

# HOPI – A High-speed Occultation Photometer and Imager for SOFIA

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## ABSTRACT

HOPI is a special-purpose science instrument for SOFIA that is designed to provide simultaneous high-speed time resolved imaging photometry at two optical wavelengths. We intend to make it possible to mount HOPI and FLITECAM on the SOFIA telescope simultaneously to allow data acquisition at two optical wavelengths and one near-IR wavelength. HOPI will have a flexible optical system and numerous readout modes, allowing many specialized observations to be made. The instrument characteristics required for our proposed scientific pursuits are closely aligned to those needed for critical tests of the completed SOFIA Observatory, and HOPI will be used heavily for these tests.

Our main scientific interest is in the use of HOPI for observing stellar occultations. In a stellar occultation, a star serves as a small probe of the atmospheric structure of a solar system object or the surface density structure of a planetary ring or comet. Such observations provide information at kilometer-scale spatial resolution that would otherwise require a space mission to obtain. This work makes use of SOFIA's mobility, freedom from clouds, and near-absence of scintillation noise to provide the best possible occultation data.

The addition of a coarse grism in a filter position would make it suitable for lunar occultations and other spectrally resolved time series observations. Also, the low atmospheric scintillation for airborne photometry gives HOPI the potential to detect P-mode stellar oscillations in sunlike stars. HOPI will be available for Guest Investigator use on a collaborative basis, and potential Guest Investigators should contact the PI prior to proposing to insure that the proposed observations are feasible and make the best use of HOPI's capabilities.

**Keywords:** CCD, airborne, imaging, photometer, SOFIA.

## 1. INTRODUCTION

HOPI is a unique member of the first-generation SOFIA instrument complement. It is the only "Special-Purpose" instrument and the only one sensitive in the silicon detector optical wavelength range. It might seem odd at first glance to include an optical instrument in the instrument complement for an observatory that is primarily intended for infrared observations. HOPI capitalizes on the mobility of an airborne platform and its freedom from clouds in order to make observations of ephemeral events. The primary scientific application HOPI is designed for is observation of stellar occultations by solar system objects (see Figure 1). The occulted star probes the occulting body's atmosphere or the extinction in a comet or ring system.<sup>1</sup> The time history of the occulted star's brightness (its lightcurve) can be analyzed to derive information on the vertical density, pressure, and temperature of a planetary atmosphere over an altitude range that is not well observed by flyby or orbiting spacecraft.<sup>2</sup> A tenuous cometary atmosphere, or coma, affects the occulted star through narrowband absorption by gas and by broadband absorption by dust.<sup>3</sup> Although the spatial resolution is limited by Fresnel diffraction to about a kilometer for bodies in the outer solar system, the location of airless limbs or planetary rings can be identified with astonishing accuracy, on the order of tens of meters, if a bright star is occulted.<sup>4</sup> For certain studies, occultations provide a low-cost (albeit opportunistic!) alternative to spacecraft observations.

SOFIA's operational altitude provides another notable advantage over groundbased observatories. Groundbased observations of stars suffer from scintillation noise due to turbulence in the upper reaches of the troposphere.<sup>5</sup> This effect is much less pronounced when observations are made from an observatory operating above the tropopause.<sup>6</sup> This is due in part to the lower density at flight altitude and in part to the stable, stratified nature of the stratosphere. This gives SOFIA instruments the capability of achieving very high photometric precision for bright objects. HOPI is being designed to take advantage of this capability for two main scientific applications. The first is *asteroseismology*, the study of stellar interiors by means of oscillations seen on the surface of the star.<sup>7</sup> For distant stars, the normal modes cannot be spatially resolved, so the P-mode oscillations that are accompanied by small brightness fluctuations are the ones to be observed. Very low scintillation noise will be critical in order to make successful observations. The second application is observation of *transits*

of planets orbiting other stars across the disk of their parent stars. A transit is similar to an occultation, except in this case the transiting object is near to, and much smaller than, the “occulted” star so only a small fraction of the stellar disk is obscured. A great deal of information about the transiting planet and its parent star can be gleaned from transit observations, particularly from very precise photometric observations.<sup>8</sup> We look forward to using HOPI to make significant contributions in both of these exciting new fields of research.

