A Test of Airborne Kinematic GPS Positioning for Aerial Photography

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ABSTRACT: An airborne photogrammetric test was conducted by the Ministère de l'Énergie et des Ressources, Government of Québec, in November 1987 to assess the accuracy of the Global Positioning System (GPS) for three-dimensional aircraft positioning. The GPS positioning and aerial photography were contracted out to Nortech Surveys (Canada) Inc., Calgary, and Hauts-Monts Inc., Québec City. Nortech's differential kinematic positioning methodology and software were used. This multi-purpose software, which is based on the combination of code and carrier phase measurements, is operationally flexible and suitable for real-time applications. The test was conducted with a Piper Aztec aircraft equipped with a Zeiss camera. Other equipment included two TI4100 receivers and Nortech-designed Computer Addressable Precision Timing Systems (CAPTS) for the precise time-tagging of the camera shutter. The distance between the aircraft and the monitor station did not exceed 20 km. The internal consistency of the GPS positions was analyzed in terms of the flight misclosures from takeoff to landing. These misclosures were smaller than one metre in all three coordinate components. This is considered excellent in view of the satellite geometry available during the test. This was a blind test for Nortech Surveys and Hauts-Monts. The external accuracy was subsequently assessed independently by the Québec Government using ground control stations [Moreau and Perron, 1988]. The results confirmed the submetre accuracy quoted above. The use of this GPS positioning methodology in real-time would be well suited for a variety of extensive airborne applications where cost effectiveness becomes an important factor.

INTRODUCTION

DURING THE PAST SEVERAL YEARS, the Global Positioning System (GPS) has established itself as an accurate kinematic positioning system for many land, marine, and aircraft applications. Early airborne tests conducted by Nortech Surveys (Canada) Inc. with TI4100 receivers at velocities up to 275 km h^{-1} resulted in an accuracy of 5 m in differential pseudo-range mode (Lachapelle *et al.*, 1984). An early analysis of carrier phase measurements by Bossler *et al.*, (1980) led to the conclusion that such measurements could result in cm accuracies in static differential mode. The use of carrier phase measurements for kinematic positioning led to two different formulations, namely that by Hatch (1982) where code and carrier measurements are combined, and that by Mader (1986) which is based on pure carrier measurements. The first method results in a lower accuracy but is operationally more flexible and can be used in real-time if a data link is available. The second method is operationally very stringent and requires post mission computations; moreover, losses of phase lock, which can be caused by masking, multipath, power outages, etc., must be avoided and satellites below an elevation angle of 20° are not generally observed to reduce tropospheric and other effects. However, the decimetre accuracy achievable is one order of magnitude better than that of the first method (e.g., Lucas and Mader, 1988; Hein *et al.*, 1988).

The objective of the test described herein (See also Moreau and Perron (1988)) was to assess the three-dimensional aircraft GPS positioning accuracy achievable for photogrammetric missions using an operationally flexible methodology and algorithm which could potentially be applied in real-time for greater cost effectiveness. The real-time methodology and algorithm developed by Nortech for the Canadian Hydrographic Service for marine applications (Lachapelle *et al.*, 1988) were used. This algorithm, which is based on Hatch's formulation, has led to kinematic positioning accuracies of the order of 1 to 2 m using four satellites simultaneously in differential mode over distances of up to 1,000 km (e.g., Lachapelle *et al.*, 1986). The current project was conducted by the Québec Ministére de l'Énergie et des Ressoures (MER), and the GPS positioning and aerial photography were contracted out to Nortech Surveys (Canada) Inc. and Hauts-Monts Inc. The test flights took place over the Québec City area (latitude 46° 46′ N, longitude 288° 37′ E) on 15 and 16 November 1987. This was a blind test in the sense that the contractors were required to provide the three-dimensional coordinates of the centers of the aerial photographs to MER. The subsequent photogrammetric data reduction and comparisons with properly flagged geodetic coordinates were conducted directly by MER. The results of these comparisons, which provide an external accuracy measure of the aircraft positions, are presented by Moreau and Perron (1988).

METHODOLOGY

EQUIPMENT

The aircraft used for the experiment was a Hauts-Monts Inc. twin engine Piper Aztec equipped with a Zeiss camera. The fuselage of the aircaraft above the passenger's compartment was altered to mount a TI4100 antenna directly above the optical axis of the camera as described in Moreau and Perron (1988). This provided a clear horizon in all directions down to an elevation angle of approximately 5° which was the cut-off angle used during the test flights.

