DSM Quality Assessment of GF-7 Satellite

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Abstract

The Gaofen-7 (GF-7) satellite was launched on November 3, 2019. It can achieve 1:10000 scale stereo mapping and serve the application needs of basic surveying and mapping, natural resources monitoring and geographic information resource construction. These application rely on high-precision digital surface model (DSM) products as data support. Therefore, it is of great significance to analyze the quality of DSM products produced by Gaofen-7. This paper uses GF-7 optical stereo images from the regions of Zhaodong and Tianjin in China to extract DSMs. And the difference DSM is produced by subtracting the 0.5m resolution aerial reference DEM and the 30m resolution COP30 product in the same area. The quality of DSM products is evaluated by comparing and analyzing the difference DSM. The results show that when the DSM produced by the GF-7 satellite uses the aerial DEM as a reference, the elevation accuracy can reach 0.97 m in the Zhaodong area and 1.54 m in the Tianjin area, and the details of the objects are well depicted; when the COP30 product is used as a reference, the elevation positioning accuracy can reach 1.29 m in the Zhaodong area and 2.42 m in the Tianjin area, which can correctly show the overall situation of the surface objects. Among them, the elevation accuracy in the Tianjin area is relatively poor, mainly because there are many water areas and buildings in this area, and the COP30 product has data missing in this area, which affects the accuracy. In general, the quality of the DSM products generated by the GF-7 satellite is good. Through effective ground control and further processing, the DSM products can fully meet the needs of practical applications such as 1:10000 scale mapping.

1. Introduction

Digital surface model (DSM) refers to a ground elevation model that includes the heights of surface buildings, bridges, trees, etc. It covers the elevation of other surface information on the ground, and is widely used in surveying, hydrology, engineering construction, communications, military and other fields.

Since more and more satellites have improved their accuracy and acquired stereo mapping capabilities, generating DSM from ultra-high resolution stereo images has been an open and promising research topic. Many scholars have studied methods for extracting DSM from stereo images and evaluated the accuracy of DSM products from different satellites.

Aguilar M Á et al. (2013) tested and evaluated the quality of DSM extracted from 15 pairs of different stereo images composed of panchromatic very high resolution (VHR) images from GeoEye-1 (GE1) and WorldView-1 (WV2) satellites. Gruen and Wolff (2007) developed a new set of methods and tools to process ALOS and PRISM data to generate digital surface models (DSMs), and got an accuracy of 1-5 pixels. Baltsavias et al. (2008) used Cartosat-1 stereo images to evaluate the image quality and the quality of the produced DSMs, with the best result accuracy (RMSE) reaching 1.3m. Durand A et al. (2013) studied various methods for obtaining stereo images through the flexibility of Pleiades-HR 1A/1B satellites and producing DSMs, then studied the advantages and disadvantages of these methods, and compared them with LiDAR data to evaluate their product quality. In order to improve the ZY3-03 satellite elevation accuracy in the absence of ground control points, Qv D et al. (2021) used ICEsat/GLAS laser points as elevation control points for auxiliary adjustment. The experimental results showed that the elevation accuracy of the generated DSM was improved by an average of 2.47 m.

Gaofen-7 (GF-7) is China's first civilian sub-meter-level high-resolution optical transmission stereo mapping satellite. It was successfully launched on November 3, 2019. The dual-line array optical stereo camera on board can effectively obtain panchromatic stereo images with a width of 20 kilometers and a resolution better than 0.8m. It can be widely used in the construction and application of digital surface models and plays an important role (Cao, H et al., 2020). In order to ensure the accuracy and reliability of the DSM produced by GF-7, it is necessary to conduct a full quality assessment on it.

This paper uses GF7 optical images of two scenes of Heilongjiang Zhaodong Experimental Area and two scenes of Tianjin Experimental Area to extract DSM, and uses the aerial reference DEM and COP30 products of the same area to make difference DSM, and compares and analyzes the elevation accuracy, so as to evaluate the quality of DSM products produced by GF7 satellite and verify the elevation accuracy to ensure that it can meet the needs of practical applications such as 1:10000 mapping.The main design indicators of GF-7 satellite are shown in Table 1.

