Hartmann Sensor Manual

ACTIVE OPTICAL SYSTEMS

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Version 1.0 – 10/2/12

Table of Contents

1 Introduction

The Hartmann wavefront sensor was developed in 1904 by J. Hartmann to do optical metrology of large optics. Hartmann's original sensor was fabricated by combining a plate with an array of holes and photographic film. Electronic imagers replaced the photographic film. In 1971 Roland Shack suggested using a lens array instead of the array of holes for better optical efficiency, thereby creating the Shack-Hartmann wavefront sensor. The modern Hartmann sensor consists of a lens array (Shack-Hartmann) or an aperture array (Hartmann) in front of an electronic (CCD or CMOS) imager.

The Hartmann sensor described here consists of an aperture array mounted in front of a commercially available web camera. This manual will begin by describing the operation of a general Hartmann sensor. Then the installation will be described. Finally the operation of the software will be described.

1.1 Device Operation

A beam of light illuminating a Hartmann sensor is divided into pieces by the sub-apertures of the aperture array. The position of each spot diffracted from the apertures is directly proportional to the average wavefront slope. Wavefront slope measurements are made differentially by comparing the position of the diffracted spots on the sensor with those measured for a reference wavefront. The ratio of the motion of the spot position in both axes to the distance between the aperture array and the imager is the gradient of the wavefront. The wavefront can be reconstructed by integrating the measured wavefront gradient.

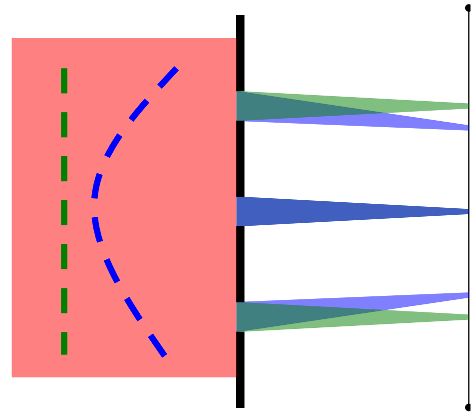


Figure 1.1.1 - Reference wavefront (green) and measurement wavefront (blue).

Figure 1.1.1 shows an example of a reference wavefront, shown in green, superimposed on a wavefront being measured (blue) in 1D. The dotted lines show the wavefront impinging on the aperture array. The motion of the spots is directly proportional to the average slope over the sub-apertures.

1.2 Limitations of Hartmann Sensing

Hartmann sensing is a very powerful technique for measuring both intensity and phase simultaneously, but it has some limitations. The spatial resolution of a Hartmann sensor is inherently lower than the underlying imager because accurate spot determination requires an array of camera pixels. The temporal resolution of a Hartmann sensor is typically limited by the camera frame rate, but can be also limited by the image processing required to create a wavefront or wavefront slope from the image.

The slope measurement accuracy of a Hartmann sensor is limited to its ability to determine the spot position accurately. There are several things that impact the accuracy of this measurement. Spot position determination is typically done using centroiding or taking the first moment of the spot. This accuracy of this measurement is proportional to the number of bits of resolution in the intensity measurement and the number of pixels being illuminated, but is typically accurate to around 1/10th of a pixel size. Averaging over many frames can be used to increase the resolution, but only by the square root of the number of averages. Another thing that impacts spot position determination accuracy is structure on the intensity pattern illuminating a sub-aperture. This effect can be mitigated to some extent by moving from an aperture array to a lens array (Shack-Hartmann wavefront sensing), but there will always be coupling between the intensity variations and the spatial variation of the slope. In the case where there is significant variation in the wavefront slope and the intensity over a sub-aperture, the Hartmann sensor can be thought of as measuring a weighted-average of the wavefront slope over that sub-aperture.

2 Quick-Start Installation Guide

- Install the AOS software.
- Plug in the camera.
- Set it up to be properly illuminated.
- Run the AOS Adaptive Optics software.

