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ZOOM OPTICAL SYSTEM FOR THERMAL CAMERA IN OPTICAL RANGE 8-14 µm

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Abstract: Continuous infrared zoom systems with image quality and image stabilisation maintained throughout the workflow are increasingly being used. A long-wave infrared continuous zoom optical system with a 6x zoom ratio operating with an uncooled detector was designed. The optical system has a focal length from 37,5 mm to 225 mm, and the F/# is 1,5. The system includes 7 lenses with 3 even aspheres. The results show that the MTF function is very close to the diffraction limit curve over the entire focal range, proving that the system meets the specifications.

Keywords: Zoom optical system; Thermal infrared; Zoom ratio.

1 INTRODUCTION

The infrared zoom (IR) optical system is capable of detecting, tracking and continuously acquiring information, so with the development of the new generation of uncooled detectors, much more compact zoom thermal imaging devices were born [1, 2]. Because the IR zoom optical system has a continuously variable focal length, to ensure the image quality of the system in the entire focal range, image compensation must be calculated. The calculation of image compensation is usually based on two methods: optical compensation and mechanical compensation. According to the optical compensation method, the image plane can only be stabilised at a few different focal positions, so this method is suitable for designing optical systems with low zoom ratios. In contrast, the mechanical compensation method ensures that the optical system changes focus continuously over a certain range and is therefore widely used in high-ratio IR zoom optical systems. This paper refers to the design of a mechanically compensated IR-zoom optical system, using *7* lenses, with a high zoom ratio, which meets the research direction of versatile thermal imaging equipment.

2 CALCULATION OF A ZOOM IR OPTICAL STRUCTURE

From the general theory of the mechanically compensated IR zoom system [1, 2, 3, 4, 5], the principal diagram of the mechanically compensated zoom system is selected including the following four main groups shown in Fig.1:

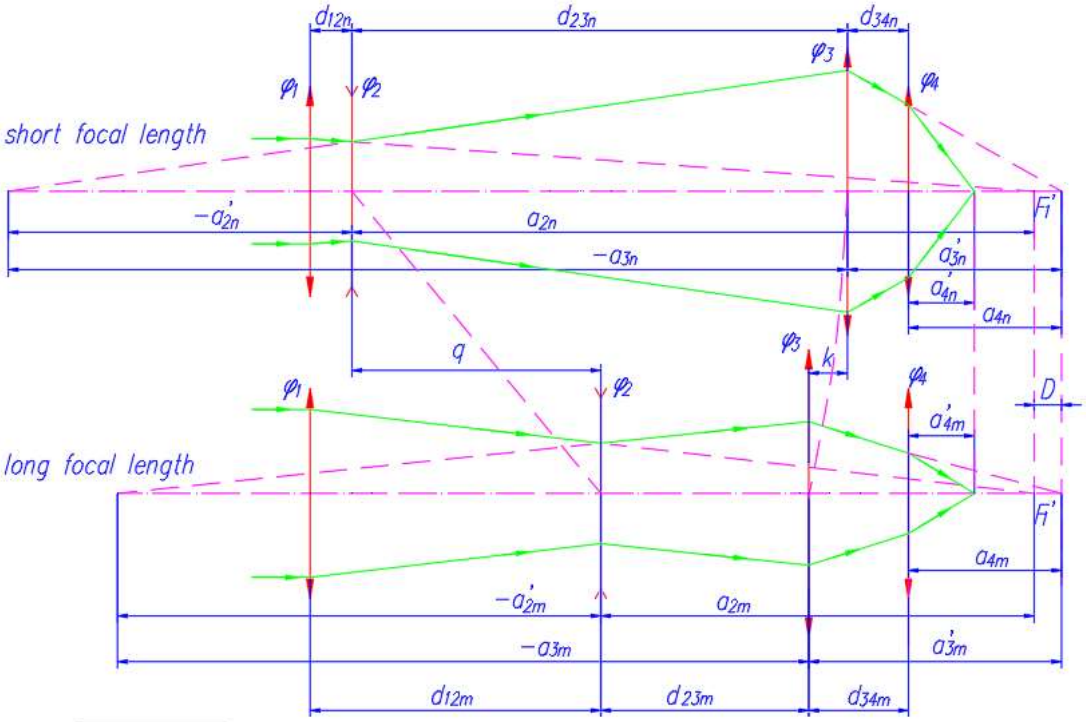


Fig. 1 Diagram of the principle of positive compensation in the IR zoom optical system
Source: authors.

