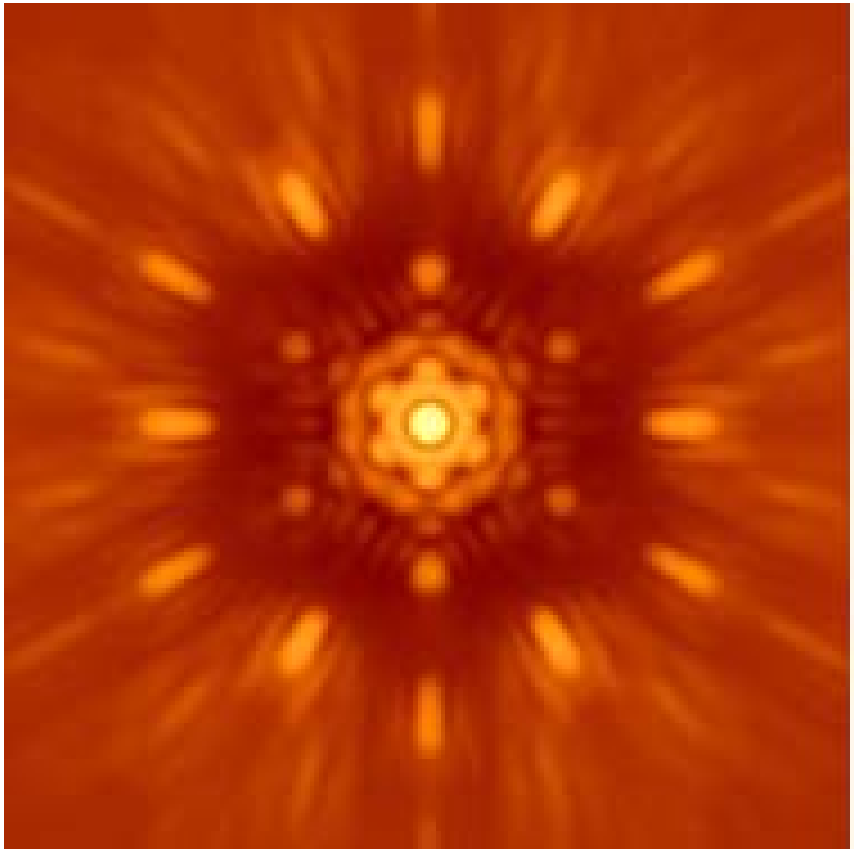

Raw Image (log plot)

