Ball Aerospace & Technologies Corp.

External Occulter Planet Finder Mission at L2

A Potential "Customer" for Robotic Servicing

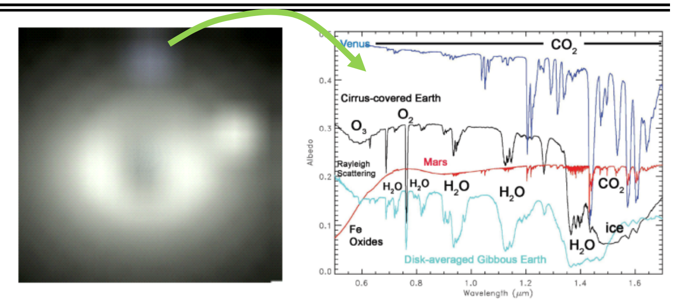
Charley Noecker (BATC)

in collaboration with

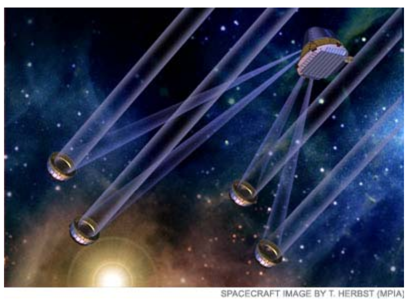
University of Colorado
Goddard Space Flight Center
Northrop Grumman Aerospace Systems
Princeton University

Terrestrial Planet Finder with Occulters

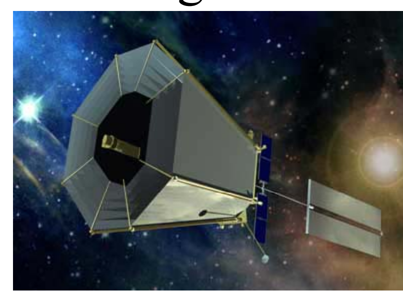
- The search for planets like Earth, hosting biology like our own
- Three families of instrument concepts



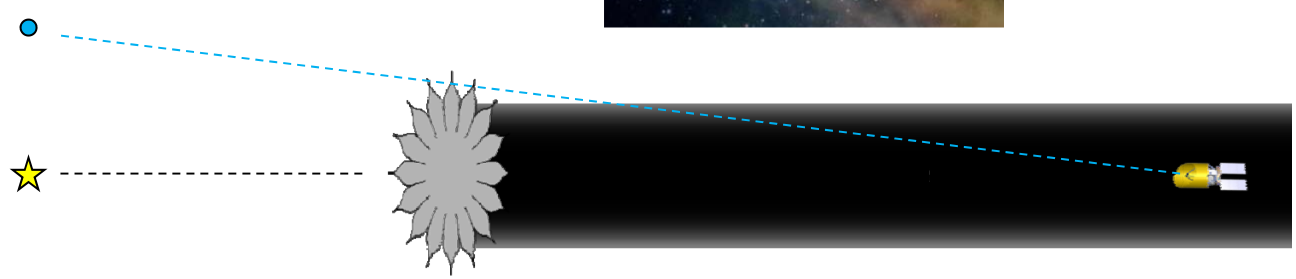
  - Mid-infrared nulling interferometer



  - Visible light coronagraph



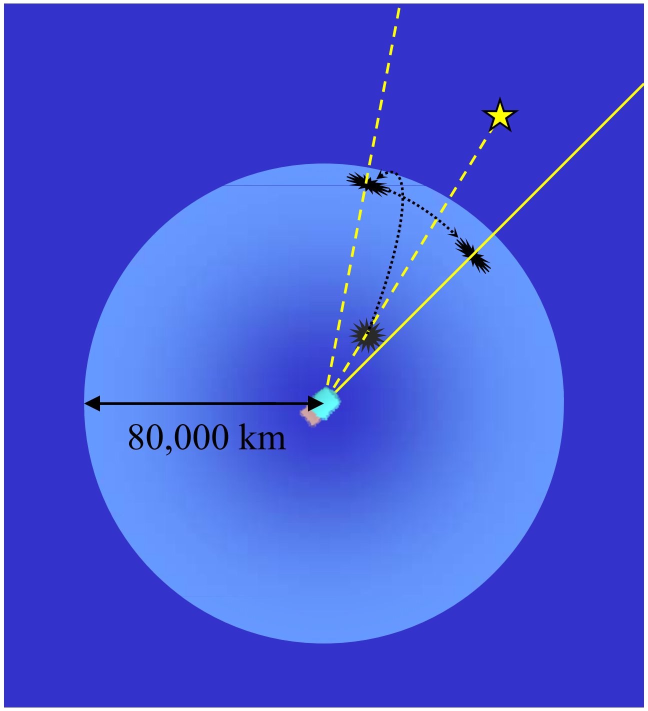
  - Visible light external occulter



- Occulter is as ancient as blocking the sun's glare with a hand

Technical challenge

- Planet-star angle < 0.5 μrad and brightness ratio $\sim 10^{-10}$.
  - Requires occulter's angular size also < 0.5 μrad and shadow depth $\sim 10^{-10}$
- Optical diffraction requires a very large occulter, very far away
  - Diameter: 30-100m
  - Separation distance: 30,000-100,000 km
- Move occulter from star to star
  - Typical slew angle between stars is 10-20°
    → 9,000-18,000 km travel
- Seek >120 target observations in 5 years
  → dozens of exoplanets and their spectra



“Fuel Is Science”

