VRS GPS SUPPORTED BUNDLE ADJUSTMENT WITH SELF-CALIBRATION FOR UNMANNED AERIAL VEHICLE IMAGES

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ABSTRACT: UAV (Unmanned Aerial Vehicle) is currently used in civil purpose such as mapping and disaster monitoring. One of UAV advantages is to collect high resolution images for mapping. However, due to payload limitations of UAV, it is difficult to mount metric aerial camera and precise POS (Positioning and Orientation System) device. Instead, only the non-metric camera and the low-cost POS device can be installed. For mapping demands, the Trimble BD970 GNSS OEM board will be carried on the UAV to collect the L1/L2 carry phase measurements during fight time for promoting the flying trajectory accuracy by VRS (Virtual Reference Station) GPS technique. Meanwhile bundle adjustment with self-calibration will be employed for AT (Aerial Triangulation) to overcome the imperfect calibration of non-metric camera by the close-range photogrammetric approach. The offset between image perspective center and GPS antenna center, called GPS antenna offset, has to be faced even though the VRS GPS can provide the flying trajectory information in centimeter level. Therefore, the drift parameters will be utilized to solve the GPS antenna offset problem while performing bundle adjustment with self-calibration, i.e. AT, for precise positioning and orientation of UAV images. All in all, this study will discuss the feasibility of high-accuracy GPS supported AT for UAV images to promote the mapping possibility for UAV images in the future.

1. INTRODUCTION

UAV (Unmanned Aerial Vehicle) is currently used in civil purpose such as mapping and disaster monitoring. One of UAV advantages is to collect high resolution images for mapping (Hruska *et al*., 2005). However, due to payload limitation of UAV, it is difficult to mount metric aerial camera and precise POS (Positioning and Orientation System).Instead, only the non-metric camera and the low-cost POS device can be installed. For mapping demands, the flying trajectory recorded by GPS on UAV must reach centimeter level to support the bundle adjustment of UAV images, i.e.AT (aerial triangulation), for precise positioning and orientation of UAV images. Thus, the numbers of ground control points can be reduced. In conventional AT, the establishment of the ground control points is time-consuming and constitutes the major financial costs in aerial photogrammetry projects, especially in non-accessible area. By promoting the accuracy of flying trajectory recorded by GPS on UAV, the GPS supported AT can be implemented for the precise positioning and orientation of UAV images. Both L1/L2 DGPS (Differential GPS) technique and VRS (Virtual Reference Station) GPS technique can achieve centimeter level for collecting precise flying trajectory. However, the L1/L2 DGPS technique must set up a reference station in the mapping area during flight time. Instead, an actual physical reference station is unnecessary by using VRS GPS technique. Practically, it allows the user to access data from a non-existent reference station, called Virtual Reference Station (VRS) at any location within the network coverage area. Therefore, this study will focus on the discussion on VRS GPS technique to support AT of UAV images. Two problems, GPS antenna offset and imperfect camera parameters, should be concerned in this study. The GPS observation equations obtained from flying trajectory should take the GPS antenna offset, i.e. the offset between the GPS antenna center and the perspective center of UAV images, in account. Drift parameters will be introduced to deal with the GPS antenna offset problem. On the other hand, because the camera carried on UAV is non-metric camera, self-calibration bundle adjustment will be implemented to solve the imperfect camera parameters calibrated by the close-range photogrammetric approach. Finally, this study will discuss the feasibility of high-accuracy GPS supported bundle adjustment with self-calibration for UAV images through the related simulated experiments.

2. METHODOLOGY

The topic of this study is to use VRS GPS techniques to support AT for UAV Images. Therefore, four important key points about this study will be described in this section: (1) VRS GPS techniques for precise flying trajectory; (2) linear drift parameters for solving the GPS antenna offset; (3) appropriate configuration of ground control points; (4) self-calibration bundle adjustment for compensating the imperfect camera parameters.

2.1 VRS GPS techniques for precise flying trajectory

The conventional kinematic positioning approach is based on L1/L2 carry phase measurements processed in double differences, called L1/L2 DGPS technique. However, the L1/L2 DGPS technique has some limits in AT procedure. The first one is the baseline distance limit. Generally, the baseline should be shorter than 30 km (Cramer, 1997; Bruton, 2001).The second one is the reference station which must be placed in mapping area during flight time. New positioning approach, called VRS GPS technique, doesn't require an actual physical reference station. A virtual reference station is established during data processing. Thus it allows the user to obtain data from a virtual reference station at any location within the network coverage area by internet such as Figure 1. With VRS GPS technique, users within the reference station network can operate consistently at greater distances without degrading accuracy (Vollath *et al*., 2002).

