Progress on the occulter experiment at Princeton

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ABSTRACT

An occulter is used in conjunction with a separate telescope to suppress the light of a distant star. To demonstrate the performance of this system, we are building an occulter experiment in the laboratory at Princeton. This experiment will use an etched silicon mask as the occulter, with some modifications to try to improve the performance. The occulter is illuminated by a diverging laser beam to reduce the aberrations from the optics before the occulter. We present the progress of this experiment and expectations for future work.

1. INTRODUCTION

An important element of NASA’s strategic plan is the search for and characterization of exoplanets, particularly terrestrial planets within the habitable zone of their parent star. A discovery of an Earthlike planet, with atmospheric constituents indicative of life, would revolutionize planetary science. Numerous researchers are studying various concepts, from coronagraphy to multi-satellite interferometry, to create the high-contrast needed to study exoplanets. One such approach is the use of an external occulter.

An external occulter, or \textit{occulter} for short, is an opaque, specially-shaped screen which is placed in front of a telescope for high-contrast imaging. Its purpose is to eliminate most of the coherent light from a star before it reaches the telescope optics, but to allow incoherent light from any nearby objects to enter. Unlike conventional coronagraphic approaches, which are limited by the quality of the internal telescope optics and must be accompanied by complex wavefront control systems, occulter-based systems can use conventional telescope optical tolerances as the bright light from the star never enters the telescope. In order to image an extrasolar planet, the occulter must be designed to account for diffraction so that the overall imaging system achieves a contrast (the ratio between the intensity of the bright object to that of the target) of better than $10^{-10}$ over as broad a band of wavelengths as possible and at as small an angle as possible relative to the star (the inner working angle). This sets design limits on the occulter (such as size, shape and distance).

The idea of using an occulter to image planets was first proposed in 1962 by Lyman Spitzer at Princeton.\textsuperscript{1} Since then there have been a number of occulter-based mission concepts incorporating different apodization approaches.\textsuperscript{2–5} All of these approaches share the same basic architecture: a large occulting screen on a separate spacecraft flying far (tens to hundreds of thousands of kilometers) from its associated telescope. This distance gives the occulter a small angular size, theoretically allowing objects within 0.1 arcseconds or less of a star to be imaged.

Previous occulter experiments have been performed by laboratories at the University of Colorado\textsuperscript{6} and Northrop Grumman Space Technologies (NGST)\textsuperscript{7} to verify performance of hypergaussian occulter shapes. At Princeton, we are undergoing a series of similar tests to verify our optimized designs\textsuperscript{5} in monochromatic and broadband light. In this paper, we will provide an overview of the theory and experimental setup, and report on the progress of the experiment.

2. BACKGROUND

The procedure for creating occulter shapes by optimization is explained in depth in Vanderbei et al. 2007.\textsuperscript{5} We will review it briefly in Sec. 2.1 and 2.2.
2.1 Propagation framework

Our analytical work is based on Babinet’s principle, which is just a special case of the superposition principle satisfied by solutions to linear differential equations. In this context, the principle tells us that the sum of the electric field from light propagating through a hole \(E_h\) and the field from light propagating past the complement of that hole, i.e. our occulter, \(E_o\) is the same as that of light passed unobstructed through that space \(E_u\). We can write this as:

\[
E_o = E_u - E_h
\]  
(1)

This simple substitution is useful because it allows us to replace the integral that directly defines \(E_o\), which is an integral that extends to infinity and is hence difficult to compute numerically, with an integral that simply extends to the tips of the occulter and is much easier to compute using simple numerical quadrature. This equation provides the basis for all of our optimization calculations. \(E_u\) can be found exactly by solving the Helmholtz equation; we assume that the incoming wave from the star is the plane wave solution.

