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Optical design of a hemispheric, long wave infrared panomorph lens for total situational awareness

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ABSTRACT

The proliferation of security and surveillance missions in urban environments dictates the greater use of optical systems in situational awareness for ground vehicle protection. The need for total situation awareness requires unique optical based systems combining visible and thermal imaging, advanced image processing, and analytic functionalities. These sensors must provide a full hemispheric field of view with a high refresh rate in low cost and compact packages. This paper describes the design of a fast panomorph lens for the 8-12 µm IR band with hemispheric capabilities in a single integrated package that can be added to actual platforms to enhanced situation awareness systems. The various tradeoffs that were explored are detailed (material, size, relative cost, tolerances, F/#). The advantages and disadvantages of the panomorph design are compared to reflective, diffractive and other refractive solutions.

Keywords: Panomorph lens, panoramic, lens design, infrared, LWIR, situation awareness, image rendering

1. INTRODUCTION

Panoramic imaging is of growing importance in many surveillance programs around the world[1-3]. While primarily valued for its ability to image a very large field of view (180° X 360°, hemispheric), other characteristics such as its ability to reduce the number of sensors and to increase the pixel/cost ratio are also important benefits of panoramic imaging—particularly if the panoramic imager is designed to increase the number of pixels in the zones of interest, as is the panomorph[4].

The particular applications addressed in this design study were for an infrared lens operating over the LWIR spectral band (8-12um) to monitor a field of view of 185 degrees over the complete 360 degree azimuth for situation awareness. The system must satisfy the following optical conditions:

F/#:	1.0 (real f-number or less)
Waveband:	LWIR (8-12um)
MTF @ Nyquist (1 lp/2pixels):	Min 75%
Sensor:	16 mm X 12 mm, 640X480 pixels, 25 µm pitch
Anamorphic ratio:	4:3 (to match sensor ratio)
Image footprint max:	620 X 460 (elliptical footprint)
Distortion profile:	High resolution on the edge, lower in the center (see next section)
HFOV:	185°
VFOV:	185°

In this paper, we summarize the panomorph lens concept, we discuss various optical challenges to meet the design requirements and we present the lens design as well as performances of the designed IR panomorph lens.

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Note that this paper was primarily a design study intended to discuss the design of an IR panomorph lens. Such new type of panoramic lens is well-known in video surveillance but presents several challenges from a lens design point of view. The reader should note that further optimisation could in fact yield improved systems.

The design of a panomorph lens requires that the designer thinks in terms of 3D design space. This might seem like common sense but the majority of lens designs are rotationally symmetric about the optical axis. Unfortunately, the panomorph lens design, X-Y axis are different (anamorphic) and must be modeled and optimized simultaneously.

2. PANOMORPH LENS CONCEPT

The panomorph lens design is a particular design form of a wide angle lens which includes anamorphic and custom pixels to angle image mapping. The anamorphic feature provides a perfect match of the hemispheric field of view to the sensor 4:3 format. A standard panoramic lens produces a circular image footprint which becomes elliptical after the anamorphic correction (Figure 1). The second feature is the custom angle to pixel image mapping which is an innovative manner to cover the field of view by the sensor for the next generation of smart optics system[5].

Figure 1 shows a typical scenario where the FOV is divided into three zones of interest. By controlling the optical distortion within the lenses, we were able to design and build a completely new type of panoramic IR imager.

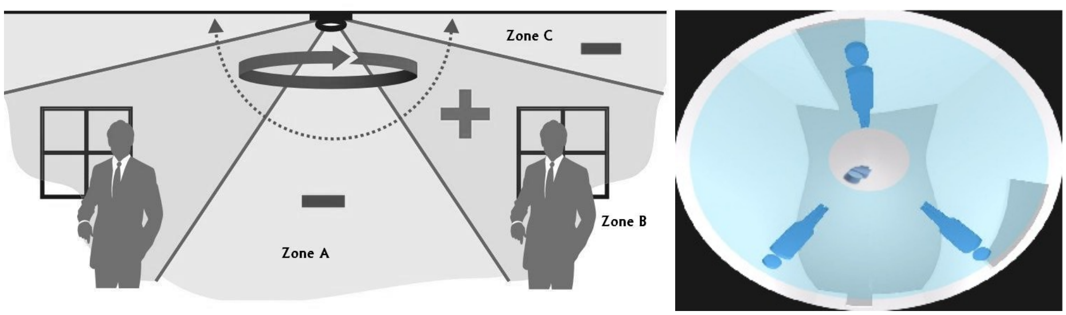

Figure 1: Specific security zones and image footprint on the sensor (elliptical).

