Alignment characterization in micro and nano technologies.

José Manuel López-Alonso,[1] Javier Alda,[2] and Glenn Boreman.[1]

[1] College of Optics and Photonics, CREOL, University of Central Florida,
Orlando, FL USA 32816-2700
E-mail: joselope@creol.ucf.edu; boreman@creol.ucf.edu

[2] Optics Department, University Complutense of Madrid.
School of Optics. Av. Arcos del Jalón s/n, 28037 Madrid, Spain.
E-mail:j.alda@fis.ucm.es

Abstract

The use of lasers as probe sources is very extended in micro and nano technologies. Therefore, the characterization of the beam is critical for the utter development of the measurement. Typically, The beam is projected on the detectors using optical elements and lenses. The alignment procedure is not always very good, and the difficulties increases when infrared radiation is involved. Even with very accurate positioning elements some misalignments are produced. The misalignment is most responsible for the appearance of coma aberration. In the case of a pure Gaussian beam shape they are going to produce a slightly comatic aberrated beam. In this paper we propose a method to characterize the direction and amplitude of this comatic aberration. The method is sensible enough to characterize slightly aberrated beams normally used to deconvolve detector's spatial response. It is based on a statistical analysis of the beam shape in different directions respect to its center. Simulations including the effect of noise are presented too and some applications to micro and nano metrology are exposed.

1. Introduction

Infrared detectors are used in a large number of systems including imaging applications. In recent years, not only semiconductor devices have been used in the infrared, but infrared antennas.[1] In these types of detectors, the spatial response is a very important figure of merit because it provides information about the radiation collection efficiency of the device. For other types of detector, it provides the effective collection area. In both cases a reference infrared signal is focused onto detector and the signal response is scanned in two orthogonal directions. The resulting 2D map is the convolution of the detector spatial response with the reference signal. The spatial response is obtained through a deconvolution process.[2,3] An infrared laser is normally used for these purposes. They are normally affected by instability problems that have been addressed in a previous contribution.[4] The spatial response is obtained from a deconvolution procedure. This deconvolution uses the spatial irradiance map of the illuminating beam. This is why the the knowledge of the map of irradiance of the beam is so important. If the laser is properly working and the optical alignment is carefully done it is possible to assume a general Gaussian shape for the incoming beam. But this is not the case in most of the cases. Then, a residual misalignment is present. This introduces

Electro-Optical and Infrared Systems: Technology and Applications II, edited by Ronald G. Driggers, David A. Huckridge,
Proc. of SPIE Vol. 5987, 59870K, (2005) · 0277-786X/05/$15 · doi: 10.1117/12.631216

aberrations into the beam. The principal type of aberration depends on the ability to align and experimentally set the optical elements up along the optical train. For example, when visible radiation is used, the alignment is better obtained and the most contributing aberration is spherical aberration.[5] In the case of infrared wavelengths, some of the authors have identified comatic aberration as the principal one, although quite weak. In these conditions, coma introduces small deviations from the nominal Gaussian beam shape and makes difficult to identify the angle and its global contribution.

Section 2 of this contribution explains the experimental set-up and the procedure to obtain a sound irradiance distribution from the knife-edge measurement of a tightly focused, diffracted and aberrated laser beam. At the same time, we propose an upgrade of the method by taking into account the irradiance distribution at the far field. The experimental part of this new approach has not been yet implemented. Section 3 presents the analytical model of the beam. The Principal Component Analysis (PCA) is explained in section 4 and applied to the description of diffracted and comatic Gaussian beams. Sections 5 and 6 are devoted to a detailed analysis about the validity and robustness of the PCA method in the description of these beams. Finally, section 6 summarizes the main contributions of this paper.

2. Experimental setup

The typical optical train used to characterize the spatial responsivity of micro- and nano-photonic devices in the infrared uses a set of lenses and beam control elements that provide a well collimated beam. In our case, this train includes polarization control elements, mechanical and/or acoustoptic modulators, and several infrared optical lenses acting as relay, collimation, or focalization elements. The optical source in the infrared is typically realized with a CO_2 laser having an emission very close to the TEM00 Gaussian mode. In several previous contributions we have assumed that the beam can be modeled as a Gaussian beam weakly disturbed by diffraction and aberrations. For the infrared, due to the practical difficulties encountered to properly align the incoming beam along the combined optical system, we have justified that the most contributing aberration is coma. This is because the beam is filling the aperture of the last collimation lens. On the other hand, in our experimental set-up, this lens is a high-quality element where spherical aberration is kept under control. However, when visible light is used to analyze the devices, the alignment is easier and spherical aberration is the one playing the main role. Several practical improvements can be made to reduce the misalignment and therefore minimize the comatic contribution. For example, when ZnSe lenses are used, a visible laser beam can be propagated through the optical train to align the optical axes of the elements and the propagating optical beam.

