Searching for Earth-Like Planets:

NASA's Terrestrial Planet Finder Space Telescope

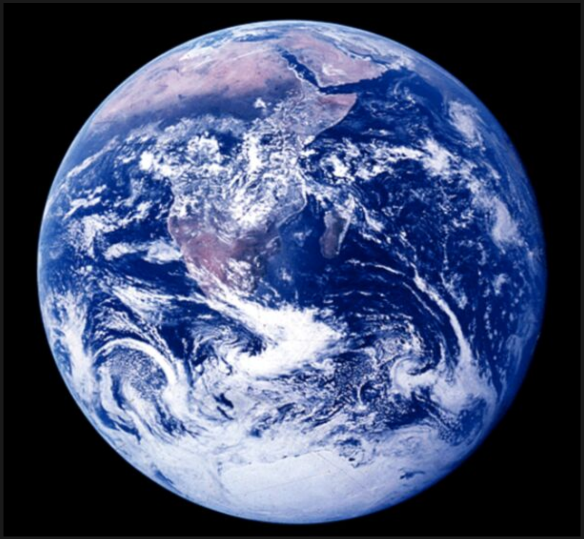
Robert J. Vanderbei

January 11, 2004
Amateur Astronomers Association of Princeton
Peyton Hall, Princeton University

Member: Princeton University TPF Team
http://www.princeton.edu/∼rvdb

The Big Question: Are We Alone?

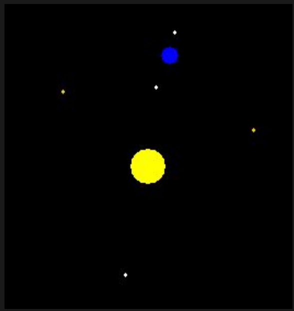
- Are there Earth-like planets?
- Are they common?
- Is there life on some of them?



Extrasolar Planets—Where We Are Now

There are more than 120 Extrasolar planets known today.

Most of them have been discovered by detecting a sinusoidal doppler shift in the parent star's spectrum due to gravitationally induced wobble.

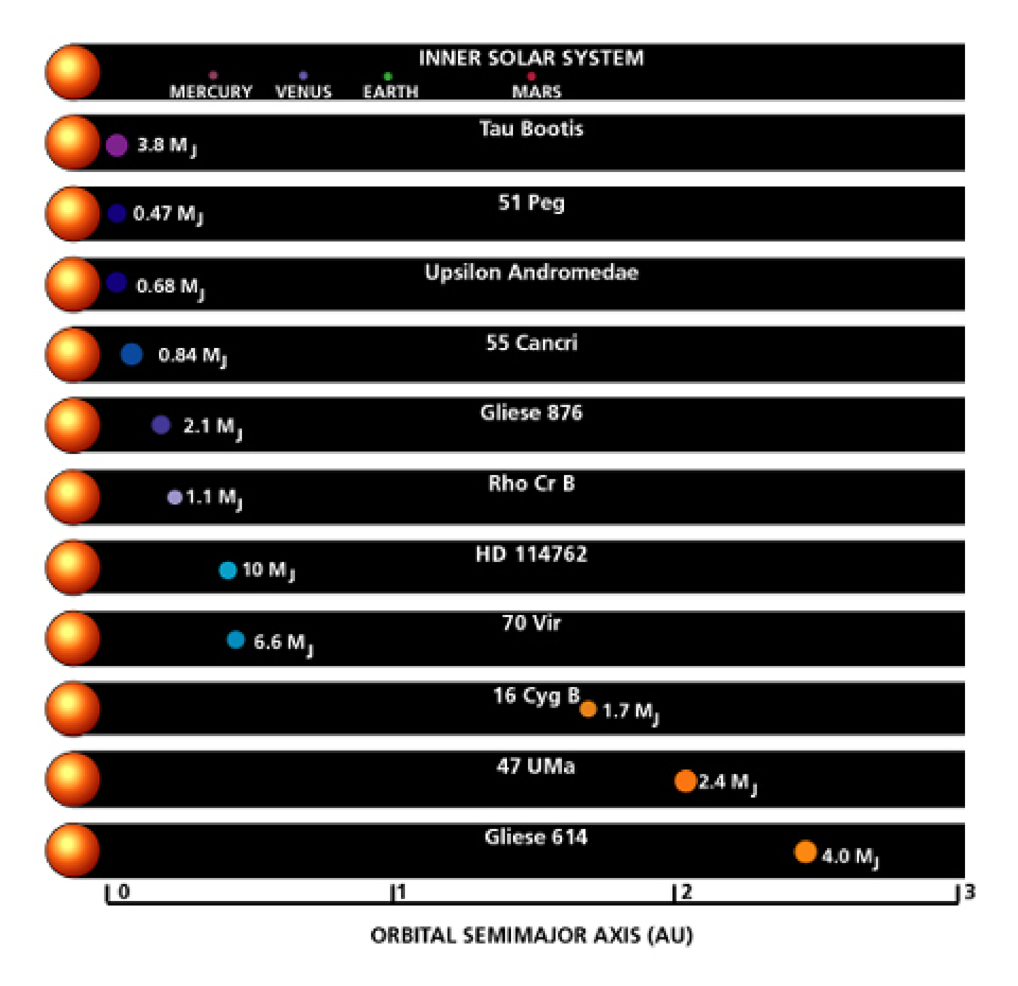


This method works best for large Jupiter-sized planets with close-in orbits.

One of these planets, HD209458b, also transits its parent star once every 3.52 days. These transits have been detected photometrically as the star's light flux decreases by about 1.5% during a transit.

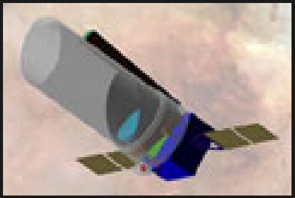
Recent transit spectroscopy of HD209458b shows it is a gas giant.

Some of the Extrasolar Planets



Future Extrasolar Planet Missions

- 2006, Kepler a space-based telescope to monitor 100,000 stars simultaneously looking for "transits".



- 2007, Eclipse a space-based telescope to directly image Jupiter-like planets.

- 2009, Space Interferometry Mission (SIM) will look for astrometric wobble.
- 2014, Terrestrial Planet Finder Coronagraph (TPF-C) space-based telescope to directly image Earth-like planets.
- 2020, Terrestrial Planet Finder Interferometer (TPF-I) space-based telescope to directly image Earth-like planets.

Terrestrial Planet Finder Telescopes

- DETECT: Search 150-500 nearby (5-15 pc distant) Sun-like stars for Earth-like planets.

- CHARACTERIZE: Determine basic physical properties and measure "biomarkers", indicators of life or conditions suitable to support it.

