

HIPO Flight Experience

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HIPO's first flight,
June 2011



SOFIA Community Task Force

A distraction or two



Outline

- HIPO Overview
 - HIPO science and test goals
 - Key HIPO design features
- SCAI Overview
 - SOFIA Characterization and Integration (SCAI) flights, 2011
- First science result and next steps
- Aero-Optics and related topics
 - A review of aero-optical issues
 - Imaging and photometric impact
- Plans in this area:
 - Measure the actual situation during a commissioning test in October
 - Attempt observations in Cycle 1
- Questions?

HIPO Science Goals

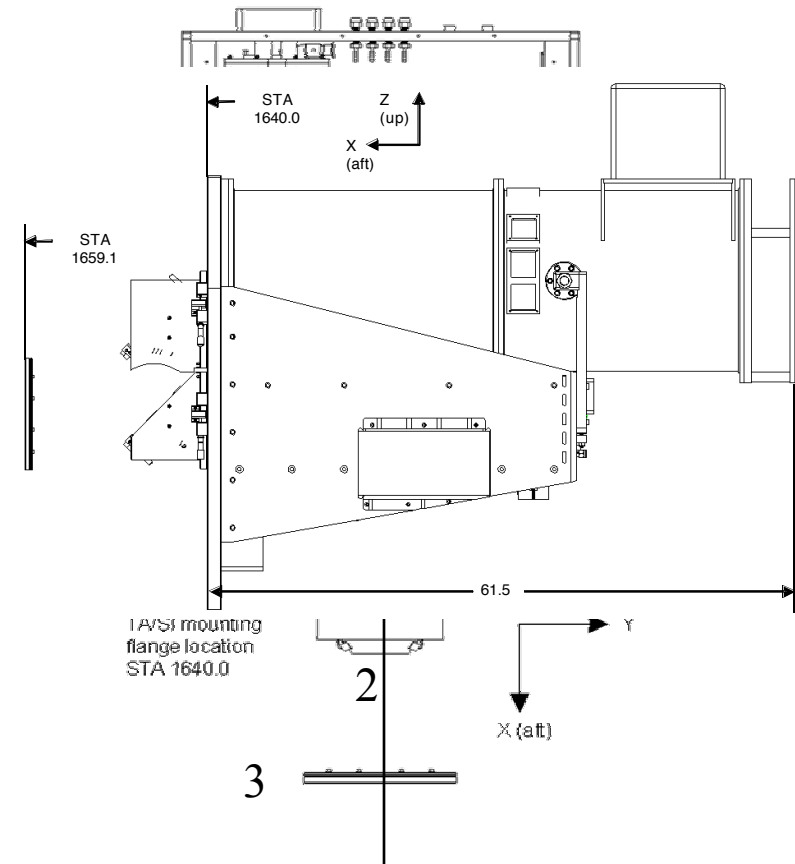
- Stellar Occultation Observations
 - Atmospheric sounding & accurate sizes of solar system objects
 - Pressure, density, temperature at microbar atmospheric levels
 - Multi-wavelength observations important – “FLIPO” configuration
 - Vertical and horizontal atmospheric structures can be resolved
 - Repeated occultations can track atmospheric changes
 - Spatial resolution of a few km at 30 AU for KBO sizes
- Extrasolar planet transits
 - Multi-wavelength transit observations at $\sim 10^4$ SNR (we hope!)
 - FLIPO configuration of particular interest - 0.3 to 5 microns
 - Planetary temperatures, radii, atmospheric composition, ...
- Asteroseismology
 - Obtain necessary SNR for measuring oscillations in bright stars
 - Short observing periods available (by *Kepler* standards)

HIPO Observatory Test Goals

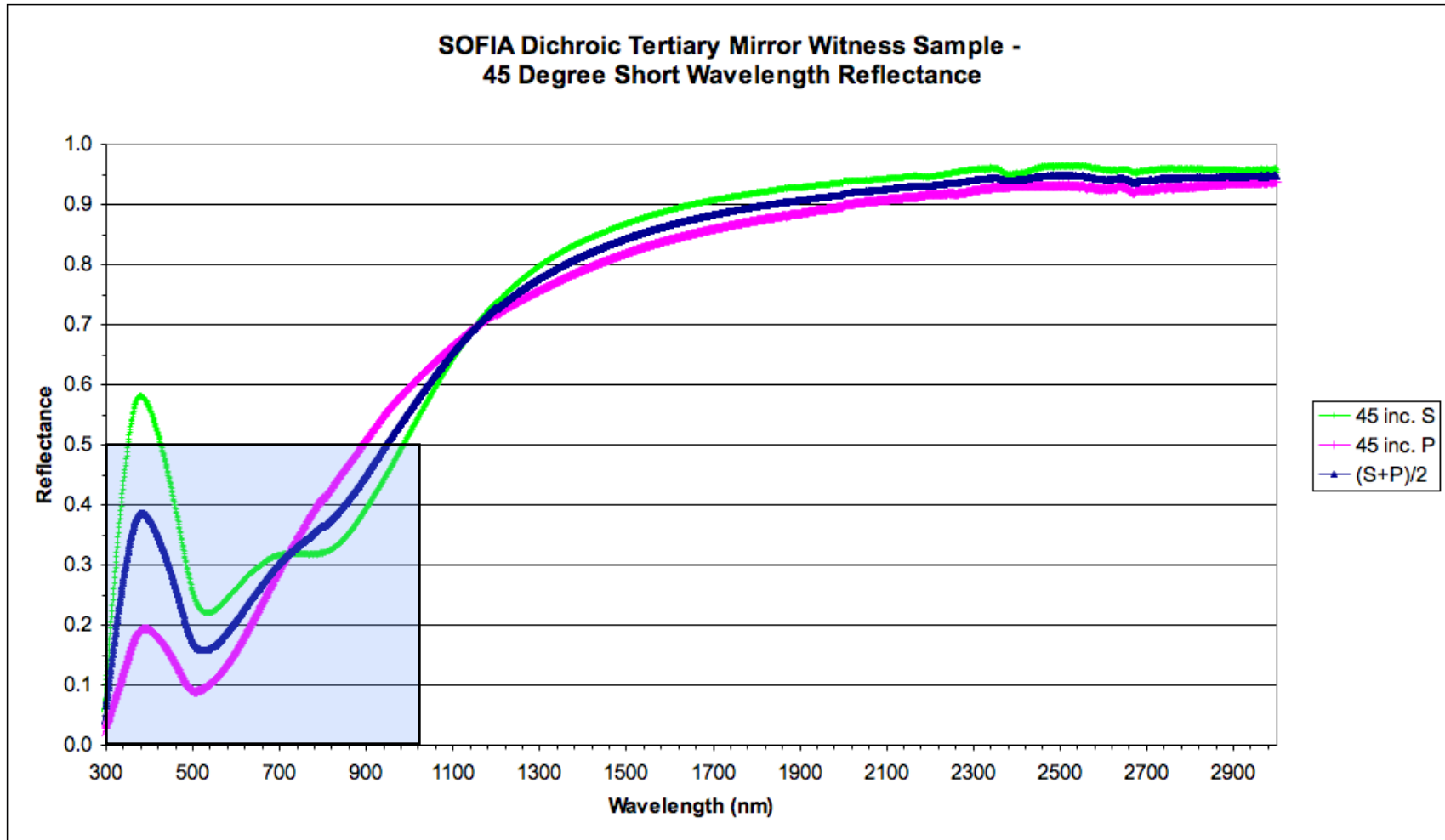
- Evaluate image quality budget
 - Seeing due to shear layer turbulence and cavity (dome) seeing
 - Wavelength dependent; FLIPO configuration important
 - High-speed imaging to freeze shear layer
 - Optical figure and alignment
 - Shack-Hartmann wavefront sensing capability
- Evaluate image motion (jitter, drift)
 - Very stiff structure
 - Frame rates to 2 KHz continuous, 10 KHz burst
 - Accurate timing
- Evaluate pointing accuracy
 - Accurate focal plane mapping to telescope and sky
 - Low distortion

