New Worlds Imager

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New Worlds Imager
An Alternative to TPF

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Erik Wilkinson
Mike Leiber
Jim Leitch
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Ron Polidan
Chuck Lillie
Willard Simmons  MIT

and growing...
Let's Find the Future Home of Mankind

Let's Do It NOW!!

Let's Find Life Elsewhere in the Universe
Exo-Planets

- Exo-planets are the planets that circle stars other than our Sun.

- There are probably 10,000 exo-planets within 10pc (30 light years) of the Earth.

- Planets are lost in the glare of parent star.

- The Earth as viewed from light years is 10 billion times fainter than the Sun.
Planet Finding: Extinguish the Star

Planet-Star Contrast Ratio

Angular Separation (milli arcsec)

Star/Planet contrast ratio

- at 1.0μ
- at 10.0μ
- sun@10pc

 Courtesy of N-G
Terrestrial Planet Finder

Telescopes must be *PERFECT* to suppress scatter:
\[ \lambda/5000 \text{ surface, } 99.999\% \text{ reflection uniformity} \]

TPF is very difficult

Is there any easier way?
New Worlds Imager vs. New Worlds Observer

Two Levels of Difficulty

New Worlds Observer
- Two Spacecraft
- Goal is Finding Planets
- Science from Photometry and Spectroscopy
- Technology is In-Hand Today

New Worlds Imager
- Five Spacecraft
- Goal is True Imaging of Earth-like Planets
- MUCH Tougher – Technology 10-15 years out
Initially New Worlds was a Pinhole Camera

Perfect Transmission  
No Phase Errors  
Scatter only from edges – can be very low

Large Distance Set by 0.01 arcsec requirement  
diffraction: \( \frac{\lambda}{D} = 0.01'' \rightarrow D = 10m \)  
@500nm  
geometric: \( F = \frac{D}{\tan(0.01'')} = 180,000km \)
Diffraction Still a Major Problem for Pinhole

Answer: Shape the Aperture (Binary Apodization)

Developed by Princeton Group for Apertures
The Occulter Option

✦ Smaller Starshade
  – Create null zone, image around occulter

✦ Observe entire planetary system at once
The Diffraction Problem Returns

Several previous programs have looked at occulters
Used simple geometric shapes
  – Achieved only 10⁻² suppression across a broad spectral band
With transmissive shades
  – Achieved only 10⁻⁴ suppression despite scatter problem

http://umbras.org/

BOSS

Starkman (TRW ca 2000)
Occulters Have Very Poor Diffraction Performance
- The 1818 Prediction of Fresnel led to the famous episode of:
  - Poisson’s Spot (variously Arago’s Spot)
  - Occulters Often Concentrate Light!

Must satisfy Fresnel Equation, Not Just the Fraunhoffer Equation

Must Create a Zone That Is:
- Deep Below $10^{-10}$ diffraction
- Wide A couple meters minimum
- Broad Suppress across at least one octave of spectrum

Must Be Practical
- Binary Non-transmitting to avoid scatter
- Size Below 150m Diameter
- Tolerance Insensitive to microscopic errors
The Vanderbei Flower

- Developed for Aperture in TPF focal plane
- Was to be only $25\mu$ across
- Vanderbei had determined it would work for the pinhole camera but did not work for occulter.
The Apodization Function

Found this in April. Extended in June.
This Function Extinguishes Poisson’s Spot to High Precision

\[ A(\rho) = 0 \quad \text{for} \quad \rho < r_1 \]

and

\[ A(\rho) = 1 - e^{-\left( \frac{\rho-r_1}{r_2} \right)^{2n}} \quad \text{for} \quad \rho > r_1 \]
Suppression of Edge Diffraction Can Be Understood Using Fresnel Zones and Geometry