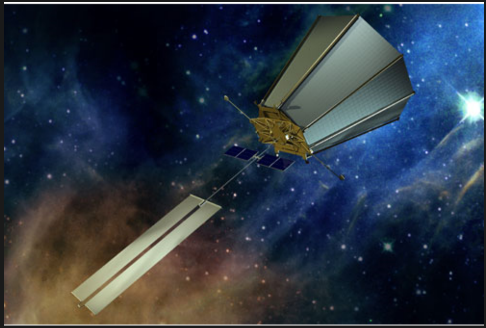
Why Is It Hard?

- If the star is Sun-like and the planet is Earth-like, then the reflected visible light from the planet is 10^{-10} times as bright as the star. This is a difference of 25 magnitudes!
- If the star is 10 pc (33 ly) away and the planet is 1 AU from the star, the angular separation is 0.1 arcseconds!

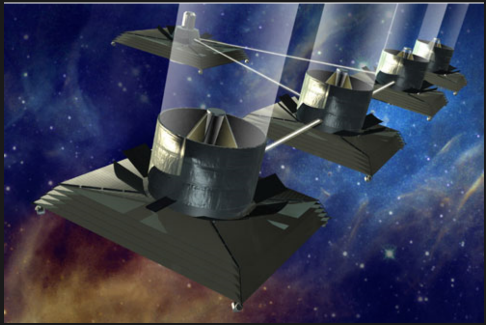
Originally, it was thought that this would require a space-based infrared nulling interferometer (TPF-I).

However, the current plan is first to build a single large visible-light telescope with an elliptical mirror (4 m x 10 m) and a *shaped pupil* for diffraction control (TPF-C).

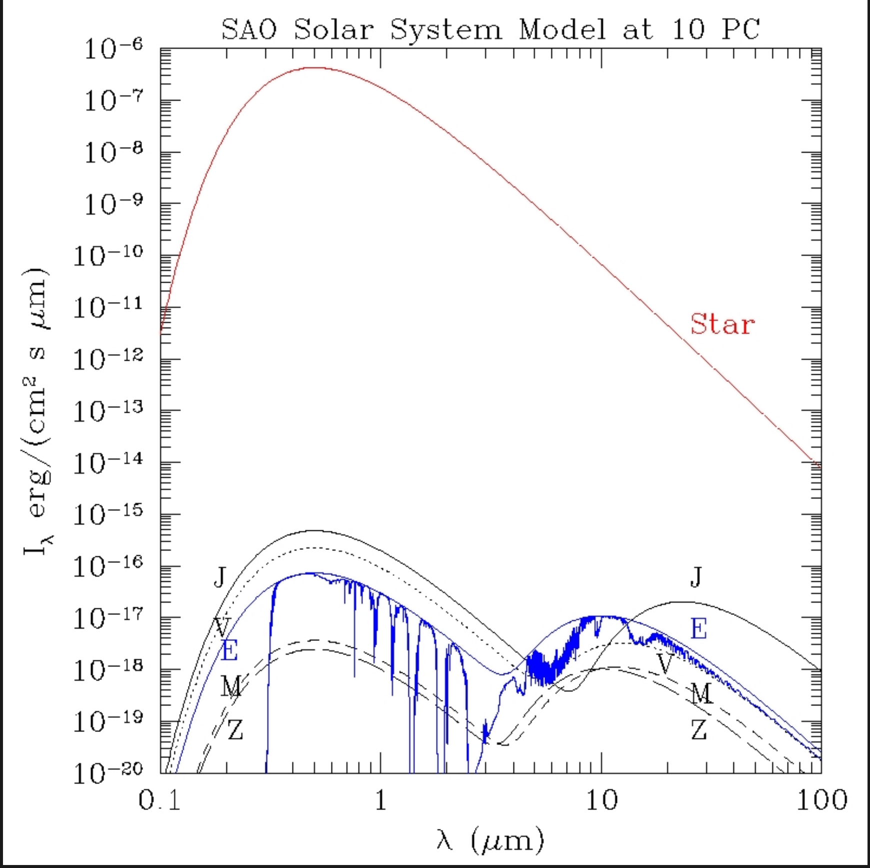
TPF-Coronagraph



TPF-Interferometer

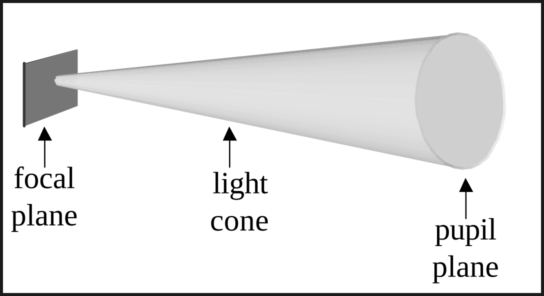


Visible vs. Infrared



The Shaped Pupil Concept

Consider a telescope. Light enters the front of the telescope—the *pupil plane*.



The telescope focuses the light passing through the pupil plane from a given direction at a certain point on the *focal plane*, say $(0, 0)$.

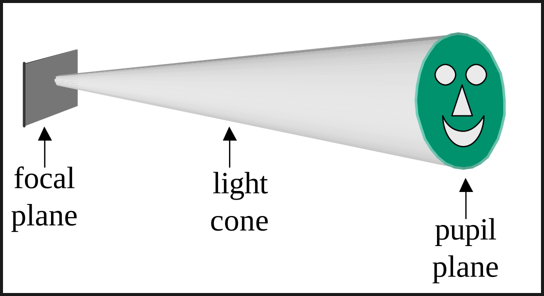
However, a point source produces not a point image but an *Airy pattern* consisting of an *Airy disk* surrounded by a system of *diffraction rings*.

These diffraction rings are too bright. An Earth-like planet is only about 10^{-10} times as bright as its Sun-like star. The rings would completely hide the planet.

By placing a mask over the pupil, one can control the shape and strength of the diffraction rings. The problem is to find a shape that puts almost no light in a *dark zone* that is very close to the Airy disk.

The Shaped Pupil Concept

Consider a telescope. Light enters the front of the telescope—the *pupil plane*.



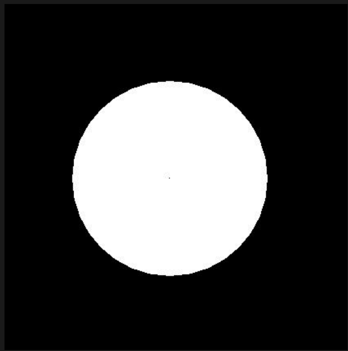
The telescope focuses the light passing through the pupil plane from a given direction at a certain point on the *focal plane*, say $(0, 0)$.