The main source of uncertainty in the validation of the measurements of the spatial responsivity of optical antennas is the precise knowledge of the illuminating beam. This spatial responsivity is obtained after applying an iterative deconvolution algorithm on the measured signal. This signal is considered as the convolution of the actual spatial response map and the irradiance distribution of the laser beam that incides on the device. To characterize the beam we rely on the knife-edge measurement of the focusing spot and a fitting procedure that includes a model of the beam. The knife-edge technique is the only one available when highly focused beams are used. The transversal size of the beam is comparable, or even smaller than the size of the individual pixel element used in focal plane arrays devoted to the characterization of laser beams. However, it is also possible to expand the beam, just by propagating it in free space, until its transversal size is manageable by image forming systems. Then, the irradiance distribution can be easily defined as the far field distribution of that one lying on the focusing plane. In this case, the measurement of this irradiance distribution could be included in the fitting procedure to improve the knowledge of the incoming radiation.

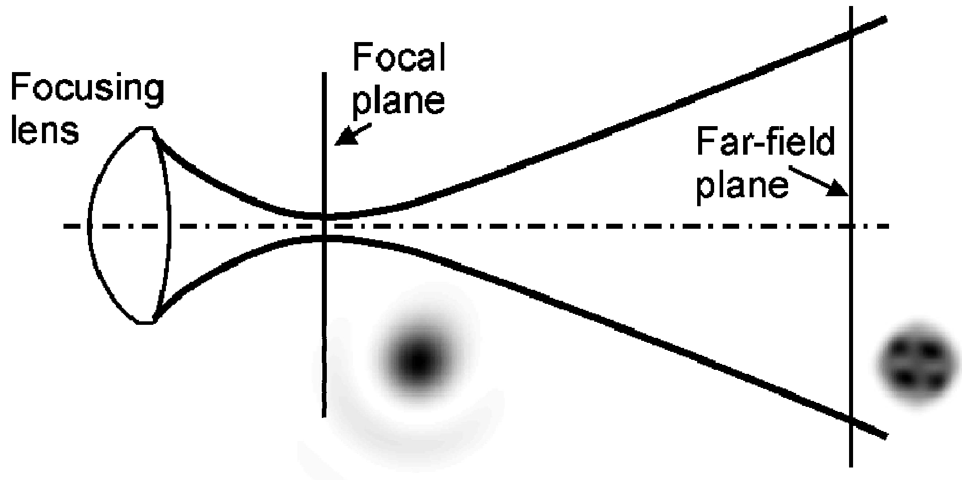

Figure 1: Visualization of the process of focalization. The size of the focus region depends on the optical system used. In a F# 1 configuration could be very small. In order to use a camera only the far field region of the beam can be collected and analyzed.

In previous contributions[3,4] we have described an appropriate method to measure the beam shape: a collection of knife edge scans is made around the focal region along vertical and horizontal directions. The noise in the scans is filtered using a Principal Component Analysis (PCA). Then, the "best focused beams" are calculated in both directions along with their uncertainties. These two profiles are fitted to a beam model that includes the Gaussian beam distribution, the effect of diffraction through the circular aperture of the lens, and a contribution of coma. When taking into account the previously calculated uncertainties in the knife edge measurements, we find a collection of fitted beams. This collection presents a mean and uncertainty that are finally taken as the best fitted irradiance distribution of the beam. This fitted beam is finally used to obtain the spatial responsivity map of the infrared antennas as the result of an iterative deconvolution algorithm. As far as we are taking into account the uncertainties coming from the measurement, the modeling, and the deconvolution, we may define a signal-to-noise ratio by calculating the quotient between the average value and the uncertainty. The PCA is able to define this quotient as signal-to-noise map of the involved variables. The results of the analysis suggests that the obtained signal-to-noise ratio for the characterization of the beam is the limiting factor for the calculation of the spatial response map of infrared antennas.[3] This could be explained because a complete 2D irradiance map has to be inferred from only two orthogonal 1D profiles.