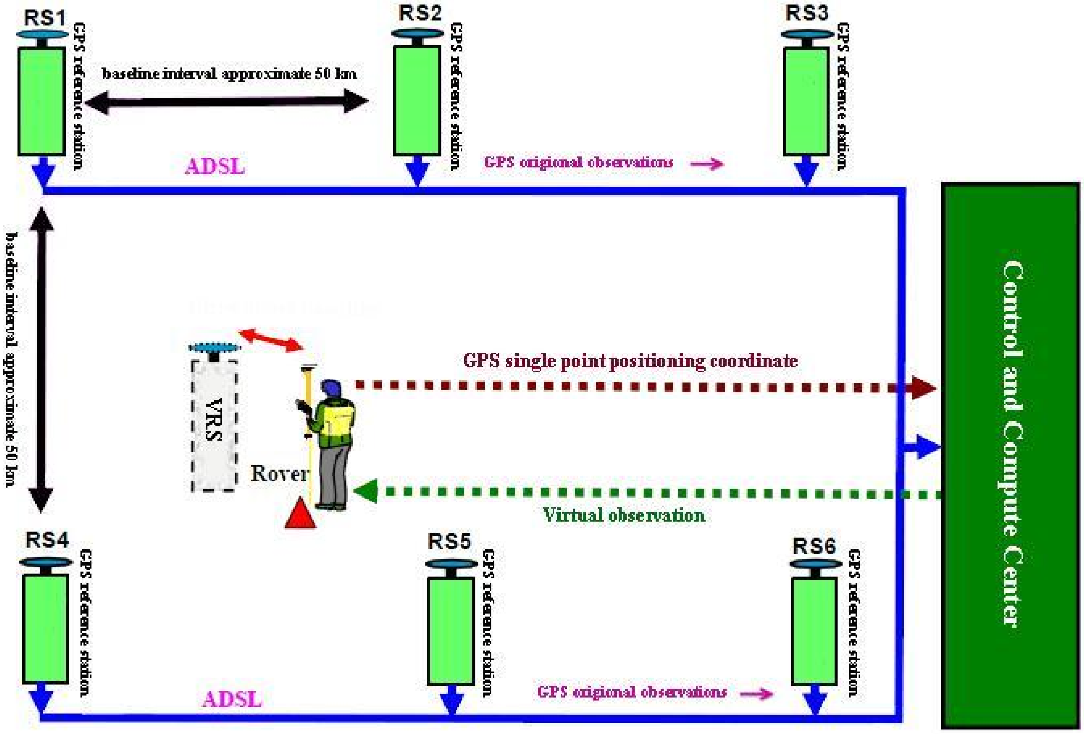


Figure 1: schematic diagram of VRS GPS positioning (NLSC, 2010)

In Taiwan, National e-GPS system is established by using VRS GPS technique. There are 78 reference stations in Taiwan such as Figure 2. With high density, the distance between reference stations is no greater than 50 km. The e-GPS system provides real-time L1/L2 differential correction to the user's receiver. The GPS corrections are available from e-GPS services of National Land Surveying and Mapping Center. Corrections are necessary to eliminate errors and improve the accuracy of GPS positions. The e-GPS networks services provide dual-frequency (L1/L2) real-time differential GPS corrections to improve accuracy for a single point positioning data. Thee-GPS service uses data from 78 reference stations to compute corrections that are more accurate than corrections from a single reference station. Then these corrections are broadcast over the internet. Some empirical investigations focus on the precision of VRS GPS technique for static point positioning, the precision of VRS GPS technique in these results did reach 2 centimeter level in terrestrial test (Retscher, 2002; NLSC, 2010). Therefore, in this study, VRS GPS will be selected for AT of UAV images.

