ABWI AIRBORNE BINOCULAR WHISKBROOM IMAGER: CAMERA PRINCIPLES AND THE WORKFLOW

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ABSTRACT:

The common imaging methods of airborne cameras are linear array pushbroom and area-array interval exposure, and the sensors or lens of them cannot be rotated. With the development of oblique photogrammetry and UAV mapping, there are new advances in airborne whiskbroom sensors. Because of their unique imaging method, they can obtain the side texture information of features more efficiently. ABWI is a new generation of airborne sweeping sensors with the dual-view area-array whiskbroom imaging method. It has a maximum sweeping field of view of 120° and can also acquire spectral information in four bands (RGB and NIR) at the radiometric resolution of 12 bits. Additionally, the camera system is equipped with a laser ranger to assist with other measurement purposes. This paper introduces the camera structure, imaging principle and corresponding data processing workflow of ABWI, and summarizes its advantages and new application scenarios.

1. INTRODUCTION

The desire to explore and measure the Earth's surface has existed since ancient times. However, due to the rudimentary means of data acquisition and data processing, for a long time, humans have spent a lot of time and effort but only produced rough maps. For decades, imaging sensors and related processing technologies have significantly improved. Sensor load platforms have also become increasingly diverse (Ji, 2018, Zhang et al., 2021). Consequently, the data we acquire have been significantly improved in terms of spatial resolution, spectral resolution, radiometric resolution, and temporal resolution (Jensen, 2015, Sun, 2013). These advancements have greatly facilitated and promoted land surveying, urban planning, and other related projects.

Airborne sensors are commonly used in the mapping of many local areas due to their lower cost, higher spatial resolution, and more flexible aerial flight operation compared to spaceborne sensors. The imaging methods of the mainstream airborne sensors are linear array pushbroom and the area-array camera with interval exposures (Jensen, 2015). On this basis, some sensors increase their field of view to improve aerial flight efficiencies, such as multi-camera stitching imaging (Dong et al., 2022, Zhou et al., 2021) or single-view sweeping imaging (Liu et al., 2002, Pechatnikov et al., 2008, Raizman and Gozes, 2015). This paper will introduce an airborne sensor with the dual-view sweeping imaging method.

ABWI (Airborne Binocular Whiskbroom Imager) is a new generation of the airborne sweeping imaging sensor developed by XIOPM (Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences). It makes up for the shortage of area-array whiskbroom cameras in China and also provides a new solution for digital city construction and land resource surveying.

In Section 2, we introduce the camera structure, imaging principle and sensor parameters of ABWI. Then its data processing software, workflow and product results are presented in Section 3. Finally, ended with ABWI's advantages and new application scenarios.

2. HARDWARE

ABWI, an airborne dual-view area-array imager with a maximum sweeping FOV of 120°, adopts the two-pass continuous sweeping imaging method. It can not only acquire top and side view images with very high spatial resolution, but also achieve the good spectral and radiometric standards. Meanwhile, due to its very large cross track FOV, the ABWI is very efficient for aerial flight operations and oblique photogrammetry.

2.1 Camera Structure

As shown in Figure 1, ABWI's camera system is composed of a 2D scanning platform, a POS system, two multispectral area-array cameras and a laser ranger. The 2D scanning platform consists of an outer roll frame, an inner pitch frame and a base. The outer roll frame and inner pitch frame are controlled by the roll encoder and pitch encoder respectively.

Both multispectral area-array cameras and the laser ranger are mounted in the inner pitch frame and are not movable. In other words, the relative position relationships among these sensors and the inner pitch frame are fixed (this will be explained later in more detail). Therefore, the attitudes of these sensors relative to the platform are controlled by the roll encoder and pitch encoder. The POS system is mounted on the base of the 2D scanning platform. Since the platform is fixed to the aircraft, the attitude angle of the platform base measured by the POS system is the same as the aircraft. This feature is very meaningful for the attitude angle compensation of the sensors.

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The data acquisition principle and key point of the whiskbroom sensor is changing the sensors' roll angles periodically when the aircraft is flying straight forward. However, the attitude of the aircraft varies at different times, which seriously affects the quality of data acquisition. Due to the roll encoder and pitch encoder of ABWI, they can compensate for the additional pitch and roll angles caused by aircraft attitude changes (Detailed parameters can be seen in Table 1).