- The occulter is a true binary optic
  - Transmission is unity or nil

- Edge diffraction from solid disk is suppressed by cancellation
  - The power in the even zones cancels the power in the odd zones
    - Need enough zones to give good deep cancellation
      - Sets the length of the petals
  - Petal shape is exponential \( \sim \exp(-((r-r_1)/r_2)^{2n}) \)
    - \( r_2 \) is scale of petal shape
    - \( n \) is an index of petal shape
    - \( r_1 \) is the diameter of the central circle
Doing the Math
(Cash, 2005)

The Residual Intensity in the Shadow is

$$I_s = E_s^2$$

By Babinet’s Principle

$$E_s = 1 - |E_A|$$

where $E_A$ is field over Aperture

So We Must Show

$$\frac{2\pi}{2\pi d} \left| \int_0^{2\pi} \int_0^{\pi} e^{\frac{ik\rho^2}{2d}} e^{-\frac{ik\rho s \cos \theta}{d}} \rho \, d\rho \, d\theta + \int_0^{\infty} \int_{\rho_1}^{\infty} e^{\frac{ik\rho^2}{2d}} e^{-\frac{ik\rho s \cos \theta}{d}} e^{-\left(\frac{\rho-\rho_1}{r_2}\right)^2} \rho \, d\rho \, d\theta \right| = 1$$

$d$ is distance to starshade, $s$ is radius of hole, $k$ is $2\pi/\lambda$

To one part in

$$\sqrt{C} \approx 10^{-5}$$
**Contrast Ratio**

The preceding integral shows the contrast ratio is

\[
R = \left[ \frac{(2n)!}{r_1^{2n} r_2^{2n} \left( \frac{d\lambda}{2\pi} \right)^{2n}} \right]^2
\]

- \( n \) is an integer parameter, currently \( n=4 \)

To keep \( R \) small \( r_1 \sim r_2 \)

- this is the reason the occulter has that symmetric look
The off axis performance shows a rapid rise to unit transmission for the radii greater than the inner edge of the habitable zone.
Modified Rendering
“Standard” Observatory Views the Starshade

~0.1” resolution is needed (just to separate planets)

High efficiency, low noise spectrograph (e.g. COS)
Count rate estimation

Assuming visible solar flux and a half-earth viewed at 10 pc,

\[ C \propto \frac{F_S r_E^2 D_T^2}{\varepsilon \gamma d_S^2} \]

Can achieve 5 counts per second with 80% efficient 10 meter telescope

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Time required for S/N=10 detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 meter</td>
<td>33.3 minutes</td>
</tr>
<tr>
<td>2 meter</td>
<td>8.3 minutes</td>
</tr>
<tr>
<td>4 meter</td>
<td>2.1 minutes</td>
</tr>
<tr>
<td>8 meter</td>
<td>31 seconds</td>
</tr>
</tbody>
</table>
Another Issue: Scattered Light

- Sunlight Scatters Off Starshade
- Can be Controlled in Multiple Ways
  - Look at right angles to sun
    - Imposes restrictions on revisit times
  - Operate in shadow
    - Earth’s umbra
    - With additional shade
      - Likely hard at L2
      - Easier in heliocentric orbit
Starshade Tolerances

Position
- Lateral: Several Meters
- Distance: Many Kilometers

Angle
- Rotational: None
- Pitch/Yaw: Many Degrees

Shape
- Truncation: 1mm
- Scale: 10%
- Blob: 3cm² or greater

Holes
- Single Hole: 3cm²
- Pinholes: 3cm² total
Fly the Telescope into the Shadow
New Worlds Imager

Dropping It In
Typical Observing Timeline

 Alignment  3 days  Travel
  – Other astrophysics

 Deep Photometry  1 day  Find Planets

 Preliminary Spectroscopy  1 day  Classify Planets

 Detailed Studies  3 days  Search for
  – Deep Spectroscopy
  – Extended Photometry

 Return After Months
  – 

 Measure Orbits
  New Planets from Glare

 Water
 Surface Features
 Life ?!
The First Image of Solar System

Uranus
Galaxies
Zodiacal Light
Jupiter
Saturn
Neptune

10 arcseconds
Great Science with Small Telescopes

Lower limit on telescope size set by need to acquire adequate signal and resolve planets from one another
- 1 m diameter telescope needed to see 30M object in minutes
  - Resolution of 0.1 arcsec
- 2 m diameter gives count rate 0.2 sec⁻¹ for Earth at 10 pc at half illumination