3 General Wavefront Sensor Usage

3.1 Warnings and Usage Advice

- **Cleaning:** The Hartmann array is not designed to be cleaned. It can be sprayed gently with pressurized air to remove dust, but aggressive cleaning will damage the device. Damage induced by cleaning will void the warranty.
- **Mounting:** Each device has specific mounting suggestions below. *It is not recommended to mount the wavefront sensor using the beam tube at the front-end of the camera.*
- **Saturation:** It is very important to avoid saturating the camera during operation. Saturation can result in inaccurate measurements. There is some ability for the user to control the gain and exposure interval in software, but in extreme cases, this will have to be addressed in hardware via absorbing neutral density filters. *Do not use reflecting neutral density filters!* They will cause the Hartmann spots to be corrupted such that an accurate measurement cannot be made.
- **Slope Dynamic Range:** The Hartmann sensor has a certain range of slopes over which it can accurately measure. The maximum dynamic range is obtained when the edge of the focal spots reach the edge of the areas of interest (AOIs). Beyond this point, the Hartmann sensor cannot accurately measure the slopes without heroic processing.
- **Camera Parameters:** Each Hartmann sensor has a set of parameters obtained during calibration of the device. It is important to make sure that these parameters are used during the operation of the device.
- **Imaging:** When imaging onto the wavefront sensor, plan on creating the image on the lens/Hartmann array, not on the image sensor itself.
- **Non-English Windows Operating Systems:** The software is designed for US English Windows Operating Systems. Many of the data files for the AOS software use comma separated values (CSV) with decimal numbers. Some foreign operating systems switch the characters such that commas and periods mean different things. If using a foreign

operating system, the meaning of commas and periods in numeric values may need to be switched before the software will operate properly.

3.2 Typical Hartmann Sensor Use – Quick Start Guide

Hartmann sensors measure the differential tilt between two images. When using a Hartmann sensor, the reference can be taken by the user or can be that provided by AOS. The next section describes how to align a Hartmann sensor to an absolute reference file. The following section describes how to create a relative reference file and use the AOS Hartmann Wavefront Sensor (HWFS).

3.2.1 Comments about Reference/Calibration Files

Upon startup the software tries to load the calibration data in a file called defaultCal.txt. If this file does not exist, the user gets a warning message and the sensor loads without any calibration data. The user can overwrite the existing defaultCal.txt file with a new calibration file at any time by deleting the old file and renaming the new calibration file to defaultCal.txt. The user can load a calibration file at any time using the File-Open-Calibration menu option. The terms reference and calibration as will be used interchangeably throughout this manual.

3.2.2 Alignment to an Absolute Reference

The reference image provided by AOS is taken under relatively uniform illumination of a planar wavefront. When using the AOS reference (also referred to as the absolute reference), it is critical to align the sensor to that reference. To facilitate this, the wavefront sensor needs to be mounted on a kinematic stage that allows the sensor to be tilted in the two axes perpendicular to the beam propagation direction. There are several different ways of creating a mount like this. Figure 7.1.1 shows an AOS Hartmann Sensor attached to a ThorLabs KM100P Kinematic Prism Mount in such a way as to enable both of these axes to be manipulated. Unfortunately, the mount shown here does not allow the sensor angle to be manipulated independent of motion the sensor relative to the optical axis, but for fine tuning the sensor position it is effective.

The procedure for aligning the HWFS an absolute reference is:

1. Align the sensor by eye so that it is normal to the incident beam.
2. Launch the HWFS software.
3. Load the absolute reference (calibration) file.
4. Turn off tilt removal in the Setup Tab.
5. Begin acquisition in continuous mode.
6. Adjust the two tilt axes to minimize the tilt by looking at the wavefront amplitude in the Wavefront Display Window, tilt amplitude in the Slopes Display Window, or rms tilt amplitude in the Analysis Tab.