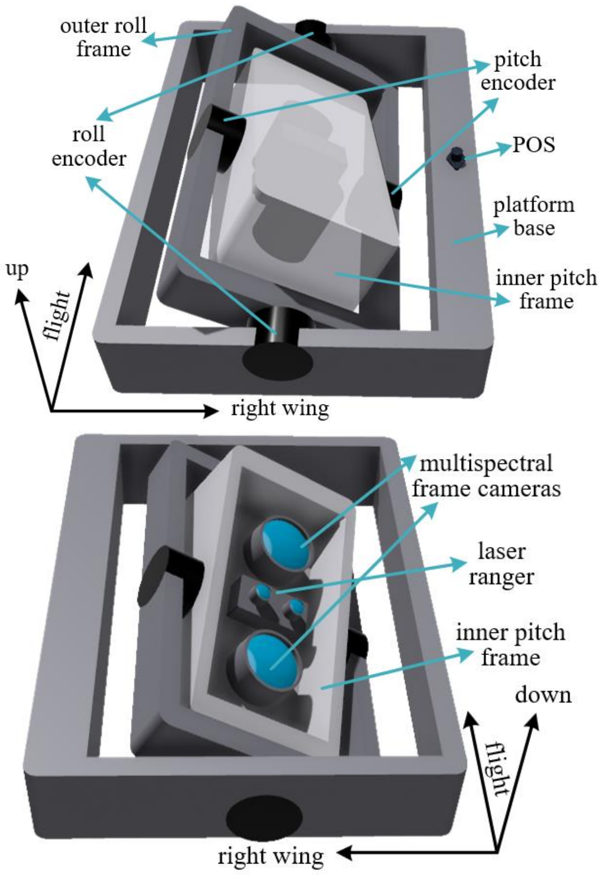

Figure 1. Structure of ABWI

Figure 2 represents the relative position relationships among the sensors. The two multispectral area-array cameras have identical parameters but different orientations to increase the along track FOV and the data acquisition efficiency. The angle between the primary optical axes of the two multispectral area-array cameras is 3.5°, and the angle is divided equally into two halves by the vertical axis when the angles of the POS system and encoders are 0s. For each multispectral area-array camera, its FOV in flight direction is 4.17°. So, there will always be overlapping areas between the two cameras' images when the aircraft is at the normal altitude. This overlap rate (ratio of the overlapping area to the single camera image) decreases as the flight altitude gets higher, and eventually converges to 16% (when the relative flight height is higher than 1km).

The laser ranger is positioned in the middle of the two camera loads, parallel to the vertical axis. It's mainly used to obtain distance information between the aircraft and the measured feature at the moment of each exposure. This information can control the relative altitude of the aircraft and assist the aerial triangulation in the data processing.