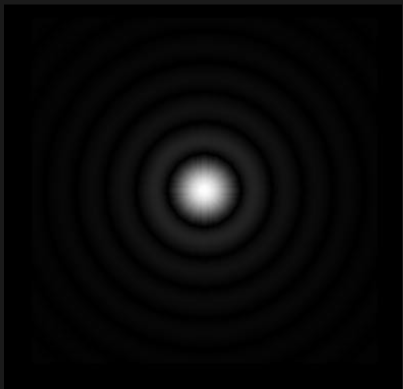
However, a point source produces not a point image but an *Airy pattern* consisting of an *Airy disk* surrounded by a system of *diffraction rings*.

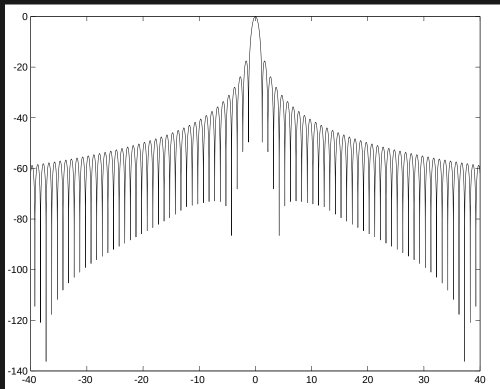
These diffraction rings are too bright. An Earth-like planet is only about 10^{-10} times as bright as its Sun-like star. The rings would completely hide the planet.

By placing a mask over the pupil, one can control the shape and strength of the diffraction rings. The problem is to find a shape that puts almost no light in a *dark zone* that is very close to the Airy disk.

Circular Aperture—Airy Pattern



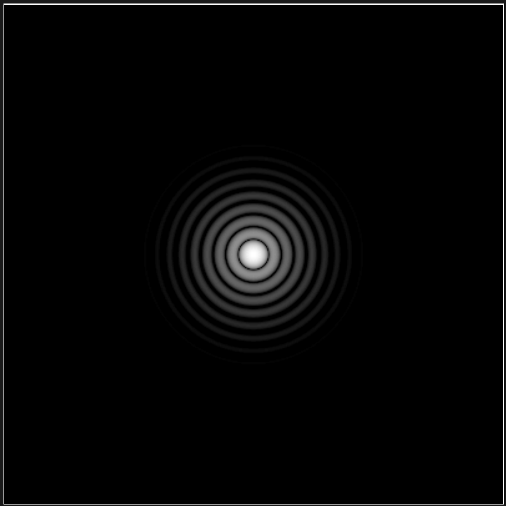




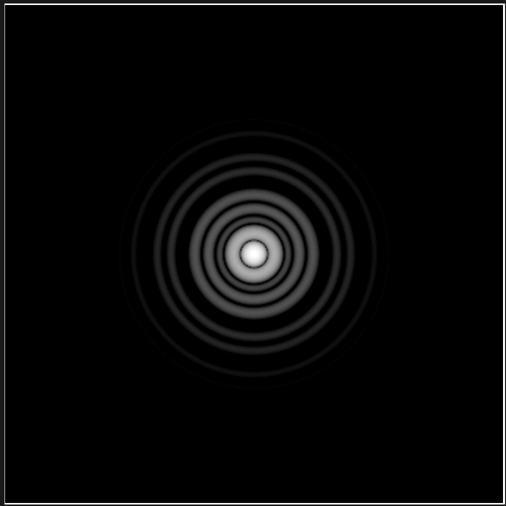
Central Obstructions are an Example of a Shaped Pupil

Logarithmically scaled plots of 2-D point spread functions for apertures with and without a 30.3% central obstruction. White is 1 and black is 10^{-4}.

Without (Tak Refractor):



With (Questar):



Spiders are another Example of a Shaped Pupil

Pleiades image taken with Tak FSQ-106N equipped with *dental floss* spiders.

Spiders are another Example of a Shaped Pupil

Pleiades image taken with Tak FSQ-106N equipped with *dental floss* spiders.

Performance Metrics

Inner and Outer Working Angles: ρ_{iwa} and ρ_{owa}

Contrast: Ratio of intensity of light in *dark zone* to the intensity at the center of the PSF.

Airy Throughput ($\mathcal{T}_{\text{Airy}}$)*:* Amount of light falling within the inner working angle measured as a percent of the total amount of light entering a clear aperture.

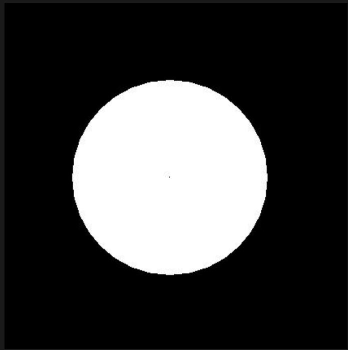
Comment on Units Angular quantities, like ρ_{iwa}, are given in units of wavelength over aperture (λ/D). Hence, the statement $\rho_{\text{iwa}} = 6$ means an angle of $6\lambda/D$ radians. For $\lambda = 500$nm and $D = 10$m, this translates to $6 \times 500 \times 10^{-9}/10 = 3 \times 10^{-7}$ radians, which is the same as 0.062 arcseconds.

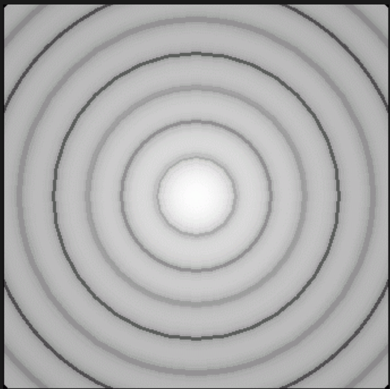
A planet 1au from its star when viewed from 10 parsecs (33ly) has an angular separation of 0.1 arcseconds.

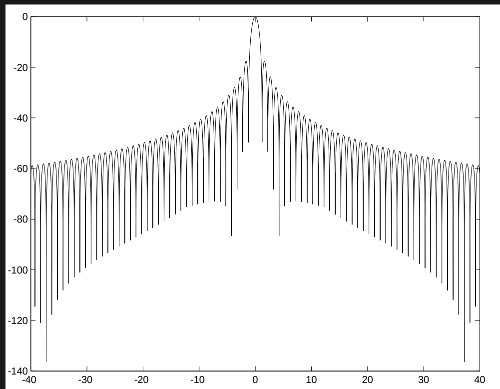
Circular Aperture—Airy Pattern

$$\text{FWHM} = 1.02 \quad \rho_{\mathsf{iwa}} = 1.24 \quad \mathcal{T}_{\mathsf{Airy}} = 84.2\%$$

No dark zone.