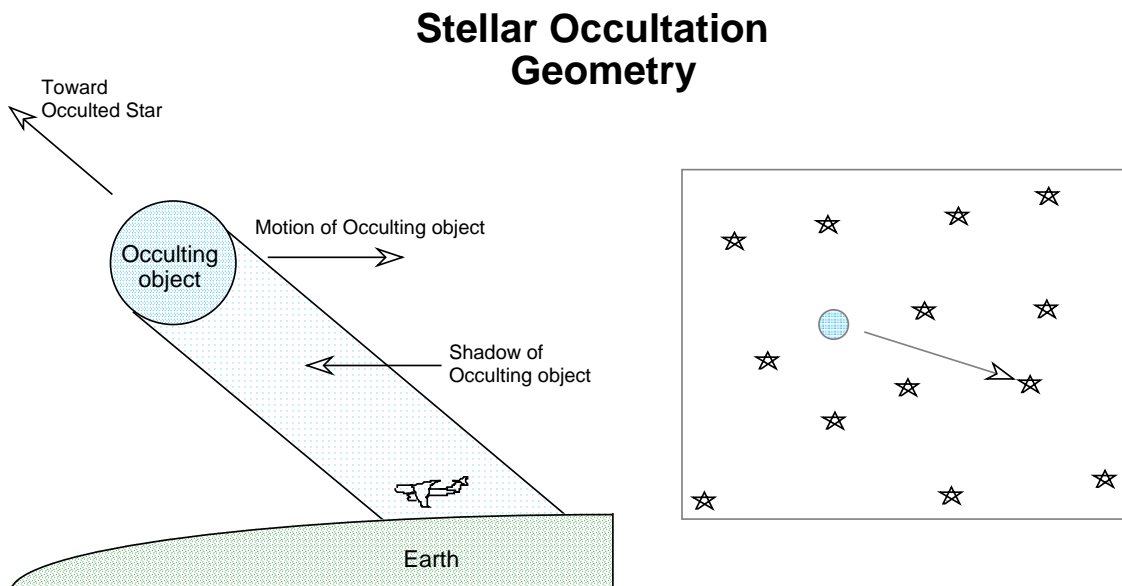


Figure 1. Occultations occur when an object passes between an observer and a star. These events can be considered in two ways. On the left, one can think of the star casting a shadow of the object on the Earth. The observer must be located so that the shadow passes over this point. An airborne platform has an obvious advantage for this. On the right, the observer's view shows the object moving on the sky toward, and ultimately in front of, the occulted star.

The instrument requirements imposed by HOPI's scientific program are closely aligned to those needed to test and troubleshoot an airborne telescope.<sup>9</sup> These requirements are being folded into the HOPI design to insure that it will be a valuable resource for the SOFIA test program.

HOPI is currently between its Preliminary and Critical Design Review stages. It will proceed through detailed design during calendar 2000, and will be completed in late 2001. Its schedule is coordinated with the development schedule of FLITECAM because the two instruments are being designed to mount either together or separately on the SOFIA telescope. HOPI and FLITECAM will be tested on Lowell's Perkins telescope during 2002 so that they will be well-understood by the time they are needed for testing of the SOFIA telescope in the third quarter of 2002.

## 2. REQUIREMENTS

The applications described in the previous section lead to the instrument requirements summarized below. A few of the requirements deserve additional comment. The timing and position requirements are imposed by occultations. In order to analyze more than one track through an occultation shadow, the time of each integration and the position of the observer must be known with sufficient accuracy that these are not limiting uncertainties. Occultations also define the speed and noise requirements since data must be obtained at sufficiently high rates that the lightcurve is fully sampled. Most of the optical requirements are actually imposed by the telescope testing application. The optical image quality of SOFIA is expected to be on the order of 3" FWHM, but HOPI must have sufficiently good optical performance that it will not degrade the image quality of the SOFIA system. Precise photometry also restricts the design in that optical components must be placed far enough from any focal plane that dust or optical imperfections will not cause significant photometric variation. Redundancy of components normally in the system, and ease of swapping in spare parts are important aspects of an occultation instrument. Failure of a component at a critical moment can cause complete loss of an event, so this risk must be minimized to the greatest extent practical. HOPI will be relatively insensitive to telescope pointing problems, but we will design it to allow for future installation of an image motion compensation system if necessary.

