Tolerancing panoramic lenses

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ABSTRACT

Tolerancing a lens is a basic procedure in lens design. It consists in first defining an appropriate set of tolerances for the lens, then in adding compensators with their allowable ranges and finally in selecting an appropriate quality criterion (MTF, RMS spot size, wavefront error, boresight error…) for the given application. The procedure is straightforward for standard optical systems. However, it becomes more complex when tolerancing very wide angle lenses (larger than 150 degrees). With a large field of view, issues such as severe off-axis pupil shift, considerable distortion and low relative illumination must be addressed. The pupil shift affects the raytrace as some rays can no longer be traced properly. For high resolution imagers, particularly for robotic and security applications, the image footprint is most critical in order to limit or avoid complex calibration procedures. We studied various wide angle lenses and concluded that most of the distortion comes from the front surface of the lens. Consequently, any variation of the front surface will greatly affect the image footprint. In this paper, we study the effects on the image footprint of slightly modifying the front surface of four different lenses: a simple double-gauss for comparison, a fisheye lens, a catadioptric system (omnidirectional lens) and a Panomorph lens. We also present a method to analyze variations of the image footprint. Our analysis shows that for wide angle lenses, on which the entrance pupil is much smaller than the front surface, irregularities (amplitude, slope and location) are critical on both aspherical and spherical front surfaces to predict the image footprint variation for high resolution cameras. Finally, we present how the entrance pupil varies (location, size) with the field of view for these optical systems.

Keywords: Tolerances, Panoramic Lenses, Distortion, Pupil aberration, Aspheric, Sensitive Analysis, Calibration.

1. INTRODUCTION

Tolerancing a lens is a well-known procedure in lens design. It begins by defining an appropriate set of tolerances for the lens, adding compensators with their allowable ranges and finally selecting an appropriate quality criterion (MTF, RMS spot size, wavefront error, boresight error…) for a given application. The procedure is relatively straightforward for standard optical systems, using both sensitive and statistical (Monte-Carlo) analysis.

However, it becomes more complex when tolerancing very wide angle lenses (larger than 150 degrees). For wide angle imaging systems, on which the front surface is generally large compared to the other lenses in the system, tolerance analysis can be more challenging and proper tolerances have to be specified to ensure that required performances are obtained. They are often very sensitive [1] and ray tracing errors are frequent in optical design programs at large field angles due to large entrance pupil shifts.

This paper identifies another important difference in tolerancing panoramic systems. It is known that localized slope errors have different impact if they are on surfaces close or far from the aperture stop [2-3]. For panoramic imagers, these localized errors on the front surface were found to be even more critical. The principal reason for this is that the footprint for a given field angle is usually small compared to the surface diameter near the front surface. Because of this, localized slope errors create wavefront tilt instead of contributing to wavefront RMS error as they do near the stop when the full surface is illuminated for each field of view. Also, these problems with localized slope errors become more complex on aspherical surfaces and new tolerancing indications have been proposed [3-4] for an optical system with a small field of view. In this paper, the influence of a small localized error is studied, but specifically on the spherical or aspherical front surfaces of panoramic systems.

Also reported in this paper is the influence of the front surface on the entrance pupil position. For panoramic systems, the entrance pupil generally moves away from the optical axis as the field angle increases [5], making it harder for optical design programs to trace rays in the systems. For this reason, it will be interesting to see how this displacement is linked to variations of the front surface for panoramic imaging systems.

While section 2 of this paper is mainly about describing the four optical systems used in this study and explaining the method used, section 3 presents and discusses the various results.

Optical System Alignment, Tolerancing, and Verification III, edited by José Sasián,
Richard N. Youngworth, Proc. of SPIE Vol. 7433, 74330D · © 2009 SPIE
CCC code: 0277-786X/09/$18 · doi: 10.1117/12.826139

2. DESCRIPTION OF THE ANALYSIS METHOD

This section explaining the method used is divided into three parts. Subsection 2.1 presents the four optical systems used for comparison, explaining their characteristics. Subsections 2.2 and 2.3 explain the analyses performed on each of these optical systems, respectively for surface errors and entrance pupil locations, all using the optical design program Zemax.

2.1 The four optical lenses

To compare the variations in performances caused by errors on the front surface, many lenses were analyzed, only four of these being presented here. These are: a simple double-gauss lens for reference [6], a fisheye refractive lens [7], a catadioptric omnidirectional system [8] and a Panomorph lens [9]. All these imagers are scaled to use a 1/3'' detector and the three panoramic ones are limited to a maximum field of view of 170^o for easier comparison. Table 1 is a quick reference with important details about these systems.

