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# 可见红外一体化宽幅空间光学系统设计

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**摘 要**:为了满足空间遥感相机对分辨率越来越高的要求,设计研究了一种具有较高空间分辨率的可见光与红外光一体化的空间光学系统,可同时实现多谱段成像功能。可见光分系统的工作波段为0.45~0.9 μm,焦距为5 m,$F$数为10,视场角为0.7°×2.3°,在500 km的轨道位置处成像幅宽大于20 km;中波红外分系统的工作波段为3~5 μm,焦距为1.5 m,视场角为0.2°×2°,$F$数为3,满足100%的冷光阑效率。两路光学系统共用前端同轴三反系统的主次镜,通过视场分割的形式实现双波段同时工作。整个系统用到了8个反射元件,设计结果满足各项指标要求。

**关键词**:光学设计;大视幅;一体化设计;空间相机;离轴三反
**中图分类号**:O439 **文献标识码**:A **doi**:10.3788/gzxb20265502.0222002

## 0 引言

从2000年美国发射的TSX-5卫星,到2014年韩国航天航空所发射的Kompsat-3A卫星,再到我国于2015年底发射的“高分四号”卫星,各国的光学遥感相机逐渐朝着高分辨率、大口径、多谱段的方向发展[1]。与单一的可见光成像光学系统相比,可见光与红外一体化光学系统具有多种优势。一方面,它能获取目标在不同光谱范围内的信息,从而实现对目标更全面地观测和更准确地分析。可见光主要用于获取物体的外观特征和表面信息,而红外光能够穿透一些物体并获取其内部结构和热分布等信息。例如,在森林火灾的监测中,可见光可以用来观察火情的扩散情况,而红外光则可以用来分析火源的热点。另一方面,它可以实现全天时、全天候的空间遥感探测。与传统的可见光成像系统相比,红外光学系统的隐蔽性更强,在夜晚、沙尘、浓雾等低照度或气候恶劣的环境下均有良好的探测性能[2]。同时,结合制冷型红外探测器更低的噪声等效温差(Noise Equivalent Temperature Difference, NETD)、更远的作用距离、更高的探测灵敏度,可以轻易实现对远距离军事目标的高分辨率探测与识别[3]。

空间光学系统可以分为透射式、折反式以及反射式三种设计形式。透射式系统无光线遮拦且易于装配,可以实现大视场的光学设计,但是对于大口径的光学系统难以实现轻量化。折反式系统虽然可以实现大口径的光学设计,但是对于大视场、有红外探测需求的系统,红外折射材料类型较少、透过率低、热稳定性差、价格昂贵[4],且透镜色差难以校正,透镜口径大小存在限制,难以在空间探测领域广泛应用。反射式系统兼具大口径、大视场、长焦距、宽波段和轻量化等优势,在空间光学系统的设计中频频出现。

李瑞昌等[5]设计研究了视场(Field of View, FOV)为1.4°×0.6°的可见光与中波红外一体化反射式光学系统,可见光路焦距为6 000 mm,$F$数为11.8,中波红外光路焦距为1 280 mm,$F$数为2.5,全系统总共用了9个反射元件。郭钰琳等[6]设计了适用于制冷型中波红外探测器和可见光探测器双波段的共口径折反式光

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学系统，两个波段的光路共用卡塞格林系统，利用分光镜实现分光，并通过透镜校正像差。YAN A Q等[7]设计了一个结构紧凑、长焦距、大视场的可见光与短波红外共口径折反式一体化光学系统，其中短波红外光路采用了四个制冷型探测器，并使用视场分割器实现了宽场拼接，满足系统宽场成像和高灵敏度探测的设计指标。

当前的可见红外一体化光学系统大多采用折反式的设计形式，系统需要使用多个光学元件消除色差，且无法兼顾长焦距、大口径、大刈幅、轻量化的设计指标。本文基于近轴像差理论求解系统的初始结构，利用光学设计软件对初始结构进行优化设计，通过合理设置视场避免光线遮拦。对于中波红外光路，系统的实出瞳与探测器冷阑的位置重合，实现了100%冷光阑效率。

## 1 技术指标与光学方案

### 1.1 主要技术指标

结合大气窗口和探测器的响应谱段范围，同时考虑到成像目标的光学特性，可见光(Visible, VIS)的工作波段选择在0.45～0.9 μm之间，中波红外(Mid-Wave Infrared, MWIR)的工作波段选择在3～5 μm之间。空间相机的运行轨道高度拟定为500 km，主要的任务需求如表1。

**表1 空间相机的任务需求**

**Table 1 Requirements for space camera**

| Requirements | VIS | MWIR |
|---|---|---|
| Aperture/mm | 500 | 500 |
| Resolution/m | ≤0.7 | ≤6 |
| Imaging width/km | ≥20 | ≥17 |
| Distortion | ≤1.5% | ≤1% |

为了满足空间相机的任务需求，根据地元分辨率和成像刈幅的计算公式可以分别求出光学系统的焦距和视场角大小，即

$$\mathrm{GSD}=\frac{a\cdot H}{f} \tag{1}$$

$$\omega=\arctan\left(\frac{W}{2H}\right) \tag{2}$$

式中，GSD为地元分辨率(Ground Sample Distance, GSD)；$a$为像元尺寸；$H$为空间相机运行的轨道高度；$f$为光学系统的焦距；$W$为地面成像刈幅；$\omega$为光学系统的半视场角。根据表1中列出的各项需求可以算出一体化光学系统中可见光波段的焦距应不小于5 m，全视场不小于2.3°；中波红外波段的焦距应不小于1.5 m，全视场不小于2°。

表2呈现了本文设计参数及调制传递函数(Modulation Transfer Function, MTF)等相关像质评价，表明本文对宽幅一体化、长焦距、大口径和轻量化的综合性能实现。

**表2 设计参数比对**

**Table 2 Comparison of design parameters**

| Parameters | Design in this thesis | Design in Ref.[5] | Design in Ref.[6] |
|---|---|---|---|
| FOV/[(°)×(°)] | 0.7×2.3 | 1.4×0.6 | 0.38×0.43 |
| Focal length/mm | 5 000/1 500(VIS/MWIR) | 6 000/1 280(VIS/MWIR) | 500/600(VIS/MWIR) |
| Aperture/mm | 500 | 512 | 125 |
| MTF | 0.26/0.5(VIS/MWIR) | 0.35/0.4(VIS/MWIR) | 0.3/0.2(VIS/MWIR) |
| Number of lenses | 8 | 9 | 16 |

### 1.2 光学方案

光学系统设计形式的选择在光学设计中十分重要，合适的系统结构形式可以减小光学设计、加工、装调和集成的难度，缩短系统的研制周期。综合考虑空间相机的口径、体积、重量、环境适应性等要求，光学系统

光路采用共孔径分视场的一体化设计方案，如图1所示。可见光和中波红外两波段共用前端同轴三反结构的主次镜，在后端采用视场分割的形式通过两个折轴镜折转为可见光成像光路和中波红外成像光路，实现双波段同时成像。为了最大程度减小主镜的开孔尺寸，将一次像面的位置设在主镜中心附近。对于可见光分系统来说，其形式为偏视场使用的同轴三反结构[8]；对于中波红外分系统而言，其前端为可见光分系统的主、次镜，通过折轴镜进入后端的三镜消像散（Three-mirror Anastigmats，TMA）离轴结构[9]。