To be manufacturable, an occulter needs to be a simple opaque mask of some predetermined shape. In other words, at some places it is solid and allows nothing to pass whereas at other places it is open and transparent. We approach the goal of designing an opaque occulter in a roundabout way: we begin by assuming the occulter to be apodized, with an azimuthally-symmetric apodization. With this assumption, the occulter-telescope system can be modeled by a single Fresnel integral:

\[
E_o(\rho) = E_0 e^{\frac{2\pi i}{\lambda z}} \left( 1 - \frac{2\pi}{i\lambda z} \int_0^R A(r) J_0 \left( \frac{2\pi \rho}{\lambda z} \right) e^{\frac{2\pi i}{\lambda z} (r^2 + \rho^2)} r dr \right),
\]  
(2)

where \((r, \theta)\) are polar coordinates in the plane of the occulter, \((\rho, \phi)\) are polar coordinates in the plane of the telescope aperture, \(A(r)\) is a function in \([0, 1]\) which describes the attenuation of the electric field due to the occulter, \(\lambda\) is the wavelength of light, and \(z\) is the distance between the telescope and the occulter. We can convert this apodized formulation into a binary occulter by converting the edges into shaped spikes, called petals. The idea is that if a circle of radius \(r\) is drawn, some fraction of the circumference will be covered by a petal. We make the edge of a petal follow \(\theta = \frac{\pi}{N} A(r)\), where \(N\) is the number of petals, and so the fraction of that circle covered at \(r\) will be \(A(r)\), approximating the continuous attenuation with a discrete function.

Analytically, the net effect is to add perturbation terms to the integral in Eq. 2:

\[
E(\rho, \phi) = \left. E_0 e^{\frac{2\pi i}{\lambda z}} \right| \left( 1 - \frac{2\pi}{i\lambda z} \int_0^R A(r) J_0 \left( \frac{2\pi \rho}{\lambda z} \right) e^{\frac{2\pi i}{\lambda z} (r^2 + \rho^2)} r dr \right)
\]

\[
- E_0 e^{\frac{2\pi i}{\lambda z}} \sum_{j=1}^\infty \frac{4(-1)^j \pi}{i\lambda z} \left( \int_0^R e^{\frac{2\pi i}{\lambda z} (r^2 + \rho^2)} J_{jN} \left( \frac{2\pi \rho}{\lambda z} \right) \sin \left( \frac{j\pi A(r)}{\pi z} \right) r dr \right) \times (\cos \left( jN(\phi - \pi/2) \right)),
\]

where \(N\) is the number of petals around the edge. High-order Bessel functions rise very slowly near 0, so adding a large number of petals ensures that the perturbation due to petals is negligible within the shadow.

2.2 Optimization

We can use Eq. 2 as the basis for a linear optimization, by discretizing the profile \(A(r)\) and the integral, and constraining the real and imaginary parts of the integral by a contrast at each value of \(\rho\). We also ignore the \(e^{\frac{2\pi i}{\lambda z}}\) term, as it disappears in the intensity. Ideally, we would use \(Re(E_o)^2 + Im(E_o)^2 \leq 10^{-c}\) as our constraint, but the optimization is simplified by making it linear, so we make the slightly conservative approximation: \(-10^{-c/2}/\sqrt{2} \leq Re(E_o) \leq 10^{-c/2}/\sqrt{2}\). We can extend this over a broad spectral band by discretizing the target spectral band and repeating the constraints at each wavelength. Other conditions, such as monotonicity and smoothness, can be enforced to ensure the profile developed is physically feasible.
Lastly, we can improve the performance of the optimization by making the contrast (or the square root of contrast) one of the optimization variables, and using this as the cost function. This guarantees that, for the linear problem, we always find the deepest contrast possible given the set of parameters we input: $z$, $R$, etc. This optimization problem can be written out as:

\begin{align}
\text{Minimize : } & \quad c \\
\text{subject to : } & \quad Re(E_o(\rho; \lambda)) - c \leq 0 \\
& \quad -Re(E_o(\rho; \lambda)) - c \leq 0 \\
& \quad Im(E_o(\rho; \lambda)) - c \leq 0 \\
& \quad -Im(E_o(\rho; \lambda)) - c \leq 0 \\
& \quad \forall \quad \rho \leq \rho_{\text{max}}, \quad \lambda \in [\lambda_{\text{min}}, \lambda_{\text{max}}] \\
& \quad A(r) = 1 \quad \forall \quad 0 \leq r \leq a \\
& \quad A'(r) \leq 0, \quad |A''(r)| \leq \sigma \quad \forall \quad 0 \leq r \leq R.
\end{align}

### 2.3 Scaling

Occulters in space are large and far away from their telescopes to achieve the necessary inner working angle; designs such as THEIA\textsuperscript{8} and NWO\textsuperscript{4} are tens of meters across, and operate at tens of thousands of kilometers of separation. For a laboratory setting, we wish to create a version of the occulter that produces the same electric field as a full-size occulter; we can do this via scaling relations, by keeping the Fresnel numbers, $N_o = \frac{z^2}{\lambda z}$ and $N_t = \frac{\rho^2}{\lambda z}$, constant.