The first lens, included in this analysis to show the difference between panoramic imaging systems and a standard imaging system, is a 28^o double-gauss lens (DGL) from Zemax samples [6]. The front surface is a spherical lens, with a diameter of 3.99 mm. The optical layout of this system is shown in figure 1a.

The second lens is a standard 170^o fisheye lens (FEL) from a patent [7]. The front surface is also spherical, with a diameter of 3.57 mm. This panoramic lens is a good example of all of the refractive imaging systems with spherical surfaces that were tested. The optical layout of this system is shown in figure 1b.

The third optical system uses a mirror instead of a lens as a front surface and is a good example of a 170^o catadioptric omnidirectional system (CDS). It is partly inspired by the system from Kweon [8], but uses a different mirror as the front surface, defined as an even asphere mirror instead of an odd asphere mirror, allowing easier analysis in Zemax. The front mirror diameter is 33.24 mm. The optical layout of this system is shown in figure 1c.

The last lens presented here is a 170^o Panomorph lens (PML) from Immervision [9]. It is an example of a system composed of an even asphere front surface of 40.83 mm with a very unique shape chosen to control the distortion pattern. Also, it is an anamorphic system, giving different performances along the X or the Y axis. For these reasons, it is an interesting lens to study. The optical layout of this system is shown in figure 1d.

2.2 Analysis of front surface error

The first step when tolerancing a surface, even before adding errors, is to define a quality measurement for the system. In the case of a panoramic imager, it is interesting to look at the image footprint, which is how the height H on the detector is related to the field angle θ. A frequently used measurement of this displacement of H is the measurement of the displacement error. The usual approach for this is the measurement of distortion, where the curve of H vs θ is compared to a theoretical reference curve. This reference is sometimes $H=f*\tan(\theta)$ or more often in the case of panoramic systems where θ goes over 90 degrees $H=f\theta$. However, for some lenses like the PML, the H vs θ curve is chosen to greatly depart from the $H=f\theta$ behavior and a better measurement than the usual distortion is to directly plot the derivative of H vs θ (sometimes also called the distortion for such panoramic lenses), which is the resolution at a given field angle θ. The curve of $dH/d\theta$ is presented for all four optical systems. Also, to show the link between this measurement and the front surface, the derivative from the shape of the front surface Z vs the field angle θ ($dZ/d\theta$) is shown for each lens.

Table 1: Quick reference of physical properties for the four analyzed lenses.

	DGL	FEL	CDS	PML
Full field of view (degrees)	28	170	170	170
Front surface type	Spherical lens	Spherical lens	Even asphere mirror	Even asphere lens
Front surface diameter (mm)	3.99	3.57	33.24	40.83
0^o entrance pupil diameter (mm)	2.48	0.45	0.13	0.34
Ratio of 0^o entrance pupil / Front surface diameter	0.62	0.13	0.0039	0.0083
Gaussian bump FWHM (mm)	14.88	2.7	0.78	2.04

