ADVANCES IN GPS-ASSISTED HELICOPTER PHOTOGRAMMETRY AND ITS APPLICATION TO HIGH PRECISION HIGHWAY PROFILING

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ABSTRACT

An efficient road network is essential for a country's economic activity. Therefore, it is necessary to minimise any effects of maintenance and expansion programmes. Around ten years ago, Photarc Surveys Limited of Harrogate UK decided to address the problem of using traditional terrestrial survey techniques to provide essential highway profiles. A non-contact photogrammetric system was conceived and developed to provide the necessary data without disturbing traffic flow. A Zeiss UMK 10/1318 Universal Camera is 'cradled' out of the rear door of a Bell 206B Jet Ranger helicopter to capture images of the highway from a typical altitude of 75m. Single model analytical analysis is then utilised to give regular grids of road spot heights to RMSE ±0.005m using control points surveyed at 40m intervals along the hard shoulder of the highway (Smith and Joy, 1995a).

Despite the ability of the system to provide clients with cost effective profiles, the requirement for full ground control along the hard shoulder is undesirable both for financial and safety reasons. The Institute of Engineering Surveying and Space Geodesy became involved in late 1993 with two distinctive aims. These were, firstly, that aerial triangulation should be applied in the analytical analysis to quantify the potential for reducing ground control. Secondly, that the Institute should apply its extensive experience in kinematic GPS research to the existing photogrammetric system.

This paper presents the most recent system developments and details the bundle estimation analysis undertaken to investigate performance. Finally, details are given of the current work and future plans.

1. INTRODUCTION

An efficient road network is essential for a country's economic activity. Therefore, it is necessary to minimise any effects of maintenance and expansion programmes. Around ten years ago, Photarc Surveys Limited of Harrogate UK decided to address the problem of using traditional terrestrial survey techniques to provide essential highway profiles. A non-contact photogrammetric system was conceived and developed to provide the necessary data without disturbing traffic flow.

A Zeiss UMK 10/1318 Universal Camera is 'cradled' out of the rear door of a Bell 206B Jet Ranger helicopter to capture images of the highway from a typical altitude of 75m. Single model analytical analysis is then utilised to give regular grids of road spot heights to RMSE ±0.005m using control points surveyed at 40m intervals along the hard shoulder of the highway (Smith and Joy, 1995a). Further details of the system's development program and proven performance is dealt with in Boardman (1994).

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2. PRELIMINARY CONSIDERATIONS FOR HELICOPTER PHOTOGRAPHY

The use of aerial triangulation and GPS have been investigated by many eminent researcher's with respect to fixed wing aircraft photography and it is not the intention of the author to retread this ground. However, the use of low altitude helicopter flight is more novel and such an investigation had to consider the unique operational characteristics of this aerial platform (Hansen and Joy, 1995). Preliminary theoretical analysis showed that to achieve the ±0.005m heighting precision level, GPS derived perspective centre coordinates would be required at RMSE Z=±0.007m (height). This is very high,

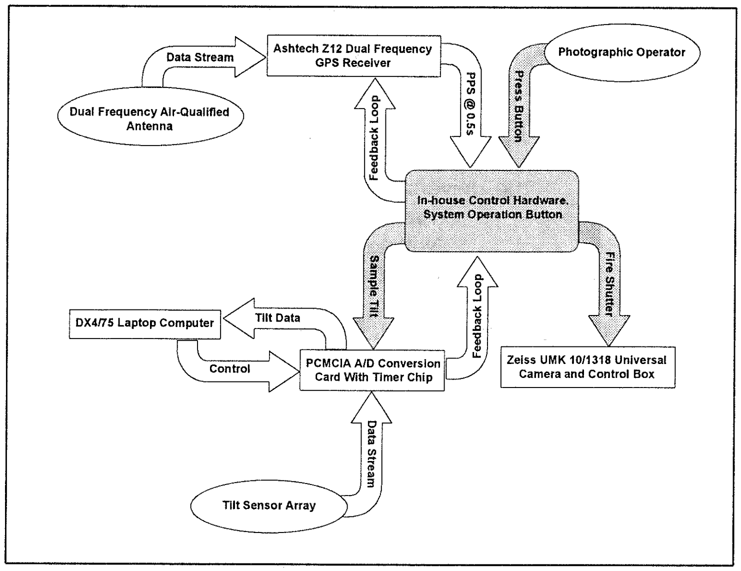

Figure 1 - Overview of the Nottingham approach to GPS-Photogrammetry Integration.

but GPS would still be useful in reducing plan control requirements (RMSE plan ≅±0.025m). Reduced highway heighting precisions of between ±0.010m and ±0.020m would obviously relax these requirements.