In which, φ_1 is the **front fixed group**, φ_2 is the **variable/transform group**, φ_3 is the **compensatory/offset group**, and φ_4 is the **rear fixed group**. When the optical system is at the short focal position, the variable group φ_2 close to the front fixed group φ_1 and the positive compensation group φ_3 is near the rear fixed group φ_4. When the system moves to the long focal position, the variable group φ_2 shifts to the right and the compensatory group φ_3 shifts in the opposite direction, forming the shortest distance d_{23m} between the variable group and the compensatory group [2, 3].

To determine the initial structure of the system, Gaussian optical calculations are used, and the focal lengths of the displacement groups (variable group and offset group) f'_2 and f'_3 are respectively preselected. The structure of the optical system diagram is taken from the long focal position as a basis for the calculation. Horizontal magnifications at the long focal position of the shifting groups are β_{2m} and β_{3m} respectively.

The following expression can be established from the optical figure in the diagram in Figure 1:

$$d_{23m} = -a_{3m} - (-a'_{2m}) = a'_{2m} - a_{3m}, \qquad (1)$$

in which d_{23m} is the shortest distance between the variable group and the compensatory group (at the long focal position); a'_{2m} is the distance of the image point built across/through the variable group; a_{3m} is the object point distance to the offset group.

The horizontal magnifications of the displacement groups are calculated as follows.

$$\beta_{2m} = \frac{f'_2}{a_{2m}+f'_2} = -\frac{a'_{2m}-f'_2}{f'_2}, \qquad (2)$$

$$\beta_{3m} = \frac{f'_3}{a_{3m}+f'_3} = -\frac{a'_{3m}-f'_3}{f'_3}. \qquad (3)$$

Transforming Equations (2) and (3) to get:

$$a'_{2m} = f'_2(1-\beta_{2m}), \qquad (4)$$

$$a_{2m} = \frac{f'_2}{\beta_{2m}} - f'_2, \qquad (5)$$

$$a_{3m} = \frac{f'_3}{\beta_{3m}} - f'_3. \qquad (6)$$

Substituting equations (4) and (6) into (1) to get the distance:

$$d_{23} \; = f'_2(1-\beta_{2m}) + f'_3(1-\frac{1}{\beta_{3m}}). \qquad (7)$$

Let us consider the optical system at the short focal position. According to optical construction, there are:

$$q = d_{12n} - d_{12m}, \qquad (8)$$

$$q + a_{2m} = a_{2n}, \qquad (9)$$

where q is the displacement of the group φ_2; d_{12n} is the distance between group φ_1 and group φ_2 in a short focal position; d_{12m} is the distance between group φ_1 and group φ_2 in a long focal position; a_{2n} is object distance to group φ_2 in a short focal position.

Using the formula in Eq. (2) for calculating the horizontal magnification of the variable group at the short focal position, we obtain:

$$a_{2n} = \frac{f'_2}{\beta_{2n}} - f'_2 \qquad (10)$$

Substituting (5) and (10) into (9) and transforming to get:

$$\beta_{2n} = \frac{f'_2 \cdot \beta_{2m}}{q \cdot \beta_{2m} + f'_2}. \qquad (11)$$

Equation (11) calculates the horizontal magnification of the point object through the variable group at the short focal position β_{2n} depending only on the amount of displacement q, the focal length f'_2 and the horizontal magnification β_{2m} at the long focal position [2].

Find the magnification β_{3n} of the compensation group at the short focal position:

From the geometric relationship of the distance of object–image points through the zoom unit, it is easy to find the relationship between variable group magnification and offset group magnification when shifting from the long focal position to the short focal position (zoom equation) as follows [3].

$$f'_3\left(\frac{1}{\beta_{3m}} + \beta_{3m} - \frac{1}{\beta_{3n}} - \beta_{3n}\right) + f'_2\left(\frac{1}{\beta_{2m}} + \beta_{2m} - \frac{1}{\beta_{2n}} - \beta_{2n}\right) = 0. \qquad (12)$$

