Optically Scaled External Occulter Data Analysis

http://umbras.org

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Abstract: **We present analysis of results from an optically scaled external occulter test. The display describes the optical scaling and the results of WASI-UMBRAS occulter tests performed at Fresnel numbers of 10 and 40 since August of 2004.**

This experiment was performed to emulate a hypothetical telescope-occulter space mission designed to directly image extra-solar planets. Although not capable of detecting faint objects around the target star (Polaris), some goals could be achieved:

Experiment Goals

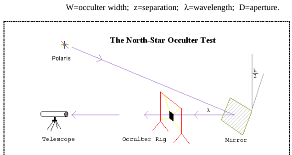
- Characterize non-symmetric occulted diffraction pattern.
- Validate focal-plane alignment sensing technique.
- Demonstrate utility and feasibility of scaled ground testing.

Astrometry and photometry of multiple field sources in numerous sequential images is required.

Optical Scaling Logic

Fresnel Number definition: $F_N = \frac{W^2}{z \cdot \lambda}$ ⇒ $W = \sqrt{F_N \cdot z \cdot \lambda}$

W=occulter width; z=separation; λ=wavelength; D=aperture.



$D \propto \sqrt{z}$

D=4m;
z=20,000 km

D=9mm;
z=100m

The optical scaling is directly derived from:

1. Preserving ratio of occulter size and telescope aperture from the hypothetical space telescope-occulter system.
2. Preserving ratio of apparent sizes of the PSF and occulter as viewed by the telescope.

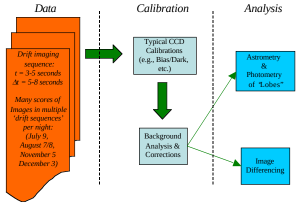
"Polaris Test" Demonstration Equipment

- F/5 Televue NP 101-mm refractor.
- Masked down to 11 & 24 mm.
- Optional Barlow: system f/# from 50 - 100.
- Mounted atop 8"+ alt/az for stability.
- ST-7X, TEC-cooled, 768x512 CCD camera.
- M675X laptop data acquisition/storage.
- Green laser for optical alignment.

- Hand-crafted (P. Henze) occulter-rig.
- 12-inch diameter light shroud tube.
- Square-rail optical bench.
- Mid-tube occulter placement slot.
- 1- and 2-inch square occulters.
- 9 "1/10th-wave flat & mirror cell (GSFC).
- Alt-az mirror mount.
- Red laser for optical alignment.

Data & Processing Pipeline

Data processing and analysis required construction of special reduction code.



The Data

The data obtained for the passive behind-the-occulter-drifts were typically 3- or 5-second integrations through 11-mm (w/ 25-mm occulter) or 25-mm (w/ 50-mm occulter) circular apertures, at 5- or 8-second cadences. The occulters were square in shape, separated from the telescope by ~ 100-metres.

Results displayed in this poster feature the two most 'central' occultations achieved.

Ancillary data for calibration purposes were obtained including:

- Mirror drift sweeps across the optical flat (to characterize image scale, reflectance uniformity, and field flatness)
- Exposure sweeps (detector linearity checks)
- Tracked star images (not through the optical flat--to characterize the unocculted PSF)

Occultation datasets obtained in 2004:

March 13:	First attempts using a 6-wave rectangular flat.
April 09:	Alignment technique tests; 6-wave rectangular flat.
May 29:	Additional equipment(upgrades) testing.
July 09:	Drift and observing technique testing with new 9-inch 1/10th-wave optical flat mirror.
August 07:	Mirror and Exposure Sweeps. First high-quality occultation at F_N=10, near-central pass.
November 05:	7 occultation sequences at F_N=10 and 40 + calibrations. One near-central pass at F_N=40.
December 03:	7 occultation sequences at F_N=10 and 40 + calibrations. Peak focus unreachable.

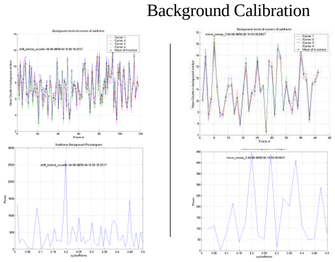
1.9 GB (2564 FITS files) of occultation & calibration data.

Calibrations

The data were calibrated with typical steps:

- A super-bias was applied to each frame.
- With 3-5 second integrations, dark current is small and currently ignored in this report.
- Photometric tilts and background around the target star were corrected with a linearly extrapolated 4-corner surface fit to the mean backgrounds of 400-pixel boxes surrounding the star path during each drift.

Background Calibration



Low-signal level photometry was an important goal, so accurate background corrections were sought.

Example time-series background photometry is shown in the upper panels for the August 08 drift sequence (left) and a mirror sweep (right), with corresponding FFTs below showing time-correlation checks.