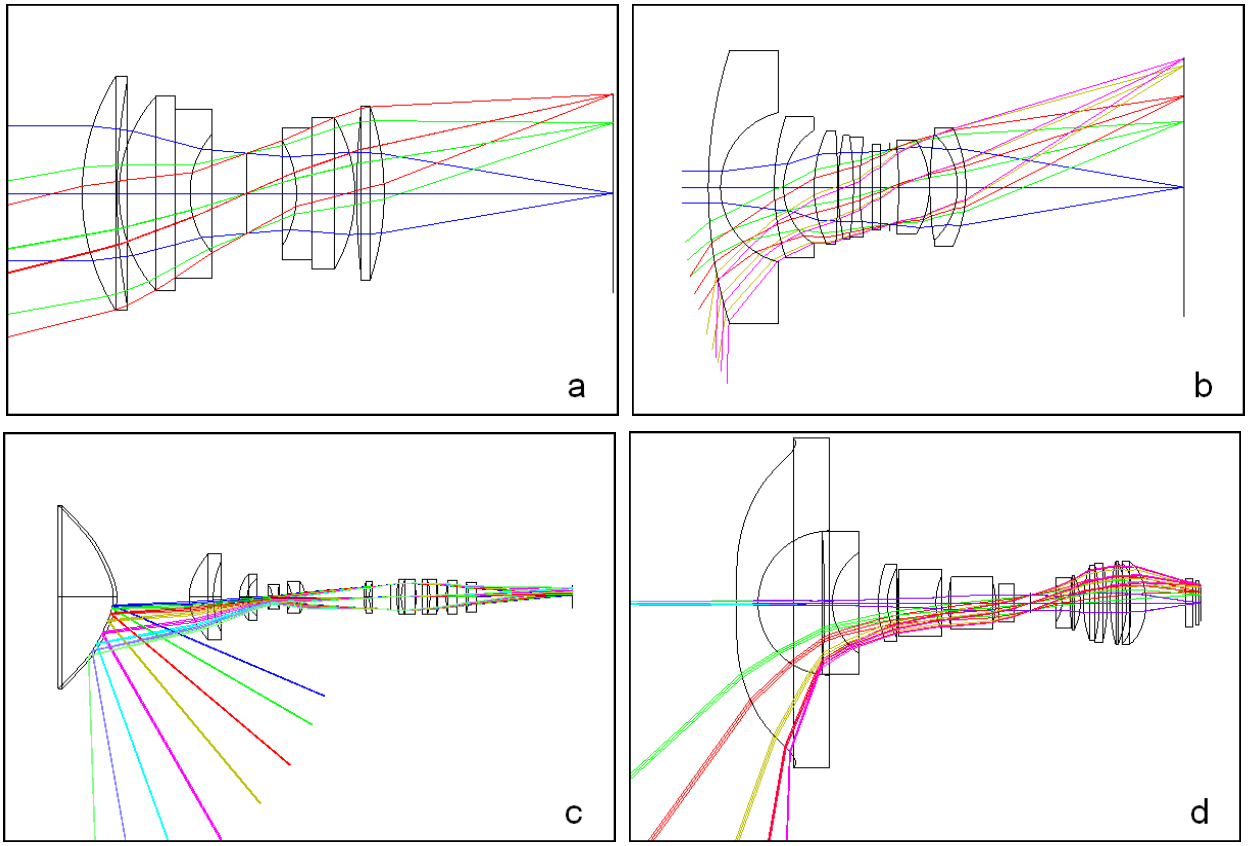

Fig. 1. Optical layout of the four optical systems: a) DGL b) FEL c) CDS d) PML.

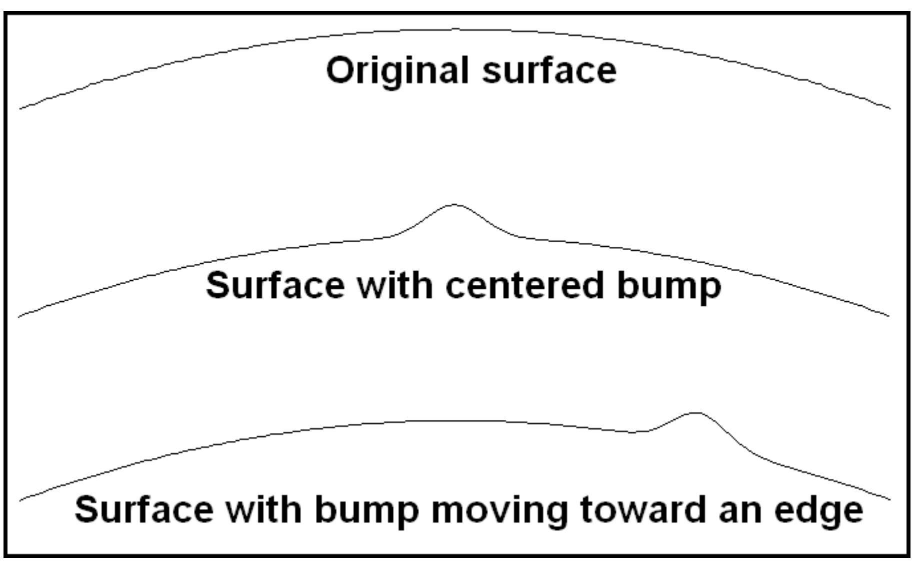

Fig. 2. Examples with exaggerated amplitude showing a moving Gaussian bump on a surface.

The next step in evaluating the impact on performances of the front surface errors is to add the actual error to the surface and check again the selected quality criterion. To illustrate a local surface error, it was chosen to use small Gaussian bumps since the maximum slopes they produce are proportional to their height and to the inverse of their width. The amplitude of each bump is set at 10 μm while their FWHM is set at 6 times the entrance pupil diameter at 0^o. The reason for this choice of width is to compare each optical system in a similar manner even if their front surface diameters differ considerably after the scaling was done to use the same detector for each system. The bump is superposed to a surface in Zemax as a grid sag surface with a .dat file containing only the bump created in Matlab.

This Gaussian bump is then displaced over the surface to 11 different positions equally spaced from the center of the surface to the edge as illustrated in fig. 2. For each position of this bump, the difference in dH/dθ is saved and all 11 are then plotted on the same graph, allowing a quick comparison of the effects.