Consider a small occulter, scaled from the full size by a constant $a$, illuminated by a collimated beam. Letting $r' = r/a$, $R' = R/a$, $\rho' = \rho_0/a$, and $z' = z/a^2$, Eq. 2 becomes:

\begin{equation}
E_o(\rho) = E_0 e^{ikz} a^2 \left(1 - \frac{2\pi e^{-ikz}}{i\lambda z} \int_0^{R'} A'(ar') J_0 \left(\frac{2\pi r'r'}{\lambda z}\right) e^{\frac{2\pi r'r'^2}{\lambda}} dr'\right).
\end{equation}

Ignoring the constant phase factor, this is identical to Eq. 2, showing that scaling under constant Fresnel number ensures the equivalent field. We will drop the phase factor for subsequent calculations, as it has no effect on the intensity measurements.

### 2.4 Outer ring

The biggest challenge in performing a laboratory-scale test arises in physically placing the occulter. In space, the occulter is not attached to any additional structures that may cause diffraction. In a lab setting, the materials used to place the occulter can have a sizable effect on the light diffracted into the shadow at the plane of the telescope; for example, the Colorado experiment in Schindhelm et al. 2007\textsuperscript{6} found that much of the scattered light was from the wires used to hang the occulter in their tunnel.

Our approach to mitigating the diffraction problem is to create a second ring to go around the outside of the occulter, so that the open region around the occulter is annular. Similarly to the optimization of the occulter, we put a smooth attenuation on the outside of this annular opening to create an edge that interferes negligibly with the high-contrast central regions of the shadow. It can effectively be mounted in a hole in a wall, since the only light that needs to pass the occulter goes through this ring. This also keeps stray light to a minimum, as it can all be contained on one side of this “doughnut”. Mathematically, we write the equation for a general shadow from a doughnut-shaped hole:

\begin{align}
E_1(\rho, z) &= \frac{2\pi e^{-ikz}}{i\lambda z} \int_0^{R_1} J_0 \left(\frac{2\pi r}{\lambda z}\right) B(r) e^{\frac{2\pi r^2}{\lambda}} dr + \int_{R_1}^{R_2} J_0 \left(\frac{2\pi r}{\lambda z}\right) e^{\frac{2\pi r^2}{\lambda}} dr
\end{align}
where $B(r)$ and $C(r)$ are apodization profiles. Here $B(r)$ is monotonically increasing, and goes to 1 at $R_1$, while $C(r)$ is monotonically decreasing, starts at 1 at $R_2$, and goes to 0 at $R_3$.

If we let $B(r) = 1 - A(r)$, and $R_1 = R$, then Eq. 6 can be written:

$$E_1(\rho, z) = 2\pi e^{\frac{\pi i \rho^2}{\lambda z}} \left( - \int_0^R J_0 \left( \frac{2\pi r \rho}{\lambda z} \right) A(r) e^{\frac{-\pi i r^2}{\lambda z}} r dr \right) + \int_0^{R_2} J_0 \left( \frac{2\pi r \rho}{\lambda z} \right) e^{\frac{-\pi i r^2}{\lambda z}} r dr + \int_{R_2}^{R_3} J_0 \left( \frac{2\pi r \rho}{\lambda z} \right) C(r) e^{\frac{-\pi i r^2}{\lambda z}} r dr.$$  \hspace{1cm} (6)

We now let $E_\Delta = E_o - E_1$; this is the difference between a perfect copy of the two-spacecraft system and our annular approximation. We would like to make the magnitude of this much smaller than the magnitude of $E_o$, across the region corresponding to the aperture of the telescope. Using Eq. 5 and Eq. 7:

$$E_\Delta(\rho, z) = 1 - 2\pi e^{\frac{\pi i \rho^2}{\lambda z}} \left( \int_0^{R_2} J_0 \left( \frac{2\pi r \rho}{\lambda z} \right) e^{\frac{-\pi i r^2}{\lambda z}} r dr \right) + \int_{R_2}^{R_3} J_0 \left( \frac{2\pi r \rho}{\lambda z} \right) C(r) e^{\frac{-\pi i r^2}{\lambda z}} r dr.$$  \hspace{1cm} (7)

