PHOTOGRAMMETRIC METHODS FOR THE INFLIGHT VERIFICATION OF ATTITUDE SENSOR ACCURACY

Andrew R. Marshall
BHP Engineering
Land Technologies Division
Australia

ABSTRACT

Photogrammetric techniques have been used to calibrate medium grade aircraft Attitude and Heading Reference Systems (AHRS) under dynamic conditions. The purpose of the calibration was to determine the accuracy of the sensor measured attitude, comprising heading, pitch and roll, inflight and under operational conditions. Although sensor attitude accuracy was known for select "ideal" conditions, conformance to specifications was unknown under a variety of inflight conditions, including immediately after radical manoeuvering and as a function of different inflight alignment techniques. This paper covers in detail the photogrammetric aspects of the AHRS verification trial and describes the aspects of network design, equipment configuration and data processing dealing with dynamic photogrammetric metrology. Included are significant developments in both equipment configurations and software design for applications in dynamic photogrammetry.

Key Words : Close Range Photogrammetry, Dynamic, Network Design, Cailbration, Accuracy, Attitude

INTRODUCTION

Dynamic photogrammetry involves the photogrammetric metrology of on object subject to some form of motion. In many cases this motion will not influence the static type of photogrammetric approach as it is either negligible or may be effectively ignored. For example, in cases where a fixed datum is not required and the shape of the object is not influenced by the motion, the motion can be considered to be non-existent and free network procedures utilised. Where precision metrology of objects subject to significant vibration is required, strobe lighting can be used to effectively "freeze" the object, based on assumptions of systematic motion, and therefore allow a static type approach. The true dynamic case is evident where metrology is required of an object subject to random motion and positioning is required with respect to some fixed and absolute datum.

In the case of the AHRS verification trial the requirement was to position a transiting helicopter with respect to a fixed and static datum. This positioning was required to determine the helicopter attitude (heading, pitch and roll) for the purpose of sensor accuracy verification. This is therefore an application of true dynamic photogrammetry where object motion is not systematic and where the datum is fixed.

The photogrammetric procedures adopted and developed for the trial needed to include design and implementation considerations relevant to both conventional close range photogrammetry as well as those applicable to a dynamic situation. The conventional design procedures, which are well understood and documented (Fraser, 1984), needed to be augmented by considerations of the influence of motion of a subset of the target array on the resulting survey precision and accuracy.

These factors, which were incorporated rigourously into the network design for this application of dynamic close range photogrammetry, include the influence of motion of part of the target array on datum recovery, the degradation in the conventional bundle adjustment least squares solution for the case where the cameras are not accurately synchronised and the influence of motion on target visibility and photographic clarity.

In addition to these photogrammetric considerations, additional factors needed to be addressed in order to ensure that the resulting derived helicopter attitudes could be accurately referenced to the measured sensor attitudes. Timing of the photogrammetric work needed to be referenced to the on-board timing reference, in this case the GPS time standard. A technique for ensuring that timing correlation was adequate for referencing the two data sets was developed for the trial.

In the following sections the AHRS attitude verification trial will be described in detail. This coverage will include a detailed evaluation of the various design procedures adopted, will outline the developments for least squares analysis in cases of dynamic metrology and will detail the AHRS trial, both methodology and results.

TRIAL DESCRIPTION

The purpose of the trial was to "..obtain data to estimate the inflight accuracy of the Attitude and Heading Reference System (AHRS) as fitted to the Seahawk naval helicopter." (DOD,RAN,1991) Specifications for the trial were to determine instantaneous heading, pitch and roll of the helicopter in transit over an established control network to an accuracy of ± 0.2 degrees. The heading determination was to be with respect to true north. In addition, the time reference of each instant was to be extracted for correlation with attitude data from the sensor data bus.

Figure 1 : Seahawk Naval Helicopter

The Seahawk naval helicopter, as shown in figure 1, is part of the Australian Navy's air fleet and had exhibited degraded performance in terms of attitude determination. In order to effectively verify the performance of the helicopter attitude sensor, multiple transits were to be made by the helicopter, in all cardinal and inter-cardinal directions, before and after rigourous flight manoeuvres and based on two different AHRS alignment procedures. Specifications for the AHRS stated that the sensor ".. shall be capable of determining attitude, heading, position and velocity ....from take-off to landing, after alignment and in any of the required operating modes." (DOD,RAN,1991)

The AHRS accuracy verification trial was undertaken over four days in April 1991 at a Naval airbase south of Sydney and was designed to determine performance of the sensor under these various conditions.

The operational considerations for the trial were as follows :

1. Determination of helicopter attitude over a complete sortie, which comprised twelve initial passes, being passes in all cardinal and inter-cardinal directions, a thirty to forty minute wait while the helicopter performed a series of inflight manoeuvres, then a repeat of the initial sequence. Repeat of this sortie sequence on seven further occasions, each comprising variations in take-off and alignment methods, with various model sensors and with/without simulated failure of GPS/Doppler position updates. A final sortie was undertaken with the helicopter performing a series of banking and hovering manoeuvres. A total of approximately 200 helicopter transits needed to be recorded.