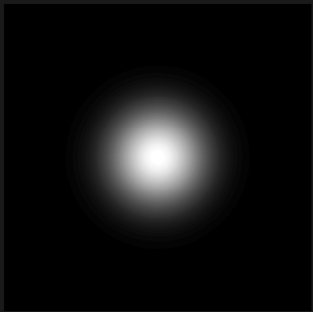


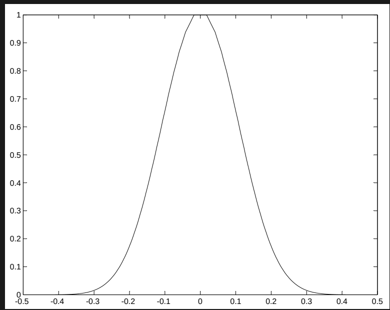
Apodization

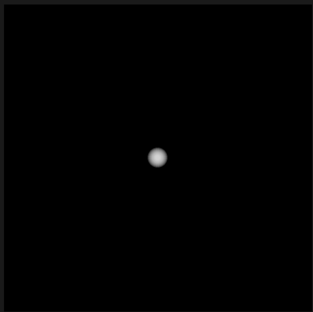
A mask is all-or-nothing. What about using tinted glass, where the degree of tint varies over the aperture? This is called *apodization*.

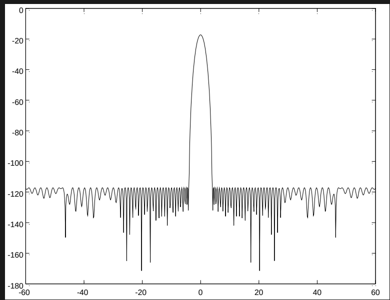
$$\mathrm{FWHM} = 2 \quad \rho_{\mathsf{iwa}} = 4 \quad \mathcal{T}_{\mathsf{Airy}} = 9\%$$

Excellent dark zone. Unmanufacturable.









Home Page

Title Page

Contents

Page 17 of 32

Go Back

Full Screen

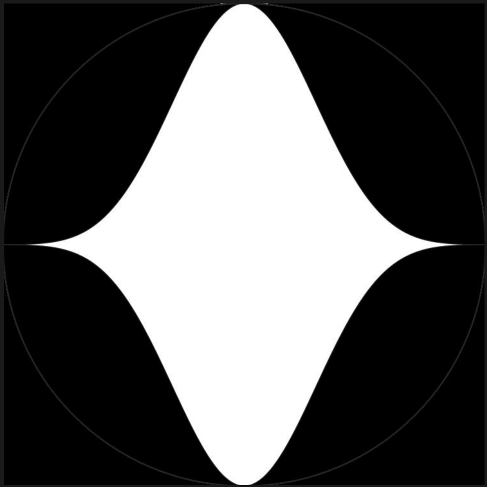
Close

Quit

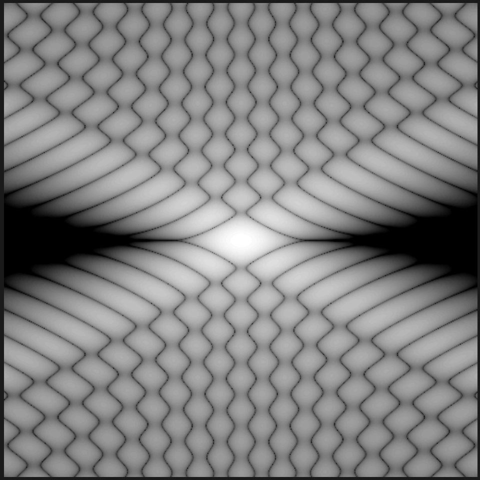
David Spergel's One Pupil Mask

$$\mathrm{FWHM} = 1.9 \quad \rho_{\mathsf{iwa}} = 4 \quad \mathcal{T}_{\mathsf{Airy}} = 43\%$$

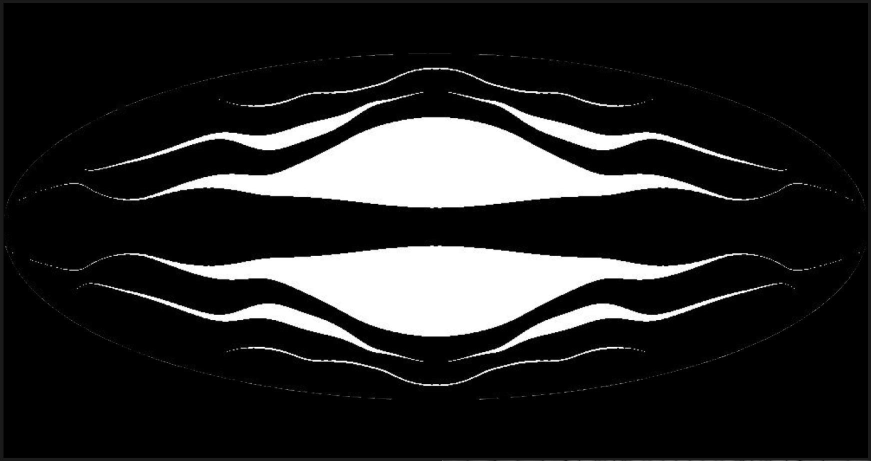
Small dark zone...Many rotations required

