

# Compact Telecentric Objectives: A systematic exploration of ‘another’ PNP triplet

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This paper describes a special microscope objective form with low numerical aperture and a telecentric image. The basic form combines a Telephoto lens with a telecentricity enforcing field lens of positive power. Typical designs in the visible spectrum and their evolution as a function of telephoto ratio is presented.

## 1 Introduction

Cooke Triplet anastigmat is a classical PNP triplet with a characteristic stop position at the central negative lens. This symmetry about the stop enables superior aberration correction especially those related to coma, distortion and lateral color. It is the objective of this paper to describe another PNP triplet in details, where such symmetry about the stop is not employed.

## 2 PNP Telecentric objectives: Design form

Pupil matching, retrofitting into existing periscope designs, and vignetting-free imaging requirements are some reasons why objectives must be designed with an externally accessible stop. In optical designs with an external stop, the aberration correction advantages that come with the symmetry about the stop are not available.

light from the infinite conjugate position, and a telecentricity enforcing field lens close to the image plane [2]. Such telecentric objectives are commonly used in applications such as metallurgical and semiconductor inspection, as well as in projection optics for pixelated panels.

It is worth describing at this stage that the so-called symmetry factor [2], which is a ratio of the entrance pupil diameter and the image circle diameter, determines the complexity of the design form. Also, telephoto ratio which is the ratio of the optical system’s total track length (TTL) to its effective focal length (EFL), describes the compactness of the design.

## 3 Systematic design study for VIS Waveband

A systematic design study with the requirements presented in Tab. 1 is conducted. The procedure is briefly described as follows:

For the given first order optical parameters such as entrance pupil diameter, effective focal length, and field of view, a starting optical design that fulfills the constraints such as telecentricity, stop location, back focal distance etc., is designed.

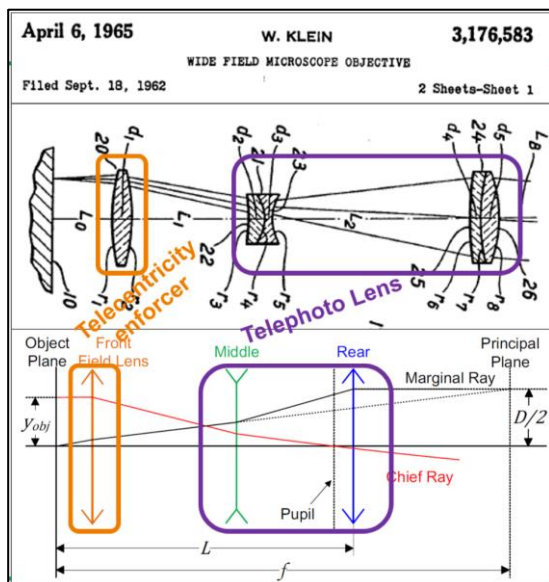


Fig. 1 PNP Microscope objective. Top figure from [1] shows a historical example. Bottom figure from [2] presents the paraxial components of the design form.

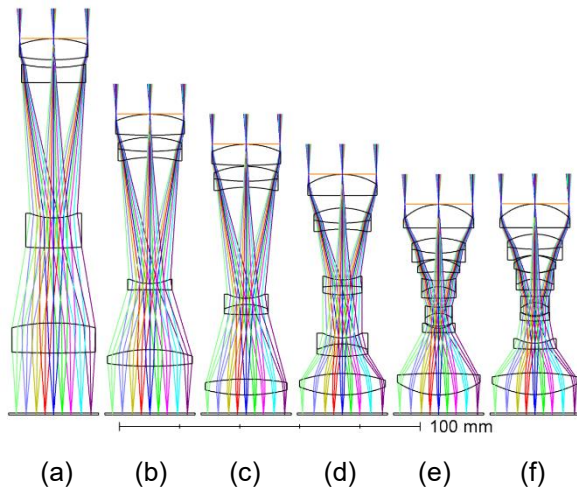
Fig. 1 above presents this microscope objective form as a combination of telephoto lens focusing

