Are They Out There?
The Search for Habitable Planets

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Terrestrial Planet Finder Coronagraph

with inputs from:

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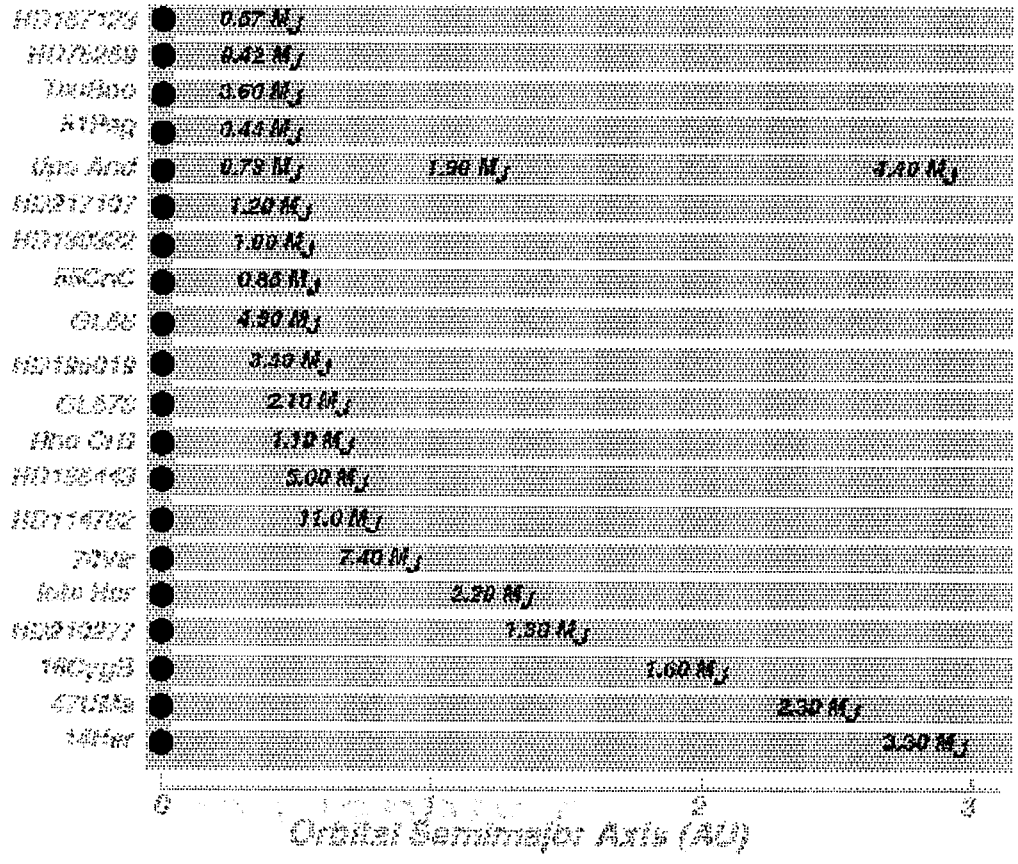
Astronomy – the first natural science

- Once Astronomy was the most important science for society
  - Stonehenge, Aztec calendar stone, etc. –
    - Astronomy dictated the patterns of primitive man's life – when to plant crops, migrate, predict major natural occurrences that impact lives
    - Astronomical skill impacted survival of a people
  - Nicolas Copernicus – 1473-1543
    - Earth rotates and revolves around sun (based on visual observations) (died before ideas became popularly known) – huge impact on man's views of himself
  - Galileo Galilei – 1564-1642
    - Invented telescope
    - Observed moons rotating around Jupiter
    - Supported Copernican system (forced to renounce his theories)
  - Johannes Kepler – 1571-1630
    - Developed laws of planetary motion
    - Calculated most exact astronomical tables - accuracy did much to establish truth of heliocentric solar system
- Clocks, calendars, other sciences dominate our lives today
- So why are we suddenly interested in finding earth-like planets?
  - Can't justify costs based on science fiction

Because we know there are planets out there!

- In the last few years, we have discovered over 100 Jupiter-sized planets in amazingly short orbits around other stars!
- Method:
  - Very good ground-based telescopes
  - Sense and correct the atmospheric perturbations
    - Laser beams that reflect back to sensor
    - Deformable mirror corrects wave front
  - Look for star movement using Doppler effect

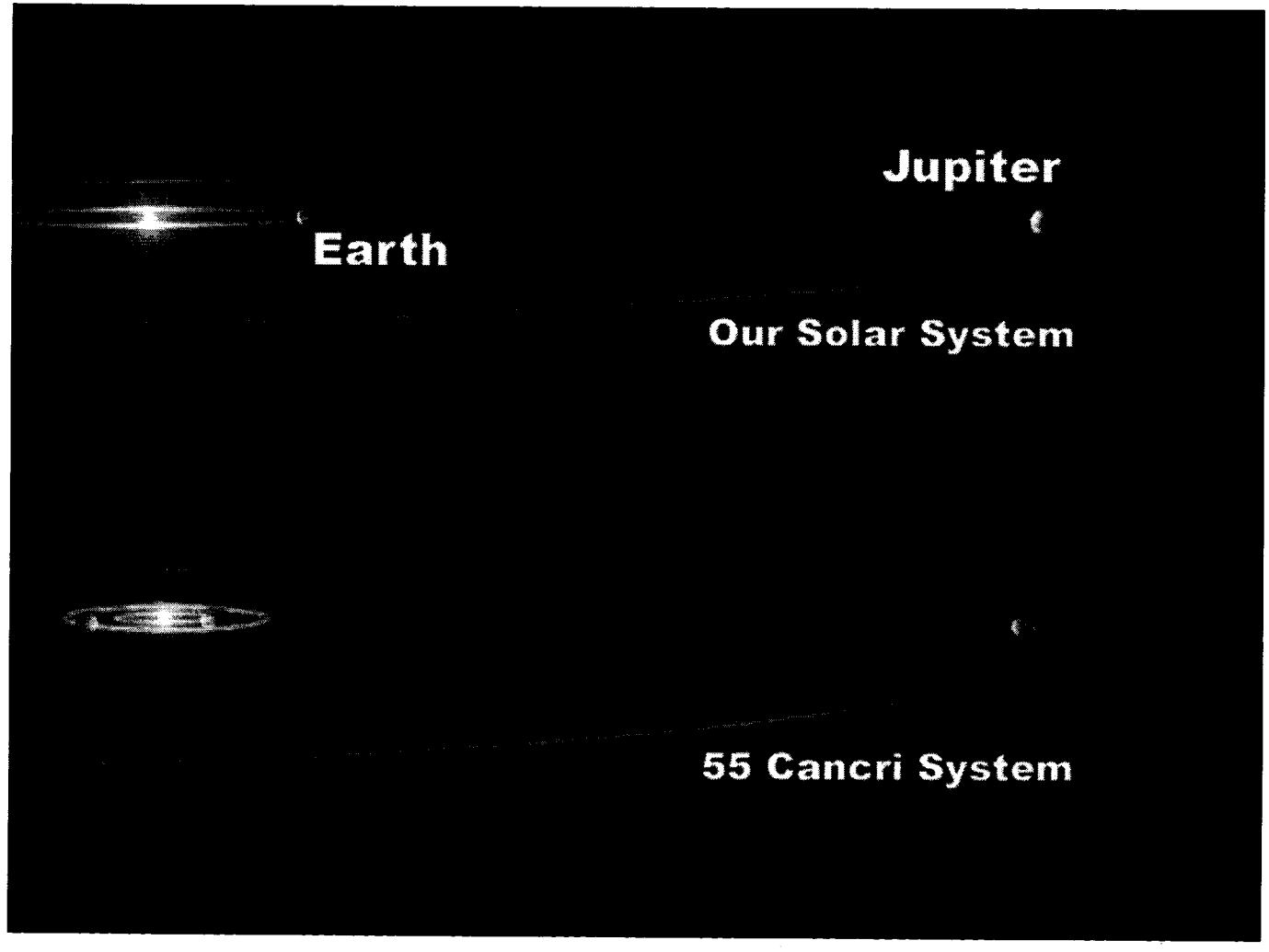


- Star movement enables calculation of:
  - Orbit parameters - radius and period
  - Mass of detected planets
- This method is optimized for Large Gas Giants with small orbits

Gas Giant Planets

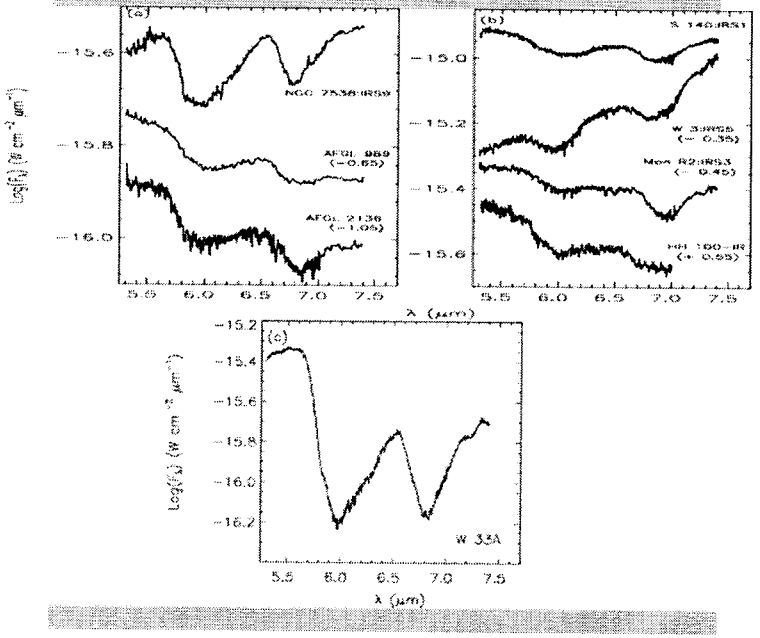
- ~10% of stars appear to have planets
- Most planet orbits << 2-3 AU
- Half may be multiple systems?

- Planets on longer periods starting to be identified
  - 55 Cancri is a solar system analog – Jupiter sized Gas Giant planet at Jupiter orbit 5.2 AU
- Discovering planets that can carry life now seems important!



Four Fundamental Facts About the Search for Planets and Life: First Two

1. Planets are a common outcome of star formation
   - Modern theory of *star* formation makes *planet* formation likely
2. The necessary ingredients of life are widespread
   - Observation reveals uniformity of physical and chemical laws
   - Origin of the elements and their dispersal is well understood
   - Carbon bond is unique and ubiquitous! Forget Silicon life.