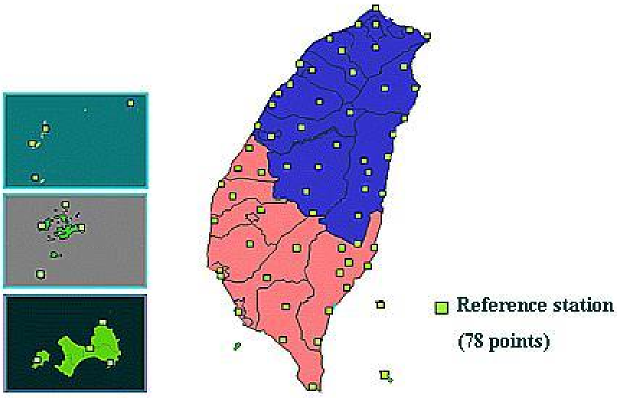


Figure 2: configuration of VRS GPS reference stations in Taiwan (NLSC, 2010)

2.2 Linear drift parameters for solving the GPS antenna offset

The location data by VRS GPS technique is corresponding to the GPS antenna phase center. There is a spatial offset between the GPS antenna center and the camera perspective center, such as Figure 3.In precise AT for mapping demands, the GPS antenna offset, which can be described by equation (1), should be considered.

Figure 3: the offset between the GPS antenna center and the camera perspective center

$$\begin{bmatrix} X_{projection} \\ Y_{projection} \\ Z_{projection} \end{bmatrix} = \begin{bmatrix} X_{GPS} \\ Y_{GPS} \\ Z_{GPS} \end{bmatrix} - \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} \tag{1}$$

$X_{projection}$,$Y_{projection}$,$Z_{projection}$, coordinates of camera perspective center
X_{GPS},Y_{GPS},Z_{GPS} , coordinates of GPS antennacarry phase center
ΔX,ΔY,ΔZ , offset between GPS antenna carry phase center and camera perspective center

Drift parameters are introduced in GPS supported AT by Colomina (1989), Ackermann (1990), and Friess (1990), to deal with time shift, interpolation, and undetected signal interruptions between satellite and receiver. Blankenberg (1992) discovered the drift parameters to compensate the system error caused by residuals of GPS antenna offset vector. Thus the GPS antenna offset doesn't need to precise. LPS ORIMA software (Hinsken *et al*., 2002) can deal with the unknown GPS antenna offset. If the offset vector is unknown, it is recommended to introduce one set of GPS drift parameters per strip. This will compensate most of the influence of the offset vector. In fact, the size of UAV is smaller than the aircraft for conventional aerial photogrammetry. The GPS antenna offset is hard to be determined precisely by terrestrial survey method. In this study, the drift parameters are regarded as unknown. Additionally, the other remaining error can be compensated by drift parameters. For example, time shifts, interpolation, and different geodetic datum have appeared to be systematic, these systematic effects can be eliminated by means of appropriate additional parameters such as drift parameters (Blankenberg, 1992).The drift can be attributed to remaining uncertainties in a priori corrections (e.g. atmospheric refraction), and unmodelled error effects (e.g. satellite orbit errors), in spite of applying differencing techniques. The sensitivity of kinematic positioning with respect to an uncertainty of the initial ambiguity parameter has to be mentioned in particular. During a time interval, such as 10-15

minutes, this drift error is approximately linear. Special analyses have shown that incorrect ambiguities cause noticeable drifts in the subsequent kinematic positioning (Friess, 1991).
Therefore, these systematic errors can be modeled by six parameters one constant, and one time-dependent shift per strip. Since the GPS recorded positions are treated as observation in the bundle adjustment, it is possible to estimate these six drift parameters. The antenna coordinates are treated as observations instead of the exposure station coordinates. The GPS antenna offset is regarded as constant, thus the new observation equation (2) is as the following:

$$\begin{bmatrix} X_i^{GPS} \\ Y_i^{GPS} \\ Z_i^{GPS} \end{bmatrix} + \begin{bmatrix} V_{X_i}^{GPS} \\ V_{Y_i}^{GPS} \\ V_{Z_i}^{GPS} \end{bmatrix} = \begin{bmatrix} X_i^{PC} \\ Y_i^{PC} \\ Z_i^{PC} \end{bmatrix} + \left(\begin{bmatrix} ax \\ ay \\ az \end{bmatrix} + \begin{bmatrix} bx \\ by \\ bz \end{bmatrix} \times (t - t_0) \right) \tag{2}$$