3. DEVELOPMENT OF AN INTEGRATED GPS-CAMERA SYSTEM

There have been several stages to the development of the system. The Stage One investigations of system development (integration methodology and initial flight trials) were fully reported to the United Kingdom Photogrammetric Society (Smith and Joy, 1995a) and to an ISPRS-FIG Joint Workshop in Barcelona (Smith and Joy, 1995b). An integrated GPS Photogrammetry camera system has now been developed from the original prototype. Using the latest in receiver technology coupled with in-house hardware and control software, perspective centre coordinates can be derived at each instant of exposure. Despite the use of an array of tilt sensors to give approximate camera tilts, the main interest is in position at this stage. As the motion of a helicopter is less predictable than that of a fixed wing aircraft, interpolation between GPS coordinate solutions would not be desirable. Therefore, the Nottingham system uses the Pulse Per Second (PPS) output of an Ashtech Z12 receiver to fire the camera on a GPS measurement epoch. The delay between the rising edge of the PPS output and the instant of exposure is compensated for through the controlling circuitry without the need to modify the UMK camera or control box. This delay was calibrated in the laboratory with the typical camera settings and orientation (to reproduce operational conditions) as 56.74ms with a standard deviation of 0.42ms. At the usual airspeed of 15mph, this deviation corresponds to a 2.8mm error which illustrates the adequate repeatability of the UMK 10/1318 mechanism.

Figure 1 provides an overview of the system showing the dependancy of each component. Further information concerning the refined system can be found in Smith et al (1996).

The GPS position information is post-processed using the 'On-The-Fly' kinematic software developed independently at Nottingham (Hansen and Joy, 1995). This software uses a combination of two ambiguity search techniques coupled with the option for direct resolution of the widelane ambiguities. Such an approach significantly reduces the number of integer combinations which must be searched. Cycle slip detection and correction software is also available within the IESSG for difficult portions of data.

4. GROUND BASED EVALUATION TRIAL

An important part of the testing of the refined Nottingham system was a ground based evaluation trial. By taking photography of a large building facade whilst moving the system on a trolley, truth positions could be calculated for the antenna phase centre in a similar approach to that reported in Hansen and Joy (1995) and widely understood. A feedback loop in the system also enabled recording of the pulse time, ensuring that the timer chip was functioning correctly. Table 1 summarises the results for two frames of photography which were observed twice (observations a and b).

Frame	dX (m)	dY (m)	dZ (m)	dL (m)
4_4a	0.036	0.046	0.053	**0.076**
4_4b	0.039	0.041	0.050	**0.075**
3_1a	0.048	0.016	0.030	**0.058**
3_1b	0.037	0.012	0.031	**0.049**

Table 1 - Summary of Position Discrepancies.

It can be seen from preliminary evaluation of the vector length (dL), that the relative accuracy is approximately 6cm. However, such a measure is affected by the accuracy of the GPS processing which can easily vary at the centimetre level. The photogrammetric accuracy is also a factor that must be taken into account, particularly as some of the targets were badly blurred.

Additionally, these analysed frames were over exposed due to a fault in the internal mechanism of the UMK. Knowledge of this factor possibly explains the position discrepancy of 0.9cm between frames 3_1a and 3_1b.

To explain the difference between the vector offset accuracy (dL) for the two separate frames it is necessary to look at the standard errors of the NOTF software L1 carrier phase solution. It can be seen that the standard errors are higher for x,y and z in the case of frame 4_4, corresponding to the greater offset vector. In good geometric conditions, NOTF has been shown to comfortably resolve the ambiguities for positioning at the 2cm level. Unfortunately, the satellite geometry during the evaluation trial was adversely affected by the building facade.

Frame	σx (m)	σy (m)	σz (m)
3_1	0.0397	0.0197	0.0348
4_4	0.0460	0.0250	0.0439

Table 2 - Standard Errors for NOTF L1 Carrier Phase Solution at Exposure Station.

In summary it is clear that the new integrated system performs significantly better than the previous one. The evaluation trial was not perfect in that the photography was over-exposed due to a fault in the internal mechanism, and the satellite geometry was obscured by the height of the building facade. However, the trial objectives had still been met successfully.

5. COMBINED ESTIMATION OF SIMULATED GPS DATA IN A REAL FLIGHT TRIAL

As part of the planning of a final flight trial, it was felt that some combined block estimation work with simulated GPS data should be undertaken. The photographic data was from the 15 frame initial evaluation trial undertaken in March 1994 (Smith and Joy, 1995a). All measured points were targets to represent typical control points. Targets were also used at the minor control points since the field surface was 'soft'. The raw GPS data was simulated from the positions provided from a fully controlled photogrammetric block, with information on the satellite geometry provided from the IGS precise ephemeris. Conventional kinematic OTF processing was then used to obtain exposure station coordinates.