## PRINCIPAL HOPI REQUIREMENTS:

- Wavelength Range: 0.35-1.1  $\mu\text{m}$  (0.30-1.1  $\mu\text{m}$  goal)
- CCD Quantum Efficiency:  $\geq 85\%$  peak,  $\geq 40\%$  from 0.35  $\mu\text{m}$  to 0.85  $\mu\text{m}$ .
- Throughput of HOPI optics:  $\geq 70\%$  from 0.4 to 0.9 microns
- Spectral Resolution: Defined by filters, as narrow as 0.003  $\mu\text{m}$ , with  $\geq 6$  position motorized filter wheels on both channels. Refocus for each filter is acceptable.
- Number of channels: 2 with 1, 2, or 3 subframes per channel  
Interchangeable parts for redundancy
- Time & 3-D posn accuracy: 50  $\mu\text{sec}$  and 30 meters, with logging, for both HOPI and FLITECAM
- Maximum Frame Rate: 20 ms for three 80"x80" subframes per CCD  
10 ms for one 80"x80" subframe per CCD
- Read Noise:  $\leq 6$  electrons max;  $\leq 3$  electrons for slow read
- Field of View on SOFIA: square, 5.6 arcmin on a side, 8 arcmin diagonal.
- Pixel scale on SOFIA: 1 "/pixel for occultations, 1/3 "/pixel for testing (Goal - 0.055 "/pixel)
- Optical system: 80% enclosed light in 2 pixel box (Goal, 1pixel)  
Distortion well characterized for chopper performance evaluation  
Shack-Hartmann capability in one channel,  $\geq 20$  spots across pupil with x-y adjustment of Shack-Hartmann MLM  
Pupil mask with x-y adjustment  
Allow use with 1.8-m Perkins f/17 telescope for instrument checkout  
Goal - Avoid optics near a focus for maximum photometric precision  
Goal - Allow for an evacuated light path to the gate valve  
Goal - Allow use of single CCD with no optics for maximum throughput  
Goal - Provide a pupil imaging mode and Focault test capability
- Co-Mounting: Optional simultaneous mounting with FLITECAM
- Data System: Modular to allow use on various telescopes and subsequent addition of features.
- Data Format: Simple FITS, 2d or 3d files, one per subframe
- Safety/Reliability: Meet FAA requirements; have in-flight swappable components and spares.
- Future improvement: Allow for future implementation of high-speed image motion compensation using the SOFIA secondary mirror or an internal optic

## 3. IMPLEMENTATION

### 3.1. Overview

SOFIA instruments will be divided into three sections: the telescope-mounted optical and detector system, electronics located in a small rack on the telescope counterweight flange, and electronics located in one or more large racks on the aircraft floor. HOPI will not have any electronics in the counterweight rack, so the instrument functionality will be divided between the telescope and the floor-mounted rack. Figure 2 shows a block diagram of the full HOPI system showing its division of functionality.

As mentioned above, we have found redundancy to be essential for occultation work. Figure 2 shows our approach to minimizing single-point failures. To some degree, the parallel nature of the computer system is also driven by our desire to limit the amount of activity in any given machine in order to keep the reliability of the system high. A feature that is not obvious in Figure 2 is that the supervisory machine can double as a data acquisition machine, and either data acquisition machine can take on the supervisory functions if necessary. Items that are not redundant in the normal instrument configuration will be easily exchanged with spare units.

### 3.2. Detectors, Electronics, and Timing

Occultations are fast events, the shadow velocity being comparable to the Earth's orbital velocity of  $\sim 30$  km/sec. Integration times can therefore be as short as  $\sim 10$  ms. Thus, even for relatively bright objects, occultation data are normally in the read-noise limited regime. High quantum efficiency, low noise, and high speed are all requirements of the detector and its controller. Since low noise and high speed are not compatible requirements, we must have the flexibility to choose on an event-by-event basis whether to optimize the noise or sacrifice noise for speed. Characterizing the images in an airborne telescope place even greater demands on the speed of the CCD and its control electronics.

