Data processing of Zhuhai-1 hyperspectral satellite

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Abstract. The Zhuhai-1 hyperspectral satellite (The Qust No.1), which was launched on 26 April 2018 is the learning and research crystallization of Qingdao university of science and technology in cooperation with Obit aerospace technology company. The Qust No.1 satellite is equipped with a high-resolution hyperspectral camera, achieving global remote sensing coverage and providing high-quality hyperspectral data for relevant scientific and commercial remote sensing applications. Based on the Qust No.1 imagery for Jiaozhou bay, the radiation, atmospheric, orthographical corrections together with the image enhancement and spectral information extraction are analysed and discussed in detail in this paper. The results indicate that there are high imaging quality and excellent information collection ability for the Zhuhai-1 satellite, which has good application prospect in many aspects such as vegetation monitoring, precision agriculture, etc.

1. Introduction

The remote sensing technology is a novel science covering many subjects and fields, which mainly undergoes two stages of the aircraft remote sensing and carrier platform using the aircraft and satellite as the main medium, respectively [1]. It refers to adopting the remote sensing devices carried on the aircraft, spacecraft and satellites to detect the ground objects, thus recognizing their features through the record, transmission and analysis [2]. The remote sensing technology can detect the object from multiple angles, large ranges and multiple spectra, obtaining the real-time feature information regularly, which is widely used in meteorological monitoring, resource exploration, surveying and mapping together with the military monitoring and other aspects of national economy and military [3]. It can provide the earth observation data with higher resolution, becoming one of most dynamic technologies in present world [4].

According to the spectral resolution, the remote sensing technology is classified into three categories. The band range within the order of $10^{-1} \lambda$ is called the multispectral remote sensing, while the band ranges within the order of $10^{-2} \lambda$ and $10^{-3} \lambda$ are called the hyperspectral remote sensing and ultrafast spectroscopy remote sensing, respectively [5]. The hyperspectral remote sensing is a multi-dimensional information acquisition technology combining traditional two-dimensional imaging technology with one-dimensional spectroscopy [6]. Compared with the multispectral remote sensing image, the hyperspectral remote sensing image has high spectral resolution and large information content, which improves the ability of the ground object recognition [7]. It can identify some ground objects that cannot be detected by traditional panchromatic remote sensing and multispectral remote sensing, which is a major breakthrough in the remote sensing field, becoming the main force of the
earth land, sea and air observation [8]. In the past decades, the research on the hyperspectral remote sensing has never stopped in China. The hyperspectral sensor has become one of the basic systems in China's airborne remote sensing system. In particular, the Chinese academy of sciences (CAS) has played a very important role in high-tech development [9-11]. The Qust No. 1 hyperspectral satellite successfully launched on 26 April 2018, which carried the hyperspectral camera with high resolution. There are 32 spectral bands covering the electromagnetic spectrum from visible to near infrared, whose spatial resolution and spectral resolution are better than 10 m and 2.5 nm, respectively. With the width of over 150 km and the imaging range of 150 km×2500 km, this hyperspectral satellite can realize one global scan within five days.

On basis of the observation data, the image quality of the Qust No. 1 satellite is evaluated by the radiation, atmospheric, orthographical corrections and spectral information extraction and synthesis together with the vegetation and hydrological analysis. This work provides a theoretical and practical guidance for the hyperspectral remote sensing information processing of the Qust No. 1 satellite.

2. Theoretical analysis and data processing

2.1. Acquisition of the hyperspectral remote sensing information

The Jiaozhou bay in Qingdao is selected as the research area, and the hyperspectral satellite data is extracted from the image taken on March 19, 2019 of the Qust. No. 1 satellite whose band is in range of [450nm, 960nm]. The center longitude and latitude are 120.0719 E and 36.1915 N, respectively. The original image is composed of digital quantitative values, as shown in Figure 1.

![Figure 1. Original images corresponding to (a) the band 1, (b) the band 6 and (c) the band 12, respectively.](image)

The output digital number of the original image is the electrical signal converted by the ground optical information using the hyperspectral camera, whose value reflects the brightness information and spectral information of the ground. The radiation calibration refers to establishing the relationship of the output digital quantitative information for each element and the irradiance information in the observation field, and the hyperspectral correction formula used by the Qust No. 1 satellite is

\[
L = a_{gain} \cdot \frac{dn}{TDIS} + b_{offset},
\]

where \(L\) and \(dn\) represent the irradiance and digital number, while \(a_{gain}\), \(TDIS\) and \(b_{offset}\) stand for the gain coefficient, integral series and deviation coefficient of the radiometric calibration, respectively. The original image containing only the digital information can be transformed into a

![Figure 2. True color image synthesized by the bands 1, 6 and 12 after the radiometric calibration.](image)

![Figure 3. Reflectivity image after atmospheric correction.](image)

![Figure 4. Three-dimensional visualization of terrain.](image)
hyperspectral image containing the irradiance information by the radiometric calibration, shown in Figure 2.