The data processing was performed with the in-house software TABBY (its name does not serve as an acronym) running on an SGI Indigo Workstation. TABBY is a combined GPS Bundle Estimation program written by the author during the period of research and has undergone a suitable level of testing prior to operational use. The familiar collinearity equations are used alongside observation equations for the antenna-phase centre offset vector. Control points are introduced as weighted observations because of the precision required by the application. For this adjustment work, the vector offset was held fixed in magnitude in the observation equations and no self-calibration or drift parameters were estimated. The primary aim was to quantify the effect of adding phase centre observations into a bundle estimation in the simplest manner possible.

A Priori estimates for the control standard errors were entered as $\pm$0.005m in plan and $\pm$0.002m height. The a priori image coordinate standard error was 3μm. Table 3 shows positional standard errors for both the control and the unknown points in the photographic test field resulting from processing of several strip combinations. No GPS positions were used, just as in a traditional photogrammetric block. These results are an update from those in Smith and Joy (1995a) and show that the control point standard errors are significantly improved in plan and marginally in height for all cases.

It can be seen that there is an improvement in precision by the addition of photographic strips, with control points consistently of a higher precision to the unknown points. The Centre+Right block is poor because of blurring dictating observation of fewer points. In further discussions this configuration will be ignored as the Centre+Left block is more representative of the precision increase that would be expected.

GPS antenna coordinates were then entered in the estimation under 4 distinct control configurations. These were GPS with no ground control, GPS with 4 full 3D control points in the corners of the block, GPS with the same 4 points plus 6 height points, GPS with the full control configuration, and the values from Table 3 (no GPS used) for comparison. The average standard error for the antenna phase centre positions was 0.5cm plan and 0.7cm height (discussed at the end of this section).

Configuration	Unknown Point Standard Errors (mm)			Control Point Standard Errors (mm)		
Centre	3.0	3.0	4.1	2.6	2.6	1.8
Centre+Left	3.0	2.9	3.8	2.6	2.6	1.8
Centre+Right	3.2	3.0	4.3	2.6	2.7	1.8
Full Block	2.9	2.9	3.7	2.5	2.6	1.8

Table 3 - Conventional Bundle Estimation On Pontefract Test Field.

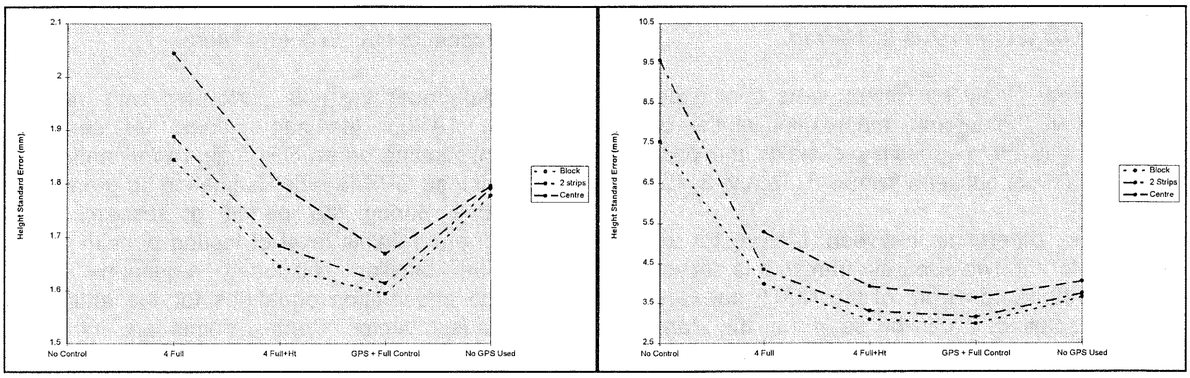

Figure 2 - Effect of Additional Strips On (a) Control (b) Unknown Point Height SE Under Different Control Strategies.