2.3 Pupil shift with the field of view

For panoramic imagers, it is important to consider the shape of the front surface because the effects it has on the entrance pupil of the system can be significant. To clearly see these effects, the entrance pupil must be found for each field angle defined in the Zemax lens file, respectively 4 and 7 in our case for standard and panoramic systems. To do so, for each field of view Hy, two rays are launched from a point on the aperture stop surface through the object space. These 2 rays are for fields of view Hy+ε and Hy-ε, where ε is very small. The interception (or the distance of closest approach) of these two rays after all the refractions is then the image of this point of the stop through the object space, which is by definition the entrance pupil. By repeating this procedure for each point on the stop and for each field of view, it is easy to obtain a figure of the optical layout superposed with the different pupils from each field of view.

3. RESULTS AND ANALYSIS

3.1 Link between surface shape and distortion

The first result presented here is the relation between the front surface and the total distortion of the system. As explained in section 2, as a measurement of distortion, the derivative of the height H on the detector vs the field angle θ is used since it is more representative than comparing it to a reference H=fθ ray and it is a direct measurement of the local resolution of the system. For spherical front surfaces like in the DGL and the FEL, as visible by comparing the top and middle rows of fig. 3, it is hard to see a direct link between these two since the distortion has no significant feature. For the DGL, note that the scale on the curve of dH/dθ varies less than 3%, meaning there is almost no distortion in this system. Still, these two systems were tested to manually remove the front surface and it was clear that most of the distortion in the systems really came from that surface. Next, for aspherical front surfaces with major changes in curvatures like in the CDS and the PML, as visible by comparing top and middle rows of fig. 4, the total distortion of the system is greatly linked to the shape of the first surface. It is easy to see in these two cases that for each significant change in curvature on the front surface (dZ/dθ), an important change in curvature is also produced in the total distortion of the system (dH/dθ). Of course, the total distortion is not only produced by the front surface, but also by other elements in the system, explaining the differences in the curves. One possible explanation why the front surface has such a major impact on the distortion as compared to other surfaces is because it produces the greatest angular variations on the rays and thus the final angle θ for a given height H is greatly decided by this surface.

3.2 Front surface localized errors

Now, the impact of the preceding observation is applied at tolerancing the front surface of these lenses. If a local change of curvature on the front surface has a severe impact on the distortion curve, a local error on this surface must also have a great impact. To test this, Gaussian bumps at different locations from center to edge are added to the front surface. Each bump has the same 10 μm amplitude and a FWHM of 6 times the entrance pupil for each system. Results are shown at the bottom row of figures 3 and 4, where each color represents a new location of this error on the surface. Not shown however are the same errors with negative amplitudes of –10 μm which were tested, giving similar but inverted results. The first remark here is that these bumps create localized errors. The positive slope is quickly compensated by the negative one, meaning that for fields of view before or after the bump, rays are not affected by the bump and so the curve of dH/dθ goes back to the original values when away from the bump.

Now, the important observation from these tests is that for the DGL, the impact on the distortion profile is the same at every location of the bump, while for the three panoramic imagers, the consequences highly depend on its location on the front surface. This means that for panoramic lenses, when defining maximum allowed tolerances (on amplitude or spatial frequency of the errors) for the front surface, it is also required to define in what region of the surface these maximum tolerances are defined. Using tolerances that are too tight everywhere on the surface may unintentionally increase fabrication costs while using too loose tolerances everywhere could produce regions with undesirable effects. Also, these defined regions should be based on the original distortion curve since, as can be seen for the two systems of figure 4, the region where the impact on the distortion is worse greatly depends on the original distortion curve of the system. The amplitudes of the errors produced by these bumps reproduce almost perfectly the shape of the original distortion curve. This observation also explains why the variations on the DGL are almost constant, since the distortion varies less than 3% on the full field of view for this system. Interestingly, for the FEL (and other similar systems tested), the errors produced seem to follow the negative of the distortion curve, possibly meaning that the absolute distortion has to be used. In short, it is important to consider the effects of distortion on tolerancing errors differently for different regions of the front surface for panoramic lenses.

3.3 Entrance pupil displacement

Another important aspect of the front surface shape is its impact on entrance pupil size and location. Fig. 5 shows that for spherical front surfaces, displacements of the entrance pupil tend to follow a curved line away from the optical axis for an increasing field of view. This displacement is often negligible for systems with a small field of view like the DGL, but has to be considered for panoramic imaging systems. Even more important is the strange behavior of this displacement for aspherical surfaces as visible on fig. 6. Instead of following a simple curve, this displacement is greatly related to the curves of distortion $dH/d\theta$ of fig. 4. In regions where the resolution increases with the field angle, the pupil moves away from the front surface and in zones of decreasing resolution, it moves toward the surface. This can be seen at fig. 6 in the back and forth motion with a turn around 60^o for the CDS. For the PML, three of these changes in direction occur, at about 40^o, 50^o and 60^o, again following the three turning points visible in the curve of $dH/d\theta$ from fig. 4.