HIPO Configuration - Optical and Mechanical

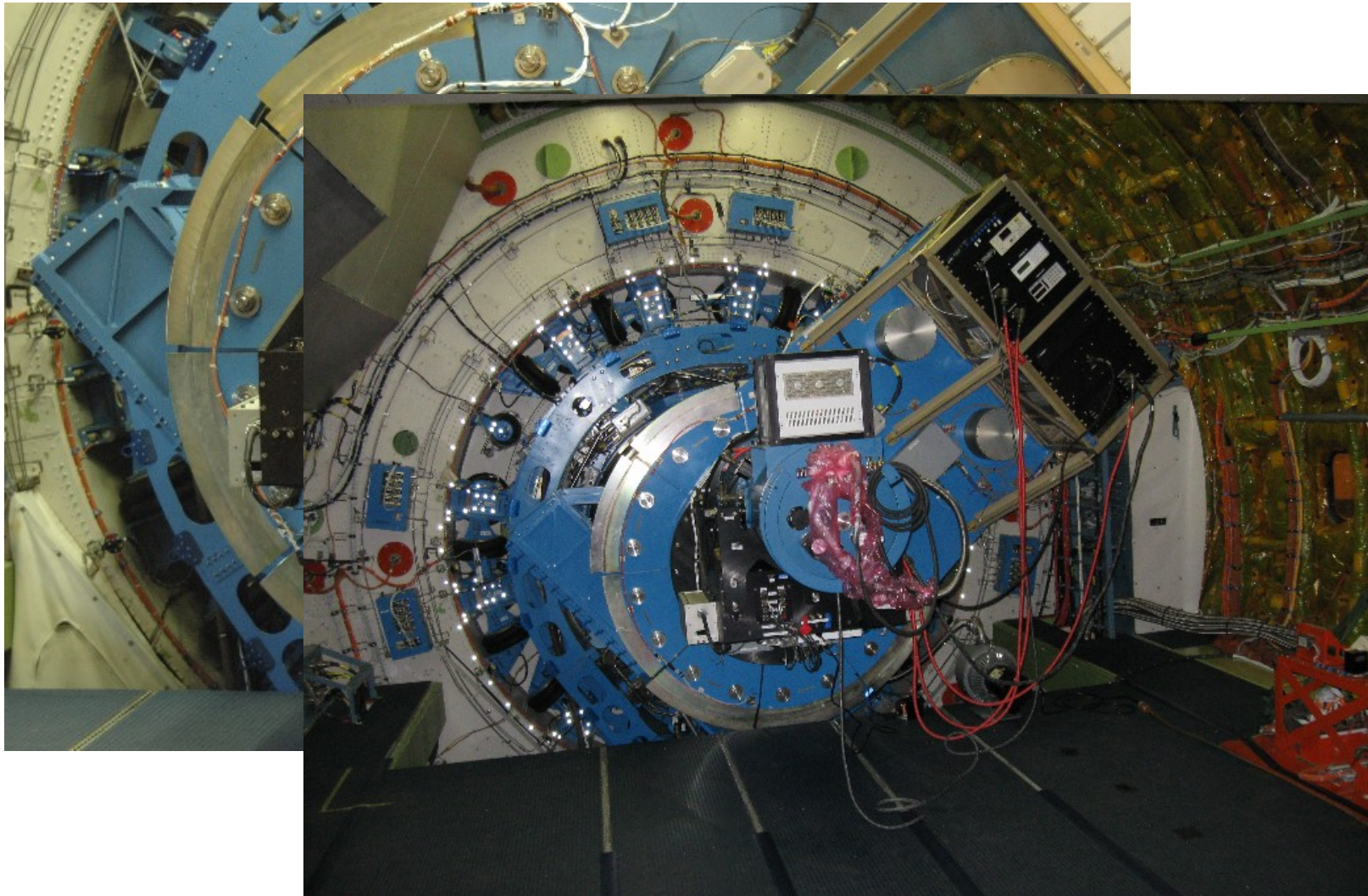
- Configuration Options
 - 1. One or two optical channels
 - Internal dichroic beamsplitter
 - 2. FLITECAM co-mount (aka FLIPO)
 - Gold dichroic beamsplitter
 - Throughput reduction
 - 3. Gate valve window
 - Eliminates possible seeing issue
 - 4. Bare CCD (no reimaging optics)
 - Major reconfiguration, not shown
 - ~30% better throughput
 - ~1' field at 0.055"/pixel
 - Binning speed penalty