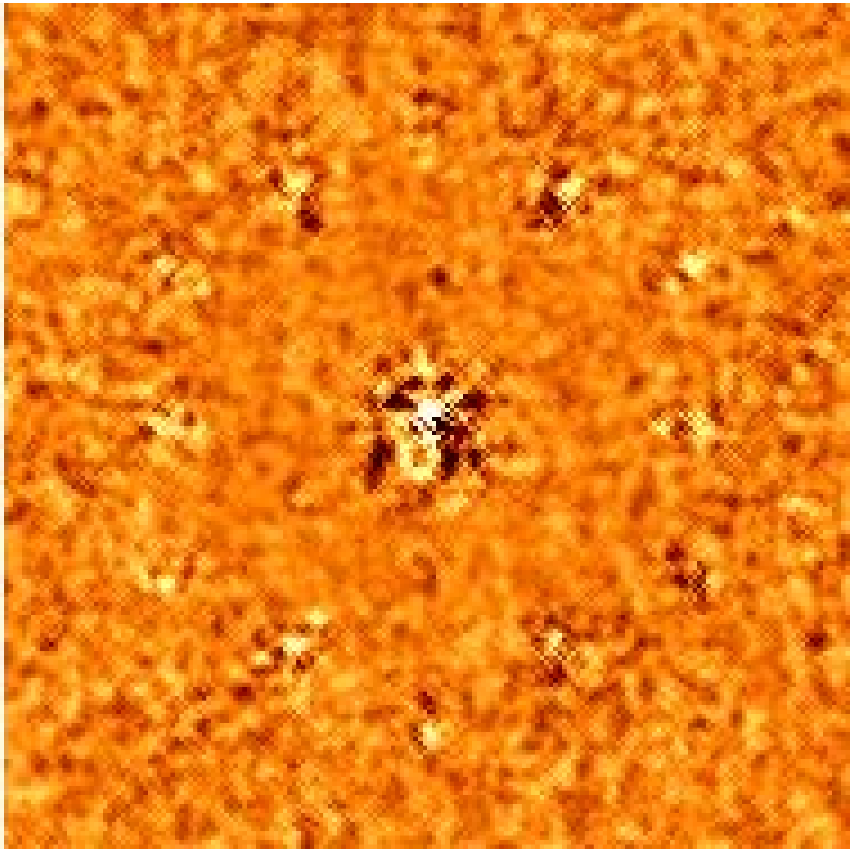

Image with reference background frame subtracted

Thermal IR System Offers Good Contrast With No Active Correction

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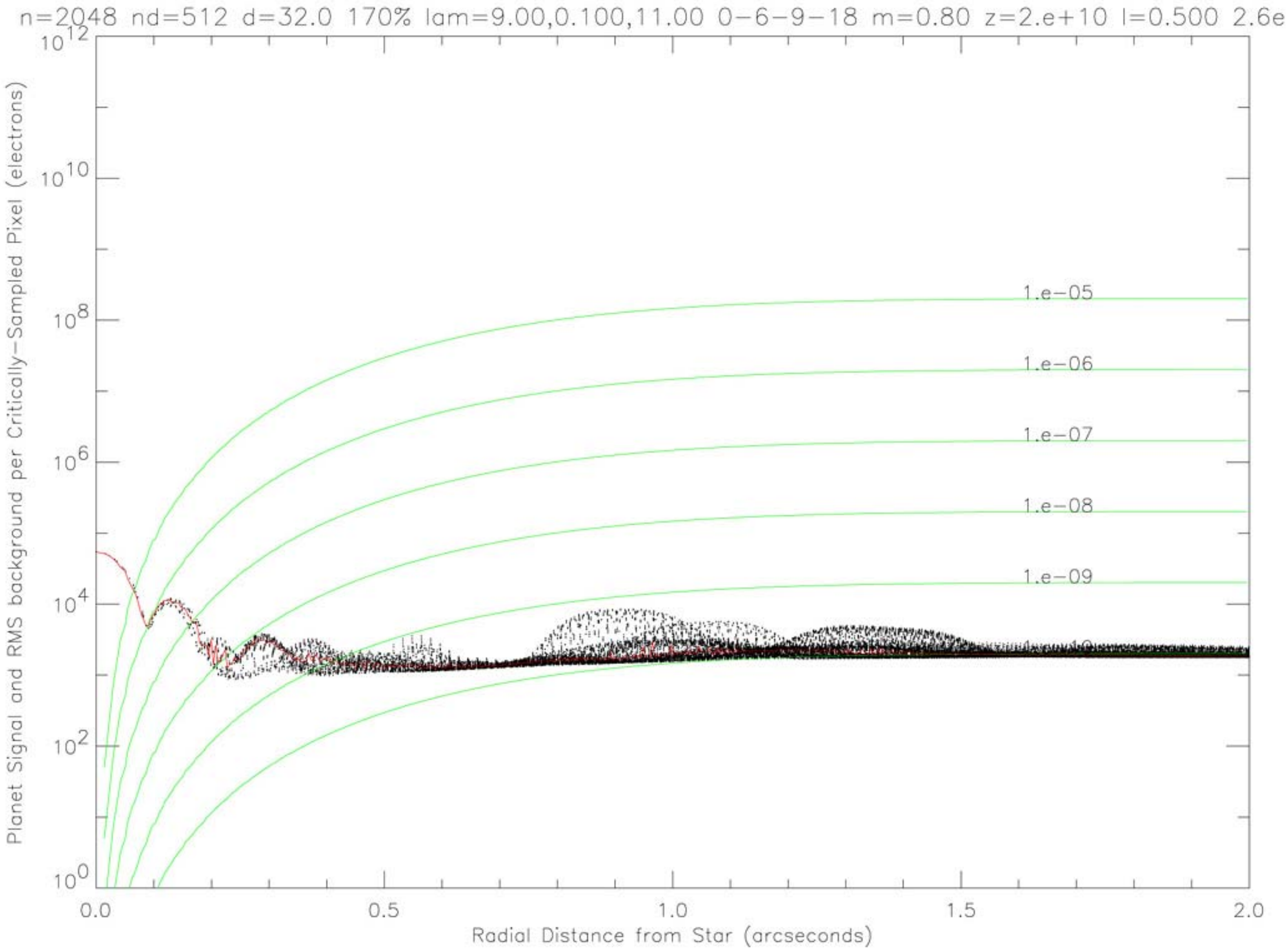

Thermal IR System: Easily Detect Our Own Solar System

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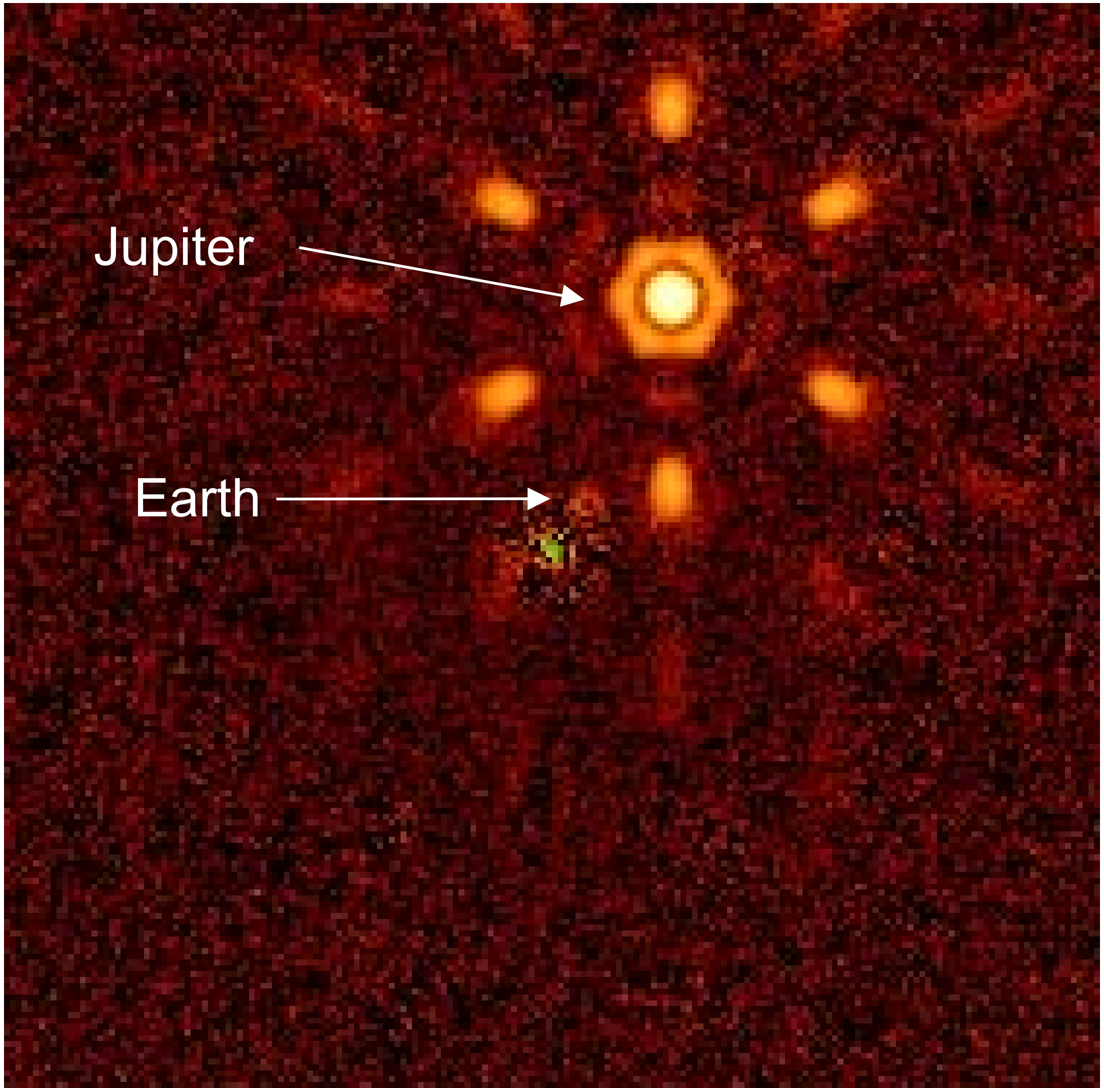