Two TI4100 GPS receivers operating in differential mode were used for the test. The aircraft operated out of Québec Airport where the GPS ground monitor station was located. Because the

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aerial photographs were taken over the Québec City area, the maximum distance between the aircraft and the monitor station did not exceed 20 km. The TI4100 unit on the aircraft was set in User Dynamics (U.D) 3, which corresponds to a bandwidth of 15 Hz. Accelerations of up to 40 m s^{-2} are allowed with such a bandwidth; this is generally required for aircraft operations to avoid excessive losses of phase lock. However, the use of such a wide bandwidth results in a higher carrier phase noise level and makes the detection of cycle slips more difficult. The GPS receiver located at the monitor station was set in U.D. 2 (bandwidth of 8 Hz) to obtain a data output interval of 1.2 s, compatible with that of the aircraft unit. The standard Nortech procedure is to set the monitor receiver in U.D. 0 (bandwidth of 0.7 Hz), in which case the data interval is 3.0 s. It was specified in this case to have the same interval on both receivers to retain the option of reducing the observations with a post-mission technique based on pure carrier phase measurements at some later date. Both TI4100 units were set in P code mode.

Two Nortech-developed Computer Addressable Precision Timing Systems (CAPTS) equipped with rubidium oscillators were available for the test. The unit used on the aircraft was connected to an external HP Series 200 computer to provide a 5 MHz signal input to the receiver and to time precisely the camera shutter openings. The unit at the monitor was used to provide an external rubidium oscillator to the receiver. The intended use of the rubidium clocks of the two CAPTS was to constrain the range biases in the presence of degraded satellite geometry. A calibration of the time delay between the camera exposure time and GPS time was performed.

Although the algorithm used for the GPS position calculation can be applied in real-time provided that a data link is available to transfer differential corrections from the monitor station to the aircraft, this was not required for this test and the observations were reduced after the test flights.

Software

The software used for the reduction of the GPS measurements is a modification of HYDROSTAR, a package developed by Nortech for the Canadian Hydrographic Service (Lachapelle *et al.*, 1988) for the real-time reduction of GPS differential observations. Code and carrier observations are combined to optimize both accuracy and operational effectiveness. Pseudo-ranges are smoothed using phase measurements. The smoothed pseudo-range at epoch i is a linear combination of the measured pseudo-range (weight W1) at i and of the smooth pseudo-range at epoch (i-1) calculated for i using the measured phase difference over the interval (i-1, i); the weight assigned to this differential phase term (W2) is a function of the time elapsed since the beginning (i_o) of an observation sequence without cycle slips on a given satellite. At the initial epoch i_o, W1 is 1.00 and W2 is 0.00. Typically, after 100 measurements, i.e., after an interval of 2 minutes in U.D. 2 or 3, W1 is 0.01 and W2, 0.99, provided that no cycle slip on the satellite has been detected during that period. If this situation arises, no attempt is made to recover the cycle slip and the filter is reset at its initial (i_o) values. This relative weighting scheme can be easily modified but experience has shown that the above parameters are satisfactory.

As dual frequency observations were available, the dual frequency cycle slip detection method described in Goad (1985) was used to detect cycle slips. This method is very reliable but necessarily limited by the phase tracking noise which is significant in U.D. 2 and 3. Pseudo-range and carrier phase observations on L1 were corrected for the effect of the ionosphere using the dual frequency method. Tropospheric corrections were applied using the modified Hopfield method. Broadcast ephemerides were used.

The phase smoothed pseudo-ranges derived at the monitor station were used to calculate differential range corrections averaged over intervals of 30 seconds. Such an interval provides a reasonable compromise between accuracy and real-time data transfer requirements. Differences between successive average range corrections for any satellite did not generally exceed 20 cm. The magnitude of these differences could be reduced by decreasing the above time intervals. This would possibly increase the differential positioning accuracy by 10 to 20 cm.

The photograph coordinates were calculated using two methods. In the first case, the coordinates were interpolated linearly between the GPS fixes calculated at 1.2 s intervals. In the second case, the velocity components calculated using phase differences at the nearest measurement epoch were used to extrapolate the photograph coordinates from the nearest GPS fix. In both cases, the GPS time, which was maintained by the CAPTS with an accuracy better than 10^{-6} s, was used for interpolation. The two methods showed an agreement generally better than 10 cm, with a worst case of 25 cm.

