A FAST OBJECT-TO-IMAGE BEST SCANLINE SEARCH ALGORITHM FOR AIRBORNE LINEAR PUSHBROOM IMAGE PROCESSING

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ABSTRACT:

Airborne linear pushbroom cameras have become one of the most important imaging sensors in today's photogrammetry and remote sensing practices to collect high-resolution multi-channel seamless image strips. The object-to-image coordinate computation is a core step for the process of photogrammetric images. However, for linear pushbroom sensors, each scanline captured by linear sensor owns six exterior orientation parameters (EOPs) at instant of exposure, that is, the image point coordinates will not be accurately calculated through colinearity equations until reasonable EOPs are determined. Therefore the scanline search issue makes object-to-image coordinate transformation computationally intensive during linear pushbroom image processing. This paper presents a fast scanline search algorithm based on the novel Central Perspective Plane of Scanline (CPPS) constraints. The algorithm has the advantage of computational simplicity. According to the CPPS constraints, the best scanline search process can be simply performed through analytical geometric calculations, thus greatly releasing the burden on object-to-image coordinate computation during image processing. The feasibility and robustness of the proposed algorithm are proved through testing two types of airborne linear pushbroom images, acquired by ADS40 and STARIMAGER, respectively. Compared with the traditional mainstream algorithms, the proposed algorithm has considerably saved nearly 70% of the computation time.

1. INTRODUCTION

The linear array CCD sensors have been introduced into the field of aerial photogrammetry about a decade ago. The first commercial line scanner ADS40 was developed by Leica Geosystems, jointly with the German Aerospace Center (DLR) (Sandau et al., 2000; Fricker, 2001). At the same time, Starlabo Corporation, Tokyo designed the airborne Three-Line-Scanner (TLS) system, jointly with the University of Tokyo (Murai and Matsumoto, 2000). The system was later called STARIMAGER (Koichi et al., 2004). They are two representatives of the commercially available airborne digital imaging systems nowadays, which both adopt the linear pushbroom technique and have the capacity to simultaneously capture high-quality panchromatic, near infrared and multispectral seamless image sequences from forward, nadir and backward viewing-angles. The noticeable potentials of airborne linear pushbroom sensors in both data acquisition and application aspects have attracted great attention and many concerns from researchers of many countries (Haala et al., 2000; Tempelmann et al., 2003; Michael, 2006; Reulke et al., 2006; Li et al., 2007). China has already imported several sets of ADS40 systems for domestic digital aerial mapping applications as well as applicable feasibility research. Experiments and practices indicate that linear pushbroom images have tremendous potentials in measuring and interpreting the comprehensive conditions of ground surface.

The image point coordinate computation of the corresponding ground point plays as a fundamental link in many photogrammetric applications such as the generation of epipolar images and the orthoimage generation as well as the epipolar images based stereoscopic measurement and mapping. Nevertheless, compared with the traditional frame-based photos or CCD matrix images, the airborne linear pushbroom images have a much more complex situation to be faced with. It is well known that airborne linear sensors such as ADS40 have the capacity to provide continuous long "pixel carpet" with a GSD (Ground Sample Distance) resolution up to centimeter level (Sandau et al., 2000) and image strips simultaneously captured by line sensors with forward, nadir and backward viewing-angles along the flight have a high-overlapping ground cover, thus inducing the mass data characteristic of airborne linear pushbroom images, which leads to a really high burden on image data processing. Moreover, due to the pushbroom imaging mode, each scanline captured by line sensor owns six exterior orientation parameters (EOPs) at corresponding exposure moment, that is, the image point coordinates will not be accurately calculated through the rigorous mathematical sensor model i.e. colinearity equations until reasonable EOPs are determined. Therefore the best scanline search issue will have a heavy effect on efficiency of object-to-image coordinate computation.

The image-space-based sequential search can be considered as the most original algorithm developed and used to solve the best scanline search issue of linear pushbroom images. Since one scene of the images may contain a large number of scanlines, such an algorithm is computationally intensive, thus unsuitable for practical use. In recent years, several algorithms have been proposed in order to reduce the search region of image space and improve the search efficiency. Such efforts include the local affine-transformation window search algorithm provided by Leica Geosystems software developing kit, the bisecting window search algorithm (Liu et al., 2004), and the optimized image-space sequential search algorithm (Zhao and Li, 2006). However, all these algorithms unexceptionally give considerations merely to the image-space-based solution strategy, which is rooted on the iterative computations through colinearity equations. Although the iteration times are reduced in different degrees by various optimization approaches, the search efficiency is still unsatisfactory due to the mathematical complexity of each iteration of colinearity equations. In order to meet the urgent demands for high-performance data processing, it is still necessary to explore other more effective best scanline search strategies for object-to-image coordinate computation of airborne linear pushbroom images, rather than the existing image-space-based solution strategy.