For the 24 hour exposure modeled, the Earth is detected at S/N = 5, within reason to perform the TPF mission given the level of maturity of the model and lack of optimization

Only Earth and Jupiter were modeled in this simulation

Visible Imaging System: Performance Model Assumptions

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- All models run with Trauger's code
- Input is Solar System at 10 pc
- Mirror is 6 segment hexagonal design in a single ring around a center gap with segments 4.57 meters flat to flat, giving a full aperture of 13.7 m
- Mirror figure errors are based on analysis by Kodak
- Coronagraph spot and Lyot stop have been optimized for this system
- Overall system efficiency is 50%
- Simulations use a 28% bandpass filter at 0.8 microns
- Pixel Scale is 0.00602 arcseconds / pixel
- Have used 24 hour integration times

Visible System: Primary Mirror As Modeled

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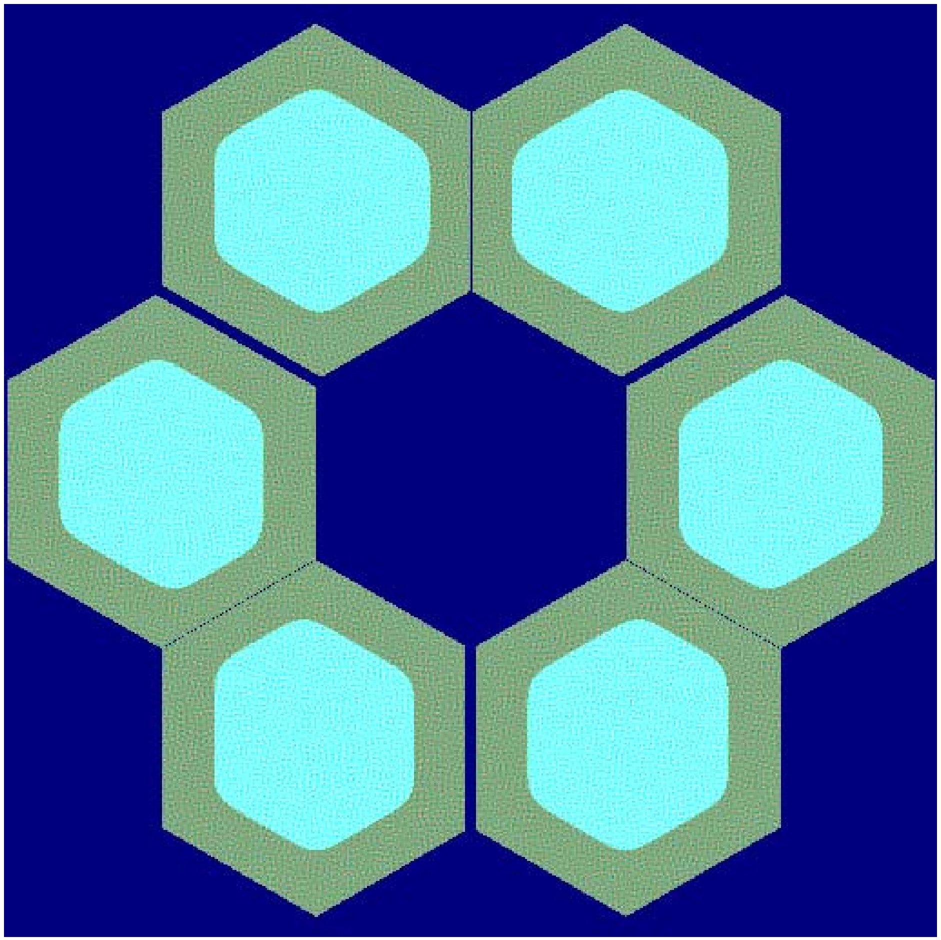
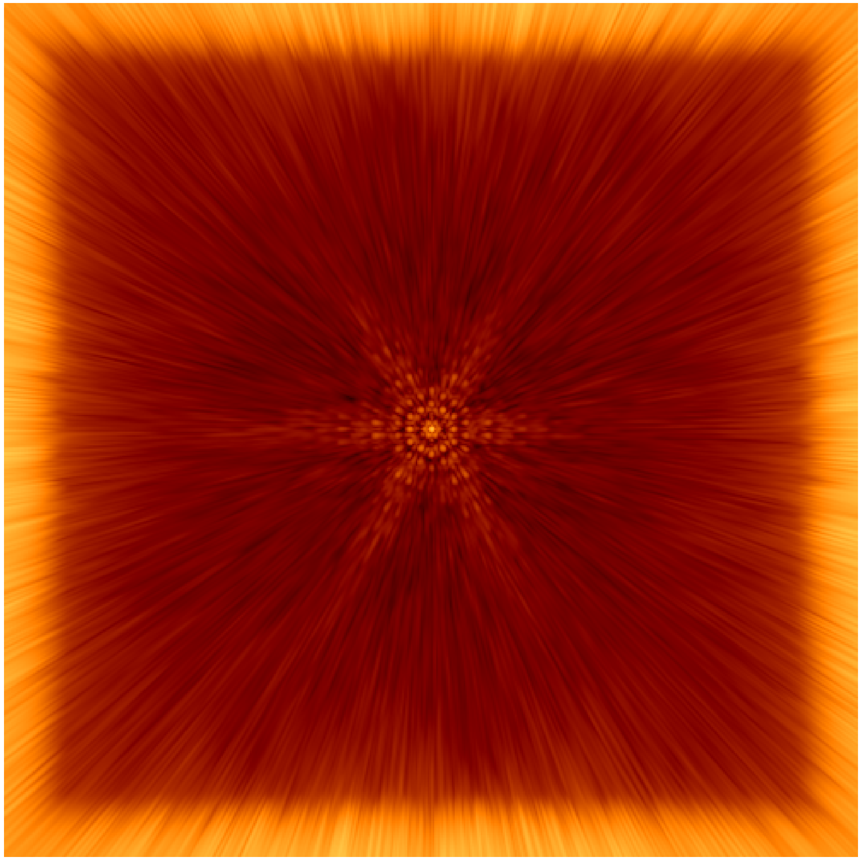