The GPS data reduction was performed with a HP Series 200 computer. The reduction time was slightly inferior to that of the measurement time. The software has since been modified to be compatible with IBM PC compatible computers. The reduction time on a Compaq 386/20 MHz computer is between 0.1 and 0.2 that of the above time.

Field Procedures

The monitor station was located near the airport at a point where the visibility was clear in all directions above 5°. Cycle slips were detected on several occasions due to flying aircraft temporarily masking a satellite. A temporary point located at the end of a runway was accurately tied to the monitor station. GPS observations at this point were made by the aircraft for a few minutes prior to every takeoff and every landing to provide three-dimensional misclosures for each flight. The aircraft was centered over the point with an accuracy of a few cm using an optical sight. Multipath was suspected at this observation site due to the presence of nearby hangars: however, no abnormally high number of cycle slips were detected.

The horizontal ground points used by MER during the photogrammetric mission were given in the NAD27 geodetic reference system. The NAD27 coordinates of the monitor station were determined by conventional methods using surrounding survey points. These coordinates were used to calculate the differential range corrections applied to the smoothed pseudo-ranges calculated onboard the aircraft. The coordinates of the photograph centers were therefore obtained in the same NAD27 system as the photogrammetric ground control points.

The vertical ground points used by MER were leveled heights referenced to the Mean Sea Level (MSL). The MSL height of the monitor station was established by conventional leveling methods. An GPS provides heights referenced to the ellipsoid, a correction was applied to the camera heights to account for differential geoid variations between the monitor and the flight lines. The geoid undulations required were calculated by the Geodetic Survey of Canada using program GDOVE (Lachapelle, 1977). The differential geoid undulation corrections to the GPS derived aircraft heights reached 57 cm at 20 km from the monitor station.

Aircraft maneuvers during test flights were restricted in order to avoid satellite masking. Meteorological data were taken every 15 minutes once the aircraft had reached the prescribed altitude of 2,500 m. Meteorological measurements made by the Airport personnel were used for the nearby monitor station. The meteorological data were used to calculate the effect of the troposphere. The ground temperature during the test ranged from 0° C to −10°C. The scale of the aerial photographs was 1:15000. The operational speed of the aircraft was of the order of 200 km h^{-1}.

RESULTS AND ANALYSIS

Flight Time and Satellite Geometry

An initial flight (No. 1) to test the proper functioning of the equipment took place on 13 November. Three test flights (Nos. 2, 3, and 4) took place on 15 and 16 November. The satellites (PRN) tracked during these flights and their Geometric Dilution of Precision (GDOP) and Position Dilution of Precision (PDOP) are given in Table 1. Nortech's standard procedure is to use a cutoff angle of 10° for precise airborne missions. In view of the limited satellite availability during the tests, satellites were observed down to elevations of 5° at the beginning and end of the flights, prior to and after the completion of the photography. In the worst case, namely Flight No. 2, the geometry was kept acceptable only at the cost of observing SV 12 at an inferior elevation angle of 5° towards the end of the flight. The poor GDOP at the start of Flight No. 3 resulted in a relatively lower Easting accuracy, the ratio between the *a priori* standard deviations of Easting and Northing components being 9.

No cycle slips were detected on the aircraft during Flight No. 2 on 15 November. During Flights No. 3 and 4, cycle slips on individual satellites were detected on some seven different occasions. These cycle slips took place at the beginning and end of the flights, prior to and after the photography, when the satellites involved were at elevations lower than 10°.

At the start of Flight No. 3, the poor dilution of precision (GDOP of 14.6) could have been improved by constraining the rubidium clocks on the CAPTS both at the monitor and on the aircraft because the PDOP is signficantly smaller (8.5). However, this was not possible for this Flight due to power problems during the one-hour period prior to takeoff; this resulted in an unstable rubidium frequency output. The rubidium clocks were warmed up properly prior to Flights 2 and 4. Solutions with both constrained and unconstrained range biases were computed. The position differences between the two solutions were less than 20 cm. This is to be expected in view of the relatively small differences between the GDOPs and PDOPs during these two flights. The constrained solutions were based on a linear fit of the rubidium clock outputs. Such solutions cannot be made in real-time and are only practical and significant when the satellite geometry is unsatisfactory.