2. Experimental Principles

A certain amount of control points and tie points are matched in the GF-7 satellite stereo images. The extraction of control points requires the use of DOM and DEM data. Then the block adjustment is performed to obtain the adjustment accuracy of control points and tie points. After removing the gross error points, the epipolar image and DSM are generated, and the DSM accuracy is analyzed. The specific process of DSM extraction and accuracy analysis is shown in Figure 1.

Sensor parameters	Dual-line array camera	Multispectral camera
Orbit	Orbit altitude: 500km Orbit type: sun-synchronous orbit	
Lifespan	8 Years	
Camera inclination	FWD: +26° BWD: -5°	-5°
Spectral range	0.45-0.90μm	Blue: 0.45-0.52μm Green: 0.52-0.59μm Red: 0.63-0.69μm NIR: 0.77-0.89μm
Resolution	FWD: 0.8m BWD: 0.65m	MUX: 2.6m
Width/focal length	>20km/5520mm	>20km/5520mm
Pixel	7μm	28μm
Signal-to-noise ratio	≥48dB（sun altitude 70°, ground reflectivity 0.65） ≥23dB（sun altitude 20°, ground reflectivity 0.05）	

Table 1. Main design indicators of GF-7 satellite optical camera

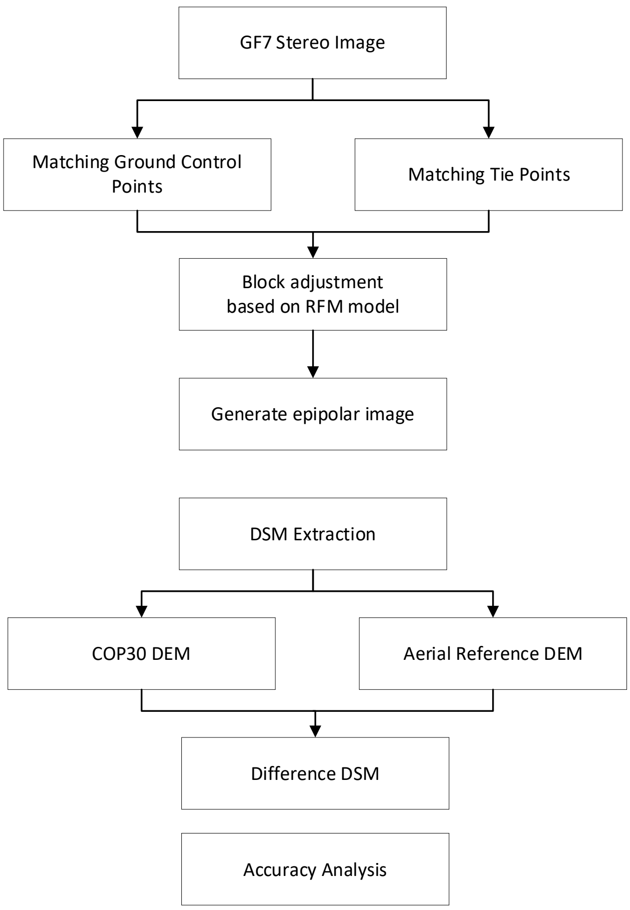

Figure 1. Experiment process

2.1 RFM Model

The rigorous imaging geometry model is closely related to the sensor, and different types of sensors require different imaging models. However, with the emergence of new sensors, the rigorous imaging geometry model's requirements for the sensor's physical properties and imaging mechanism have brought many inconveniences to the application, so the generalized imaging model RFM model has gradually replaced the rigorous imaging geometry model. The rational function model (RFM) is a generalized remote sensing satellite sensor imaging geometry model that directly uses mathematical functions to associate the geodetic coordinates of ground points with their corresponding image point coordinates using ratio polynomials. The conversion between image point coordinates and geodetic coordinates can be achieved through the forward and inverse transformation models. The RFM ratio polynomial is as follows(Tao, C. V., 2001):

$$X=\frac{\mathrm{N}_S\left(\mathrm{L,B,H}\right)}{\mathrm{D}_S\left(\mathrm{L,B,H}\right)};\ \mathrm{Y}=\frac{\mathrm{N}_L\left(\mathrm{L,B,H}\right)}{D_L\left(\mathrm{L,B,H}\right)} \tag{1}$$