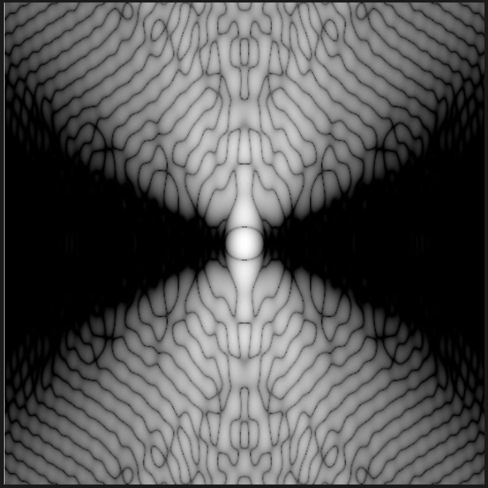


PSF for Single Prolate Spheroidal Pupil



My Multiple Pupil Mask





$\mathrm{FWHM} = 2.0 \quad \rho_{\text{iwa}} = 4$

$\mathcal{T}_{\text{Airy}} = 30\%$

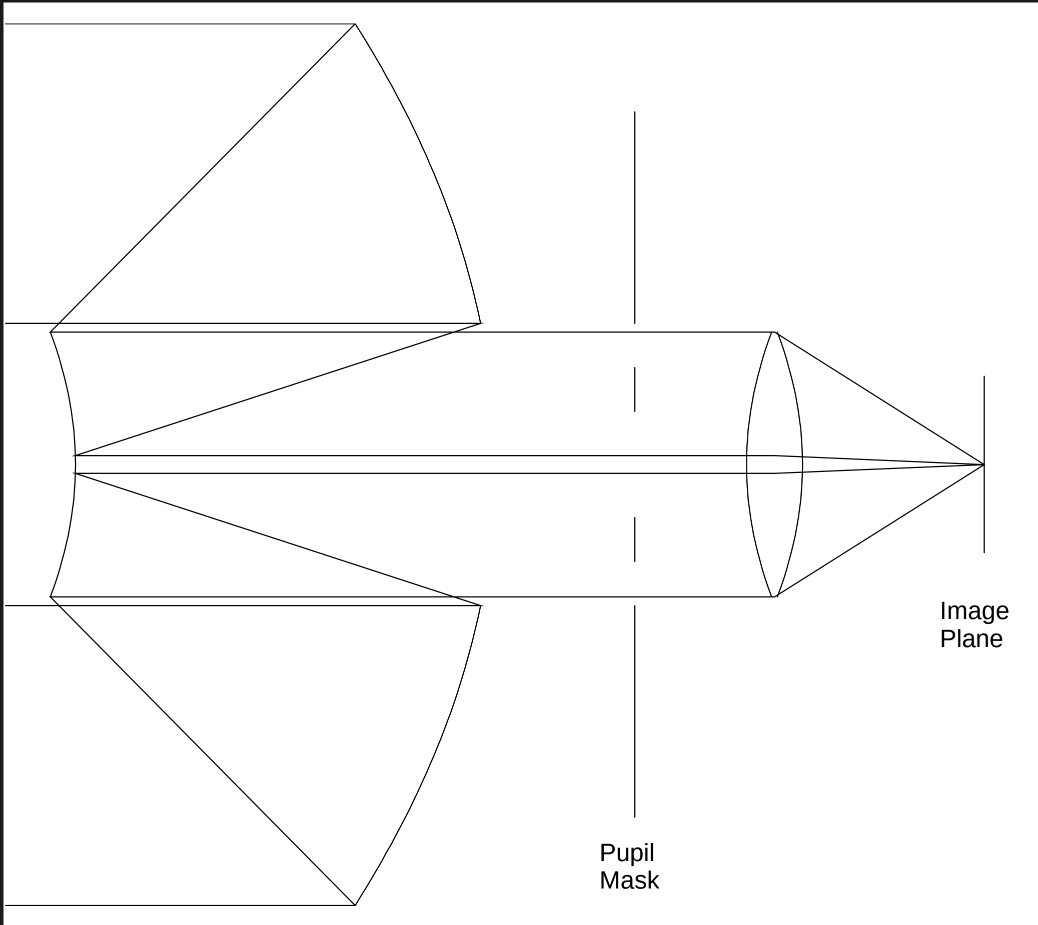
Throughput relative to ellipse

11% central obstr.