Therefore, this paper proposes a fast algorithm for best scanline search issue of airborne linear pushbroom images, based on the novel Central Perspective Plane of Scanline (CPPS) constraints of object space. The organization of the whole paper is as follows: after a brief analysis on the various existing algorithms, the principles of the new algorithm are described; then the workflow of proposed algorithm is described in detail followed by experimental results with analysis and conclusions.

2. OVERVIEW OF EXSITING ALGORITHMS

For airborne linear pushbroom sensors, the sensor model can be approximately considered to be parallel projection in the pushbroom forward direction, derived from the relatively small field angle of line sensor; whereas in the linear sensor direction, the geometric sensor model of central perspective images is strictly conformed to, that is, colinearity equations are still used to mathematically describe the coordinates relationship between object space and image space (Zhang et al., 2004; Zhang, 2005). One of the mathematical forms of the colinearity equations can be expressed as (Wolf and Dewitt, 2000).

$$\begin{aligned} x &= -f\,\frac{a_1(X-Xs_i)+b_1(Y-Ys_i)+c_1(Z-Zs_i)}{a_3(X-Xs_i)+b_3(Y-Ys_i)+c_3(Z-Zs_i)} \\ y &= -f\,\frac{a_2(X-Xs_i)+b_2(Y-Ys_i)+c_2(Z-Zs_i)}{a_3(X-Xs_i)+b_3(Y-Ys_i)+c_3(Z-Zs_i)} \end{aligned} \tag{1}$$

where X,Y,Z are the ground point coordinates, x,y are the image point coordinates, f is the focal length, Xs_i,Ys_i,Zs_i are the coordinates of exposure station of scanline indexed with i, and $a_i,b_i,c_i\,(i=1,2,3)$ are the elements of rotate matrix derived from angular EOPs of scanline indexed with i.

Generally speaking, the existing scanline search algorithms used in airborne linear pushbroom image processing are all based on the image-space-based search criterion. In other words, the image point coordinates calculated out will be theoretically equal to the calibrated coordinates of the imaging sensor when the EOPs of the best scanline are employed. The iterative search process with a certain step value sequentially in image space is carried out as an original algorithm, as shown in Figure 1. However, there is a large search range in image space as one scene of airborne image often contains at least tens of thousands of scanlines along the strip, which results in the correspondingly huge iteration times; what is more, the computation through colinearity equations is somewhat sophisticated in itself. Consequently, such an image-space sequential search algorithm will be imaginably undesirable (Liu et al., 2004). Recently, some improved algorithms have emerged to cut the search cost, including the two-dimensional affine transformation based window search, the bisecting window search and so on.

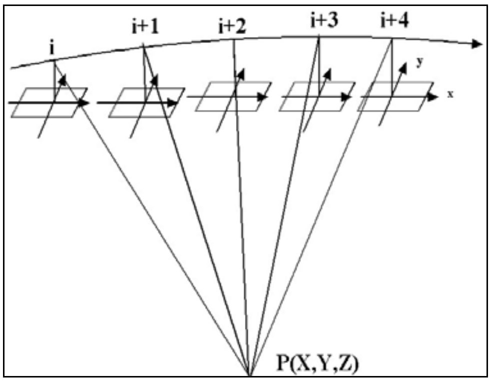

Figure 1. Principle of image-space-based sequential search algorithm

The affine-transformation-based window search is an algorithm in the pseudo code provided by Leica Geosystems software development kit. The algorithm pays attention to the approximate affine transformation relationship between object space and image space as for linear pushbroom images (Zhang et al., 2004). To a certain extent photogrammetric rays of image strip in the pushbroom forward direction can be regarded parallel projection, thus the local affine transformation relationship between ground space and image space can be established in approximation. Relying on the considerable initial search value provided by iterative object-to-image affine transformation, the sequential search range of image space can be effectively decreased.