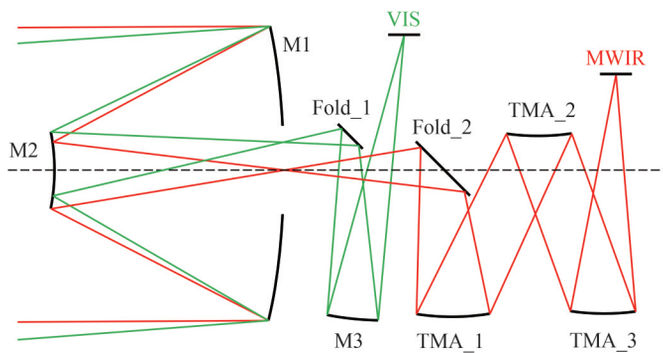



图1　光学系统光路结构

Fig. 1　Layout of the optical system

在探测器的选型方面，光学系统可见光时间延迟积分型CMOS图像传感器（Time Delay and Integration-CMOS，TDI-CMOS）的像元数为12 288×128，像元大小为7 μm，使用3片相同的探测器在像面上采用“品字形”的排列方式，仅利用了光学系统像面上非渐晕区域的一部分，可以实现36 000×128的像元阵列，达到25.2 km的画幅宽度，如图2所示。中波红外分系统选用一款大面阵制冷型红外探测器，其像元数为3 000×2 500，像元大小为18 μm。该探测器由玻璃窗口、滤光片、冷光阑和焦面组成，焦面与冷光阑的距离为90 mm，如图3所示。

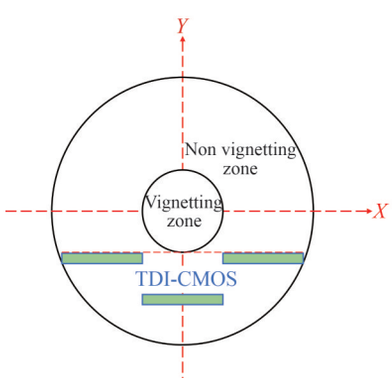



图2　偏视场“品字形”排布的TDI-CMOS

Fig. 2　TDI-CMOS with offset field-of-view arranged in a triangular pattern

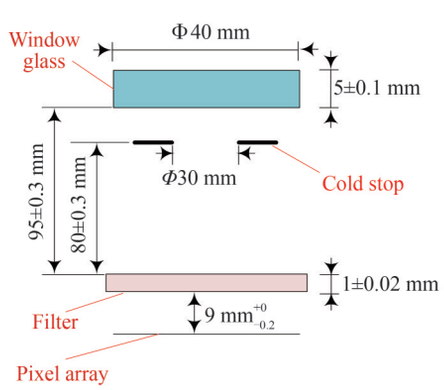



图3　中波红外探测器光学接口

Fig. 3　Optical interface diagram of medium wave infrared detector

## 2　初始结构与像差计算

### 2.1　同轴三反初始结构求解

为了解决同轴系统难以同时实现大视场与长焦距的设计难题，离轴TMA结构于20世纪70年代被提出，常常被应用于对空间分辨率和视场要求较高的空间光学系统光路的设计中。离轴TMA的初始结构设计一般是由同轴三反系统离轴化而来，同轴三反系统的初始结构参数可根据初级像差理论进行求解[10]。如图4所示，三反系统的有效焦距为$f'$，主镜（M1）、次镜（M2）、三镜（M3）三个反射镜的曲率半径分别为$R_1$、$R_2$、$R_3$，主镜到次镜的距离为$d_1$，次镜到三镜的距离为$d_2$，三镜到像面的距离为$l_3'$，次镜对主镜的遮拦比为$\alpha_1$，

三镜对次镜的遮拦比为$\alpha_2$,次镜和三镜的垂轴放大率分别为$\beta_1$、$\beta_2$,三面反射镜的物方孔径角和像方孔径角分别为$u_1$、$u_2$、$u_3$和$u_1'$、$u_2'$、$u_3'$,$-e_1^2$、$-e_2^2$、$-e_3^2$分别为三个反射镜的二次曲面系数。

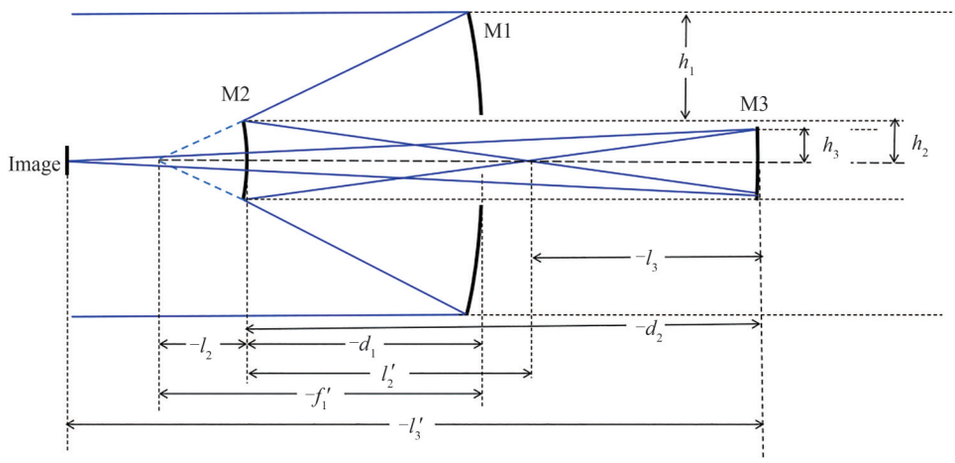



图4 同轴三反系统的初始结构

Fig. 4 Initial structure of the coaxial three-mirror reflective system

在同轴三反系统中,由近轴光学理论可得

$$\alpha_1=\frac{l_2}{f_1'}\approx\frac{h_2}{h_1} \tag{3}$$

$$\alpha_2=\frac{l_3}{l_2'}\approx\frac{h_3}{h_2} \tag{4}$$

$$\beta_1=\frac{l_2'}{l_2}\approx\frac{u_2}{u_2'} \tag{5}$$

$$\beta_2=\frac{l_3'}{l_3}\approx\frac{u_3}{u_3'} \tag{6}$$

根据几何关系有

$$R_1=\frac{2}{\beta_1\beta_2}f' \tag{7}$$

$$R_2=\frac{2\alpha_1}{\beta_2(1+\beta_1)}f' \tag{8}$$

$$R_3=\frac{2\alpha_1\alpha_2}{1+\beta_2}f' \tag{9}$$

$$d_1=\frac{1-\alpha_1}{\beta_1\beta_2}f' \tag{10}$$

$$d_2=\frac{\alpha_1(1-\alpha_2)}{\beta_2}f' \tag{11}$$

$$l_3'=\alpha_1\alpha_2 f' \tag{12}$$

场曲$S_{\mathrm{Ⅳ}}=0$,根据初级像差理论有

$$\beta_1\beta_2=\frac{(1+\beta_1)\beta_2}{\alpha_1}-\frac{1+\beta_2}{\alpha_1\alpha_2} \tag{13}$$