Figure 2 presents the field of view (angularly) as a function of the position in the FPA. The FOV ranges from 0 (vertical) to 90 (horizontal) degrees and the dimension *d* is the half dimension of the sensor (from the centre) The dashed line represents the linear relation (f-theta distortion) between the field of view and the position on the FPA, as seen with a fisheye lens. As discussed earlier, the constant resolution is not ideal. A linear function means a constant slope or a constant pixel/degree ratio. The solid line represents a relationship between the FOV and the pixel that is typical with a panomorph lens. We can see that:

- for a small angle (Zone A) the slope is high, which corresponds to a lower pixel/degree resolution;
- the slope is lower in Zone B with a peak in the middle, which corresponds to a higher pixel/degree resolution;
- and finally, in Zone C, the slope is high again, which means lower resolution.

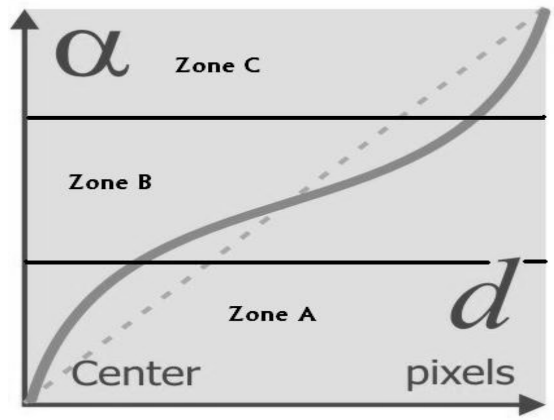

Figure 2: The ideal FOV (α) vs the position (d) on the sensor for the case study presented in Figure 1.

For the resolution, we define i zones (1 to n) where each zone covers an angle θ_i with a number of pixels N_i we can describe the resolution for each zone as well as the nyquist frequency associated ($Fnyq_i$):

$$Fnyq_i = \frac{N_i}{2 \cdot \theta_i}, \qquad (1)$$

with the following limit condition:

$$\sum_{i=1}^{n} N_i = \sum_{i=1}^{n} 2 \cdot Fnyq_i \cdot \theta_i = \#\, pixels \cdot \qquad (2)$$

This mathematical function represents a discrete form which can be represented by an integral when n is very large.

3. PANOMORPH LENS DESIGN

3.1 Starting Lens Configuration

The first step in designing a panomorph lens is to adapt a wide angle lens design typically used in the visible spectral region to the infrared. Figure 3 shows a very simple design form which is the basis of virtually all wide angle lens designs today. Using glass substitution to correct chromatic aberration and with lenses split, we can design any type of wide angle lenses. This kind of lens is an inverse telephoto type.

Telephoto construction is a compact design form, the back focal distance is long, even when the focal length is short which makes it practical for a wide angle lens. However by decreasing the focal length, the inverse telephoto will suffer from considerable barrel distortion. But if the barrel distortion is increased instead of being corrected, the result is a so-called Fish-eye lens, which covers an entire hemispheric field of view.

As previously stated, the panomorph lens concept has an anamorphic focal length. By adding anamorphic elements such as cylindrical lenses into the design, the circular image on the sensor will be stretched to an ellipse. This operation will increase the number of pixels used on the sensor to image the hemispheric field of view by 30% (on a 4:3 sensor ratio).

