GPS Controlled Photography

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Greg is a geodetic surveyor employed by the Land Information Centre. He has been involved with the application of GPS since the first receivers were introduced to this country. Greg is currently undertaking a Master of Engineering degree in the field of GPS controlled photogrammetry. His research will address the operational and technical problems associated with the daily deployment of this technology.

Introduction

The costs associated with traditional mapping techniques have always been high. Ongoing photogrammetric research has continually investigated various techniques to reduce these costs.

The Land Information Centre (the Centre) is currently utilising new technology and processes to capture photographic and photogrammetric data. Digital imagery is a fast developing discipline which the Centre is embracing. In support of this process traditional methodologies associated with airborne image capture and mapping have been revolutionised. The ground survey component so heavily relied upon has been moved to the airborne camera platform radically changing the process of mapping and the products so derived.

This paper highlights some of the considerations in implementing such a program and performance derived from the capture process

The Photogrammetric Problem

Establishment of ground control is a substantial measure of the map making process. Various methods have been used in the past to reduce the amount of ground control without sacrificing accuracy. The photogrammetric solution is the reproduction of the camera station position through the geometry of overlapping stereo photographs. Figure 1 illustrates this problem in a photographic strip.

It can be seen that the relationship between the adjoining photographs will be dependent on the photogrammetric observations on the images. When there is no ground control, particularly vertical control, from model to model there will be an amount of flex in the vertical sense along the strip, twisting around the longitudinal axis and rotation from image to image.

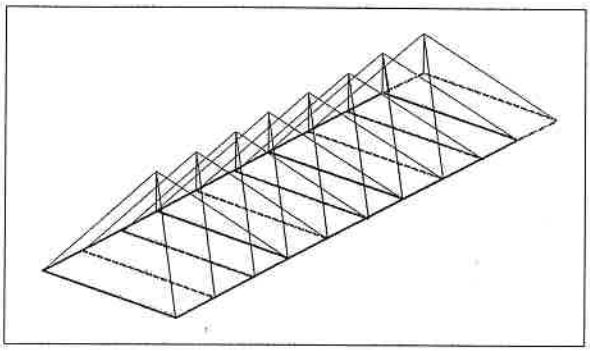

Figure 1 Strip of overlapping photographs

Along the strip the triangulation tends to be strong, the observation of points perpendicular to the strip direction making it so. But the strip is weak in the vertical sense being sensitive to observation errors.

As a result, traditional triangulation requires control approximately every 4 to 6 models. Advances in photogrammetric stereo plotters have improved on this but there is still a requirement for horizontal and vertical control around the edges of the adjustment block and vertical control throughout the interior. For example the ground survey to support

1:50000 photography of the ANGLEDOOL 1:250000 mapsheet in northern New South Wales required the establishment of 69 ground control points. Upon completion, upwards of 90 points were occupied in support of this survey. Over an area of this size the survey component is a substantial portion of the overall mapping cost.

Obviously savings are to be made if the ground control requirements can be reduced. Over the past 50 years a number of techniques have been used to reduce control requirements:

- statoscope
- horizon camera
- solar periscope
- airborne profile recorders (APR)
- gyroscopes

All these techniques introduce to the photogrammetric solution camera station information which is generally referred to as **auxiliary data**. If information about the camera station position can be entered into the block adjustment, the solution can then be reversed engineered reducing the ground control requirement.

The Apollo lunar space missions used auxiliary data extensively for its moon mapping program. Doppler tracking of the spacecraft produced an ephemeris - knowledge of the spacecrafts position with respect to a referencing system and time; a stellar camera provided information about the spacecraft's attitude with respect to the stellar referencing system; a radar altimeter provided the distance above the lunar surface.

This data was combined with the information from the mapping camera and was all that was required for satellite photogrammetry. Obviously, no surveyed ground control was required.

In figure 1, auxiliary data such as height information has the effect of reducing the vertical ground control requirement as the auxiliary height data "holds up" the adjustment block. Limitations to these techniques are how reliable are the data and how should it be treated within the photogrammetric adjustment. Estimates of observation precision always being the stumbling block for any adjustment.

In recent times, development of user end Global Position System hardware and software technology, has impacted considerably on the photogrammetric process. Sub-metre estimates in X,Y and Z of the camera position at the instant of exposure are now possible. If these estimates are within the required accuracy of the mapping and based on the same mapping datum then theoretically ground control can be dispensed with. This process reverse engineers the image points from the camera stations.

Unfortunately, owing to a number of reasons, this is difficult to achieve on a day to day, week by week production basis.

Data Capture System

The Centre has implemented this technology into its image capture programs. A growing trend today is the move towards digital imagery. Controlled digital imagery brings with it information that can be readily stored and retrieved spatially, delivering a myriad of applications.

The cost effectiveness of GPS controlled photography reduces this product cost even though digital imagery is still developing.

The Centre's system derives camera station coordinates from post processed GPS dual frequency P-code and phase data. This data is collected on the Centre's Cessna 421 aircraft supported by a continuously operating base station located within the Centre's building at Bathurst.