X_i^{GPS},Y_i^{GPS},Z_i^{GPS} , GPS antenna coordinates of image i
$V_{X_i}^{GPS}$,$V_{Y_i}^{GPS}$,$V_{Z_i}^{GPS}$, residuals for X_i^{GPS},Y_i^{GPS} and Z_i^{GPS}
X_i^{PC},Y_i^{PC},Z_i^{PC} , coordinates of camera perspective center i
$R(\omega, \varphi, \kappa)$, orthogonal rotation matrix composed of non-linear functions of the three angles ω, φ, κ
ax, ay, az , time independent translations of strip
bx, by, bz , time dependent translations of strip
$(t - t_0)$, time since start of strip

2.3 Configuration of ground control points

With the development of GPS technique, such as RTK (Real Time Kinematic) and PPP (Precise Point Positioning), the survey of ground control points is more convenient but still time-consuming and cost-highly in mapping projects, especially in non-accessible area. In GPS supported AT, if the precise perspective centre of UAV images can be determined by GPS technique, an intuitive imagination is that the image perspective centers can be regarded as control points, just like the ground control points were moved up into the air. Ideally, GPS supported AT doesn't require any ground control point. However, the coordinate system of GPS positioning results is WGS84 coordinate system, the mapping coordinate system is most often done in national reference system, such as Taiwan projection coordinate system: TWD97. There is no absolute geodetic transformation formula available. It is necessary to transform WGS84 coordinates into the mapping coordinate system. Therefore, at least three ground control points are necessary for datum transformation. On the other hand, the unknown drift parameters mentioned in section 2.2, raise the problem of singularities. There are two approaches to avoiding singularities (Ackermann, 1992). Two chains of vertical control points are added or two cross strips are flown, such as Figure 4(a) and 4(b). The vertical control points should locate at the side overlap, as shown in Figure 4(a), which will cause a trouble especially in non-accessible areas. Therefore, by adding the cross strip it will be convenient for establishment of control points as shown in Figure 4(b).

(a) Method 1 (b) Method 2
Figure 4: Configuration of ground control points

2.4Self-calibration bundle adjustment

The non-metric cameras use low cost lens and provide autofocus function. Thus the interior orientation of non-metric camera is more unstable than metric camera. On the other hand, most of the camera calibration is implemented by the close-range photogrammetric approach. Therefore, the camera calibration environment cannot be similar to the imaging environment of UAV images. This leads to the calibrated camera parameters by the close-range photogrammetric approach are different from those of UAV image exposure. Also, the actual system error may vary from each camera. Thus additional self-calibration parameters are introduced into the bundle adjustment, see equation (3), in this study to solve the imperfect camera calibration. The extension of the mathematical model of bundle adjustment allows the compensation of the actual systematic errors.

$$\begin{cases} x_a - x_0 + \Delta x = -f\left[\dfrac{m_{11}(X_A - X_L) + m_{12}(Y_A - Y_L) + m_{13}(Z_A - Z_L)}{m_{31}(X_A - X_L) + m_{32}(Y_A - Y_L) + m_{33}(Z_A - Z_L)}\right] \\ y_a - y_0 + \Delta y = -f\left[\dfrac{m_{21}(X_A - X_L) + m_{22}(Y_A - Y_L) + m_{23}(Z_A - Z_L)}{m_{31}(X_A - X_L) + m_{32}(Y_A - Y_L) + m_{33}(Z_A - Z_L)}\right] \end{cases} \quad (3)$$

x_a,y_a , photo coordinates of image point a
x_0,y_0 , coordinates of principal point
Δx, Δy , additional parameters for self-calibration
f , focal length of lens
X_A,X_A,X_A , object space coordinates of point A
X_L,X_L,X_L , object space coordinates of exposure station
m_{ij} , functions of omega, phi and kappa rotation angles

Grün (1978) proposed additional parameters to overcome remaining systematic errors caused by effects like non-flatness in the focal plane, non-modeled lens distortions, or anomalies in refraction. Physical meaningful error terms are estimated by using appropriate coefficients to describe the changes in the geometric values of interior orientation and additional parameters like scale, shear, radial and decentering lens distortion (Brown, 1971).The result has shown that the remaining systematic effects in height are modeled and the accuracy could be improved by using the subset of Brown's parameters for self-calibration (Cramer *et al*., 2000). The Brown self-calibration model, originally developed for frame cameras, was adapted for this study as shown in equation (4).