and by defining $D(r) = 1$ for $r \leq R_2$, $D(r) = C(r)$ for $R_2 < r < R_3$, and $D(r) = 0$ for $r \geq R_3$, we can write:

$$E_\Delta(\rho, z) = 1 - 2\pi e^{\frac{\pi i \rho^2}{\lambda z}} \int_0^{R_3} J_0 \left( \frac{2\pi r \rho}{\lambda z} \right) D(r) e^{\frac{-\pi i r^2}{\lambda z}} r dr.$$  \hspace{1cm} (8)

which is just our original Fresnel integral Eq. 2, formulated as an optimization problem with different parameters. Effectively, we are designing a second occulter for the outside of the hole, using $D(r)$ in place of $A(r)$. For this optimization, the “shadow” of $E_\Delta$ is the area in which our doughnut gives the same shadow as the occulter; we want both our $\rho_{\text{max}}$ to be greater than the size of the shadow, and our contrast to be deeper than the depth of the shadow. When these conditions are met, the shadow from the doughnut will be negligibly different from the shadow of the idealized setup: an occulter floating freely in space.

As a design note, $R_3$ is much bigger for the same $z$—that is, larger angular size of the new “occultor”—so the shadow will be easier to make in the optimization. The original occulter was defined as 1 for $r \leq a$; as a rule of thumb we might expect $a/R \approx R_2/R_3$. In practice, a design might make $R_3$ 2-4 times bigger than $R$. This size is a design trade-off: larger $R_3$ lets through more light, but also requires the collimated beam to be larger.

Most designs made this require the petals to be manufactured down to a width of 0 between the end of the inner ring petals and the beginning of the outer ring petals. Even if the two are chosen so they meet, the width may be so small as to be unmanufacturable. To compensate for this, we can introduce structural elements which change the total transmission of the mask without affecting the high-contrast regions by scaling the apodization downward. If we choose a constant $c$ such that $0 \leq c \leq 1$, and multiply the apodization by this factor,

$$E_{1c}(\rho, z) = 2\pi e^{\frac{\pi i \rho^2}{\lambda z}} \left( - \int_0^R J_0 \left( \frac{2\pi r \rho}{\lambda z} \right) cA(r) e^{\frac{-\pi i r^2}{\lambda z}} r dr \right).$$
\[ + \int_{0}^{R_2} J_0 \left( \frac{2\pi r \rho}{\lambda z} \right) ce^{\frac{\pi i}{\lambda z} r^2} r dr \\
+ \int_{R_2}^{R_3} J_0 \left( \frac{2\pi r \rho}{\lambda z} \right) cC(r)e^{\frac{\pi i}{\lambda z} r^2} r dr \]
\[ = cE_1(\rho, z) \quad \text{(10)} \]

When the apodization is converted into petals, this has the effect of introducing a set of wedge-shaped bars between each hole in the design; the width of these bars can be adjusted by changing the constant multiplier. This ensures a minimum width for the bars, so that the holes can be etched out of a single piece of material without the occulter in the center falling out. The shape of the azimuthally-symmetric main shadow will be unchanged, though the additional terms from the petals will be different, due to the \( \sin A(r) \) in Eq. 3. Fortunately, choosing appropriately large numbers of petals will ensure this is not an issue.

### 2.5 Diverging beam variation

One difficulty with a collimated beam setup is that it requires the light hitting the occulter to be a plane wave; unfortunately, any collimating mirror will introduce aberrations that will affect the wavefront at the occulter and subsequently the shadow of the occulter downstream. We can eliminate this collimating optic by modifying the setup to use a diverging beam rather than a collimated beam. Suppose the incident wave on the doughnut is a spherical wave, rather than a plane wave:

\[ E_{\text{inc}} = E_2 \frac{e^{\frac{2\pi i \sqrt{\rho^2 + r^2}}{\lambda}}}{\sqrt{r^2 + h^2}}, \]

where \( h \) is the distance along the \( z \)-axis from the source to the occulter. If the Fresnel condition

\[ h^3 \gg \frac{\pi}{4\lambda} [r^2 + \rho^2 - 2r\rho \cos(\theta - \phi)]_{\text{max}}^2 \]

is met, then we can approximate this by a parabolic wave:

\[ E_{\text{inc}} \approx E_2 \frac{e^{\frac{2\pi i h}{\lambda}}}{h} e^{\frac{\pi i h^2}{\lambda}}. \]