- Primary mirror shown with assumed figure error of 100 Å rms
- Active wavefront control is simulated with a square array of 256x256 mirror actuators with an accuracy of 1 Å rms
- Occulting spot is gaussian-graded with 0.5 transmittance at a radius of 0.15 arcseconds
- Lyot mask superimposed as shaded area and transmits 45% of the incident light

Visible System: PSF Produces Good Stellar Rejection



Raw Image (log plot)

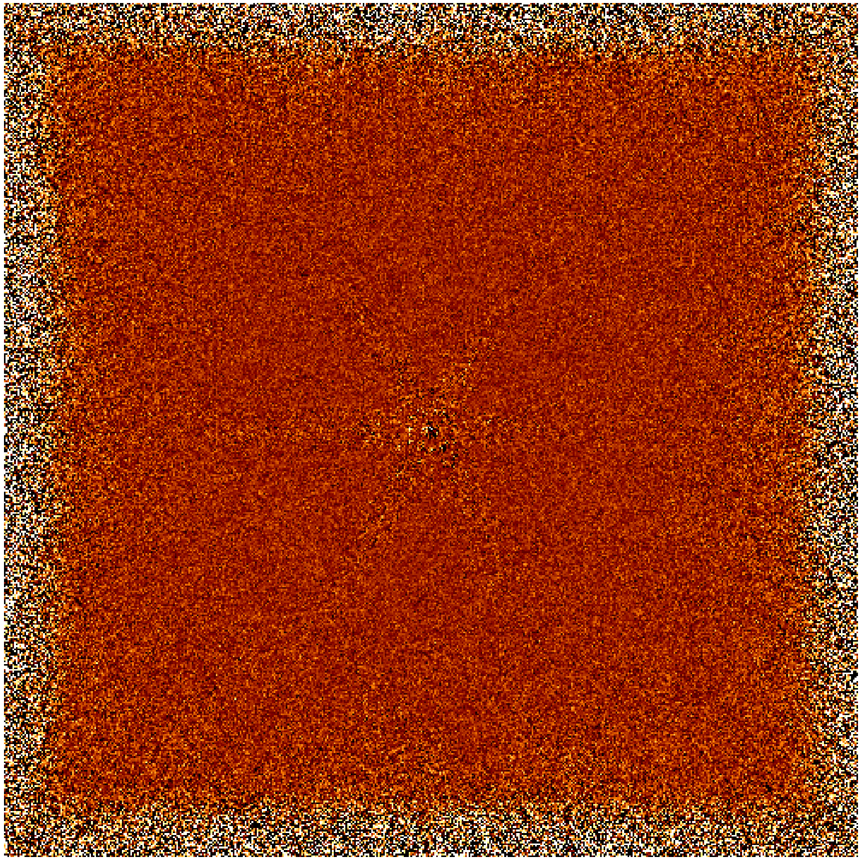


Image with reference background frame subtracted

Visible System Offers High Contrast With Active Correction

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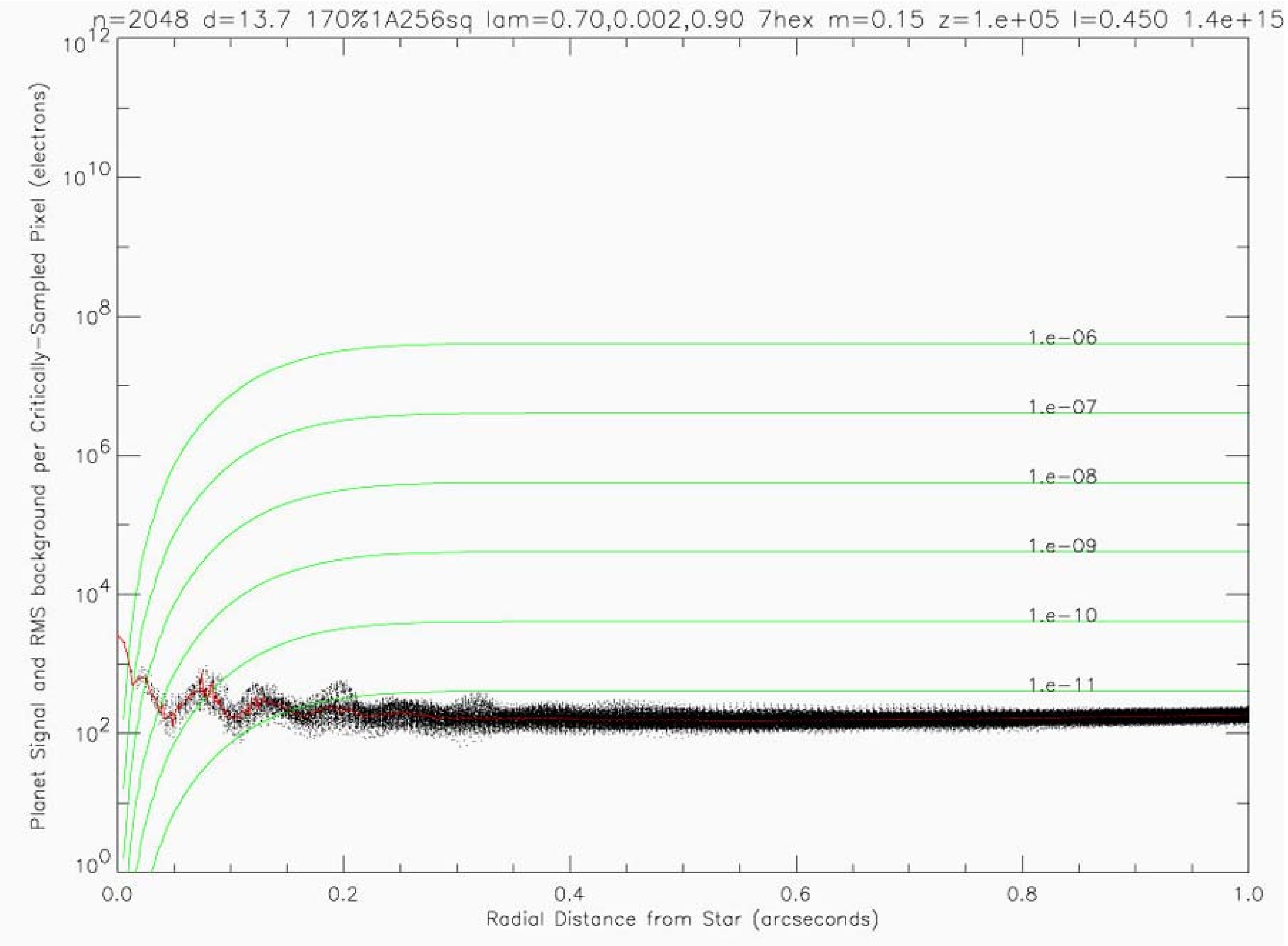