2. The trial was to be undertaken over four days with two sorties per day.

3. The helicopter was to transit at a maximum altitude of 100 metres over the control network and at a maximum velocity of 100 knots. These parameters were set as maximums for the photogrammetric work, however needed to be approached in order to ensure that the turbulent motion expected at reduced velocities and altitudes did not degrade the AHRS attitude measurement on the helicopter.

SURVEY METHODOLOGY AND DESIGN CONSIDERATIONS

The methodology adopted for the survey was based on conventional close range photogrammetric design principles with inclusion of addition considerations to account for the helicopter motion with respect to the control network. Rigourous evaluation of survey accuracy with all potential error sources, both random and systematic, was also undertaken.

Network Design

The survey methodology was determined by consideration of all relevant design principles, in terms of required survey precision, available equipment, site constraints, operational constraints as well as required survey accuracy.

Based on a required accuracy of ±0.2 degrees (one sigma) for each attitude component, along with operational requirements for minimum helicopter operational altitude, it was clear that large format metric cameras were required for the data acquisition. On the basis of the use of a CRC-1 and a CRC-2, of which there was only one of each in Australia, the proposed equipment configuration was for the two cameras to be synchronised and utilised for the trial. A third camera would have significantly improved survey reliability and precision, particularly in the second planimetric direction, however economic and equipment access constraints precluded this.

Simulation studies were undertaken in terms of both accuracy and precision. The precision studies were by standard least squares simulations based on expected random errors as well as the proposed network configuration. The heading precision varied as a function of flight heading and was due to the relatively weak two camera configuration proposed. Accuracy assessment was undertaken by determination of all potential systematic perturbing factors, such as errors in camera calibrations, including the influence of lens distortion and residual film errors, after application of reseau corrections, as well as potential systematic errors in determination of the control network orientation. In addition the influence of the datum, in particular the proposed datum configuration, on the attitude determinations was undertaken. The resulting accuracy predictions for the trial, in terms of heading determination, varied as a function of heading in the relationship of equation 1.

$$\pm 0.05^{o}(1+\sin^{2}\text{ heading}) \qquad ..(1)$$

The accuracy for pitch and roll was largely heading independent and was approximately ±0.2 degrees and ±0.5 degrees respectively. The roll accuracy was significantly reduced in comparison with the heading and pitch determinations due to the small base, approximately 1.5 metres, over which the roll was to be determined. The independence of pitch and roll from flight heading was due to the proposed use of distance measurements between all targets on the helicopter for the definition of the "aircraft system" planimetric component. Both pitch and roll components were to be determined with respect to the aircraft axes and the direction of the vertical.

Control Network

The control network was designed to reference the helicopter to the direction of true north as well as to define the direction of the vertical for pitch and roll determinations. At the operating altitude of 100 metres it was not possible to include static control targets of significant height variation. The network was essentially a planar array of eight targets in a triangular configuration, extending over an area of approximately 60 by 100 metres. The network was of arbitrary origin, with definition of the vertical by precise levelling and true north determination by solar observation. The accuracy of definition of true north was estimated to be ±30 seconds of arc, which was well within required survey tolerances.

Targeting

All targets used in the trial were retro-reflective. The targets on the static control points were a combination of 10 and 20 millimetre circles. The targets on the helicopter, however, needed to be visible with the helicopter in all possible orientations. Circular targets on the base of the helicopter would not have sufficed due to the reduction in reflectance at low incidence angles. Spherical targets, as in figure 2, were made and adhered to the base of the helicopter. This enabled target visibility at all angles of helicopter orientation with no reflectance reduction with reduced incidence angles.

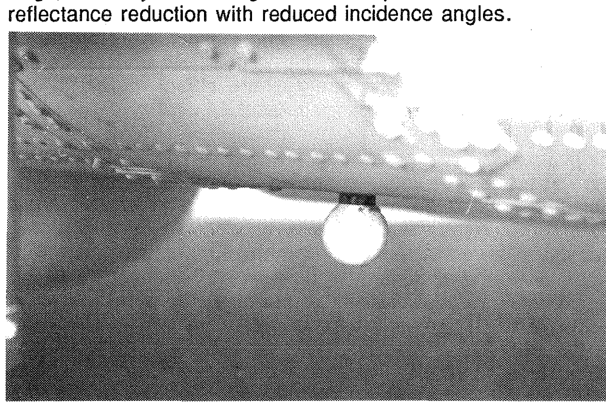

Figure 2 : Spherical Retro-Targets

The location of targets was defined by Department of Defence (RAN) personnel, and were to represent the principal longitudinal axis of the helicopter. This axis is also aligned the the AHRS sensor and hence determination of the orientation of this line in space would give a direct comparison of the AHRS heading with the true (photogrammetrically determined) heading. In addition to the targets on the principal fore-aft axis a series of targets were placed symmetrically offset from the main axis to facilitate roll determination.

A total of fifteen targets were mounted on the helicopter fuselage, as shown in figure 3.