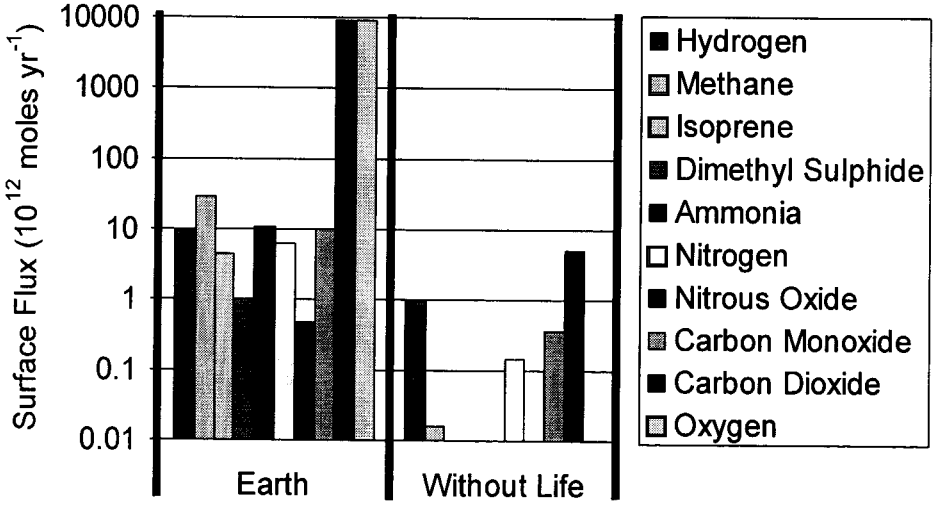


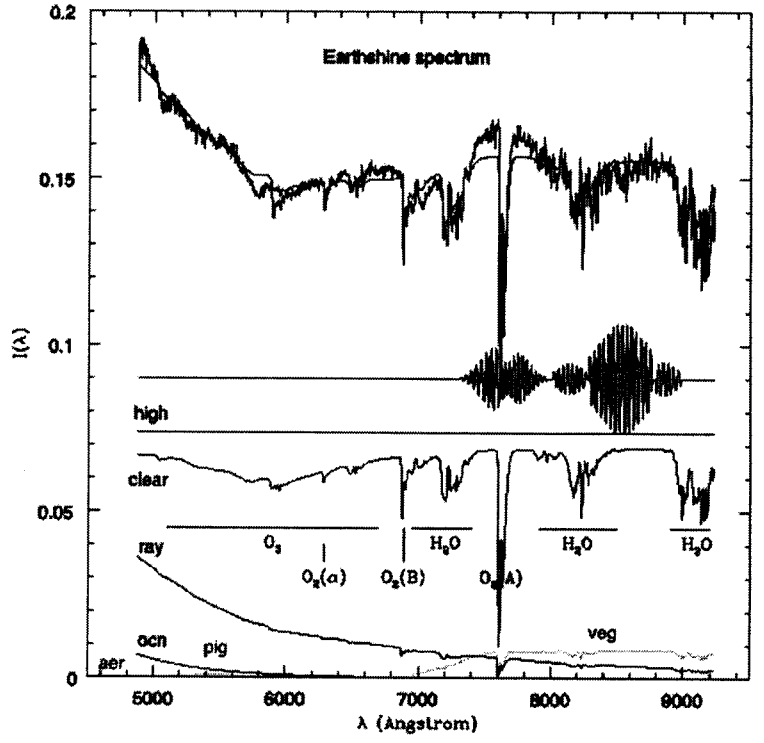
Spectral measurements of stars and gas clouds reveal gas phase, ices, mineralogical signatures of many species, incl:
H_2O, CO_2, CH_3OH, CO, CH_4, formic acid (HCOOH) and formaldehyde (H_2CO), etc.

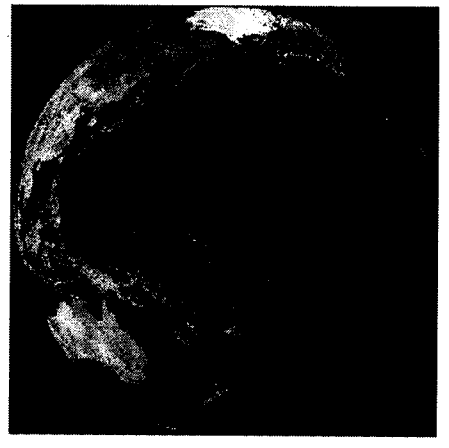
Third Fundamental Fact To Remember About the Search for Planets and Life

3. Life affects a planetary environment in a detectable way
   - Our own atmosphere reflects the presence of life

Earth's Gases With And Without Life

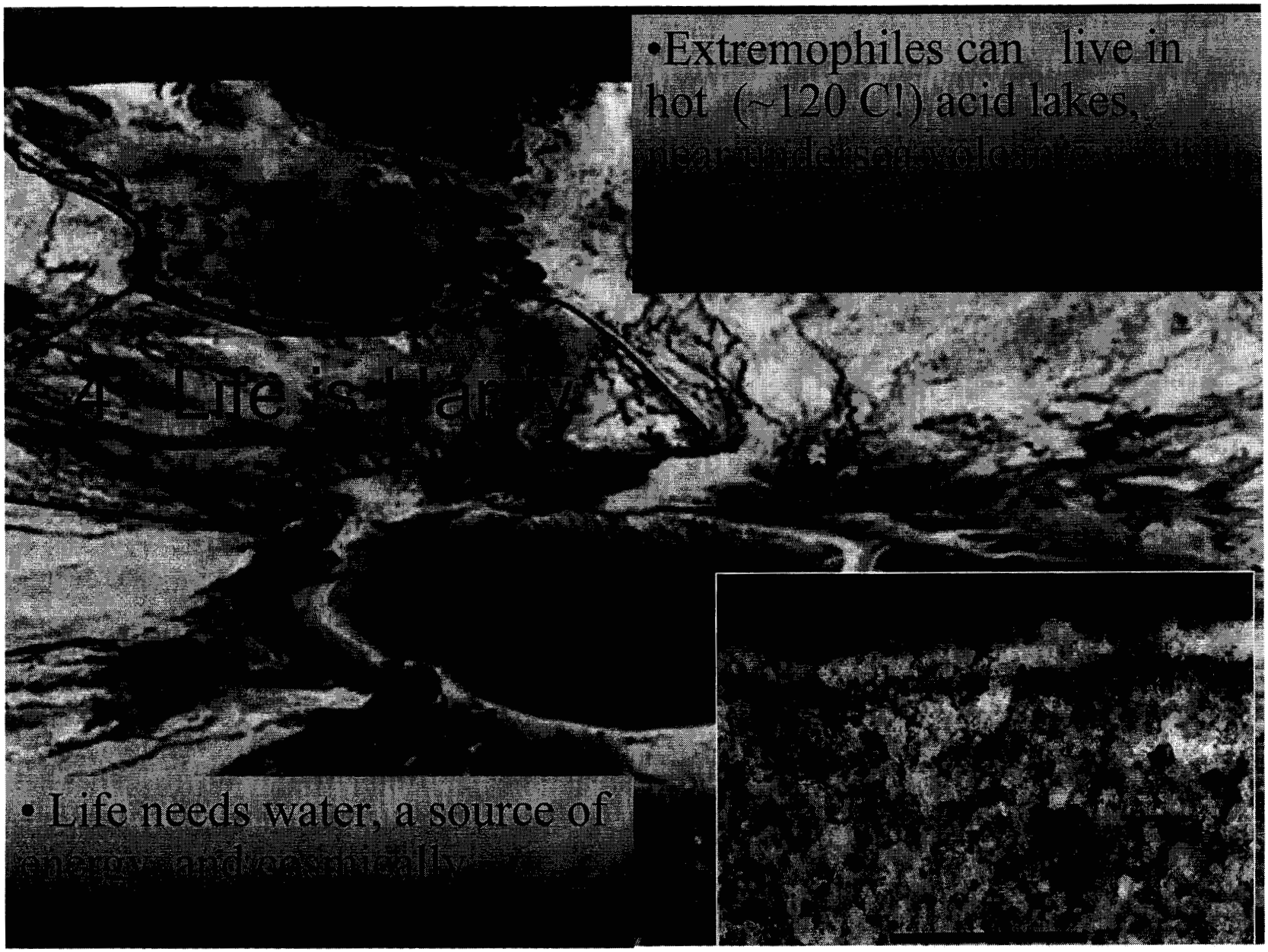






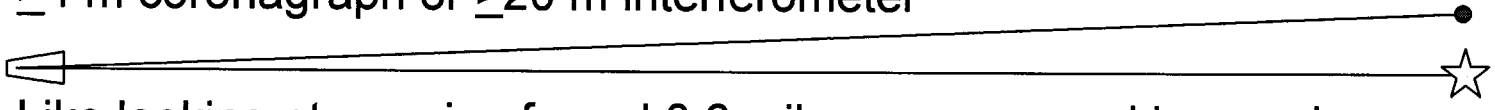
- *Oxygen* or *ozone* is most reliable biomarker
- *Water* is considered essential to life.
- *Carbon dioxide* - atmosphere and oxidation state typical of terrestrial planet.
- Abundant *Methane* can have a biological source
  - Non-biological sources might be confusing

Fourth and Last Fundamental Fact To Remember About the Search for Planets and Life



Four Hard Things About the Physics of Planet Finding

1. Sensitivity (relatively easy) - how much light needs to be collected
   - Planet detection in hours → spectroscopy in days
2. Angular resolution (hard)
   - 100 mas is enough to see planets in habital zone of ~25 stars, but requires $\geq$4 m coronagraph or $\geq$20 m interferometer

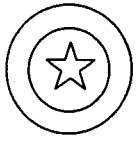


   - Like looking at a grain of sand 0.6 miles away – need large mirror
3. Starlight suppression (hard to very hard)
   - 10^{-6} in the mid-IR
   - 10^{-10} in the visible
   - 1 grain of sand is 10^{-10} the height of 100 local San Gabriel Mountains stacked on top of each other
4. Solar neighborhood is sparsely populated
   - Fraction of stars with Earths (in habitable zone) unknown
   - Unknown how far away we need to look to ensure success
   - Surveying substantial number of stars means looking to ~15-20 pc

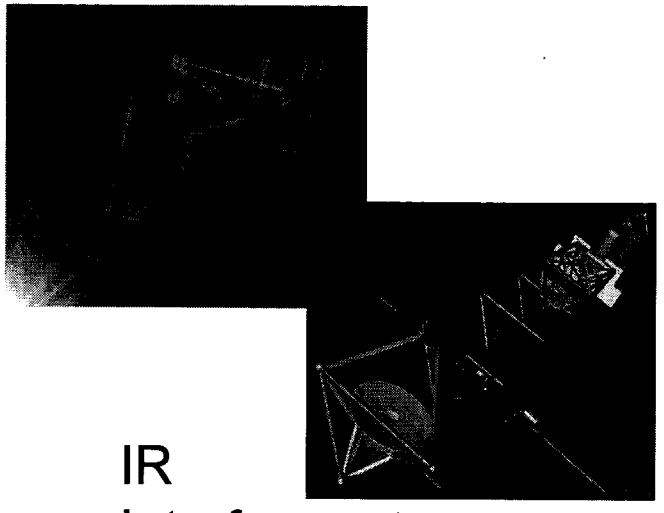
NASA-sponsored
Terrestrial Planet Finder (TPF) Program at JPL