TA Configuration – Dichroic Tertiary



HIPO (June) and FLIPO (August & October)

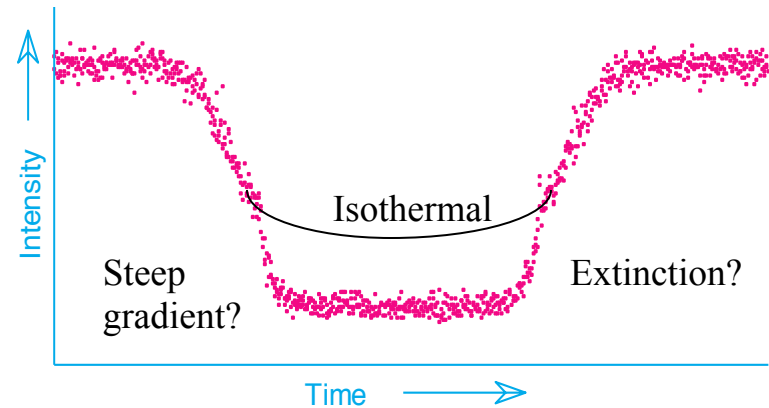


SCAI Overview

- Flight Series Overview
 - Telescope and Observatory engineering, characterization and test
 - Partial commissioning of HIPO, FLITECAM, and FLIPO
 - Demonstration science observations
- June, 2011
 - Two flights, key functional tests successfully completed
 - Fast Diagnostic Camera (FDC) flown in place of FPI
 - Successful Pluto occultation observation
- August, 2011
 - Several line-ops, FLIPO configuration.
 - Flights cancelled due to primary mirror problem.
- October, 2011
 - Four flights, FLIPO configuration
 - Observatory test and characterization
 - FLITECAM and FLIPO partial commissioning
- December, 2011
 - Three flights, primarily focused on active mass damper tests

Old Slide of 1988 KAO Pluto/P8 Light Curve

- Differential refraction is the main cause of fading of the star
- Extinction by aerosols *might* occur
- Refractive lightcurves can be inverted to provide temperature profiles in a region between UVS and radio occultations.
- Emphasis is shifting to central flash events.



Pluto/P8 occultation, 1988

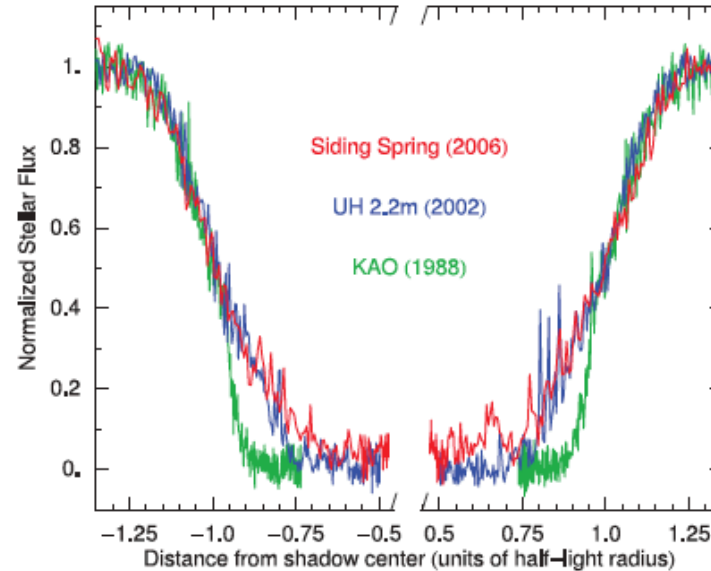
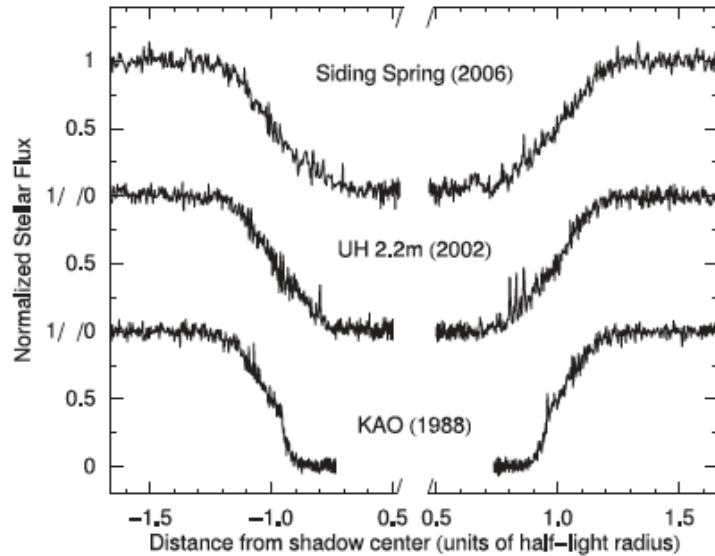
Elliot, *et al. Icarus* 77, 148-170 (1989)

- Spatial resolution is limited by diffraction, ($\sim 1\text{-}2$ km), the angular diameter of the occulted star, and the lightcurve S/N ratio

Examples of airborne planetary atmosphere occultation results:

- Discovery of the central flash phenomenon
- Discovery of Pluto's unusual atmospheric structure