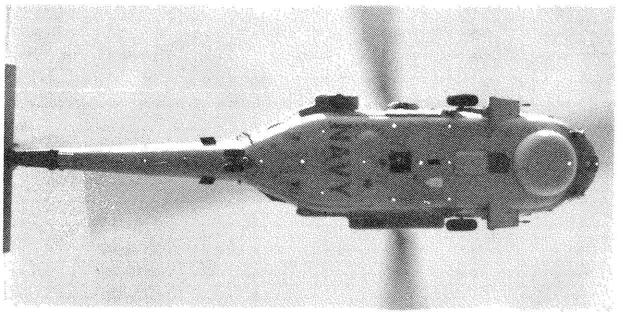

Figure 3 : Target Locations on the Helicopter

In the case of dynamic application, the motion of the object may significantly degrade the appearance of the target on the photographic film if long duration flash and film exposures are used. With the use of retro-targeting the duration of the flash dictates the clarity of the target. It was determined that the CRC-2 ring flash was not powerful enough to illuminate the target at the expected range of 100 metres. Two lamp head flashes were used, one a Metz of high power and medium duration (approximately 1/200th of a second) and the other a Norman of high power and short duration. The duration of the Metz flash proved a potential problem with target movement expected during the flash period. As shown in figure 4 the target movement resulted in an elongation of the target, with a comet tail trailer as the flash power weakened. The observations on the target proved successful by observing the "bulb" of the comet type target image.

Figure 4 : Targets Subject to Image Movement

Camera Synchronisation

Camera synchronisation was identified as one of the major dynamic design factors which needed to be addressed. Based on the selected cameras, namely the CRC-1 and CRC-2 metric cameras from GSI, it was necessary to determine a maximum allowable camera synchronisation offset to allow an effectively static solution. For example, at a velocity of 100 knots the differential motion between camera exposures in the object space, for a 1 millisecond camera synchronisation offset, with the proposed camera configuration and for a predicted image measurement precision of ± 5 μm, was 0.05 metres. Based on these survey conditions an observational precision in the object space of ± 0.005 metres was expected It was therefore necessary to synchronise the cameras at the 0.1 millisecond level in order to negate all differential motion effects between camera exposures.

The CRC-1 camera has a mechanically actuated shutter release while the CRC-2 has an electronically actuated release. In order to synchronise the two cameras it was necessary to develop a system to remotely "fire" both cameras to the desired synchronisation level. The unit developed is shown in figure 5, and includes two infra-red receivers, an infra-red remote transmitter and a pneumatically activated mechanical actuator for the CRC-1.

One infra-red receiver was connected to the CRC-2 and the other to the compressor unit, which was in turn was connected to the mechanical release on the CRC-1. Activation of the infra-red transmitter "fired" both the CRC-2 and the CRC-1 simultaneously. The trialed range of the infra-red transmitter was in excess of 100 metres.

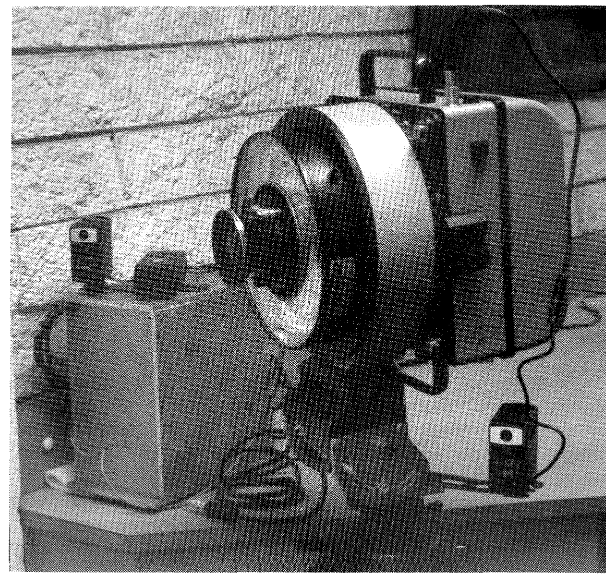

Figure 5 : Equipment for Camera Actuation

It was possible to measure the camera exposure offsets on the two cameras by laboratory methods. Photodiodes were located approximately in the image plane of each camera and connected directly to an oscilloscope. A light source was placed in front of each camera and upon "firing" the instant of shutter opening could be read directly from the oscilloscope. Exposure offset would then be the difference between the two readings. It was found that the exposure offset was at the 15 millisecond level with a variance of several milliseconds. This variance was due to the variability in the "take-up" of the pneumatic compressor unit. Due to this variance and as it was not known at what instant of the exposure the camera flash was activated and whether or not this offset was significant or constant, electronic synchronisation of the two cameras was not seen as a viable option. As an alternative to this physical determination of the exposure offset, evaluation of the least squares collinearity equations led to the development of analytical solution, taking into account all variabilities per epoch at the instant of flash triggering.