Actually, a useful 2D image can be only taken when the FPA is located in a region that can be considered as the far field. In this case, besides the filling of the acquisition device, the irradiance is related with the focal plane irradiance through a Fourier Transform. On the other hand, as far as the beam is tightly focused, the Rayleigh range of the beam is a few hundreds of microns and the far field region can be located a few centimeters away from the focal point. Then, knowing the amplitude in the far field and assuming undisturbed phase propagation in free space, amplitude in the focal plane can be inferred. The FPA is able to acquire the irradiance distribution in the far field. This irradiance distribution should be connected with the amplitude distribution calculated from the model of the beam. This calculated amplitude is going to be affected by noise and other uncertainties. However, although the estimation of the beam model parameters is not simple, this far field distribution can be used to improve the fitting of the model of the beam, and therefore, to improve the knowledge and reduce the signal-to-noise ratio of the beam irradiance illuminating the infrared antenna. In the current development of our analysis we are able to present this idea. The results and robustness of the method will be shown in future contributions.

3. Structure of the beam

As previously explained in other contributions, the main source of aberrations, after proper alignment, is coma (in the case of infrared radiation). Following the calculations made for aberrated diffracted beam, the spatial distribution of the amplitude of the beam can be modeled as:

$$E(x,y) = \exp\left(-\frac{x^2+y^2}{\omega_0^2}\right) * \left(\frac{2J_1(\upsilon)}{\upsilon} - \alpha\cos\phi\,\frac{2J_4(\upsilon)}{\upsilon} - \alpha^2\frac{1}{2\upsilon}\times\left\{\frac{J_1(\upsilon)}{4} - \frac{J_3(\upsilon)}{20} + \frac{J_5(\upsilon)}{4} - \frac{9J_7(\upsilon)}{20} - \cos 2\phi\left[\frac{2J_3(\upsilon)}{5} + \frac{3J_7(\upsilon)}{5}\right]\right\}\right), \quad (1)$$

where,

$$\upsilon = \frac{2\pi}{\lambda}\frac{a}{z}(x^2+y^2)^{1/2}\ , \quad (2)$$

being a, the aperture of the last lens used, λ the wavelength, z, the distance respecxt to the last lens, x,y, the coordinates in the focalization plane, w_0 the Gaussian waist and J_i the I Bessel function. Basically the model represents a Gaussian beam truncated by the aperture of the lens and affected by a α amount of coma in the direction given by the angle, ϕ.

A fitting algorithm using the previous model and the knife-edge measurements provides with the calculated irradiance distribution. Most of the parameters are extracted from the the experimental set up (wavelength, diameter of the aperture, distance from the aperture to the focal plane, and Gaussian width of the incoming Gaussian beam) but two are not quite easily obtained, these are the amount of coma and the coma angle orientation.

4. Principal Component Analysis.

The Principal Component Analysis (PCA) is a multivariate statistical technique used to handle a large amount of data. The starting point is a collection of *N* random variables and *M* observations of them. From the observations, the covariance matrix *S* is calculated and then diagonalized. Three different objects appear from this process: a collection of *N* eigenvalues, *N* eigenvectors and *N* principal components. The eigenvectors form a new base in which the transformed random variables are uncorrelated. The *M* observations of these transformed variables are called principal components. The name come from the following: the original variables can be seen as a transformation of these principal components. In this way, they are linear combinations of previously uncorrelated variables.[6] The coefficients of the linear combinations, the eigenvectors, are the weights of each principal component at a specific random variable. The eigenvalue gives the importance of the associated principal component in the whole data set. [6]

In this paper we use the PCA to study the comatic aberration of a highly focused and diffracted laser beam. Typically, the coma contribution is very small, and it is mainly caused by residual misalignments in the optical chain. When looking at a simulated image of the focused beam, it is very difficult to detect the coma direction. The *N* random variables are defined as radial slices of the irradiance distribution passing through the beam center, but along different angle directions. The *M* observations are the *M* points of each slice.