Flight Misclosures

Flight misclosures are listed in Table 2. For each flight, the start (prior to takeoff) and end (after landing) misclosures are given, except for Flight No. 2 where no end misclosure was calculated due to the low elevation of SV 12. The start and end misclosures consist of the differences between the survey and GPS derived coordinates of the runway station with respect to the monitor station. The distance between the two points was less than 100 m. The start misclosures are mostly due to code noise because code measurements are weighted heavily at the beginning of an observation sequence. The observation time spent by the aircraft on the runway station prior to takeoff is approximately 2 minutes, which is the time required for the carrier phase measurements to reach their maximum weight of 0.99 in the code-carrier combination filter.

The differences (Δ) between the end and start misclosures, which were calculated for Flights 3 and 4, provide a good accuracy assessment of the kinematic positioning accuracy maintained during the flights. Apart from the −4.71 m difference in Easting for Flight 3 which is due to the poor GDOP at the beginning of that flight, the differences are less than 25 cm in Northing and 65 cm in height. This is considered excellent in view of the frequent cycle slips detected during the flights. It demonstrates clearly the effectiveness of the methodology and algorithm utilized. These misclosures are comparable to or better than the corresponding values reported by Lucas and Mader (1988) when using a pure carrier phase post-mission approach.

TABLE 1. SATELLITE GEOMETRY

Flight No.			SV (PRN) tracked	GDOP	PDOP
2	(15 November)		3, 11, 12, 13		
	Start	16:30		4.7	2.9
		17:03		4.4	2.2
		17:15		4.4	2.1
	End	17:25		4.4	2.1
3	(16 November)		6, 9, 11, 12		
	Start	14:10		14.6	8.5
		14:30		6.9	3.8
		15:02		5.6	2.4
	End	15:18		5.7	2.1
4	(16 November)		3, 11, 12, 13		
	Start	16:25		4.7	2.9
		16:44		4.4	2.2
		16:48		4.4	2.1
	End	17:10		4.4	2.1

TABLE 2. FLIGHT MISCLOSURES

Flight No.		Misclosures (m) Northing	Easting	Height
2	Start	0.01	−0.01	−0.46
	End	Not computed (PRN 12 ELEV <5°)		
3	Start	0.25	−4.71*	−1.07
	End	0.48	0.33	−1.20
	Δ	**0.23**	**5.04**	**−0.13**
4	Start	0.50	−0.21	0.13
	End	0.45	0.16	−0.49
	Δ	**0.05**	**0.37**	**−0.62**

* Poor Satellite Geometry - GDOP was 14.6

Comparison of GPS and Photogrammetric Results

The GPS coordinates of the aircraft were used to fix the perspective centers of the photographs during the photogrammetric reduction process with the software program SPACE-M (Blais and Chapman, 1983). The three-dimensional coordinates of over 100 ground points were determined as part of this reduction process and compared with the geodetic coordinates of these points. The accuracy of the ground point coordinates as determined by photogrammetry, but excluding the GPS error contribution, was estimated at about 30 cm. The rms difference between photogrammetric and geodetic coordinates was of the order of 50 cm horizontally and 90 cm vertically. The corresponding GPS error contribution is therefore 85 cm and 40 cm, respectively. These values can be considered as external accuracy estimates. See Moreau and Perron (1988) for details.

CONCLUSIONS

The methodology described above provides a sub-metre accuracy which is sufficient for a wide range of aerial photogrammetric and other precise airborne applications. The method can be used in real-time for optimal cost effectiveness and allows for a large degree of operational flexibility. The procedures are largely automated, and the utilization of the system under adverse field conditions does not require a high level of training. This system is therefore cost effective for extensive airborne applications.

The Norstar 1000, a high precision C/A code GPS receiver built by Norstar Instruments Ltd, a wholly-owned subsidiary of Nortech Surveys (Canada) Inc., uses the same methodology as that described herein. The differential software is internal to the

receiver and real-time accuracies at the 1 m level with the five-channel version of the receiver have been confirmed (Fenton *et al.*, 1987). The use of the seven-channel version with a better satellite constellation, together with the on-going efforts of the Nortech Group to improve its GPS hardware and software components, will no doubt result in increasingly cost effective GPS products.

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