Transforming equation (12) to find β_{3n}:

$$\beta_{3n}^2 - b.\beta_{3n} + 1 = 0. \qquad (13)$$

where b is the coefficient that has the value:

$$b = -\frac{f'_2}{f'_3}\left(\frac{1}{\beta_{2n}} - \frac{1}{\beta_{2m}} + \beta_{2n} - \beta_{2m}\right) + \left(\frac{1}{\beta_{3m}} + \beta_{3m}\right). \qquad (14)$$

Solve the quadratic equation to find the value of β_{3n} according to the expression:

$$\beta_{3n} = \frac{b \pm \sqrt{b^2-4}}{2}. \qquad (15)$$

This expression shows that, during zooming, corresponding to one magnification of the transform group, there will be two magnifications of the compensating group that satisfy the requirement for image surface stability.

Calculate the amount of displacement k of the compensation group:

From the diagram in Figure *1*, it can be seen that the optical zoom objective system has a fixed image plane, which implies the following.

$$a'_{4n} = a'_{4m}. \qquad (16)$$

Therefore, their conjugate segments must be equal:

$$a_{4n} = a_{4m}. \qquad (17)$$

The amount of displacement k of the compensation group is equal to:

$$k = d_{34m} - d_{34n.} \qquad (18)$$

Combining (17) with (18) we have:

$$k = (d_{34m} + a_{4m}) - (d_{34n} + a_{4n}) = a'_{3m} - a'_{3n.} \qquad (19)$$

From the expression for calculating horizontal magnification according to Gaussian optics, the values of the image line segment built through the compensation group in the two configurations can be calculated as follows.

$$a'_{3m} = f'_3(1 - \beta_{3m}), \qquad (20)$$

$$a'_{3n} = f'_3(1 - \beta_{3n}). \qquad (21)$$

Substituting a'_{3m}, $a'_{3n}$from (20) and (21) into the expression (19) to get:

$$k = f'_3(\beta_{3n} - \beta_{3m}). \qquad (22)$$

The effective focal length of the optical system at the long focal position is

$$f'_m = f'_1 . \beta_{2m} . \beta_{3m} . \beta_4, \qquad (23)$$

where β_4 is the horizontal magnification of the rear fixed lens group. Due to the requirement that the image plane does not change, β_4 remains constant during the zooming process of the zoom objective system.

The general focal length of the optical system at the short focal position is:

$$f'_n = f'_1 . \beta_{2n} . \beta_{3n} . \beta_4. \qquad (24)$$

The zoom ratio is formed by the variable focal length of the zoom objective and is defined as Γ:

$$\Gamma = \frac{f'_m}{f'_n}. \qquad (25)$$

Combining (23), (24), and (25) we have the following relationship of the product of magnifications of mobile components in two polar configurations:

$$\Gamma = \frac{\beta_{2m} . \beta_{3m}}{\beta_{2n} . \beta_{3n}}. \qquad (26)$$

Equation (26) shows the relationship of the zoom ratio of the objective zoom optical system Γ to the product of the horizontal magnifications of the moving components in the two extreme configurations.

The distance between the variable group and the offset group at the short focal position is (see Figure 1):

$$d_{23n} = q + d_{23} \quad + k. \qquad (27)$$

Calculate the focal length f'_1 according to the formula:

$$f'_1 = d_{12n} + a_{2n}. \qquad (28)$$

Replace a_{2n} in Equation (10) into Equation (28) to get:

$$f'_1 = d_{12n} + f'_2\left(\frac{1}{\beta_{2n}} - 1\right). \qquad (29)$$

Calculating the total length of the objective optical system: If the length of the objective optical system L is considered as the distance from the position of the fixed lens group in advance to the position of the image plane, then L can be calculated by the expression:

$$L = d_{12n} + q + d_{23m} + k + d_{34n} + a'_{4n}. \qquad (30)$$

From the formulas built above, the initial structure of the optical system can be found [1, 2, 3].

3 DESIGN OF THE IR ZOOM SYSTEM

3.1 Feature criteria of the optical zoom system to be designed

Choosing a set of design criteria for the IR zoom optical system based on the working distance of the equipment calculated according to Johnson's standard, combined with the selection of Flir's 640 x512 uncooled detector, which is commercially available, is valued as in Table *1*.