To enhance the robustness of the calculation, where $(\mathrm{L,B,H})$ represents the standardized latitude, longitude and elevation, $(\mathrm{X,Y})$ represents the standardized image point coordinates. The image and object space coordinate standardization formulas are as follows:

$$\begin{aligned} X&=\frac{x-X_{\text{off}}}{X_{\text{scale}}} & L&=\frac{\varphi-\varphi_{\text{off}}}{\varphi_{\text{scale}}}\\ Y&=\frac{y-Y_{\text{off}}}{Y_{\text{scale}}} & B&=\frac{\lambda-\lambda_{\text{off}}}{\lambda_{\text{scale}}}\\ & & H&=\frac{h-h_{\text{off}}}{h_{\text{scale}}} \end{aligned} \tag{2}$$

where, X_{off} , X_{scale} , Y_{off} , Y_{scale} represent the image-space coordinate standardization parameters; φ_{off}, φ_{scale}, λ_{off}, λ_{scale}, h_{off}, h_{scale} present the object-space coordinate standardization parameters. The above parameters can be obtained through the RFM parameter file.

2.2 Space Intersection based on RFM Model

Based on the RFM model, space intersection is to obtain the ground point coordinates by intersecting the coordinates of the forward and backward image points. The model formula is:

$$\begin{aligned} x&=X_{\text{scale}}\times\frac{Num_{\mathrm{S}}\left(u^0,v^0,w^0\right)}{Den_{\mathrm{S}}\left(u^0,v^0,w^0\right)}+X_{\text{off}}\\ y&=Y_{\text{scale}}\times\frac{Num_{\mathrm{L}}\left(u^0,v^0,w^0\right)}{Den_{\mathrm{L}}\left(u^0,v^0,w^0\right)}+Y_{\text{off}} \end{aligned} \tag{3}$$

where, (x, y) represents the measured coordinates of the control point on the image, (u^0, v^0, w^0)represents the standardized value of the initial values of latitude, longitude and elevation, and X_{off}, X_{scale}, Y_{off}, Y_{scale} can be obtained through the RFM file. The error equation can be listed as follows:

$$\begin{bmatrix} V_1\\ V_2\\ V_3\\ V_4 \end{bmatrix}=\begin{bmatrix} \frac{\partial X_l^{'}}{\partial\varphi} & \frac{\partial X_l^{'}}{\partial\lambda} & \frac{\partial X_l^{'}}{\partial h}\\ \frac{\partial Y_l^{'}}{\partial\varphi} & \frac{\partial Y_l^{'}}{\partial\lambda} & \frac{\partial Y_l^{'}}{\partial h}\\ \frac{\partial X_r^{'}}{\partial\varphi} & \frac{\partial X_r^{'}}{\partial\lambda} & \frac{\partial X_r^{'}}{\partial h}\\ \frac{\partial Y_r^{'}}{\partial\varphi} & \frac{\partial Y_r^{'}}{\partial\lambda} & \frac{\partial Y_r^{'}}{\partial h} \end{bmatrix}\begin{bmatrix} d\varphi\\ d\lambda\\ dh \end{bmatrix}-\begin{bmatrix} x_l-X_l^{'}\\ y_l-Y_l^{'}\\ x_r-X_r^{'}\\ y_r-Y_r^{'} \end{bmatrix} \tag{4}$$

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where $(x_l, y_l), (x_r, y_r)$ represents the measured image point coordinates of the left and right images, and (X_l', Y_l') (X_r', Y_r') represents the approximate image point coordinates calculated by standardized geodetic coordinates.
The error equation can be simplified as:

$$V = B\hat{x} - l \tag{5}$$

The adjustment result is:

$$\hat{x} = \left(B^T B\right)^{-1} B^T l \tag{6}$$

where the calculation result $\hat{x}$ is the correction number of latitude, longitude and elevation. The corrected number needs to be substituted into the formula for iterative calculation to obtain the final result, that is, the initial value of the geodetic coordinate $(\varphi_0, \lambda_0, h_0)$plus the correction number of the unknown parameter in $\hat{x}$ to obtain the new geodetic coordinate (φ, λ, h), which is then substituted into the error equation for calculation.

