

## 光学学报

## 基于反射点源的光学遥感卫星像点提取及精度验证

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**摘要** 定标自动化水平与像点提取精度是光学遥感卫星在轨几何定标效率及精度提升的关键因素。提出一种以轻小型、自动化的反射点源为地面控制点的高精度像点提取方法,匹配参数化模型拟合获取点源像点坐标,并利用有理函数模型进行精度验证。在轨实验结果初步表明,与模板匹配法等常规方法相比,反射点源法提取的像点坐标精度优于0.05 pixel,经有理函数模型验证,像点定位精度优于0.05 pixel。反射点源不仅能够实现高精度的像点提取,还能够实现光学遥感卫星在轨几何辐射综合定标,对提高我国遥感测绘精度和定标自动化水平有重要意义。

**关键词** 几何定标; 像点提取; 反射点源; 精度验证; 有理函数模型

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## 1 引言

光学遥感卫星作为全球空间信息获取的重要工具,在自然资源调查和监测、交通道路规划、基础测绘等领域发挥着关键作用,对推动经济发展有重要意义<sup>[1]</sup>。然而,卫星发射和在轨运行期间会受到空间环境和各种干扰力的影响,导致卫星成像系统的实验室检校参数发生变化,从而增大成像模型定位误差,影响光学遥感卫星产品量化应用。因此,定期或不定期对光学遥感卫星进行在轨几何定标、获取高精度的内外方位元素,成为决定卫星影像定位精度的重要因素<sup>[2-3]</sup>。

光学遥感卫星在轨几何定标主要涉及地面控制点、卫星姿轨数据及控制点影像像点等数据源。具有良好几何特征的自然地物或人工靶标作为地面控制点为卫星相机提供了稳定的参考坐标和校准数据,在卫星影像的校正和量化应用中起到了重要作用。控制点及其像点坐标作为相机几何定标的输入参数,其测量和提取精度直接影响到卫星相机内外方位元素检校的准确性和精度。当前,地面控制点和星上位姿的测量精度已达到 cm 甚至 mm 级别,但是控制点影像的像点提取主要依赖人工选点或像点测量算法。人工选点依靠主观判断,误差可达 0.5~1.0 pixel<sup>[4-5]</sup>;测量算法一般误差也在 0.3 pixel<sup>[6-7]</sup>。航空遥感制作的高精度数字正射模型(DOM)和数字高程模型(DEM)利用影像匹配算法可以获取大量的控制点和像点坐标,但是航空

影像和卫星影像存在异源与时差等问题,使得控制点影像像点提取精度无法与地面测量精度相匹配<sup>[8]</sup>。恒星作为典型的点源目标,几何形态好且星图像点提取精度高,理论上可以实现快速自动的几何定标,但是对卫星平台的机动能力要求较高,目前尚未实际应用<sup>[9-11]</sup>。因此,随着在轨运行光学遥感卫星数量的不断增加和卫星影像分辨率的不断提升,在轨几何定标的自动化和控制点影像像点提取的精度提升对于提高卫星相机参数检校与影像量化应用来说具有重要意义。

本文提出以轻小型、自动化的类恒星源-反射点源作为地面控制点,匹配点源影像像点提取算法,结合基于反射点源的光学遥感卫星在轨定标实验与像点提取精度验证,以期提高光学遥感卫星像点提取精度,进而提高光学遥感卫星在轨几何定标精度与遥感影像定位精度。

## 2 基本原理

### 2.1 像点提取

反射点源目标能够将入射的太阳光线反射至卫星相机,从而形成点激冲辐射。经过光学追迹与模拟分析,相机接收的反射光斑仅为反射点源镜面上 cm 甚至 mm 量级的小区域,具有相对于背景环境高得多的亮度、相对于相机分辨率小得多的尺寸,可以作为类恒星源目标<sup>[12]</sup>。由光学原理与傅里叶光学可知,光学遥感卫星成像系统可作为线性位移不变系统,因此以反

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射点源作为输入的物像关系可表示为

$$g(x, y) = f(x, y) * h(x, y) + b = h(x, y) + b, \quad (1)$$

式中:  $g(x, y)$  为卫星影像;  $f(x, y)$  为成像目标;  $h(x, y)$  为成像系统的点扩散函数;  $*$  为卷积符号;  $b$  为背景值。