New Worlds Imager

Earth
Mars

50,000 seconds

Uranus
Saturn
Jupiter
Neptune

400,000 seconds
Zodiacal light

- Planet detectability depends on system inclination and telescope resolution
  - Face-on 0.3 AU² patch of zodi equal to Earth’s brightness
- Zodiacal light can wash out planets at low inclinations
Zodiacal Light – 0.05” IWA

Pole-on

Edge-on

New Worlds Imager
New Worlds Imager

S. Seager

R > 100 spectroscopy will distinguish terrestrial atmospheres from Jovian with modeling

W. Cash – University of Colorado
Photometry

Calculated Photometry of Cloudless Earth as it Rotates

It Should Be Possible to Detect Oceans and Continents!
Alternate Operations Concepts

- **Ground based telescope**
  - Relay mirror at GEO
  - South Pole

- **Space based telescope**
  - As JWST instrument
  - Dedicated telescope and mission
Occulter and Detector Craft
Functions

☞ Propulsion
☞ Station keeping
☞ Alignment establishment and maintenance
  – Measurement and reporting of relative location
☞ Data transfers
☞ Pointing requirements dependent on tolerancing of occulter
  – Pointing error results in an error in the occulter shape by projection
☞ What is the role of the ground in directing the two SC?
  – Cost trade?
Largest problem is solar radiation pressure
- Pinhole craft's cross sectional area: 7150 m²
- Craft will be thrown out of libration point orbit after several days

**Total stationkeeping ∆V [m/s]**

<table>
<thead>
<tr>
<th></th>
<th>L₂</th>
<th>L₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>20,000 km</td>
<td>10.2</td>
<td>20.3</td>
</tr>
<tr>
<td>200,000 km</td>
<td>9.8</td>
<td>20.7</td>
</tr>
</tbody>
</table>

**Number of burns during exposure**

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>20,000 km</td>
<td>6700</td>
<td>3740</td>
</tr>
<tr>
<td>200,000 km</td>
<td>6700</td>
<td>3810</td>
</tr>
</tbody>
</table>
**Formation Flying Simulation**

Stationkeeping $\Delta V$ estimated in STK/Astrogator

- Detector craft assumed active; pinhole craft assumed passive
- Control box of 10 cm half-width defined
- Active S/C thrusts when box boundaries reached
- Gravity of Earth, Sun, Moon included, plus solar radiation pressure
- Separations of 20,000 km and 200,000 km considered at Earth-Sun $L_2$ and $L_5$
Up to 150 m New Worlds Observer Will Fit in an ELV Heavy
New Worlds Deploys Like Solar Arrays

Simple, robust, proven deployment scheme

Simple low cost solar array style deployment
TRUE PLANET IMAGING

Earth Viewed at Improving Resolution

3000 km
1000 km
300 km
100 km
Solar System Survey at 300km Resolution
NWI Concept

starshades

combiner

collector craft

1500km

50,000km
Holding the Array

- Field star beams
- Planet beams
- Delay Lines – Mixers - Detectors
- Primary collector
- Field star collimator
- Planet collimator
- To combiner
Planet Q-Ball

Imperfection visible with adequate signal

One Imperfection

Fringes as Telescopes Separate

Information is there:
We will study the realistic limits of two element interferometers
Resolution Limitation Set By Signal

- At 10 km resolution the interferometer is photon-limited
- Need Much Bigger Telescopes – Too Expensive
The Phase II Study

Two Year Study Began on September 1

Observer Mode Well Understood
- Complete Architecture Study Completed in First Year
- Laboratory Demonstration of Diffraction Suppression

Imager Mode More Difficult
- Will Study Requirements in Detail
- Will Look for Ways to Make the Mission More Affordable
Conclusion

By 2011

By 2018

New Worlds Imager