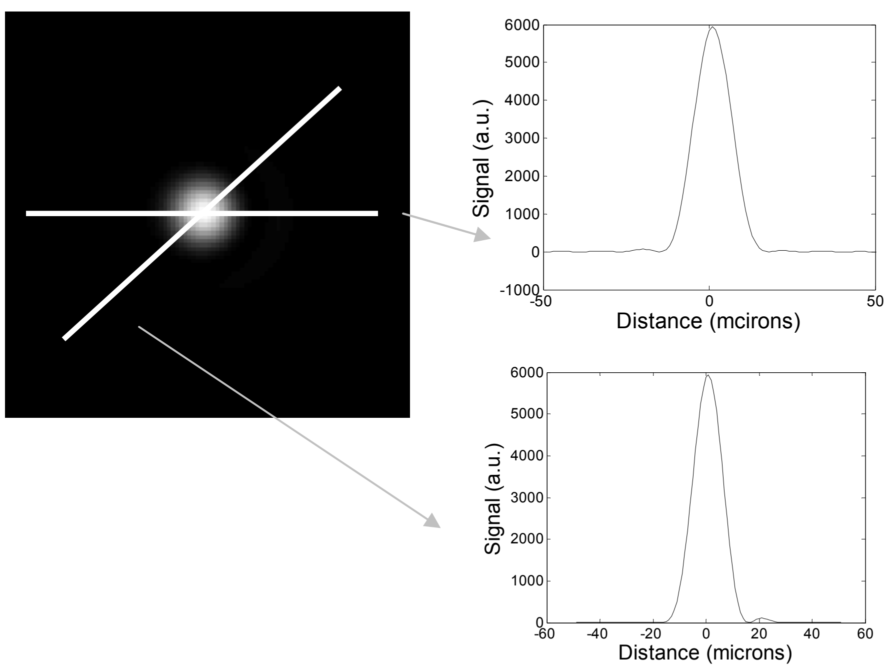

Figure 1: Different slices at different angles are taken from the original simulated beam. It is possible to see how the symmetry properties of the two selected profiles are different

In figure 1 we see how the irradiance profiles for two slices at different angles are different for the case of a slightly comatic and diffracted Gaussian beam. The differences are caused by coma. This is the only one contribution having an angular dependence. Then, we expect the appearance of a single principal component given the same shape in all angles (Gaussian profile) and a second one responsible for the asymmetry introduced by coma. In order to test this hypothesis we have simulated a beam with the parameters of Table 1.

Wavelength	10.76 microns
Aperture radio	0.025 m
Focal distance	0.050 m
Angle	10 degrees
Coma	0.1
Gaussian width	6 microns

Table 1: Parameters selected for simulation. The coma parameter is given as a fraction of the wavelength.

In order to apply the PCA, four hundred slices (*N*=400) are taking covering all possible directions. The resolution in angular units is 0.9 degrees. When applying the PCA, the expected principal components appear. They are shown with the corresponding eigenvectors in figure 2.