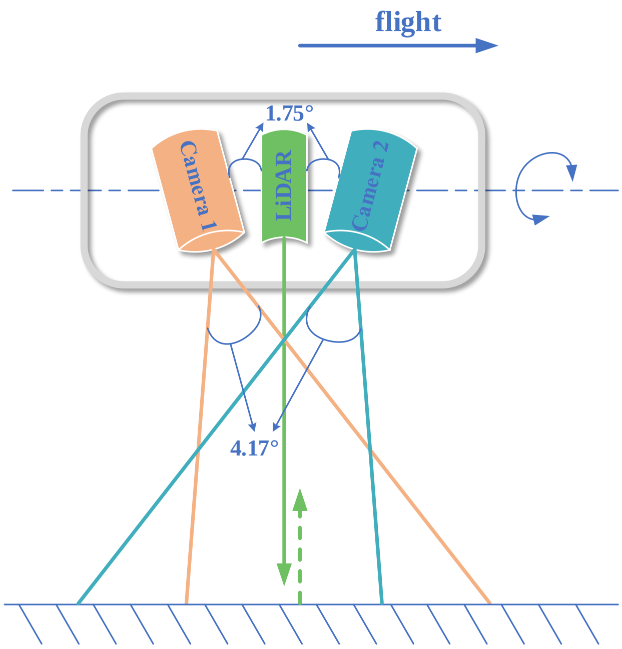

Figure 2. Structure of sensors

2.2 Imaging Principle

The imaging mothed of ABWI is area-array whiskbroom. The scanning mode is two-pass continuous sweeping, which can be seen in Figure 3. The parallelism of the two-pass zigzag sweeping trajectory is ensured by the roll encoder and pitch encoder. Besides the roll angle compensation, the roll encoder controls the sweeping range and speed. The maximum sweeping FOV can reach 120°. These mean that the sweeping range doesn't have to be symmetric with the vertical axis and ABWI can be used like the side-looking radar for side-looking only. Meanwhile, the overlap of the sweeping direction is approximately 1/3, and the overlap of the flight direction is subject to the speed of the aircraft. The highest frame rate of exposure is 15 Hz. Therefore, ABWI can provide very detailed data for oblique photogrammetry and stereo mapping (Sun and Xia, 2017).

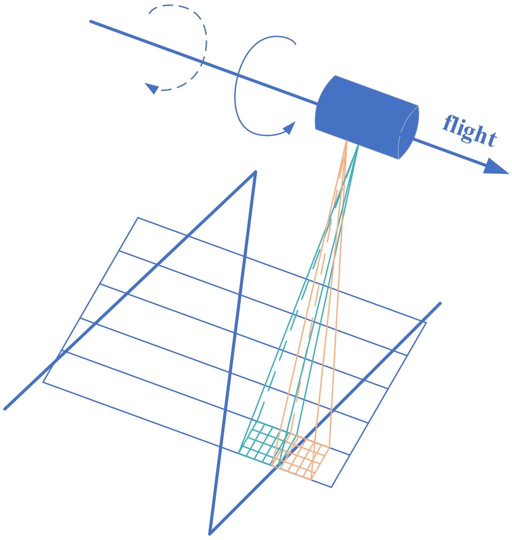

Figure 3. Imaging principle of ABWI

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2.3 Sensor Parameters

The hardware configuration and parameters of ABWI are excellent whether in geometric characteristics or spectral characteristics or accessories. More detailed parameter information is shown in Table 1.

As for the geometric characteristics, ABWI has a pixel size of 6.4*6.4μm² and a focal length of 450mm. And it has a ground sample distance of 0.03m when the relative flight altitude is 2000m. Meanwhile, although the FOV of the single lens at each exposure is only 4.17°*3.13°, the maximum sweeping FOV (cross track FOV) can reach 120° by the whiskbroom imaging method. And the frame size of one single camera is 5120*3839 (5120 represents the flight direction). These values indicate that ABWI is able to meet both the outstanding spatial resolution and a large field of view.

As for the spectral and radiometric characteristics, ABWI can capture the RGB and NIR information with the radiometric resolution of 12 bits. These features are very difficult to combine in one imaging system, because the remote sensors always have to make trade-offs among many characteristics such as geometric, spectral and radiometric characteristics (Dong et al., 2022). ABWI's spectral and radiometric characteristics are also good when it has excellent geometric characteristics.

As for the accessories, ABWI has a high-precision POS system, which can record the IMU and GPS information of the aircraft more accurately. What's more, ABWI is equipped with a laser ranger. It can obtain the relative distance between the aircraft and the ground feature. This information can feed back to the flight altitude control system and assist the aerial triangulation in the data processing as the POS data do. In addition, the roll encoder and pitch encoder can compensate for the additional changes in pitch and roll angles.