MISSION – TWO PARTS

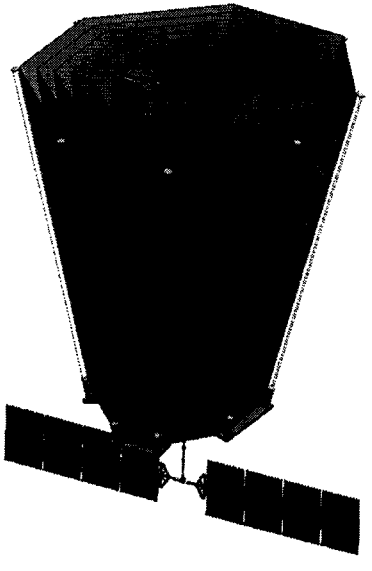
- Search 30 to 150 nearby stars and detect planets in the habitable zone
  - Habitable zone (where liquid water can exist)
  - Defined for each star by its brightness



- Spectrally characterize the atmosphere to determine if any are terrestrial planets



IR Interferometers

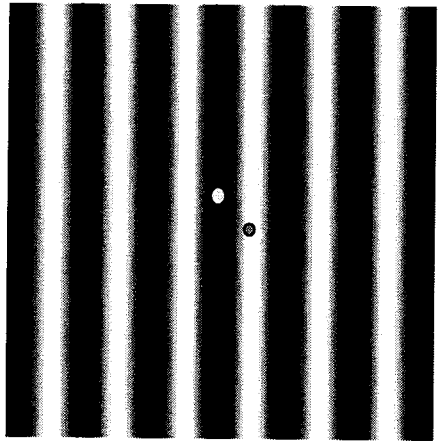


Visible Coronagraphs
(my system)

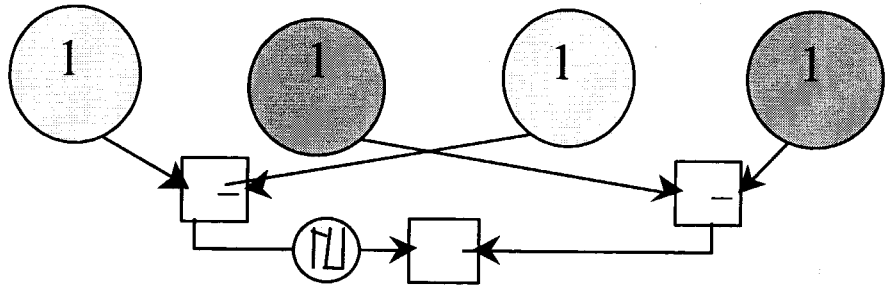
PROGRAM STRUCTURE

- Competition: two teams developing two types of instruments
- Down select – choose between the two in 2006
- Success – develop at least 1 architecture that will succeed and be technically ready by 2006
- Launch Date - 2015

Instrument Approaches

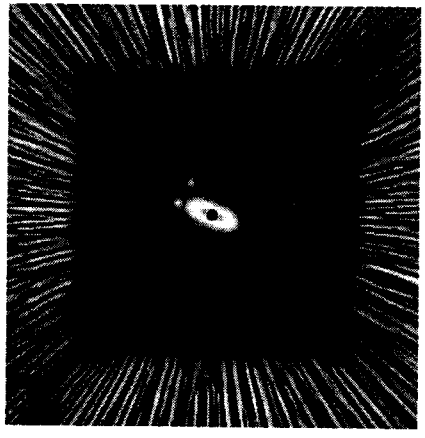


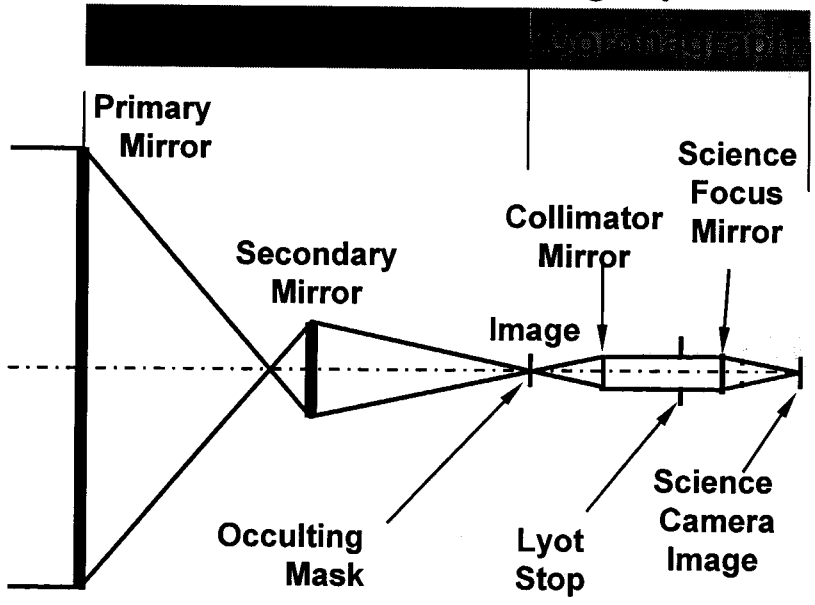
Interferometer

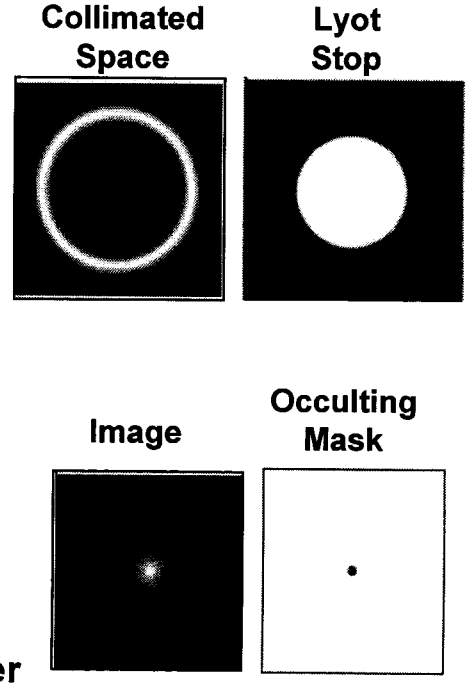


- Shift phase of one input beam by π rad
- Rotate Array
- Chop the pairs

Coronagraph





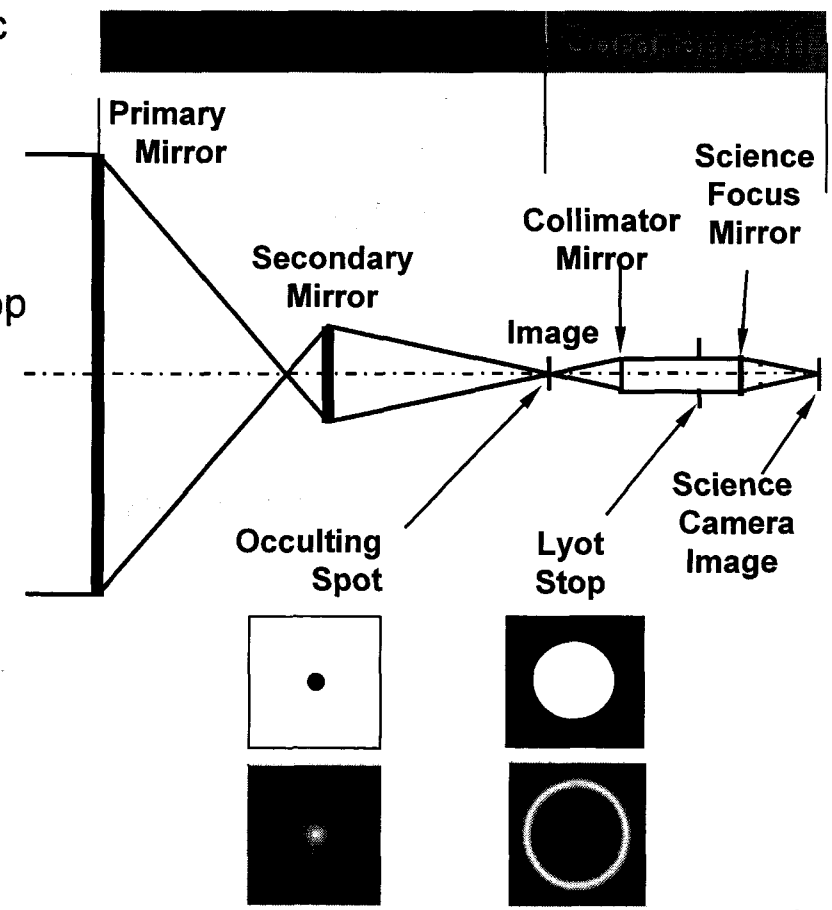


- Coronagraph blocks star light (10^{-10})
- Removes most diffracted light and scatter

Coronagraph Background

- History
  - ~1850: Astronomers started trying to create an instrument that would block sunlight to study the sun's corona
  - 1932: Astronomer Bernard Lyot built 1st working coronagraph

- Lyot's contribution:
  - Stray sunlight, diffraction scatter, & atmospheric effects overwhelming the corona
    - » On the top of a mountain, very smooth optics
  - Diffraction from the telescope aperture and occulting mask can be controlled by collimating the light, adding occulting mask & diffraction stop
    - » equivalent to a mathematical Fourier transform
    - » Kicks diffracted light out to the edges of the field where it can be blocked with a Lyot stop\



- TPF Coronagraph Challenge:
  - Same problem with stray light, diffraction scatter and environmental effects – star light easily overwhelms an earth-like planet – 10^{10} contrast
  - Use WFS&C, advanced technology to reach solution