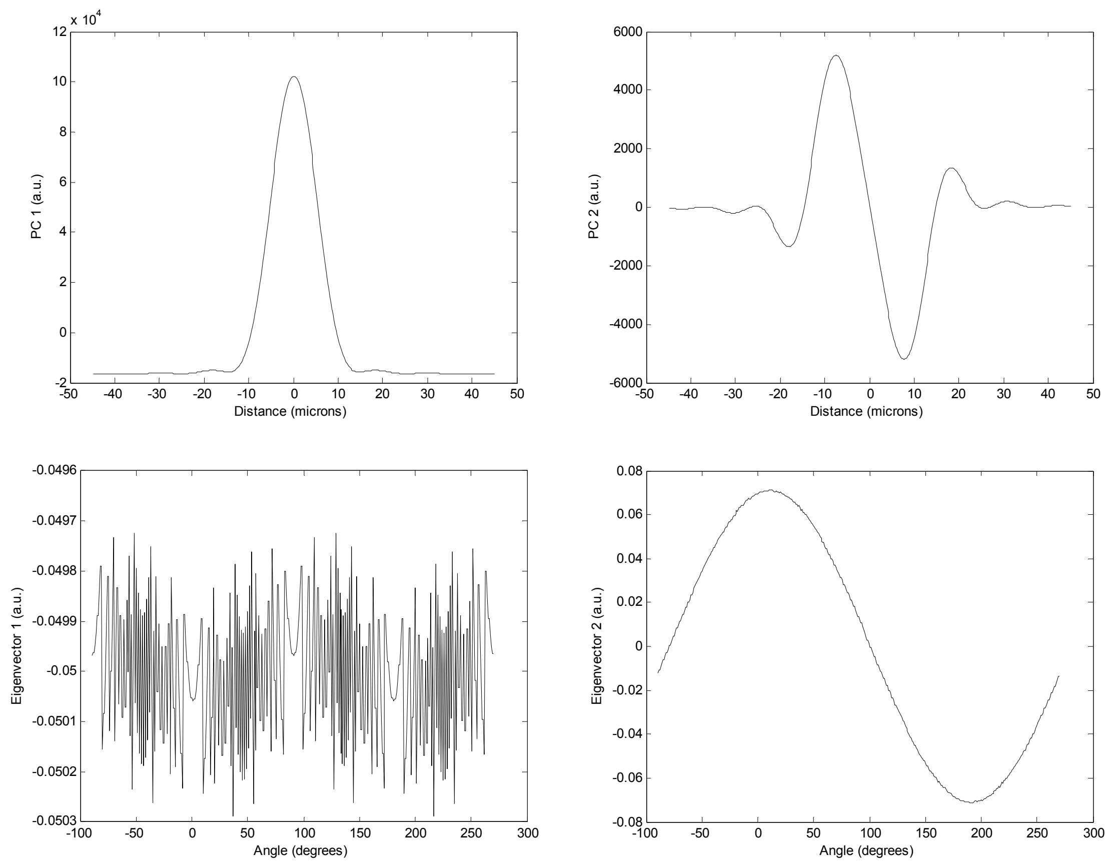

Figure 2: First and second principal component (Top left and right) with their corresponding eigenvectors (Bottom) for the simulated beam of Table 1. Note that the bottom left figure, corresponding with the first eigenvector spans over a very narrow range of variation (from -0.0503 to -0.0497), however, the bottom right figure, corresponding to the second eigenvector ranges from -0.08 to 0.08. This means that the contribution of the diffracted Gaussian distribution can be taken as constant.

The first principal component resembles the diffracted Gaussian shape of the beam. Its weight in all slices (first eigenvector) is almost the same in all of them. Second principal component is driven by a left-right asymmetry. Exactly what we expect from coma and in the position where it is expected. Moreover, the weight of if changes with angle, showing a maximum around the correct angle (10 degrees) and a minimum over an orthogonal direction. By the properties of PCA, the maximum amplitude of eigenvectors is always $\sqrt{2/N}$, being N, in this case, the number of slices. Then, it is possible to fit the eigenvector to an equation of type:

$$\sqrt{\frac{2}{N}}\cos(f\theta+\delta) \qquad (3)$$

Being f a frequency, θ, the angle of the slice and δ, a phase parameter. Then, the position of maximum can be calculated as $\theta = -\delta / w$. When applying to the previous beam, the result is 10.9º with a resolution of 0.9º. This is in good agreement with the data coming from the simulation (10º). The power of the method is revealed when we calculate the relevance of the second principal component in the total data set. This can be calculated as the ratio of the associated eigenvalue to the sum of all eigenvalues. The result is that it represents only the 0.39% of the total variance in the data set. The same approach is applied to a new beam, with the same characteristics of Table 1, but with a coma angle of 120 degrees. The results are shown in figure 3.