$$\begin{aligned} \Delta x &= \Delta x_0 + x[a_1(r^2 - r_0^2)^2 + a_2(r^4 - r_0^4) + a_3(r^6 - r_0^6)] + b_1 x + b_2 y \\ &\quad + \frac{x}{f}[c_1(x^2 - y^2) + c_2 x^2 y^2 + c_3(x^4 - y^4)] + d_1 xy + d_2 x^2 + d_3 x^2 y + d_4 xy^2 + d_5 x^2 y^2 \\ \Delta y &= \Delta y_0 + y[a_1(r^2 - r_0^2) + a_2(r^4 - r_0^4) + a_3(r^6 - r_0^6)] + \frac{y}{f}[c_1(x^2 - y^2) + c_2 x^2 y^2 + c_3(x^4 - y^4)] \\ &\quad + d_6 x + d_7 x^2 + d_8 x^2 y + d_9 xy^2 + d_{10} x^2 y^2 \end{aligned} \quad (4)$$

Thus, by using self-calibration bundle adjustment for AT of UAV images, not only the exterior orientations for each image are estimated but also the coordinates of new object points and additional parameters for camera self-calibration are determined simultaneously.

3. RESULTS

3.1 Experiment Design

Due to flight application procedure in Taiwan, no test data for VRS GPS supported AT are collected at this moment. Therefore, in this section two tests are designed to discuss the feasibilities of this study: (1) the test of kinematic VRS GPS at high-speed movement; (2) the test of VRS GPS supported AT for UAV images with simulation data.

3.1.1 Kinematic VRS GPS at high-speed movement

For mapping demands, in the future the Trimble BD970GNSS OEM board, short for Trimble BD970 as shown in Figure 5, will be carried on the UAV to collect the L1/L2 carry phase data during fight time for promoting the flying trajectory accuracy by VRS GPS technique. Therefore, Trimble BD970 is used to access and process GPS data in this test first. Trimble BD970 is more advanced than other GPS log hardware. This board can log 50 records per second. Except for precision, Trimble BD970is light-weight, only1.2 Kg (with internal battery, radio standard antenna), and it can be installed on the UAV with limited payload. The specification of Trimble BD970 is shown in Table 1.

Figure 5: Trimble BD970 GNSS OEM board

Table 1: Trimble BD970 format

Dimensions(L x W x H)	100 mm x 60 mm x 11.6 mm
Initialization time	Typically, less than 10 seconds
Initialization reliability	Typically>99.9%

For simulation of high speed movement of UAV, the antenna was attached on the top of a vehicle such as Figure6, and then the vehicle was driven with speed approximately 100 km/hour and moved on the national highway from Ankeng Interchange to National Chengchi University. The GPS log rate is 5Hz and kinematic VRS GPS position in real time (the receiver status of VRSGPS real-time positioning shown in Figure 7) is realized via internet to connect NLSC e-GPS service. The Trimble BD970 will record the GPS originalL1/L2 phase observation data and VRS GPS positioning results in real time simultaneously. Then L1/L2 carry phase DGPS positioning results are calculated to check VRS GPS positioning results. The reference station for L1/L2 carry phase of DGPS was placed on the top of the general building in National Chengchi University.