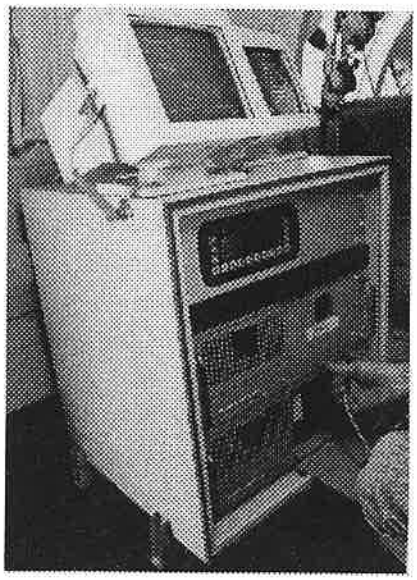

Figure 1 Data collection and navigation system installation

Unlike first and second generation GPS/camera systems the Centre's aircraft installation is based around the CAAP (Computer Assisted Aerial Photography) package. This is a camera control and navigation system developed in Sweden specifically for photogrammetric application. Figure 2 is an image of the aircraft installation. It consists of:-

- ASHTECH Z12 GPS receiver
- 24V DC 486DX2/66 rack mount computer
- 240V AC 486DX2/66 rack mount computer
- 24V DC to 240V AC 1500W invertor
- 2 x 9" monochrome VGA displays
- Flat screen liquid crystal monochrome VGA pilots display
- AUSNAV RDS FM receiver

The heart of the CAAP system is the integrated navigation and photo-mission software package, NAVPRO, which provides on-strip, ferry and stand-alone flight navigation, plus automatic triggering of the airborne camera at pre-determined positions. Pre-planned exposure point coordinates are inputted via strip data files which, in conjunction with GPS receiver coordinates, derive graphical steering information displayed on the pilot's control panel , and also control firing of the camera shutter. An acknowledging pulse, captured against the GPS time scale, is recorded within the receiver. Interpolated single-point position coordinates for every exposure are collected in NAVPRO and logged in a "results" file.

This installation has been refined over the last 12 months with the modification of the power supply and inclusion of AUSNAV. A more suitable pilots screen is to be fitted within the coming weeks that will improve the operational environment of the aircraft cockpit. The Centre is also looking into acquiring a navigation package that will support

on route guidance, supplementing NAVPRO. Figure 3 is a schematic of the data management, navigation and logging system installed on the Centre's aircraft.

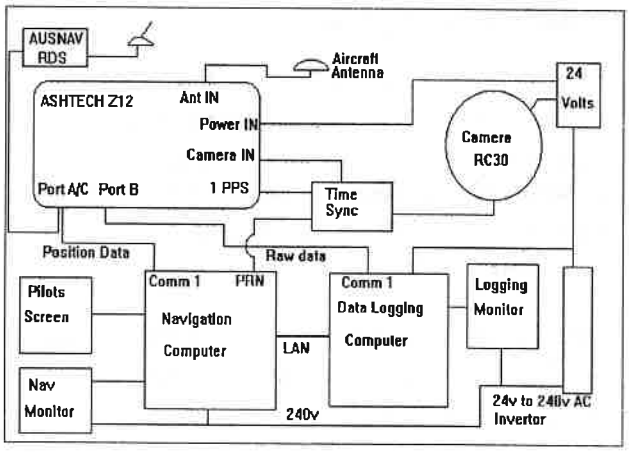

Figure 2 Aircraft system schematic

Supporting this operation is the Centre's ASHTECH Z12 base station. It can be programmed to record data at 1Hz 24 hours a day, 7 days a week. It is supported by an uninterruptable power supply and software which is self backing up in the event of a network failure. The base station is backed by 2 computers running independent logging programs. One computer maintains the existing base station logging system, the other supports the aircraft operation. The former system provides a data backup in the event of the primary logger failure.

A typical mission is no longer just a case of looking through a drift sight and manually navigating along plotted lines on a map. Each photographic mission is subject to the following procedure:

- Determine the extent of the mapping area as requested by the client.
- Determine the photographic coverage for triangulation.
- Generate AMG end point coordinates using in house GENAMAP scripts.
- From end point coordinates generate strip files using CAAP software.
- Create check plot using strip file coordinates.
  This plot is the final OK to transfer strip files to the aircraft. Errors are identified at this stage and are corrected.
- The aircraft is deployed to the mapping area using NAVPRO for guidance and camera control.
- Post mission the collected raw data is transferred by DAT tape to the Centre's computer network for post processing with the base station data.
- Camera station coordinates are combined with image point observations and adjusted using the bundle software PATB-GPS.

This data collection system has been in operating primarily in western NSW since May 1995 providing GPS positions for over 5000 camera stations. At this stage less than 0.1% photo centres have been lost due to a system failure.

System Performance

A gauge of the systems navigation performance is provided in Tables 1, 2 and 3. Run 11 of the COBAR 1:250000 mapsheet, selected randomly from those available, was flown twice, the first time was the 10/7/95, Day 191, before the installation of AUSNAV. Table 1 demonstrates the variability of uncorrected single point GPS. The best indicator in the table is the easting value, for an east-west run the camera will expose as it crosses the nominated easting, the pilot is responsible for the exaggerated

variation in the northings. The system in this case has been within 50m of the nominated easting for every exposure.

Table 2 is the same flight plan as table 1, flown on 8/11/95, Day 312, using AUSNAV. Of initial concern is the offset in the easting position from the planned. This results from the time synchronisation between the GPS receiver and the computer time. In this case the synchronisation was in the order of 1.1 seconds which is the result of a poor "sync". Consequently the computer triggers the camera according to the GPS position at a computer time , not the GPS time. The time offset is generally less than 1 sec. Usually the magnitude of the time offset is available after the flight but in this case the option to record it was not active.

Table 3 highlights the performance of the real time position information corrected by AUSNAV. The differentially corrected position output from the receiver in real time is compared to the post processed position. The results are extremely encouraging when it is realised that the differential corrections are generated from receivers located over 400kms away.

There are associated cost savings in having the capability to execute aerial photography in this way. This system now makes it possible to break runs if cloud or other problems cause an abort. It is a simple matter to "pick up where we left off". Planning a rigorous photographic pattern has reduced the aerotriangulation photo marking and observation time by 400%. The amount of image points to be observed are reduced, the amount of exposures are reduced, direct navigation has increased aircraft efficiency, the move to a 2 man crew has reduced away costs and increased aircraft endurance. Unlike other operations no base station is deployed to the aircraft project area.