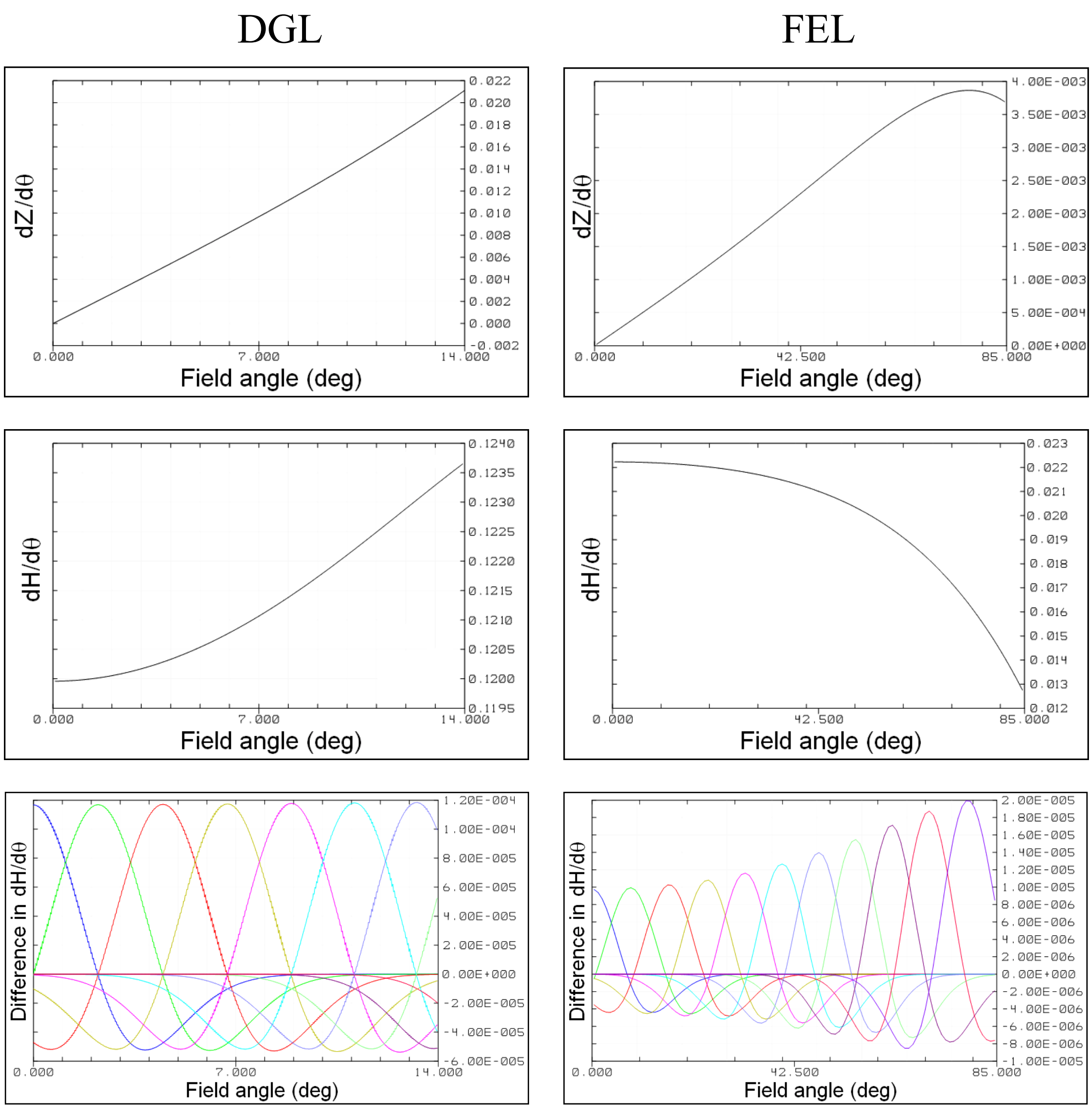

Fig. 3. Curves for the DGL on the left and the FEL on the right. **Top:** The derivative of the front surface shape vs the field angle. **Middle:** The derivative of the final height on the detector vs the field angle. **Bottom:** Impact on the distortion of a Gaussian bump moving on the front surface at 11 different locations from center to edge.

