

# DESIGN STEPS TO TEMPERATURE AND PRESSURE INSENSITIVE OPTICAL SYSTEMS FOR DIGITAL AERIAL IMAGING

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## ABSTRACT:

Imaging from air has evolved from film cameras to digital cameras over the last years. Here we give the design steps of an aerial objective lens for a given CCD sensor. Matching to the pixel pitch of the sensor and providing desired field of view according to CCD size are traditional steps. Besides these, to minimize the environmental effects, design should be insensitive to the temperature and pressure as much as possible. Performance of a lens, designed at room temperature and pressure will be degraded if temperature and pressure changes. This is firstly caused by the change of relative refraction indices of materials, and secondly thermal expansion or contraction of both glass and housing materials. Here it is shown that according to the environmental working conditions, custom designs are necessary to provide images with sufficient resolution up in the air. These design principles are also valid for the fore optics of spectroscopic imaging tools. Since designs are insensitive to temperature and pressure, working environmental range is wide.

## 1. INTRODUCTION

Digital aerial imaging is today getting popular due to inherent advantages over film technology. Excluding chemical processing of films and directly coupling to digital storage systems are two of several advantages. Objective lens selection is an important part of the job for aerial photographic system users and designers. CCD detectors are most common digital detectors for sensing. And therefore, compatibility between selected lens and CCD sensor should definitely be controlled. There are many criteria for a lens, to use it for a given sensor. Providing desired field of view is a first order requirement. As performance criteria, there are many properties to check such as RMS spot size, encircled energy, Strehl ratio, MTF etc. Most common criteria are spot sizes and MTF. In this paper we will use MTF plots as performance criteria. Apart from these traditional requirements, aerial objectives should be insensitive to environmental effects as much as possible. This means that MTF should not be severely degraded at different working environments.

In this paper we have shown the design steps of an objective lens for aerial photographing applications. To find an appropriate lens among the commercial ones may be difficult and custom design becomes unavoidable. Here we designed a custom lens for a given CCD sensor and working environment. Design is sufficiently insensitive to temperature and air pressure around the lens.

## 2. THEORY

### 2.1 Field of View and MTF

Field of view of a lens is a function of sensor dimension and focal length of the lens. Designers generally use the equation below to find the half of the field of view and use it in design software.

$$\tan(\theta / 2) = \frac{d_{diagonal} / 2}{f} \quad (1)$$

Here  $d_{diagonal}$  is the diagonal dimension of the sensor. Generally objective designs are circularly symmetric and half field of view is enough and moreover preferred. If the sensor is decided and desired field of view given, then focal length becomes fixed. Our sensor is decided and it has 60 Mpixel (8956 x 6708, 54 mm x 40 mm) with pixel pitch of  $6\mu$ . Also for geometric sampling distance of aerial photographs,  $f$  is selected as 70 mm. Therefore our field of view is determined and it becomes 51.2 degree which is wide enough for aerial photographic applications.

For resolution criterion we will use MTF value at Nyquist frequency of the sensor. Nyquist frequency is defined as  $1/2p$  ( $p$  is pixel pitch) for a sensor, meaning that sensor itself cannot resolve the details greater than this frequency. For  $6\mu$  pitch size Nyquist frequency becomes approximately 83 lp/mm. Hence our aim is to design 70 mm and 25.6 degree half field of view lens, with sufficient MTF value (~30%) at 83 lp/mm.

Actually for now, one important design criterion is forgotten; aperture. Comparing with similar lenses, we decided  $f\#$  as 5.4 which makes entrance pupil diameter approximately 13 mm.

### 2.2 Temperature and Pressure

After these requirements we can design our lens. But generally designs are made at a reference temperature and pressure that is 20°C and 1 atm. To use this lens at different temperatures and pressures we should take care of effects of temperature and pressure from the beginning.

Athermalization is a well-known term used for optical systems insensitive to temperature differences. Main effect of temperature change to optical systems is defocus. Therefore movement of one of the lenses in the system through proper direction can compensate this defocus. This is called "mechanical compensation". This can be realized either a motorized structure ("active" athermalization), or proper multilayer design of housing ("passive" athermalization). Another method is both "optical" and "passive"; proper selection of optical materials can compensate the effect of both other glasses and housing.

In this design we preferred passive optical athermalization.

The effect of pressure comes when relative refractive indices change due to air pressure. Actually refractive indices of materials are defined relatively to air at a reference temperature and pressure. If it is said absolute refractive index it means that reference air pressure is zero: vacuum. Relative and absolute refractive indices depend on each other as follows

$$n_{abs} = n_{rel} n_{air} \quad (2)$$

This means that when the materials are put in low pressure environment, their relative refractive indices increase, since absolute index is constant and low pressure means low refractive index of air. This causes increase of refractive power of the system and therefore also causes defocus.