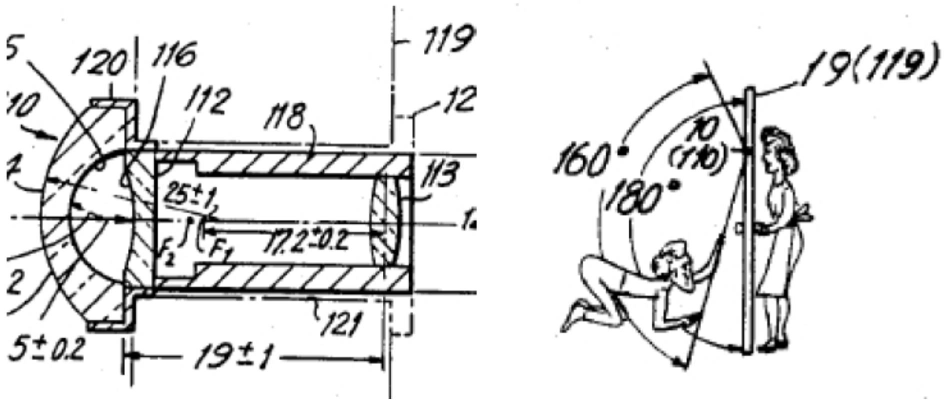

Figure 3: US Patent 4082434[6].

Figure 4 shows the 4 lens starting configuration of figure 3 modified to a panomorph lens design. This starting point uses only germanium spherical and cylindrical lenses. We limit the FOV to +/- 88 degrees but have already set the f-number to 1 (0.96). The anamorphic ratio was also set to the final values (4:3).

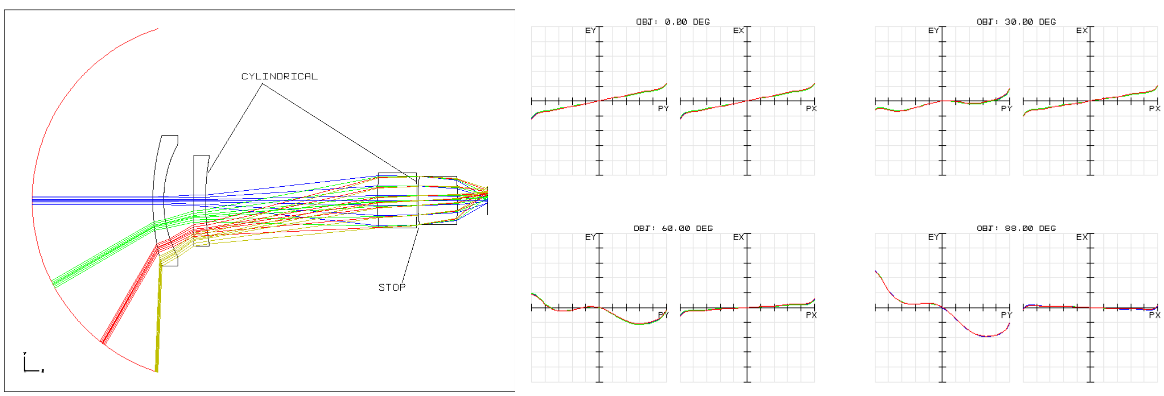

Figure 4 Starting configuration, 4 lenses, all germanium (ray fan scale is 200 µm)

Notice that the first spherical surface is a dummy surface. This dummy helps the design process; it helps the software to locate the entrance pupil to avoid any ray failure. The large index of refraction of germanium offers some advantage because it limits the curvature of the first element (easier to manufacture). We can also notice that the lens is naturally split around the stop, the front group is composed of a strong negative group which is collimated by a positive lens. The first group forms a kind of afocal wide angle attachment.

The second group, after the stop, is an objective lens. Consequently, this second group can use an existing objective lens design or a modified version of an existing objective. This is very interesting because some IR lenses are already well proven, well corrected as well as athermalized. In a sense, the panomorph lens design is reduced to the design of an anamorphic afocal attachment or an inverse high magnification Galilean telescope.

In practice, using the parameters of the second group will help to control the panomorph lens design, particularly the lateral color and the spot size at high angle (larger than 70 degrees).

3.2 Hybrid refractive/diffractive design

In the starting lens prescription, the amount of chromatic aberration is low. Most of the lenses in the design were of germanium. Germanium presents several advantages: the material is available, inexpensive and its very high index of refraction makes it easier to correct aberrations than with other lower index materials. Its high index of refraction helps to control the radius of curvature of the optical element. This is particularly useful in this design where high bending is required to redirect the rays at high angle to the focal plane.

Since the dispersion of the germanium is low, it works pretty well in the 8-12 μm band, however germanium becomes much more dispersive in the 3-5 μm band. To extend the covered waveband, previous infrared optical designs have used a diffractive surface on one germanium lens (diamond turned kinoform) to counteract the residual dispersion on the LWIR band. The resulting component is called a diffractive optical element (DOE).

