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The power hyperspectral all-sky camera

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This study presents a new fish-eye lens for optical atmospheric observations, designed in the Main Astronomical Observatory (MAO) of the National Academy of Science of Ukraine. It has been tested under laboratory conditions in Kiev. The fish-eye lens MAO-08 is intended for observations of faint extended objects in white light or narrow spectral bands with variable passband filters VARISPEC. Besides having high power, this lens can be used for meteor observations. A field test has been conducted in the Polar Geophysical Institute (PGI) observatories located at the Kola Peninsula and Spitsbergen.

1 Introduction

The fish-Eye lens is most often used for cloud monitoring, observations of atmospheric phenomena, meteor showers, and comets and asteroids (Sebag et al., 2008; Skidmore et al., 2008; Castro-Tirado et al., 2008; Sandahl et al., 2008; Jenniskens et al., 2011). For observations of broad band images in the visible part of the spectrum, commercial fish-eye lenses with small aperture can be used, coupled to a high-sensitive Charge Couple Device (CCD) detector. However, when it comes to obtaining narrow-band images of auroral emission lines with high temporal resolution, researchers face a much more complicated task. Firstly, narrow-band interference filters are needed to isolate the emissions. Maximum sensitivity depends mainly on the sensitivity of the detector and the lens aperture ratio. Secondly, the filters require collimation with parallel light in order to obtain optimum bandpass.

A standard technique is to use an additional telecentric lens system (Sandahl et al., 2008; Jenniskens et al., 2011; Syrjäsuo, 2005). The telecentric lens system narrows the beam to a few degrees and transfers the image onto the camera. As a consequence, the length of the system becomes rather long. The MAO-08 lens does not use a telecentric lens system and has a large aperture ratio of approximately $f/0.8$.

2 Main parameters

2.1 Optical layout

The ultra wide-angle lens MAO-08 is designed for observations of faint extended objects (meteors, noctilucent clouds, aurora, nightglow, twilight phenomena, etc.). It can be used with interference filters, variable spectral bandwidth filters, or without any filters (white light). Figure 1 shows the optical layout of the lens. The first part converts the 180° field of view (FOV) to a narrow beam of approximately 6°, where interference filters may be inserted. The back part focuses the collimated light onto the detector plane. The design is compact with unique optical characteristics.

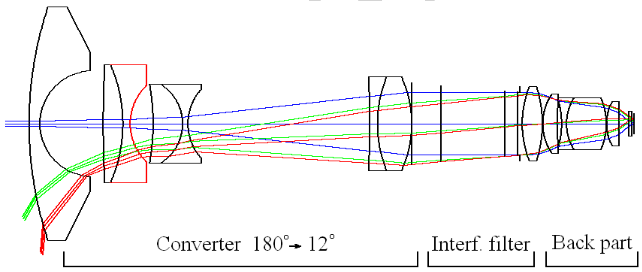


Figure 1 – Layout of the MAO-08 lens.

2.2 The basic technical data

The basic technical data are as follows:

1. paraxial focal length: 1.6 mm;
2. FOV: 180°;
3. linear FOV on detector plane: 4.2 mm diameter circle;
4. aperture ratio: $f/0.8$;
5. spectral range: 430–750 nm;
6. resolution: center, 100 mm^{-1}; edge, 70 mm^{-1};
7. back working distance: 5.8 mm (or 4.2 mm up to the protective glass of the detector);
8. dimensions (with covers): length, 235 mm; diameter, 103 mm.

2.3 Image quality

When designing the lens, special attention was paid to the quality of the image. The lens is capable of focusing light within one to two pixels (10 μm for one pixel). Figures 2 and 3 are taken from the calculation program and demonstrate the high quality of the image.

Figure 2 shows the calculated spot diagram of the lens. The designation "RMS Radius indicates the average value of the scattering of rays from an ideal spot. These numbers (5–9 μm) correspond roughly to the resolution of the lens.

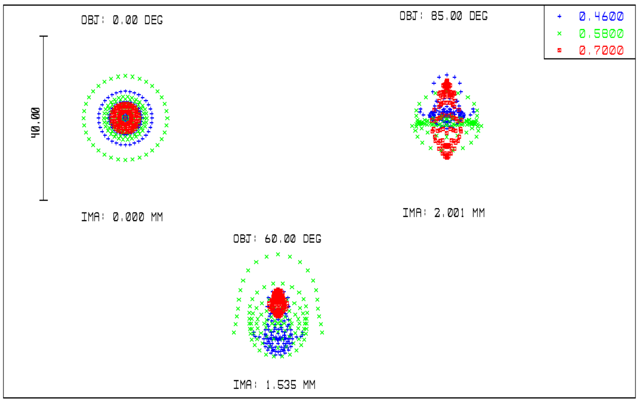


Figure 2 – The spot diagram of the MAO-08 lens in white light.

Figure 3 shows the MTF (modulation transfer function) of the lens (for white light) taking into account the diffraction. This graph shows the dependence of image contrast versus spatial frequency. Usually, the critical level of contrast is equal to 7%. Consequently, the figure shows that the resolution of the lens across the entire FOV exceeds 100 line pairs per millimeter, and only for the tangential beams to 60° it decreases to 70 line pairs per millimeter.