Least Squares Solution

Network simulations, with the camera exposure offset determined to be at the 15 millisecond level, displayed significant errors in the least squares solution. This was not unexpected due to the relatively weak geometric network proposed. In the proposed target array there were to be eight static control targets, ground based, and up to fifteen airborne targets. In the least squares solution the offset errors between the two exposures did not only distort the dynamic targets but errors were distributed across the whole target array In fact the control targets were influenced to a greater degree with introduction an orientation bias into the derived helicopter attitudes. This bias induced onto the control targets was due to both the larger number of airborne targets, as compared to control targets, and because of the close object space location of all airborne targets. Table 1 shows the influence on selected image coordinate residuals for the CRC-2, with a simulated 15 millisecond camera exposure offset error.

POINT	Xμm	Yμm	REMARKS
A	-71.	24.	Static
B	45.	-11.	Static
C	-167.	-60.	Static
D	14.	-112.	Static
B1	0.	4.	Dynamic
B2	9.	8.	Dynamic
B3	21.	12.	Dynamic
B4	21.	15.	Dynamic
B5	18.	10.	Dynamic

Table 1 : Simulated Image Residuals with a 15 Millisecond Exposure Offset (with No Analytical Offset Determination)

On the basis of the expected motion of the helicopter during the offset period, ie 15 milliseconds of transit at uniform attitude, an analytical approach was developed. This approach is dependent on the motion being stable and in a uniform direction during the offset period. For this trial, on the basis that the helicopter would be flying in on "steady" approach, this assumption was valid.

Consider the standard collinearity equations of the least squares bundle adjustment. If motion is assumed to be constant then the object space offset between camera exposures can be solved as an unknown in the adjustment process. In addition to the standard parameter set, three additional unknowns representing the object space offset between the two exposures in each coordinate direction, can also be determined. If considering only two cameras the equations take the following form, however the equations can readily be extended to multiple cameras configurations with multiple camera offsets, ie one set for each camera pair.

$$x_i - x_0 + f\,\frac{m(X_j - X_i + \Delta X) + m(Y_j - Y_i + \Delta Y) + m(Z_j - Z_i + \Delta Z)}{m(X_j - X_i + \Delta X) + m(Y_j - Y_i + \Delta Y) + m(Z_j - Z_i + \Delta Z)} \quad \text{DYNAMIC} \qquad ..(2)$$

$$x_i - x_0 + f\,\frac{m(X_j - X_i) + m(Y_j - Y_i) + m(Z_j - Z_i)}{m(X_j - X_i) + m(Y_j - Y_i) + m(Z_j - Z_i)} \quad \text{STATIC} \qquad ..(3)$$

where
- f is the principal distance
- x_i is the x image coordinate
- x_0 is the x image principal point offset
- X_j, Y_j, Z_j are the coordinates of point j
- X_i, Y_i, Z_i are the coordinates of camera i
- ΔX, ΔY, ΔZ are the exposure offsets

These equations can similarly be developed for the y image coordinate. Note that in the case of static targets, ie where no object space movement due to the camera exposure offset is expected, the coefficient components ΔX, ΔY and ΔZ are set to zero and do not contribute to the estimation of the camera exposure offset, however do provide a datum reference for the determination. The equations shown include the three additional parameters for camera exposure offset in three dimensional space. For the added assumption that motion is restricted to the horizontal plane, then only two additional parameters need be solved, with ΔZ being explicitly constrained to zero.

Table 2 shows a sample of the resulting image residuals after inclusion of parameters in the least squares solution for determination of the object space camera exposure offset. For this simulated data set a 15 millisecond exposure offset was introduced. The recovered camera offset estimates were 0.546, 0.543 and 0.005 metres in X, Y and Z respectively. This corresponds to a recovered heading of 45.1 degrees (simulated 45 degrees) and a velocity of 99.7 knots (simulated velocity 100 knots). Of interest is the distribution of part of the offset into the Z component, due primarily to the relatively weak network configuration which was proposed.

POINT	Xμm	Yμm	REMARKS
A	-11.	5.	Static
B	4.	-6.	Static
C	-6.	0.	Static
D	2.	-6.	Static
B1	0.	2.	Dynamic
B2	-2.	-1.	Dynamic
B3	0.	8.	Dynamic
B4	3.	1.	Dynamic
B5	0.	-6.	Dynamic

Table 2 : Simulated Image Residuals with a 15 Millisecond Exposure Offset (with Analytical Offset Determination)

With further simulations and solution for only the planimetric shift component, ie assumption of horizontal flight over the 15 millisecond period, the recovered offsets were 0.547 and 0.546 in X and Y respectively. This corresponds to a recovered heading of 45.05 degrees and a velocity of 100.09 knots. In the case of a weak network, the use of these additional parameters needs to be carefully selected in order not to degrade the solution or introduce biases. In the case of the AHRS trial the assumption of horizontal flight during the period of exposure was adopted and the resulting least squares solution was restricted to a planimetric camera exposure offset solution.