2.3 Block Adjustment based on RFM Model

The RFM parameters generated by the orbit and attitude data transmitted by the satellite have obvious systematic errors. This paper adopts the affine transformation model and uses control points to correct the RFM. The error equation formula is as follows:

$$\begin{aligned} F(x) &= f_0 + f_1 \times X + f_2 \times Y + X - x \\ F(y) &= e_0 + e_1 \times X + e_2 \times Y + \mathrm{Y} - y \end{aligned} \tag{7}$$

where, (x, y) represents the measured coordinates of the control point on the image, (X, Y) is the projection value of the ground control point onto the image plane using RFM, and $(f_0, f_1, f_2, e_0, e_1, e_2)$ is the affine transformation parameter of the image plane.

3. Experimental data and analysis

The experimental areas of this paper are Zhaodong area of Heilongjiang Province and Tianjin area of China. Among them, the terrain of Zhaodong area is flat and the landform types are simple. The terrain of Tianjin area is relatively flat, but the landforms are complex, with more buildings and water bodies. This paper uses the L1-level dual-line array stereo images of Gaofen-7 in two scenes of Zhaodong area and two scenes of Tianjin area for experiments, including panchromatic images taken by the forward-looking camera and the backward-looking camera. The imaging time of Zhaodong area is March 2021, and the imaging time of Tianjin area is April 2023 and May 2024 respectively. All images are clear and have no cloud cover. The resolution of the forward-looking image is 0.8m, and the resolution of the backward-looking image is 0.65m. The reference DEMs used in the experiment are the 30-meter resolution COP30 products and 0.5-meter resolution aerial DEM products of Zhaodong and Tianjin areas, respectively. The 30-meter resolution COP30 products are used to evaluate the overall situation, and the 0.5-meter resolution aerial DEM is used to evaluate the elevation details. The aerial reference DEM shading maps of the two areas are shown in Figures 2 and 3.