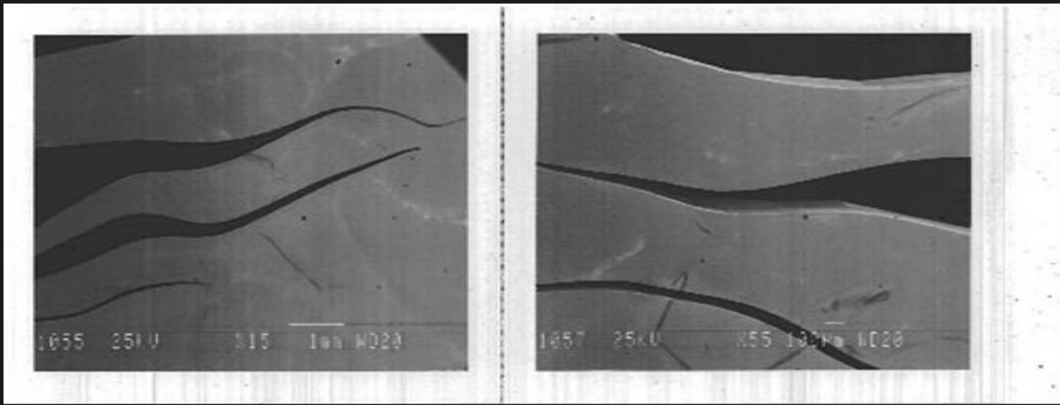
Easy to make

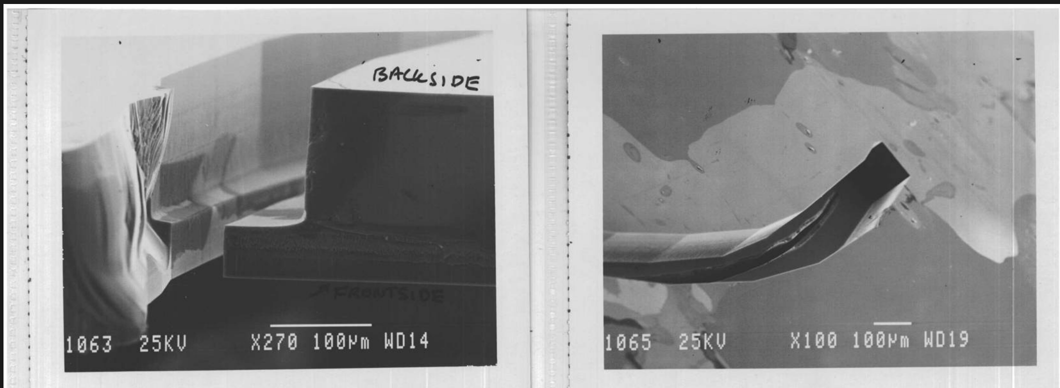
Very few rotations

Mask Placement



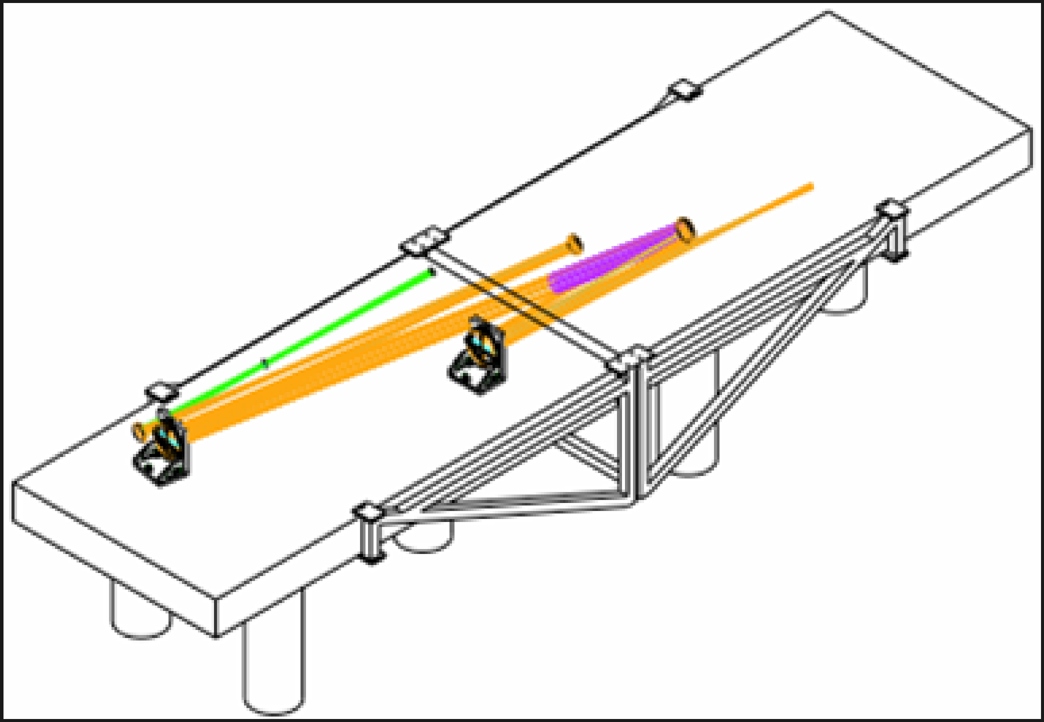
Masks from NIST





Home Page
Title Page
Contents
Page 21 of 32
Go Back
Full Screen
Close
Quit

Our Optical Bench Layout



Our TPF Optics Lab

Jeremy Kasdin tinkers with the laser.

Home Page

Title Page

Contents

Page 23 of 32

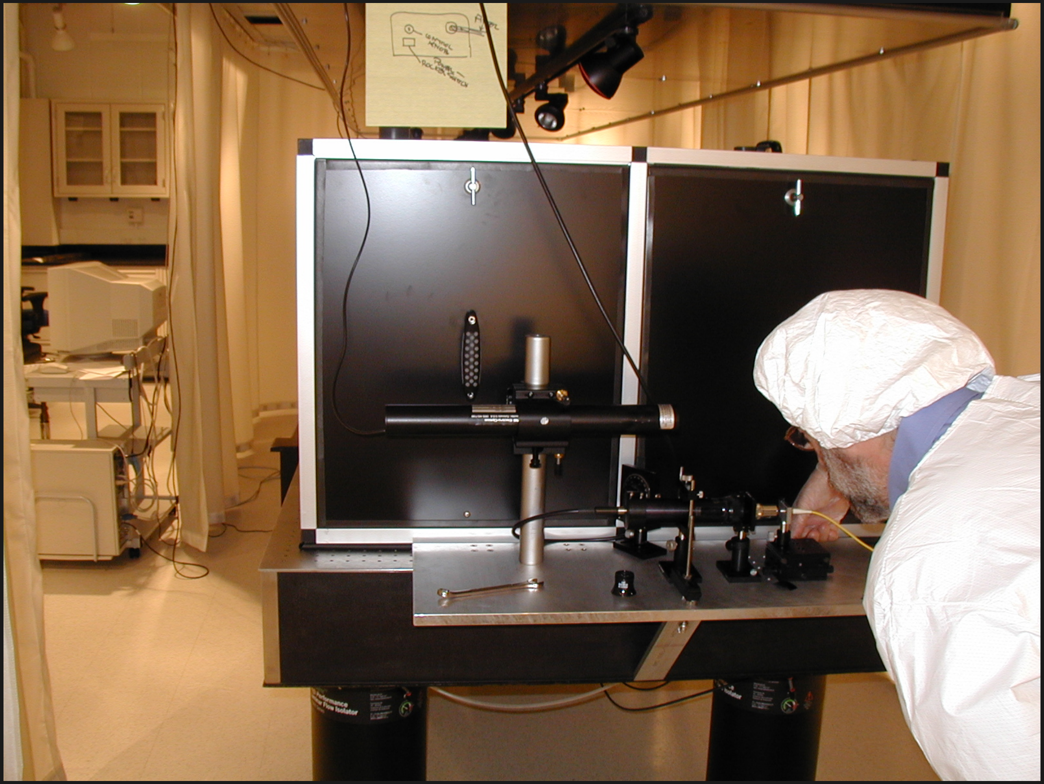
Go Back

Full Screen

Close

Quit

Our TPF Optics Lab

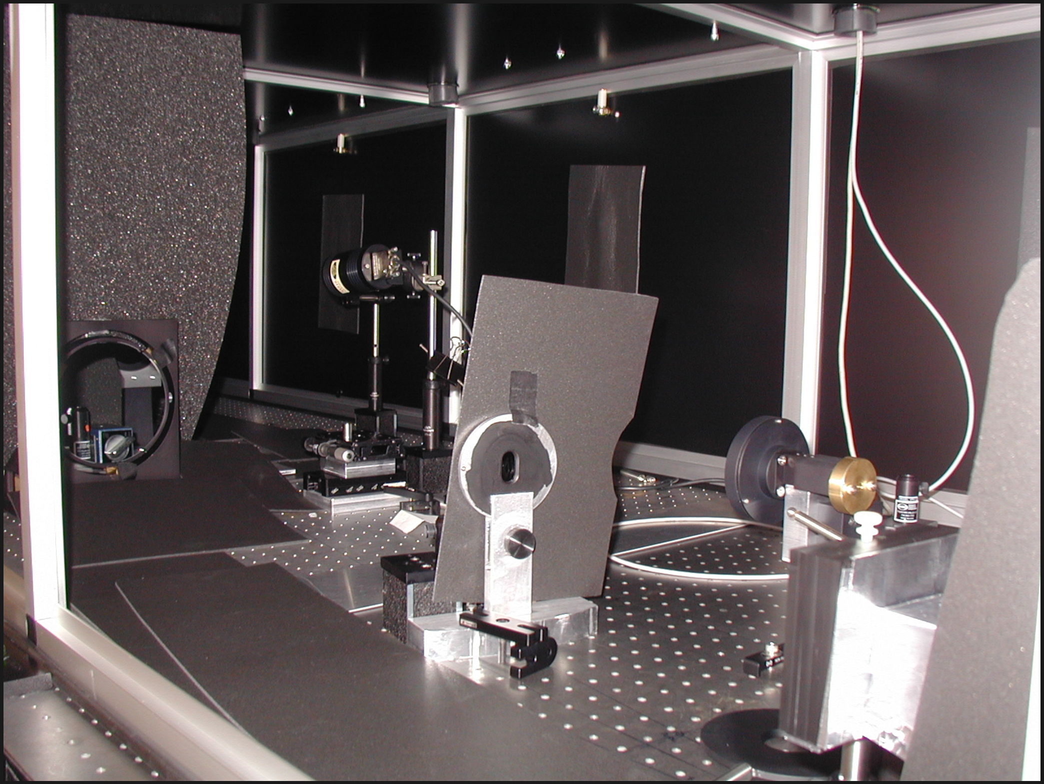


Jeremy adjusts the intensity.