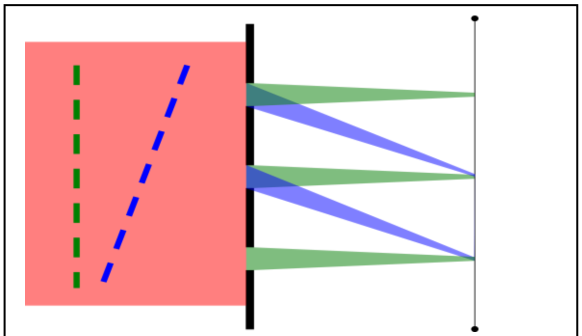


Figure 3.2.1 - Illustration of how a tilted wavefront (blue) can be exactly one slope dynamic range away from the reference wavefront (green)

With this procedure, it is possible to align the sensor such that the tilt is off by exactly one dynamic range of the wavefront sensor. The only way of determining this is to compare the reference image and the measured image on the

HWFS. The corner sub-apertures of the AOS HWFS are not well illuminated due to the limited size of the Hartmann screen clear aperture, so a user can look at these corner sub-apertures to determine if the HWFS is well aligned to the beam. The corner sub-apertures should be equally illuminated when the beam is larger than the Hartmann sensor. If they are not, adjust the angle of the camera to make the corners look equally illuminated and repeat the alignment procedure above.

3.2.3 Creating a Relative Reference

A differential measurement is commonly used when trying to determine the effect of a change to an optical system. Examples include trying to measure the effect of moving a lens or the effect of a deformable mirror on the wavefront. To make a differential measurement, it is unnecessary to align the HWFS to an absolute reference file. Instead, a relative reference file can be created by acquiring an image and pressing the Create Reference button. When the image is acquired, the HWFS software automatically assumes that the user wants to analyze that image relative to the existing calibration/reference data. With a new setup these results are often not very meaningful and should be ignored until a valid calibration can be obtained.

3.2.4 Making Wavefront Measurements

After a valid reference is established, the wavefront sensor can be used to make wavefront measurements. Assuming that the setup is valid, this can be accomplished using the Acquire or Continuous Acquire buttons. There is more detail on the setup below, but the most important things to get correct is the separation between the Hartmann array and the imaging sensor and the pixel size. These will be set properly and stored in a reference file for your sensor that is provided by AOS. Each sensor will have a different separation value since they are hand assembled, so make sure this is correct before making measurements.

4 Comments on Specific Hartmann Wavefront Sensors

4.1 Firewire Wavefront Sensors

The AOS software is compatible with all the Firewire cameras manufactured by Allied Vision Technologies (AVT). These cameras have proven to be robust and easy to use, but do require a 1394 Firewire port on the computer. Since these ports are becoming less common, we are directing more of our customers to GigE cameras.

Figure 3.2.1 –Images of 6-pin and 4-pin firewire connectors

4.1.1 Power

Our Firewire wavefront sensors require power from the Firewire port or power being applied to the camera directly. Figure 3.2.1 shows the 4-pin and 6-pin connectors for the Firewire A standard. The 4-pin Firewire adapters that are on most laptop computers do not provide power, so the cameras will not work using only this connector. Most laptop PC-card or PCMCIA cards that provide a 6-pin interface to Firewire do not provide power without application of that power over an external connector.

We only recommend using a 6-pin desktop Firewire connector. For laptop use, you will need to make sure you can get power to the camera. We recommend a Apricorn AFW6-4 adapter available at the time of this writing from www.newegg.com. We also recommend getting a FireCard400-e from Unibrain which has an external power adapter connector that can receive external power for powering the cameras (see http://www.unibrain.com/ for more details).

4.2 GigE Wavefront Sensors

The AOS software supports any of the GigE cameras available from Allied Vision Technologies (www.alliedvisiontec.com). We have found that these sensors work with many standard gigabit Ethernet cards, but not all of them. AVT has an application note entitled, "Hardware Selection for AVT GigE Cameras" (available currently at http://www.alliedvisiontec.com/fileadmin/content/PDF/Support/Application_Notes/Hardware_Selection_for_AVT_GigE_Cameras.pdf) that lists the different tested hardware for GigE camera acquisition including adapters and switches.