Parameters	ABWI	A3 Edge
Focal Length (mm)	450	300
Pixel Size (μm²)	6.4*6.4	7.4*7.4
Single Frame Size (pixels)	5120*3839	4864*3232
Single Lens FOV (degree)	4.17*3.13	6.9*4.6
Max. Cross Track FOV (degree)	120	106
Along Track FOV (degree)	7.7	13.5
IFOV (mrad)	0.0142	0.0247
2000m GSD (m)	0.03	0.05
Frame Rate (fps)	15	8
Max. Pitch Angle Compensation (degree)	±9	(optical compensation)
Bands	4 (RGB+ NIR)	4 (RGB+ NIR)
Radiometric Resolution (bits)	12	12
Lens	2	2
Laser Ranger (Bool)	True	False

Table 1. Parameter comparison of ABWI and A3 Edge

Table 1 represents the parameter comparison of two area-array whiskbroom imagers. A3 Edge is a commercial digital aerial camera developed by an Israeli corporation called VisionMap. A3 is a family of digital aerial cameras and photogrammetric processing systems (Raizman and Gozes, 2015). It includes two area-array whiskbroom imagers (A3 and A3 Edge) and a data processing system (A3 LightSpeed). A3 Edge is the next generation of A3. ABWI also has an old generation, but it's loaded on the UAV (Zhao et al., 2022).

From the parameter comparison table, we can know that both airborne area-array whiskbroom imagers have very excellent characteristics and can outperform most airborne imagers in geometric characteristics. But these two airborne imagers achieve this high performance in different ways. ABWI has a higher spatial resolution (smaller IFOV) but smaller single lens FOV and along track FOV, while A3 Edge has a larger FOV but lower spatial resolution (this resolution is still very high in airborne imagers). And the maximum cross track FOV of ABWI is larger than A3 Edge. This means that if ABWI acquires data of the same FOV as A3 Edge, ABWI needs to sweep faster and has the shorter exposure time. However, ABWI has a faster frame rate and higher spatial resolution. Therefore, ABWI can have a more flexible flight altitude and sweep smaller angles to acquire the same size area at the same GSD.

Additionally, the compensation method of ABWI is mechanical structure compensation and post-processing algorithm, while the method of A3 Edge is optical compensation. In terms of physical structure, ABWI can compensate for the pitch angle and roll angle. Due to the variation of the yaw angle is always the smallest when the aircraft is flying straight forward, we can make the compensation of the yaw angle during the data processing with the help of POS data, as well as motion in XYZ direction. A3 Edge can compensate for forward motion and roll rotation by optical compensation, and vibration by the stabilizer. The compensation range of A3 Edge is unknown, but it may be enough for most situations. The optical compensation requires a higher manufacturing technique and can achieve higher integration than mechanical structure compensation, but it also costs more and is not convenient for maintenance.

Apart from these, ABWI is integrated with a laser ranger, which provides more auxiliary information for controlling flight altitude and aerial triangulation. And it can achieve higher precision than other imagers when there is no GCP (ground control point).

Overall, both ABWI and A3 Edge are very outstanding among airborne imagers, but each of them has its own characteristics.

3. DATA PROCESSING

The data processing software DPGridApx of ABWI is developed by the RSGIS DPGrid Group in Wuhan University (WHU RSGIS DPGrid Group, 2022). The DPGridApx is a member of the DPGrid software series. Users just need to import the raw data, click the mouse a few times, wait for the data to be processed, and can get the final product such as DOM, DSM and 3D Models. This software is also a distributed processing system based on cluster computers, which can run on either common personal computers or high-performance servers (Xi and Duan, 2020).

3.1 Workflow

The data processing of ABWI contains four main steps: pre-processing, radiometric correction, geometric correction, and digital geographic product production. Relatively speaking, the main difference in data processing between cameras with different imaging methods or structures is the pre-processing. This is because the other steps are more mature and the input and output formats are more fixed. The main purpose of pre-processing is to improve the image quality and to convert the raw data into a more standard format for participation in the later processing directly. The whole data processing workflow of ABWI is shown in Figure 4.