恒星作为典型的点源目标, 在星相机获取星点影像后, 通常以高斯函数模拟成像系统的点扩散函数, 从而还原目标真实情况或者进行目标中心定位<sup>[13-14]</sup>。反射点源作为类恒星源, 其成像特性和恒星一致。结合地面点源成像实验, 可采用近似高斯模型来表征光学遥感卫星成像系统的点扩散特性, 具体表示为

$$g(x, y) = k \exp \left[ -\frac{(x-x_0)^2}{2\sigma^2} - \frac{(y-y_0)^2}{2\zeta^2} \right] + b, \quad (2)$$

式中:  $k$  为系数因子;  $(x_0, y_0)$  为点源目标中心像点坐标;  $\sigma, \zeta$  为系统成像时横向和纵向的标准偏差。

式(2)共有  $\mathbf{X} = [k \ b \ x_0 \ y_0 \ \sigma \ \zeta]$  6 个参数, 对式(2)进行泰勒级数展开并进行线性化, 得到整体参数解算的误差方程, 表示为

$$\mathbf{V} = \mathbf{A}\mathbf{C} - \mathbf{L}, \quad (3)$$

式中:  $\mathbf{A}$  为误差方程式系数构成的系数矩阵;  $\mathbf{C}$  为  $\mathbf{X}$  的改正数构成的增量矩阵;  $\mathbf{L}$  表示点源像素值和预估像素值之间的差值向量。它们各自表示为

$$\begin{cases} \mathbf{C}^T = [dk \ db \ dx_0 \ dy_0 \ d\sigma \ d\zeta] \\ \mathbf{A} = \begin{bmatrix} \frac{\partial g}{\partial k} & \frac{\partial g}{\partial b} & \frac{\partial g}{\partial x_0} & \frac{\partial g}{\partial y_0} & \frac{\partial g}{\partial \sigma} & \frac{\partial g}{\partial \zeta} \end{bmatrix}, \\ \mathbf{L} = \mathbf{g} - \mathbf{g}' \end{cases}, \quad (4)$$

式中,  $\mathbf{g}'$  为当前参数计算下的像素估计值。

根据光学遥感卫星点源成像实验与仿真分析, 在传感器点扩散函数的作用下, 反射点源影像一般可扩散至 3~7 pixel 之间。选取反射点源遥感影像中心 5 pixel × 5 pixel 范围内的响应值进行参数解算, 可列写 25 个方程, 并根据最小二乘平差原理求解参数的改正数  $\mathbf{C}$ 。根据计算结果, 在提供参数初值的情况下进行循环迭代, 直至参数变化稳定, 得到模型参数  $\mathbf{X}$ , 进而获得点源像点坐标。上述过程具体表示为

$$\mathbf{C} = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{L}, \quad (5)$$

$$\mathbf{X}^{\text{new}} = \mathbf{X}^{\text{old}} + \mathbf{C}. \quad (6)$$

## 2.2 精度验证

利用有理函数模型(RFM)进行反射点源像点提取精度验证, 其在数学意义上是对严格成像模型(RPM)的最佳拟合<sup>[15]</sup>。RFM 综合考虑了多个因素对结果的影响, 以综合性建模的方式实现了准确的目标定位, 其结构形式简单, 便于使用, 具体定义为

$$\begin{cases} l_n = \frac{\sum_{i=0}^3 \sum_{j=0}^3 \sum_{k=0}^3 a_{1ijk} U^i V^j W^k}{\sum_{i=0}^3 \sum_{j=0}^3 \sum_{k=0}^3 a_{2ijk} U^i V^j W^k}, \\ s_n = \frac{\sum_{i=0}^3 \sum_{j=0}^3 \sum_{k=0}^3 a_{3ijk} U^i V^j W^k}{\sum_{i=0}^3 \sum_{j=0}^3 \sum_{k=0}^3 a_{4ijk} U^i V^j W^k} \end{cases}, \quad (7)$$

式中:  $a_{1ijk}, a_{2ijk}, a_{3ijk}, a_{4ijk}$  ( $i=1, 2, 3, j=1, 2, 3, k=1, 2, 3$ ) 为有理多项式系数(RPC);  $(l_n, s_n)$  和  $(U, V, W)$  分别为像方和物方的正则化坐标。正则化公式表示为

$$\begin{cases} l_n = \frac{l - L_0}{L_1}, \quad s_n = \frac{s - S_0}{S_1}, \\ U = \frac{B - X_0}{X_1}, \quad V = \frac{L - Y_0}{Y_1}, \quad W = \frac{H - Z_0}{Z_1} \end{cases}, \quad (8)$$