Auxiliary Data

Triangulation bundle adjustment software is not generally designed to accept camera station coordinates. As previously mentioned, research in this area has been ongoing since the first proposals to utilise GPS to deliver camera station coordinates. Researchers have dedicated much time and energy to the process of solving for "ambiguities" or "integers" to obtain that "fixed" solution, somewhat guaranteeing the quality of the solution.

The operating aerial camera is a dynamic platform. Early GPS equipment required that some sort of initialisation was required before a mission could begin. This in most cases required determining the fixed integer baseline from the aircraft to the nearby base station before the aircraft departed and then manoeuvring the aircraft in such a way that cycle slips or loss of lock was avoided. The early limited GPS constellations also restricted mission times.

Today, with a full GPS constellation and using low elevation tracking the Centre's operation tracks a minimum of 5 common satellites in good PDOP at all times. The ASHTECH Z12 and PNAV software does not require initialisation on the ground, in fact the system is capable of solving for "ambiguities" after becoming airborne and within acceptable range of the Centre's base station.

Table 1

Post Processed positions for Day 191 COBAR Run 11						
Planned Exposure Point	East	North	PNAV East	PNAV North	Diff East	Diff North
SH551411*POP*1	353516	6484089	353513.7	6484022.1	2.3	66.9
SH551411*POP*2	357954	6484120	357931.9	6484065.3	22.1	54.7
SH551411*POP*3	362393	6484151	362375.6	6484206.4	17.4	-55.4
SH551411*POP*4	366832	6484182	366793.9	6484159.8	38.1	22.2
SH551411*POP*5	371271	6484213	371235.7	6484225.8	35.3	-12.8
SH551411*POP*6	375710	6484244	375681.2	6484199.6	28.8	44.4
SH551411*POP*7	380149	6484275	380129.5	6484127.2	19.5	147.8
SH551411*POP*8	384588	6484306	384576.4	6484157.9	11.6	148.1
SH551411*POP*9	389027	6484337	389024.9	6484290.3	2.1	46.7
SH551411*POP*10	393466	6484368	393455.7	6484321.2	10.3	46.8
SH551411*POP*11	397904	6484400	397894.4	6484414.4	9.6	-14.4
SH551411*POP*12	402343	6484431	402330.8	6484416.0	12.2	15.0
SH551411*POP*13	406782	6484462	406750.6	6484421.0	31.4	41.0
SH551411*POP*14	411221	6484493	411169.7	6484357.6	51.3	135.4
SH551411*POP*15	415660	6484524	415611.0	6484489.7	49.0	34.3
SH551411*POP*16	420099	6484555	420064.8	6484481.2	34.2	73.8
SH551411*POP*17	424538	6484586	424514.8	6484516.6	23.2	69.4
SH551411*POP*18	428977	6484617	428948.6	6484634.3	28.4	-17.3
SH551411*POP*19	433416	6484648	433408.2	6484615.8	7.8	32.2
SH551411*POP*20	437854	6484679	437846.2	6484646.4	7.8	32.6
SH551411*POP*21	442293	6484711	442289.2	6484653.0	3.8	58.0
SH551411*POP*22	446732	6484742	446749.0	6484695.3	-17.0	46.7
SH551411*POP*23	451171	6484773	451187.0	6484660.4	-16.0	112.6
SH551411*POP*24	455610	6484804	455614.6	6484721.5	-4.6	82.5
SH551411*POP*25	460049	6484835	460060.7	6484740.4	-11.7	94.6
SH551411*POP*26	464488	6484866	464496.2	6484809.9	-8.2	56.1
SH551411*POP*27	468927	6484897	468919.8	6484940.7	7.2	-43.7
SH551411*POP*28	473366	6484928	473358.1	6484820.4	7.9	107.6
SH551411*POP*29	477804	6484959	477814.8	6484880.5	-10.8	78.5
SH551411*POP*30	482243	6484991	482232.2	6484974.1	10.8	16.9
SH551411*POP*31	486682	6485022	486672.3	6484943.2	9.7	78.8
SH551411*POP*32	491121	6485053	491109.9	6485054.5	11.1	-1.5
SH551411*POP*33	495560	6485084	495548.9	6485031.0	11.1	53.0
SH551411*POP*34	499999	6485115	499991.4	6485072.4	7.6	42.6
SH551411*POP*35	504438	6485146	504426.7	6485125.3	11.3	20.7