TPF CORONAGRAPH SYSTEM STUDIES

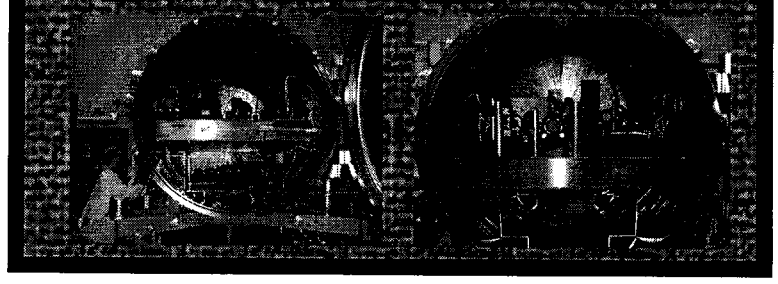
Exploring the physics of light

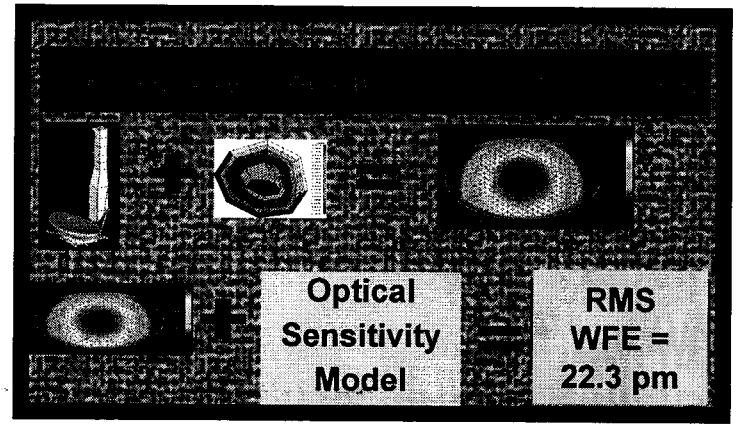
System Studies

Technology Studies

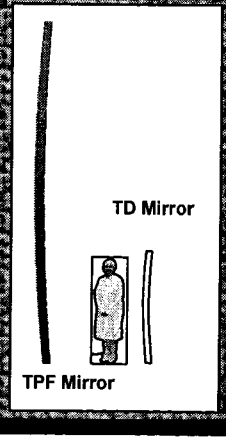
High Contrast Imaging Testbed

- Guest Testing of Coronagraph Concepts
- Wavefront Sensing and Control
- Stable Vacuum Environment
- Flexible layout to try alternate concepts