Visible System: Easily Detect Our Own Solar System

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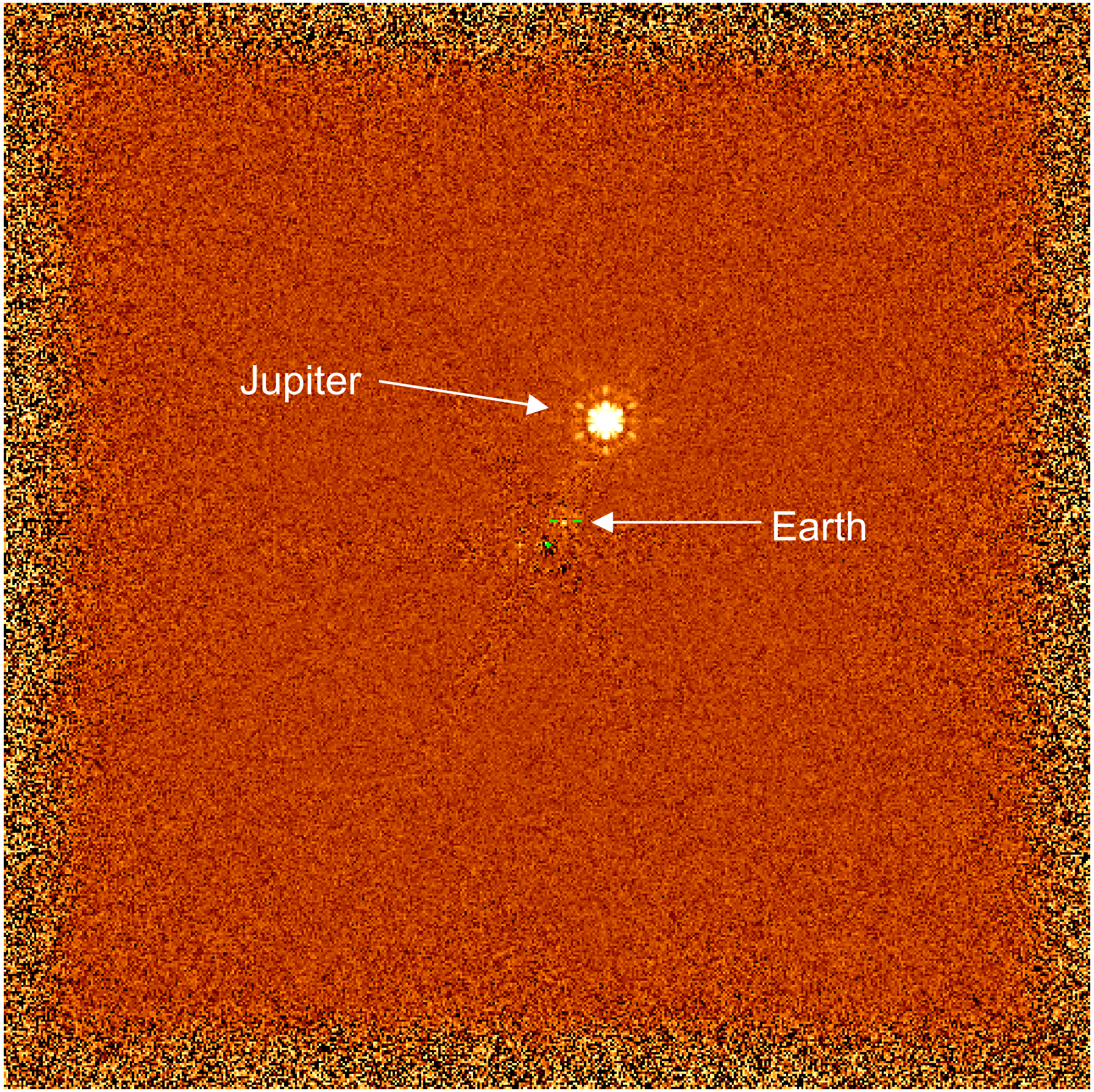

For the 24 hour exposure modeled, the Earth is detected at S/N = 5, within reason to perform the TPF mission given the level of maturity of the model and lack of optimization