Pluto Occultation: Vertical Structure



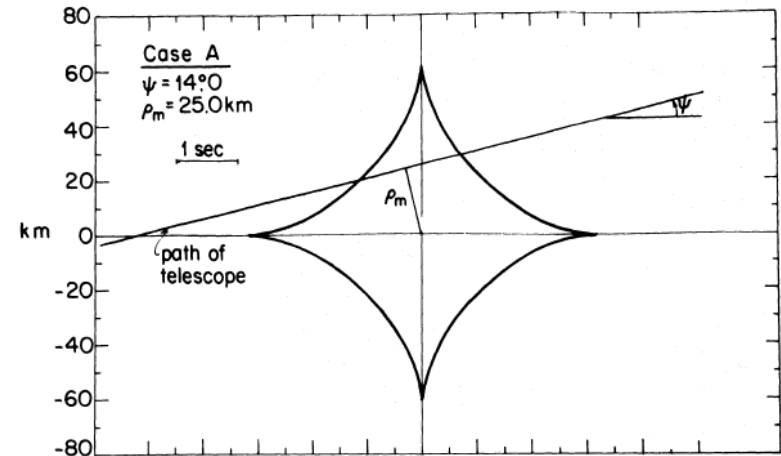
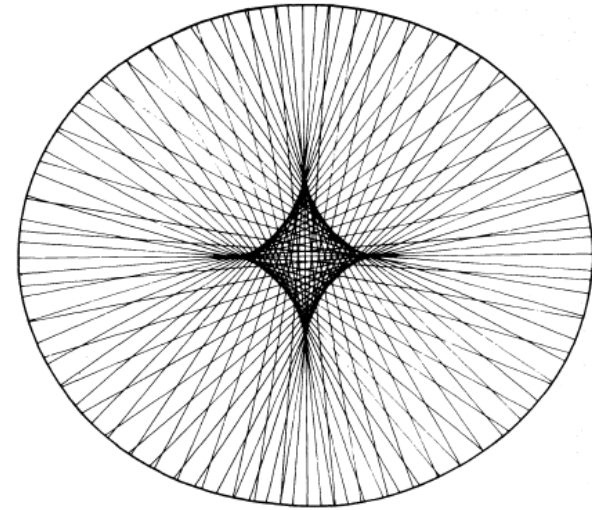
Elliot, et al.
AJ 134, 1 (2007)

- Morphology of occultation light curves changing
- Uncertainty regarding extinction vs. thermal gradients
 - 2002 event showed higher lower baselines in the near-IR
 - Might be sub-micron haze or nearby faint red unocculted star
- Resulting uncertainty in radius of solid surface
- What is New Horizons going to see in July 2015?

Pluto Occultation: Central Flash

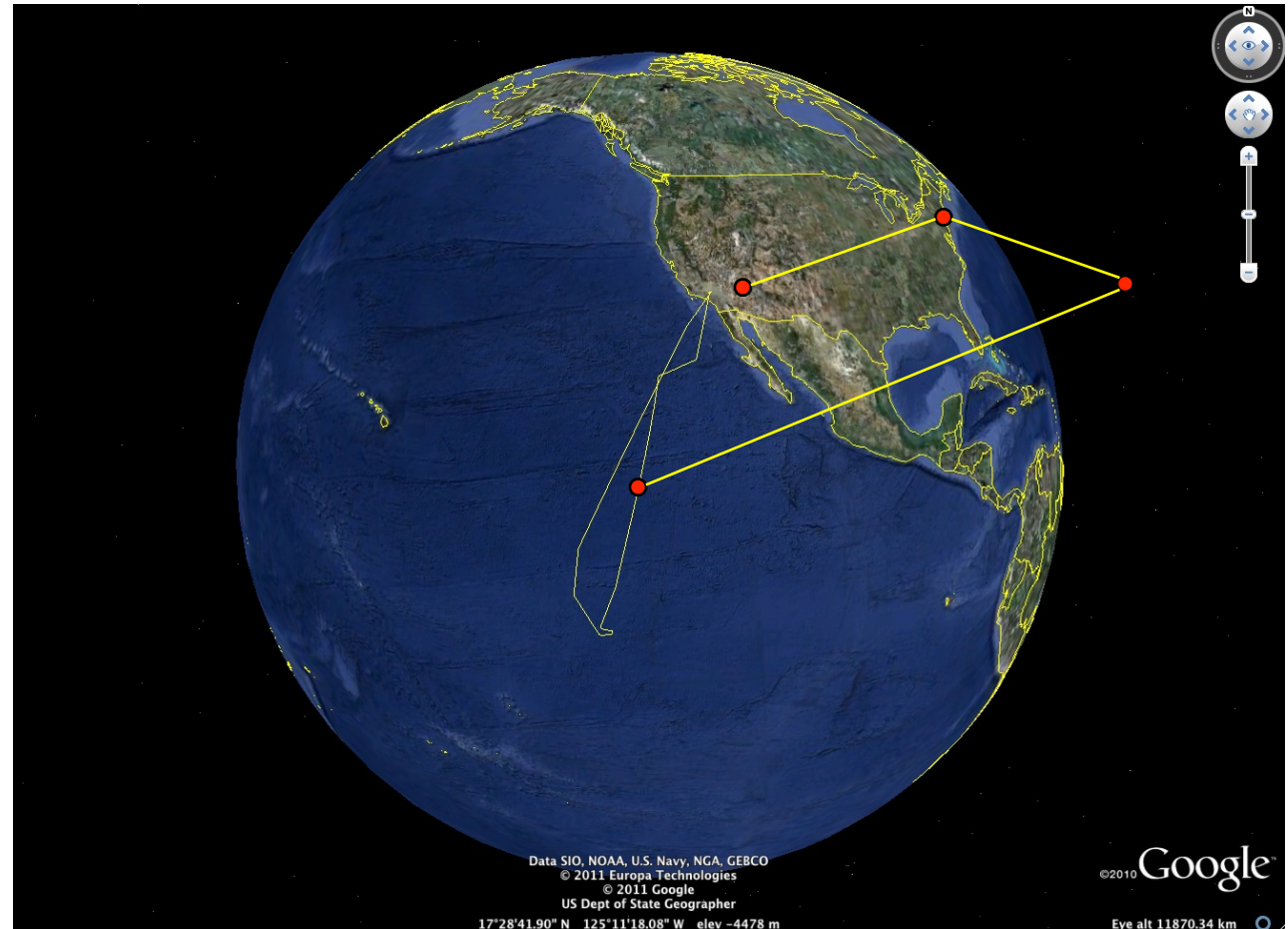
- Occurs due to focusing around the limb of the planet
- Shape is the evolute of the ellipse
- Characteristic size is the planetary radius times the oblateness of the isobars
- Sensitive to structure at lower altitude
- Zonal winds can be important
- Actual brightness distribution is continuous and complex
- Off-center tracks are asymmetric