The calibration coefficient of the detected pixel is not a fixed value in the process of satellite operation, and it is affected by the temperature of the cold focal plane and cavity mirror radiation. Therefore, the calibration equation is corrected by the spaceborne radiation source such as the blackbody and sun, thus achieving the high precision on-orbit calibration.

2.2. Atmospheric correction together with the terrain visualization and orthographic correction

Because of the radiometric calibration not taking into account the influence of atmosphere radiation, the reflective information of the earth surface can not be directly reflected. The actual radiation received by a hyperspectral camera includes the reflected radiation from the sun directly to the earth's surface together with the reflected radiation from the sunlight scattered by the atmosphere on the earth's surface and the upward scattering of the atmosphere. The purpose of the atmospheric radiation correction (FLAASH) is to eliminate the influence of the atmosphere on the irradiance through the analysis of the surface gas column, so as to accurately invert the reflective information and provide the accurate data for the next level product. The FLAASH algorithm based on the MODTRAN4 model is composed of the operation parameter, detector parameter, atmospheric parameter, field of view geometric parameter and surface parameter, which completes the solution of the atmospheric transmittance, atmospheric profile and atmospheric scattering property, achieving the correction of the atmospheric factor.

If ignoring the effect of the thermal radiation from ultraviolet to infrared bands, the irradiance received by the detector can be expressed as

\[
L' = \frac{A\rho + B\rho_s}{1 - \rho_s S} + L_0, \tag{2}
\]

where \( L' \) and \( L_0 \) represent the total radiation and atmospheric radiation, while \( \rho \) and \( \rho_s \) stand for the reflectivity corresponding to the pixel position and the average reflectivity of the surrounding area, and the value of \( \rho_s \) is obtained by using the atmospheric point diffusion function to convolve the image. The relationship between the reflectivity of the atmospheric surface and actual object is obtained:

\[
\rho^*(\theta_s, \theta_t, \phi_s, -\phi_t) = \rho_s(\theta_s, \theta_t, \phi_s, -\phi_t) + \frac{T(\theta_t)}{1 - \rho S} \left[ \rho e^{-\tau \cos \theta_t} + \rho_t(\theta_t) \right]. \tag{3}
\]

Here \( \rho^* \) and \( \rho_s \) are the apparent reflectance and equivalent reflectance, while \( \theta_s \) and \( \theta_t \) together with \( \phi_s \) and \( \phi_t \) are the zenith angles and direction angles of the sun together with the hyperspectral satellite, respectively; \( \tau \) is the optical thickness of the atmosphere, and \( T(\theta_t) \) and \( \rho_t(\theta_t) \) are the transmittances of the transmission path and atmospheric scattering.

The imaging process of the hyperspectral satellite is affected by the topographic relief, atmospheric refraction, camera aberration, and the orthographic correction can eliminate the image distortion caused by the imaging process, which also make the image more intuitive and abundant than a two-dimensional image. To correct the terrain, the first step is to determine the actual elevation information of the ground, namely, the digital elevation model (DEM). The GMTED2010 model adopted in this paper is a global multi-resolution terrain elevation model, which is established by the United States Geological Survey and National geographic space intelligence agency using the latest data. The surface reflectance by the atmospheric correction is depicted in Figure 3, and the hyperspectral image can be mapped to three-dimensional surface graph through the DEM model, as shown in Figure 4. From Figure 4, the terrain information and reflectivity information can be obtained simultaneously, and the urban buildings are mainly distributed in coastal and alluvial plain areas with relatively flat terrain while the farmland mainly distributed in inland plain areas.
The remote procedure call (RPC) model as the orthotropic correction model, the mathematical mapping from two-dimensional pixel coordinate system to the actual three-dimensional surface coordinate system is established through the mathematical method, which adds the ground elevation information to the orthographic correction of the hyperspectral image. In simple terms, the RPC model is rational corrected function, which adopts the ratio polynomial to associate the geodetic coordinates of the ground points with their corresponding pixel coordinates. The three-dimensional visualization images before and after orthographical corrections are shown in Figure 5. Compared with the image before orthographical correction, the road curve is smoother and the distribution of the buildings is more fitting to the terrain, indicating that the orthographic correction has achieved its intended correction effect.

Figure 5. Three-dimensional visualization images before (a) and after (b) the orthographical correction.

2.3. Fourier transform and the linear spectral unmixing
There are 32 spectral bands for the Qust No. 1 hyperspectral camera, whose wavelength is in a range of [465 nm, 940 nm] and spectral resolution better than 2.5nm, and the spectral response curves of all bands are depicted in Figure 6.