Annular Aperture With Coronagraph Can Do TPF Mission

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- Estimates of slew, pointing, acquisition time, settling times for this large structure are <4 hours
- This leaves >12 hours of integration time for the detection observations
- The models show SNR = 5 in 24 hours
  - This should be possible to improve by the required factor of 2 given additional time to thoroughly optimize the design
  - Bennett's simple model shows the required performance is easily obtained using a more continuous primary mirror (annular rather than made up of hexes)
  - A slightly larger primary mirror will also be considered in phase 2

Functional Block Diagram

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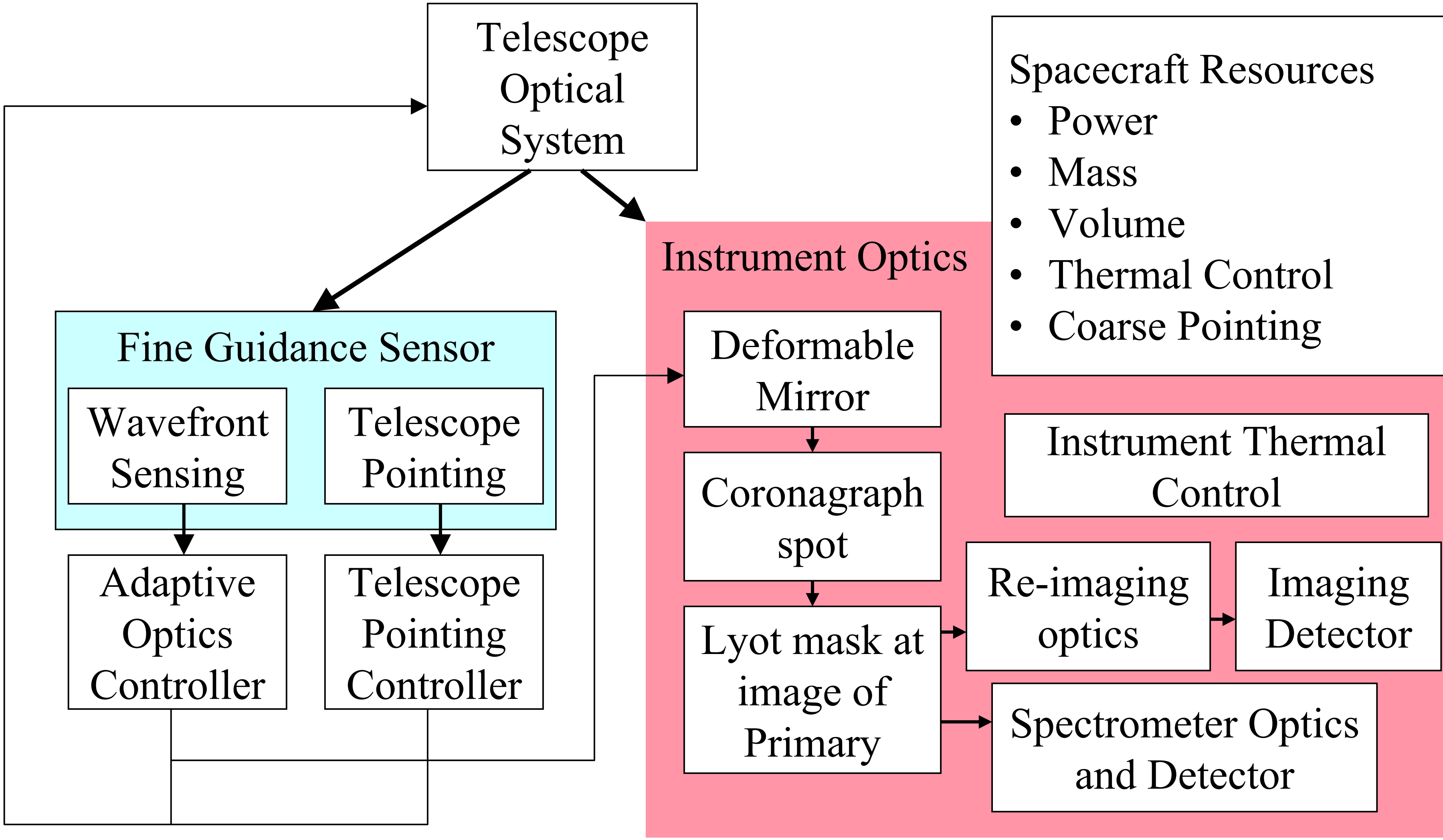

Error Budget

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- Top level error analysis performed
- Kodak evaluated the error budget for the telescope components
- John Trauger provided an estimated level of errors in the coronagraphic instrument which he used in his system model
- All components evaluated for the level of risk and technology development needed to make this system work