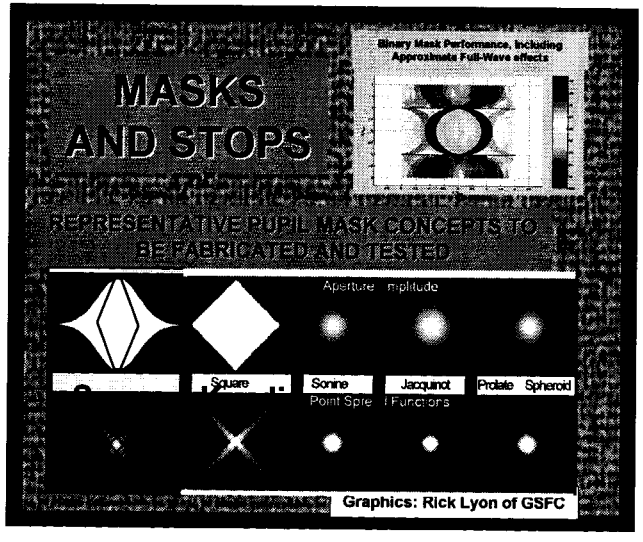


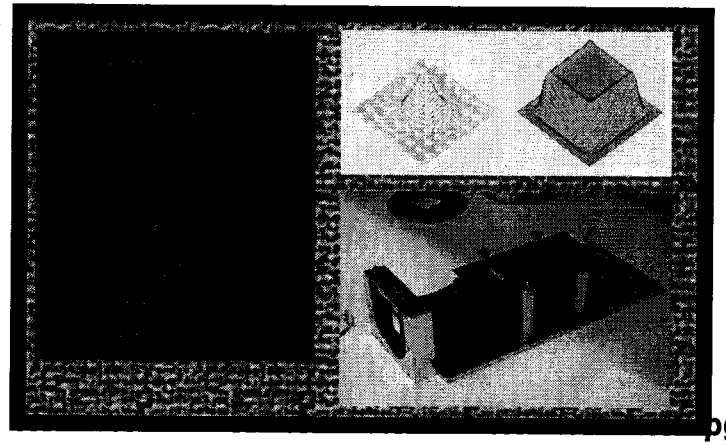


TPF PRIMARY MIRROR



MASKS AND STOPS



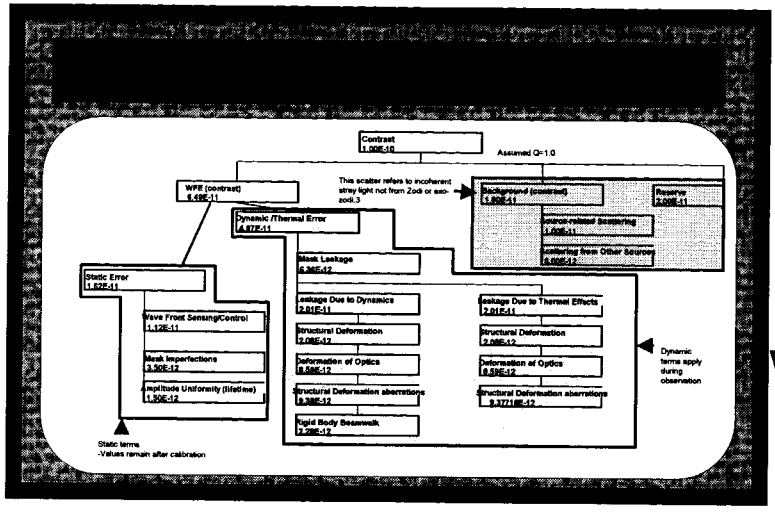


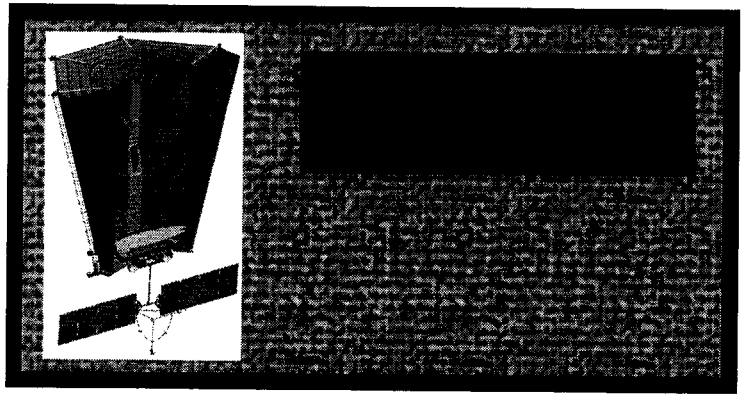
TPF CORONAGRAPH SYSTEM STUDIES

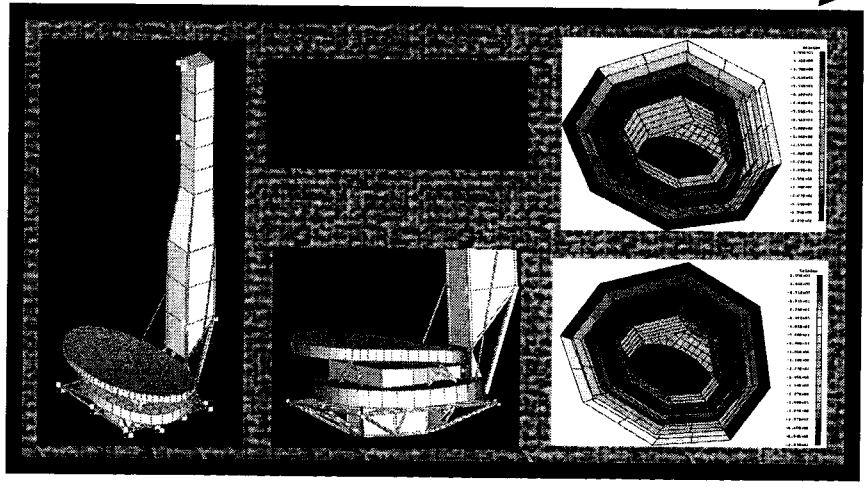
Engineering a solution

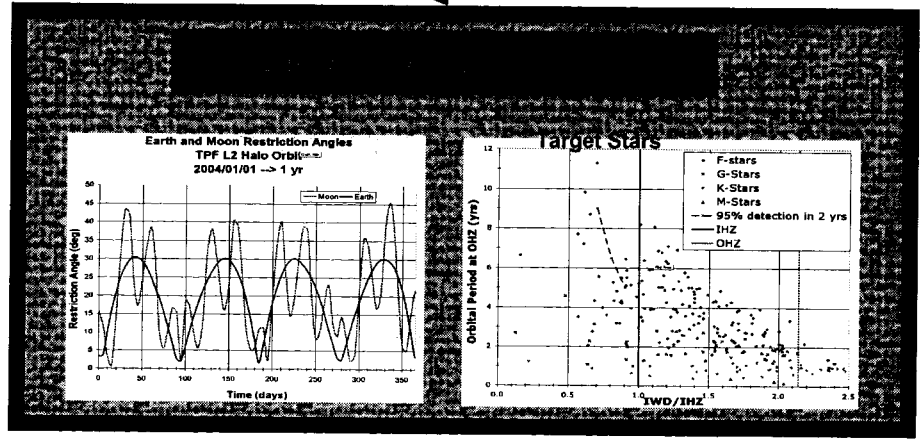
System Studies

Technology Studies



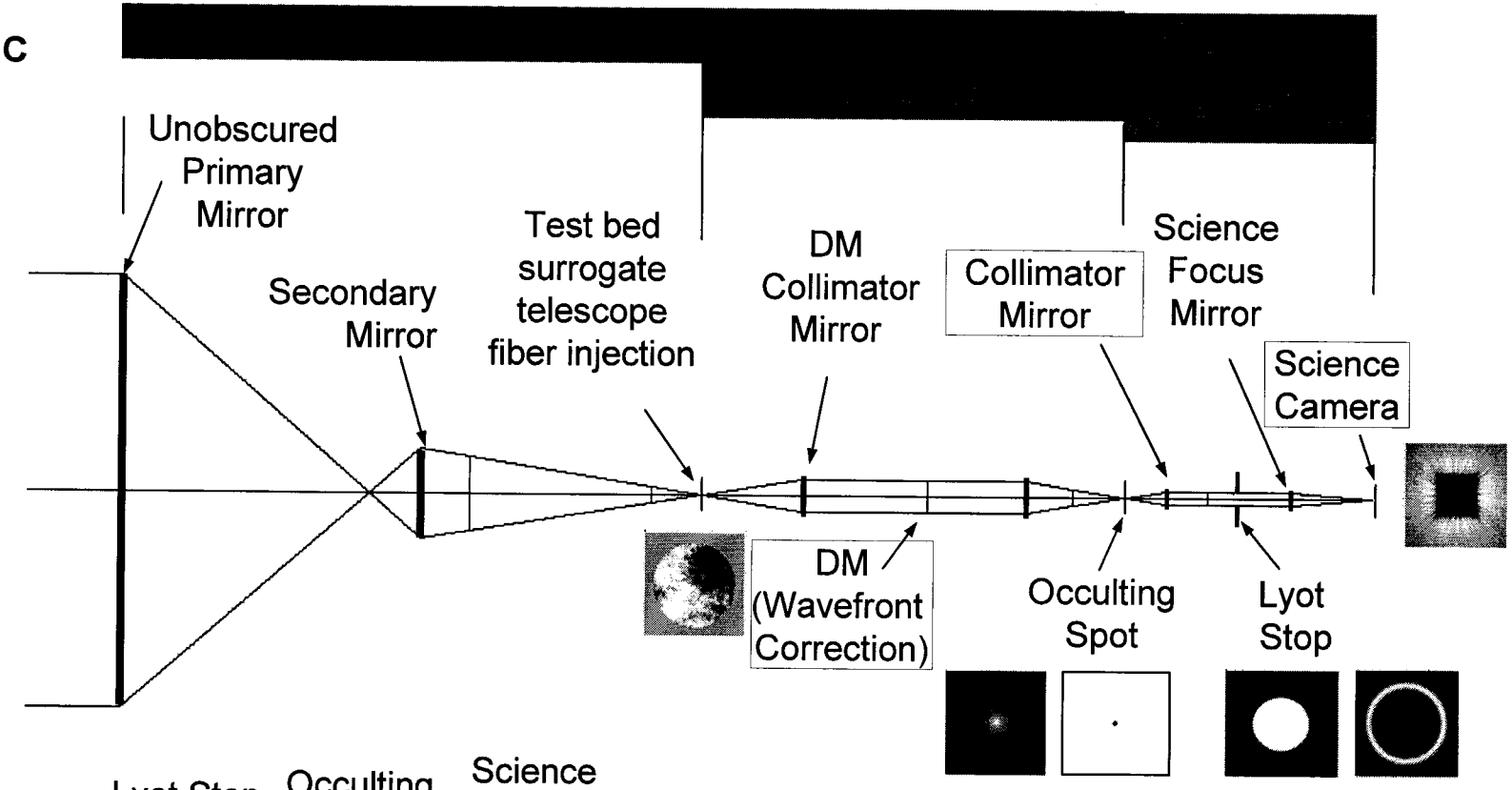




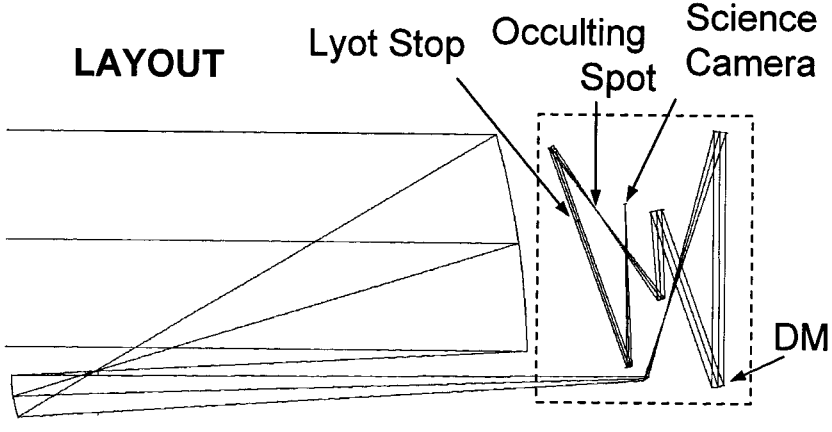


TPF Coronagraph Description - Optics

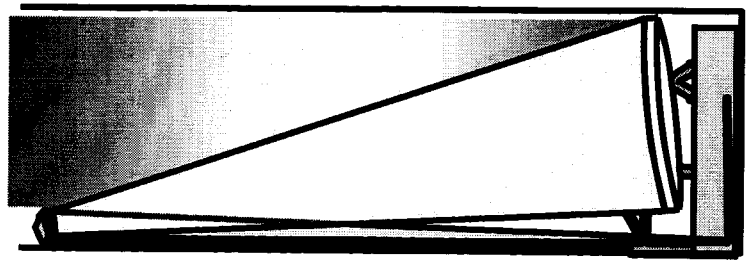
SCHEMATIC



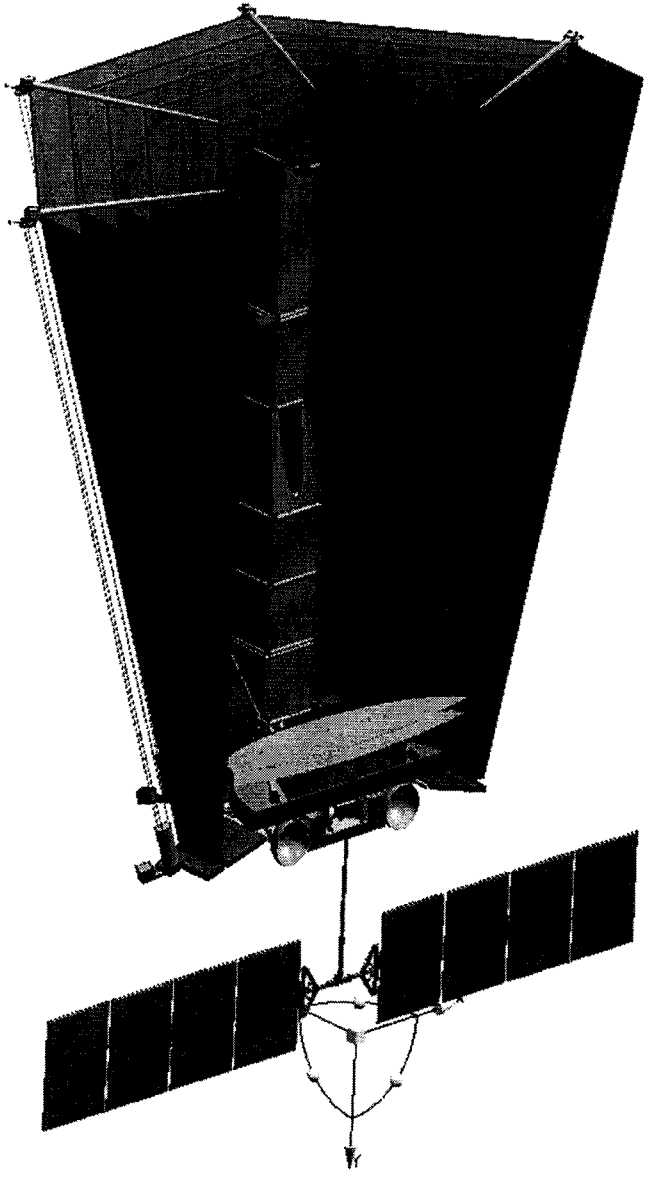
LAYOUT

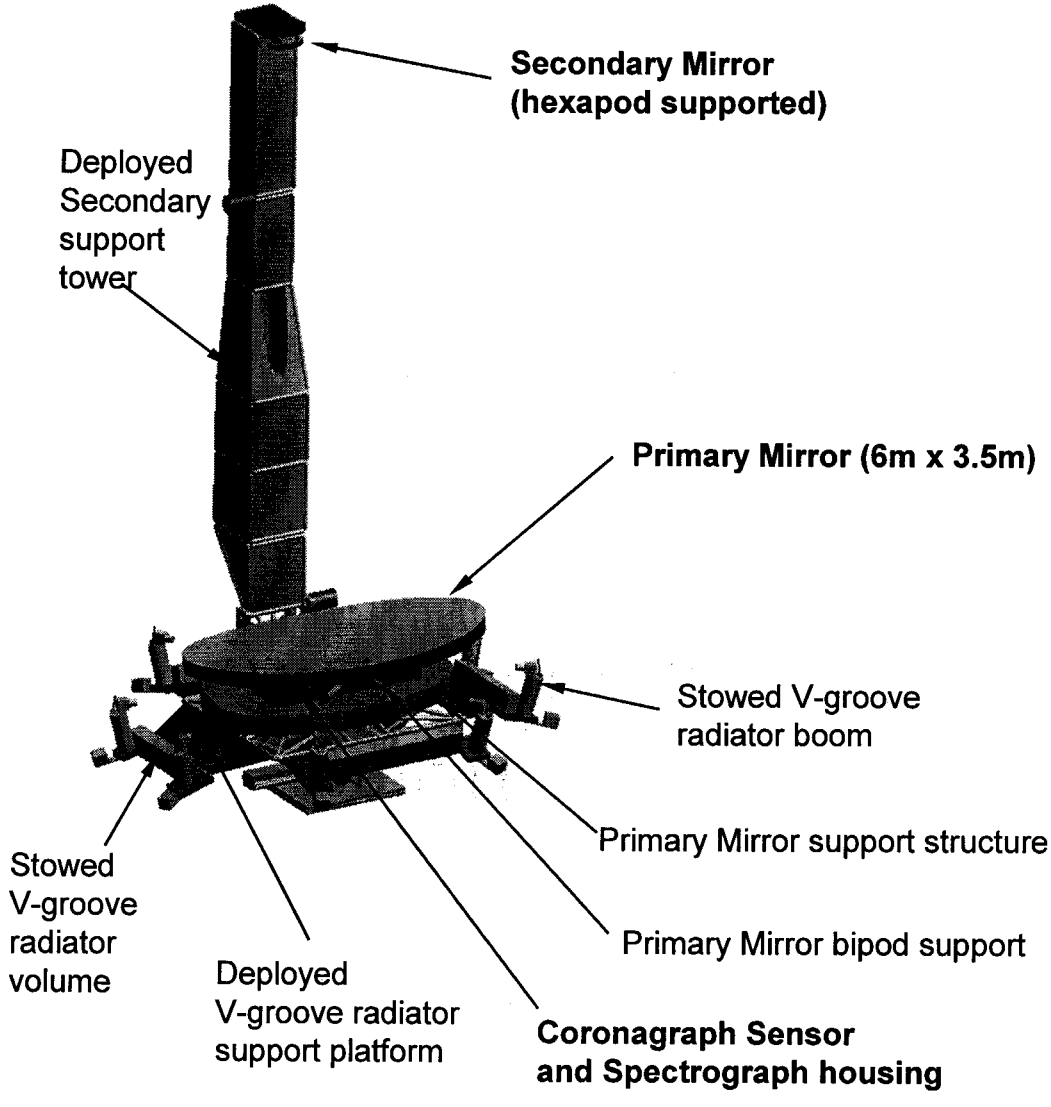


TELESCOPE



TPF Coronagraph Minimum Mission Conceptual Design





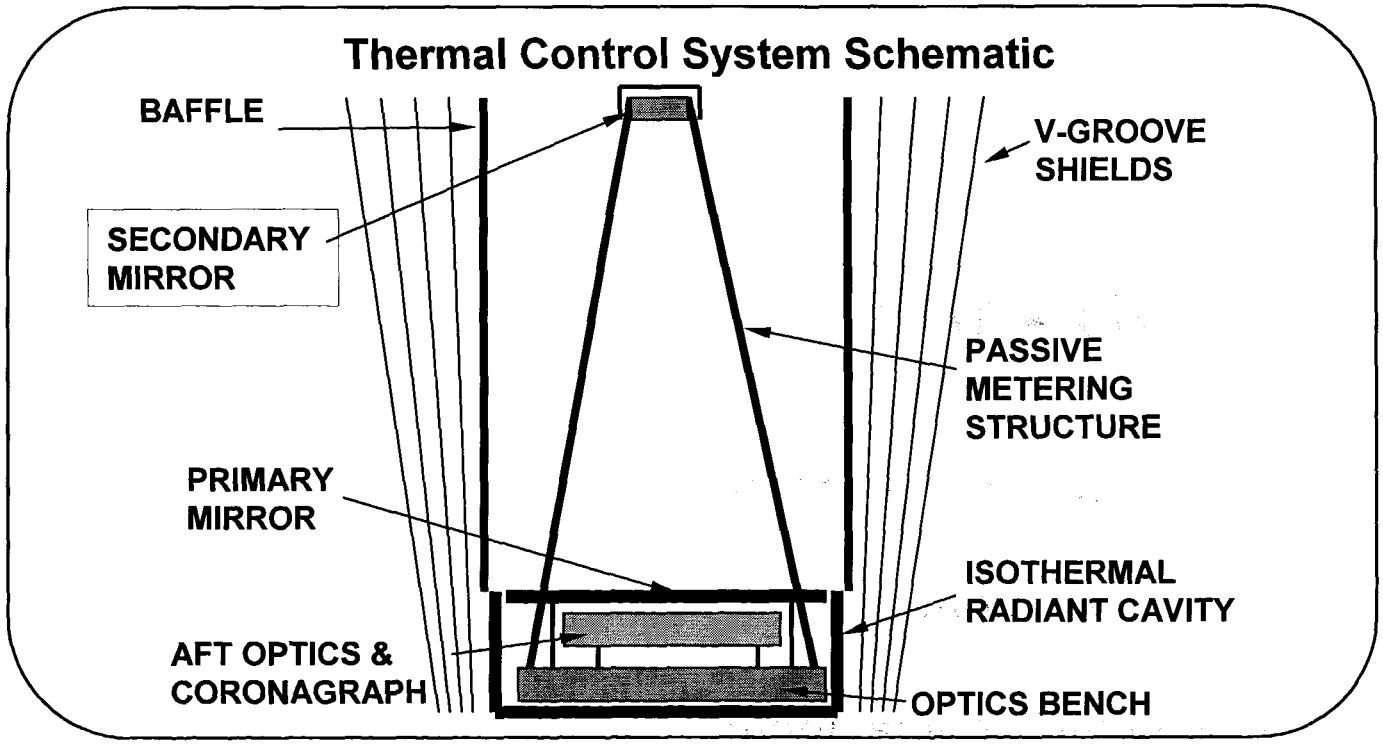
Thermal Design Concept - Cocoon