式中:  $(l, s)$  和  $(L, B, H)$  分别为像方行列坐标和物方经纬度高程坐标;  $S_0, L_0, X_0, Y_0, Z_0$  为正则化平移参数;  $S_1, L_1, X_1, Y_1, Z_1$  为正则化尺度参数。

经传感器校正影像产品生成的 RFM 模型系数直接定位误差较大, 但是误差呈现出一定的系统性<sup>[16-17]</sup>。研究发现, 在 RFM 的像方空间附加仿射变换模型对定位误差的补偿效果最好<sup>[18-19]</sup>, 因此采用此方式对反射点源像点提取精度展开验证。具体表示为

$$\begin{cases} x = l + \Delta l \\ y = s + \Delta s \end{cases}, \quad (9)$$

$$\begin{cases} \Delta l = a_0 + a_1 l + a_2 s \\ \Delta s = b_0 + b_1 l + b_2 s \end{cases}, \quad (10)$$

式中:  $(x, y)$  为控制点对应影像中的像点量测坐标;  $(l, s)$  为 RFM 模型利用地面控制点坐标计算的影像行列坐标。

利用平差后的模型对影像上测量的像点展开验证, 即

$$\begin{cases} \Delta x = x - (l + \Delta l) \\ \Delta y = y - (s + \Delta s) \end{cases}, \quad (11)$$

式中:  $\Delta x, \Delta y$  为光学遥感卫星飞行方向和探测器线阵方向上的定位误差。

## 3 实验数据处理

光学遥感卫星基于反射点源目标的像点提取及精度验证实验如图 1 所示。分别沿卫星的飞行方向与电荷耦合器件(CCD)线阵方向集中布设 18 个反射点源设备(从右下向上, S 形顺序, 依次标记为  $P_1, P_2, P_3, \dots, P_{17}, P_{18}$ ), 相邻点源目标间距为 20 m(避免反射点源影像之间出现重叠)。专业测绘人员采用 RTK-GPS 对反射点源阵列的几何位置进行高精度测量, 以获取地面控制点坐标。

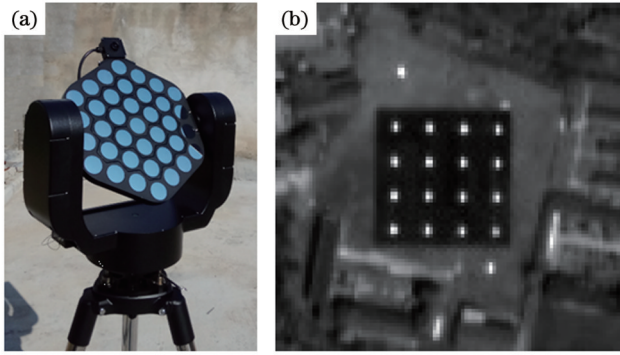


图1 在轨验证实验。(a)反射点源;(b)反射点源影像  
Fig. 1 In orbit verification experiment. (a) Reflected point source; (b) image of reflected point source

反射点源由多个组件构成,包括反射镜组件、姿态调控组件、电控系统和太阳敏感器等。其中:反射镜组件的作用是将入射的太阳光线反射至卫星相机,形成点激冲辐射。通过调整反射镜的数量来调谐反射的能量,以适应不同分辨率光学遥感卫星相机的动态范围,使得传感器响应高端且不饱和。电控系统根据卫星过顶预报参数,通过姿态调控组件调整反射镜组件姿态,实现卫星过顶成像时的光路对准,从而将太阳光反射至卫星相机。利用太阳敏感器进行太阳运动轨迹的连续跟踪观测,标定反射点源目标的系统误差及空间指向(精度优于 $0.1^\circ$ )。

通过分析反射点源目标的遥感影像可知,点源反射的太阳光束在光学遥感卫星相机成像系统点扩散函数作用下,集中分布在 $3\text{ pixel} \times 3\text{ pixel}$ 范围内,如图2所示。根据像点提取原理,选择点源目标影像 $5\text{ pixel} \times$