Optical Telescope Assembly Wavefront Error Budget

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Terrestrial Planet Finder

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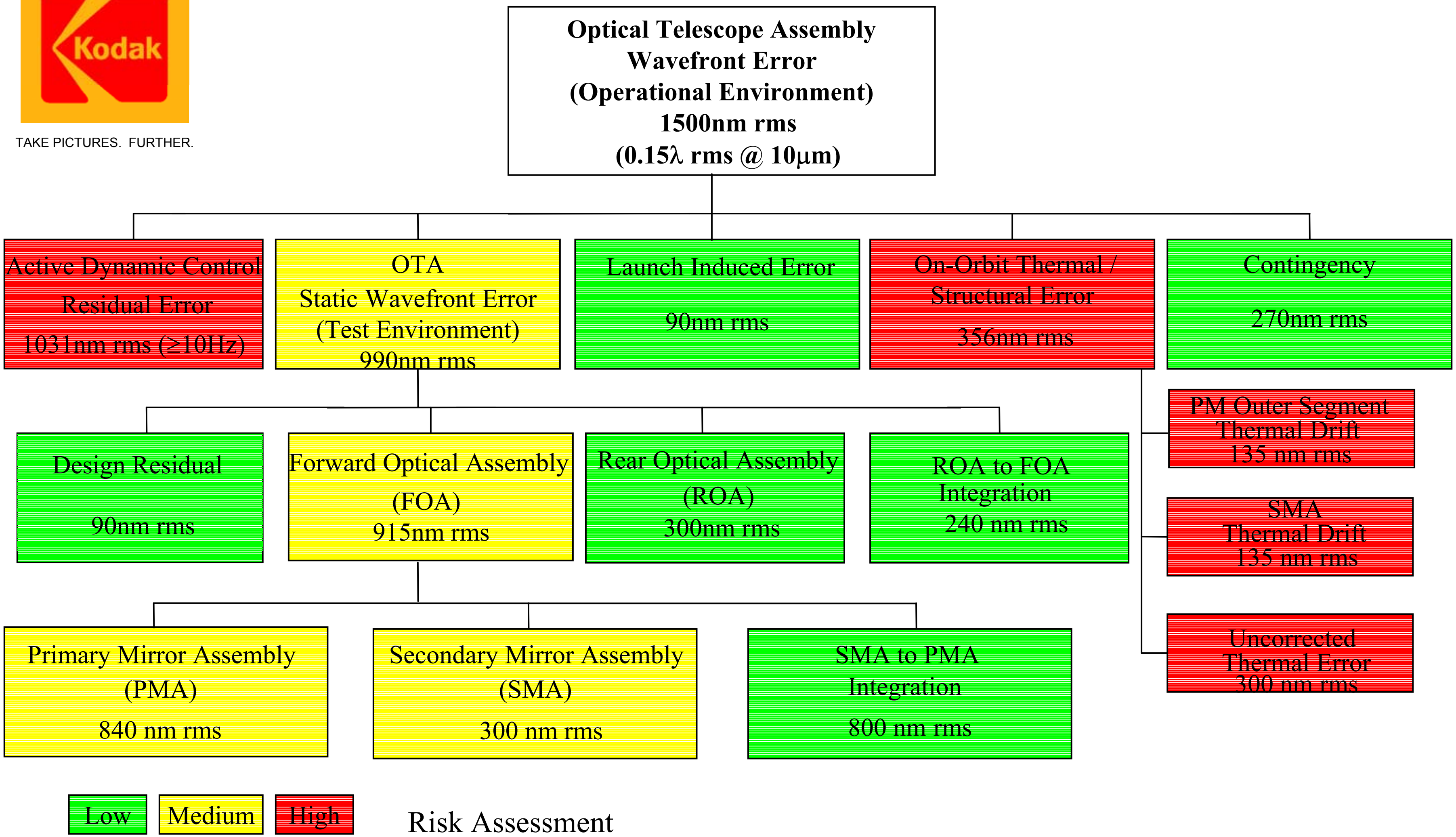

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Primary Mirror Figure & Phase Wavefront Error Budget

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Kodak

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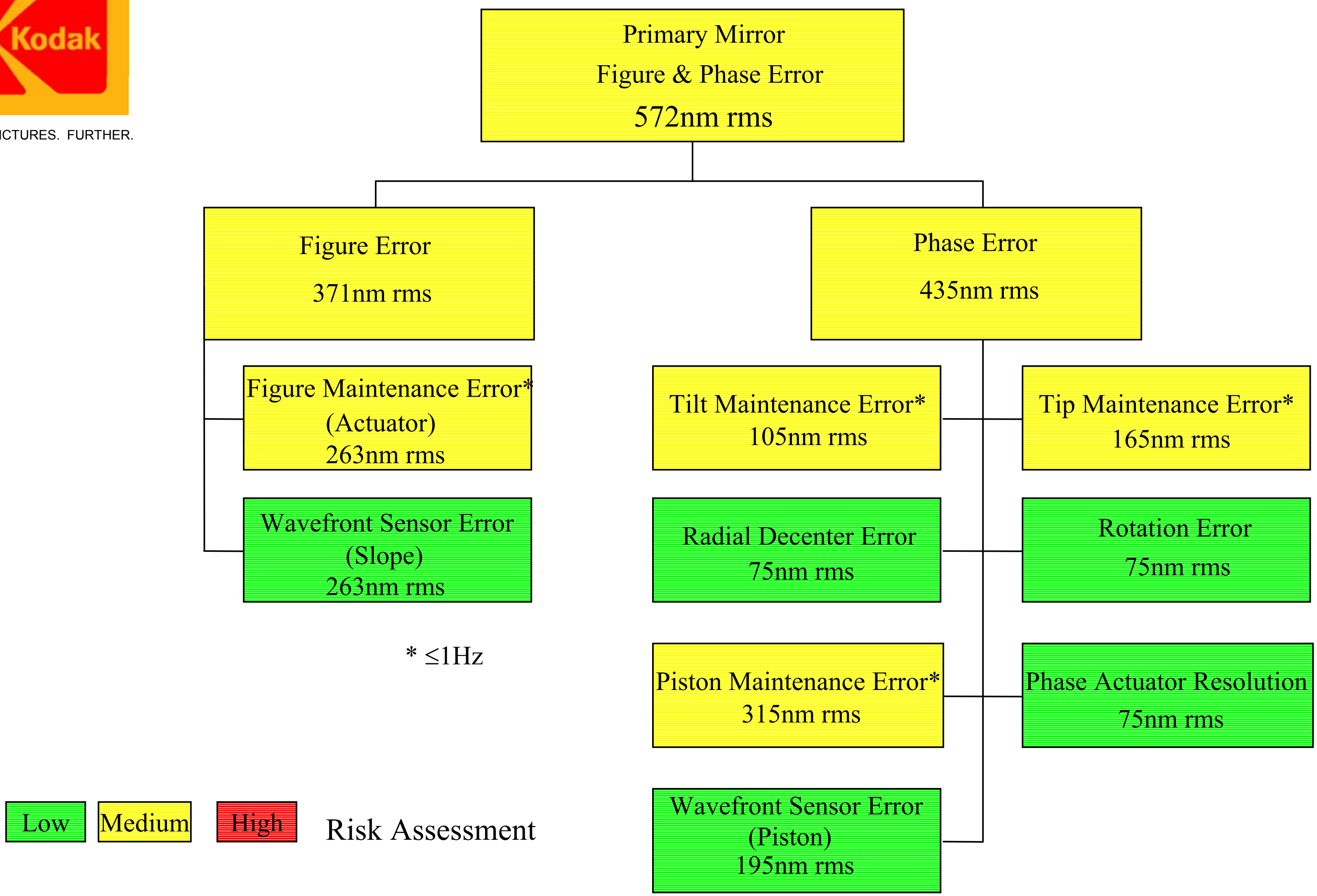