Our TPF Optics Lab

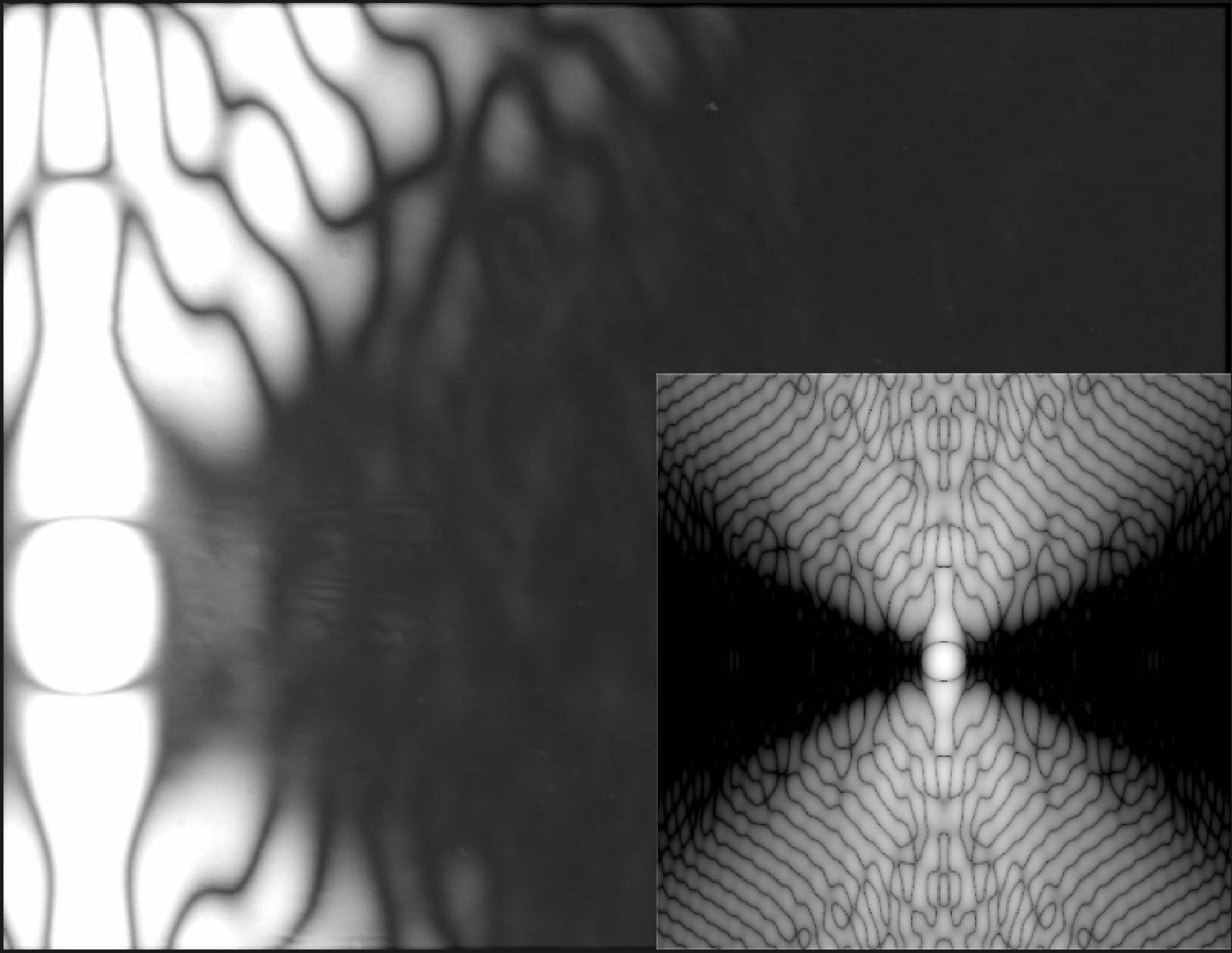
Yours truly pointing at his Starlight Express camera. Can't see it?

Our TPF Optics Lab



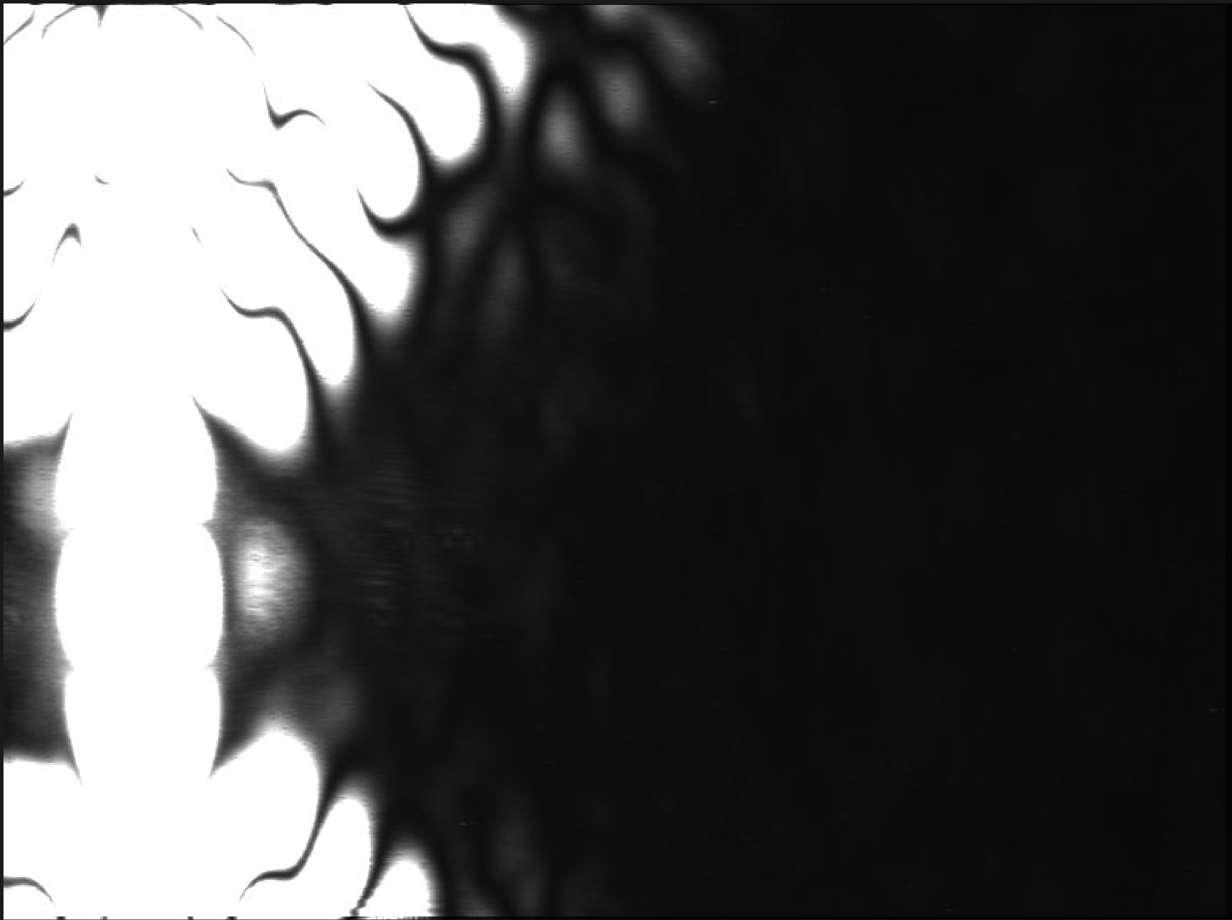
How about now?