同时根据消球差、慧差和像散的要求,可以得到

$$S_{\mathrm{Ⅰ}},S_{\mathrm{Ⅱ}},S_{\mathrm{Ⅲ}}=0 \tag{14}$$

式中,$S_{\mathrm{Ⅰ}}$、$S_{\mathrm{Ⅱ}}$、$S_{\mathrm{Ⅲ}}$分别表示球差、慧差、像散对应的赛德尔像差系数,利用Matlab软件编程求解式(3)~(14),根据符合系统要求的轮廓参数$\alpha_1$、$\alpha_2$、$\beta_2$即可得到系统初始结构参数。

### 2.2 离轴TMA结构

需要注意的是,在本文的设计中,可见光分系统采用同轴三反结构形式,中波红外离轴TMA系统初始入射光线不是平行光,物距不是无限远,即$u_1\neq0$,$l_1\neq\infty$。离轴的方式有三种,分别是光瞳偏置、视场偏置和镜面离轴,本文的中波红外分系统主要采用光瞳偏置的方式进行离轴设计。光瞳偏置是一种让孔径光阑偏移原本共轴光路,从而避免中心光线遮拦的离轴方式,如图5所示。

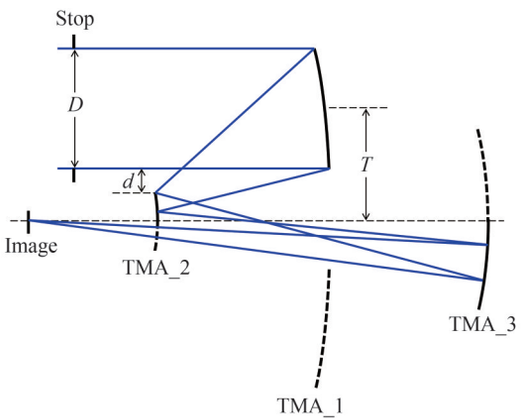



图5 光瞳偏置的离轴TMA初始结构

Fig. 5 Initial configuration of the pupil off-axis TMA optical system

图5中,$D$为系统的入瞳直径,$T$为光瞳离轴量,$d$为光线打在一镜(TMA_1)的下边缘与二镜(TMA_2)的上边缘之间的距离。当$d>0$时,系统无光线遮拦。假设二镜对一镜的遮拦比为$\alpha_1$,则光瞳的离轴量可以表示为

$$T=\frac{D+d}{1-\alpha_1}-\frac{D}{2} \tag{15}$$

由于光瞳坐标发生平移,系统不再具备旋转对称性,传统的近轴像差理论不再适用[11],通常需要结合矢量像差理论对其进行分析。光瞳偏置后,系统的矢量波像差表达式为

$$W=\sum_j\sum_p^{\infty}\sum_n^{\infty}\sum_m^{\infty}(W_{klm})_j(\boldsymbol{H}\cdot\boldsymbol{H})^p\left[(\boldsymbol{\rho}+\boldsymbol{T})\cdot(\boldsymbol{\rho}+\boldsymbol{T})\right]^n\left[\boldsymbol{H}\cdot(\boldsymbol{\rho}+\boldsymbol{T})\right]^m \tag{16}$$

式中,$W_{klm}$为表面的波像差系数,$k$表示视场坐标的幂次,$l$表示孔径坐标的幂次,用$k$、$l$描述像差对视场和孔径的依赖关系,$\boldsymbol{H}$为归一化的视场矢量,$\boldsymbol{\rho}$为归一化的光瞳矢量,$\boldsymbol{T}$为归一化光瞳偏心矢量。离轴后的系统会引入大量非对称像差,仅通过常规的球面或非球面难以校正系统像差。得益于光学自由曲面加工制造技术的发展,将自由曲面引入离轴系统中可以有效校正系统的非对称像差。

## 3 系统设计

根据第1节中空间相机的任务需求和计算结果,将可见红外一体化光学系统的设计指标列于表3。其中,系统的视场角用矩形视场表示,成像像高与探测器感光面的尺寸匹配。

**表3 一体化光学系统的设计指标**

**Table 3 Design specifications of integrated optical system**

| Design specifications | VIS | MWIR |
|---|---|---|
| Entrance pupil diameter/mm | 500 | 500 |
| Effective focal length/mm | 5 000 | 1 500 |
| $F$-number | 10 | 3 |
| FOV/[(°) × (°)] | 0.7×2.3 | 0.2×2 |
| Pixel/μm | 7 | 18 |

### 3.1 可见光分系统

根据可见光系统的设计需求,再考虑到三镜到像面的距离随着三镜的放大率增大而增加,合理设置$\alpha_1$、$\alpha_2$、$\beta_2$的数值。根据Matlab程序可以得到同轴结构的初始参数分别为$R_1=-2\ 059.150\ 8$ mm,

$R_2$=－639.538 5 mm，$R_3$=742.833 mm，$d_1$=－767.038 2 mm，$d_2$=1 569.477 3 mm，$l_3'$=1 506.135 8 mm，$-e_1^2$=－0.562 3，$-e_2^2$=－1.432 6，$-e_3^2$=-1.002 7。

在同轴结构的基础上，考虑到光学元件之间装配间距以及系统的结构紧凑性，在所成一次像面的后端大于150 mm的距离处放置折轴镜1，由于三个反射镜之间并无偏心和倾斜，此时的光学布局为有折轴镜的共轴三反系统。将主镜设为光阑，次镜对主镜的遮拦比小于0.35，将反射镜的曲率半径、间距和圆锥系数作为优化变量，在光学设计软件中进一步优化。为了在满足光学系统设计指标的同时消除光线遮拦，将光学系统的中心视场在$Y$方向上偏移1.05°，同时将三镜设为非球面继续优化，最终设计结果如图6所示，结构参数如表4所示。

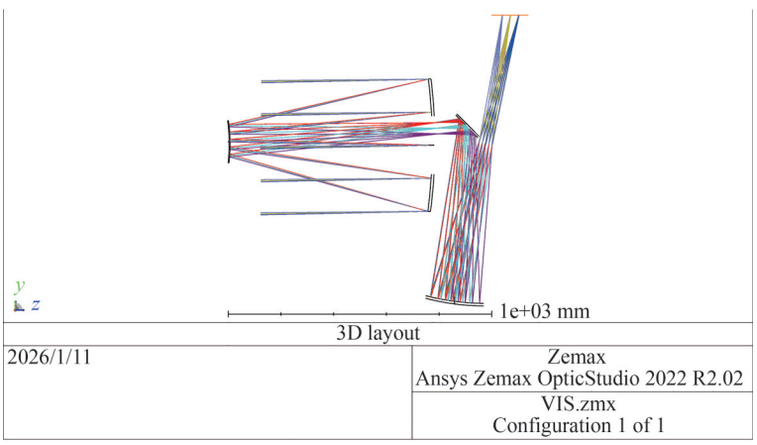



图6 可见光部分光学布局

Fig. 6 Optical layout of visible part

**表4 可见光分系统结构参数**

**Table 4 Structural parameters of visible light subsystem**

| Parameter | Surface type | Radius/mm | Thickness/mm | Conic | 4th | 6th | Tilt angle |
|---|---|---|---|---|---|---|---|
| M1 | Quadradic | －1 984.504 8 | －767.038 2 | －0.938 7 | — | — | — |
| M2 | Quadradic | －627.077 1 | 969.477 3 | －2.562 6 | — | — | — |
| Fold_1 | Plane | Infinity | －600 | — | — | — | 45° |
| M3 | Asphere | 903.506 6 | 1 093.132 4 | －1.002 3 | $9.984\,5\times10^{-11}$ | $4.362\,4\times10^{-17}$ | — |
| Image | — | — | — | — | — | — | — |