Elliot, et al., ApJ 217,661 (1977)



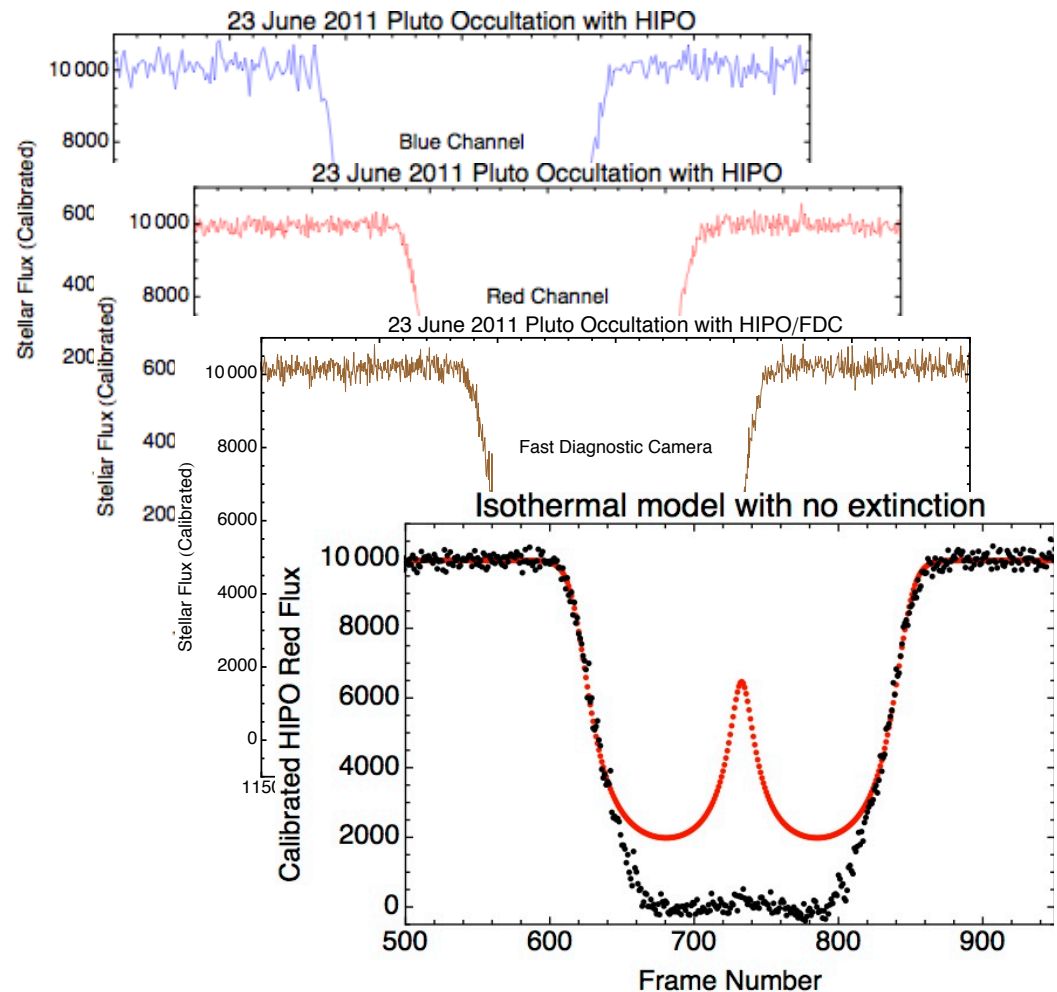
Pluto Occultation Observational Circumstances

- Plan of attack:
- Early calibration leg
- Test work
- Final prediction
 - Data from USNO Flagstaff Station
 - ftp to MIT for instant analysis
 - Iridium telephone update to flight deck
 - Flight plan updated
- Turn at updated time
- Observe event
- Test work on the way home till sunrise



2011 Pluto Occultation Light Curves

- Central brightening seen in all lightcurves
- Post-event fit to two chords indicates impact parameter ~ 100 km
 - Solution supported by USNO observation at high airmass
- Expected to see a much brighter and sharper central flash than this
 - Strong thermal inversion?
 - Extinction?
 - If so, episodic



Results and Issues

- Vertical Profile
 - There has to be a thermal inversion somewhere – cold surface
 - Pure inversion models need very steep gradients
 - Pure haze models are hard on the central flash
 - Maybe both things are going on? Difficult problem.
 - FLIPO can help crack this nut
- Central Flash
 - Can't support much extinction
 - Off-center position
 - Possibly due to simple geometry
 - Possibly an asymmetry in the atmosphere
- Time Variability
 - Structure is variable and we are under-sampling it.
 - New Horizons will get a very detailed look ... once