Diffraction efficiency must be considered when using a DOE. The scalar diffraction efficiency for a DOE designed for λ_0 as function of wavelength can be calculated from the following equation:

$$\eta = \left[\frac{\sin\left(\pi (\lambda / \lambda_0 - 1 \right)}{\left(\pi (\lambda / \lambda_0 - 1 \right)} \right]^2 \qquad (1)$$

For a design wavelength of 10 μm, the average diffraction efficiency is about 96% over the 8-12 μm LWIR band (about 93% over the 3-5 μm MWIR), values that are acceptable for most applications. Stray light produced by the remaining 4% is diffracted into orders other than the desired one. This can be a problem and should be studied carefully.

The rotationally symmetric DOE can be described by a phase function (approximation)

$$\varphi(r) = \frac{2\pi}{\lambda_0}\left(-\frac{1}{2f_0} r^2 + B r^4\right), \qquad (2)$$

where f_o is the focal length of the DOE and B, the correction parameter. As the phase function is wavelength-dependent, it produces a large dispersion.

The effect of this dispersion can be represented as aberrations in the exit pupil of the optical system. These aberrations are principally defocus (W_{20}), which compensates for the chromatic focal shift of the system and spherical aberration (W_{40} or spherochromatism). After a simple manipulation, one obtains the following approximate result for the on-axis focal point shift:

$$W_{20} = \frac{-\lambda_0 h_s^2 (\lambda - \lambda_0)}{2\lambda^2 f_0}, \qquad (3)$$

where h_s is the radius of the DOE and the spherical aberration term is given by

$$\frac{W_{40}}{h_s^4} = \left(\frac{\lambda_0}{\lambda 2 f_0} \right)^3 - \frac{\lambda_0}{\lambda} B, \qquad (4)$$

Because the DOE is computer-generated, it is possible to select a parameter B that reduces the spherochromatism. The spherical aberration term can then be minimized during the design process.

For a panomorph lens design, it can be interesting to use the DOE as an anamorphic phase function. Instead of f_o you can have only a power in the x or y direction and equation (2) will be defined only in x or y. Consequently, the DOE will have an impact only on the x or y direction. Further analysis will show that astigmatism and field curvature is not the same in both axes for a panomorph lens design. Anamorphic DOE (x or y) can be used to compensate the field curvature.

In the literature, we found no evidence of a publication or a study on the design of panomorph lens using DOEs. This kind of design looks very interesting and should be studied in the near future.

3.3 Refractive Design

At the time of writing this paper, the use of refractive lenses appears as the most straightforward solution for designing a panomorph lens. Some design studies were conducted to determine whether a catadioptric wide angle lens could be a solution. However, all studies in the infrared concluded that the catadioptric configuration is not practical[7]. The main reasons were the dimensions of the system and the tight tolerances.

By using only refractive materials, material selection becomes an important step not only to provide an appropriate chromatic correction but also to provide resistance and athermalisation. Table 1 provides a list of commonly used IR materials including the index of refraction at 10 µm, the computed V-number (8-12 µm) as well as thermal properties.

Table 1: Infrared Material Properties between 8-12µm

Material	n (10 µm)	V (8-12 µm)	Dn/DT	α (mm^{-1})
Amtir-5	2.7398	172	1.00E-06	2.37E-05
Amtir-4	2.6431	235	-2.3E-05	2.70E-05
Amtir-3	2.6027	110	9.1E-05	1.40E-05
Amtir-2	2.7613	149	5.00E-06	2.24e-05
Amtir-1	2.4981	109	7.20e-05	1.20e-05
IG2	2.4967	105	6.00e-05	1.21e-05
IG4	2.6084	175	3.60e-05	2.04e-05
IG6	2.7775	162	4.10e-05	2.07e-05
Gasir1	2.4944	120	5.50e-05	1.70e-05
ZnSe	2.4065	58	6.10e-05	7.10e-05
ZnS (IR)	2.2	22.6	5.40e-05	6.50e-05
GaAs	3.2778	104	1.47e-04	5.70e-06
Germanium (GE)	4.0032	864	3.96e-04	6.10e-06

3.3 Panomorph Lens Design

The panomorph lens design, like other systems with very large field angles, has significant entrance pupil aberration. The position of the entrance pupil shifts with the field angle. This forces the use of a robust algorithm for the localization of the entrance pupil and the determination of its size and shape. Fortunately in the LWIR (even in the MWIR), the high index of refraction helps to limit the surface curvature of the front element which limits the displacement of the entrance pupil and helps the design process compared to the visible region.