From the set of indicators, it is necessary to design and allocate the component focal lengths and the distance between the components (groups) of the zoom objective to obtain the zoom ratio and maintain the overall length of the optical system. At the same time, no collision of the components occurs when moving.

Tab. 1 The set of criteria and features of the optical zoom system to be designed

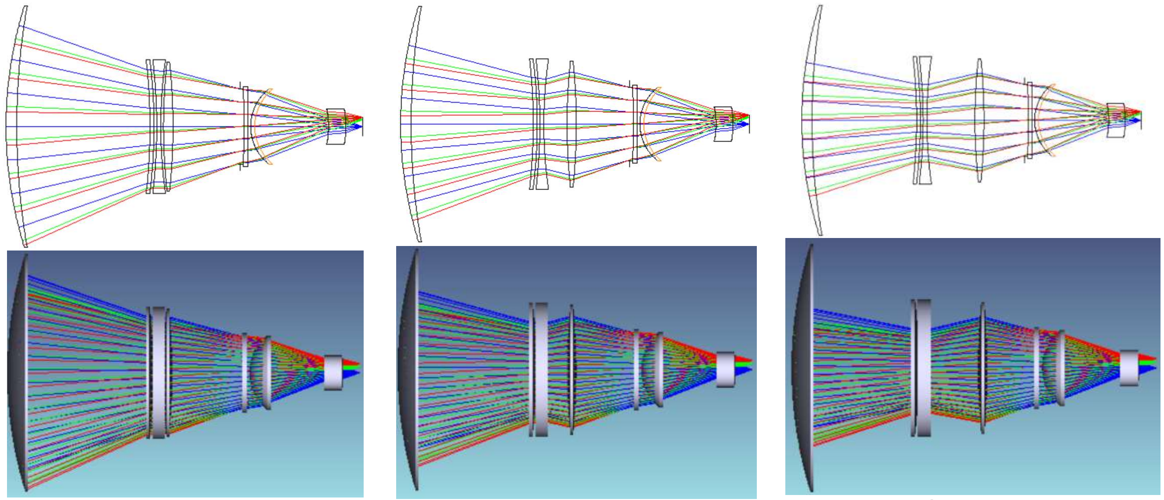
No.	Parameter	Value
1	Detector, pixel	640 x 512
2	The pitch of the detector pixels, μm	17
3	Working wavelength range, μm	8 ~ 12
4	Working focal range, *mm*	37,5~225
5	F/#	1,5
6	Zoom ratio, *times*	6
7	Lens length L, mm	≤ 300

Source: authors.

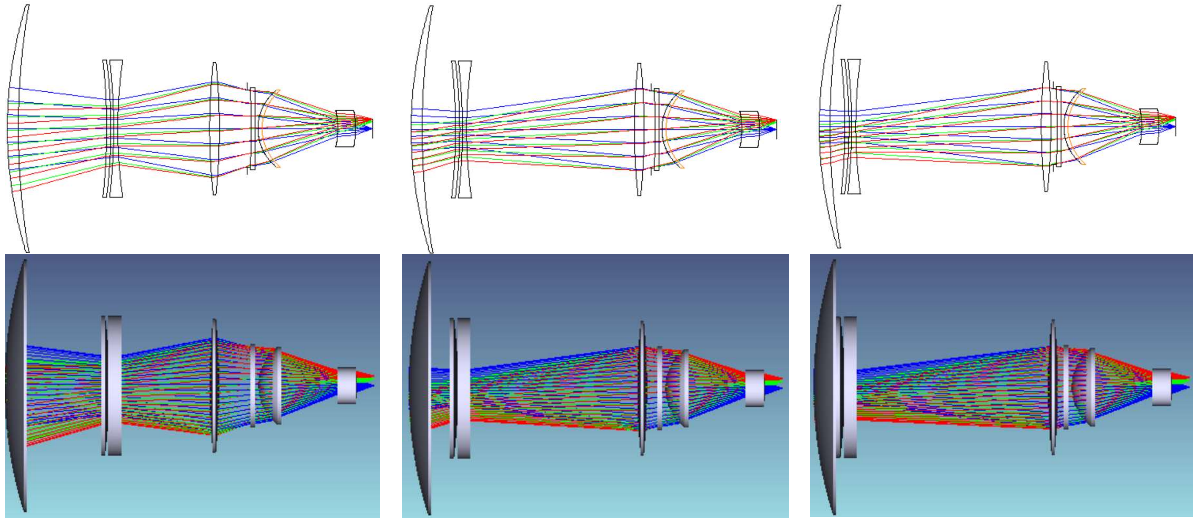
3.2 Design results

The distribution of this IR zoom system is: +, '-', '+', and '+' in which the mobile group '-' performs zooming, and the movable group '+' performs image plane offset compensation. The movement of these two moving groups is ensured by a special cam mechanism.