4.2.1 Power

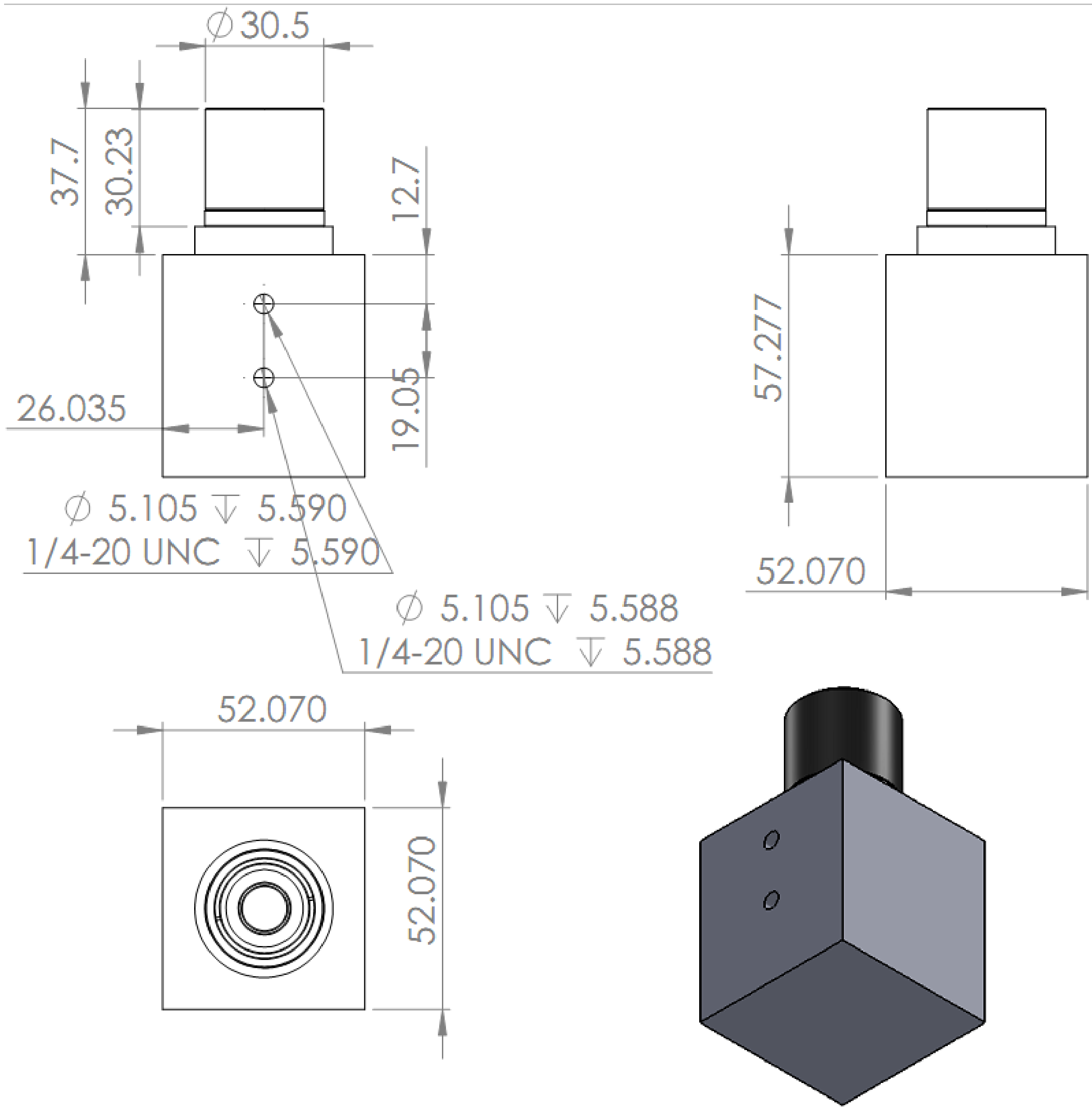
Power to these cameras is provided either via a secondary port (often 12-pin Hirose) or over the GigE link directly via the Power-Over-Ethernet (PoE) standard. The power application is camera specific, so customers are encouraged to consult the camera manual for proper power application.

4.3 SU320KTSW-1.7RT IR Wavefront Sensor

Do not mount the camera by the front end. This will cause damage to the sensor. Use the screw holes under the camera body.

4.3.1 Mechanical Drawing

Below is a drawing of the approximate dimensions of the SU320KTS WFS in millimeters.



NOTE: Dimensions are in millimeters.