Summary

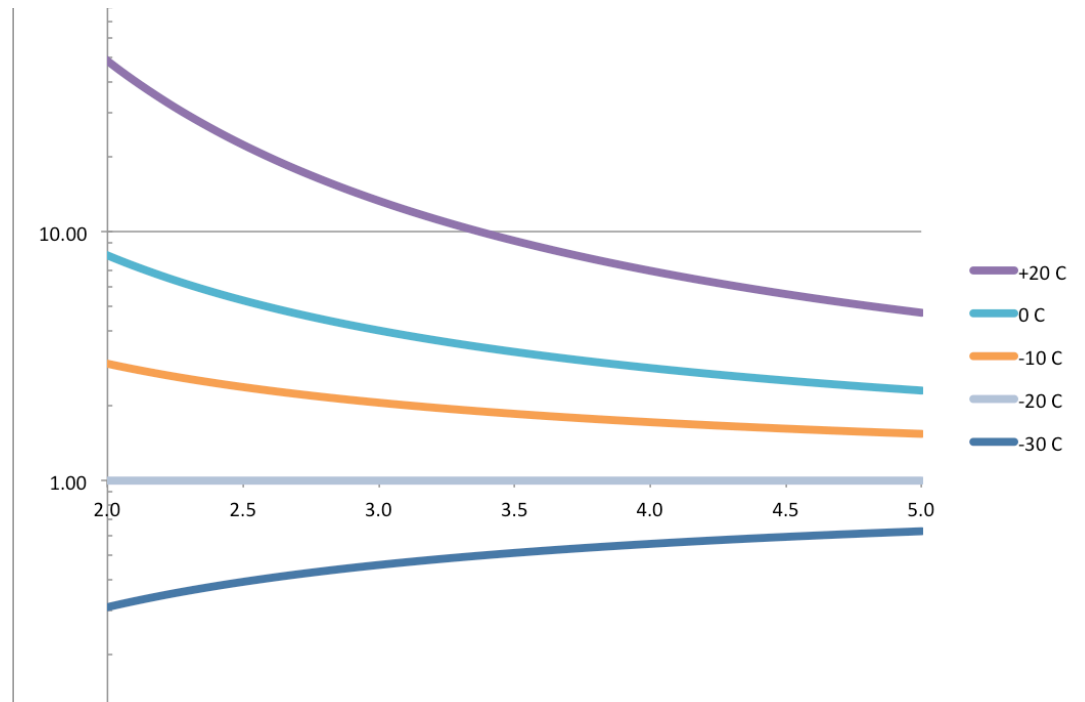
- Unambiguous but weak, broad central brightening seen
- SOFIA chord ~ 100 km from the center of the shadow
 - 4.5 mas prediction astrometry accuracy
- Central flash strongly attenuated
 - Probably in part due to thermal inversion
 - Almost certainly some extinction involved also
 - Possible, but unlikely, that central flash is significantly offset
- Precisely targeted occultation work demonstrated
- Next Steps:
 - Monitor atmospheric structure as New Horizons flyby nears
 - Attempt central chords for best understanding
 - Determine timescales for variability
 - FLIPO observations to search for particle size effects

We thank the SOFIA program for its willingness to attempt this challenging observation at such an early stage of SOFIA science operations and the US Naval Observatory Flagstaff Station for allowing us to use their facilities to obtain our prediction astrometry observations.

Lowell's SOFIA work was supported by a grant from USRA, MIT's prediction work was supported by the NASA Planetary Astronomy Program and the National Science Foundation, and the FDC work was supported by the DSI.

An important FLIPO improvement

- FLIPO improvement
 - FLIPO beamsplitter now runs at +20C
 - SI blower should drop to -20C
 - Background reduced
 - 20x at K band
 - 10x at 3-3.5 um
 - New coating should give another ~2x improvement
 - Reduction in emission from FLITECAM window a further improvement



Ratio of emission from FLIPO beamsplitter to emission at -20C (vertical) vs. wavelength (um)

Airborne Imaging, I

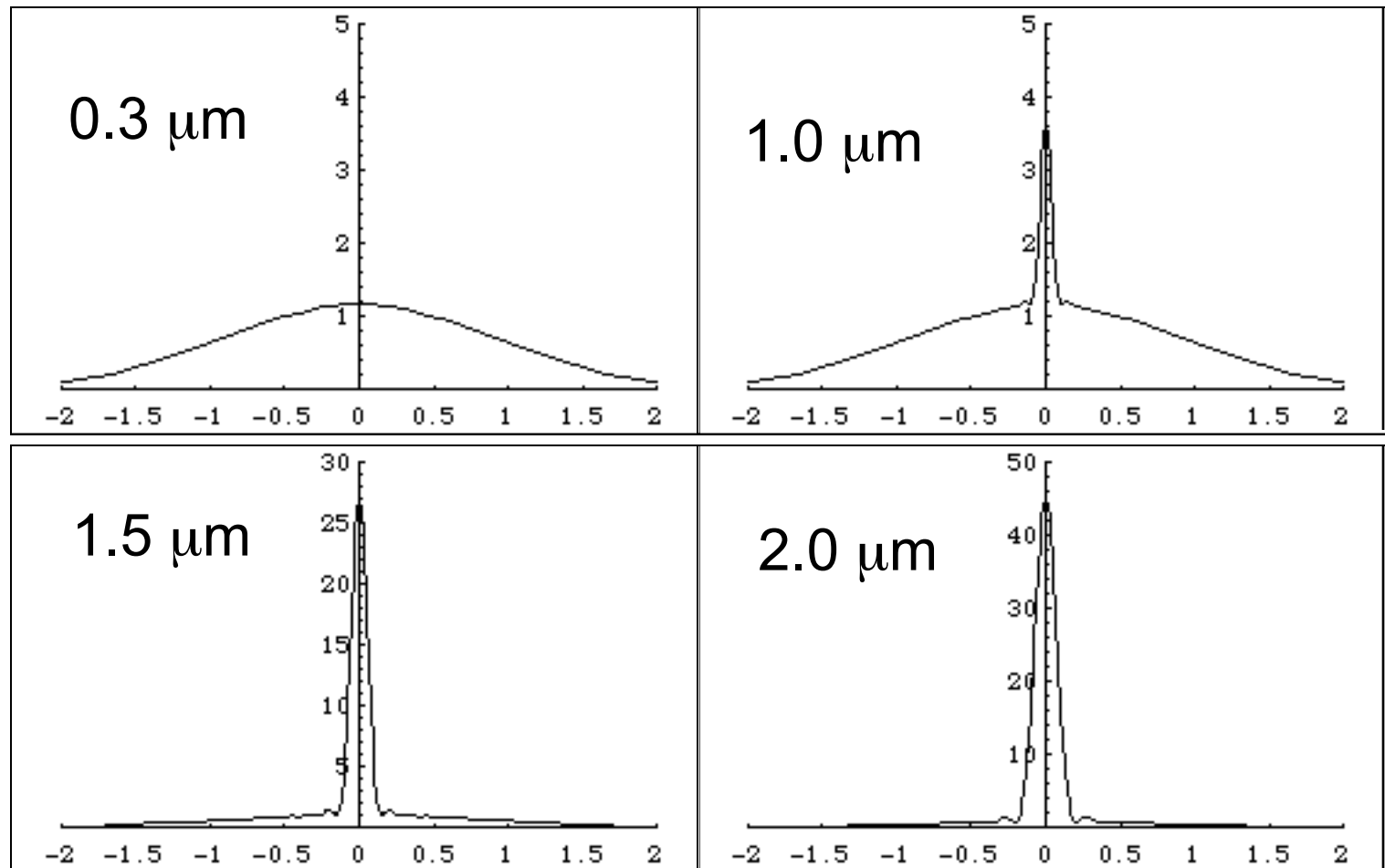
- Free atmosphere seeing presumably negligible
- Shear layer seeing - FAST!
 - Strongly wavelength dependent. Major factor for HIPO.
 - Broad images with extended wings
 - PSF size depends on Mach number and mean density
- Telescope cavity seeing
 - More on this in a minute
- Optical figure error and alignment (includes focus)
 - Separable using Shack-Hartmann analysis
 - Focus has strong temperature dependence. Well understood.
 - Some temperature-dependent astigmatism seen
- Jitter
 - Active work area. Won't discuss this today.