The bisecting window search is another improved algorithm recently proposed and employed in the indirect geometric rectification process of ADS40 Level0 image (Liu and Wang, 2007). The algorithm has received much more attention for improving the searching efficiency from both speed and accuracy aspects. The main procedure is as follows: choose image interval between the first and the last scanline as the initial search window; then iteratively halve the search window by comparing the three pairs of image point coordinates calculated through colinearity equations, respectively employing the EOPs of the first, the middle and the last scanline of the search window; finally, sequential search is carried out in the final bisecting window within a threshold size.

By evaluating the performance of the above optimization algorithms most often employed nowadays, it is found that although they all make achievements in providing proper initial scanline for the post sequential search process thus optimizing the original image-space sequential search algorithm in different degrees, the calculation amount spent in obtaining proper initial scanline is also a little high to some extent, especially for the affine transformation based window search as several times of colinearity equations based computations are still needed to determined the local affine transformation parameters; besides, no matter what search speedup approaches are considered in these algorithms, for every best scanline search it still need many times of colinearity equations based computation. That is, the main problems for the existed algorithms are image-space-based solution strategy. Therefore, the fundamental solution is to explore some more effective search criterions to replace the existing image-space-oriented one based on which the best scanline search process is accomplished.

3. DESCRIPTION OF THE PROPOSED ALGORITHM

3.1 Basic Principles

As illustrated in Figure 2, let the CPPS be the spatial plane determined by CCD line sensor and the projection center of each scanline at corresponding instant of exposure. Under normal conditions, in order to acquire the qualified and applicable pushbroom images, some rules should be kept during the imaging process: (1) they are approximately parallel and will not intersect with each other in the effective imaging range of object space, (2) the speed of the aircraft must be as stable as possible, and (3) the distance between the adjacent planes should be approximately equal.

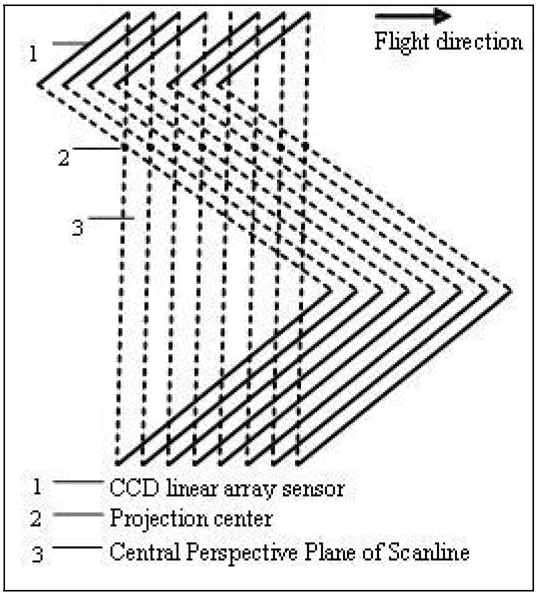

Figure 2. Illustration of Central Perspective Plane of Scanline (CPPS)

In the proposed fast best scanline search algorithm based on the novel CPPS constraints of object space, if the two nearest neighbour CPPSs between which the ground point stands can be searched (see Figure 3), the best scanline can be positioned by interpolating the two nearest CPPSs according to the co-planarity constraints among the corresponding ground point, exposure station and image point.

As shown in Figure 3, P_l and P_r are the two nearest neighbour CPPSs of the ground point (X, Y, Z), d is the approximate distance between the adjacent CPPSs, $\vec{n}$ is the normal vector of CPPS.

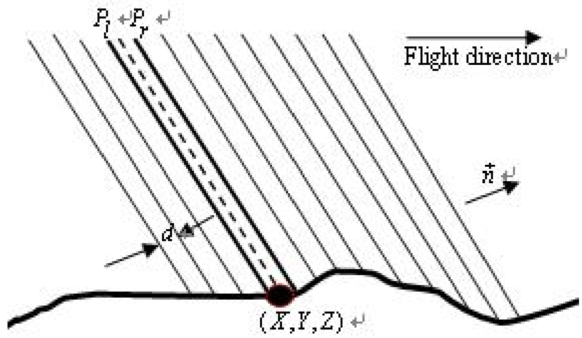

Figure 3. Principle of the proposed CPPS constraints based search algorithm

3.2 Sensor Segmentation and Scanline Compensation

Nevertheless, the definition of CPPS given above exists in the ideal condition hypothesizing all of CCD detectors of a linear sensor allocate with rigorous colinearity. However, that is hardly the case actually due to the unavoidable mounting error of CCD detectors on focal plane as well as the arrangement error in CCD detector itself; for high-precision metric cameras such as ADS40 and STARIMAGER are calibrated with focal plane coordinates of each CCD detector respectively provided, hence the line sensor itself should not directly be processed as a line in practical utilizations (Zhang, 2005). That is, the CPPS definition actually does not exist in this condition, or by definition the CPPS is not ideally "plane" but irregular "surface" instead, which makes the rigorous parametric presentation of CPPS a rather complicated work.