To perform the optical system calculations, formulas from (*1*) to (*30*) are used. The optical materials Ge and ZnS, which are common and easy to machine and have different refractive indices and Abbe coefficients, are chosen. They help to eliminate axial chromatic aberration. The structure of the system at *six* different focal positions is shown in Figure *2*.



a) $f' = 225$mm. b) $f' = 180$mm. c) $f' = 135$mm.



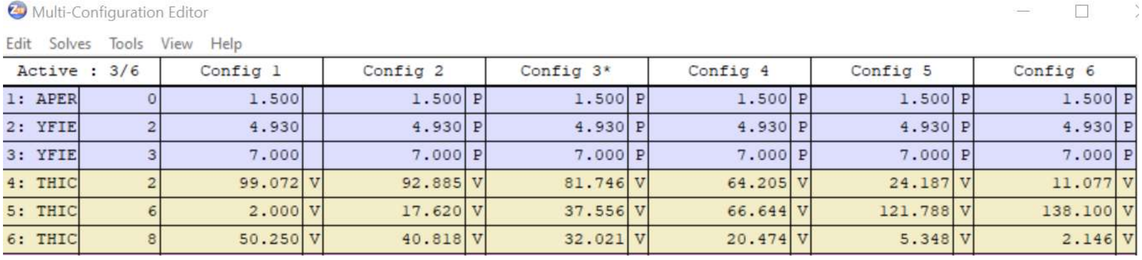
d) $f' = 90$mm. e) $f' = 45$mm. g) $f' = 37,5$mm.

Fig. 2 Structure of the IR zoom optical system
Source: authors.

The optical system consists of 7 lenses, of which 6 are made of Ge and 1 is made of ZnS. The fixed group φ_1 is a single lens made of Ge, the variable group φ_2, which has negative power, consists of two lenses that perform the zoom, the third group φ_3 is a positive lens that compensates for the image plane shift. The most complex rear fixation group φ_4 consists of 3 lenses to eliminate residual aberrations from the front groups. The system has *3* even aspherical surfaces to eliminate higher-order aberrations. Applying the multi-configuration optimization in Zemax [6], the structure of the IR-zoom optical system is given in Table *2* with the multi-configuration variable being the distances between groups $\varphi_1, \varphi_2, \varphi_3, \varphi_4$. During the design process, the sum of these three distances is constant and equal to *151,32* mm; the image plane is kept stable. The total length of the system is *265* mm and the constant F# is *1,5*.

Table 3 shows the Lens Data Editor of Configuration *1* (*f'=225* mm), in which the optical surfaces numbered *2, 10,* and *14* are even aspheres to reduce aberrations. The system Stop on the ninth surface with a semi-diameter of *27,97 mm* is unchanged.