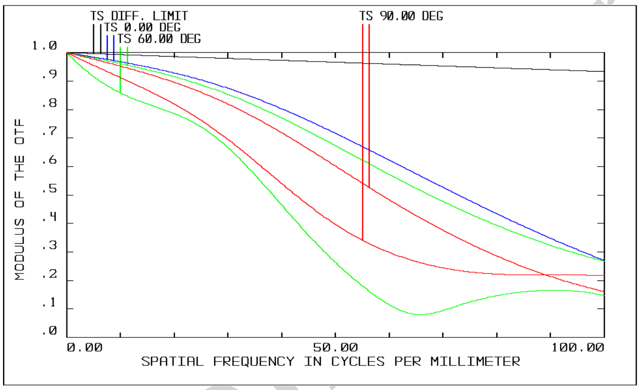


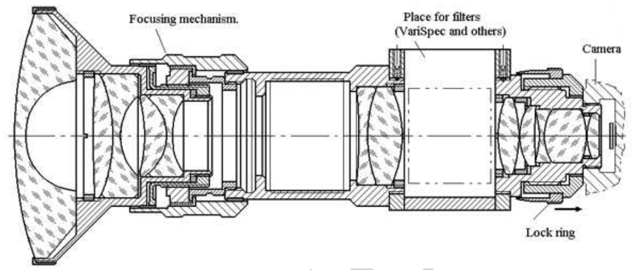
Figure 3 – Polychromatic modulation transfer function.

2.4 Mechanical design

The MAO-08 lens has a module design and consists of three units (Figure 4):

1. a forward part, which develops a FOV and determines the distortion;
2. a box for fixing optical filters; and
3. a back part, determining power and correcting the basic aberrations.

These units are assembled with thread M45 × 1 mm and can be unscrewed for change of the box. The maximal length of the box on an optical axis is 62 mm. Other dimensions of the box are not regulated. The counter nut (lock ring) on a back part of the lens serves for fixing the lens on the camera as cameras can differ on depth of arrangement and thickness of a protective glass of a matrix. Precise focusing is carried out by the focus ring located on the forward part of lens. The lens was designed to work from −40° C to +40° C and the field tests from −28° C to +5° C indicated no issues in the mechanical design.



(a) Assembled lens.

(b) Lateral view of the lens.

Figure 4 – General view of the MAO-08 lens.

2.5 Laboratory and field testing

The laboratory testing of the lens was conducted in the Laboratory for Atmosphere Optics, which is part of the Main Astronomical Observatory of the National Academy of Sciences of the Ukraine. Figure 5 shows the results of lenses' laboratory tests. An artificial star was presented to the lens. The image of the star (in the FOV center) was photographed through a microscope.

Figure 5 (*left*) shows the image of a star in white light. One division of this scale corresponds to 5.5 μm in the focal plane of the lens. Figure 5 (*right*) shows the image of a star with the monochrome filter at a wavelength of 650 nm. The image scale of both panels is the same. The structure of the point is clearly visible and corresponds to the spot diagram (Figure 2). The halo around the point is not visible, because it is too weak.

The lens tests were conducted under field conditions in the PGI observatories at Apatity (67°.58 N, 33°.31 E), Lovozero (67°.97 N, 35°.02 E), and Barentsburg (78°.09 N, 14°.21 E), during different weather conditions. We have developed an imager which consists of an MAO-08 lens and a low-cost white light CCD camera. We have used the Stingray F-046B in Apatity and Lovozero and the Stingray F-145B in Barentsburg.

Figure 5 – *Left*: image of artificial star created by the lens in laboratory tests in white light. *Right*: the same, at 650 nm.

Lens tests in field conditions have confirmed the high quality of the images, as is well illustrated by the photograph in Figure 6 (*left*).

It must be noticed that no filters were used, i.e., exposures were made with the full aperture. Thus, the relative focus was equal to 1:0.72, which allowed short exposures. However, at such relative focus the quality of the image is satisfactory, and corresponding to the calculations.

The photograph shows the ray auroral arc, obtained at Barentsburg in white light with an exposure of approximately 0.9 s. There are a plenty of constellations and stars visible in the photograph, and even the Milky Way is seen.

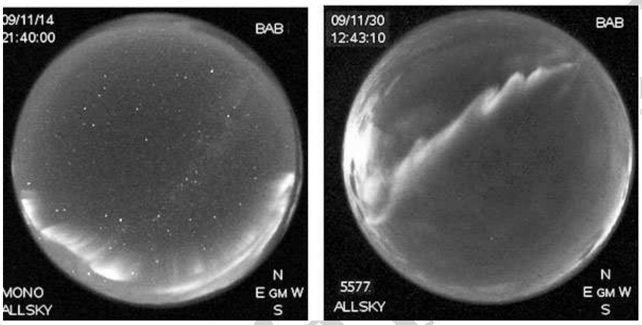


Figure 6 – All-sky images of aurora in white light (*left*) and at $\lambda \approx 557.7$ nm (*right*).

Figure 6 (*right*) shows the weak auroral folds in the emission at 557.7 nm, obtained with an exposure of approximately 9 s using a narrow-band interference filter ($\Delta\lambda \approx 2$ nm).

3 Conclusions

The MAO-08 lens has a large relative aperture of about $f/0.8$, which exceeds the corresponding value of other lenses designed for faint extended objects. It can be used with interference filters, variable spectral bandwidth filters, or without any filters (white light). The design allows interference filters to be inserted directly into the lens.

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