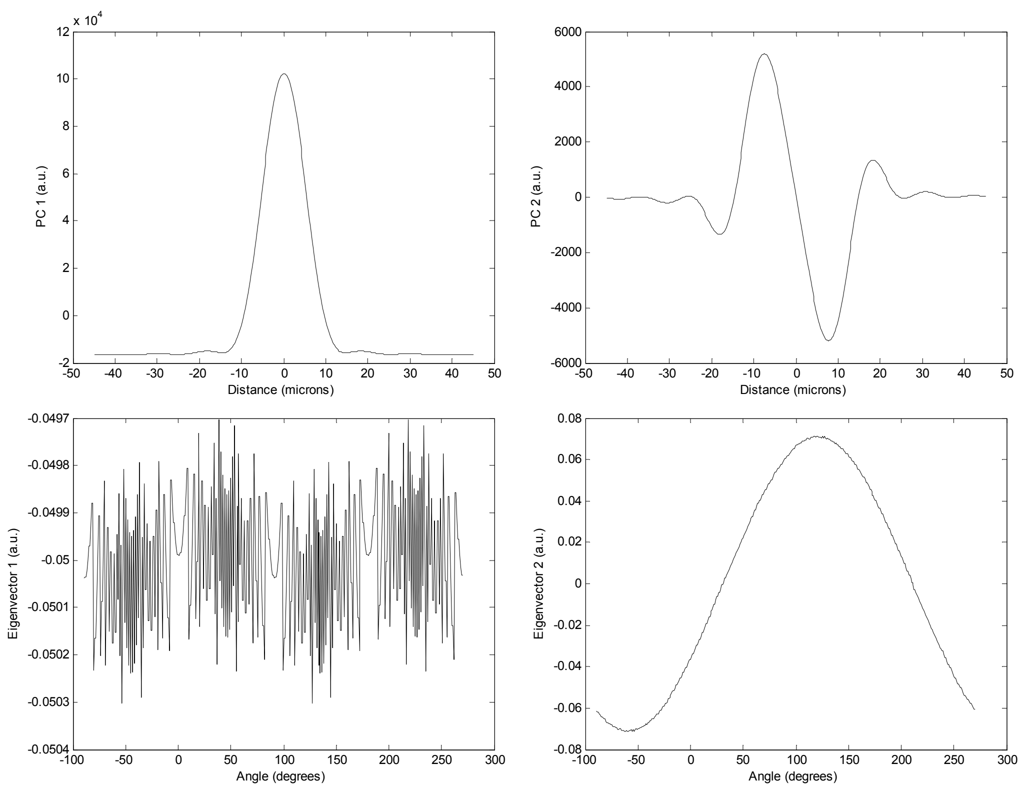

Figure 3: First and second principal component (top left and right respectively) with their corresponding eigenvectors (bottom) for the simulated beam of Table 1. The orientation of the coma has been changed to 120º. The behavior is the same of Fig. 2, and the angle of the coma is clearly identified.

5. Validation of the method and coma calibration.

The most important assumption of the method is that the angular dependence introduced by coma is revealed as an angular dependent principal component whose weight over the angle directions reveals the direction of comma. The following question is how this structure depends on the actual degree of coma. It is expected that when coma increase to a very large amount, the distortion in the Gaussian shape of the beam is going to be very large. Then, it is possible that the structure of principal components changes too, and the interpretation of their weights and shapes over all angle directions becomes more difficult.

In order to validate the method a new set of beams is simulated. The parameters are again the same as Table 1, but now changing the amount of coma from 0.01 to 1. The results are shown in the figure 4.