Figure 6: GPS antenna attached on the top of the vehicle

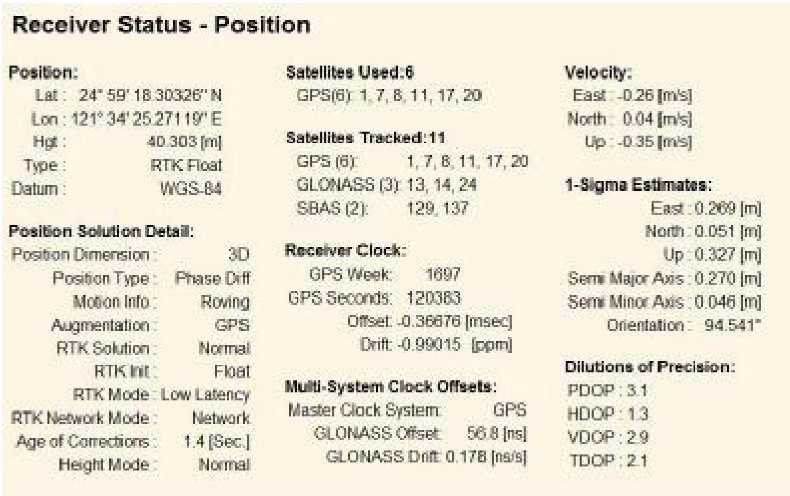


Figure 7: Receiver status of VRS GPS real-time positioning

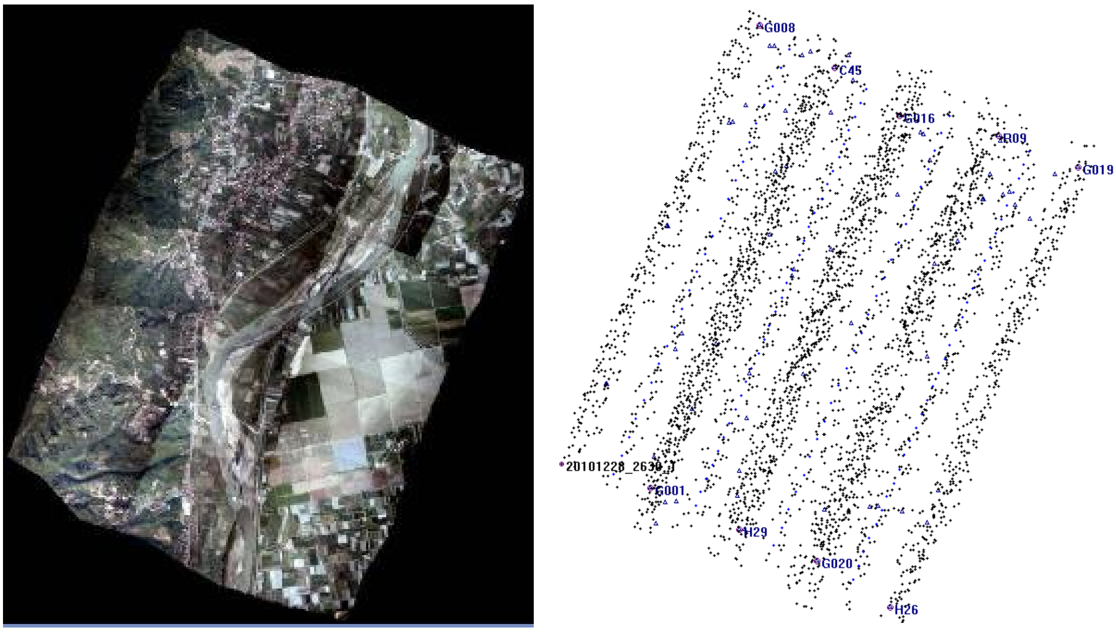
3.1.2 Test of VRS GPS supported AT for UAV images with simulation data

Due to no real data available, simulated data will be used to tested for the feasibility of VRS GPS supported bundle adjustment with self-calibration, i.e. AT, for UAV images by LPS ORIMA. The simulated data was generated from a UAV photogrammetry project. The project area was located in the mountain area of Kaohsiung City in Southern Taiwan such as Figure 8(a). The exterior orientation parameters with GPS antenna offsets are regarded as GPS observations. The simulated GPS antenna offset vector is (0.10m, 0.10m, 0.40m) in this study. Also the image point observations, GPS observations, and ground control points were generated with random error according to their related observation accuracy as shown in Table 2.