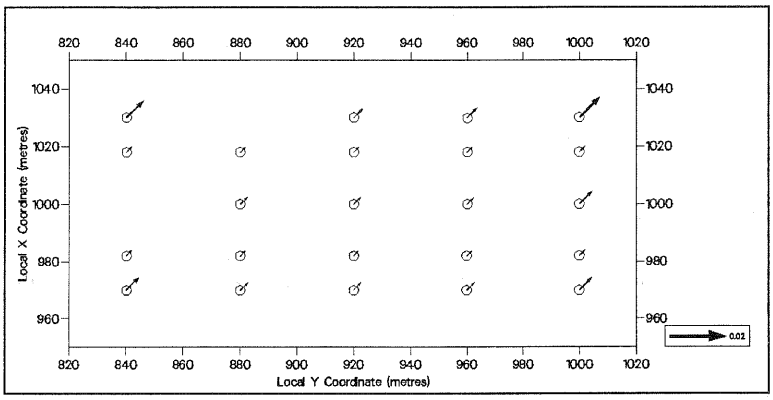

Figure 3 - Heighting Standard Error Distribution Plot for Centre + Lateral Strip (vector unit is metres).

Figure 2 show how the photographic configuration influences the height standard error for the block when the control configuration is altered (they are presented as lines passing through the 5 points defined by the x-axis labels). The addition of a lateral strip to the main centre strip (the 2 strips line) gives a marked improvement in overall precision. The improvement gained by adding the third strip is not so great, which is encouraging when the cost of additional strips of photography is considered. However, with a lateral strip flown in this manner (60% overlap) much of the photograph is unused in the analysis and the far set of control points are not covered. This leads to the standard error pattern for the heights shown in Figure 3 (only the magnitude of the vectors is important). All the far points (those on the top row) have higher height standard errors because they appear on less photographs. The near points (those on the lower lines) show an improvement when compared to a similar plot of only the centre strip. To alleviate this problem, simulated analysis is underway (see Section 6) to investigate the use of a second centre strip, identical to the first but offset in the flight direction by half a photograph 'length'. It is expected that this will improve the standard error pattern from Figure 3.

Table 4 gives a detailed summary of the results for the full block of photography. Processing without control as in the last row leads to a marked decrease in precision. When control points are included in the adjustment, it can be seen that heighting precision is decreased when only four full control points are used in the corners of the block. This implies that there is not so much scope for reduction of height control if the highest precision measurement is required. This result was expected, knowing that reducing plan control would still reduce the overall cost of a photographic flight.

Control Config.	Unknown Point Standard Errors (mm)			Control Point Standard Errors (mm)		
GPS Block	2.4	2.1	3.0	2.1	1.9	1.6
GPS 4 full + height	3.0	2.3	3.1	3.0	2.5	1.6
GPS 4 full	3.2	2.5	4.0	3.2	2.9	1.8
GPS no control	8.9	4.9	7.5	N/A	N/A	N/A

Table 4 - Combined Bundle Estimation With Different Control Configurations.

The precision of the antenna coordinates was derived from a comparison with the true values. Unfortunately, these simulated coordinates were of an unrealistic precision. The simulated data was immune to multipath, geometric effects and cycle slips that would be expected in real flight, giving the results limited physical meaning.

The analysis was extended to investigate how the ground point precision was affected by gradually reducing the precision of the antenna coordinates (between the range 1cm - 5cm at 0.5 cm intervals). This showed results from using more realistic antenna coordinate precisions. Three control point configurations were used, namely no control points, 4 full 3D control points in the corners of the block, and 4 full control plus 6 height control points within the block.

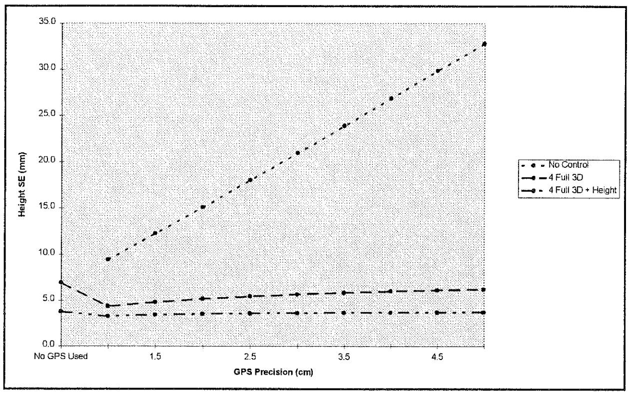

Figure 4 - Effect Of Antenna Precision Degredation On Unknown Point Height Precision (Three Control Strategies).

Figure 4 shows how the antenna precision effects the overall height precision of the unknown points measured in the block. The same data was used throughout the analysis under the three afore mentioned control configurations, with only the antenna coordinate/SE file being altered for each estimation. It is clear that the degredation causes a near-linear degredation of precision when no ground control is used within the photographic block. By comparison, the controlled blocks do not show such a marked degredation. It is not clear from Figure 4 what the relationship is between the other two configurations. To investigate this further we must look at Figure 5a) and b) where the no control strategy has not been plotted.