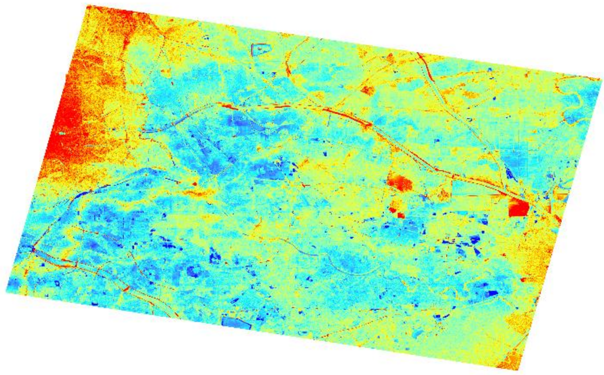


Figure 2. Tianjin area aerial reference DEM shading map

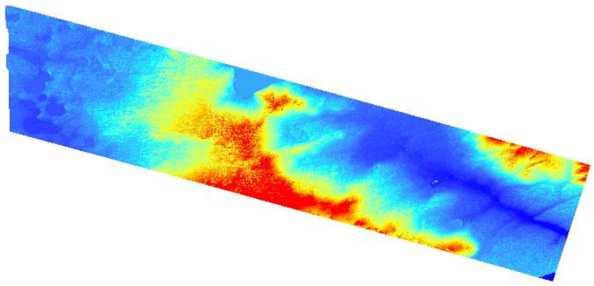


Figure 3. Zhaodong area aerial reference DEM shading map

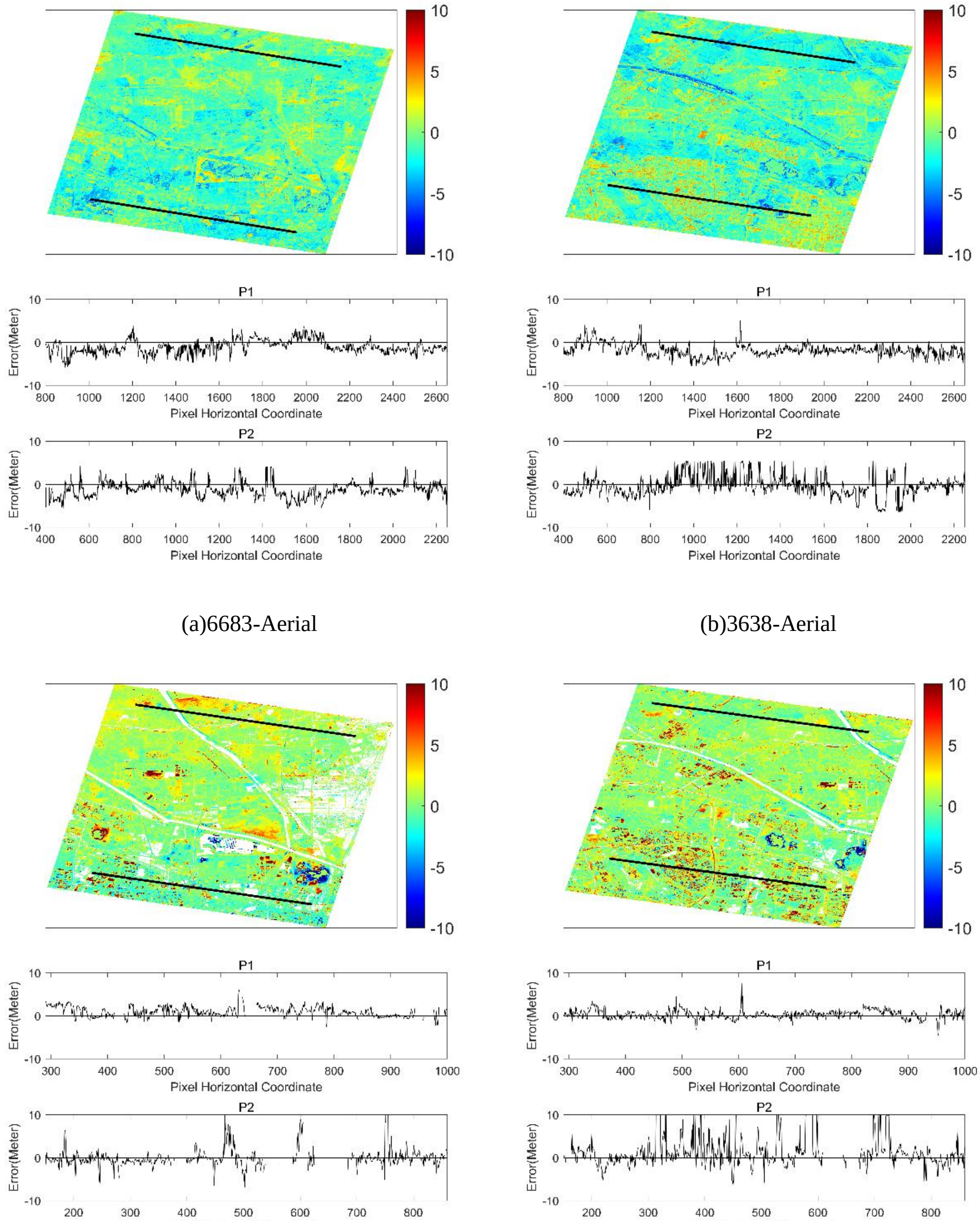
The experiment uses four GF7 dual-line array images to generate four DSMs, which are subtracted from the COP30 product and the aerial reference DEM to obtain the corresponding difference DSM. Since the acquisition time of satellite data and reference data is not consistent, there is a certain time-varying difference or constant elevation difference between DSM and reference DEM data, and the difference values with excessive elevation changes need to be eliminated. This paper eliminates outliers according to the principle of 3 times the standard deviation.

In order to evaluate the quality of DSM produced by GF-7, this paper uses mean, standard deviation and root mean square error (RMSE) as evaluation criteria to count the elevation difference between DSM and reference DEM. The mean, standard deviation and root mean square error of all pixels in the entire test area are counted on each difference DSM, so as to achieve an overall evaluation of the DSM elevation difference value and achieve the purpose of evaluating the quality of GF-7 DSM products. In order to more intuitively and clearly show the difference in elevation between the experimental DSM and the reference DEM and analyze the quality of the DSM products produced by the Gaofen-7 satellite, two profile lines are drawn on each difference DSM.

The specific information of each image and the statistical results of the difference DSM are shown in Table 2. The spatial distribution of the difference DSM in the two experimental areas and the profile line results are shown in Figures 4 and 5.