Timing

During design for the trial, timing specifications were set at 1 second. This timing was for correlation of photogrammetric derived attitude data and the AHRS derived data. The timing reference was to be the GPS time standard which was encoded onto all attitude outputs on the AHRS data bus. In principle this was a simple task with correlation of the CRC-2 clock, determined as the photogrammetric time reference, to the GPS standard with clock drifts being determined at regular intervals. The CRC-2 time was printed on all exposures, ensuring easy reference. During trial testing, however, it was determined that timing was significant at the 0.1 second level, and as the least count of the CRC-2 clock was 1 second an independent timing mechanism needed to be established.

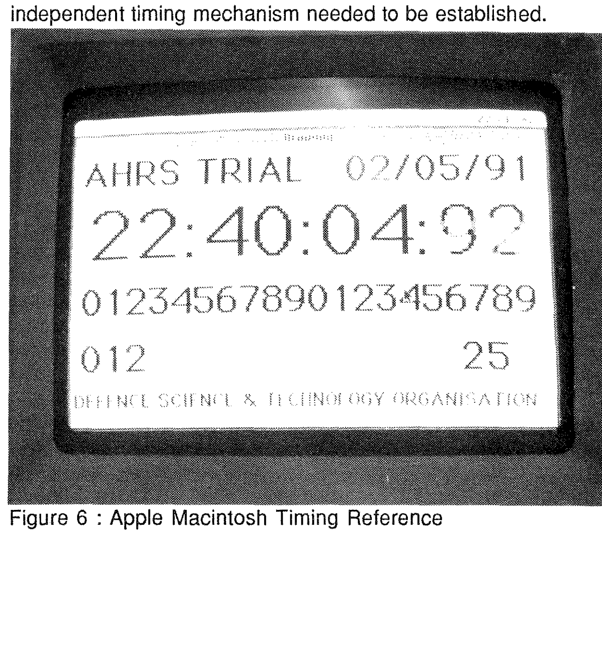

Figure 6 : Apple Macintosh Timing Reference

An Apple Macintosh computer was programmed to display the computer clock time to 0.01 seconds, with a secondary linear output of the time at 0.1 second intervals for an easier determination of time to this significance level. This was necessary because of the rapid scrolling of the tenth and hundredths significant figures on the computer screen. The computer clock was synchronised to GPS time, with corrections for drift, before and after each sortie. This output is shown in figure 6. With reference to figure 7, a video camera then imaged the computer screen with its time display, a GPS receiver displaying GPS time and the CRC-1 camera. The GPS time display was not suitable on its own due to the fact that its display was only to the nearest second. As the camera was triggered the video camera screen was blanked out by the CRC-1 flash. Time for each exposure, at the GPS standard, was then extracted in post-processing by viewing the video and noting the time of exposure.

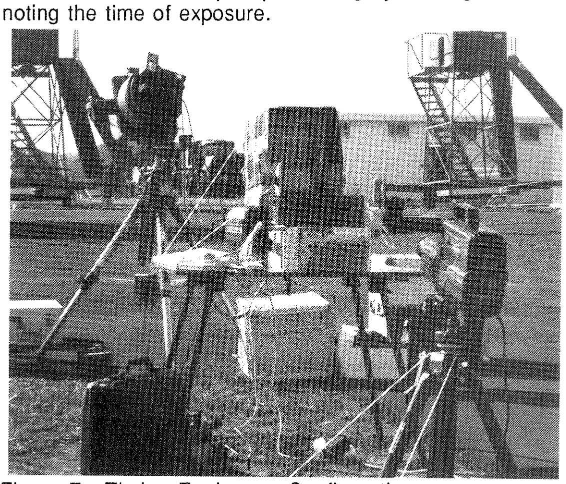

Figure 7 : Timing Equipment Configuration

Determination of Attitude

The determination of attitude was via derivation from the measured quantities, ie X, Y and Z coordinates for each aircraft target. Definitions for the required attitude parameters were as follows :

Heading - clockwise angle between true north and the main fore-aft axis of the aircraft
Pitch - the angle in the vertical plane between the horizontal and the main fore-aft axis of the aircraft
Roll - the angle in the pitched plane between the horizontal and the cross axis of the aircraft

In order to improve internal reliability, multiple determinations of each quantity were undertaken. This involved two independent assessments of pitch, three independent assessments of roll and a heading assessment comprising all measured targets on the main fore-aft axis of the aircraft. In general at least five targets were used for heading determination, with solution via a two dimensional least squares best fit line. In this context an "independent" assessment refers only to the fact that separate targets were used for each determination. Independence from any external biasing factor was therefore not achieved.

RESULTS

The AHRS accuracy trial was undertaken in early 1991. A total of 212 passes were made comprising 192 in the standard sortie configuration, 14 in a hovering mode and 6 in tight banking turns. The hovering configurations were requested in order to assess, via comparison with inflight data, the effectiveness of the analytical camera exposure offset solutions. Banking configurations were included to give a feel for the AHRS performance during, rather than immediately after, radical manoeuvres.

Estimates for all attitude elements were derived for all sortie passes. In isolated cases oil discharging from the helicopter exhaust covered several targets eliminating the retro-refelectance of the target. In such cases, which were particularly for roll determinations, there was reduced data on the integrity of the determinations.