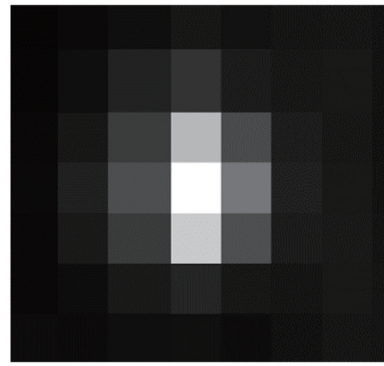


图2 反射点源影像  
Fig. 2 Image of reflected point source

$5\text{ pixel}$ 内的响应值进行参数化拟合,如图3所示,即可获取反射点源目标影像的像点坐标,如表1所示。

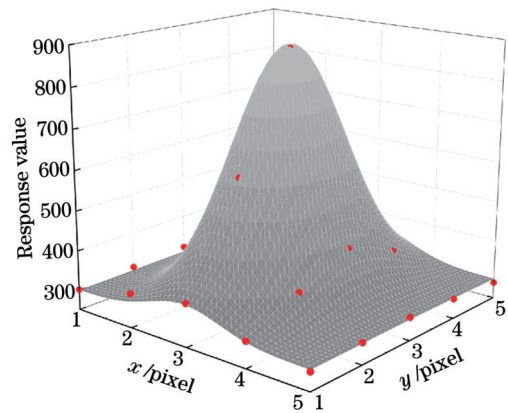


图3 曲面拟合  
Fig. 3 Surface fitting

表1 反射点源像点坐标

Table 1 Pixel coordinates of reflected point source image

Position	$x_0/\text{pixel}$	$y_0/\text{pixel}$	Position	$x_0/\text{pixel}$	$y_0/\text{pixel}$
$P_1$	12201.984	10136.056	$P_{10}$	12184.156	10125.470
$P_2$	12203.410	10125.823	$P_{11}$	12184.315	10115.786
$P_3$	12203.768	10116.189	$P_{12}$	12184.472	10106.093
$P_4$	12203.975	10106.509	$P_{13}$	12184.630	10096.376
$P_5$	12204.124	10096.858	$P_{14}$	12176.634	10080.741
$P_6$	12194.434	10096.645	$P_{15}$	12174.948	10096.056
$P_7$	12194.233	10106.227	$P_{16}$	12174.764	10105.925
$P_8$	12194.083	10116.030	$P_{17}$	12174.549	10115.615
$P_9$	12193.865	10125.718	$P_{18}$	12174.391	10125.415

光学遥感卫星影像经传感器校正,并附带有RFM参数文件。根据反射点源法像点提取原理拟合得到点源像点坐标和有理函数模型的像方投影坐标,对仿射变换模型参数进行平差,然后将仿射变换模型附加在有理函数模型的像方坐标上以获取平差后的像方坐

标,结果如表2所示。进而将该坐标值与反射点源法像点提取值进行比较得到定位误差,如图4所示,定位精度如表3所示,其中:RMSE表示每个方向上的均方根误差;RMSE-DM表示去除最大值后每个方向上的均方根误差。可以看出,光学遥感卫星飞行方向和探

表 2 平差后的定位坐标  
Table 2 Positioning coordinates after adjustment

Position	$x_0$ /pixel	$y_0$ /pixel	Position	$x_0$ /pixel	$y_0$ /pixel
$P_1$	12201.990	10136.072	$P_{10}$	12184.133	10125.507
$P_2$	12203.569	10125.884	$P_{11}$	12184.298	10115.767
$P_3$	12203.737	10116.175	$P_{12}$	12184.488	10106.096
$P_4$	12203.958	10106.499	$P_{13}$	12184.653	10096.398
$P_5$	12204.116	10096.788	$P_{14}$	12176.673	10080.708
$P_6$	12194.402	10096.628	$P_{15}$	12174.950	10096.182
$P_7$	12194.210	10106.288	$P_{16}$	12174.755	10105.895
$P_8$	12194.029	10116.005	$P_{17}$	12174.584	10115.609
$P_9$	12193.808	10125.705	$P_{18}$	12174.380	10125.325