Table 2

Post Processed positions for Day 312 COBAR Run 11

Planned Exposure Point	East	North	PNAV East	PNAV North	Diff East	Diff North	Velocity East
SH551411*POP*1	353516	6484089	353640.5	6484069.9	-353640.5	-6484069.9	119.3
SH551411*POP*2	357954	6484120	358078.7	6484054.4	-358078.7	-6484054.4	117.4
SH551411*POP*3	362393	6484151	362525.3	6484045.6	-362525.3	-6484045.6	115.5
SH551411*POP*4	366832	6484182	366967.1	6483977.5	-366967.1	-6483977.5	119.6
SH551411*POP*5	371271	6484213	371405.8	6484025.6	-371405.8	-6484025.6	120.7
SH551411*POP*6	375710	6484244	375848.0	6484087.9	-375848.0	-6484087.9	120.9
SH551411*POP*7	380149	6484275	380274.7	6484100.5	-380274.7	-6484100.5	120.1
SH551411*POP*8	384588	6484306	384720.5	6484091.1	-384720.5	-6484091.1	120.3
SH551411*POP*9	389027	6484337	389162.6	6484066.6	-389162.6	-6484066.6	120.4
SH551411*POP*10	393466	6484368	393592.1	6484051.7	-393592.1	-6484051.7	120.3
SH551411*POP*11	397904	6484400	398039.3	6484184.1	-398039.3	-6484184.1	121.4
SH551411*POP*12	402343	6484431	402477.4	6484364.7	-402477.4	-6484364.7	121.8
SH551411*POP*13	406782	6484462	406918.3	6484526.2	-406918.3	-6484526.2	121.9
SH551411*POP*14	411221	6484493	411354.9	6484694.5	-411354.9	-6484694.5	124.4
SH551411*POP*15	415660	6484524	415791.5	6484860.9	-415791.5	-6484860.9	124.5
SH551411*POP*16	420099	6484555	420225.7	6484823.6	-420225.7	-6484823.6	123.6
SH551411*POP*17	424538	6484586	424661.7	6484722.5	-424661.7	-6484722.5	123.4
SH551411*POP*18	428977	6484617	429111.2	6484619.7	-429111.2	-6484619.7	123.2
SH551411*POP*19	433416	6484648	433558.9	6484523.6	-433558.9	-6484523.6	122.4
SH551411*POP*20	437854	6484679	437992.6	6484434.1	-437992.6	-6484434.1	122.5
SH551411*POP*21	442293	6484711	442437.9	6484454.9	-442437.9	-6484454.9	123.9
SH551411*POP*22	446732	6484742	446875.5	6484546.3	-446875.5	-6484546.3	124.0
SH551411*POP*23	451171	6484773	451308.4	6484648.6	-451308.4	-6484648.6	124.8
SH551411*POP*24	455610	6484804	455737.8	6484753.5	-455737.8	-6484753.5	124.3
SH551411*POP*25	460049	6484835	460185.4	6484781.8	-460185.4	-6484781.8	125.4
SH551411*POP*26	464488	6484866	464629.1	6484788.9	-464629.1	-6484788.9	127.2
SH551411*POP*27	468927	6484897	469072.1	6484866.4	-469072.1	-6484866.4	126.8
SH551411*POP*28	473366	6484928	473501.8	6484952.9	-473501.8	-6484952.9	126.6
SH551411*POP*29	477804	6484959	477934.8	6485030.9	-477934.8	-6485030.9	126.5
SH551411*POP*30	482243	6484991	482368.3	6485117.1	-482368.3	-6485117.1	127.3
SH551411*POP*31	486682	6485022	486819.4	6485185.4	-486819.4	-6485185.4	128.4
SH551411*POP*32	491121	6485053	491264.9	6485216.1	-491264.9	-6485216.1	129.5
SH551411*POP*33	495560	6485084	495694.9	6485248.5	-495694.9	-6485248.5	128.9
SH551411*POP*34	499999	6485115	500146.5	6485303.6	-500146.5	-6485303.6	127.6
SH551411*POP*35	504438	6485146	504576.4	6485383.5	-504576.4	-6485383.5	126.0

Table 3

Difference between PNAV Post Processed Position and Real Time AUSNAV positions COBAR Run 11 Day 312

Planned Exposure Point	PNAV East	PNAV North	AUSNAV East	AUSNAV North	Diff East	Diff North
SH551411*POP*1	353640.5	6484069.9	353639.5	6484070.0	-353639.5	-5932659.0
SH551411*POP*2	358078.7	6484054.4	358078.4	6484054.5	-358078.4	-5932643.5
SH551411*POP*3	362525.3	6484045.6	362524.8	6484045.8	-362524.8	-5932634.8
SH551411*POP*4	366967.1	6483977.5	366966.7	6483977.8	-366966.7	-5932566.8
SH551411*POP*5	371405.8	6484025.6	371405.6	6484025.5	-371405.6	-5932614.5
SH551411*POP*6	375848.0	6484087.9	375847.6	6484087.7	-375847.6	-5932676.7
SH551411*POP*7	380274.7	6484100.5	380274.3	6484100.4	-380274.3	-5932689.4
SH551411*POP*8	384720.5	6484091.1	384719.9	6484090.8	-384719.9	-5932679.8
SH551411*POP*9	389162.6	6484066.6	389162.1	6484066.5	-389162.1	-5932655.5
SH551411*POP*10	393592.1	6484051.7	393591.9	6484051.6	-393591.9	-5932640.6
SH551411*POP*11	398039.3	6484184.1	398039.0	6484183.5	-398039.0	-5932772.5
SH551411*POP*12	402477.4	6484364.7	402477.6	6484364.3	-402477.6	-5932953.3
SH551411*POP*13	406918.3	6484526.2	406918.3	6484525.9	-406918.3	-5933114.9
SH551411*POP*14	411354.9	6484694.5	411354.4	6484694.9	-411354.4	-5933283.9
SH551411*POP*15	415791.5	6484860.9	415790.0	6484859.7	-415790.0	-5933448.7
SH551411*POP*16	420225.7	6484823.6	420224.3	6484822.3	-420224.3	-5933411.3
SH551411*POP*17	424661.7	6484722.5	424660.4	6484720.9	-424660.4	-5933309.9
SH551411*POP*18	429111.2	6484619.7	429110.0	6484618.0	-429110.0	-5933207.0
SH551411*POP*19	433558.9	6484523.6	433557.4	6484522.3	-433557.4	-5933111.3
SH551411*POP*20	437992.6	6484434.1	437991.3	6484432.5	-437991.3	-5933021.5
SH551411*POP*21	442437.9	6484454.9	442436.3	6484453.6	-442436.3	-5933042.6
SH551411*POP*22	446875.5	6484546.3	446873.9	6484544.8	-446873.9	-5933133.8
SH551411*POP*23	451308.4	6484648.6	451306.9	6484647.8	-451306.9	-5933236.8
SH551411*POP*24	455737.8	6484753.5	455736.7	6484752.6	-455736.7	-5933341.6
SH551411*POP*25	460185.4	6484781.8	460184.4	6484781.1	-460184.4	-5933370.1
SH551411*POP*26	464629.1	6484788.9	464627.8	6484788.3	-464627.8	-5933377.3
SH551411*POP*27	469072.1	6484866.4	469071.1	6484865.6	-469071.1	-5933454.6
SH551411*POP*28	473501.8	6484952.9	473500.8	6484952.0	-473500.8	-5933541.0
SH551411*POP*29	477934.8	6485030.9	477933.9	6485030.1	-477933.9	-5933619.1
SH551411*POP*30	482368.3	6485117.1	482367.4	6485116.1	-482367.4	-5933705.1
SH551411*POP*31	486819.4	6485185.4	486818.9	6485184.5	-486818.9	-5933773.5
SH551411*POP*32	491264.9	6485216.1	491264.3	6485215.1	-491264.3	-5933804.1
SH551411*POP*33	495694.9	6485248.5	495694.6	6485247.4	-495694.6	-5933836.4
SH551411*POP*34	500146.5	6485303.6	500146.3	6485302.2	-500146.3	-5933891.2
SH551411*POP*35	504576.4	6485383.5	504576.0	6485382.2	-504576.0	1.2