Figure 8 shows the CRC-1 in operation during the trial with the helicopter approaching the control network centroid. The centroid of the network was marked by a vehicle in order to ensure correct helicopter transits.

Figure 8 : AHRS Trial - CRC-1 Operation

Prior to all sorties the helicopter underwent a series of AHRS alignment procedures. This included both runway as well as airborne alignments. The airborne alignments (DV/DG) were to simulate take-off from a naval vessel, with alignment required independent of the motion of the vessel. Figure 9 shows the helicopter undergoing a runway alignment prior to sortie commencement. Also visible is the CRC-2 camera and the infra-red remote devices.

Figure 9 : Helicopter Alignment and CRC-2

Figure 10 shows a typical exposure from the CRC-2. The control network at the base of the image covers the full field of view and extends to the trees on the far side of the runway. In this image the helicopter is transiting at approximately 100 metres above the ground.

Of considerable difficulty was the determination of the correct instant to take the exposure. In theory this was when the helicopter was over the centroid of the control network, however the actual exposure location varied significantly. This was due to both the difficulty in determining the correct location of the helicopter with respect to the control network as it approached in a direct path and due to the fact that the helicopter pilot was not able to transit the correct location at all times. The variability in exposure locations was approximately 40 metres in X and 60 metres in Y. Due to the excessive costs involved with reflying a poor transit, the offset passes were generally accepted.

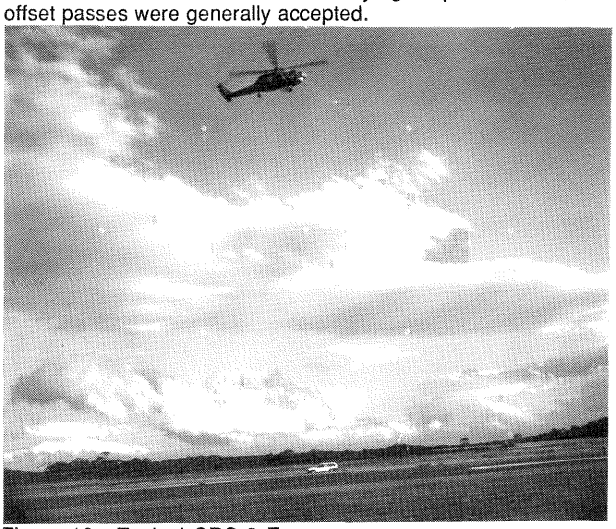

Figure 10 : Typical CRC-2 Exposure

All photography was measured on a Kern DSR-14 analytical plotter, with a nominal observation precision of ±5 microns. Each sortie pass was adjusted by a full bundle adjustment with two dimensional estimates for camera exposure offsets. Calibration data, in terms of a priori estimates for camera lens distortions, were applied in a pre-processing mode. Distances were measured between all aircraft targets and included in the adjustment process. Residuals on observed distances as well as residuals on control estimates were within the a priori estimates.

Results for the trial showed that commission precision specifications were met in all cases. In terms of single point positioning, a typical precision of ±5 mm in X, ±10mm in Y and ±7mm in Z was achieved. These estimates were independent of aircraft heading, however the heading precision estimates were all flight direction dependent. Roll and pitch estimates were heading independent due to the use of the measured distances for determination of the "aircraft" system planimetric component of each. Table 3 shows the typical precisions, as a function of heading, for each attitude component.

COMPONENT	HEADING	PRECISION
ROLL	ALL	$\pm0.50^0$
PITCH	ALL	$\pm0.10^0$
HEADING	0^0	$\pm0.05^0$
	45^0-135^0	$\pm0.15^0$
	180^0	$\pm0.05^0$
	225^0-315^0	$\pm0.15^0$

Table 3 : Attitude Precision Estimates

The precision of the hovering and banking configurations was also derived. Hovering conformed with the standard sortie passes and confirmed the effective reduction of camera exposure offsets. Banking precisions conformed in pitch and roll but were marginally degraded in heading. This degradation was due to the need to undertake three dimensional camera exposure offset determinations because of the curvature in the undersurface of the helicopter.

Comparison of the photogrammetrically derived attitude estimates with the AHRS measured data was undertaken by an independent consultant. Comparisons were undertaken for all estimated quantities on an individual pass basis, and was with respect to all measured quantities including measured true heading, magnetic heading, pitch and roll. Examples of these comparisons are included in Figures 11 to 14, being comparisons for the first four sorties.