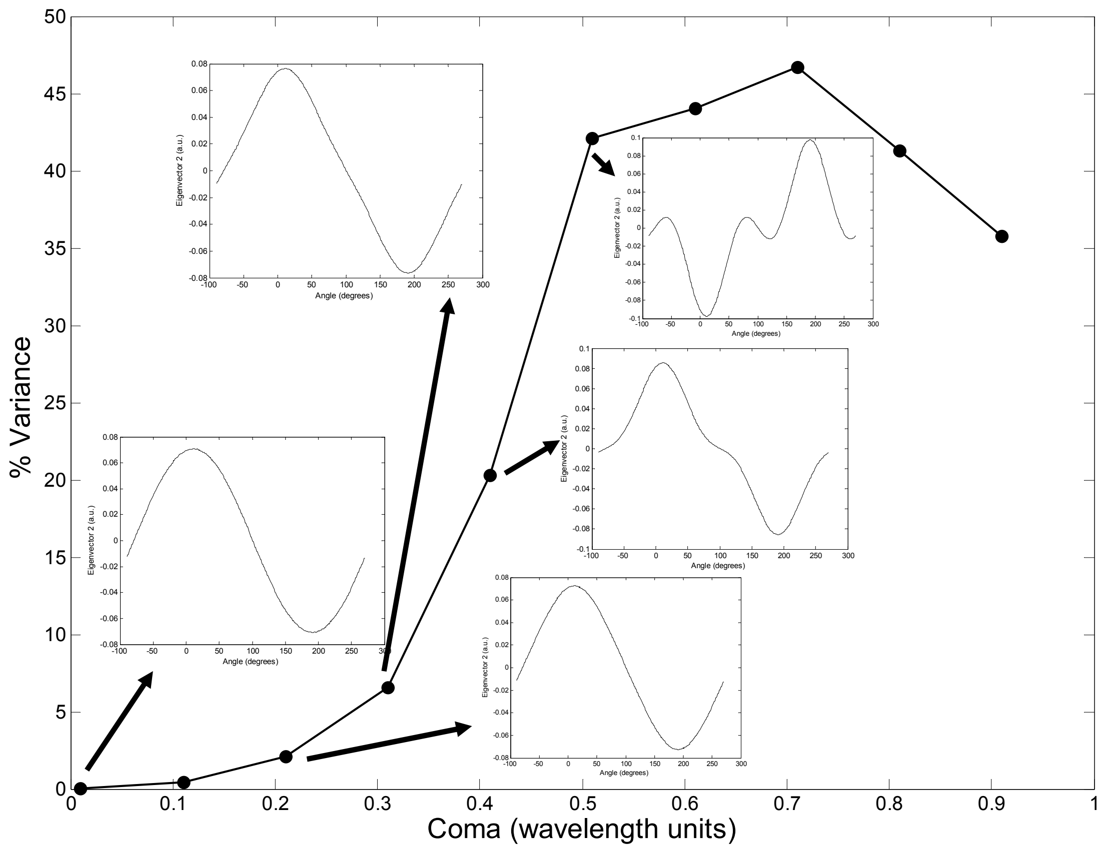

Figure 4: Percentage of variance explained by the second principal component versus the amount of coma. The corresponding eigenvectors are shown in the same graph

The variance due to the second principal component increases with the coma till around 0.5 coma. But the structure explained in the previous sections of this paper can only be seen to approximately 0.4 coma. With higher coma, the weight of the second principal components has a complex structure over the angular directions, although it reaches the maximum values at the expected angular directions. This makes difficult to relate them with the coma angle in an easy way. For large coma (0.5-1), other principal components appear as relevant and the method can no longer be applied. This validates the method for slightly comatic beams. Fortunately, when using a visible laser beam the alignment of the optical train is better obtained and the residual coma is quite low.

Another advantage of the PCA method is that the amount of coma can be extracted for the analysis. The amount of variance explained by the second principal component seems to be a good metric for this purpose. It is shown versus comatic aberration in figure 5 with a more detailed calculation.

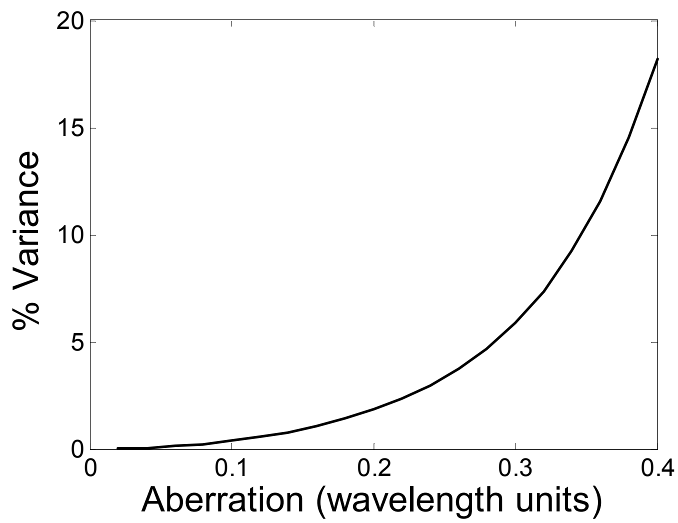

Figure 5: Percentage of variance explained by the second principal component as a function of comatic aberration.

The plot of figure 5 is very well fitted to a curve of type:

$$\%V = A\alpha^{b} \tag{4}$$

Where $\%V$ is the percentage of variance explained by the second principal component, α is the amount of coma, in wavelength units, and A and b are the fitting parameters. An important characteristic of this fitting is that these parameters are independent of the coma angle and only depends on the experimental situation (F#, focal distance, and aperture). Then, the method can be calibrated for each experimental situation in order to extract the amount of coma too.

6. Validation respect to noise.

In order to test the robustness of the method to noise we have simulated beam shapes with different levels of Gaussian noise respect to the maximum of the beam. The parameters of the beam are the same of Table 1. The percentage of variance explained by the second principal component and its weight over different angle directions are calculated versus the signal to noise ratio respect to the maximum of the beam. The results are shown in figure 6.