"Ambiguity" resolution is not a requirement for the Centre's operation at this stage and probably won't be unless special very large scale photography is required. The core requirement of the position solutions is the exposure to exposure relativity, not the absolute position. Figure 4 is a modification of figure 1, it shows the same strip strengthened by the inclusion of the measures between adjacent camera stations. The triangulation is immediately braced but it is not oriented or located in space. Adjacent strips are built into a block adjustment and in the same way that a 3 dimensional GPS ground survey is rotated and scaled into a local control network, adjoining strips are translated, rotated and scaled to each other through the common photo image points.

With this information it is possible to successfully triangulate a block with only 3 ground control stations. In a minimal constraint solution ground control is not held fixed.

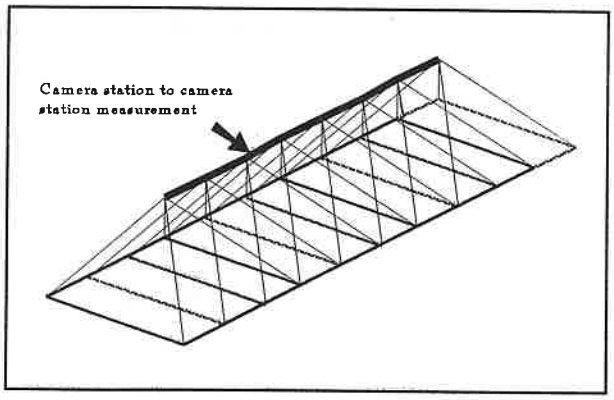

Figure 4 Strip with GPS positions

Although this example considers the camera station to camera station relativity, the PATB-GPS triangulation software accepts position information. The differences in position between adjacent strips are accommodated in the PATB software buy solving for what is termed as "drift" parameters. The software is modelled around the premise that each strip is internally correct but is non aligned with the adjoining strips. Offsets and rotations are removed by tie points between adjoining strips and tie runs down the edge of each block.

For the GPS solution then, absolute position is not critical but the relationship between successive photographs is. Testing is underway at this time to determine how well the hardware/software can deliver this consistency. It appears from initial results that the product can deliver somewhere in the area of 0.25m relative in X,Y and Z over distances up to 1000km from base.

A few areas of concern have occurred over the past operational period. One was the detection of an along track error resulting from incorrect time tagging of the camera exposure pulse. This was detected at the triangulation stage of the COBAR block. It was first thought to be a 48m error in the determination of the aircraft position but the inclusion of the adjoining strip information into the adjustment revealed that the error was in the opposite direction! A positional error was considered unlikely as the two strips under investigation were flown back to back on the same day. The error was found to be an along track displacement. After scrutiny it was determined that the time lag was in the order of 0.5sec. The antennae centre coordinates have been recalculated using a corrected time tag so that induced errors illustrated in figure 5 can be reduced.

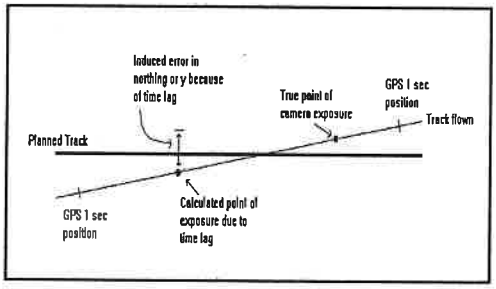

Figure 5 Induced time lag errors

The quality of results is reliant on the satellite tracking stability. Most of the data collected so far has been from photo runs which take approximately 20 to 25 minutes to complete. Best results occur when the satellite constellation is stable i.e. no satellites added or removed from the solution, no change of reference satellite and no losses of lock. The software is still very robust in the event of any of the above occurring and during short PDOP outages, as it uses a Kalman filter to provides predictive motion information to the kinematic solution, which stabilises the result.

Generally, the processing has been very standardised but problems have been encountered with bad ephemerides, control segment switching and missing data epochs at the base station at the time of camera exposure. All have been satisfactorily recovered from.

The real test of the GPS camera station coordinates is at the triangulation stage. The GPS antenna phase centre positions are entered into the block adjustment by way of an offset vector. This vector accounts for the eccentricity of the principle point of the camera film plane to the GPS antenna. The vector on the Centres aircraft is short, approximately 1m and almost vertically above the camera.

The associated errors which result from the "un-locked" relationship between antenna and camera, in the Centre's case, are small. There are 3 rotations to consider:

- rotation around the longitudinal wing axis or pitch. This error is not critical as it will generally be a constant value for stable flight, it will be embedded in the along track offset solved for in the bundle solution. The error from pitch tends to be very stable as the aircraft has particular attitudes for various photographic scenarios.
- rotation around the fuselage axis or roll. This error is a random value, pilots skill at keeping the wings level during exposure will minimise its effect. 1° of roll is 0.017m in a 1m vector.
- rotation around the vertical axis or yaw. This error can be discounted for the Centre's aircraft but for those machines with large eccentricities this becomes an important consideration.