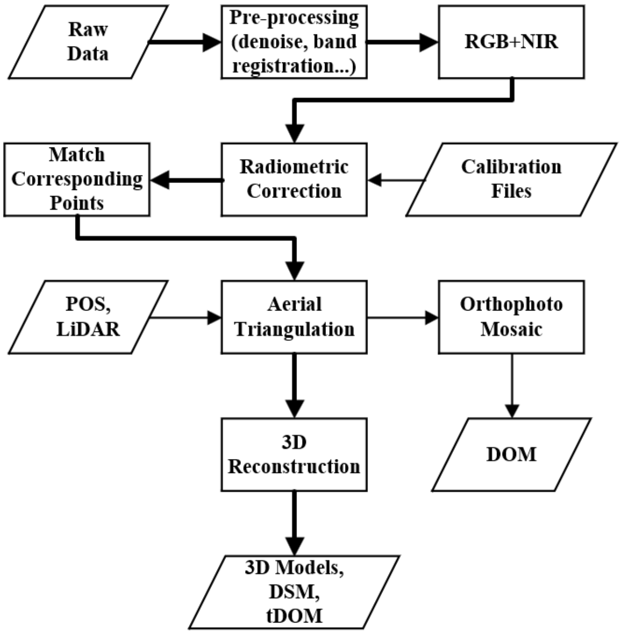

Figure 4. Workflow of ABWI

3.1.1 Pre-processing: The pre-processing of ABWI includes POS data interpolation, coordinate system conversion, geometric calibration, radiometric calibration, denoise, image motion compensation and image registration.

POS data interpolation is very important and necessary, because the sampling times of IMU, GPS and each sensor are different. We have to interpolate the values of IMU and GPS to match each exposure of the sensors. The coordinate system conversion involves converting the attitude of the focal plane of the cameras from the image space coordinate system to the photogrammetric coordinate system. Additionally, since the POS system records the attitude of the 2D scanning platform rather than the camera, the angles of the roll and pitch encoders must be taken into account to obtain the attitude of the focal plane. Radiometric calibration is adjusting different gains and biases of different bands and different pixels in the same band. Geometric calibration is to recover the right and accurate position of each pixel. Denoise is mainly to remove some noise generated in the hardware circuit, such as dark current noise. Image motion compensation is to compensate for the pixel motion caused by the movement and rotation of the sensor during the exposure period. As for ABWI, its pitch and roll angle have been compensated by mechanical structure. So the compensation of yaw angle and motion in XYZ direction is what image motion compensation does. Finally, the image registration is to stack different bands together and make sure each pixel with the same coordinate at different bands is the same ground feature.

After pre-processing, we can acquire multispectral images with relatively right geometric and radiometric information and corresponding POS data. With these data, the rough location on the ground of each image and the position and orientation of the camera at each exposure can be recovered, which can be seen in Figure 5.

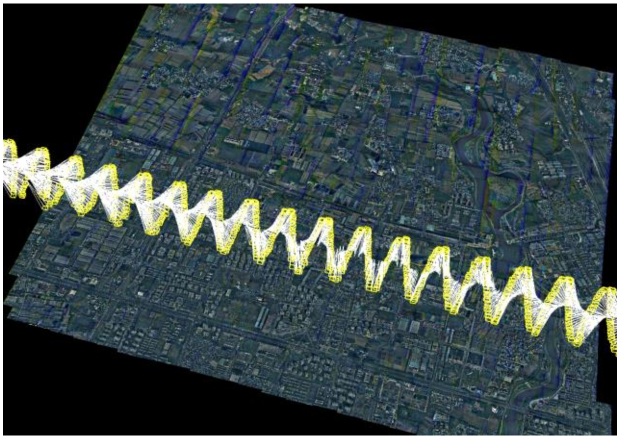

Figure 5. The rough spatial distribution of images and rough position and orientation of focal planes at each exposure

3.1.2 Radiometric correction:

Figure 6. Comparison before and after relative radiometric correction of local radiation distortion

Radiometric correction includes relative and absolute radiometric correction. The relative radiometric correction is to correct the radiation distortion of local regions within the image. This distortion can be caused by errors in the pre-processing or the large side-looking angle of cameras, because the larger the side-looking angle, the longer the optical path and the more complex the interference sources involved. Such problems are very common in sensors with a large field of view (Yang et al., 2010, Tian et al., 2016). The absolute radiometric correction is optional, but it's necessary for quantitative analysis. It transfers the gray value of each pixel in each band into the corresponding reflectance. Figure 6 represents the result comparison of the relative radiometric correction of radiation distortion within a single image.