光学系统的成像质量用点列图和调制传递函数进行评估。如图7所示，光学系统MTF接近衍射极限，在71.43 lp/mm的奈奎斯特采样频率处各视场的MTF值均大于0.26。如图8所示，各视场弥散斑均方根

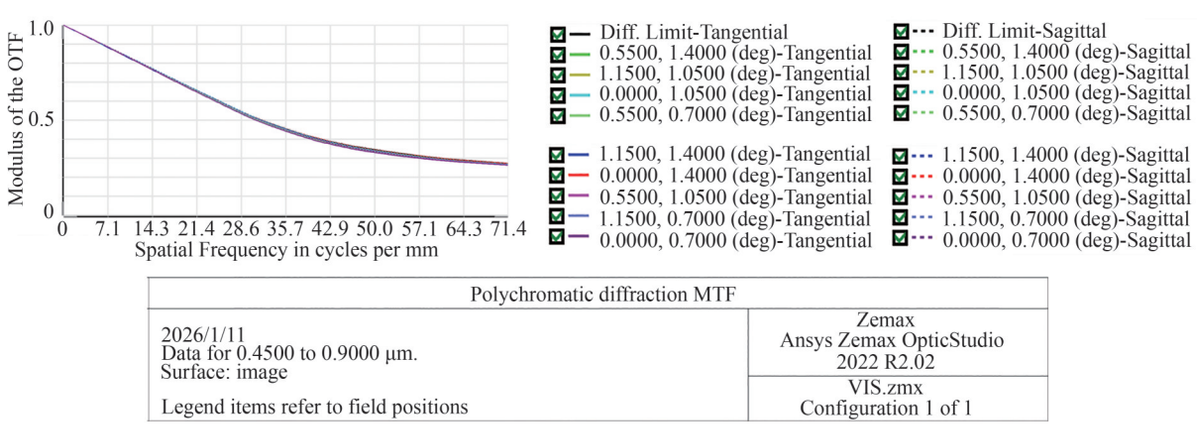
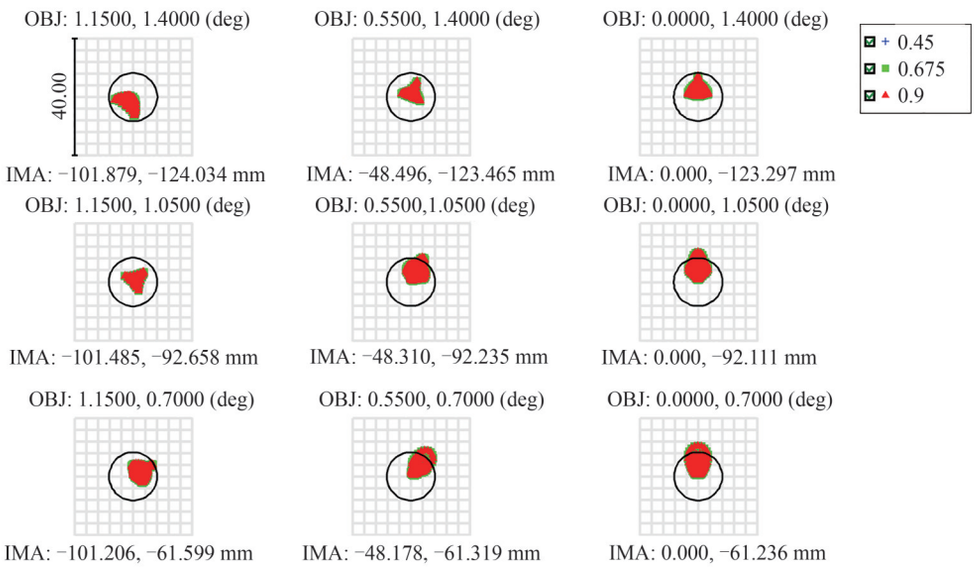



图7 可见光分系统的调制传递函数曲线

Fig. 7 Modulation transfer function of visible part

（Root Mean Square，RMS）半径均不大于5 μm，小于艾利斑尺寸大小。如图9所示，系统的最大畸变值为1.274 0%，出现在边缘视场（1.15°，1.4°）处。

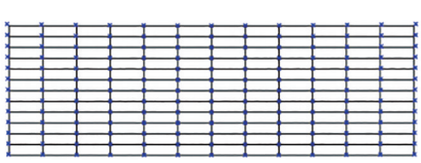



Surface: IMA

| Spot diagram | |
|---|---|
| 2026/1/11<br>Units are μm. Airy radius: 8.235 μm. Legend items refer to wavelengths<br>Field 1 2 3 4 5 6 7 8 9<br>RMS radius 3.276 2.393 3.189 2.013 4.400 4.784 3.560 4.911 4.708<br>GEO radius 6.421 5.812 7.237 4.983 9.377 10.219 7.869 10.667 10.474<br>Scale bar：40 Reference : chief ray | Zemax<br>Ansys zemax OpticStudio 2022 R2.02<br>VIS.zmx<br>Configuration 1 of 1 |

图8　可见光分系统的点列图

Fig. 8　Point plot of visible part



| | |
|---|---|
| 2026/1/11<br>Field: 2.3000 w 0.7000 h degrees<br>Image: 201.77 w 62.01 h millimeters<br>Maximum distortion: 1.2740% SMIA TV distortion: 0.0000%<br>Scale: 1.000X, wavelength: 0.6750 μm | Zemax<br>Ansys Zemax OpticStudio<br>2022 R2.02<br>VIS.zmx<br>Configuration 1 of 1 |

图9　可见光分系统的畸变网格

Fig. 9　Distortion grid of visible part

### 3.2　中波红外分系统

中波红外分系统与可见光分系统共用前端三反的主次镜结构，后端通过折轴镜2将光线引入离轴TMA结构中校正像差。为了避免折轴镜2对可见光分系统产生光线遮拦，一次像面到折轴镜2的距离应不小于280 mm。

利用光学设计软件计算出前端主次镜结构的焦距约为3 525 mm，意味着后端的离轴校正镜组的放大率大小约为0.426才将该值压缩到1 500 mm。通过合理设置镜面放大率和镜间遮拦比求解同轴三反的初始结构，并初步通过将离轴TMA结构的光瞳在$Y$方向上偏置200 mm来消除光线在同轴三反系统的中心遮拦。