One other assumption about the camera station coordinates has to be considered. The position at the instant of exposure is calculated by interpolation. The receivers are currently logging at 1 second update rates. The aircraft generally flies 80 to 100m/sec. The question is how linear is the motion of the aircraft during this second? Table 4 illustrates the error in interpolated movement in a worst case.

The trajectory file was modified so that the preceding and trailing records for each exposure were deleted. This in effect creates a period where the position is interpolated over 3 seconds. The reasons for the large differences result from a marked increase in velocities at the highlighted epochs. For one second data and these velocities it can be assumed that the interpolated values are generally linear. This supports those positions derived when one or two epochs is lost at the base station.

Even though the processing quality indictors look acceptable problems can emerge in the block adjustment, hence the discovery of mysteries such as the timing error above. At this stage error estimates of 8μm for image observation (0.4m for 1:50000 photography) and GPS positions of 0.25m are compatible within the adjustment, offset parameters have not exceed 2m and drift has been less than 1gon.

From this scale photography it is possible to extract point positions and height better than 2m from ortho-rectified imagery provided the digital terrain model is current and image scan resolution is suitable.

Summary

The implementation of this technology has proven the viability of GPS controlled camera stations in the photogrammetric process. The associated savings in ground control are now directed more towards developing products. Not only has large reductions in control survey been achieved but within the photogrammetric process the data flow from the camera to triangulation to product has been enhanced.

The production of a complete digital mapping product and its associated applications has come a step closer with this technology.

Table 4

Comparison of 1 second and 3 second solutions to evaluate linear motion

Day 034_96	Normal 1 Second Solutions			3 Second Solutions			Differences		
Exposure Time	Easting	Northing	Height	Easting	Northing	Height	Diff E	Diff N	Diff H
22:23:22.838975	280041.03	6261537.01	8054.15	280041.00	6261537.03	8054.14	0.033	-0.026	0.014
22:23:58.481613	281765.69	6265267.53	8050.09	281765.60	6265267.43	8050.43	0.091	0.094	**-0.339**
22:24:34.81961	283490.92	6269024.46	8053.84	283490.98	6269024.52	8053.95	-0.054	-0.062	-0.116
22:25:11.051817	285342.28	6272700.65	8055.78	285342.21	6272700.62	8055.40	0.070	0.037	**0.387**
22:25:47.806375	287189.51	6276401.75	8056.03	287189.52	6276401.63	8056.18	-0.015	0.114	-0.145
22:26:24.404092	288993.36	6280081.76	8057.05	288994.13	6280081.56	8056.99	**-0.777**	**0.198**	0.063
22:27:01.260795	290904.30	6283758.57	8059.80	290904.44	6283758.59	8059.80	-0.142	-0.012	-0.007
22:27:37.645288	292816.66	6287406.19	8061.99	292816.64	6287406.21	8061.95	0.019	-0.016	0.041
22:28:13.910516	294738.06	6291047.45	8058.96	294738.07	6291047.44	8058.97	-0.009	0.008	-0.010
22:28:50.459339	296679.30	6294718.68	8057.94	296679.26	6294718.64	8057.89	0.041	0.041	0.050
22:29:27.102348	298432.60	6298450.17	8060.21	298432.79	6298450.15	8060.10	-0.185	0.020	0.104
22:30:04.268498	300094.49	6302239.00	8059.89	300094.66	6302238.94	8060.06	-0.169	0.057	-0.176
22:30:40.962637	301850.64	6305958.24	8065.66	301851.12	6305958.13	8065.69	**-0.480**	**0.103**	-0.029
22:31:17.434617	303810.14	6309598.64	8069.78	303810.15	6309598.68	8069.38	-0.014	-0.037	**0.397**
22:31:53.497689	305747.56	6313208.69	8071.83	305747.67	6313208.63	8071.89	-0.108	0.061	-0.055
22:32:30.025254	307710.05	6316850.04	8069.44	307709.99	6316849.99	8069.40	0.057	-0.050	0.032
22:33:06.581829	309649.74	6320481.29	8070.74	309649.63	6320481.37	8070.55	0.107	-0.079	0.190
22:33:43.613264	311409.84	6324207.96	8067.33	311409.95	6324208.04	8067.45	-0.105	-0.078	-0.113
22:34:20.775549	313159.77	6327955.82	8072.51	313159.93	6327955.72	8072.42	-0.161	0.099	0.081
22:34:57.844176	314961.42	6331682.25	8076.33	314961.48	6331682.20	8076.20	-0.054	0.047	0.136
22:35:34.137899	316843.27	6335328.38	8081.89	316843.29	6335328.49	8081.45	-0.018	-0.113	**0.440**
22:36:10.616878	318746.62	6338995.45	8076.67	318746.62	6338995.40	8076.35	-0.001	0.043	**0.322**
22:36:47.331601	320525.70	6342721.52	8075.15	320525.72	6342721.54	8075.32	-0.018	-0.021	-0.171
22:37:23.839997	322342.42	6346422.58	8071.43	322342.42	6346422.58	8071.69	0.000	0.006	**-0.259**
22:38:00.413614	324189.41	6350121.07	8078.65	324189.37	6350121.11	8078.61	0.038	-0.037	0.041
22:38:36.763723	326057.20	6353773.43	8075.91	326057.20	6353773.48	8075.84	0.007	-0.055	0.074
22:39:13.558310	327905.32	6357472.13	8080.16	327905.28	6357472.15	8080.05	0.042	-0.021	0.113
22:39:50.332331	329718.26	6361176.18	8082.34	329718.15	6361176.21	8082.24	0.113	-0.036	0.101
22:40:27.049445	331546.48	6364878.36	8082.88	331546.47	6364878.40	8082.88	0.005	-0.047	-0.002
22:41:03.644179	333395.18	6368561.51	8082.26	333395.16	6368561.52	8082.28	0.019	-0.007	-0.020
22:41:40.117677	335233.10	6372228.55	8088.92	335233.06	6372228.59	8088.62	0.040	-0.041	**0.302**
22:42:16.970215	337064.27	6375939.35	8082.88	337064.30	6375939.38	8082.96	-0.024	-0.035	-0.073
22:42:53.539131	338924.21	6379607.11	8080.21	338924.17	6379607.06	8080.38	0.044	0.049	-0.165
22:43:30.294111	340831.22	6383263.80	8091.64	340831.16	6383263.88	8091.40	0.055	-0.084	**0.236**
22:44:06.944627	342753.92	6386929.35	8081.94	342754.07	6386929.25	8082.08	-0.145	0.104	-0.142
22:44:43.537344	344661.47	6390582.44	8093.94	344661.36	6390582.44	8093.66	0.113	-0.004	**0.280**
22:45:20.055358	346521.91	6394247.20	8092.72	346521.94	6394247.25	8092.64	-0.033	-0.045	0.079
22:45:56.829577	348326.80	6397971.00	8088.13	348326.97	6397970.99	8088.17	-0.172	0.009	-0.036
22:46:33.241136	350095.70	6401689.92	8089.25	350095.79	6401689.80	8089.26	-0.092	0.126	-0.008
22:47:09.599908	351920.86	6405387.10	8089.69	351920.86	6405387.07	8089.64	0.006	0.023	0.051
22:47:45.959905	353780.28	6409073.45	8092.07	353780.18	6409073.49	8092.01	0.102	-0.041	0.061
22:48:22.364921	355625.88	6412765.88	8096.06	355625.90	6412765.88	8095.97	-0.019	-0.003	0.094

