Characterizing the shape of infrared beams

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This article describes a way to characterize the shape of the infrared beams that are often used to test sensors and detectors.

Strongly focused Gaussian-beam lasers are often used to test the response of detectors and sensors whose size is comparable to the illuminating wavelength. At this scale, it’s important to characterize the shape of the incident beam. Unfortunately, experimenters cannot assume that they are working with a general Gaussian beam shape (GBS). As a result, the optics necessary to focus the laser cannot be perfectly aligned, which introduces aberrations that alter the beam shape. In some cases, the spot is so small that its light has to be treated as a vector wave, making its shape dependent on its polarization. At least for infrared lasers, the power signal can be unstable as well. These fluctuations have to be taken into account because they can blur the beam’s focus.

Intrinsic fluctuations and misalignments in an infrared beam can be modeled as a small amount of coma aberration. We use a combination of experimental measurements and pre- and post-processing of the signal to calculate the angle and amount of coma of very slightly comatic beams. This can then be used to characterize the misalignments: an approach that has been validated for noise in the data set and coma amount.

We have applied principal component analysis (PCA) to deal with fluctuations in the signal and slight variations from the GBS. This statistical technique is used to analyze the variance of a group of objects by looking at the original collection as linear combinations of other, uncorrelated objects: the principal components. Each principal component is responsible for a certain amount of variance in the original objects. If some of the components can be related to noise or a given structure in the data, they can be filtered out by a process called rectification. PCA uses both the strength of the signal and its correlation to obtain the principal components. This makes it possible to separate signals that have very slight differences in amplitude, but large differences in their correlations. This type of analysis has been applied in various ways in other papers.

Figure 1. Using principal component analysis (PCA) on a collection of knife-edge scans. Small amounts of noise coming from fluctuations in the laser signal produce noise in the calculation of the second moment of the beam as a function of the optical axis (top). Applying PCA by taking each scan as an object makes it possible to locate the best focus position (bottom).

In practice, the beam is strongly focused and then its focal region is scanned in both horizontal and vertical directions, using a knife-edge method. Taking the derivative of these scans creates an intensity profile of the beam for each optical axis. The second moment of these profiles is then plotted as a function of position on each optical axis, to locate the best focus. PCA can be applied over several scans to filter the noise (see Figure 1). The final accuracy of the focus position is on the order of a wavelength.

The two focus profiles (horizontal and vertical) are then introduced into a 2D model of the beam, which is used as a fitting model. We use a slightly comatic Gaussian beam as our model because small misalignments tend to produce asymmetric beams that are easily modeled as a comatic aberration passing through a circular aperture: the last lens. Since we know

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Figure 2. Applying PCA horizontally and vertically locates the best focus, and the uncertainties in each direction (left). These values are introduced into a model of the beam to calculate its parameters, including the width, and the amount and angle of coma.

Figure 3. Applying PCA to the intensity of a beam at its best focus position. The parameters of the model are shown. In this case, the basic objects are the intensity profiles at various angles (top left). PCA reveals a first principal component (PC 1), resembling the Gaussian shape of the beam. The weight of this shape over different angles is displayed as Eigen 1, showing it is approximately equal over all angles. The second principal component (PC 2) corresponds to an asymmetry between left and right. It is at its greatest at 10° (see Eigen 2) and at its smallest in a direction rotated 180°. This component describes the coma at different angles.

The uncertainty in the horizontal and vertical profiles for each point, new horizontal and vertical profiles can be calculated and a new set of fitting parameters obtained (figure 2). It is possible to filter out this ‘fitting noise’ by applying the PCA method over the 2D beams corresponding to each group of the fitting parameters.5–8

A 2D version of the beam shape is calculated from only two directional profiles. A more useful approach would use a 2D beam-profile image. This is only possible in the far-field region, where the beam shape could be imaged by a focal-plane-array camera. Because the far field is just a propagation of the focus field, the two are related by a Fourier transform. Assuming certain characteristics, it is possible to obtain a profile at the focus point from the far field.

We use the PCA method again. In this case, different profiles of the focus are taken at different angles, digitally. These become the new set of objects. A first principal component (PC 1) appears related to the Gaussian beam shape. A second principal component is responsible for the asymmetry in the beam, and its contribution is greatest in a given direction (figure 3). The percentage of variance explained by this second component is directly related to the amount of coma present.

The method also provides a tool to calculate misalignment, through the amount of coma and its direction. We have validated the method with respect to coma and the level of noise in the image. It gives good results for aberrations of up to 0.4 coma (measured in wavelength units), and provides good signal-to-noise ratios in the image:9 greater than 10.

Our combination of measurements and statistical analysis has created a new way of characterizing the focus and distortions of an infrared beam. This is important because such beams are often used to test sensors and detectors. Our next step is to extend the method to other wavelengths, depending on the capabilities of the cameras available. We also want to automate the process.

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References