By using the line connecting detectors at both ends of the line sensor to present all of the original discrete detectors in approximation, and in this way, the hypothetically ideal CPPS based on which the object-oriented search will be executed is derived. The correctness of the best scanline search results based on object-space geometric constraints is closely linked with the approximation degree of hypothetical CPPSs with the real sensor situation. Therefore, with a further thinking, a more effective solution strategy is dividing the whole CCD linear array into several segments and using a straight line to approximately present each of them. In this way, CPPSs are computed with each CCD line segment, based on which the best scanline search will be carried out. For line sensor that can not be regarded directly as an ideally straight line, scanline compensation aiming at the CPPSs-based object-space search result is in need to achieve the high search accuracy; and the computation amount of compensation rigorously based on the colinearity equations is in proportion with the deviation degree of imaging detector from the ideally straight sensor line, the bigger the deviation value is, the more computation amount will be needed. The mentioned sensor segmentation strategy can considerably restrict the detector deviations, thus minimizing the compensation cost to the most degree.

3.3 Workflow of the Proposed Algorithm

Derived from the above analysis, the realization of the whole algorithm is mainly followed by three sections: (1) computing parameters of CPPSs, (2) searching the best scanline based on CPPSs, and (3) compensating computation for the accurate value of best scanline.

Computing parameters of CPPSs. This is a preprocessing phase before searching the best scanline, which consists of the following steps:

Step 1: Segment the line sensor.

Based on the calibrated focal plane coordinates of each CCD detector, the famous Douglas-Peuker algorithm (Douglas and Peuker, 1973) is adopted to segment the original line sensor into N line segments. Use the straight line connecting detectors at both ends of each segment to approximately present each linear array. Therefore, there are N CPPSs for each scanline.

Step 2: Compute the coefficients of CPPSs.

Let $a \times X + b \times Y + c \times Z + d = 0$ be the plane equation of the CPPS, and the coefficients a,b,c,d are computed by

$$\begin{aligned}(a, b, c) &= \vec{n} \\ d &= -a \times Xs - b \times Ys - c \times Zs\end{aligned} \tag{2}$$

where a,b,c,d are the coefficients of CPPS, $\vec{n}$ is the normal vector of CPPS, and Xs,Ys,Zs are the coordinates of the corresponding projection center.

Searching the best scanline based on CPPSs. This phase contains the following steps:

Step 1: Decide the imaging sensor segment of the ground point.

Estimate the pixel coordinates of the ground point by two-dimensional object-to-space affine transformation, the six transformation parameters of which can be easily obtained while computing the parameters of CPPSs. Based on the estimated pixel coordinates (l,s), the sensor segment to which the imaging detector indexed with s belongs can be determined, and CPPSs of this segment will be chosen for the subsequent best scanline search.

Step 2: Search two adjacent CPPSs of the ground point.

Assume that the ground point is located between two adjacent CPPSs separately symbolized with P_l and P_r (see Figure 3). Search CPPSs P_l and P_r, which have the indexes i and $i+1$.

① Compute the initial value of i, which is equivalent with n computed by Eq. (3);

$$n = (\text{int})\frac{D}{d} \tag{3}$$

where n is the estimated count of scanlines between the ground point and the first CPPS of the image, D is the distance from ground point to the first CPPS of the image, and d is the approximate distance between the adjacent CPPSs which is computed by

$$d = g \times \cos\alpha \tag{4}$$

where g is the GSD, α is the viewing-angle of the line sensor.

② Iteratively verify the relationship between the ground point and CPPSs indexed with i and $i+1$.