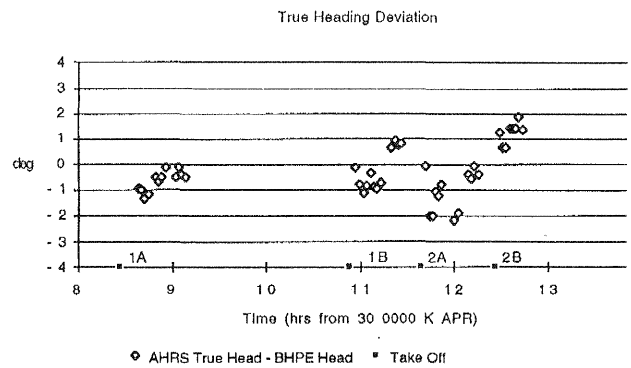

Figure 11 : AHRS - Photogrammetric Attitude Comparison - True Heading Deviation

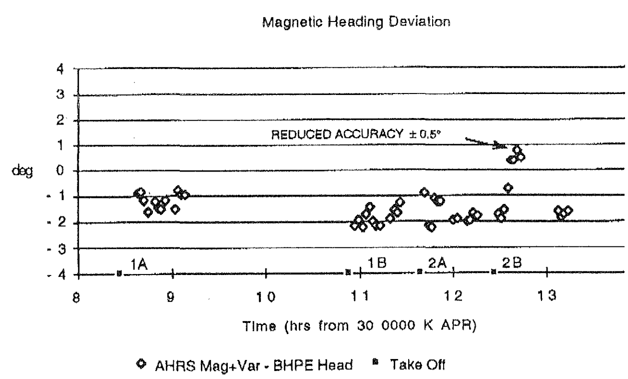

Figure 12 : AHRS - Photogrammetric Attitude Comparison - Magnetic Heading Deviation

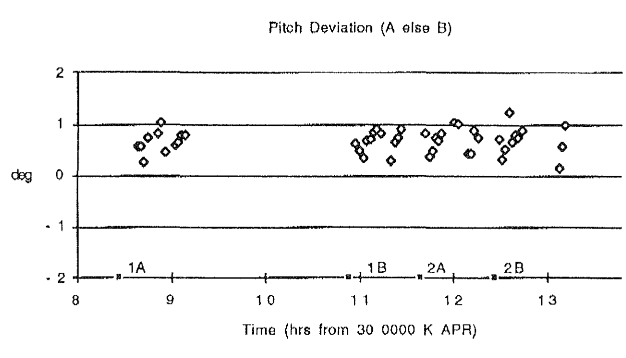

Figure 13 : AHRS - Photogrammetric Attitude Comparison - Pitch Deviation

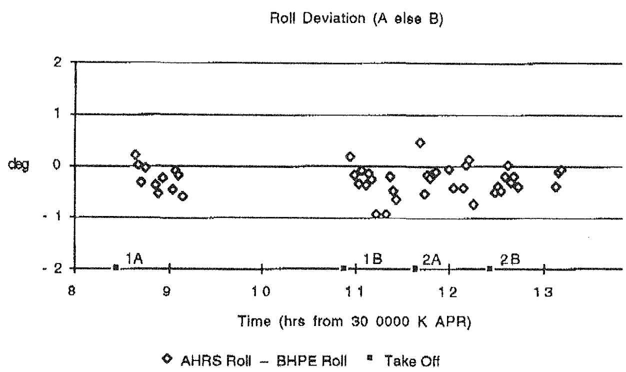

Figure 14 : AHRS - Photogrammetric Attitude Comparison - Roll Deviation

With all the above cases it is worth noting the distribution of the differences. In Figure 11, for example, the AHRS in sortie 1A clearly shows a systematic error in the determination of heading. This error is not due to any photogrammetric bias, which would be in the form of a linear offset across the full data set, and conforms to the expected errors in the sensor.

The comparisons also included data sets as a function of the two types of initial sensor alignment. Figure 15 shows the deviation in true heading as a function of initial sensor alignment. Deviation, in general, is larger with the VG/DG alignment, which is the reduced accuracy inflight alignment procedure. Figure 16 shows magnetic heading deviation as a function of initial sensor alignment. The deviation in magnetic heading is significantly reduced in comparison with the true heading deviations, showing a larger true heading bias particularly with VG/DG alignment. Note that the data set in figures 15 and 16 comprise data from all sorties.

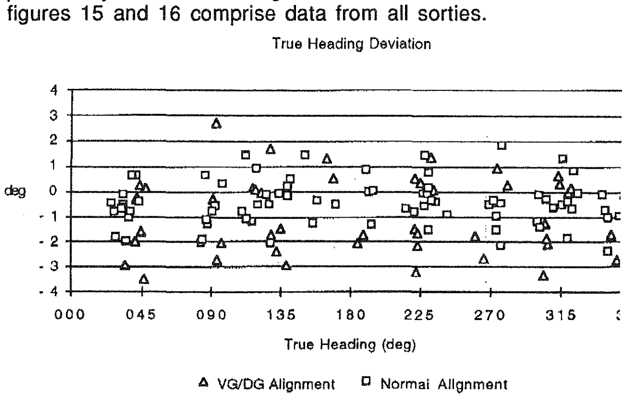

Figure 15 : AHRS - Photogrammetric Attitude Comparison - True Heading Deviation as a Function of Alignment