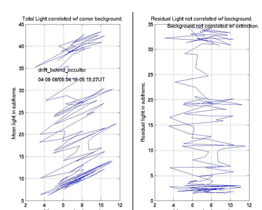
Some of the drift sequences contained hints of a weak ~20-25-second background level periodicity. Correlation was reduced with background removal (not shown).

Did visible cirrus cause extinction? How good was background subtraction?

Some individual drifts and mirror sweeps showed variable photometry as a function of time and location of the target on the mirror (the target star drifts across the field during an occultation set), typically near the edges of the mirror.

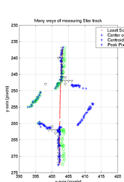
Background correction allowed a check for high-altitude cloud extinction.

Plotting successive full-frame photometry versus background--after background removal--allowed verification of whether the background correction was complete.



Before background subtraction   *After background subtraction*

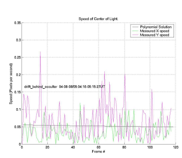
Path Measurement and Drift Speed



In the August 08 sequence, the star wobbled around its mean path by ~ 0.5 arcseconds.

The wobble in the post-August tests was much greater and largely due to vertical refraction, probably due to the horizontal path lying close to the ground and local atmospheric conditions.

Star path determination was useful as an image scale check and for determining the path of the star behind the invisible occulter. Velocity checks verified mirror stability.

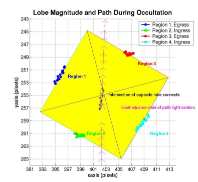


Speed of star varies significantly from frame to frame, but no large discontinuity (mirror shift) is seen.

Results

Analysis is ongoing, pending acquisition of comparison data with higher performance occulters. Preliminary reductions show that light suppression levels appear to be in accord with theory and that scaling relations hold. The reductions indicate that deducing the location of the star to good accuracy behind simple occulter shapes is possible.

Example Drift Path Behind Occulter



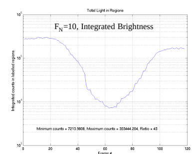
Occulting square is traced by light lobes (diffraction)

Most drift sequences did not yield near-centrality occultations. However, one good candidate at F_N=10 and another at F_N=40 was achieved.

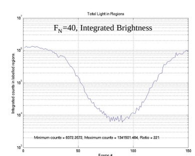
Astrometry of the drifting star (Polaris) centroid while out of occultation allowed a path determination. Shown at left is the derived track relative to the derived occulter position and orientation in the August 08 data set.

For the cases of deep central occultations, the diffraction lobes allowed determination of the relative star and occulter locations.

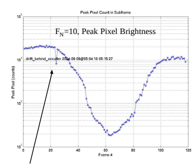
Occultation Comparison: F_N=10 vs F_N=40



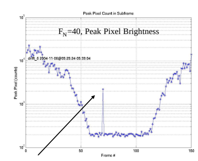
The occultation did not appear symmetric in signal level at the beginning and end due (in part) to the star remaining behind the occulter support rod at the end of this drift sequence.



More than 99% of starlight is suppressed at mid-occultation for this simple occulter. Total signal from a single frame scene 'flash' illumination (see below) is small.



This single-frame peak-pixel signal-level drop with no corresponding drop in integrated light (see above panel) indicates a telescope or optical bench "bump".

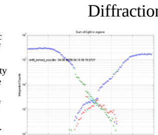


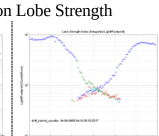
Peak pixel spike is due to a 'flash' illumination of the scene for purpose of verifying occulter location during eclipse.

Compare with F_N=10 panel at left--peak pixel brightness at higher F_N is very flat-bottomed.

Diffraction Lobe Strength

Logarithmic measures of diffraction lobe intensity appear to be good measures of occultation progression.

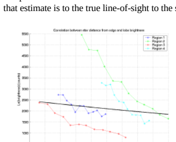




When diffraction lobes are confused, the ratio of integrated light in a region to the peak pixel intensity gives another measure of occultation progression.

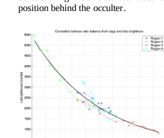
Relative Lobe Intensity Measures Alignment

Plotting lobe strength vs. distance from a presumed star position behind the occulter shows how close that estimate is to the true line-of-sight to the star.



Least-squares path: Erroneous predicted position.

A line connecting opposite diffraction lobe centers-of-light is an accurate measure of star position behind the occulter.



-- With a correction applied to the star position.

Acknowledgements

This work was supported in part by Computer Sciences Corporation, Laurel, Md. and by the Space Telescope Science Institute which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. Special thanks to the Westminster Astronomical Society for their support in preparing and conducting the tests. The data reduction and analysis was performed largely as a masters degree class project in JHU's *Optics and Matlab* course instructed by Eric Rogala in the fall of 2004.