由于所设计的系统视场偏大，仅仅通过光瞳偏置无法很好地校正系统像差，故分别将折轴镜后的三个反射镜在$Y$方向上的偏心量作为变量，同时将反射镜的面型由二次曲面升级为关于$YOZ$面对称的$XY$多项式自由曲面（仅含$X$的偶次项），并逐步增加面型的阶数进行优化[12]。在优化过程中，可以通过光线追迹结

果获取镜面边缘坐标，再根据点线关系消除离轴TMA结构的光线遮拦。由于光学设计软件中无法同时设置入瞳与出瞳，在设计过程中，入瞳位置处于前端同轴三反主镜上，要实现100%冷阑效率，需将所有视场的边缘光线在冷阑位置重合，并严格约束出瞳大小与冷阑尺寸匹配[13]，同时还需控制中心光线与冷阑面垂直。最终设计结果如图10所示，结构参数如表5所示。离轴TMA结构均采用基本偏心，无倾斜量，三个自由曲面的最高阶次均不超过7。

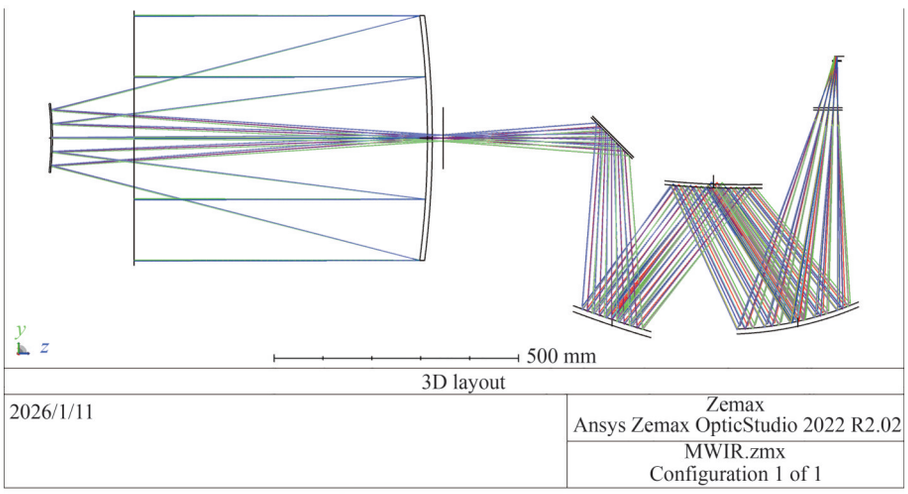



图10 中波红外部分光学布局

Fig. 10 Optical layout of MWIR part

**表5 中波红外分系统结构参数**

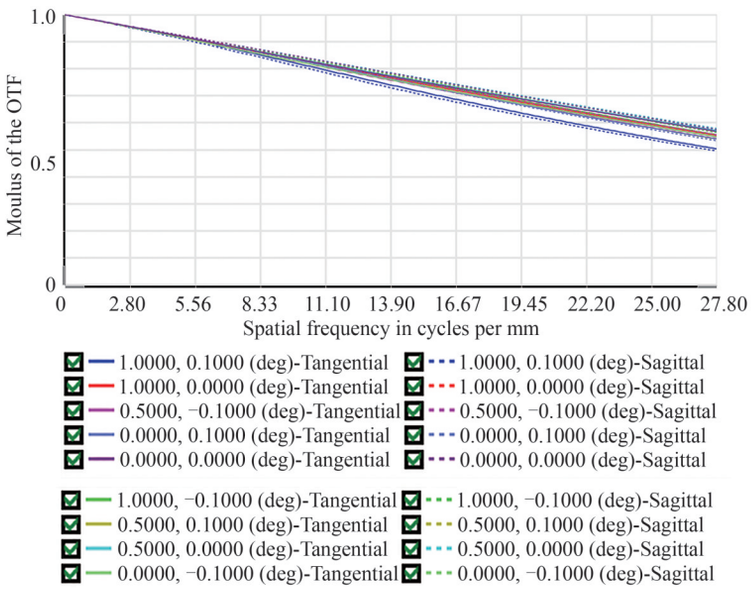
**Table 5 Structural parameters of MWIR part**

| Parameter | Surface type | Radius/mm | Thickness/mm | Conic | *Y* decenter/mm | Tilt angle |
|---|---|---|---|---|---|---|
| M1 | — | — | — | — | — | — |
| M2 | — | — | 1 143.618 9 | — | — | — |
| Fold_2 | Plane | Infinity | −432.860 2 | | — | 45° |
| TMA_1 | *XY* polynomial | 1 711.107 9 | 329.991 2 | 2.798 7 | −221.082 6 | — |
| TMA_2 | *XY* polynomial | 275.135 7 | −240.093 3 | −1.132 3 | −87.426 7 | — |
| TMA_3 | *XY* polynomial | 295.432 1 | 400.044 3 | −1.307 8 | −182.297 7 | — |
| Window glass | — | Infinity | 5 | — | — | — |
| | — | Infinity | 15 | — | — | — |
| Cold stop | — | Infinity | 80 | — | — | — |
| Filter | — | Infinity | 1 | — | — | — |
| | — | Infinity | 9 | — | — | — |
| Image | — | — | — | — | — | — |

如图11所示，中波红外分系统MTF接近衍射极限，在27.78 lp/mm的奈奎斯特采样频率处各视场的MTF值均大于0.5。如图12所示，各视场下弥散斑均方根(RMS)半径最大为9.9 μm，小于艾利斑尺寸大小。如图13所示，系统最大相对畸变量为−0.833 0%，畸变得到良好校正。

根据自由曲面面型参数通过Matlab仿真得到三个*XY*多项式自由曲面的二维矢高图，如图14。

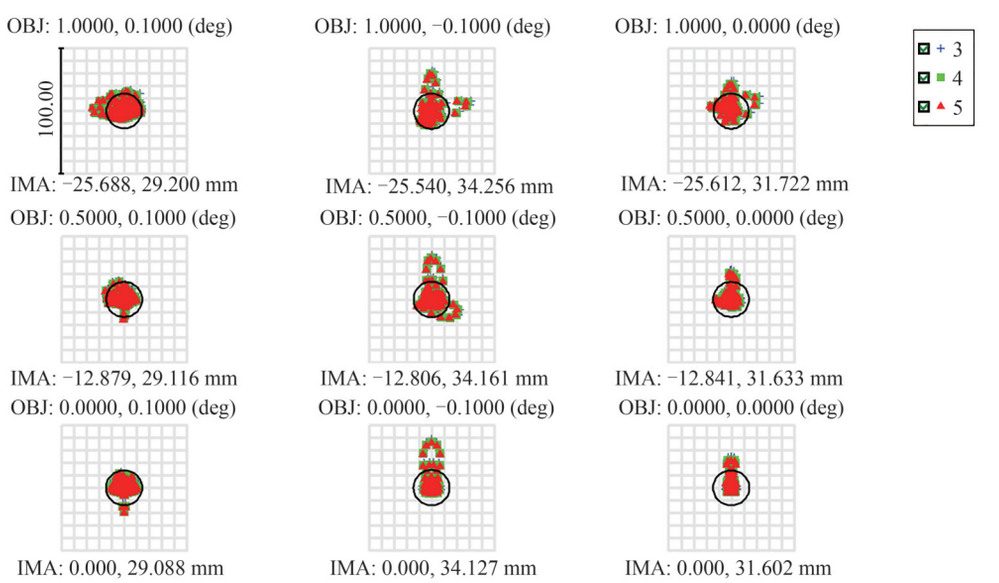
自由曲面的加工与检测通常采用非球面的方式，依据自由曲面和最佳非球面的偏离量来进行加工，该偏离量的最大值决定了自由曲面的加工及检测难度[14]。针对本文的自由曲面计算出的自由曲面与最佳非球面的矢高差如图15所示，三个自由曲面的最大偏离量不超过65 μm，加工检测难度不大。




| Polychromatic diffraction MTF | |
|---|---|
| 2026/1/11<br>Data for 3.0000 to 5.0000 μm.<br>Surface: image<br><br>Legend items refer to field positions | Zemax<br>Ansys Zemax OpticStudio 2022 R2.02<br><br>MWIR.zmx<br>Configuration 1 of 1 |