Scene	Area	Date	Center Long/Lat	Mean/m	Standard Deviation/m	RMSE/m
6683	Tianjin	2023.04.09	E117.5, N39.1	-0.860632 /0.643772	1.537135 /2.416108	1.761668 /2.500402
3638	Tianjin	2024.05.21	E117.4, N39.1	-0.919974 /0.876650	1.670518 /2.727591	1.907087 /2.865006
1619	Zhaodong	2021.03.14	E125.7, N46.0	-0.616186 /-1.316722	1.403440 /1.849730	1.532752 /2.270518
7950	Zhaodong	2021.03.09	E125.7, N46.2	0.240880 /-0.117438	0.971552 /1.286402	1.000968 /1.291751

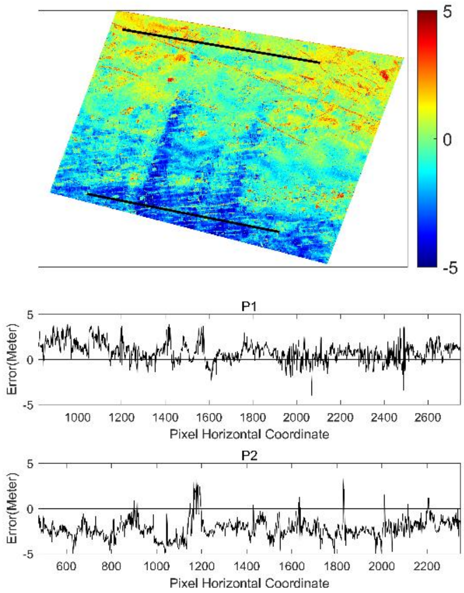
Table 2. Image information and Statistical results of Difference DSM



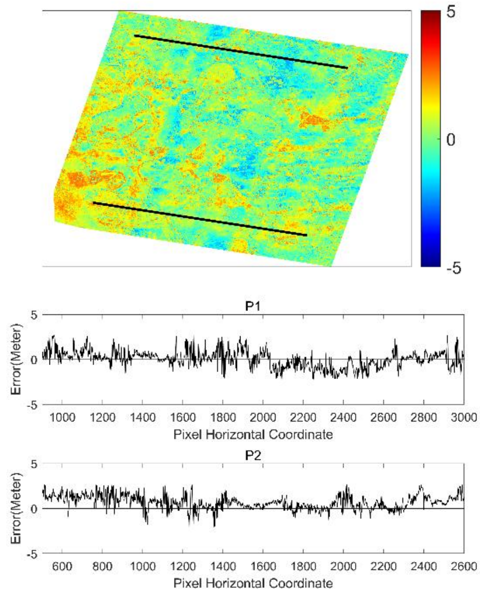
(a)6683-Aerial (b)3638-Aerial

(c)6683-COP (d)3638-COP

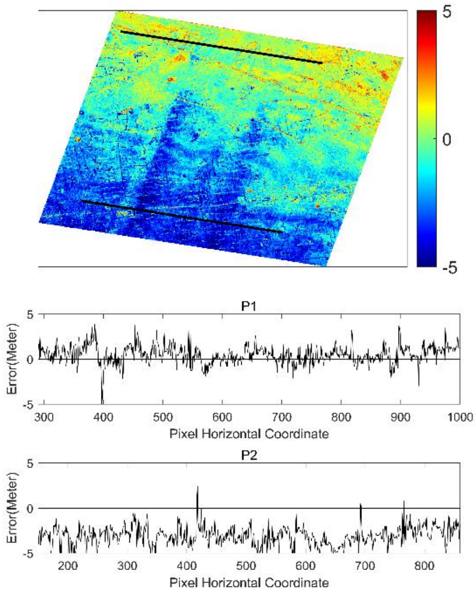
Figure 4. Difference DSM and profile line between DSM and reference DEM in Tianjin area



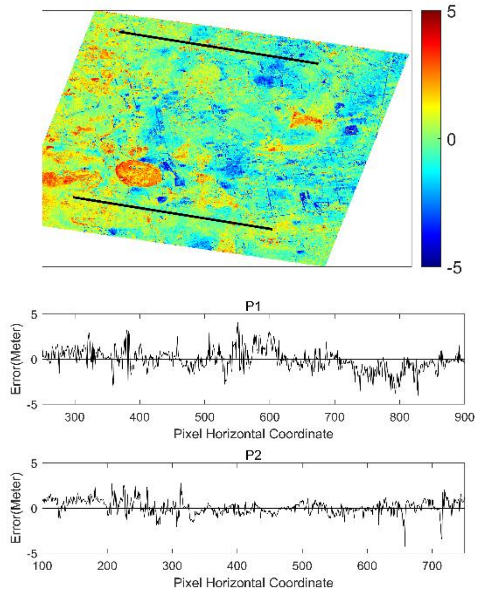
(a)1619-Aerial



(b)7950-Aerial



(c)1619-COP



(d)7950-COP

Figure 5. Difference DSM and profile line between DSM and reference DEM in Zhaodong area