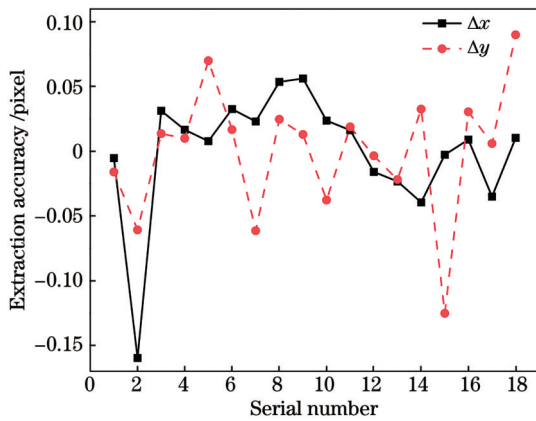


图 4 像点提取精度

Fig. 4 Pixel extraction accuracy

表 3 点源法像点提取精度验证

Table 3 Verification of the pixel extraction accuracy using the point source method

Direction /pixel	RMSE	RMSE-DM
$\Delta x$	0.0466	0.0291
$\Delta y$	0.0483	0.0377
Plane	0.0671	0.0476

测器线阵方向上的均方根误差优于 0.05 pixel, 平面精度优于 0.07 pixel, 在去除最大值  $P_2$ 、 $P_{15}$  后两个方向上的均方根误差优于 0.04 pixel, 平面精度优于 0.05 pixel。实验结果初步表明, 反射点源能够实现高精度的遥感影像像点提取, 满足光学遥感卫星几何定标对于高精度靶标的应用需求。

## 4 分析与讨论

在光学遥感卫星反射点源像点提取方法及精度验证中, 以“小”而“亮”、类恒星的自动化反射点源目标作为地面控制点, 匹配模型拟合算法获取高精度的像点

坐标, 进而以有理函数模型验证点源像点提取精度, 不仅要考虑反射点源结构形式与影像特征, 还要对像点提取算法准确性等进行分析讨论。

反射点源反射至卫星入瞳的光斑、辐射亮度远高于地面背景, 且空间尺度相对卫星相机分辨率小得多。相对于 SPOT 卫星的主动式点源 (聚光灯), 反射点源不需要大功率电源供电以及光谱非一致性校正<sup>[20]</sup>; 相对于 IKONOS 等卫星对深空恒星成像, 反射点源不需要卫星平台翻转或姿态调整<sup>[21]</sup>。反射点源目标的数量和反射辐射亮度自主可控, 且其影像信噪比较高, 优于一般恒星影像; 此外, 其能够在光学遥感卫星对地观测状态下进行在轨几何定标, 不存在恒星定标中光谱非一致问题, 且具有较好的几何形态, 可以获取高精度的地面坐标。采用模板匹配法与非线性优化求解法对反射点源法提取的像点坐标 I 进行准确性检验, 其中: 模板匹配法通过计算理想情况下不同相位的模拟影像与点源影像的相关系数, 根据相关系数的最大值确定点源靶标质心的坐标 II; 非线性优化求解法通过拟合成像系统的一维点扩散函数, 进而获取影像像点坐标 III。结果如表 4 所示, 三种方法的像点提取结果较为一致。像点提取结果与均值的差异如表 5 所示, 最大误差为 0.0472 pixel, 优于 0.05 pixel, 展现了光学遥感卫星反射点源像点提取方法的准确性, 像点提取精度优于方形对顶角标志和人工提取自然地物<sup>[6, 22]</sup>。

通过模板匹配法等常规方法验证了反射点源目标的像点提取精度优于 0.05 pixel。进一步结合有理函数模型对反射点源像点提取结果进行精度验证。模板匹配法与非线性优化求解法平差后的定位结果如表 6 所示, 精度验证结果如表 7 所示。去除最大值后, 反射点源法、模板匹配法、非线性优化求解法提取的像点坐标在飞行方向和传感器线阵方向的定位精度优于 0.04 pixel, 平面精度优于 0.05 pixel, 进一步说明反射点源法像点提取的准确性。