As a result of our panomorph lens design study, we found a combination of five lenses, Ge, Ge, ZnS (IR), Ge and ZnS(IR). This lens composition is illustrated in Figure 5 along with the associated ray curves in Figure 6. Compared to the performance and the configuration of the starting design, it is seen how two additional lenses have improved performance. The edge of the field shows the separation of the ray curves between the wavelengths corresponding to the LWIR band (lateral color).

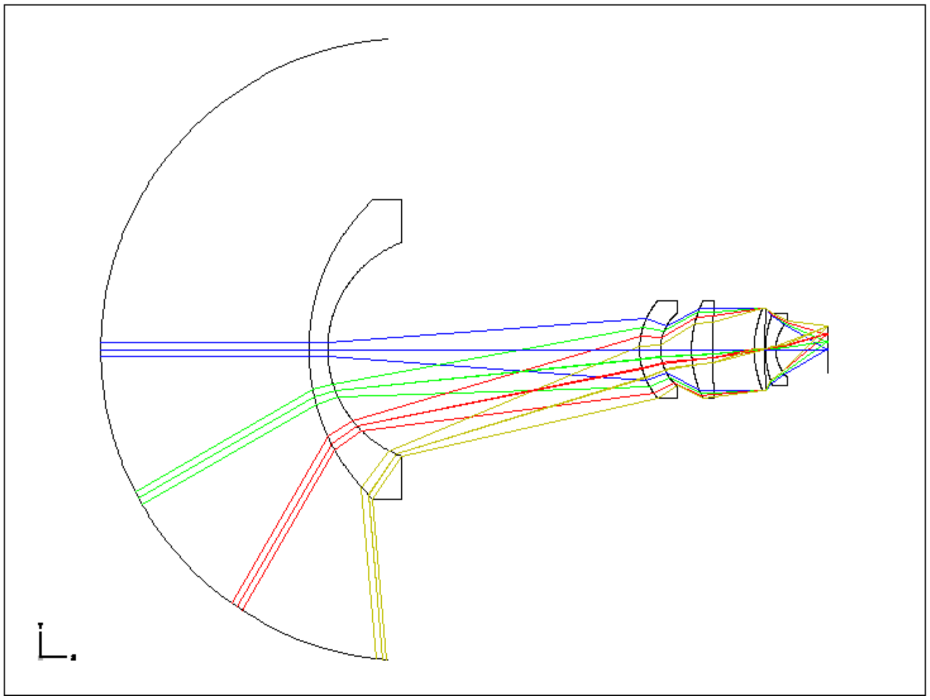

Figure 5: First design layout (lenses 2 and 4 are cylindrical, lenses 1 and 5 are aspheric)

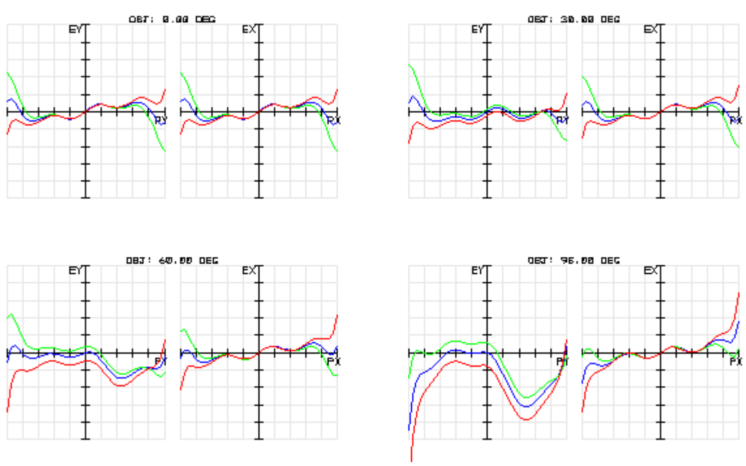

Figure 6: Ray aberration curves for the long axis (scale 20 µm)

The anamorphic nature of the lens is clearly visible on the ray aberration plots. The ray aberrations on the long and on the short axis are quite different. Consequently, the asymmetric fields must be taken into account during the design process to cover the entire field of view. This is the main difference between the design of the panomorph lens compared to a standard wide angle lens.