图 11　中波红外分系统的调制传递函数曲线

Fig. 11　Modulation transfer function of MWIR part




Surface: IMA

| Spot diagram | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 2026/1/11<br>Units are μm.<br>Field:<br>RMS radius:<br>GEO radius:<br>Scale bar: 100 | Airy radius: 14.16 μm. legend items refer to wavelengths<br>1<br>8.590<br>25.537<br>Reference: chief ray | | 2<br>8.651<br>32.430 | 3<br>7.381<br>25.373 | 4<br>6.591<br>16.570 | 5<br>9.163<br>35.312 | 6<br>6.136<br>23.574 | 7<br>6.347<br>20.139 | 8<br>8.545<br>38.604 | 9<br>6.123<br>24.638 |
| | | | | | | | | | Zemax<br>Ansys Zemax OpticStudio 2022 R2.02<br><br>MWIR.zmx<br>Configuration 1 of 1 | |

图 12　中波红外分系统的点列图

Fig. 12　Point plot of MWIR part

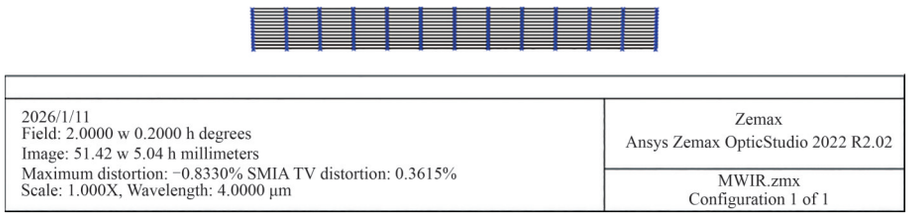



图 13 中波红外分系统的畸变网格

Fig. 13 Distortion grid of MWIR part

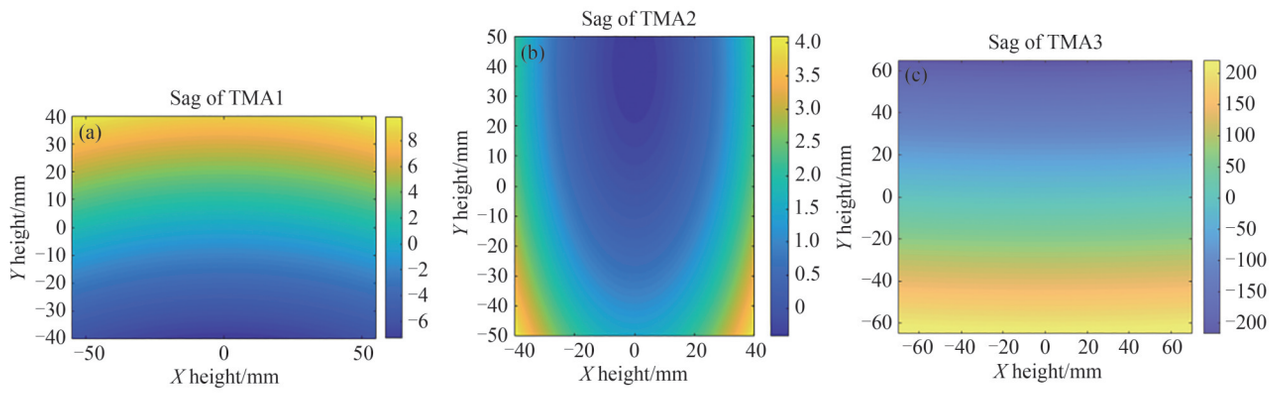



图 14 自由曲面的二维矢高图。(a)TMA1 的二维矢高图;(b) TMA2 的二维矢高图;(c) TMA3 的二维矢高图

Fig. 14 Two-dimensional sag map of a freeform surface. (a) Two-dimensional sag map of TMA1; (b) Two-dimensional sag map of TMA2; (c) Two-dimensional sag map of TMA3

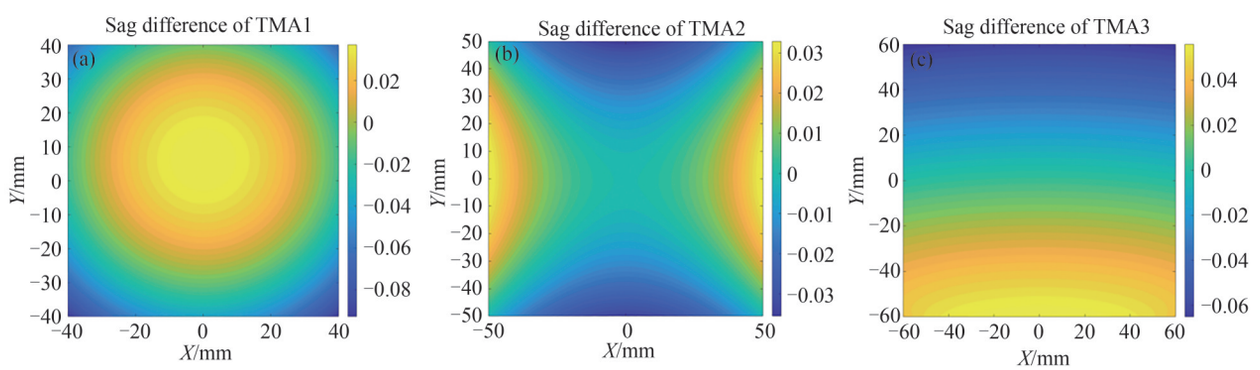



图 15 自由曲面与最佳非球面矢高差。(a) TMA1 与最佳非球面矢高差;(b) TMA2 与最佳非球面矢高差;(c) TMA3 与最佳非球面矢高差

Fig. 15 Sag difference between freeform surface and optimal aspheric surface. (a) Sag difference between TMA1 surface and optimal aspheric surface; (b) Sag difference between TMA2 surface and optimal aspheric surface; (c) Sag difference between TMA3 surface and optimal aspheric surface