The spectral response with high quality and resolution make the Qust No. 1 hyperspectral camera have good perform in both image dimension and spectral dimension. Because of various substances having their own unique spectral response curves, the specific band information of the hyperspectral image is extracted and processed to obtain the image spatial distribution of different substances. Through the false color image synthesis, the image at the characteristic band is projected to the same image, which can identify the spatial distribution of the specific substance, as shown in Figure 7. The vegetation has two absorption bands of 450nm and 650nm in the visible band, and a reflection peak is formed near 540nm. Therefore, the RGB synthesis can be carried out by two infrared bands and one blue band to enhance the vegetation.

Figure 7. False color image enhancement, where (a) vegetation enhancement, (b) land enhancement and (c) farmland enhancement.

Figure 8. Fourier transform spectrum.

The image dimension information can be transformed into the frequency domain information by the Fourier transform, and one has

$$F(u,v) = \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x,y) e^{-j2\pi(x/M+y/N)},$$

(4)

where $f(x,y)$ is the image with the size of $M \times N$. The fast Fourier transform is adopted to obtain two-dimensional spectrum by the gradual iteration, which can monitor the quality of the
hyperspectral image in the frequency domain. Besides, a certain frequency channel can be set to filter and optimize the response image, as shown in Figure 8. After the Fourier transform, two-dimensional digital image is transformed into frequency domain image, which is mainly composed of low-frequency components, indicating that the image has less high-frequency noise, the image brightness distribution is uniform and smooth, and the quality of the hyperspectral image is high.

In the imaging process of a hyperspectral camera, some noises will inevitably be introduced. A hyperspectral image $X = [x_1, x_2, x_3, \ldots, x_n]^T$ with $b$ bands and $n$ pixels, is considered to be composed of signal and noise.

$$X(p) = X_s(p) + X_n(p),$$  \hspace{1cm} (5)

where $X_s(p)$ and $X_n(p)$ are the signal and noise at the position $p$. At present, the signal and noise are generally considered to be independent, and the image covariance matrix is the sum of signal and noise covariance.

$$S = S_s + S_n,$$  \hspace{1cm} (6)

The minimum noise fraction (MNF) concentrates the main information of a multi-band image in the first few bands, and it is also a linear transformation including essentially two principal component analyses. The first transformation is to use the noise covariance matrix in the principal component to separate and re-adjust the noise in the data, so that the transformed noise data has only the smallest variance and no inter-band correlation. The second transformation is to transform the principal component of the noise whitening data, and the noise fraction is defined as:

$$NF = \frac{a^T S a}{a^T S_n a}.$$  \hspace{1cm} (7)

According to the noise fraction, the coefficient matrix of the MNF transform is determined, which needs to satisfy the conditions:

$$\begin{cases}
Y = a^T X \\
S^{-1} S_n a = \lambda a
\end{cases}$$  \hspace{1cm} (8)

The MNF transformation is transformed into solving the problem of eigenvalues and eigenvectors, and the SNR of each component after the MNF transform is $1/\lambda' - 1$. Therefore, the MNF transform can rank the components according to their quality and extract the components with less noise, thus achieving the effect of de-noising and dimensionality reduction. The MNF transform eigenvalue and its result diagram is shown in Figure 9. In order to extract and locate the target substance, we hope that the photons received by the hyperspectral camera interact with only one substance. However, the pixel observations are the mixture of various substances in most cases. The end element extraction can find the pixel with the highest purity, and the dimensionality reduction and de-noising based on the MNF make it possible to extract high purity pixel accurately.

Figure 9. MNF transform eigenvalue and its result diagram.

Figure 10. End element extraction result.
element extraction contains the spectral characteristics of various substances and provides the basis for specific spectral analysis, which can be used for the linear spectral unmixing, so as to achieve the creation of the special material spectral library together with the ground object recognition and other follow-up work.

Figure 11. Spectral linear unmixing result.  

The linear spectral unmixing is based on the assumption that there is no interaction between substances and the photons interact with different kinds of substances. It can be deduced that the mixed pixel is formed by the linear superposition of the pure pixel (terminal element) in the spectral characteristic space. On the premise of the known terminal element, the pure material is extracted from the mixed pixel through the linear decomposition, achieving the task of the object recognition, as shown in Figure 11.

2.4. Remote sensing of vegetation

The accuracy of the early stage of the remote sensing processing provides the reliable background data for the subsequent inversion of the specific parameters of the object, which enables us to analyze the specific information of the object from multiple levels and aspects by the hyperspectral image. Taking the remote sensing of vegetation as an example, the application of the remote sensing satellite data in providing valuable information for the actual production is introduced.