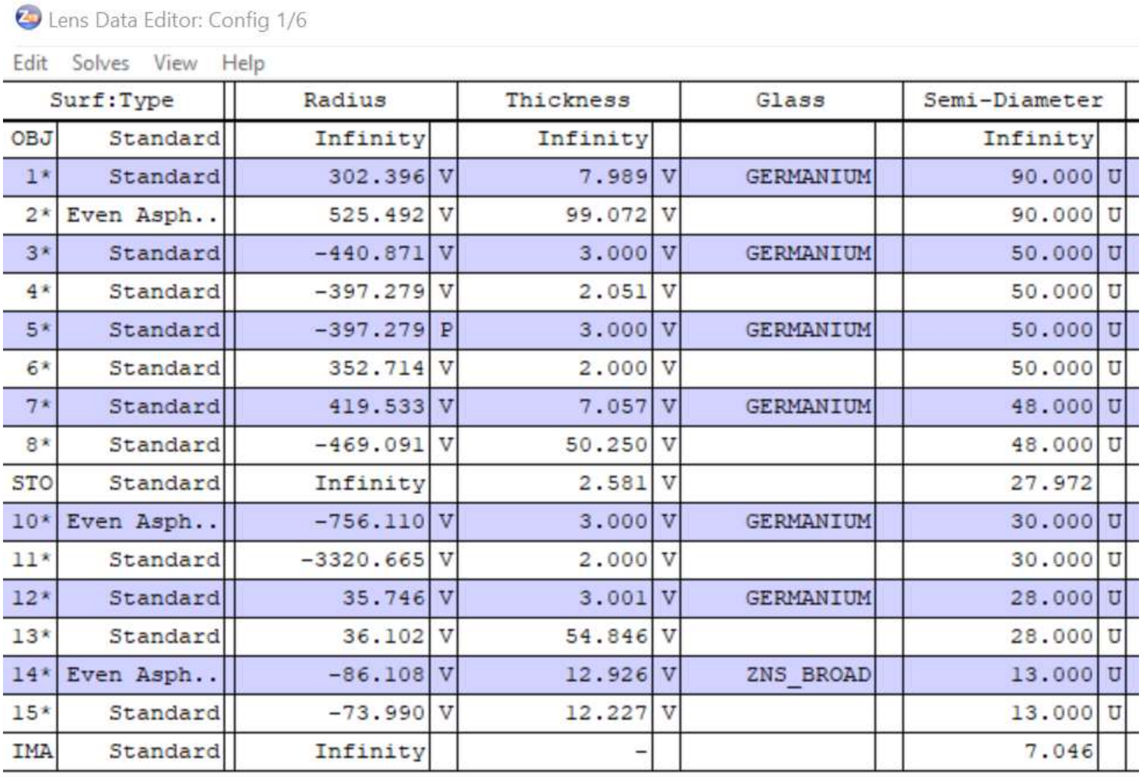
Tab. 2 Multi-configuration variable of the IR zoom optical system



Active : 3/6		Config 1		Config 2		Config 3*		Config 4		Config 5		Config 6	
1: APER	0	1.500		1.500	P	1.500	P	1.500	P	1.500	P	1.500	P
2: YFIE	2	4.930		4.930	P	4.930	P	4.930	P	4.930	P	4.930	P
3: YFIE	3	7.000		7.000	P	7.000	P	7.000	P	7.000	P	7.000	P
4: THIC	2	99.072	V	92.885	V	81.746	V	64.205	V	24.187	V	11.077	V
5: THIC	6	2.000	V	17.620	V	37.556	V	66.644	V	121.788	V	138.100	V
6: THIC	8	50.250	V	40.818	V	32.021	V	20.474	V	5.348	V	2.146	V

Source: authors.

Tab. 3 The Lens Data Editor of Configuration 1 (f'=225 mm)

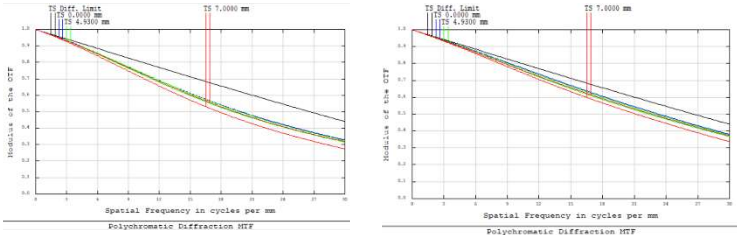


Surf:Type		Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard	Infinity		Infinity				Infinity	
1*	Standard	302.396	V	7.989	V	GERMANIUM		90.000	U
2*	Even Asph..	525.492	V	99.072	V			90.000	U
3*	Standard	-440.871	V	3.000	V	GERMANIUM		50.000	U
4*	Standard	-397.279	V	2.051	V			50.000	U
5*	Standard	-397.279	P	3.000	V	GERMANIUM		50.000	U
6*	Standard	352.714	V	2.000	V			50.000	U
7*	Standard	419.533	V	7.057	V	GERMANIUM		48.000	U
8*	Standard	-469.091	V	50.250	V			48.000	U
STO	Standard	Infinity		2.581	V			27.972	
10*	Even Asph..	-756.110	V	3.000	V	GERMANIUM		30.000	U
11*	Standard	-3320.665	V	2.000	V			30.000	U
12*	Standard	35.746	V	3.001	V	GERMANIUM		28.000	U
13*	Standard	36.102	V	54.846	V			28.000	U
14*	Even Asph..	-86.108	V	12.926	V	ZNS_BROAD		13.000	U
15*	Standard	-73.990	V	12.227	V			13.000	U
IMA	Standard	Infinity		-				7.046	