3.1.3 Geometric correction: The main purpose of geometric correction is to calculate the more accurate position and orientation of cameras. Matching the corresponding points and aerial triangulation are very important steps of geometric correction. Its accuracy directly determines the geometric accuracy of the final products, such as the geographical coordinate accuracy and stitching error between adjacent images. As shown in Figure 7, it represents the detailed results around the stitching lines in the orthophoto mosaic. The cyan lines are the stitching lines. From the zoom-in area, we can find the stitching accuracy is better than half a pixel, which means the accuracy of the geometric correction is pretty well.

Figure 7. Features around the stitching lines

Table 2 and Table 3 show the planar residuals of ground control points (GCP) and check points (CKP), and they represent all RMS values are less than 0.25m. The distribution and planar residuals of the control and check points can be seen in Figure 8 and Figure 9 respectively.

PointID	ΔX	ΔY
GCP1	0.07176	-0.208217
GCP2	-0.040279	-0.175404
GCP3	0.184166	0.126489
GCP4	-0.051793	-0.036139
GCP5	0.215889	0.1242
RMS	0.134149	0.146186

Table 2. Planar residuals of ground control points (unit: m)

PointID	ΔX	ΔY
CKP1	-0.210626	-0.107277
CKP2	0.026849	-0.265622
CKP3	-0.102258	0.215350
CKP4	-0.017592	0.095521
CKP5	-0.323807	-0.125631
CKP6	0.277659	-0.162390
CKP7	-0.253787	-0.236674
CKP8	0.303593	0.265618
CKP9	-0.255781	0.128402
CKP10	0.168885	-0.081099
RMS	0.220979	0.181479

Table 3. Planar residuals of check points (unit: m)