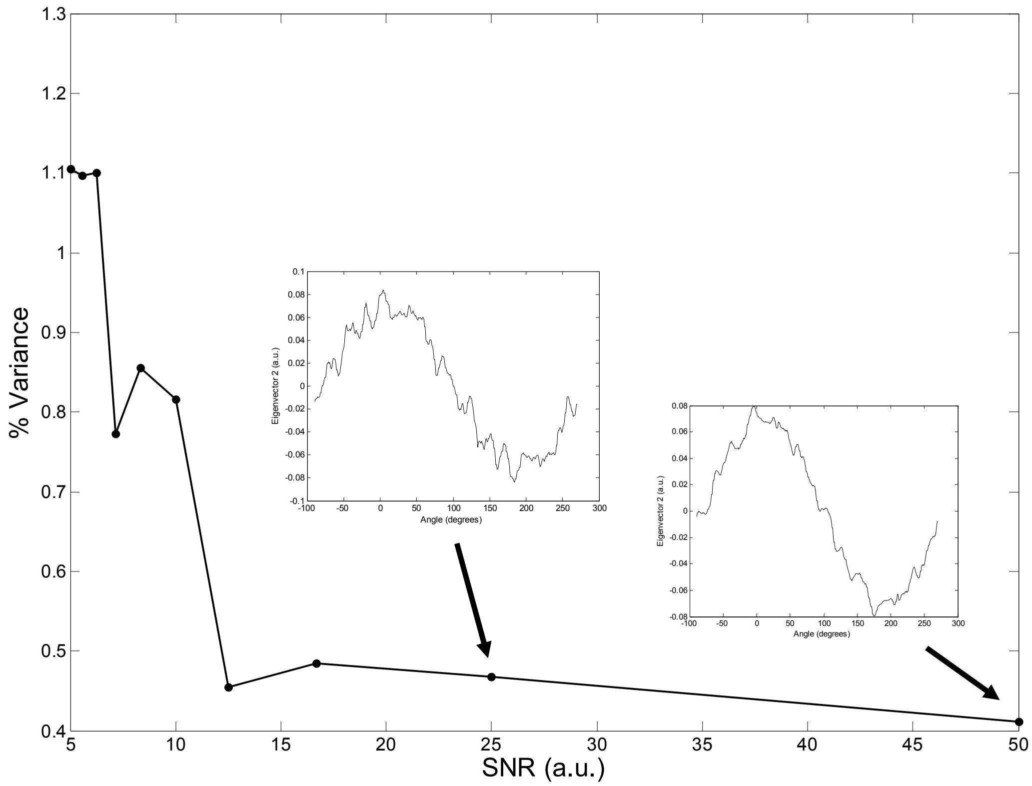

Figure 6: Percentage of variance explained by second principal components and its eigenvector for different signal to noise ratios

For signal-to-noise ratios larger than 10, the noise strongly affects the results, but the second principal component and its eigenvector can be easily fitted to give the angle and amount of coma. We have to remember that this signal to noise ratio is calculated respect to the maximum value of beam. This means that the method is still applied even when the standard deviation of noise is 1/10 of the maximum signal.

7. Conclusions

The improvement in the knowledge of the spatial distribution of irradiance illuminating an infrared antenna is highly desired to produce a more accurate determination of its spatial responsivity map. The use of the far field distribution is proposed in this paper as a way to increase the number of data fed on the modeling of the beam. On the other hand, coma has been identified as the most contributed aberration in the experimental set-up used for the characterization of the devices. The results of coma have been analyzed by using the PCA as a method to extract the parameters characterizing coma The method provides with a tool to calibrate the experimental setup and extract the values of the contribution of the coma and its angle of orientation. These parameters are important to calculate. They are included in more sophisticated fitting routines to model a beam shape used in micro characterization of detectors. Our results show that the PCA is able to evaluate this parameters for weakly aberrated (until 0.5λ of coma) diffracted and tightly focused beams. The methods can be also applied to noisy data.

References

1. F.J. González and G.D. Boreman, "Comparison of dipole, bowtie, spiral and log-periodic IR antennas," Infrared Phys. Technol., **46**, 418-428, (2005).
2. J. Alda, C. Fumeaux, I. Codreanu, J. Schaefer, G. Boreman, "A deconvolution method for two-dimensional spatial-response mapping of lithographic infrared antennas," Appl. Opt., **38**, 3993-4000, (1999).
3. J.M López-Alonso, B. Monacelli, J.Alda, G. Boreman, "Uncertainty Analysis in the measurement of the spatial responsivity of infrared antennas" Appl. Opt., **44**, 4557-4568 (2005).
4. J. M. López-Alonso, B. Monacelli, J. Alda, and G. D. Boreman, "Infrared laser beam temporal fluctuations: characterization and filtering," Opt. Eng., **44**, 054203, (2005).
5. C. Fumeaux, J. Alda, G. Boreman, "Lithographic antennas at visible frequencies", Opt. Lett., **24**, 1629-1631 (1999).
6. J.M. López Alonso, J. Alda, E. Bernabeu "Principal component characterization of noise for infrared images" Appl. Opt., **41**, 320-331 (2002).