V-Groove Radiator Cocoon:

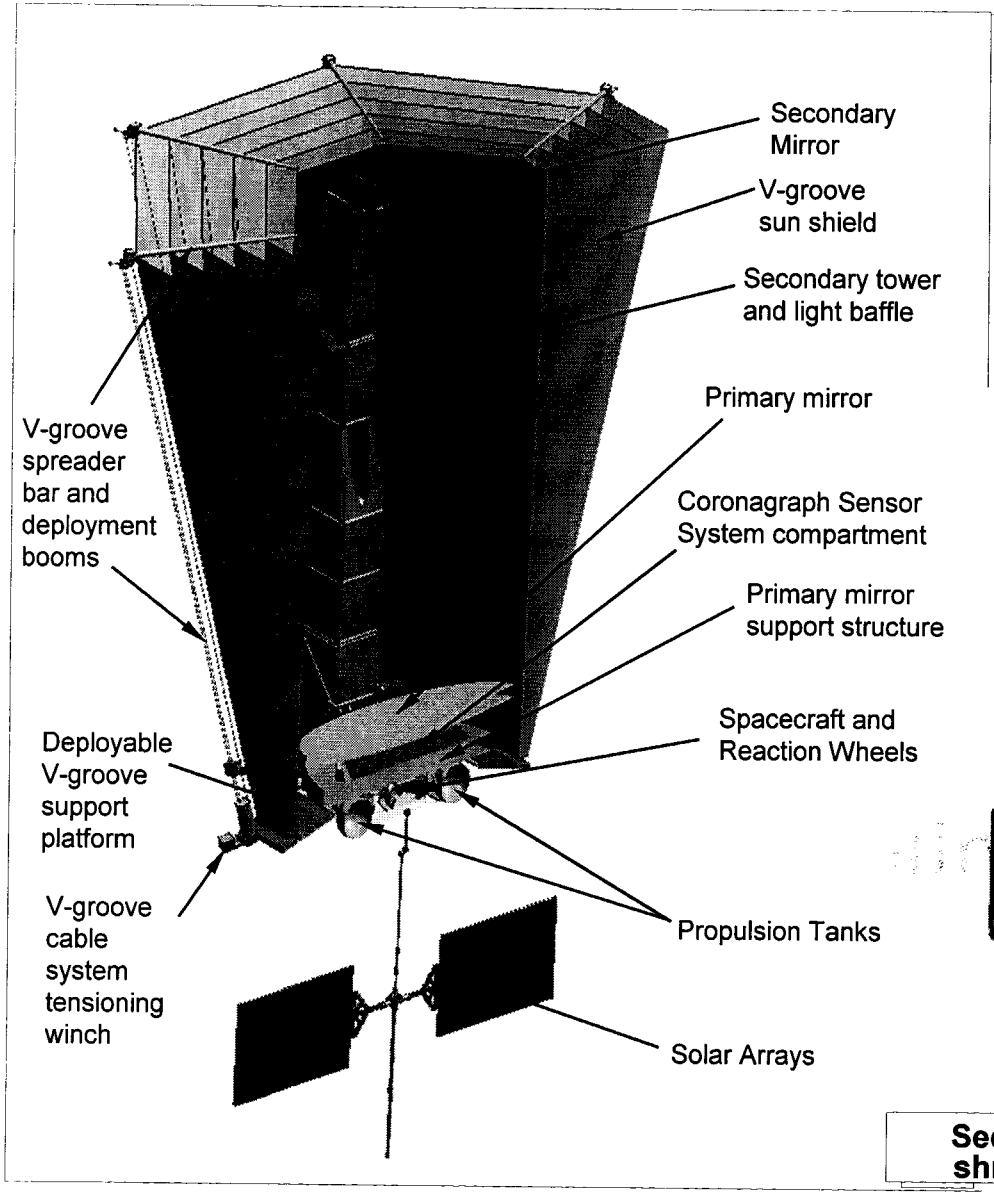
- Sunshine heats one side of radiator – outer v-groove shield heats up and emits IR light
- Shiny surfaces reflect IR light outward into space

Cocoon Advantages:

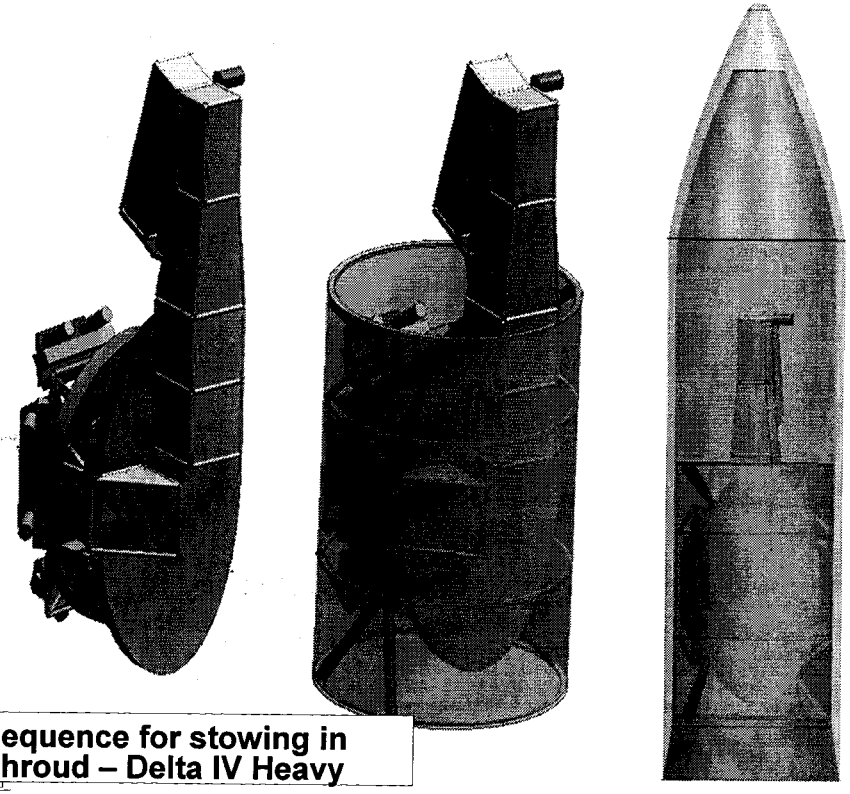
- Fully blocks sun light, earth or moon shine from telescope baffle at near 90° angle
- Isolates baffle by keeping heat from sun in outer layers
- Deploys in same direction as telescope baffle



Coronagraph Baseline Design Concept



- **TPF Coronagraph, Minimum Mission Design**
  - Primary Mirror: 6 x 3.5 meters
  - Delta IV-H Launch vehicle w/ currently available fairing
  - CG centered during launch



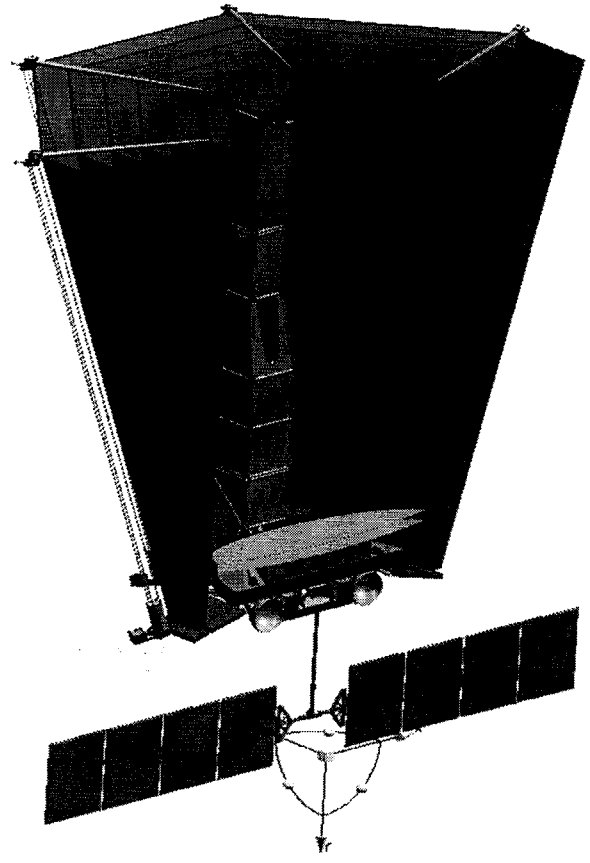
Sequence for stowing in shroud – Delta IV Heavy