Parameter	Value [Units]
Entrance Pupil Diameter (EPD)	22.5 mm
Image Circle Diameter	25 mm
Spectral Waveband	450 to 700 nm (VIS)
Full Field of View (FFOV)	9.5°
Effective Focal length (EFL)	150mm
Back focal distance	>6mm
Telecentricity (Chief Ray Angle)	<0.5°
Stop Position	External and accessible
Total track length (TTL)	Variable: ~125 to 70mm

Tab. 1 Optical parameters for the systematic study

The starting design was allowed a relatively large total track length that enables a non-strained design with superior optical performance. An example of such a design is shown in the left most optical system labelled (a) on Fig. 2.

As next steps, the design was gradually constrained in terms of total track length, which required adding more lenses to maintain optical performance. Performance was evaluated using the average Modulation Transfer Function (MTF) at a selected spatial frequency of 50 lp/mm and distortion correction. A target average MTF of 50% at 50 lp/mm was set as a benchmark for all designs.



**Fig. 2** Results of the systematic study showing the evolution of design complexity in terms of number of lenses, versus telephoto ratio

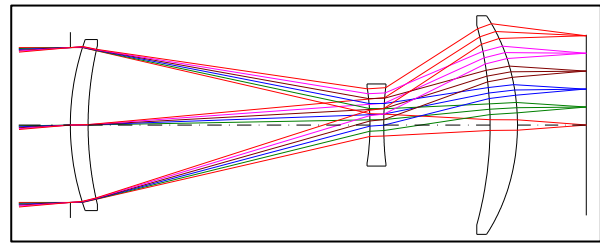
As can be observed from left to right in Fig. 2, the number of lenses increase from 4 to 11 as the total track length shortens from 125mm to 70mm (telephoto ratio: 0.83 to 0.47). The first two designs (a) and (b) exhibit good correction leading to close to diffraction limited performance. For the next two designs (c) and (d) in Fig. 2, good performance can still be obtained by effectively controlling pupil coma which causes image distortion [3] [4].

For the two rightmost designs (e) and (f) in Fig. 2, that utilize 10 and 11 lenses, it is almost impossible to fully correct lateral color and field curvature, while effectively controlling pupil coma. Two aspheres are employed in the right most design (f) that provide some additional degrees of freedom and help the design deliver acceptable performance. The two aspheres are placed, one at the pupil position on lens 1 (spherical correction) and one at the field lens close to the image plane (distortion correction).

It was recognized that at a total track length of 70mm (Telephoto ratio: 0.43), the design has reached its limits in terms of delivering the required optical performance, given the constraints related to stop position, telecentricity and back focal distance.

#### 4 Mid-Wave Infrared (MWIR) design

Just to illustrate a total contrast in complexity, a Mid-wave infrared (MWIR) optical design that operates in the 3.5 to 5 $\mu$ m waveband is presented in Fig. 3.



**Fig. 3** MWIR PNP telecentric objective

All first order optical properties are kept the same, as in Tab 1, except that it operates in a thermal infrared waveband. An all-Silicon design is feasible with a diffractive optical element (DOE) on the back surface of Lens 1 enabling color correction. All three lenses in this case are aspheric lenses and a diffraction limited performance is feasible along with superior distortion performance.

#### 5 Conclusion

A systematic study on PNP telecentric objective designs showed that as the design is compacted (reducing TTL), more corrective lenses are required to achieve acceptable MTF and distortion performance. Designs with longer track lengths (telephoto ratios greater than 0.75) attained near diffraction-limited performance with fewer lenses, while shorter track length designs (telephoto ratios below 0.5) required up to 11 lenses and in some cases aspheric surfaces as well. It can be concluded that at a telephoto ratio around 0.43, the complexity and number of lenses have reached practical limits for given constraints, marking this a design boundary for such external stop telecentric PNP objectives. A systematic design study without the external stop position constraint could be a subject of future studies.

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