Table 2

Post Processed positions for Day 312 COBAR Run 11

Planned Exposure Point	East	North	PNAV East	PNAV North	Diff East	Diff North	Velocity East
SH551411*POP*1	353516	6484089	353640.5	6484069.9	-124.5	19.1	119.3
SH551411*POP*2	357954	6484120	358078.7	6484054.4	-124.7	65.6	117.4
SH551411*POP*3	362393	6484151	362525.3	6484045.6	-132.3	105.4	115.5
SH551411*POP*4	366832	6484182	366967.1	6483977.5	-135.1	204.5	119.6
SH551411*POP*5	371271	6484213	371405.8	6484025.6	-134.8	187.4	120.7
SH551411*POP*6	375710	6484244	375848.0	6484087.9	-138.0	156.1	120.9
SH551411*POP*7	380149	6484275	380274.7	6484100.5	-125.7	174.5	120.1
SH551411*POP*8	384588	6484306	384720.5	6484091.1	-132.5	214.9	120.3
SH551411*POP*9	389027	6484337	389162.6	6484066.6	-135.6	270.4	120.4
SH551411*POP*10	393466	6484368	393592.1	6484051.7	-126.1	316.3	120.3
SH551411*POP*11	397904	6484400	398039.3	6484184.1	-135.3	215.9	121.4
SH551411*POP*12	402343	6484431	402477.4	6484364.7	-134.4	66.3	121.8
SH551411*POP*13	406782	6484462	406918.3	6484526.2	-136.3	-64.2	121.9
SH551411*POP*14	411221	6484493	411354.9	6484694.5	-133.9	-201.5	124.4
SH551411*POP*15	415660	6484524	415791.5	6484860.9	-131.5	-336.9	124.5
SH551411*POP*16	420099	6484555	420225.7	6484823.6	-126.7	-268.6	123.6
SH551411*POP*17	424538	6484586	424661.7	6484722.5	-123.7	-136.5	123.4
SH551411*POP*18	428977	6484617	429111.2	6484619.7	-134.2	-2.7	123.2
SH551411*POP*19	433416	6484648	433558.9	6484523.6	-142.9	124.4	122.4
SH551411*POP*20	437854	6484679	437992.6	6484434.1	-138.6	244.9	122.5
SH551411*POP*21	442293	6484711	442437.9	6484454.9	-144.9	256.1	123.9
SH551411*POP*22	446732	6484742	446875.5	6484546.3	-143.5	195.7	124.0
SH551411*POP*23	451171	6484773	451308.4	6484648.6	-137.4	124.4	124.8
SH551411*POP*24	455610	6484804	455737.8	6484753.5	-127.8	50.5	124.3
SH551411*POP*25	460049	6484835	460185.4	6484781.8	-136.4	53.2	125.4
SH551411*POP*26	464488	6484866	464629.1	6484788.9	-141.1	77.1	127.2
SH551411*POP*27	468927	6484897	469072.1	6484866.4	-145.1	30.6	126.8
SH551411*POP*28	473366	6484928	473501.8	6484952.9	-135.8	-24.9	126.6
SH551411*POP*29	477804	6484959	477934.8	6485030.9	-130.8	-71.9	126.5
SH551411*POP*30	482243	6484991	482368.3	6485117.1	-125.3	-126.1	127.3
SH551411*POP*31	486682	6485022	486819.4	6485185.4	-137.4	-163.4	128.4
SH551411*POP*32	491121	6485053	491264.9	6485216.1	-143.9	-163.1	129.5
SH551411*POP*33	495560	6485084	495694.9	6485248.5	-134.9	-164.5	128.9
SH551411*POP*34	499999	6485115	500146.5	6485303.6	-147.5	-188.6	127.6
SH551411*POP*35	504438	6485146	504576.4	6485383.5	-138.4	-237.5	126.0