For designers these theoretical considerations of temperature and pressure are important but there is not much thing to do. Generally design softwares handle these issues. Important thing is to be aware of these effects from the beginning of the design, and to guide the software properly.

If the system is totally sealed then the effect of pressure can be ignored. Here we assume that inside of our lens is sealed. But air pressure outside of the lens may change. Therefore just front and end lenses will be affected from air pressure.

### 3. DESIGN

Taking into considerations of all points mentioned above, we started from a Gaussian type objective. Gaussian type objectives are very common for wide angle applications. We assumed that working environment is  $-40\text{ }^{\circ}\text{C} / +40\text{ }^{\circ}\text{C}$  and pressure is between 1 – 0.6 atm. This corresponds the altitude of 3500 - 4000 m. Housing material is assumed aluminum with linear thermal expansion coefficient of  $23 \times 10^{-6} / ^{\circ}\text{C}$ . All spaces between lenses and detector are accepted as housing. We used ZEMAX™ software. Layout of the final design is shown in Figure 1. Figure 2, 3, 4, 5 and 6 show the MTF at different working environments.

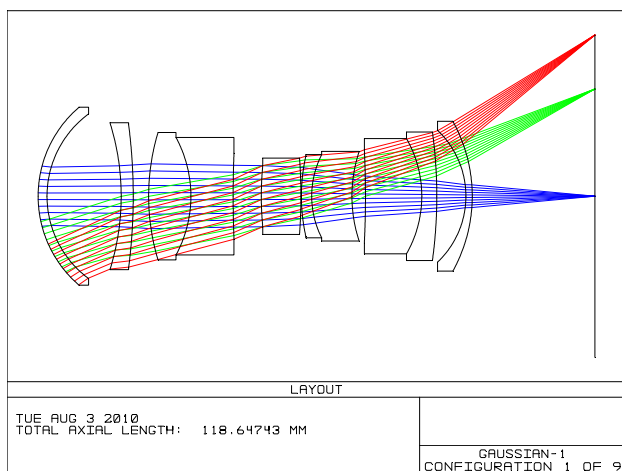


Figure 1. Layout of final design of the objective

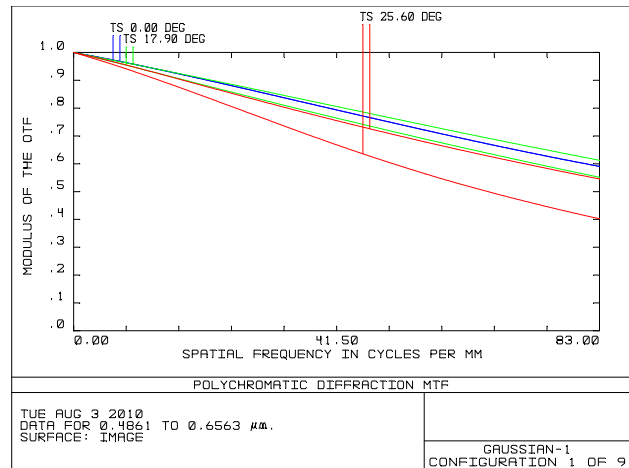


Figure 2. MTF of nominal design, at 20°C and 1 atm

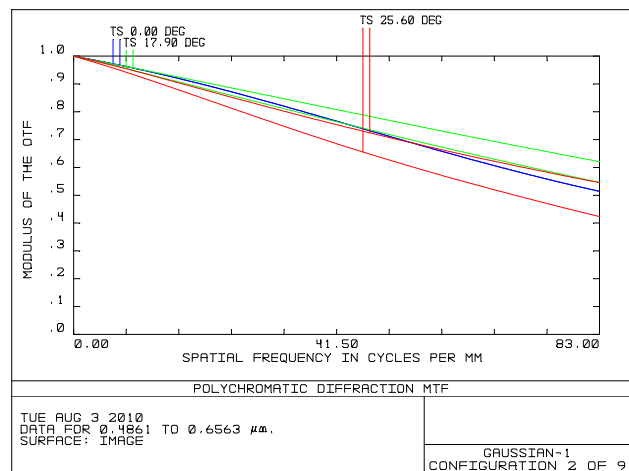


Figure 3. MTF at -40°C and 1 atm

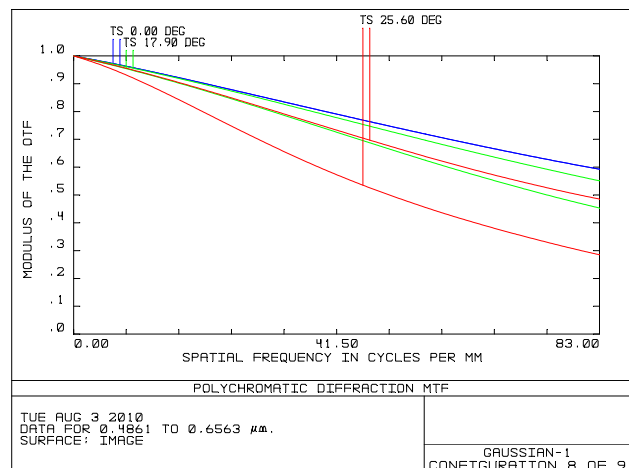


Figure 4. MTF at -40°C and 0.6 atm

Maximum frequency is 83 lp/mm in all graphics; this is the Nyquist frequency of the sensor as mentioned above. All the MTF values above 30% at 83 lp/mm, except the tangential MTF at the edge of the field at -40°C and 0.6 atm.