Airborne Imaging, II

Figure from original instrument proposal call

Diffraction and shear layer scattering only

Signs of this behavior appear in FLIPO images



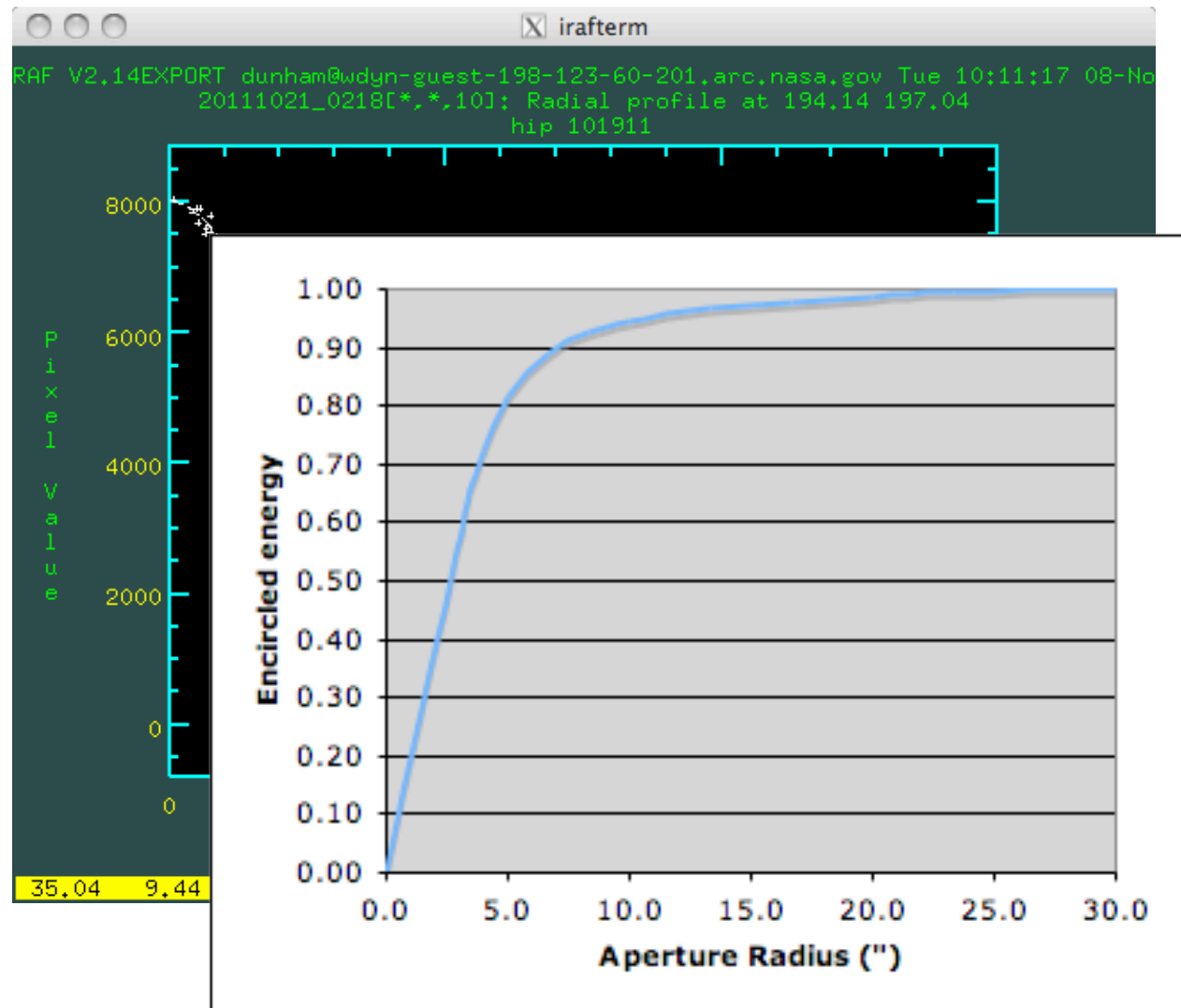
Airborne Imaging, III

Long exposures like this 1 second one have a smooth profile with broad wings, very similar to KAO images.

There is significant encircled energy at large aperture radii, as expected.

Kolmogorov OTF is $C \cdot \exp(-(f/f_0)^{5/3})$. PSF isn't analytic, but has broad wings as observed.