# HOPI High-Level System Design - Electronics & Data System

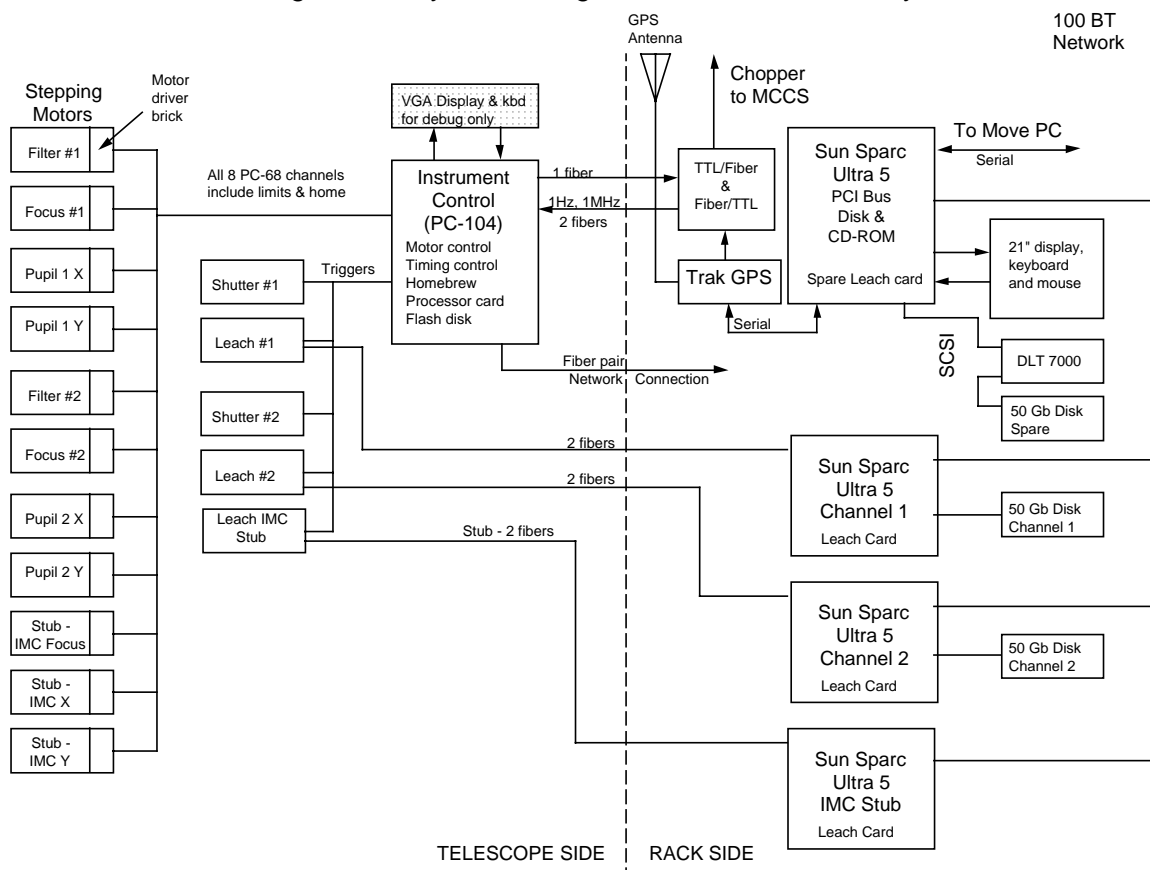


Figure 2. In this block diagram of HOPI, the items on the left are part of the instrument package mounted on the telescope while those on the right are mounted in the rack. We plan to run only fiber optic cables between these packages in order to eliminate ground loops on SOFIA and reduce lightning susceptibility at Lowell. The computer at the top right serves a supervisory role, including user interface, image display, and real-time data analysis. The machines located below it in the diagram are dedicated to reading the CCDs and writing to disk.

We selected the EEV CCD47-20 as the detector for both HOPI channels. This device is thinned, backside illuminated, and antireflection coated for excellent quantum efficiency. One of our devices has a standard AR coat for good response over a broad band. This will normally be used in the red channel of HOPI. The other CCD has an AR coating that is optimized for good blue and UV sensitivity and will normally be used in the blue channel. The CCD47-20 has a fast, high-gain on-chip amplifier. The read noise at slow scan speeds is  $\sim 3$  electrons, rising to  $\sim 6$  electrons at 1 Mpx/sec read rate. It is a frame transfer device, a necessity for occultation work. The dead time between integrations in an occultation is simply the time required to carry out the parallel shifts in the frame transfer. The 1K square format is a good fit to the 8 arcmin diameter SOFIA focal plane when reimaged to produce  $1/3''$  unbinned pixels. We will achieve the  $1''/\text{pixel}$  scale for occultations by binning the CCD. Of course, other binning options will also be available.

Occultations and airborne telescope testing both require unusual CCD readout modes. High-speed frame-transfer readout is critical to the success of our occultation work, and the ability to obtain finite strings of images at intervals as short as a few hundred microseconds is needed to fully characterize the short-exposure PSF of an airborne telescope.<sup>9</sup> We also require more conventional readout modes, and binning options will be needed in all of these modes. The variety of required operational modes implies that a fast programmable CCD controller is required. We have selected the SDSU Gen II controllers<sup>10</sup> for HOPI because they meet our flexibility, speed, and noise requirements and are readily available. There is one new development that we helped drive in the SDSU controller, namely the new PCI interface card. This was important due to the fact that Sun no longer manufactures S-bus computers. These cards are now in production.