### 3.3 系统分析

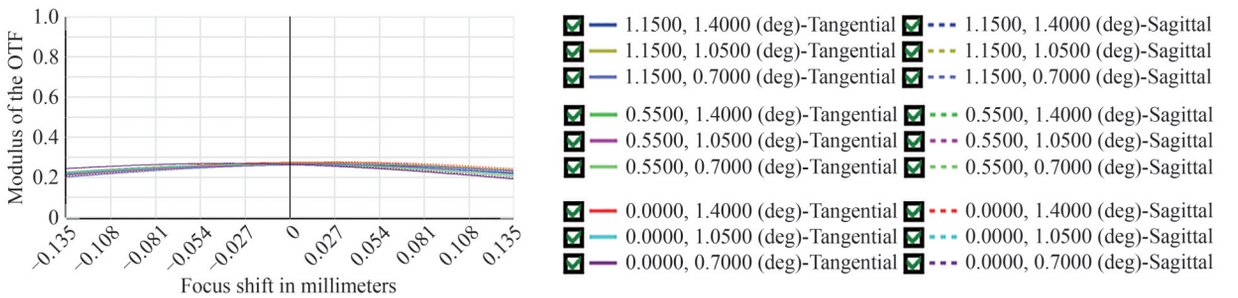
#### 3.3.1 离焦分析

光学系统的焦深公式可以表示为[15]

$$\delta = \pm 2\lambda F^2 \tag{17}$$

式中,$\lambda$取工作波段中心波长,$F$为系统F数。根据式(17)计算可得可见光系统的焦深为±0.135 mm,中波红外系统的焦深为±0.072 mm。利用光学设计软件对两个分系统进行离焦分析,分别得到系统在焦深范围内变化时的MTF曲线,如图16、图17所示。

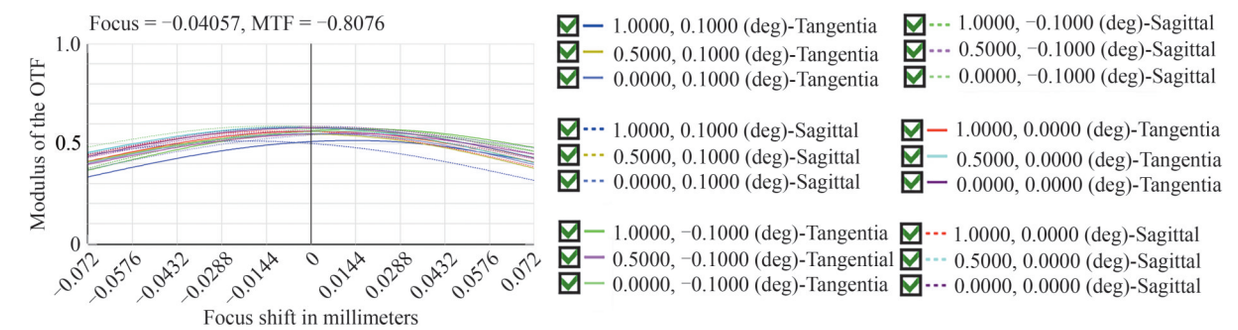
由图16可知,可见光分系统在±0.135 mm焦深范围内变化时,MTF在71.43 lp/mm奈奎斯特频率处优于0.2;由图17可知,中波红外分系统在±0.072 mm焦深范围内变化时,MTF在27.78 lp/mm奈奎斯特频率处优于0.32。两个分系统在焦深范围内成像质量良好。




| Polychromatic diffraction through focus MTF | |
|---|---|
| 2026/1/11<br>Data for 0.4500 to 0.9000 μm.<br>Spatial Frequency: 71.4300 cycles per mm.<br><br>Legend items refer to field positions | Zemax<br>Ansys zemax OpticStudio 2022 R2.02<br><br>VISof.zmx<br>Configuration 1 of 1 |

图 16　可见光分系统离焦 MTF

Fig. 16　Off-focus MTF of visible part




| Polychromatic diffraction through focus MTF | |
|---|---|
| 2026/1/11<br>Data for 3.0000 to 5.0000 μm.<br>Spatial frequency: 27.7800 cycles per mm.<br><br>Legend items refer to field positions | Zemax<br>Ansys Zemax OpticStudio 2022 R2.02<br><br>MWIRof.zmx<br>Configuration 1 of 1 |

图 17　中波红外分系统离焦 MTF

Fig. 17　Off-focus MTF of MWIR part

### 3.3.2　公差分析

在对光学系统开展加工与装配前，需对其核心部件的公差进行合理分配，从而能在现有工程条件下，以较低成本达成良好的成像质量[16]。系统公差涵盖透镜材料公差、加工公差和装配公差，鉴于现有加工装配条件，同时基于以往反射系统的公差分配，给出相对宽松的公差值，如表 6 所示，以系统后截距为补偿量，利用光学设计软件进行公差分析。

**表 6　公差分配**

**Table 6　Allocation of tolerances**

| Tolerance type | Tolerance value |
|---|---|
| Lens thickness and air gap | ±0.02 mm |
| Lens surface tilt | ±0.000 5 rad |
| Lens surface decentering | ±0.02 mm |
| Lens local aperture | 0.2 |
| Lens aperture | 2 |
| Lens refractive index | ±0.001 |
| Abbe number of lens | ±0.002 |
| Conic constant (quadric) | ±0.001 |
| Curvature radius (quadric) | ±0.02 |

为了分析公差对系统最终成像结果的影响，依据公差分配对系统进行200次蒙特卡洛分析，得到表7、表8的分析结果。如表7所示，根据初始公差分配情况，可见光系统经过蒙特卡洛分析后，MTF值在其奈奎斯特频率处有90%的概率优于0.22，如表8所示，中波红外系统MTF值在其奈奎斯特频率处有90%概率优于0.47，公差分析结果表明系统有较好的容差特性。

**表7 可见光系统系统蒙特卡洛分析结果**

**Table 7 Results of Monte Carlo analysis for visible part**

| Probability | MTF |
|---|---|
| 90% | 0.217 965 04 |
| 80% | 0.242 745 39 |
| 50% | 0.290 565 76 |
| 20% | 0.318 640 02 |
| 10% | 0.335 669 76 |

**表8 中波红外系统系统蒙特卡洛分析结果**

**Table 8 Results of Monte Carlo analysis for MWIR part**

| Probability | MTF |
|---|---|
| 90% | 0.473 278 94 |
| 80% | 0.476 327 93 |
| 50% | 0.494 725 32 |
| 20% | 0.507 410 12 |
| 10% | 0.519 677 18 |

### 3.4 一体化光学系统

两光路组合后的光学系统如图18所示，系统总长约为1.6 m，高度约为1.1 m。整个系统只用了8个反射元件（其中2个折轴镜均为平面反射镜），可实现可见光和中波红外双波段同时成像，且光学性能均满足表2设计指标。

