AN039

Extending Hartmann Wavefront Sensor Dynamic Range

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1 Introduction

Hartmann and Shack-Hartman wavefront sensors suffer a fundamental limitation on the measureable slope dynamic range. The traditional dynamic range of a Hartmann or Shack-Hartmann wavefront sensor is the slope over an individual sub-aperture where the edge of the spot reaches the edge of the pixel region designated for the sub-aperture. Mathematically, this can be represented as

$$\frac{d\phi}{dx}_{\max} = \frac{\left(\frac{d_{sub}}{2} - r_{spot}\right)}{f}$$

where d_{sub} is the sub-aperture spacing, f is the separation between the aray and the imager, and r_{spot} is the radius of the focal spot (typically $f\lambda/d_{aperture}$).

Figure 1.1 illustrates an example of the slope dynamic range being exceeded with added tilt. The calibration beam in green puts the spots directly behind the sub-apertures. The blue beam with added tilt causes the light from the sub-apertures to appear to be directly behind the adjacent sub-apertures. If the overall beam position on the sensor or the fact that the top sub-aperture is missing a spot altogether is considered, even this situation may be recovered.

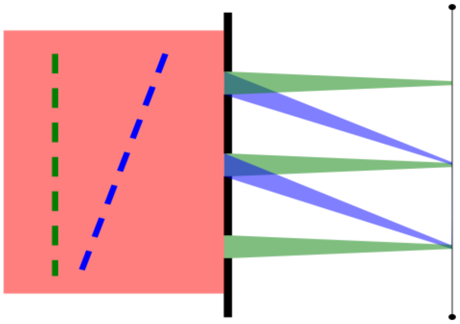

Figure 1.1 – Illustration of dynamic range being exceeded in a Hartmann sensor

There are more severe situations that can occur with severely aberrated wavefronts. A virtually unrecoverable situation is when the adjacent sub-aperture tilt steers light from each into the other's pixel array. In this case with a traditional Hartmann sensor, the sensor would be entirely unable to discern the spot origin and, therefore, the correct wavefront slope over the sub-aperture. This severity of aberration is extremely rare, but is mentioned here only for completeness.

The most common cases of dynamic range being exceeded are with wavefront tilt and focus terms. Tilt causes all the spots to move around the same amount. Focus causes the spots to spread out or move together. Since these are the most common terms, they will be the primary focus of this document.

1.1 Nomenclature

In this document, we will refer to the area of pixels allocated to a sub-aperture as an area of interest or AOI.

1.2 Sensing Dynamic Range Problems

Before we address the dynamic range problem, it is important to talk about how to sense dynamic range challenges. Generally the techniques are:

- Examine spot location in AOIs and sense when the spots are too close to the AOI edges.
- Examine intensity in the AOIs and determine whether multiple spots or no spots are in the AOIs.

2 General Strategies for Dynamic Range Extension

Control over optical parameters of the Hartmann or Shack-Hartmann sub-aperture array can enable even more solutions, but we will limit this discussion to a typical Hartmann sensor with a standard uniform sub-aperture or lens array.

2.1 Spot Tracking for Slowly Varying Aberrations

For slowly changing aberrations, it is possible to adjust the position of the AOIs with each measurement to center them on the spot position. This technique works well when measuring an evolving aberration like atmospheric aberrations or a slowly adjusting focus. If the spots begin to come together such that the AOIs overlap, the AOI size may need to be adjusted.

2.2 Tilt Dynamic Range Extension with Overall Beam Intensity Tracking

For tilt aberrations, the beam tracking can often be accomplished by tracking the overall position of the beam. By performing a centroid on the WFS image and comparing it with the position of the reference beam, the tilt of the beam can be approximated. This process only works well when the beam does not leave the sensor.

2.3 Focus Dynamic Range Extension with Spatial Frequency Analysis

Wavefront focus changes the spacing between the Hartmann spots. One way of determining the overall focus is to analyze the period of the spots on the Hartmann sensor. This can often be accomplished most easily with a Fourier transform of the image or potentially the sum of the image in one direction. The average spatial period relative to the design period is directly related to the average focal power of the system. Therefore, the focal power can be extracted from this analysis and the motion of the AOIs can also be determined.

2.4 Manual Adjustment for Focus and Tilt

The AOS software has the ability to move the AOIs manually. The software can move the AOIs in both directions to compensate tilt, can expand and contract the AOI spacing to compensate focus terms, and can change the AOI sizes to avoid the AOIs overlapping as the spacing changes.

2.5 Zernike Term Subtraction

The AOS software allows for subtraction of Zernike terms from the reference. If it is clear which Zernike is causing the problem, individual Zernikes can be removed manually. This could be done automatically as well or by searching over various Zernikes using the spot position as a metric for the search.

A variant on this is to move the AOIs with focus and tilt terms to find when the spots are nearest the center of the AOIs. This can be done with examination of intensity (only one spot per AOI), but is likely better to center the spots in the AOIs.

2.6 Analysis against Multiple Reference Files

In the case where the large dynamic range is in a known term, the aberration can be analyzed against a set of reference files. One example of this is ophthalmic applications. Human eyes can often be located well in measurement systems, but they will have a variety of different focal powers. A set of reference files can be created with a variety of focus terms. When the measurement is analyzed against this set of reference files, the spot position in the AOI can be used to detect the most appropriate reference and make a good measurement.

2.7 General Searching

The most general case is to use the new image to create a new set of references and then map the input AOIs to the output AOIs by minimizing the spacing between the two sets of AOIs. This is a nonlinear search, but can be aided with knowledge of the expected aberrations. This is very time consuming, but can be accomplished with modern computers relatively quickly. This is an inverse variant on binary optic intensity remapping (U.S. Patent 5864381). This has not yet been implemented in the AOS software.

3 Analysis of the Hard Limitations to Dynamic Range Extension

There are a variety of factors that can create a hard limitation on the extension of the dynamic range of the Hartmann-type wavefront sensor. For tilt, this is typically the ability of light to get from the array to the camera. For higher-order aberrations, this is typically where the diffracted spots run together. As an example, we will consider focus. The tilt dynamic range of a focus term can be extended until there is very little separation between the spots. Figure 3.1 shows the derivation of the minimum radius of wavefront curvature. For a Shack-Hartmann wavefront sensor case where the lens array is on a 150 micron pitch and has a 5.2 mm focal length and the radius of the focal spot is 29.1 microns, if we want a minimum separation, s, between the focal spots at the edge of a beam of 3 times the spot radius, the minimum radius of curvature would be 8.9 mm or 112 diopters. This kind of analysis can be derived for any aberration term.

$$\phi = \frac{r^2}{2R}$$

$$\frac{d\phi}{dr} = \frac{r}{R}$$

$$s = \left[\frac{d\phi}{dr}\left(r_{\max}\right) - \frac{d\phi}{dr}\left(r_{\max} - d_{lens}\right) \right] \bullet f_{lens}$$

$$s = \frac{d_{lens}}{R} f_{lens}$$

$$R_{\min} = \frac{d_{lens} f_{lens}}{s}$$

Figure 3.1 - Derivation of the Minimum Radius of Curvature