The most unusual aspect of the HOPI electronics is the requirement that the data acquisition be tightly synchronized to UTC. This will be achieved by using a hardware trigger signal derived from a GPS time standard as a DSP interrupt. We used the same approach successfully in our earlier occultation CCD systems.<sup>11, 12</sup>

### 3.3. Optics

HOPI requires a very flexible optical layout in order to meet its varied requirements and goals. We have produced a preliminary set of optical designs to meet the requirements and goals, and are now entering the detailed design phase of minimizing surfaces, reducing cost, checking tolerances and ghosts, etc. Our design is being done with the aid of ZEMAX.<sup>13</sup> We will describe here the first-order design parameters and will summarize the performance of the preliminary design with the clear understanding that the final design may differ significantly.

The image scale required to map 1/3" on the sky to a single 13 micron CCD pixel is 25.64"/mm, so the collimator/camera focal reducer must demagnify by a factor of 6.1. This scale also produces a square field of view covering the 8' SOFIA field across the CCD's diagonal dimension. As mentioned earlier, the 1"/px scale will be achieved by binning. We have adopted a pupil image diameter of 23mm for the f/17 Perkins telescope and 21 mm for the f/19.6 SOFIA telescope. This allows use of readily available 25mm circular filters and implies collimator and camera focal lengths of 412 and 67 mm respectively.

The two optical channels of HOPI will be split with a single dichroic reflector (see Figure 3). The blue side will be reflected from the dichroic, the red side transmitted through it. The blue optical train is being designed to cover the 0.3-0.65 micron wavelength range while the red side covers 0.4-1.0 microns. This allows considerable latitude in the selection of the dichroic's transition wavelength for particular observations. The wide spectral range of the red side optics enables wide-band observations with the dichroic removed. The blue side optics are severely constrained by the short wavelength limit, and will be made using only fused silica and calcium fluoride lenses. Because of this we are allowing a field lens and are not requiring very low distortion in the blue optical system but are maintaining these requirements on the red side. The image quality goal applies to both channels.

Both channels will have motorized stages for focusing their respective camera lenses. This way, when HOPI and FLITECAM are mounted simultaneously FLITECAM can achieve focus using the telescope's focus mechanism and HOPI can use its own internal focus mechanisms to focus both channels. Each side will have a movable pupil mask to help control stray light. Although SOFIA will have optional baffles, we will do the best we can to control stray light internally so that it may be possible to simplify SOFIA operations by leaving the baffles out during HOPI flights.

The Shack-Hartmann optical system necessarily differs from the normal optical system since its pupil image must be about the same size as the detector, 13.4 mm. We have chosen to use a 235mm focal length achromatic stock collimator that provides pupil diameters of 13.4 and 12 mm for the Perkins and SOFIA telescopes, respectively. We will use a lens array (MLM) from Adaptive Optics Associates to provide 24 subapertures across the SOFIA pupil. Following a suggestion by Gary Chanan, the MLM will be mounted on an x-y stage to allow the pupil to be located symmetrically on the array. The Shack-Hartmann optics will be a self-contained unit including collimator, MLM, and beamsplitter with an artificial star image for calibration. This unit will be manually installed and removed in the red side optical system. The camera lens will need to be removed when this unit is in place. Figure 3 shows where the Shack-Hartmann optics will be placed.

Pupil viewing will be accomplished by replacing the red side camera lens with a shorter focal length stock lens. In addition to providing an image of the pupil, it also will be an aid in placement of the pupil mask and tracking down stray light problems. The addition of a knife edge or wire at the telescope focal plane will provide a Foucault test capability.

The goals of 0.055"/pixel image scale and maximum throughput to a single CCD will be met in a single special configuration. The dewar for the red side of HOPI could be placed directly at the telescope focus, but it is more likely that two reflections from overcoated silver mirrors will be used to simplify the conversion procedure. The purpose of the fine image scale is to search for a possible diffraction-limited spike in the PSF at wavelengths near 1 micron.