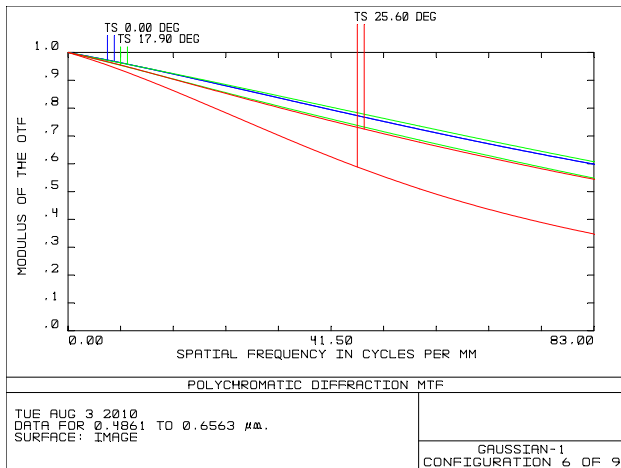


Figure 5. MTF at 40°C and 1 atm

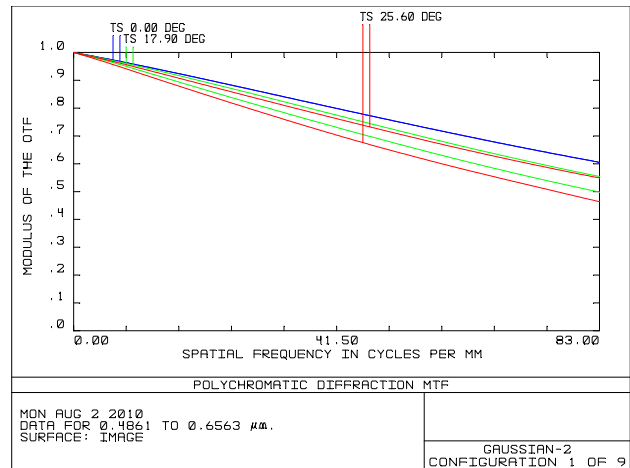


Figure 7. MTF of Nominal design of another objective

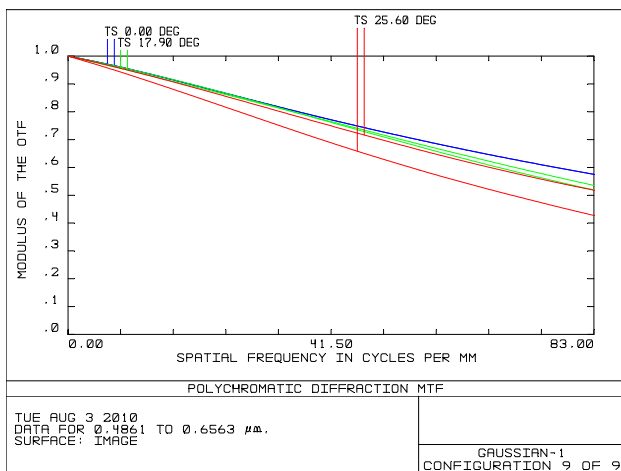


Figure 6. MTF at 40°C and 0.6 atm

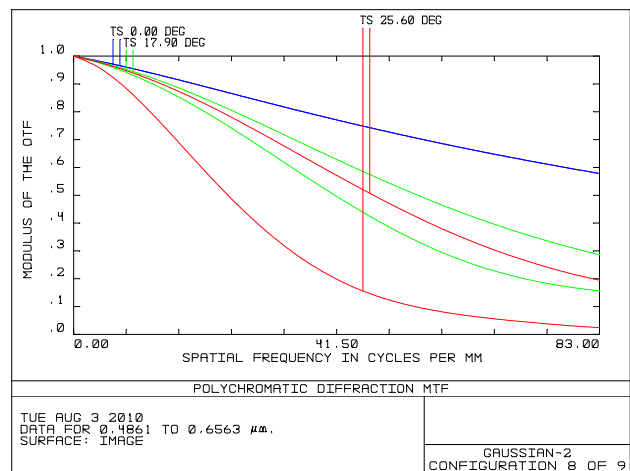


Figure 8. MTF of second objective at -40°C and 0.6 atm

This value also is slightly less than 30%. Except this, all tangential and sagittal MTF values for all fields are greater than 35% at 83 lp/mm. Hence we can say that minimum MTF is around 30%.

As another example here we give a good nominal design at 20°C and 1 atm. This is also a similar Gaussian objective but designed for just room conditions. Figure 7 and 8 show MTF of this objective at two different environmental conditions. Since environmental conditions were not taken into account during the design, performance severely degrades in Figure 8. Even designer makes an optimization for different temperatures from now on, it is not very easy to raise the MTF. Therefore for a designer, it is much better to think about environment at the beginning of the design process.

Here we can conclude that designer should be aware of the effect of environment. Not every lens may degrade this much as shown in Figure 8, but at least it should be checked.

Figure 9 and 10 show another analysis graphics of our design; RMS spot sizes and distortion map. Figure 9 shows that spot sizes are very small but not inside the airy disk. So our design is not diffraction limited but performance is sufficient for 6μ pitch size.