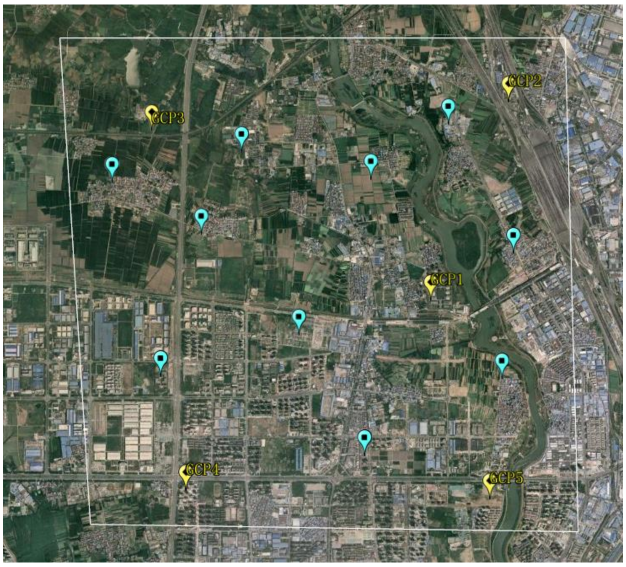

Figure 8. Distribution of control and check points

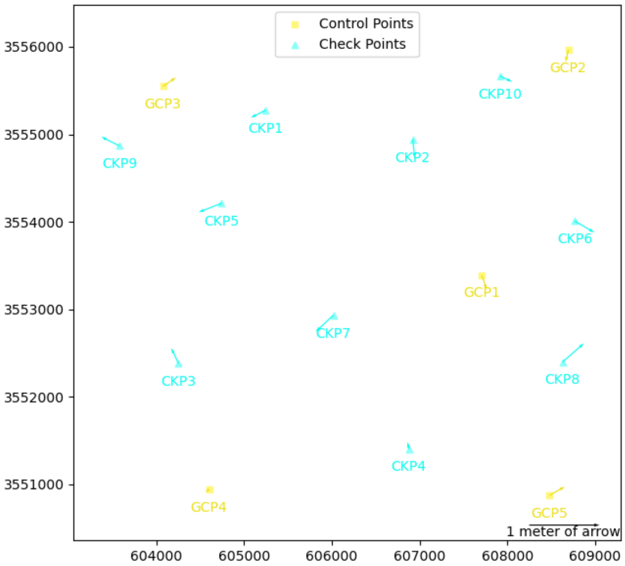

Figure 9. Distribution of planar residuals

3.2 Final Products

After the radiometric and geometric correction, the 3D reconstruction and orthophoto mosaic can reduce a lot of workloads. Meanwhile, the final products can have higher geometric accuracy and more consistent radiation information. The orthophoto mosaic is to produce the DOM (digital orthophoto map), but it's not strictly the orthophoto map. If we want to obtain the tDOM (true DOM), one solution is through the 3D reconstruction. We can reconstruct the 3D models by 3D reconstruction, and produce DSM by 3D models or simply by cloud points. As for the tDOM, we can directly utilize the 3D models or rerun the orthophoto mosaic with the assistance of DSM. The results of DOM and 3D Model can be seen in Figure 10 and Figure 11.

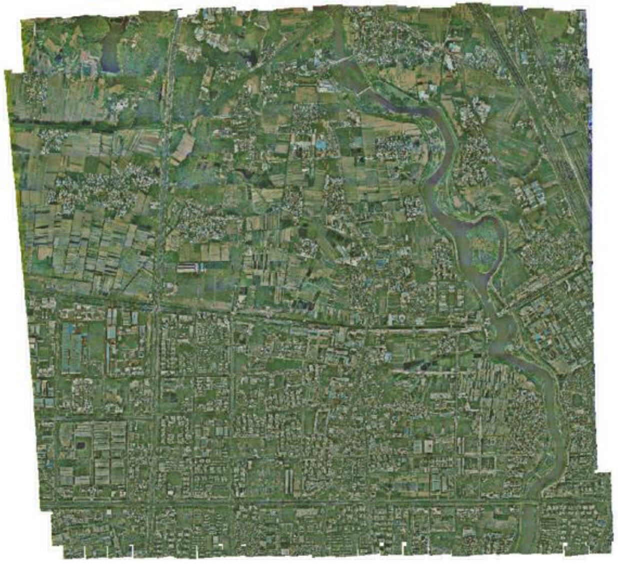

Figure 10. The DOM result of ABWI

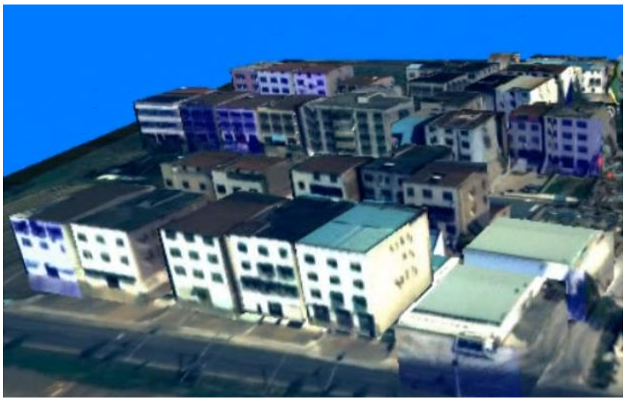

Figure 11. The 3D Model result of ABWI

4. CONCLUSION

This paper presents a new generation of an area-array whiskbroom airborne imager and the corresponding data processing workflow. The whole system of ABWI has the following advantages and application scenarios:

- Large pitch angle compensation. The pitch encoder, mounted in the 2D scanning platform, can compensate for maximum ±9° pitch angle caused by the change of aircraft attitude.
- Sweeping range and speed adjustable. The roll encoder controls the sweeping range and speed of cameras. This feature is particularly useful in many situations, where the sweeping speed can be adjusted to match different flight speeds without changing the aircraft's altitude.
- Large field of view. With the maximum sweeping angle of 120°, ABWI can acquire data when it is not feasible to fly above the measured features, and also can reduce the number of flight routes to improve the efficiency of aerial flight operations. It's very suitable for the oblique photogrammetry and border reconnaissance.
- High spatial resolution. ABWI achieves a ground sampling distance better than 0.03m at an altitude of 2km, which outperforms most airborne imagers.
- Diverse spectral information. ABWI acquires data in four bands of RGB and NIR, which is useful for applications such as ground feature classification.
- Highly automated and customizable software. The software is excellent in both hardware resource scheduling and data processing algorithms, and can also be customized to meet different customer needs.

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