Possible Detection Observing Scenario

- Star Measurement:
  1. Move to point at star target
  2. Stabilize
  3. Measure secondary mirror position and adjust
  4. Measure and correct wave front errors using deformable mirror
  5. Observe
  6. Rotate TBD° (~ 45°) about boresight
  7. Repeat steps 2 through 6, 3 times
  8. Move to point at new star target

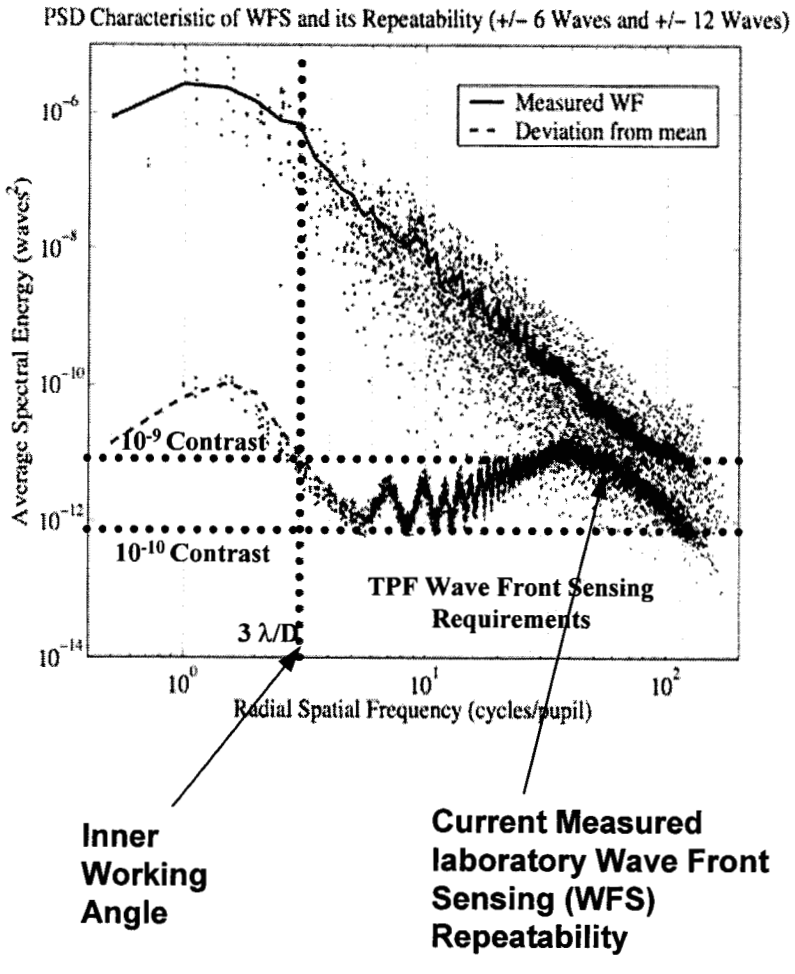
Periodic calibration (steps 3–4)

- Preliminary prediction: eight hours per star measurement for detection
- If planet is detected, spectroscopy will take several days

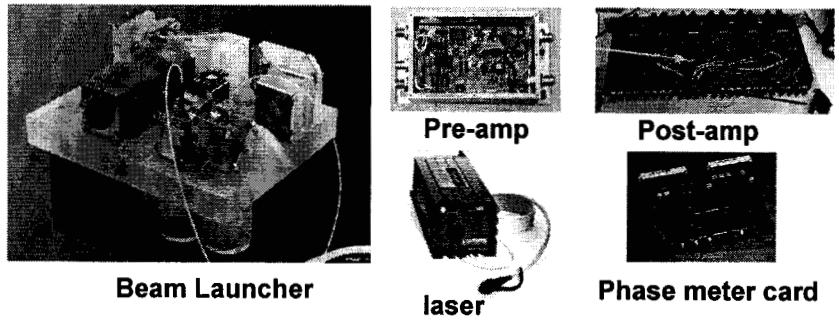


Calibration – Developing Technologies

Status: Wave Front Sensing - in work



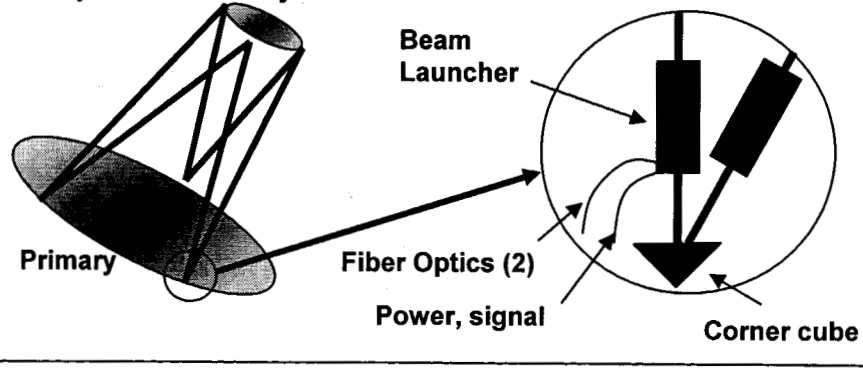
Laser Metrology System



Optical metrology based on Space Interferometry Mission Technology provides sub nanometer measurements for 6-DOF determination of the relative primary-secondary positions.

Allowed tolerances are ~ 1 nm despace, 8 nm lateral motion, 5 nanoradian tip-tilt.

SIM Metrology is capable of meeting TPF-C requirements but some work may be necessary to improve laser frequency stability.



Deployment and Observation Sequence

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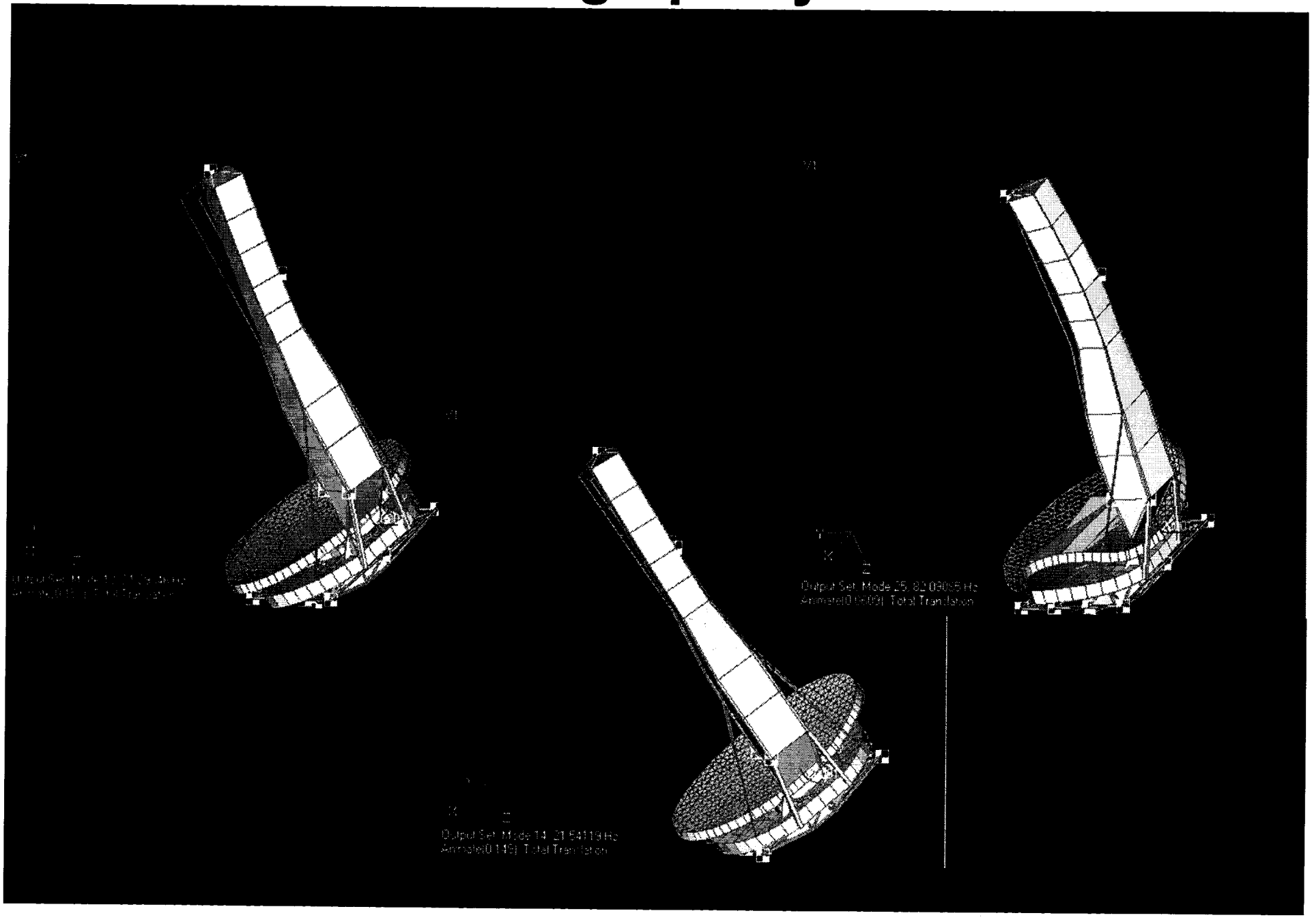
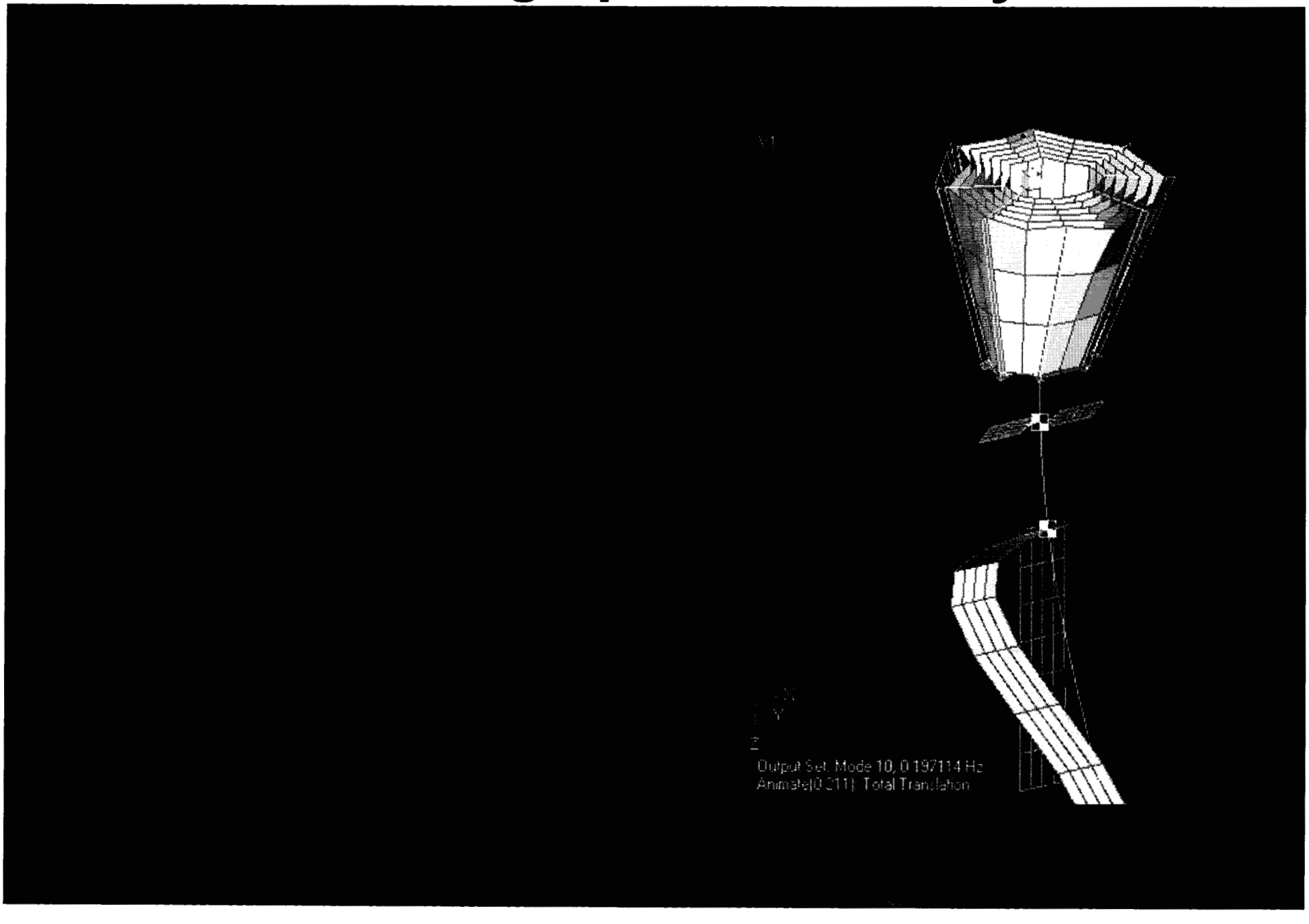
TPF Coronagraph System