Lab Results: Theory vs. Practice



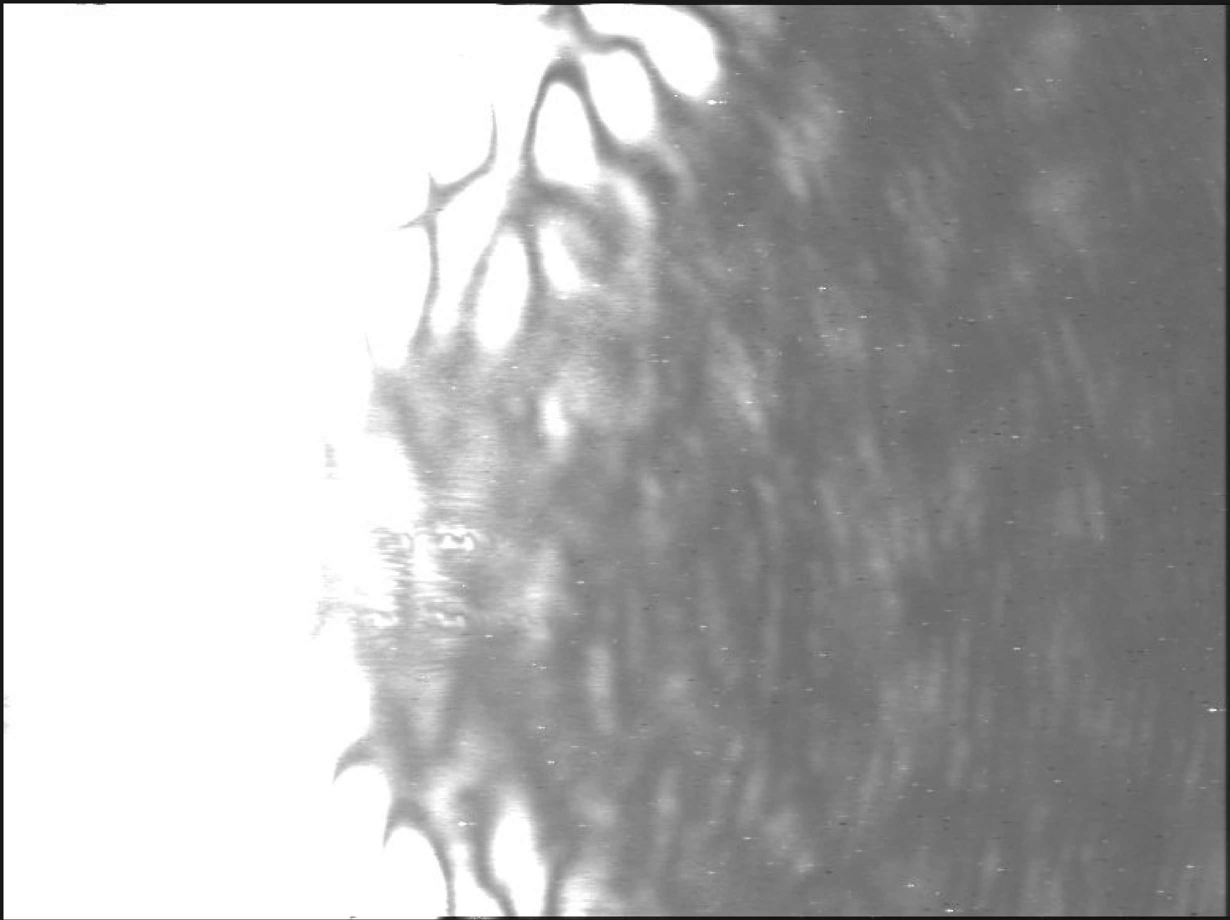
Brightest pixel $\approx 1,642,000,000$. Sum of 21 one-hour exposures.

Lab Results: 0 – 60000



Brightest pixel $\approx 1,642,000,000$. Bright blob $= 57,000 = 3.4 \times 10^{-5}$.

Lab Results: $0 - 6000$



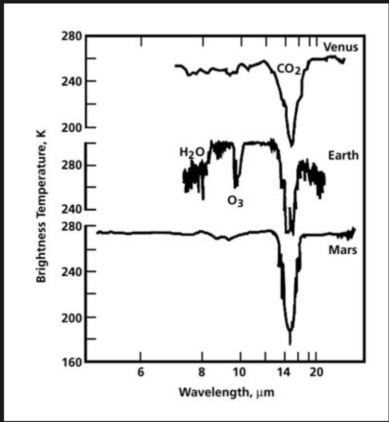
Dark valley $= 2100 = 1.3 \times 10^{-6}$. Ridge minus valley $= 200 = 1.3 \times 10^{-7}$.

Characterization

Spectroscopy

Spectra provide information on:

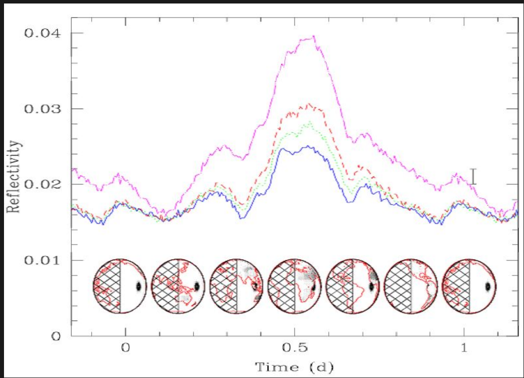
- CO_2
- H_2O
- O_3
- Chlorophyl



Photometry

Daily variation provides information on:

- weather/clouds
- existence of oceans
- rotational period
- land fraction
- ice cover



Contents