表 4 多种方式像点提取结果  
Table 4 Pixel extraction results by multiple methods

Position	II		III	
	$x_0$ /pixel	$y_0$ /pixel	$x_0$ /pixel	$y_0$ /pixel
$P_1$	12201.985	10136.056	12201.967	10136.048
$P_2$	12203.419	10125.823	12203.386	10125.826
$P_3$	12203.763	10116.187	12203.732	10116.196
$P_4$	12203.975	10106.510	12203.948	10106.521
$P_5$	12204.106	10096.854	12204.115	10096.831
$P_6$	12194.439	10096.641	12194.415	10096.641
$P_7$	12194.217	10106.227	12194.229	10106.254
$P_8$	12194.066	10116.025	12194.070	10116.016
$P_9$	12193.874	10125.722	12193.844	10125.727
$P_{10}$	12184.157	10125.470	12184.141	10125.478
$P_{11}$	12184.318	10115.783	12184.312	10115.785
$P_{12}$	12184.470	10106.096	12184.466	10106.107
$P_{13}$	12184.621	10096.379	12184.633	10096.388
$P_{14}$	12176.621	10080.742	12176.648	10080.750
$P_{15}$	12174.955	10096.056	12174.935	10096.027
$P_{16}$	12174.763	10105.924	12174.751	10105.906
$P_{17}$	12174.540	10115.611	12174.546	10115.623
$P_{18}$	12174.369	10125.409	12174.309	10125.433

表 5 像点坐标误差  
Table 5 Errors of pixel coordinate

Position	I		II		III	
	$x_0$ /pixel	$y_0$ /pixel	$x_0$ /pixel	$y_0$ /pixel	$x_0$ /pixel	$y_0$ /pixel
$P_1$	0.0062	0.0025	0.0058	0.0029	-0.0120	-0.0054
$P_2$	0.0144	-0.0010	0.0048	-0.0012	-0.0192	0.0022
$P_3$	0.0085	-0.0036	0.0141	-0.0017	-0.0226	0.0053
$P_4$	0.0088	-0.0031	0.0090	-0.0045	-0.0178	0.0075
$P_5$	-0.0089	0.0063	0.0090	0.0103	-0.0001	-0.0167
$P_6$	0.0098	-0.0012	0.0047	0.0026	-0.0144	-0.0014
$P_7$	-0.0091	-0.0087	0.0063	-0.0090	0.0028	0.0177
$P_8$	-0.0074	0.0017	0.0101	0.0063	-0.0027	-0.0079
$P_9$	0.0130	-0.0002	0.0037	-0.0047	-0.0167	0.0049
$P_{10}$	0.0051	-0.0026	0.0049	-0.0028	-0.0100	0.0055
$P_{11}$	0.0032	-0.0018	-0.0003	0.0017	-0.0030	0.0001
$P_{12}$	0.0003	-0.0028	0.0028	-0.0059	-0.0031	0.0087
$P_{13}$	-0.0068	-0.0022	0.0020	-0.0047	0.0048	0.0070
$P_{14}$	-0.0132	-0.0019	-0.0008	-0.0036	0.0140	0.0055
$P_{15}$	0.0088	0.0093	0.0018	0.0101	-0.0107	-0.0194
$P_{16}$	0.0035	0.0056	0.0051	0.0068	-0.0086	-0.0124
$P_{17}$	-0.0048	-0.0054	0.0039	-0.0011	0.0008	0.0065
$P_{18}$	0.0126	-0.0099	0.0346	-0.0039	-0.0472	0.0138

表 6 常规方法平差后的定位坐标

Table 6 Positioning coordinates after conventional method adjustment

Position	II		III	
	$x_0$ /pixel	$y_0$ /pixel	$x_0$ /pixel	$y_0$ /pixel
$P_1$	12201.990	10136.071	12201.956	10136.077
$P_2$	12203.568	10125.883	12203.543	10125.887
$P_3$	12203.734	10116.175	12203.718	10116.176
$P_4$	12203.955	10106.498	12203.947	10106.498
$P_5$	12204.111	10096.788	12204.112	10096.785
$P_6$	12194.396	10096.628	12194.397	10096.626
$P_7$	12194.205	10106.288	12194.197	10106.288
$P_8$	12194.026	10116.004	12194.010	10116.007
$P_9$	12193.806	10125.703	12193.781	10125.709
$P_{10}$	12184.130	10125.506	12184.105	10125.512
$P_{11}$	12184.294	10115.766	12184.278	10115.770
$P_{12}$	12184.483	10106.095	12184.475	10106.097
$P_{13}$	12184.647	10096.398	12184.648	10096.397
$P_{14}$	12176.664	10080.708	12176.679	10080.704
$P_{15}$	12174.943	10096.181	12174.944	10096.181
$P_{16}$	12174.749	10105.894	12174.742	10105.896
$P_{17}$	12174.579	10115.608	12174.563	10115.613
$P_{18}$	12174.377	10125.323	12174.352	10125.331