Suppose we wish to propagate the light a further distance \( z_h \) before letting it hit the camera. The electric field from a hole is then:

\[ E_h(\rho) = \frac{2\pi e^{\frac{2\pi i h}{\lambda}}}{i\lambda z_h} \int_0^{R_d} \frac{E_2}{h} e^{\frac{2\pi i h}{\lambda} \frac{z_h}{\lambda}} A_d(r)e^{\frac{\pi i h}{\lambda} (r^2 + \rho^2)} J_0 \left( \frac{2\pi r \rho}{\lambda z_h} \right) r dr \]

where \( R_d \) is an unspecified outer length and \( A_d(r) \) is an unspecified petal shape. The field from an unobstructed wave is:

\[ E_u(\rho) = E_2 \frac{e^{\frac{2\pi i \sqrt{\rho^2 + (h + z_h)^2}}{\lambda}}}{\sqrt{\rho^2 + (h + z_h)^2}} \approx \frac{E_2}{h + z_h} e^{ik(h + z_h)} e^{\frac{ik h^2}{2(h + z_h)}}, \]

Since Babinet’s principle in Eq. 1 gives that \( E_o = E_u - E_h \), the combination changes Eq. 5 to:

\[ E_o(\rho) = \frac{E_2}{h + z_h} e^{\frac{2\pi i (h + z_h)}{\lambda}} \left( e^{\frac{\pi i h^2}{\lambda}} - \frac{2\pi}{i\lambda z_1} e^{\frac{\pi i z_h}{\lambda z_1}} \right) \int_0^{R_d} A_d(r)e^{\frac{\pi i h}{\lambda} J_0 \left( \frac{2\pi r \rho}{\lambda z_h} \right) r dr}, \]

where we define \( z_1 \) so that \( \frac{1}{z_1} = \frac{1}{h} + \frac{1}{z_h} \).
Let $\gamma = \sqrt{\frac{z_h}{z_1}}$. If we make the substitutions:

\[
\begin{align*}
    u &= r \sqrt{\frac{z_h}{z_1}} = r\gamma \\
    du &= dr \sqrt{\frac{z_h}{z_1}} = dr\gamma \\
    v &= \rho \sqrt{\frac{z_1}{z_h}} = \frac{\rho}{\gamma} \\
    R_c &= R_d \sqrt{\frac{z_h}{z_1}} = R_d\gamma
\end{align*}
\]

and perform some algebraic manipulation, we can rewrite Eq. 16 as:

\[
E_o(v) = \frac{E_2}{h + z_h} \left(1 - \frac{2\pi}{i\lambda z_h} \int_0^{R_c} A_d \left(u \sqrt{\frac{z_1}{z_h}} e^{-\frac{2\pi u^2}{\lambda z_h}} J_0 \left(\frac{2\pi u}{\lambda z_h}\right) \right) du \right).
\]

If we define the occulter profile so that $A_d(u/\gamma) = A(u)$ and $R_c = R$, then we have a shadow that is functionally identical to the one in Eq. 5, except a quadratic phase term. We can also choose a $D_d(u/\gamma) = D(u)$ so that the entire doughnut scales properly. Additionally, we have the freedom to adjust $R_d$ and $h$, which allows us to configure the optical setup as desired. In particular, the mask size can be adjusted, and the size of the PSF at the camera as well.

### 3. EXPERIMENTAL SETUP AND PROGRESS

The occulter experiment at Princeton is located at the Gas Dynamics Laboratory on the Forrestal campus. It consists of a set of optics simulating a star-occulter-telescope system. The experiment is located inside a 40’x4’x8’ enclosure, which is sealed to prevent stray light from entering the experiment. A HEPA filter is kept running continuously to reduce particulate level in the enclosure.