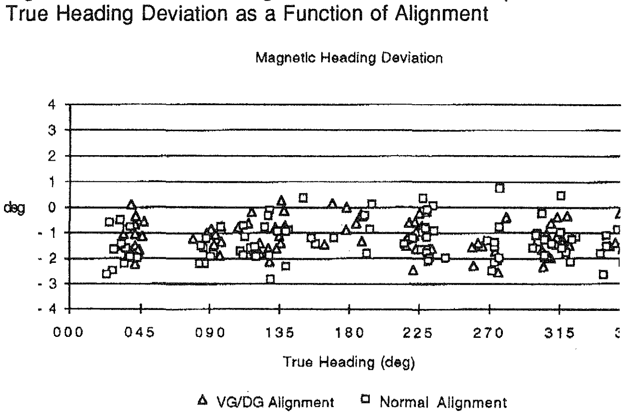

Figure 16 : AHRS - Photogrammetric Attitude Comparison - Magnetic Heading Deviation as a Function of Alignment

The inflight performance of the AHRS was successfully evaluated during the trial. Conclusions about the performance of the sensor showed a significant linear biases and heading dependent biases. These were confirmed by evaluation of the true and magnetic headings, measured on the helicopter, in conjunction with the independent photogrammetric determinations.

The independent photogrammetric accuracy assessments by the contractor confirmed the estimates derived based on the geometry and network employed. The independent estimates were based on expected performance of the AHRS sensor in conjunction with the RMS evaluation of the differences of the full data set.

FUTURE DEVELOPMENTS

The work undertaken as part of the AHRS verification trial clearly met commission precision requirements. For subsequent trials, however, proposed enhancements to the survey methodology will significantly improve assessment of AHRS accuracy and reliability. As part of any future AHRS trial these modifications would in principle include :

1. Inclusion of a third camera for improvement of survey reliability and precision in the second planimetric direction.

2. Improvement of the control network in terms of increased height range. For any trial where metrology of an aircraft inflight is required the minimum clearance is fixed and hence increased height range may not be possible.

3. Inclusion of short duration high power flash units to ensure photographic clarity is optimal.

4. Electronic synchronisation of all cameras, with elimination of residual camera exposure offsets by analytical means.

5. Inclusion of an "up-looking" video camera, located at the control network centroid, to enable accurate determination of the correct exposure locations for each transit.

CONCLUSIONS

This paper has described in detail the AHRS accuracy verification trial. Of significance are the developments in design and implementation for dynamic photogrammetry where precision metrology is required of an object subject to random motion and with respect to a static and fixed datum.

Developments have been made in the design procedures for dynamic photogrammetry. These design procedures, incorporated in the conventional design process, include assessment of the influence of camera synchronisation offsets, the requirements for targeting and the influence on the least squares solution of unresolved motion between exposures.

The least squares solution has been augmented to allow solution of the camera exposure offset. Such a solution requires assumptions concerning uniformity of motion during the exposure offset period, and such assumptions require verification with each project undertaken.

All these aspects have been successfully implemented in the AHRS verification trial. The project has demonstrated the versatility of the photogrammetric technique, in particular for dynamic applications, and has shown that photogrammetry is suited to the inflight determination of attitude sensor accuracy.

REFERENCES

BHP Engineering (1991) Seahawk Heading Reference Trial - Close Range Photogrammetry, Trial Report, Wollongong, NSW, Australia

BHP Engineering (1991) Seahawk Heading Reference Trial - Close Range Photogrammetry (Error Analysis), Wollongong, NSW, Australia

Caspary, W.F. (1987) Concepts of Network and Deformation Analysis, Monograph 11, School of Surveying, University of New South Wales, Kensington, NSW, Australia

Department of Defence(Navy) (1991) 'Report S-70B-2 AHRS Heading Accuracy - Test Plan, Internal Document, Air Warfare Systems Centre, RAN, NSW, Australia

Fraser, C.S. (1984) Network Design Considerations for Non-Topographic photogrammetry, Photogrammetric Engineering and Remote Sensing, Vol 50, pp 1115-1126

Grafarend, E.W. (1974) Optimisation of Geodetic Networks, Bolletino di Geodesica a Science Affini, Vol 33, No4, pp 351 - 406

Harvey, B.R. (1990) Practical Least Squares and Statistics for Surveyors, Monograph 13, School of Surveying, University of New South Wales, Kensington, NSW, Australia

Karara, H.M.(Ed) (1989) Non-Topographic Photogrammetry, 2nd Edition, American Society for Photogrammetry and Remote Sensing, Science and Engineering Series, Falls Church, Virginia, USA

Marshall, A.R. (1989) Network Design and Optimisation in Close Range Photogrammetry, Unisurv S-36, School of Surveying, University of New South Wales, Kensington, NSW, Australia

Shortis, M.R. (1988) Dynamic Photogrammetry Development Project Preliminary Report, Department of Surveying and Land Information, University of Melbourne, Victoria, Australia

Slama, C.C.(Ed) (1980) Manual of Photogrammetry, 4th Edition, American Society for Photogrammetry and Remote Sensing, Falls Church, Virginia, USA

ACKNOWLEDGEMENTS

The Defence Science and Technology Organization (DSTO), in particular Dr G.C.L.Searle, should be thanked for their contribution to the project, particularly in terms of project coordination and timing definition. From BHP Engineering numerous people were involved in the project, however the efforts of Michael Scott, who undertook the majority of the image observations, deserves particular recognition.