As would be expected, the configuration with the least height control is most susceptable to antenna precision degredation. When height control is used throughout, the precision degredation of the heights of the unknown points is minimal between the range 2cm - 5cm. Even at 5cm antenna precision, the contribution to the estimation process is still a positive one. The configuration using only 4 Full 3D control points shows a clear degredation by comparison. However, this is still a sub-millimetric difference between each 0.5cm antenna precision interval.

Figure 5 shows that the height precision of the control points degrades in a similar manner under both configurations. The use of additional height control appears only to transpose the line to a higher precision level.

6. Further Combined Estimation Work

The simulations discussed here have concentrated on the high precision end of antenna coordinates. This work is now being extended to investigate the properties of this degredation from 5cm precision down to 15cm precision.

Also, in addition to these estimations, work is now progressing into simulations of different flying heights, flying strategies and control configurations for a longer photographic flight. The data for this work is being completely simulated, using knowledge of the real properties of photogrammetric data at this scale. The GPS data simulation can be improved in a way which will allow the investigation of how satellite geometry affects the final bundle coordinates and standard errors.

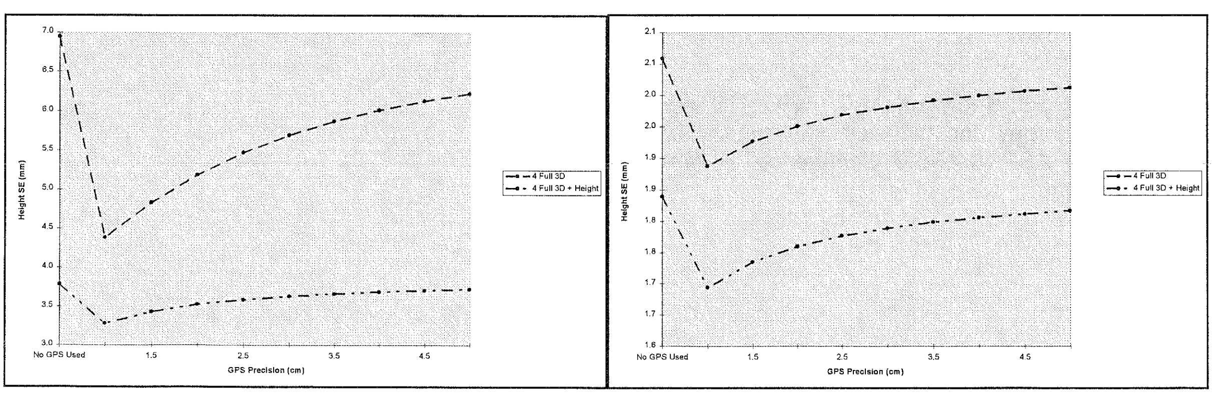

Figure 5 - Effect of GPS Antenna Coordinate Precision Degredation On (a) Unknown (b) Control Point Height SE Under Two Different Control Strategies.

7. CONCLUSIONS

The first indications from the estimation work reported here, are that GPS antenna coordinates will be beneficial to this high precision application. Such simulation analysis is an important part of photogrammetric development. However, practical experience gained through a full flight trial, is most valuable. Of course, there is also the need to test the integrated Nottingham system in true flight conditions. Using knowledge gained from the simulation work, a full flight trial is near to execution. It is hoped that the results from this work will validate the simulations and quantify the operational degredation of system precision.

9. ACKNOWLEDGEMENTS

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10. REFERENCES

Boardman J.C., 1994, High precision levelling of motorways by low level helicopter survey. *Photogrammetric Record 14(84).*

Hansen P. and Joy C.I.H., 1995 High Precision Highway Profiles using Helicopter Borne `On-The-Fly` GPS. *Paper presented at the 8th International Technical Meeting of The Satellite Division of The Institute of Navigation, Palm Springs, California 12-15 Sept. 1995.*

Smith M.J. and Joy C.I.H, 1995a Preliminary investigations into developments in using helicopter photography for highway surveying. *Photogrammetric Record 15(85).*

Smith M.J. and Joy C.I.H., 1995b Developments in an integrated in-flight positioning and orientation system for helicopter photography. *Paper presented at the ISPRS-FIG Joint Workshop "Integrated Sensor Orientation: Theory, Algorithms and Systems", Barcelona 4-8 Sept. 1995.*

Smith M.J., Joy C.I.H, Boardman J.C., 1996. The use of helicopter photography for highway surveying. *Paper presented at the ASPRS/ASCM Conference, Baltimore Maryland April 1996.*