Let $A = a_l \times X + b_l \times Y + c_l \times Z + d_l$, $B = a_r \times X + b_r \times Y + c_r \times Z + d_r$, where X, Y, Z are coordinates of the ground point, a_l, b_l, c_l, d_l are the equation coefficients of CPPS indexed with i , a_r, b_r, c_r, d_r are the equation coefficients of CPPS indexed with $i+1$. If $A \times B > 0$, self-increase or self-decrease the value of i according to the following rules:

$$\begin{aligned}A < 0 &\Rightarrow i = i - n \\ A > 0 &\Rightarrow i = i + n\end{aligned} \tag{5}$$

where n is the estimated count of scanlines between the ground point and CPPS indexed with i, which is also computed by Eq. (3) in which D is the distance from ground point to CPPS indexed with i.

When $A \times B < 0$, it is demonstrated that the ground point is located between CPPSs indexed with i and $i+1$, i.e. P_l and P_r are determined, then stop the iterations.

Step 3: Interpolate the best scanline of the ground point.

Acording to Eq. (6);

$$line = i + \frac{D_l}{D_l + D_r} \tag{6}$$

where D_l is the distance from ground point to P_l , D_r is the distance from ground point to P_r, i is the index of P_l , and $line$ is the object-space best scanline search result of the ground point.

Under the circumstance when the original line sensor itself can be directly processed as an ideally straight line, the acquired value of $line$ here is just the accurate value of best scanline.

Compensating computation for the accurate value of best scanline. In most situations, the deviation of the CCD detectors should not be ignored for airborne linear pushbroom cameras, and the object-space best scanline search result may not achieve the desirable precision, due to the errors incurred from two aspects: (1) the geometric inconsistency between the real irregular line sensor and the simplified one, and (2) the underlying uncertainty in deciding the imaging sensor segment. Therefore, the value of *line* must be further compensated by rigour colinearity equations computation, so as to reach the requested accuracy.

Sensor segmentation can effectively restrict the detector deviations within a considerable degree, which ensures the sub-pixel accuracy of the object-space search result in most cases; therefore, it is demonstrated in practice that only one or at most two times of colinearity equations compensation is needed. Finally, to reach the even higher level search accuracy, the image-space scanline interpolation is recommended.

4. EXPERIMENTAL RESULTS

In order to evaluate the performance of the developed technique, the proposed algorithm has been applied to two types of linear pushbroom images captured by airborne ADS40 camera and STARIMAGER camera, respectively. The three scenes of L0 level images with forward, nadir and backward angle of view simultaneously captured in a flight strip are used in the experiment. The image parameters are listed in Tables 1 and 2. The experiment is carried out on each scene of image as follows:

Firstly, a total of 10,000,000 grid points (1000 column $\times$ 10000 row) with image coordinates (Si, Li) are chosen from each image, and then are projected onto several elevation planes nearby the average elevation to calculate corresponding ground points (Xi, Yi, Zi) $(i = 1, 2, 3...10, 000, 000)$.

Secondly, the proposed algorithm along with the bisecting window search algorithm and affine transformation based window search algorithm are used respectively for the object-to-image coordinate computation of these ground points, with the image coordinates (Si', Li') calculated out.

Finally, the value of each Li' with its theoretical value Li is verified, so as to evaluate the correctness and accuracy of each algorithm. Besides, the efficiency comparison with the existing algorithms can be a reliable demonstration of the new algorithm proposed in this article. The experimental results are listed in Tables 3 and 4.

All the algorithms are implemented in the Microsoft Visual C++ Integrated Development Environment on a desktop computer configured with the Microsoft XP Pro operating system, the Inter (R) Celeron(R) 2.80GHz CPU and the 2.79GHz, 512MB volume memory.

Table 1. Parameters of ADS40 image data

Image	Angle of view (deg.)	Spectral channel	Image Size (line x sample)
Forward	28	Pan	40240x 12000
Nadir	0	Green	40216x 12000
Backward	14	Pan	40232x 12000

Table 2. Parameters of STARIMAGER image data

Image	Angle of view(deg.)	Spectral channel	Image Size (line x sample)
Forward	14	Blue	49199 x 14404
Nadir	0	Blue	49199 x 14404
Backward	23	Blue	49199 x 14404

Table 3. Experimental results of ADS40 images (10,000, 000 Points)