Table 2: the simulated random error in observations

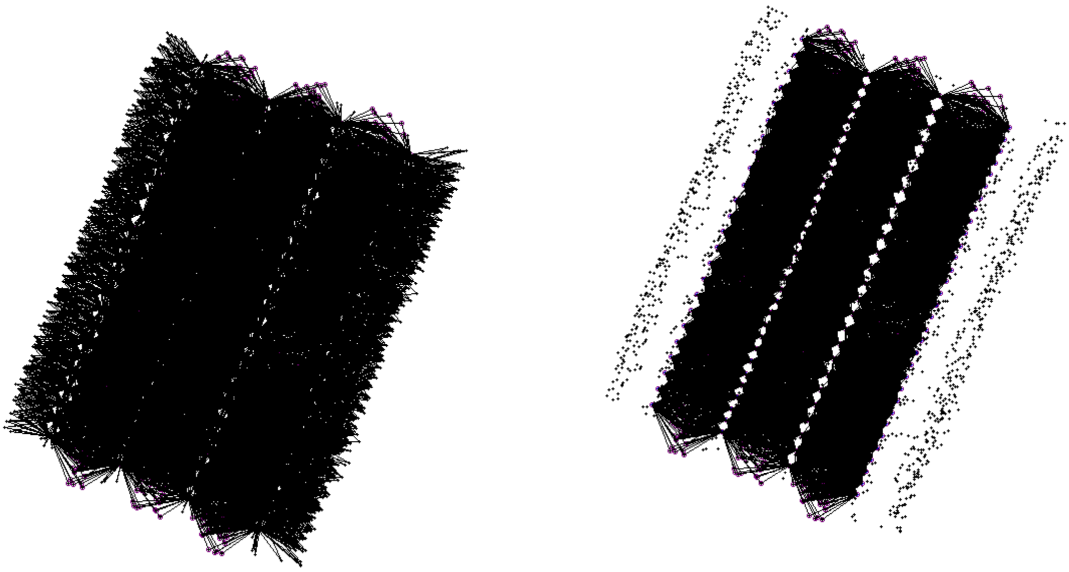
Observation type	Standard deviation	Observation number
Photo point observation	3um	26008
Ground control point	(5cm,5cm,10cm)	10
GPS data	(5cm,5cm,10cm)	112

The Brown self-calibration model, originally developed for frame cameras, was adapted for this study. There are 4 strips, 112 UAV images for this study. Side/Forward overlaps are 60%/ 80%. The control points have 10 points, the allocation is shown as Figure 8(b).In this test, abundant tie points, see Figure 9, are generated to improve the geometry of AT for UAV images. Figure 9(a) shows the connections from perspective centers to tie points in mapping area. Figure 9(b) shows the connections of tie points in overlap area between flight strips. Because the self-calibration and drift parameters are strongly correlated with the estimated exterior orientation parameters, this study will use check points to inspect the AT accuracy of UAV images. Due to no cross strip data available, the vertical control points will be simulated and placed in the overlap area. The check points have 16 points (see Figure 10).



(a) Test area (b) Configuration of ground control points

Figure 8: test area and the configuration of ground control points



(a) Connections between perspective centers and tie points (b) Connections of overlaps

Figure 9: geometry of AT

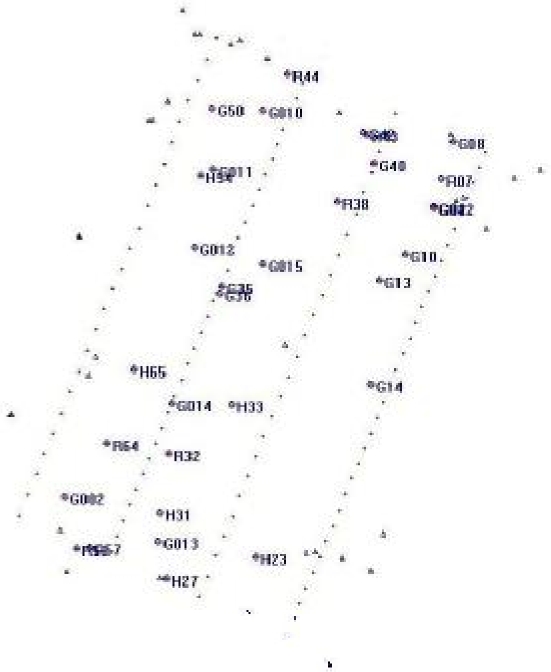


Figure 10: check point configuration

3.2 Experiment Result

3.2.1 Kinematic VRS GPS at high-speed movement

The VRSGPS trajectory is overlay on the Google Earth such as Figure 11. Some trajectory cannot collect VRS GPS data due to the occlusion from some tunnels on the high way. The VRS GPS positioning results are verified by visual approach. The positioning results of VRS GPS and L1/L2 DGPS were overlay on the Google Earth, as shown in Figure 12. The results almost locate on the same position when zooming in. By quantitative analysis, 640 points determined by L1/L2 DGPS are used to inspect the VRS GPS positioning results at the high speed movement after bundle detecting and removing. The difference statistics between VRS GPS and L1/L2 DGPS positioning results were listed in Table 3. From Table 3, the kinematic VRS GPS positioning results did reach centimeter level. Thus the precise VRSGPS positioning results can support AT for UAV images.