- Science is limited by number of stellar visits in a mission
  - Initial detection
  - Return for characterization
- Visits limited by fuel
  - Typical 1 star/2 weeks for 5 years requires total $\Delta v \sim 12{,}000$ m/s
    - High I_{sp} thrusters needed → fuel mass ~900-1200 kg Xenon
  - Fuel consumed on <u>each slew</u> is proportional to 1/(slew time T): $\Delta m_{fuel} = 8 \cdot \frac{D}{T} \cdot \frac{M_{wet}}{g \cdot I_{sp}}$
- Number of stars observed in entire mission depends directly on fuel mass

$$N \cong \sqrt{\frac{g \cdot I_{sp} \cdot T_M}{8 \cdot D} \cdot \frac{m_{fuel}}{m_{dry}}}$$

Mission duration, or time between refuelings (T_M)

Typical slew distance between stars (D)

Robotic servicing can extend mission

Scenarios with 10 year lifetime

- Option 1: Servicing after 5 years (10 yr total), rendezvous at L2 or at earth-moon L1
  - Doubles number of star observations

Refueling (recharge Xe tanks)	1200 kg
Replacing thrusters, PPUs	269 kg
Total service, payload to occulter	1469 kg
Number of star observations	250
Number of servicing missions	1

- Option 2: Higher fuel rate, servicing every 2 years, rendezvous at L2
  - 60% more stars

Each service, payload to occulter	1469 kg
Number of star observations	395
Number of servicing visits	4
Total payload to occulter	5876 kg

- Option 3: Occulter 44% farther from telescope, servicing every 2 years, rendezvous at L2
  - Better science: see planets 20% closer to star
  - More thorough search of each star, and/or
  - Choose candidate stars from 73% larger list

Each service, payload to occulter	1469 kg
Number of star observations	329
Number of servicing visits	4
Total payload to occulter	5876 kg

Robotic servicing can extend mission

Scenarios with 10 year lifetime

- Option 1: Servicing after 5 years (10 yr total), rendezvous at L2 or at earth-moon L1
  - Doubles number of star observations

Refueling (recharge Xe tanks)	1200 kg
Replacing thrusters, PPUs	269 kg
Total service, payload to occulter	1469 kg
Number of star observations	250
Number of servicing missions	1

Unserviced 10 yr mission expendables: 4,200 kg

- Option 2: Higher fuel rate, servicing every 2 years, rendezvous at L2
  - 60% more stars

Each service, payload to occulter	1469 kg
Number of star observations	395
Number of servicing visits	4
Total payload to occulter	5876 kg

- Option 3: Occulter 44% farther from telescope, servicing every 2 years, rendezvous at L2
  - Better science: see planets 20% closer to star
  - More thorough search of each star, and/or
  - Choose candidate stars from 73% larger list

Each service, payload to occulter	1469 kg
Number of star observations	329
Number of servicing visits	4
Total payload to occulter	5876 kg

Robotic servicing can extend mission

Scenarios with 10 year lifetime

- Option 1: Servicing after 5 years (10 yr total), rendezvous at L2 or at earth-moon L1
  - Doubles number of star observations

Refueling (recharge Xe tanks)	1200 kg
Replacing thrusters, PPUs	269 kg
Total service, payload to occulter	1469 kg
Number of star observations	250
Number of servicing missions	1

Unserviced 10 yr mission expendables: 4,200 kg

- Option 2: Higher fuel rate, servicing every 2 years, rendezvous at L2
  - 60% more stars

Each service, payload to occulter	1469 kg
Number of star observations	395
Number of servicing visits	4
Total payload to occulter	5876 kg

Unserviced 10 yr mission expendables: 36,700 kg

- Option 3: Occulter 44% farther from telescope, servicing every 2 years, rendezvous at L2
  - Better science: see planets 20% closer to star
  - More thorough search of each star, and/or
  - Choose candidate stars from 73% larger list

Each service, payload to occulter	1469 kg
Number of star observations	329
Number of servicing visits	4
Total payload to occulter	5876 kg

Unserviced 10 yr mission expendables: 36,600 kg

Backup

Thrusters and Power

- NEXT thruster system (NASA-Glenn)
  - 235 mN, I_{sp} = 4100 s
  - 6.85 kW to thruster
  - 7.25 kW input per Power Processing Unit (PPU)
  - Accelerator electrode life limit estimated at 730 kg Xe
  - With 3 thrusters, estimated mission Δv=10,193 m/s
- 3 PPUs and 3 thrusters, cross-strapped
  - Mounted on the outside
  - Total 269 kg
- Power needs
  - Peak power 14.5 kW
  - PPU input 80-160V
- Two 7m Ultraflex arrays
  - 9 kW each

Backup

Total Mission Fuel

- Fuel mass fraction is $\frac{m_{fuel}}{m_{dry}} = \exp\left(\frac{8 \cdot N^2 \cdot D}{g \cdot I_{sp} \cdot T_M}\right) - 1$ where
  - N is the number of star observations performed in the mission
  - D_1 is the typical slew distance between 2 stars
    ≈ (separation distance)*(typical angle between 2 stars)
  - I_{sp} ≈4200 sec is the specific impulse of the thruster and g is 9.8m/sec^2
  - T_M is the total mission time, or the time between servicing visits
- For small mass fraction, the science harvest N is

$$N = \sqrt{\frac{g \cdot I_{sp} \cdot T_M}{8 \cdot D} \cdot \frac{m_{fuel}}{m_{dry}} \cdot \left(1 - \frac{1}{4} \cdot \frac{m_{fuel}}{m_{dry}} + O\left(\frac{m_{fuel}^2}{m_{dry}^2}\right)\right)}$$

  - We have a mass fraction ~30%, so the second term is ~7.5% and the omitted terms are negligible