Table 3

Difference between PNAV Post Processed Position and Real Time AUSNAV positions COBAR Run 11 Day 312

Planned Exposure Point	PNAV East	PNAV North	AUSNAV East	AUSNAV North	Diff East	Diff North
SH551411*POP*1	353640.5	6484069.9	353639.5	6484070.0	1.0	-0.1
SH551411*POP*2	358078.7	6484054.4	358078.4	6484054.5	0.3	-0.2
SH551411*POP*3	362525.3	6484045.6	362524.8	6484045.8	0.5	-0.2
SH551411*POP*4	366967.1	6483977.5	366966.7	6483977.8	0.4	-0.3
SH551411*POP*5	371405.8	6484025.6	371405.6	6484025.5	0.2	0.1
SH551411*POP*6	375848.0	6484087.9	375847.6	6484087.7	0.4	0.2
SH551411*POP*7	380274.7	6484100.5	380274.3	6484100.4	0.4	0.1
SH551411*POP*8	384720.5	6484091.1	384719.9	6484090.8	0.6	0.3
SH551411*POP*9	389162.6	6484066.6	389162.1	6484066.5	0.5	0.1
SH551411*POP*10	393592.1	6484051.7	393591.9	6484051.6	0.2	0.2
SH551411*POP*11	398039.3	6484184.1	398039.0	6484183.5	0.3	0.6
SH551411*POP*12	402477.4	6484364.7	402477.6	6484364.3	-0.1	0.5
SH551411*POP*13	406918.3	6484526.2	406918.3	6484525.9	0.0	0.3
SH551411*POP*14	411354.9	6484694.5	411354.4	6484694.9	0.6	-0.3
SH551411*POP*15	415791.5	6484860.9	415790.0	6484859.7	1.6	1.2
SH551411*POP*16	420225.7	6484823.6	420224.3	6484822.3	1.4	1.3
SH551411*POP*17	424661.7	6484722.5	424660.4	6484720.9	1.3	1.6
SH551411*POP*18	429111.2	6484619.7	429110.0	6484618.0	1.2	1.7
SH551411*POP*19	433558.9	6484523.6	433557.4	6484522.3	1.5	1.4
SH551411*POP*20	437992.6	6484434.1	437991.3	6484432.5	1.3	1.6
SH551411*POP*21	442437.9	6484454.9	442436.3	6484453.6	1.5	1.3
SH551411*POP*22	446875.5	6484546.3	446873.9	6484544.8	1.6	1.4
SH551411*POP*23	451308.4	6484648.6	451306.9	6484647.8	1.5	0.8
SH551411*POP*24	455737.8	6484753.5	455736.7	6484752.6	1.1	0.9
SH551411*POP*25	460185.4	6484781.8	460184.4	6484781.1	1.1	0.8
SH551411*POP*26	464629.1	6484788.9	464627.8	6484788.3	1.3	0.6
SH551411*POP*27	469072.1	6484866.4	469071.1	6484865.6	1.0	0.7
SH551411*POP*28	473501.8	6484952.9	473500.8	6484952.0	1.0	0.9
SH551411*POP*29	477934.8	6485030.9	477933.9	6485030.1	0.9	0.7
SH551411*POP*30	482368.3	6485117.1	482367.4	6485116.1	0.9	0.9
SH551411*POP*31	486819.4	6485185.4	486818.9	6485184.5	0.5	0.9
SH551411*POP*32	491264.9	6485216.1	491264.3	6485215.1	0.5	1.0
SH551411*POP*33	495694.9	6485248.5	495694.6	6485247.4	0.3	1.1
SH551411*POP*34	500146.5	6485303.6	500146.3	6485302.2	0.3	1.3
SH551411*POP*35	504576.4	6485383.5	504576.0	6485382.2	0.3	1.2

References

GOLDFARB, J.M. and SCHWARZ, K.P. *"Kinematic Positioning with an Integrated INS-Differential GPS"* Proceedings of the First International Symposium on Precise Positioning with the Global Positioning System, 2, pp757-772, U.S. NOAA, NGS, Rockville, 1985

GOLDFARB, J.M. *"Aerotriangulation using an INS-Differential GPS"*. M.Sc. Thesis, Department of Surveying Engineering. Publication No. 20022, University of Calgary, November 1987

SCHWARZ, K.P., FRASER, G.S. & GUSTAFSON, P.C. *"Aerotriangulation Without Ground Control"*. International Archives of Photogrammetry and Remote Sensing, 25, Part A1, Rio de Janeiro, June 1984

FRIESS, P. *"The Effect of Camera Position and Attitude Data in Aerial Triangulation - A Simulation Study"*. Progress in Image Sensors, Preceedings of the ISPRS Symposium, Stuttgart, September 1986

LUCAS, J.R. and MADER, G.L. *"Recent advances in Kinematic GPS Photogrammetry"* . ASCE Speciality Conference "GPS 88 - Engineering Application of GPS Satellite Surveying Technology", May, 1988

LUCAS, J.R. *"Aerotriangulation without Ground Control"*. Photogrammetric Engineering and Remote Sensing, Vol53, No3, pp311-314, March 1987

MADER, G.L. *"Dynamic Positioning using GPS carrier phase measurements"*. Manuscripta Geodaetica, 11, 1986

MERCHANT, D. *"GPS Controlled Aerial Photogrammetry"*. Photogrammetric Emgineering and Remote Sensing (PE&RS), Vol LIX, No11, November 1993

SLAMA, C. C. *Manual of Photogrammetry*, 4th Edition, American Society of Photogrammetry

VAN DER VEGT, H.J.W. *"GPS Test Flight Flevoland"*,Proceedings of the 42nd Photogrammetric Week, Stuttgart University, September 1989