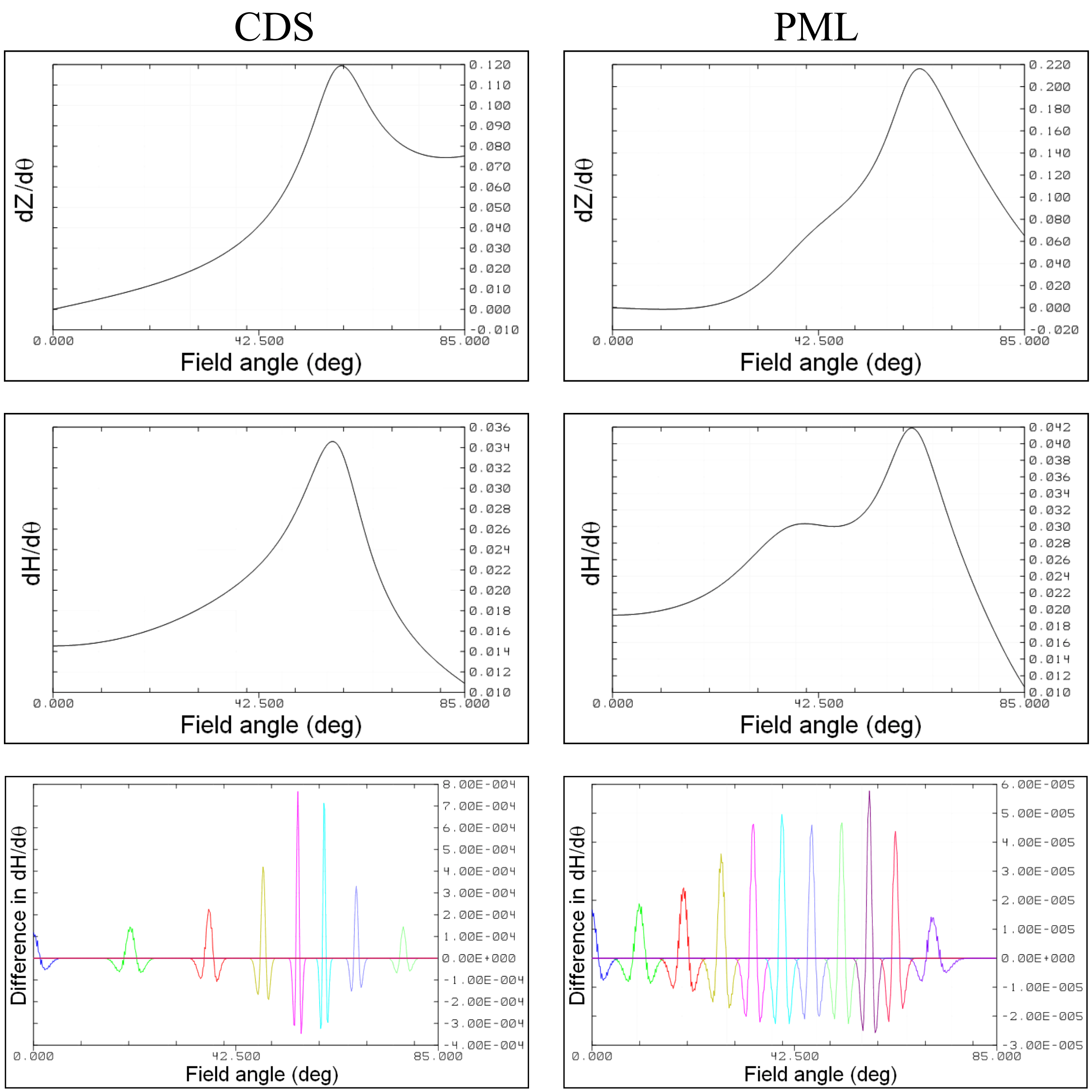

Fig. 4. Curves for the CDS on the left and the PML on the right. **Top:** The derivative of the front surface shape vs the field angle. **Middle:** The derivative of the final height on the detector vs the field angle. **Bottom:** Impact on the distortion of a Gaussian bump moving on the front surface at 11 different locations from center to edge.