表 7 多种像点提取方法精度验证

Table 7 Accuracy verification of multiple pixel extraction results

Direction /pixel	I	II	III
$\Delta x$	0.0291	0.0307	0.0306
$\Delta y$	0.0377	0.0362	0.0354
Plane	0.0476	0.0475	0.0468

在基于反射点源的遥感卫星像点提取精度验证实验中,结合反射点源布设阵列将阵列点源影像数据按照提取的像点坐标配准,可得到光学遥感卫星相机成像系统的点扩散轮廓,如图 5 所示。利用系统点

扩散模型进行参数化拟合得到相机点扩散函数,对其作离散傅里叶变换,取模并归一化得到系统调制传递函数(MTF)<sup>[23]</sup>,如图 6 所示。在获取系统 MTF 的基础上,进一步结合点源布设场区大气光学特性参数进行地面同步或准同步测量,反演实验场区气溶胶光学厚度及大气透过率等参数;利用大气和点源目标反射率等参数,经过简化辐射传输计算得到点源目标反射至光学遥感卫星的入瞳辐亮度;最后联合反射点源遥感影像响应值分析,根据遥感卫星成像系统特性建立两者间的定量关系,即可实现光学遥感卫星基于反射点源的辐射定标与像质评价<sup>[24-25]</sup>。

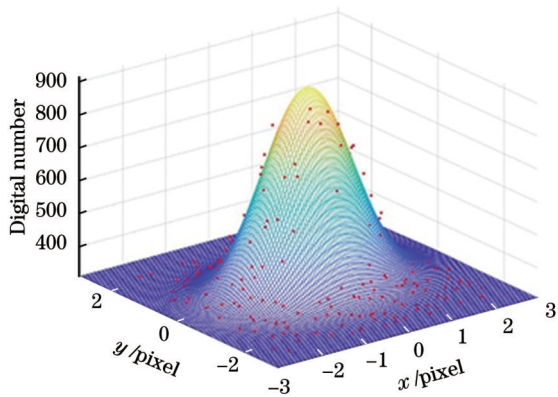


图 5 点扩散函数

Fig. 5 Point spread function

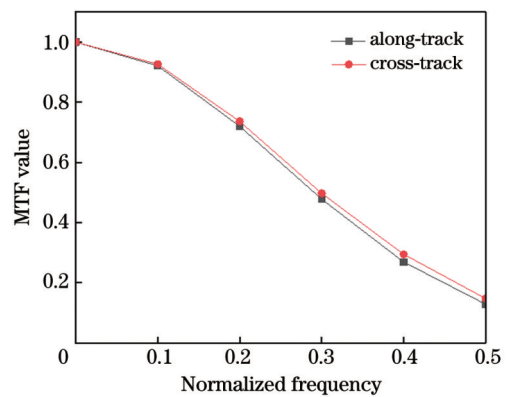


图 6 系统 MTF

Fig. 6 System MTF

## 5 结 论

光学遥感卫星反射点源法像点提取及精度验证以小型化、自动化的类恒星源-反射点源目标作为地面控制点,匹配像点提取算法,实现高精度的点源像点提取,并结合有理函数模型进行像点提取精度验证。基于反射点源的光学遥感卫星在轨实验结果初步表明:与模板匹配法等常规方法相比,反射点源法的点源像点提取精度优于 0.05 pixel,相对自然地物与人工靶标具有较高的提取精度;利用遥感影像附带的有理函数模型参数验证了反射点源定位精度优于 0.05 pixel;自动化反射点源不仅能够实现高精度的像点提取,与点源目标阵列化布设和实验场区大气光学特性参数自动化测量结合,还能够实现光学遥感卫星的像质评价与辐射定标,从而提高光学遥感卫星在轨定标的效率及精度。自动化反射点源有望在光学遥感卫星幅宽范围内网络化布设,形成卫星在轨几何定标的地面控制点,实现光学遥感卫星高精度、高频次、常态化几何辐射综合定标,为国产遥感卫星自动化定标与精度提升提供参考,对提升光学遥感卫星影像的定量化水平,拓展其应用具有重要意义。