It will be very important for HOPI and FLITECAM to co-mount on the SOFIA telescope for certain occultation events and also for telescope testing. This is a driving force behind our respective opto-mechanical designs. When both instruments are mounted, a gold dichroic beamsplitter will be placed in the beam on the telescope side of the instrument mounting flange. This will direct the IR beam up to a mirror that in turn will direct the beam into the FLITECAM dewar. The optical beam will be transmitted to HOPI. The HOPI and FLITECAM entry ports in the mounting flange will both have provision for pressure sealing. This allows the cabin/cavity pressure seal to be at the instrument mounting flange or at the facility window, located closer to the telescope in the gate valve assembly. Our KAO experience indicates that significant seeing degradation may occur in the area between the instrument and the Nasmyth tube, so we are also providing the capability of evacuating this area. Evacuation of the region around the beamsplitter also allows it to be cooled if required for lower background.

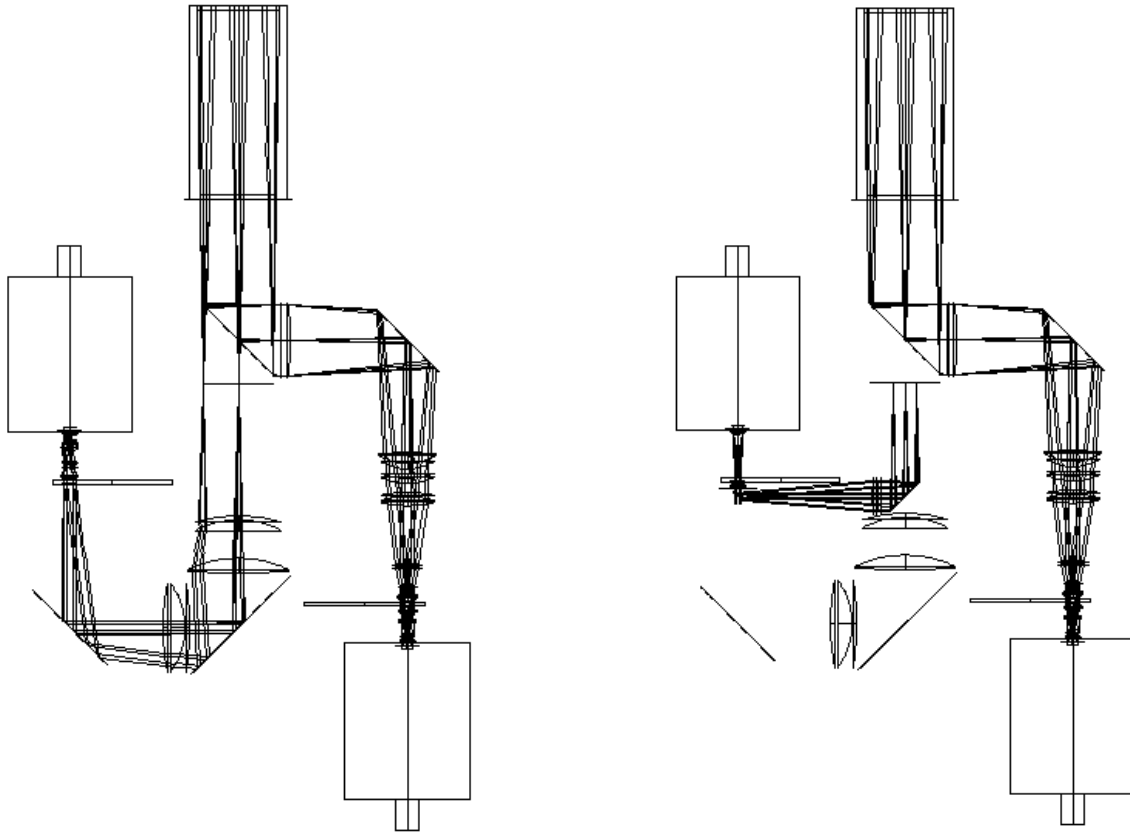


Figure 3. This figure shows the preliminary optical layout of HOPI for normal reimaged operation (left) and Shack-Hartmann testing (right). Light from the telescope enters from the top of the figure through a window in the gate valve and another window at the instrument mounting flange. The dichroic beamsplitter reflects light to the blue (right) side of the instrument while transmitting light to the red (left) side. The telescope focal plane is located just behind the dichroic beamsplitter. In both sides there is a 4-element collimator and a much smaller multi-element camera lens. When Shack-Hartmann testing is to be done, the necessary optics will be installed manually and the red camera lens removed.