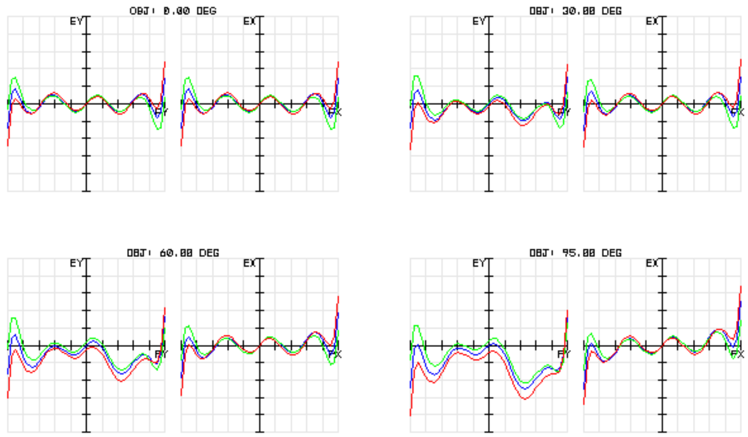

Figure 7: Ray aberration curves for the short axis (scale 20um)

The above lens design configuration offers a higher resolution on the edge of the field of view (last 20 degrees) compared to the center of the field. This non-conventional distortion is mainly produced by the first element profile. Using aspheric sag (rotationally symmetric profile) gives the degree of freedom required to impose a particular distortion. The last element is also aspheric to compensate for field curvature.

3.5 Lens Manufacturing

The panomorph lens described above uses specialized optical components such as cylindrical and aspheric lenses. Aspheric lenses are used currently in MWIR and LWIR applications because IR material can be manufactured by diamond turning with good accuracy. More recently, various anamorphic materials for IR applications have been developed for lens molding. The molded component cost decreased each year with the development of new methods, materials and the presence on the market of new suppliers. Many publications report advances in the areas each year. Consequently the use of aspheric components is totally acceptable in modern applications.

It is not more complicated to use aspheric components for the panomorph lens than it is to use them in other types of IR lenses. Although manufacturing limits may vary from one configuration to the other, obtainable and verifiable specifications routinely achieved by industry include figure accuracy to 1/10 λ per inch and typical surface roughness values ranging from 40 to 120 Å RMS. The following materials can be used for aspheric surfaces: Germanium, Silicon, Zinc, Selenide, ZnS, Mutli-Spectral ZnS, Calcium Fluoride, Barium Fluoride, Magnesium Fluoride, Lithium Fluoride, AMTIR, Gallium Arsenide.

Many suppliers can also supply both cylindrical and toroidal surfaces if required. Cylindrical lenses even with IR materials can be manufactured by standard polishing techniques as the one used for glass or can be manufactured by a multi-axis single point diamond turning machining equipment.

5. SUMMARY

The design of an infrared, 8-12 µm, panomorph lens, as described in the study above, has proven to be no more complicated than the design of other types of wide angle lenses. The methodology outlined in the text works well for moderate anamorphic lenses. We have not studied how far we can increase the anamorphic ratio but it seems that a ratio of 2:1 can be achieved based on ray aberration performances. For such very short focal lengths or hemispheric lenses, one limitation will come from lateral chromatic aberration at higher angle. The lateral color increases with the field of view due to higher resolution on the edge. It is not clear how the distortion impacts on the lateral color but at this point it should be a primary limitation since our level of panomorph design correction is sufficient to achieve lens specifications.

During this study, we also saw that we can increase the FOV up to 110 degrees (220 degrees FFOV) with a reasonable curvature on the front element. Consequently, the relative illumination was relatively well controlled, a parameter which is of primary importance for IR lenses.

Finally, we showed that the panomorph lens design is similar to any wide angle lens design. The main challenge was to control the wide angle, the lateral color and the pupil shift. Additionally, the panomorph lens design requires a particular attention to the asymmetric nature of the FOV. The designer must include both x and y fields into his merit function. The use of cylindrical optics as well as the aspheric surface required for distortion control do not appear to be limiting factors.

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