Algorithm	Proposed CPPS Constraints based search		
Sensor	PB14A	GN00A	PF28A
Time(ms)	232,672	209,993	243,086
Times of colinearity equations computation	1~2	1~2	1~2
Count of sensor segments	**16**	**2**	**23**
Algorithm	Affine transformation based window search		
Sensor	PB14A	GN00A	PF28A
Time(ms)	2,405,672	2,392,351	2,442,155
Times of colinearity Equations computation	24~26	24~26	24~26
Algorithm	Bisecting window search		
Sensor	PB14A	GN00A	PF28A
Time(ms)	763,832	757,656	763,163
Times of colinearity Equations computation	6~10	5~8	6~10

Table 4. Experimental results of STARIMAGER images (10,000, 000 Points)

Algorithm	The proposed CPPS Constraints based search		
Sensor	CCD_FB	CCD_NB	CCD_BB
Time(ms)	194,765	188,847	191,094
Times of colinearity equations computation	1~2	1~2	1~2
Count of sensor segments	**2**	**1**	**2**
Algorithm	Affine transformation based window search		
Sensor	CCD_FB	CCD_NB	CCD_BB
Time(ms)	2,314,794	2.495,426	2,503,523
Times of colinearity equations computation	24~26	24~26	24~26
Algorithm	Bisecting window search		
Sensor	CCD_FB	CCD_NB	CCD_BB
Time(ms)	653,439	649,907	655,507
Times of colinearity equations computation	5~9	5~8	5~9

The desirable accuracy that is above the 0.01-pixel-precision is obtained with all the three search algorithms. Judging from the experimental results, a comprehensive analysis on efficiency of the three search algorithms tested is given as follows, from which the advantage of the proposed algorithm is demonstrated.

As mentioned earlier in this paper, the affine transformation based window search algorithm and the bisecting window search are two representative algorithms which adopt the traditional image-space solution strategy. Of these two algorithms, the bisecting window search algorithm is obviously more superior in aspect of time-saving, inferred from results illustrated in Tables 3 and 4. By analysis, the time cost of algorithms to a certain degree is in direct proportion to the times of colinearity equations based computations, as shown in the tables, for each best scanline search, it needs about 25 times of colinearity equations based computations on average with the affine transformation based window search algorithm whereas about 8 times with the bisecting window search algorithm, and accordingly the total time expenditure of the affine transformation based window search algorithm is nearly more than three times of that of the bisecting window search algorithm.

Compared with the bisecting window search algorithm, the proposed CPPS Constraints based search algorithm not only attains the same accuracy level but also a much more desirable search speed, with time cost reduced by nearly 70% of the former. The main reason is that, the sensor segmentation process and the subsequent computation of CPPSs parameters are both accomplished in the preprocessing period beforehand using very little time, that is, for each ground point, the CPPS based search process just involves small amount of analytical geometric calculations, and for further scanline compensation only 1~2 times of colinearity equations based computation will be needed, as illustrated by the experimental results.

According to the results, it can be concluded that prevailingly the geometric straightness of the STARIMAGER line sensor is much higher than that of the ADS40 line sensor. In the experiments, with all of the detector deviations restricting within 0.004mm (about two thirds of the ADS40 detector size and four fifths of the STARIMAGER detector size), the backward, nadir and forward views of the ADS40 camera are respectively segmented into 16, 2 and 23 parts, whereas those of STARTIMAGER camera are segmented into only 2, 1 and 2 parts.

Derived from the experimental results, the number of the sensor segments does have some impact on the efficiency of the proposed CPPS constraints based search algorithm, and most often the larger the number, the more search time is needed, as shown in Tables 3 and 4. That is because theoretically if the original sensor is over-segmented, the segment length will be accordingly small, thus will incur more uncertainty for imaging segment selection. Fortunately, the scanline compensation process is able to deal with the situation of incorrect segment selection incurred by this uncertainty. It is the compensation efficiency but not the accuracy that will be affected finally, and experiment demonstrates that the effect is subtle.

5. CONCLUSIONS

An innovative best scanline search algorithm for the computation of the object-to-image coordinates of airborne linear pushbroom images has been discussed. The proposed algorithm is based on the CPPSs constraints of object space. Based on the CPPSs constraints, the computation of parameters is finished during stage of preprocessing, which will be done only once, while the computation of best scanline search merely performs simple analytical geometric calculation, which will improve the efficiency of best scanline search greatly. The experimental results clearly demonstrated the feasibility, accuracy and robustness of the algorithm. About 70% of computing time is saved by the algorithm compared with the traditional algorithms. Moreover, the higher the sensor detector straightness, the more perfect efficiency will be achieved. The algorithm is now available with the software package for airborne linear pushbroom image processing.

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