PSF width scales with mean density and with Mach^2

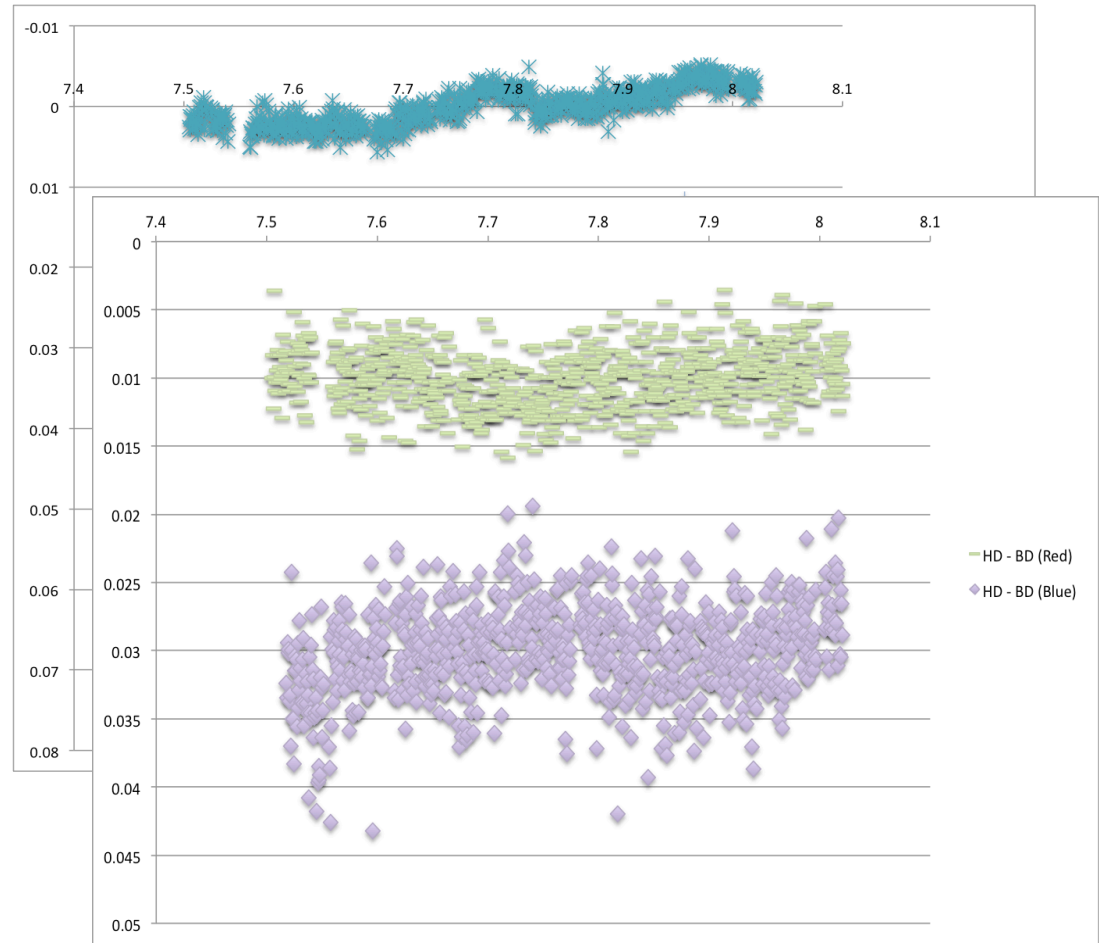


HIPO Photometric Performance

- Broad wings require large photometric aperture
 - Large aperture needed for long-term stability
 - Higher noise from background
- Variability in PSF size impacts simple aperture photometry
 - Best approach likely to be to back this out
- PSF fitting photometry might help
 - Never has in other precise photometry applications
 - PSF isn't analytic so not a simple thing to do
- Scintillation noise less than extrapolated ground-based value
 - Some noise in excess of shot noise seen.
 - May be due to near-field turbulence
 - Plan to test next month

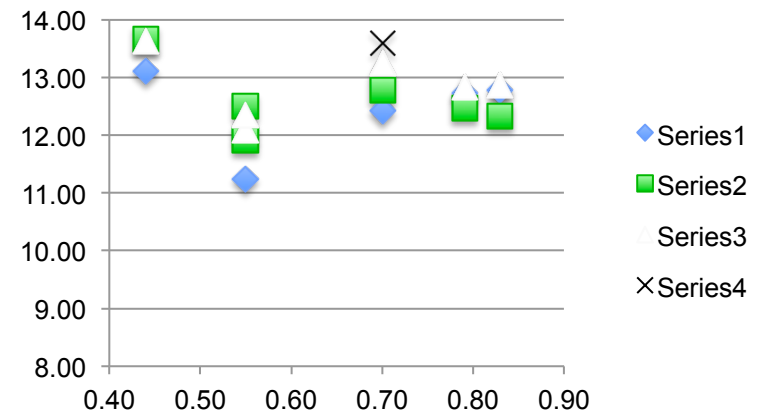
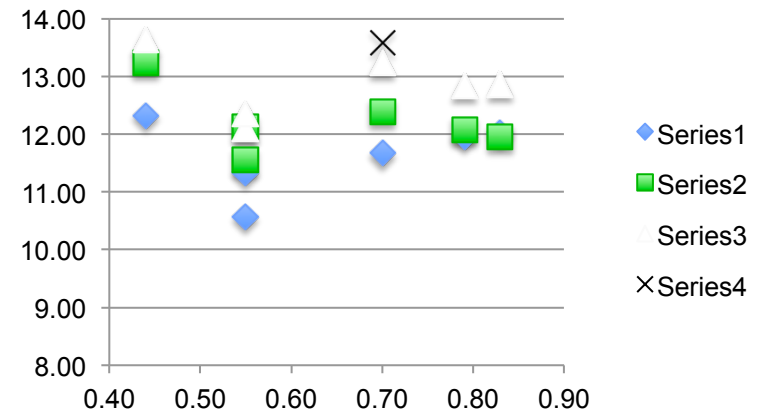
Pushing the Precision Photometry Envelope

- Extrasolar planet transits
 - High precision over several hours
- Test observations
 - Common-mode variation
 - Differential correction not fully successful
- Root cause?
 - Suspect shear layer
 - PSF scales with
 - Square of Mach No.
 - Mean density
 - Observed variation consistent with this idea.
 - Test planned to enable post-facto correction



Cavity Seeing

- Attempted to measure by forcing TA-cavity air ΔT
- Didn't have much success
 - $\Delta T = +3, +2, +2$ C
 - $\Delta T = PM - SMA_T1$
 - Need to get cavity air temp
- Plots: FWHM (pixels) vs λ
 - 12 pixels = 1"
 - Upper plot not altitude-corrected
 - Lower plot corrected
- Bad news & good news:
 - Hard test
 - Environment not bad!
 - We did our homework



Questions?



Chris Johnson, UCLA