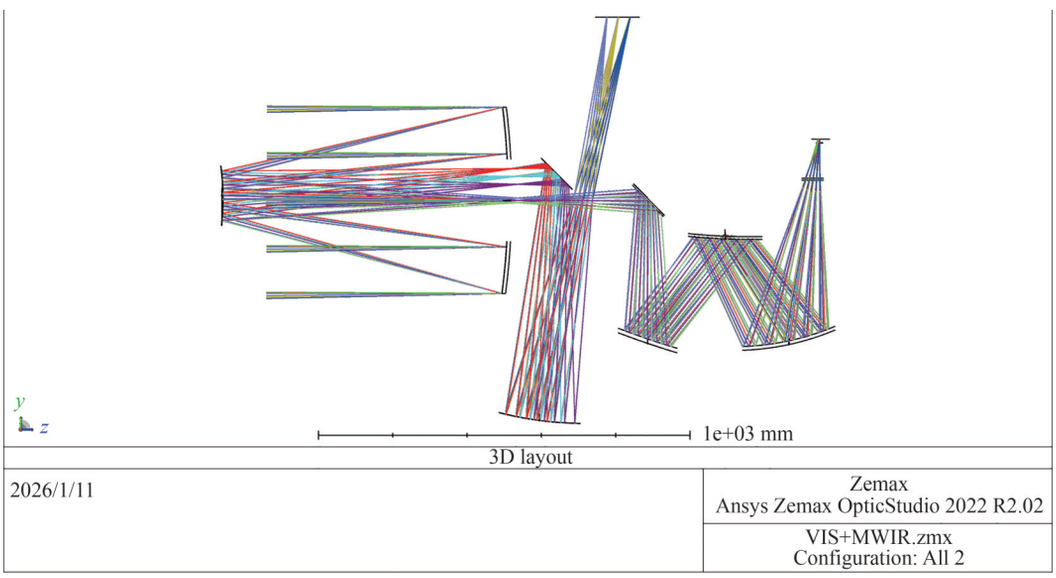



图18 可见红外一体化光学布局

Fig. 18 Visible-infrared integrated optical layout

## 4 结论

基于近轴光学理论计算并设计了一种可见光与中波红外一体化的反射式光学系统，无需考虑透射式元件导致的二级光谱问题。在装调方面，可见光分系统属于偏瞳使用的共轴三反系统，镜面中心均在光轴上，但三镜到像面的光路太长，可以考虑在三镜后增加平面反射镜压缩距离，进一步减小系统体积；中波红外分系统前端共用可见光分系统的主次镜，后端接入光瞳偏置的离轴TMA，后端的三个镜子之间仅有$Y$方向的偏心，无倾斜。在系统性能方面，可见光分系统成像质量接近衍射极限，视场相对较大且无遮拦，能满足宽幅相机的设计指标；中波红外分系统考虑到冷屏匹配问题，设计结果同时也满足成像系统使用要求。

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# Design of Visible-infrared Integrated Wide-width Space Optical System

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**Abstract**: In recent years, the development direction of space optical cameras in various countries can be summarized as high resolution, large aperture, and multi-spectral. Compared with single-band visible light imaging optical systems, visible-infrared dual-band optical systems have advantages. Infrared light can penetrate certain objects to obtain information such as their internal structure and heat distribution. At the same time, infrared optical systems have stronger concealment. When combined with visible light systems for imaging and detection of space targets, it can not only acquire rich spectral information across different bands but also achieve all-weather, round-the-clock space remote sensing detection and imaging. Space optical systems can be divided into three design types: refractive, catadioptric, and reflective. Refractive systems have no light obstruction and are easy to assemble, allowing optical design for large fields of view; however, it is difficult to achieve lightweight designs for large-aperture optical systems. Catadioptric systems can achieve large-aperture optical designs, but for systems with large fields of view and infrared detection requirements, the few available infrared refractive materials have low transmittance, poor thermal stability, and high prices. Additionally, lens chromatic aberration is difficult to correct, lens aperture sizes are limited, making it challenging to widely apply in space exploration. Reflective systems combine advantages such as large aperture, wide field of view, long focal length, broad wavelength range, and lightweight design. Currently, most visible-infrared integrated optical systems adopt catadioptric designs, requiring multiple optical elements to correct chromatic aberration, and are unable to meet design requirements for long focal length, large aperture, wide field of view, and lightweight simultaneously.

This paper adopts a reflective system structure. The initial structure of the system is solved based on paraxial aberration theory, and optimized design is carried out using optical design software, with reasonable field-of-view settings to avoid light obstruction. Considering factors such as aperture, volume, weight, and environmental adaptability of space cameras, the optical system adopts an integrated design scheme of shared aperture with separate fields of view. The visible light and mid-wave infrared bands share the front-end coaxial three-mirror primary and secondary mirrors. At the rear end, the fields of view are split and redirected via two fold mirrors into the visible light imaging path and the mid-wave infrared imaging path, achieving simultaneous dual-band imaging. To minimize the aperture size of the primary mirror, the first image plane is located near the center of the primary mirror. For the visible light subsystem, a coaxial three-mirror structure is used for an off-axis field; for the mid-wave infrared subsystem, the front end consists of the primary and secondary mirrors of the visible light subsystem, and the light path enters the rear three-mirror anastigmatic off-axis structure via a fold mirror. Regarding detector selection, the optical system uses a visible light TDI-CMOS with 12 288×128 pixels, 7 μm pixel size, and three identical detectors arranged in a 'zigzag' pattern on the image plane, utilizing only a part of the non-vignetting region of the image plane, achieving a 36 000×128 pixel array and 25.2 km swath width. The mid-wave infrared subsystem uses a large-format cooled infrared detector with 3 000×2 500 pixels and 18 μm pixel size. This detector consists of a glass window, filter, cold stop, and focal plane, with a distance of 90 mm between the focal plane and the cold stop.

The working wavelength range of the visible light subsystem is 0.45~0.9 μm, with a focal length of 5 m, an F-number of 10, and a field of view of 0.7°×2.3°. At an orbital position of 500 km, the imaging swath width is greater than 20 km. The working wavelength range of the mid-wave infrared subsystem is 3~5 μm, with a focal length of 1.5 m, a field of view of 0.2°×2°, an F-number of 3, and 100% cold stop efficiency. The two optical systems share the primary and secondary mirrors of a coaxial three-reflector system at the front end, achieving simultaneous dual-band operation through field-of-view segmentation. The entire system uses eight reflective elements. To meet system specifications and correct aberrations, the three mirrors of the front-end three-reflector system use 6th-order aspheric surfaces, while the three

mirrors of the mid-wave infrared system adopt freeform surfaces. The imaging quality of the visible and mid-wave infrared subsystems is evaluated using spot diagrams, modulation transfer functions, and distortion assessments. For both subsystems, the spot diagram RMS radii are smaller than the Airy disk radius, the MTF values at the Nyquist frequency are close to their respective diffraction limits, and distortion is controlled within an acceptable range.

A reflective optical system integrating visible and mid-wave infrared light was designed based on paraxial optical theory. This study also verifies the manufacturability of freeform surfaces in engineering practice. The maximum deviation between the freeform surfaces and the optimal aspheric surfaces does not exceed 65 μm, meeting current processing standards. A defocus analysis indicates that the system maintains good imaging quality within the depth of focus. Finally, considering current lens fabrication and assembly conditions, and based on tolerance allocations from previous reflective systems, a tolerance analysis was conducted using the system′s rear intercept as a compensating quantity. The results show that the system has good tolerance performance. In summary, the designed optical system meets the initial design specifications, does not require consideration of secondary spectral issues from transmissive elements, affords good imaging quality, and possesses practical engineering feasibility.

**Key words**: Optical design; Swath altimeter; Integrated design; Space camera; Off-axis three mirrors

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