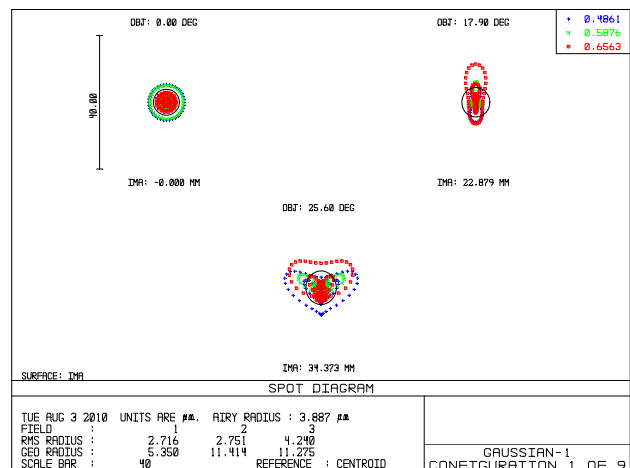


Figure 9. RMS spot sizes of nominal design at 20°C and 1 atm

Figure 10 shows field curvature and distortion map. Distortion also is another important parameter for photogrammetric applications. The graph shows ~2.5% maximum distortion. This value is not sensible by human view, but for photogrammetry it

is especially high for film cameras. But for digital aerial imaging it can be rectified digitally. It also should be noted that distortion does not change at other extreme environmental conditions.

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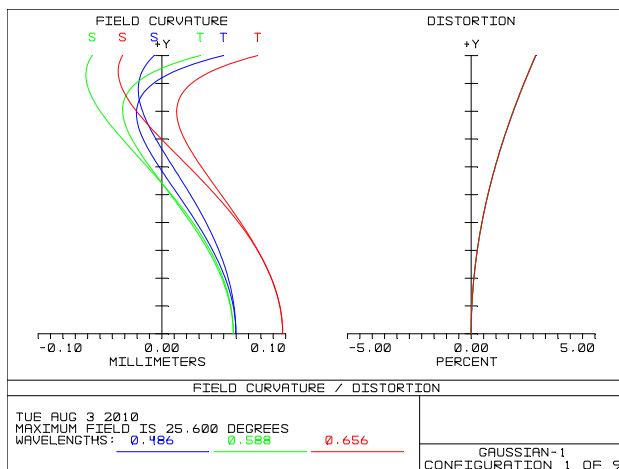


Figure 10. Field curvature and distortion of nominal design

#### 4. CONCLUSION

As a conclusion we designed an objective lens for a given CCD sensor. All environmental conditions (-40 °C / + 40 °C, and 1-0.6 atm) are included during the design for an aerial use. Minimum MTF is 30% at the edge of the field at one extreme condition. All other MTF values are greater than 30% at 83 lp/mm. Focal length of the system is 70 mm and  $f_{\#}$  is 5.4. Distortion is 2.5% and does not change with environmental conditions.

Designed lens is a proper selection for digital aerial imaging systems. For manufacturing considerations, tolerances on lenses also should be decided. Preliminary tolerance analysis has shown that lens is producible with reasonable cost.

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