With the increasingly serious environmental problems, the distribution of the earth's vegetation together with its health status has attracted more and more attention. In remote sensing observation, the vegetation belongs to the first surface of the remote sensing data, which is the most intuitive information in hyperspectral remote sensing images. The research on the remote sensing of vegetation includes identifying and locating vegetation through spectral features, and quantifying the vegetation types and specific growth conditions through the inversion of vegetation index. Although the spectral responses of different plants differ in the intensity of reflection, the peak ranges of the absorption and reflection are roughly the same because of the dominant chlorophyll, as shown in Figure 12.

Based on the response characteristics, the researchers designed a variety of vegetation indices to describe the growth and health of the vegetation. The normalized vegetation index and red edge vegetation index are adopted in this paper, and they are expressed as follows:

\[
NDVI = \frac{\rho_{\text{RE}} - \rho_{R}}{\rho_{\text{RE}} + \rho_{R}},
\]

\[
NDVI_{705} = \frac{\rho_{705} - \rho_{750}}{\rho_{705} + \rho_{750}},
\]

where \(NDVI\) and \(NDVI_{705}\) are the normalized vegetation index and red edge vegetation index, while \(\rho\) is the reflectivity, whose size describes the amount and growth of the vegetation, and the index of the green vegetation varies from 0.2 to 0.8.

As an improved version of the normalized vegetation index, the red edge vegetation index is more sensitive to the slight changes of the forest canopy and leaf window by adding the blue band information, which is mostly used for fine agriculture and forestry monitoring. From Figure 13, the normalized vegetation index simply quantifies the spatial distribution of vegetation, while the red edge vegetation index highlights the specific details of the canopy distribution. By selecting different
vegetation indices, the specific quantification of the vegetation properties can be carried out, thus providing a basis for accurately monitoring of agroforestry production.

**Figure 13.** Vegetation index, where (a) and (b) are corresponding to the normalized and red edge vegetation indices.

**Figure 14.** Forest health analysis.

**Figure 15.** Vegetation inhibition.

Based on the biologically-verified vegetation index, the monitoring and grading of the vegetation health can be achieved by analyzing comprehensively the green index and leaf pigment index together with the light utilization index and canopy water content index, as shown in Figure 14. From Figure 14, the final results ranked the vegetation according to its health status, and the image closer to red indicates the healthier vegetation. In coastal areas, the urban buildings are mainly distributed, and the vegetation distribution is relatively sparse. However, the vegetation distribution is relatively dense in inland plains and hilly areas, which has better health.

Because the vegetation is the topmost information of the hyperspectral image, the distribution of the soil and city can be highlighted through the suppression of vegetation, thus providing the help for the extraction of the next layer of spectral information, as depicted in Figure 15. Through the vegetation suppression, the urban buildings are mainly concentrated in river banks and coastal areas, and the soil properties of forest and farmland distribution areas are also different.

**Figure 16.** Agricultural crop stress analysis.

**Figure 17.** Flammability distribution analysis.

The agricultural crop stress analysis can be used to evaluate the areas suitable for the crop planting, as shown in Figure 16, and the regions with more colorful colors are less suitable for crop planting. Compared with the original data, the red area is the building land, and the result is reasonable.

Not only can the flammability distribution analysis be used for the forest planning, but it also analyzes the fire risk in different areas. It is of great significance for forestry regulation and urban safety, and the analysis results are shown in Figure 17. The brighter the color is, the stronger the flammability is. By comparing the original images, the areas with high flammability mostly contain some vegetation in the dry state, which lacks of moisture, and are prone to fire.

### 3. Conclusion

On basis of the remote sensing data of the Zhuhai-1 hyperspectral satellite (namely the Qust. No.1 satellite), the radiometric, atmospheric, orthographic corrections together with the image enhancement and spectral information extraction are adopted to improving the imaging precision. The linear radiometric correction based on gain coefficient together with the FLAASH algorithm based on the MODTRAN4 model can better complete the radiometric and atmospheric correction tasks for the Qust No. 1, while the orthographic correction based on the RPC model can realize the terrain orthographic
correction. It indicates that there is high quality in both image and spectrum dimensions for the Qust No. 1 satellite because of its high resolution and excellent spectral detector design, which can realize the image enhancement for various objects through the band combination and false color synthesis.

With a high acquisition capability of the spectral information, the Qust No.1 can extract spectral information of various characteristic objects and identify their positions. By combining of the linear spectral decommissioning and vegetation index analysis, the hyperspectral data has high application value in many application fields such as remote sensing of vegetation. This work show that the Qust No. 1 has high imaging quality and excellent information acquisition ability, realizing the forest health analysis, agricultural crop stress analysis and ignitability distribution analysis.

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