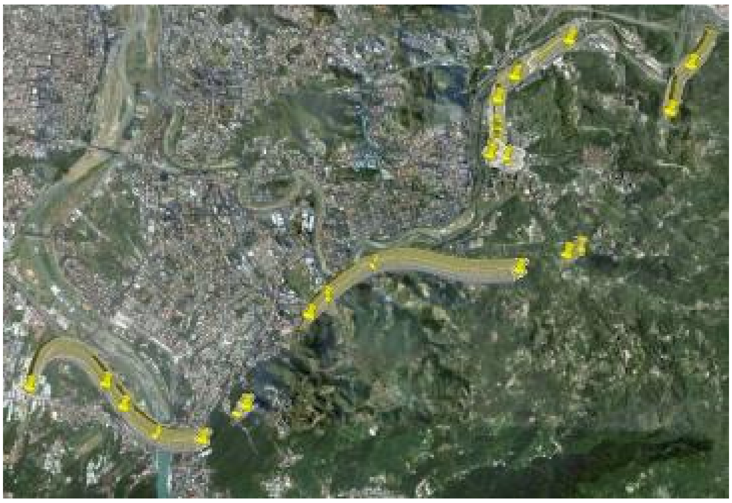


Figure 11: VRS GPS positioning result on the Google Earth

Figure 12: Part of L1/L2 DGPS and VRS GPS positioning results overlay on the Google Earth

Table 3: Statistics indicators of difference between VRS GPS and L1/L2 DGPS

	dE	dN	dh
Mean	-0.022	0.032	0.062
Minima	-0.041	-0.007	-2.185
Maxima	-0.002	0.059	0.114
RMSE	0.022	0.033	0.118

3.2.2VRS GPS supported AT for UAV images with simulation data

In this test, the check points were used to verify the accuracy of VRS GPS supported AT for UAV images. This study generated three test datasets by appending random errors in observations. Because the test area is located on mountainous area, it makes great influence in height direction when a little bit changes occur in image point observations. The accuracy of point determination in aerial photogrammetry is decided by the bundle intersection conditions that depend on the accuracy of GPS observations, exposure location, image coordinates, and the configuration of ground control points. After AT, the RMSE (Root Mean Square Error) of check points for three simulated datasets was calculated for (E, N, h), the results are shown as in Table 4. Then the mean of RMSE is calculated as shown in Table 5. The RMSE of planimetric was 1.019 m; the RMSE of vertical was 2.144 m. Due to terrestrial factor, the RMSE of height direction was greater than other directions.

Table 4: RMSE of 3datasets for GPS supported AT of UAV images (unit: meter)

dataset	E	N	h
1	0.503	0.869	2.132
2	0.437	0.888	2.221
3	0.395	0.993	2.079

Table 5: mean of RMSE for GPS supported AT of UAV images (unit: meter)

E	N	h
0.445	0.916	2.144
horizontal		vertical
1.019		2.144

4. CONCLUSIONS AND SUGGESTION

(1) The GPS reference station for VRS GPS technique is unnecessary, so only one airborne GPS receiver is required. Thus it can not only reduce the difficulty and cost of aerial photogrammetry projects, but also increase the flexibility of AT. The conventional L1/L2 DGPS supported AT can be replaced by VRS GPS from the tests in this study, which makes more extensive applications.VRS GPS supported AT will play a very important role in national fundamental surveying and mapping, especially in non-mapped areas and non-accessible areas.

(2) From the simulation data tests, for mapping demands, the RMSE of VRS GPS supported AT with self-calibration for UAV images did correspond to the 1:5,000 scale of United States National Map Accuracy Standards such as Table 6.

Table 6: ASPRS Accuracy Standards for Large-Scale Maps
Class 1 horizontal (x or y) limiting RMSE for various map scale

Class 1 Planimetric Accuracy Limiting RMSE (meters)	Map Scale
0.25	1:1,000
0.50	1:2,000
1.00	1:4,000
1.25	1:5,000
2.50	1:10,000
5.00	1:20,000

The configuration of ground control points is not discussed in this study. Therefore, it will focus on the appropriate configuration of control points for AT with self-calibration of UAV images in further study. Also, the real collected data will be used to investigate the reachable accuracy in the future.

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