5 Software

The software is now documented in the AOS Adaptive Optics Software Manual.

6 Appendix: Select Camera Parameters Summary

Parameter	Fire-i Webcam	Stingray F-033B	Guppy F-036B	Guppy F-503B	Marlin F-131B	SU320KTS W-1.7RT	Prosilica GT1920
X Pixel Size (µm)	5.6	9.9	6.0	2.2	6.7	25	4.54
Y Pixel Size (µm)	5.6	9.9	6.0	2.2	6.7	25	4.54
Maximum Resolution (pixels)	640 x 480	656 x 492	752 x 480	2592 x 1944	1280 x 1024	320 x 256	1936 x 1456
Imager Dimensions (mm)	3.6 x2.7	6.5x4.9	4.5x2.9	5.7x4.3	8.6x6.9	8.0x6.4	8.7x6.6

If your camera is not listed here, more information about the camera parameters can be found at the camera manufacturer's website.

Manufacturer	Website
Allied Vision Technologies	www.alliedvisiontec.com
Sensors Unlimited	http://www.sensorsinc.com/
Basler	http://www.baslerweb.com/

7 Appendix: Legacy Sensor Information

7.1 USB Webcam Hartmann Sensors (discontinued)

The USB Webcam Hartmann Wavefront Sensor has been discontinued and is being replaced with the Firewire Webcam Hartmann Wavefront Sensor. Here are notes for legacy users:

Figure 7.1.1 - Mounting the AOS Hartmann Sensor to a ThorLabs KM100P kinematic prisim mount

- The webcam housing is plastic, and, as such, is susceptible to fracture due to excessive force. When mounting the webcam, use care so as not to drop the device or tighten any mounting screws too aggressively so as to avoid damaging the device. Figure 7.1.2 shows how a 8-32 screw should be used to connect the webcam Hartmann sensor to a standard ½" laboratory post. AOS is not responsible for any fracture damage induced by aggressive or careless behavior.
- To facilitate alignment, the wavefront sensor needs to be mounted on a kinematic stage that allows the sensor to be tilted in the two axes perpendicular to the beam propagation direction. There are several different ways of creating a mount like this. Figure 7.1.1 shows an AOS Hartmann Sensor attached to a ThorLabs KM100P Kinematic Prism Mount in such a way as to enable both of these axes to be manipulated. Unfortunately, the mount shown here does not allow the sensor angle to be manipulated independent of motion the sensor relative to the optical axis, but for fine tuning the sensor position it is effective.

7.1.1 General Installation Notes:

- Install the software provided by the webcam manufacturer using the camera manufacturer's instructions.
- Plug in the camera if you have not already done so for the camera manufacturer's software. Set it up to be properly illuminated.
- Try running the QuickCapture program provided by the manufacturer and see if the camera is responding to light.
- Install the AOS Webcam Hartmann sensor.

Figure 7.1.2 - Mounting of the USB Webcam Hartmann sensor to a standard 1/2" post.

7.1.2 Warnings:

- **Bright Illumination:** The underlying webcam is designed with firmware that protects it from bright illumination. If the sensor is illuminated with a bright light during operation, the sensor can enter into a mode where it no longer responds. In this situation, the webcam must be unplugged and then plugged back into the computer to reset the device. In rare situations, the computer must be restarted.

7.2 Fire-I Webcam Firewire Wavefront Sensors (discontinued)

7.2.1 Instructions and Warnings

- **Camera Settings for Fire-I Wavefront Sensor:** The Fire-I wavefront sensor should be setup adjusting only the shutter.
- **Camera Settings for Marlin & Stingray Wavefront Sensor:** The Marlin & Singray wavefront sensor should be setup with a brightness of 16 and a gain of 1. The shutter is user adjustable based on the input intensity.

7.2.2 Mounting

All our Firewire wavefront sensors should be mounted using a 0.5” post into the attached KM100P ThorLabs kinematic mount. To access the 8-32 screw for the post on all horiztonally-mounted cameras (Marlin, Stingray, etc.), remove the two black socket-head cap screws under the camera to move the camera out of the way to attach the post.

7.2.3 Package Dimensions