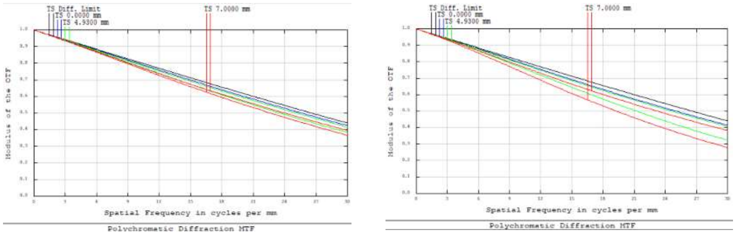
Source: authors.

3.3 Evaluate image quality

MTF is one of the criteria to evaluate the quality of the optical system image designed. The MTF functions of the system in different focal configurations are shown in Figures *3(a)* to *(g)*. The curves have a cutoff frequency of *30* lines/mm, with values above *0,25* and close to the diffraction limit, showing that the quality of the design system is acceptable [7].



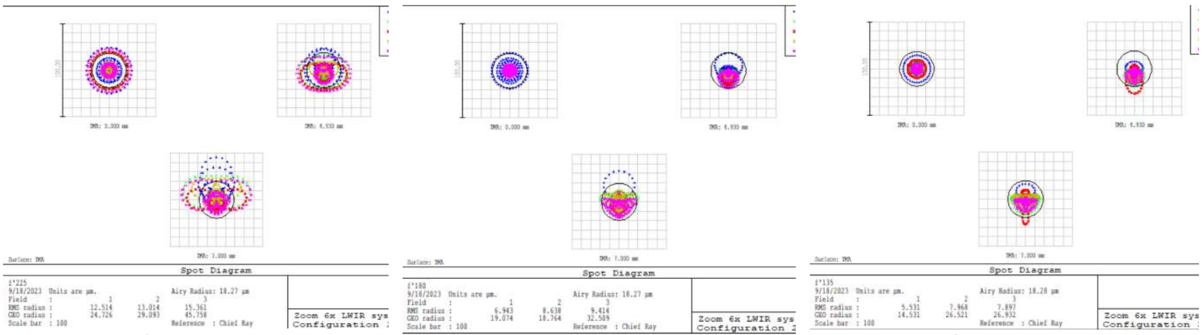
a) $f' = 225\text{mm}$ b) $f' = 180\text{mm}$ c) $f' = 135\text{mm}$



d) $f' = 90\text{mm}$ e) $f' = 45\text{mm}$ g) $f' = 37{,}5\text{mm}$

Fig. 3 MTF curve of the optical zoom system at different focal lengths
Source: authors.

The spot diagram in the image plane of the optical system is also an indicator of quality. Figure *4* shows the spot diagram of *6* different focal positions of the designed zoom optical system. In Figure *4*, it can be seen that the RMS ray spot size at all positions is smaller than the pixel size, so the zoom system satisfies the image quality requirements of the detector.



a) $f' = 225\text{mm}$. b) $f' = 180\text{mm}$. c) $f' = 135\text{mm}$.

d) $f' = 90\text{mm}$. e) $f' = 45\text{mm}$. g) $f' = 37{,}5\text{mm}$.

Fig. 4 Spot diagram at different focal positions
Source: authors.

4 CONCLUSION

An IR continuous-zoom optical system was designed in the LWIR range with a 6x zoom ratio operating with a 640x512 pixel uncooled detector. Evaluating the quality of the MTF function and the spot diagrams shows that the zoom system is quite good quality. Zoom optical system with continuously variable focal length from *37,5* mm to *225* mm, constant F/#*1.5*, compact structure, suitable for target positioning and search applications in the LWIR waveband.

The design of the infrared zoom optical system needs to continue in the direction of uniformly increasing image quality throughout the entire zoom range, paying attention to the feasibility of the motion curve of the compensation cam mechanism and further expanding the zoom ratio, meeting the increasing requirements for observing and tracking thermal targets.

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