Instrumentation Errors

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- For the Thermal IR system, no active correction is assumed
  - Primary mirror is assumed to have 100 Å surface figure on the mirror segments
  - Surface figure statistics on the primary mirror conform to an isotropic PSD scaling to 1.7 times the HST reference PSD
  - Additional thermal and dynamic fluctuations have not been modeled
- For the visible imaging system, active correction to the mirror surface is applied
  - Primary mirror figure is the same as for the thermal IR case
  - Wavefront control is simulated with a square array of 256 x 256 mirror actuators
    - Actuators map across the 13.7 m primary
    - Accuracy of positioning assumed to be 1 Å rms which has been demonstrated in the laboratory

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Technical Challenges

- Large aperture and wavefront control
  - Thermal control
  - Wavefront Error maintenance
    - Sensing
    - Feedback loops
  - Dynamical stability / correction for large structure
- Packaging and deployment
  - 5 m optical components larger than largest currently available fairing
  - Having a center gap will make deployment challenging
  - Full aperture concepts make fitting in a fairing difficult due to volume and mass considerations
  - On-orbit assembly may be best option

Dynamical System Performance Has Been Modeled For the Annular Ring Case

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Baseline system performance

		Overall	Motion < 1 Hz
Mirror Piston	(nm)	1045	544
Mirror Tip	(nrad)	1102	516
Mirror Tilt	(nrad)	1173	194

Vibration-attenuated system performance

		Overall	Motion < 1 Hz
Mirror Piston	(nm)	227	94
Mirror Tip	(nrad)	203	81
Mirror Tilt	(nrad)	240	19

Detailed model results available in supplementary material

Wavefront Control For IR System Is Extension of Current Technology

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- Layered approach required to meet dynamic control requirement
  - Kodak Active Dynamic Control and Adaptive Mirror Technology
  - Technology development needed to meet 1000x correction requirement

Assumes 35m sparse aperture with 18 - 5m hex segments

Segment and Primary Mirror (PM) frequencies drive dynamic response

Segment fn driven by areal density

PM fn driven by design

Wavefront shown for a range of PM support designs (fn) and correction capabilities

Correction goal defined from error allocation as 1.03 μm for IR system

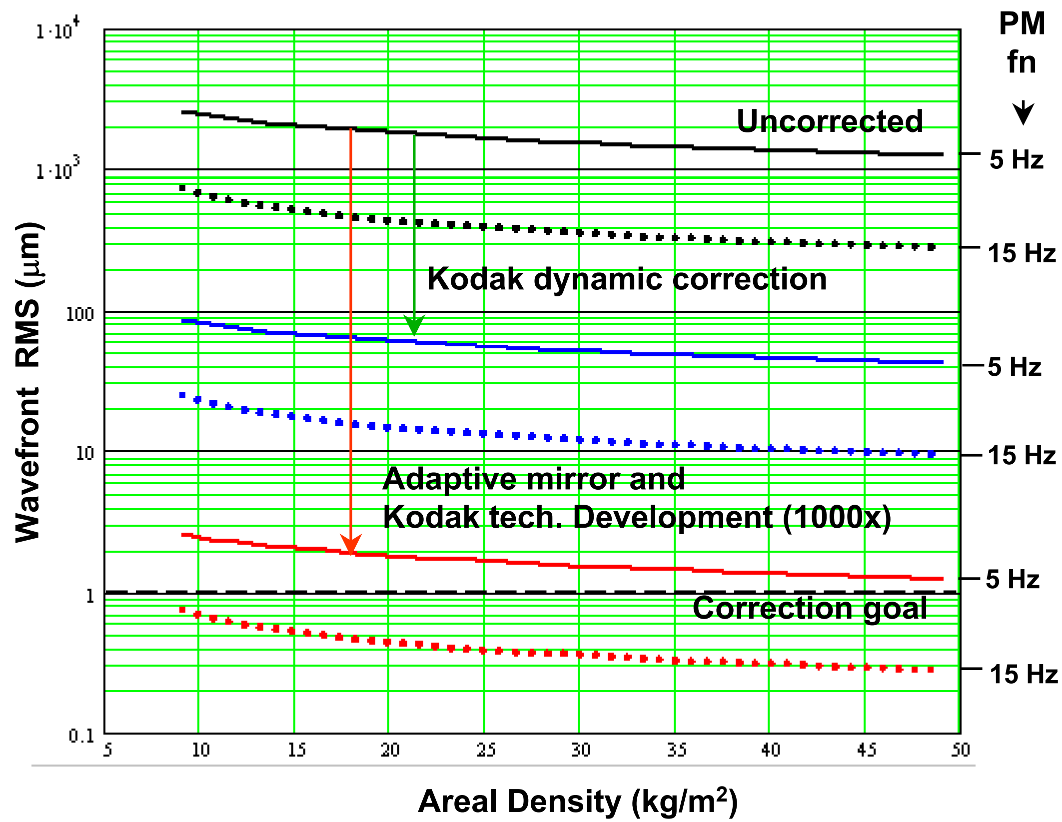

Figure Control For IR System Thermal Errors Is Within Current Technology

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Kodak figure control satisfies thermal wavefront correction requirements

- Assumes 35m sparse aperture with 18 - 5m hex segments
- Assumes max axial gradient of 0.09K in mirrors and moment due to CTE mismatch between mirror and reaction structure
- Correction goal defined from error allocation as 0.3 μm for IR system