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## Pixel Extraction and Accuracy Verification of Optical Remote Sensing Satellite Based on Reflected Point Source

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### Abstract

**Objective** The automation of calibration and the accuracy of pixel extraction are the key factors in improving the efficiency and accuracy of geometric calibration of optical remote sensing satellites in orbit. With the increasing number of optical remote sensing satellites in orbit and the continuous improvement of satellite image resolution, current level of calibration automation cannot meet future development needs. The coordinates of control points and their corresponding image points are input parameters for the geometric calibration of the camera. The accuracy of their measurement and extraction directly affects the accuracy and precision of the internal and external orientation element calibration of the satellite camera. The measurement accuracy of ground control points and on-orbit attitude has reached centimeter or even millimeter-level precision. However, the pixel extraction of control point images mainly relies on manual selection or pixel measurement algorithms, which cannot match the accuracy of control point measurements. Lightweight and automated quasi-stellar source-reflected point sources are proposed to be used as ground control points, along with an algorithm for matching pixel extraction from these sources. This will be combined with on-orbit calibration experiments based on reflected point sources to verify the accuracy of pixel extraction for optical remote sensing satellites. The objective of this paper is to improve the accuracy of pixel extraction, which in turn will enhance the geometric calibration and remote sensing image positioning accuracy of these satellites in orbit.

**Methods** First, we propose a Gaussian model-based method for pixel extraction from reflected point sources and a rational function model-based method for verifying the accuracy of pixel extraction. Based on these principles, we design an experiment to verify the accuracy of pixel extraction from reflected point sources. Second, we analyse the experimental image and extract the pixels by the reflected point source method. The accuracy of the extracted pixels is then verified by template matching and nonlinear optimization methods. Finally, we verify the accuracy of pixel extraction by the reflected point source method with a rational function model and calculate the accuracy of pixel positioning by the template matching method and nonlinear optimization method. A comparative verification of the reflected point source method is conducted.

**Results and Discussions** The pixel coordinates extracted by the reflected point source method, template matching method, and nonlinear optimization method are shown in Tables 1 and 4. The results of the three methods are relatively consistent. The differences between the extracted pixel coordinates and the mean values are shown in Table 5. The maximum error is 0.0472 pixel, which is better than 0.05 pixel, which verify the accuracy of the reflected point source method for the optical remote sensing satellite. The pixel extraction accuracy is better than that of square-shaped top-hat



markers and manual extraction of natural features. The validation results of the rational function model are shown in Table 7. After the maximum value is removed, the positioning accuracy of the extracted pixel coordinates using the reflected point source method, template matching method, and nonlinear optimization method in the flight direction and sensor line array direction is better than 0.04 pixel, and the planar accuracy is better than 0.05 pixel, further verify the accuracy of pixel extraction using the reflected point source method. The experimental results preliminarily indicate that the reflected point source method can achieve high-precision remote sensing image pixel extraction and meet the application requirements of high-precision targets for the geometric calibration of optical remote sensing satellites.

**Conclusions** The preliminary results of on-orbit tests based on reflected point sources for optical remote sensing satellites indicate that compared to conventional methods such as template matching, the reflected point source method has an extraction accuracy of better than 0.05 pixel, which is higher than that for natural objects and artificial targets. The rational function model parameters accompanying the remote sensing images are applied to verify the positioning accuracy of reflected point source method, which is better than 0.05 pixel. Automated reflected point source method not only enable high-precision pixel extraction but also combine the array configuration of point sources with the automatic measurement of atmospheric optical characteristics in the test area. Image quality evaluation and radiation calibration are achieved for optical remote sensing satellites. This can improve the efficiency and accuracy of on-orbit calibration for optical remote sensing satellites. Automated reflected point sources are expected to be networked and deployed within the field of view of optical remote sensing satellites, forming ground control points for on-orbit geometric calibration and enabling high-precision, high-frequency, and normalized geometric radiation calibration for optical remote sensing satellites. Our study provides a reference for automated calibration and accuracy improvement of domestic remote sensing satellites and is of great significance for improving the quantitative level and application of optical remote sensing satellite images.

**Key words** geometric calibration; pixel extraction; reflected point source; accuracy verification; rational function model