Figures 4 and 5 (a)(b), (c)(d) are the difference images and profiles of GF-7DSM with aerial reference DEM and COP30 products in Zhaodong and Tianjin, respectively. The positions are shown in the figure, and the ordinate represents the pixel value at the profile. Table 2 shows the detailed information of all images and the mean, standard deviation, and root mean square error of the difference images. The first row of the statistical results of the mean, standard deviation, and root mean square error comes from the aerial reference DEM, and the second row comes from the COP30 product.

Among them, when the DSM produced by the Gaofen-7 satellite uses the aerial DEM as a reference, the average elevation difference in the Zhaodong area is 0.62 m and 0.24 m, and the standard deviation is 1.40 m and 0.97 m, respectively. The average elevation difference in the Tianjin area is 0.86 m and 0.92 m, and the standard deviation is 1.54 m and 1.67 m, respectively. When the COP30 product is used as a reference, the average elevation difference in the Zhaodong area is 1.32 m and 0.12 m, and the standard deviation is 1.85 m and 1.29 m, respectively. In particular, since there are many missing data in the COP30 product within the experimental range of the Tianjin area, including water areas and buildings, which greatly affects its DEM accuracy, the average elevation difference in the Tianjin area is 0.64 m and 0.87 m, and the standard deviation is 2.42 m and 2.72 m, respectively, and the overall accuracy is low.

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For the two experimental areas, the standard deviation and root mean square error (RMSE) of the difference DSMs with the aerial reference DEM are both smaller than those with the COP30 product, indicating that the accuracy of the GF-7 DSM is generally closer to the aerial reference DEM, reflecting good detail of ground features and overall high quality.

In the Zhaodong region, due to the flat terrain, simple land cover types, and minimal changes in ground features, the difference DSMs of the GF-7 DSM with both the aerial DEM and COP30 product show good overall and detailed elevation accuracy, indicating that the elevation closely matches the actual ground features and accurately reflects the surface conditions.

For the Tianjin area, in the case of flat terrain but complex features, containing a large number of buildings and water areas, the DSM produced by GF-7 has good accuracy according to the accuracy of the difference DSM with the aerial reference DEM, which can make up for the lack of details in the lower resolution of the COP30 product in this area by depicting the overall surface conditions, and deal with the problem of missing data to improve the accuracy to a certain extent, and can be used for the actual application of DSM in this area.

4. Conclusion

This paper produces DSM through four stereo optical images of two experimental areas, and analyzes the difference DSM produced by subtraction with the aerial reference DEM and COP30 products to evaluate the quality of the Gaofen-7 satellite DSM product. The experimental results show that the elevation difference between the DSM generated by the Gaofen-7 satellite and the aerial reference DEM is small, and the details of the objects can be clearly displayed at a higher resolution, with fewer elevation mutation points. It can accurately depict the terrain for flat land and maintain a certain degree of accuracy for buildings. The overall accuracy is high.

Taking the COP30 product as a reference, at a lower resolution, the DSM product can better depict the overall situation of the surface objects, and the elevation difference is slightly larger than the difference result with the aerial DEM. In the Tianjin area, there is a large error due to the missing data of the COP30 product and the influence of buildings and water bodies, but it can still reflect the overall elevation distribution.

In addition, the DSM produced by Gaofen-7 was not specially processed for water bodies during this experiment. Instead, the elevation anomaly caused by water bodies was eliminated through the gross error elimination process to ensure that the elevation anomaly caused by water bodies did not affect the evaluation of the elevation accuracy of the entire experimental area. When the formal DSM product is produced, if special processing is performed on water bodies, it will ensure that the DSM product is more in line with the actual situation and has better quality.

In general, the accuracy of the DSM produced by GF7 is at the world's advanced level, with good elevation accuracy. It can retain the details of the objects and display the overall elevation distribution, and truthfully depict the surface conditions. If the high-quality DSM obtained is subject to certain ground control and further data processing combined with on-orbit calibration and other methods, the accuracy level will be better and can meet the practical application needs such as 1:10000 mapping.

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