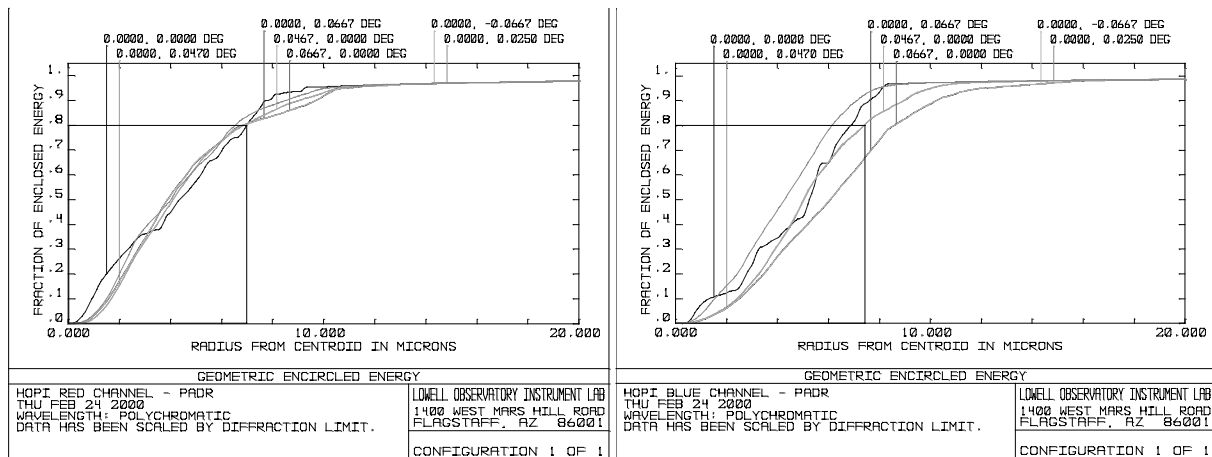


Figure 4. Enclosed light curves for the preliminary design of the red (left) and blue (right) sides of HOPI. The red side contains 80% enclosed light in a 14 micron diameter circle, essentially one pixel. The blue side has almost as good quality except at the corner of the field.

Our preliminary optical design for the blue side includes a field lens, 4-element collimator, and 7-element camera lens. On the red side there is no field lens in order to avoid photometric problems. The red collimator is also 4 elements and the camera has 6 elements. Our next design effort will attempt to reduce the number of elements, most likely at some cost to the design image quality. The performance of the preliminary optical design is very good, as can be seen from Figure 4.

### 3.4. Mechanical

The mechanical layout of HOPI is determined by four main factors: the need for mechanical stiffness; the need for flexibility in optical layout; the SOFIA flange and instrument envelope limitations; and the requirement for co-mounting with FLITECAM. The folded optical paths shown in Figure 3 result from the desire to keep the instrument as stiff as possible. The main optical mounting surface will be a commercial honeycomb sandwich optical breadboard to maximize the flexibility of the optical layout. The mechanical design has progressed only to the PDR level; detailed design will take place this year.

The optical breadboard is not an FAA-certified component, and is a major structural component of HOPI. Certification of the breadboard has been a problem that we have decided to solve by providing enough support that only one of the stainless steel plates in the breadboard can be shown to be safe under maximum loading conditions. Adding these supports is not a serious problem for us since we need to insure that the instrument is sufficiently stiff to measure image motion at the level of the 0.2" rms SOFIA requirement. Stress analysis of all the other components of HOPI is straightforward.

The bottom of the SOFIA instrument envelope is tightly constrained, so the only feasible mounting location for FLITECAM is above HOPI when the telescope is at the center of its elevation range. For best optical performance, we are designing the HOPI and FLITECAM mount so that both instruments are located at the zero spherical aberration focus location, 30 cm forward (i.e. inside the instrument) of the instrument mounting flange. This, together with the focus location inside the FLITECAM dewar, constrains the distance between the HOPI and FLITECAM optical axes to be 230 mm. As shown in Figure 5, HOPI will be in the shape of a box with FLITECAM a cylinder above it. The FLITECAM dewar is quite large, but the entrance window is offset to be near the dewar wall, thereby allowing the 230 mm constraint to be met.