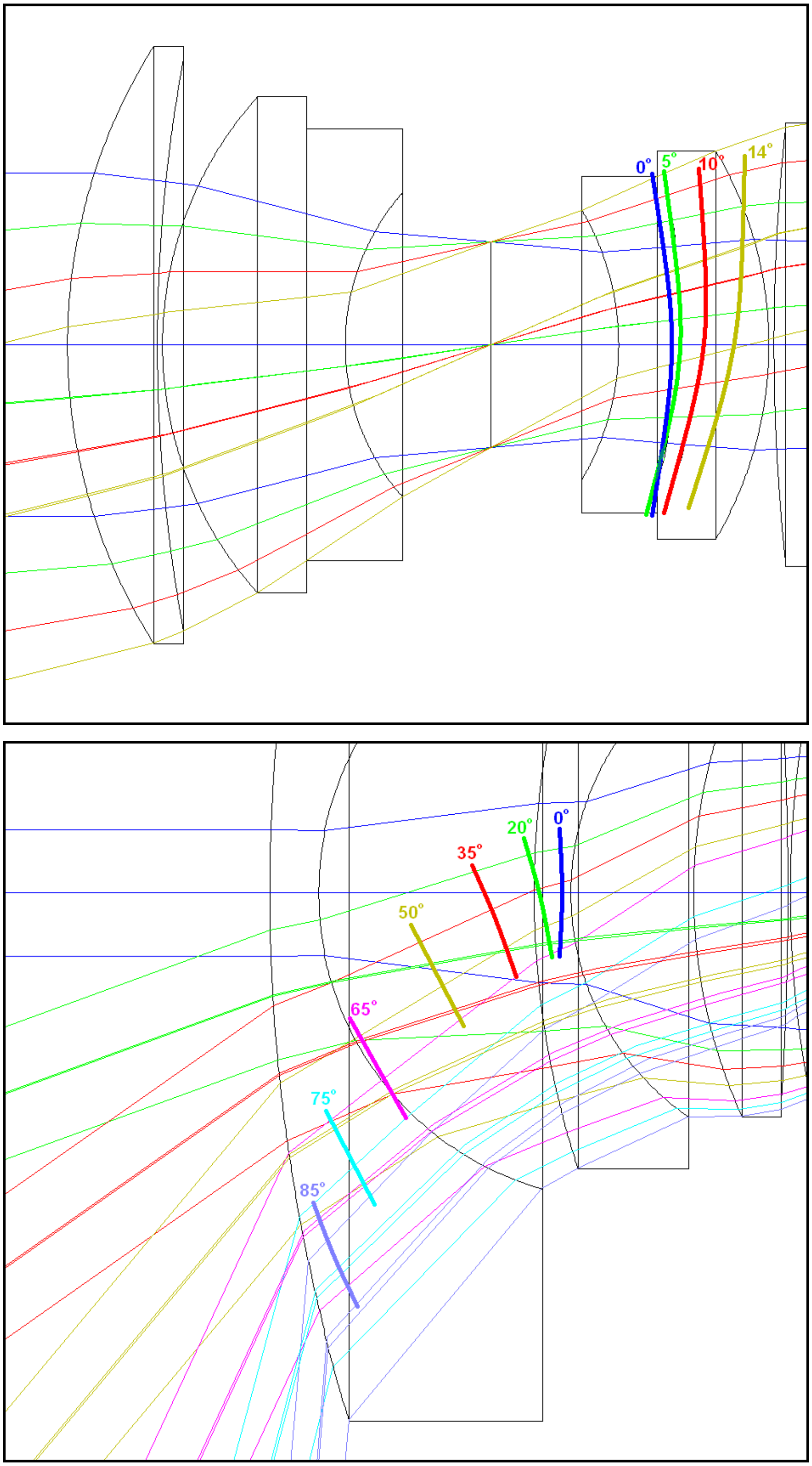

Fig. 5. Entrance pupil displacement for various fields of view. **Top:** For the DGL. **Bottom:** For the FEL.