The optics consist of three parts: the diverging beam representing the star, the occulter itself, and the camera. The laser is a 2mW helium-neon laser emitting at 632nm, with 99% of the power in the TEM$_{00}$ mode. The diverging beam is created by expanding the laser beam and focusing it through a pinhole to remove aberrations from the previous optics. As the beam is primarily Gaussian in profile, its shape and propagation properties can be predicted and modeled easily. By choosing the beam size, focal length, and pinhole size correctly, the beam can be made to have the correct radius of curvature and be of sufficient size to cover the occulter with a nearly uniform intensity. The laser and beam-shaping optics are covered by a small enclosure with a hole for the beam to enter the pinhole; this keeps the stray laser light contained and protects the optics from dust.

The diverging beam propagates 1.524m to the occulter mask. The mask is mounted and surrounded by baffling which extends to all nearby walls to ensure that the only light passing through this section must go through the holes in the occulter. The beam optics and occulter should be mounted on the same table for stability. Currently, they are mounted on separate breadboards on the same bench, but they will be replaced in the near future with a single optical table.

The occulter holes were etched, using deep reactive ion etching (DRIE) at the Microdevices Laboratory of the Jet Propulsion Lab (JPL), into a silicon wafer 101.6mm in diameter and 400$\mu$m thick. The shape of these holes was designed using the above equations, and the design of the mask is shown in Fig. 1. In order to meet manufacturing requirements of 1$\mu$m minimum feature size for gaps between petals in the etched occulter, the occulter sized for space had to be very large–376m at 96971.6km, or 400mas. It is expected to produce a reduction to $10^{-8}$ of the unocculter intensity at the center of the shadow, within a 25.4mm-diameter circle. While this particular design is unlikely to be used for flight, the performance should be representative of occulters and will serve to validate the theory experimentally.
Following the occulter, the beam propagates 9.1m to the camera, which is mounted on a separate table. The camera uses a SITE 1024x1024 back-illuminated CCD with 24μm pixels and a 16-bit readout. The camera is mounted on a 300mm long-distance travel stage, which allows the camera to sample different parts of the field from the occulter. There are currently no imaging optics on the camera, though the equipment exists to install them. Our detector is currently observing the shadow in the pupil plane rather than the image plane. When optics are installed, they will need to be sized to compensate for the quadratic phase term.

The testbed is in the process of being upgraded from a temporary configuration to a more permanent setup. Two optical tables, one for the camera and one for the occulter and beam optics, will be installed this fall, replacing an existing set of benches and breadboards. In addition, a long-travel stage for the camera will be added to provide accurate and repeatable motion for the camera across most of the shadow, and additional baffling will be installed in the enclosure. Unfortunately, the setup is currently insufficient to compare the experimentally observed images with the corresponding regions of the simulated shadow to verify performance. We display the simulated occulter shadow in Fig. 2.

However, some preliminary experimental data is shown in Figs. 3 and 4. Fig. 3 was taken by moving the camera into the bright ring surrounding the center and taking a short exposure (0.06s). Fig. 4 placed the camera near the center of the ring, and took a longer exposure (900s). Dark current noise is removed by subtracting 5 median-combined dark frames of the same exposure as the science frame. No flat-fielding is applied. The intensities of the images are scaled so that the relative difference in the exposure times is compensated, and the median intensity in the red box in Fig. 3 is set to 1. The resulting reduction in intensity is measured as the median value in the red box in Fig. 4. These suggest that the current reduction in intensity is from 1 to approximately $4.9 \times 10^{-6}$, though it may be as high as $7.5 \times 10^{-6}$, since the theoretical maximum intensity at any point in Fig. 2 is 1.49. Our suspicion is that stray light is causing the center to be at a greater intensity than expected; the effect will be assessed when the upgrades are complete.

4. CONCLUSION

We have described the theory and the setup behind the occulter experiment at Princeton, and shown the preliminary results from the testbed at a contrast of $4.9 \times 10^{-6}$. We expect that planned upgrades will improve the performance of the testbed and allow us to compare directly with theoretical results. Following these experiments, we also hope to test broadband performance and image plane results.

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REFERENCES

Figure 1. The design for the occulting optics for the experiment. The outer ring is 101.6mm in diameter.

Figure 2. The simulated shadow following the occulter, at the z-location of the camera.
Figure 3. A short exposure (0.06s) from one of the bright areas of the shadow. The intensity is scaled to place the median of the region in the red box at 1.

Figure 4. A longer exposure (900s) from one of the darker areas of the shadow. This is scaled by exposure time and the intensity scaling in Fig. 3 to give the relative intensity. The median intensity in the red box is $4.9 \times 10^{-6}$. 