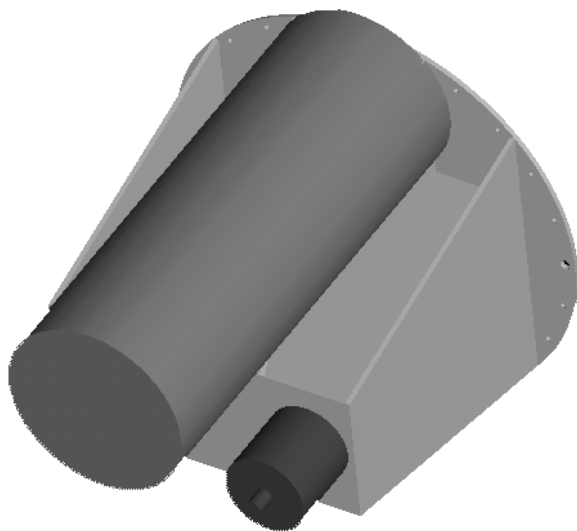


Figure 5. A simple exterior view of HOPI and FLITECAM mounted together. The FLITECAM dewar is the large cylinder mounted above HOPI's optical box structure. In this preliminary concept, one of the HOPI dewars protrudes from the back of the optical box. The main instrument mounting plate is the large round plate.

A very important aspect of the mechanical design will be to insure that access to optical components, such as the Shack-Hartmann or pupil viewing optics, will be relatively easy even with FLITECAM co-mounted. HOPI's flexibility is its hallmark, and this feature must not be compromised. It will also be necessary to insure that it is relatively easy to swap CCD controllers and dewars to aid in troubleshooting or in working around problems. This implies that the dewars and associated electronics mounts must be identical, and that the fasteners have reliably relocatable quick-release features. We will insure that our design and operational procedures will allow internal reconfiguration of HOPI in flight.

### 3.5. Cryogenic

The HOPI detectors will be cooled with liquid nitrogen rather than a cryocooler. This is largely due to operational considerations. For fire safety reasons, electrical power will not be continuously available aboard SOFIA, so the operational logistics for cryocooler systems are very awkward. Also the working fluid in the APD Cryotiger system we investigated is flammable, a safety issue that is easily avoided with a nitrogen system.

The fill tube location is determined by the orientation of HOPI when mounted on the SOFIA and Perkins telescopes. The fill tubes will be located on the top of the instrument when it is mounted on SOFIA at the end of the dewars closest to the instrument mounting flange. This will allow maximum hold time on SOFIA with good hold performance in the Perkins up-looking configuration.

The main airworthiness consideration with a liquid cryogen system is the possibility that the fill tube can become plugged with ice. This is mainly true of helium systems, but HOPI will provide redundant pressure relief paths for its nitrogen dewars. There will be a coaxial neck tube with two pressure relief valves set to two different pressures. The lower pressure valve will be the normal boiloff route, but if it becomes plugged the second valve will come into play. If both valves become plugged, the entire assembly will be designed to pop off, allowing the vent gas to escape directly out of the dewar neck. In the event that the nitrogen vessel leaks into the vacuum space, there will be a “fall-off” valve (i.e. a plate on an o-ring) that will provide a zero-pressure relief route. Both this plate and the neck tube will be restrained with lanyards to insure that they remain attached to the instrument package.

### 3.6. Software

The HOPI software requirements are driven by a number of factors. Perhaps the major one is that we are developing a series of new instruments at Lowell at this time, and we will use the same basic software package for all of them in order to reduce the integrated development time and ongoing maintenance effort. This modular software package, called LOIS, is being developed largely by Brian Taylor at Lowell and is the subject of a paper in a related conference at this meeting<sup>14</sup> to which the reader is referred for details. A typical incarnation of LOIS will include the core package with customized modules for telescope control, detector control, instrument control, on-line analysis, and miscellaneous housekeeping functions. The software interfaces to the modules are the same so it is simple, for example, to use HOPI either on SOFIA or the Perkins telescope by loading either the SOFIA or Lowell Move control module. LOIS is implemented in Tcl/Tk and ANSI C.

We have had a good deal of experience with LOIS in high-speed systems already, including the camera for the *Kepler* project laboratory test<sup>15, 16</sup> and a new camera for the LONEOS near-Earth object search at Lowell. We have been successful in getting each of these cameras to work under Solaris at a total data rate of 2 Mpx/sec, but not without a struggle. The operating system overhead is astonishingly high, and is part of the reason for the parallel architecture in the HOPI data system. It is also causing us to think seriously about moving to Linux. A real-time operating system is also a possible solution, but the cost is high and the large amount of buffer space available on the SDSU PCI card should make a real-time operating system unnecessary.

## 4. ACKNOWLEDGEMENTS

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