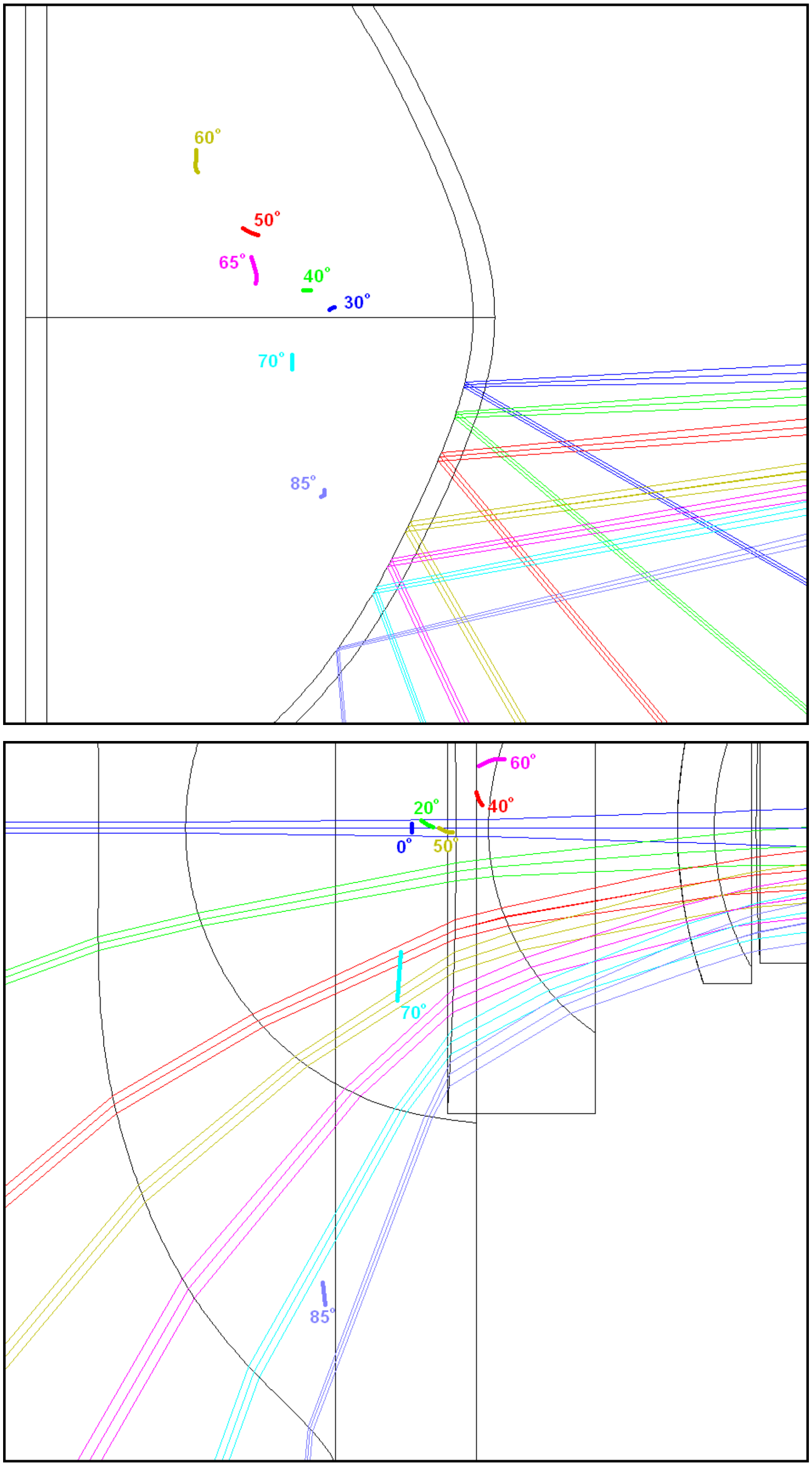

Fig. 6. Entrance pupil displacement for various fields of view. **Top:** For the CDS. **Bottom:** For the PML.

4. CONCLUSION

Tolerancing a panoramic imaging system can be a real challenge for optical designers. This is partly because optical design programs are not specifically made for these systems and have difficulties adapting to them. A common problem is how they are unable to trace rays through the entrance pupil at large field angle. In this paper, it was shown that for panoramic imagers, a given small localized surface error on the front surface can have a major impact for rays at a given field of view. They do not just scatter some light as these small errors would do on a surface near the aperture stop; they affect the wavefront. But, as was seen for three examples of panoramic systems, the impact of this error not only depends on its amplitude, its width and its curvature, but also on its position on the front surface. It was observed that this impact is related in part to the distortion produced by the front lens at this position. For aspherical surfaces, on which the maximum distortion is not always at the edge of the lens, this can produce a region with unexpectedly high tolerencing problems. Because of this, it was suggested, for these systems where some regions of the surface are more problematic, to use tighter tolerance criteria in those region and looser in other regions.

Another way to improve tolerancing efficiency for panoramic imaging systems is to help the software trace rays. For that, it is important for optical designers to understand how the entrance pupil moves with the field of view on their system and, as was shown, this displacement is not always simple. It was observed that for aspherical front surfaces, the displacements of the entrance pupil are greatly related to the front surface shape and the distortion it produces.

For all these reasons, when designing panoramic systems with particular front surfaces, it cannot be stressed enough that it is important to take into account the consequences of using this kind of surface, of course on the performances of the system, but as well during the tolerancing procedure.

ACKNOWLEDGEMENT

This research was supported by the Natural Sciences and Engineering Research Council of Canada and ImmerVision (www.immervision.com).

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