TPF Coronagraph Observatory

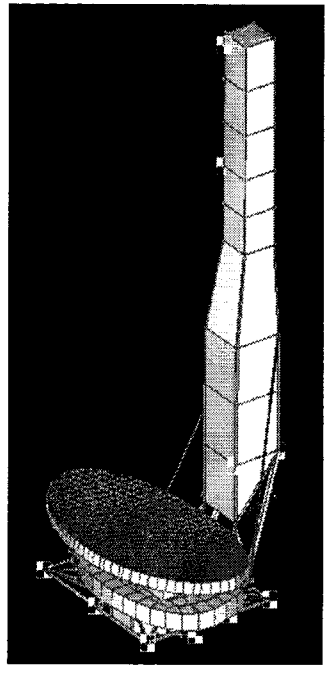


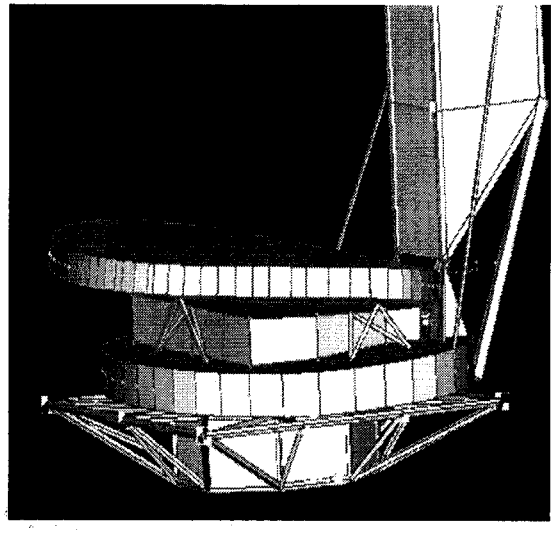
TPF Coronagraph Baseline
Observational Stability – modeling results

Two Types of SC/Telescope Isolation considered:

1Hz Passive & Active*

Results and models include solar sail and its reactions





Primary Mirror Distortion Response (picometers)

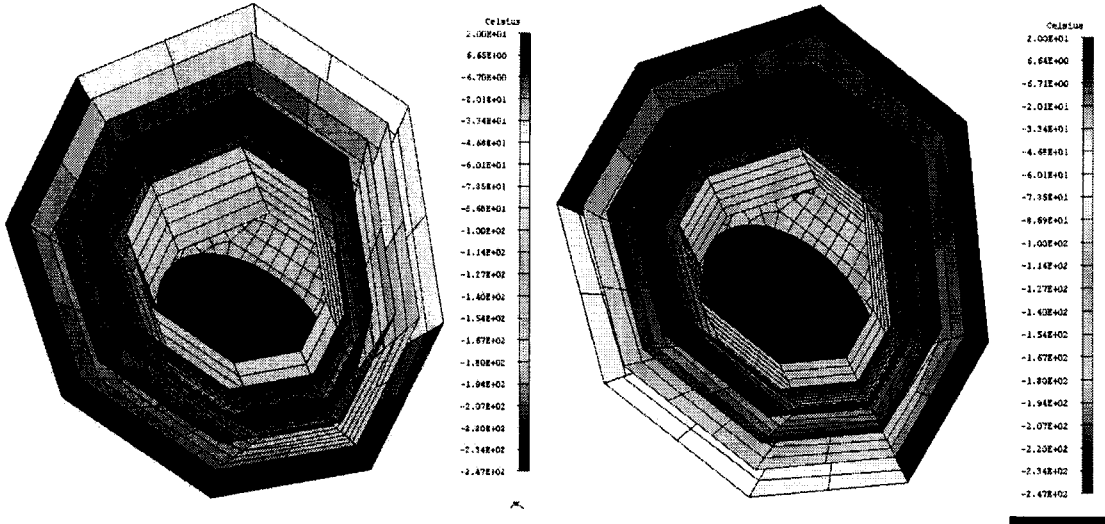
Zernike	Descr	RMS WFE1 Passive Damp	RMS WFE2 Active Damp	Req	WFE2/ Req
4	Power	194	2.43	5	0.5
5	1st Ast 45	47	0.59	10	0.1
6	1st Ast X	313	3.91	5	0.8
7	1st Coma Y	11	0.14	10	0.0
8	1st Coma X	6	0.08	1	0.1
9	1st Tref Y	31	0.39	5	0.1
10	1st Tref X	10	0.13	3	0.0
11	1st Sper	18	0.23	1	0.2
12	2nd Ast X	25	0.31	1	0.3
13	2nd Ast 45	5	0.06	1	0.1
14	1st Tetr X	21	0.26	1	0.3
15	1st Tetr Y	5	0.06	3	0.0

Units in picometers

Diameter of 1 grain of sand ~ 500,000,000 picometers

Reaction Wheel Jitter Analysis Results
– Using active isolation, meets allocated error budget

TPF Coronagraph Baseline
Observational Stability – modeling results



Thermally-induced FEM Displacements

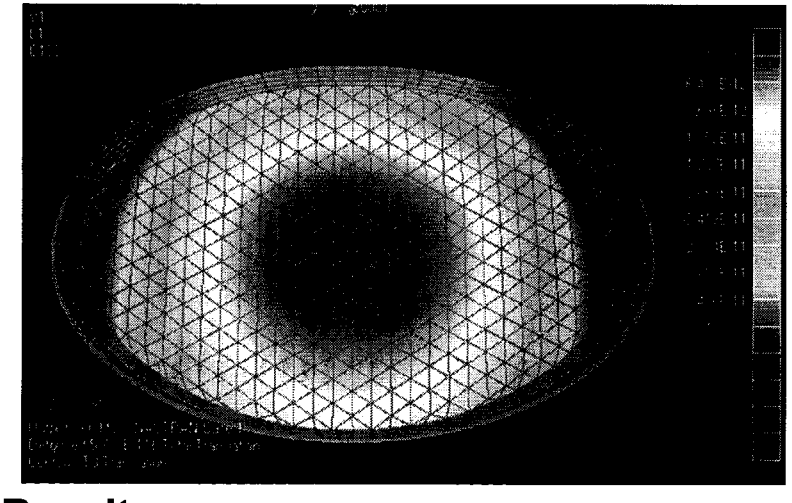
Steady-State – 6 day soak each case

Delta Temperature (Beta=90, 180 Roll)

Zernike	Descr	WFE	Req	WFE/Req
4	Power	22.80	5	4.6
5	1st Ast 45	0.35	10	0.0
6	1st Ast X	13.00	5	2.6
7	1st Coma Y	2.54	10	0.3
8	1st Coma X	0.52	1	0.5
9	1st Tref Y	6.20	5	1.2
10	1st Tref X	0.28	3	0.1
11	1st Sper	0.17	1	0.2
12	2nd Ast X	0.55	1	0.6
13	2nd Ast 45	0.04	1	0.0
14	1st Tetr X	0.41	1	0.4
15	1st Tetr Y	0.17	3	0.1

Units in picometers

Diameter of 1 grain of sand ~ 500,000,000 picometers



First Results:

-In ball park - many options for improvement

-Worst case factor: 5

Conclusion

- Technology seems feasible – just barely
  - Many new enabling capabilities are on the cusp of development
  - Physics experiments
    - Wave Front Sensing and Control
    - Deformable mirrors
    - Light Suppression - developing the contrast
      - diffraction and polarization effects
      - masks & stops
  - Engineering challenges
    - Laser Metrology
    - Active dynamic isolation
    - Deployment of thermal shade
    - Other stability issues

- I am:
  - Honored to have the opportunity to work on the Terrestrial Planet Finder program
  - Grateful for the opportunity to be involved in new technologies at such an exciting time
  - Happy to have this chance to share what we are doing with all of you