TIGHT INTEGRATION OF GNSS POST-PROCESSED VIRTUAL REFERENCE STATION WITH INERTIAL DATA FOR INCREASED ACCURACY AND PRODUCTIVITY OF AIRBORNE MAPPING

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ABSTRACT:

GNSS-Aided Inertial Navigation for Direct Georeferencing of aerial imagery and other sensors such as LIDAR is a well accepted technology that has been in use since the mid 1990's. Position accuracies of 10 cm RMS horizontal and 15 cm RMS vertical are routinely achieved using post-processed kinematic ambiguity resolution (KAR) differential GNSS processing along with specific operational restrictions that are necessary due to the nature of the airborne environment. These include: flying turns of less than 20 deg bank angle, flying less than 30 km from a reference GNSS receiver in order to correctly fix integer ambiguities, and keeping the maximum baseline separation to less than 75 km once the ambiguities are fixed. Each of these restrictions significantly reduces the efficiency of airborne mapping, and hence increases the overall cost. In order to overcome these limitations, Applanix has developed a new patent pending post-processed GNSS-Aided INS software called POSPac Mobile Mapping Suite (formerly POSPac Air 5.0). This software incorporates two new technologies, Applanix IN-Fusion™ and Applanix SmartBase™, that together provide the ability to fly turns with greater than 20 deg bank angle, and fly at distances up to 70 km from the nearest GNSS reference station, without sacrificing accuracy or reliability. This paper provides details on the new Applanix IN-Fusion technology and Applanix SmartBase module implemented in POSPac MMS. It will then present results from a series of studies into the performance of POSPac MMS using various reference station networks from around the world. Finally it will present performance and cost saving results when flying bank angles at greater than 20 degs from a series of actual survey flights.

1. INTRODUCTION

1.1 Applanix IN-Fusion Technology

High accuracy carrier phase differential GNSS processing involves searching for the correct number of integer cycles of the L1 carrier signal between the rover antenna and each satellite. Since the correct number of integer cycles is originally unknown, they are referred to as the cycle ambiguities. Estimation of the ambiguities requires a continual lock on the signal to each satellite in order for the solution to remain converged. If the aircraft turns with a bank angle greater than 15 to 20 deg, the wing can block the view of the satellites from the GNSS antenna, causing the solution to reset and begin another search. Flat turns increase the time required to fly the survey, and are problematic in restricted flight zones where there may not be enough room to safely manoeuvre. They also increase the stress level on the crew, which leads to fatigue and potential operational errors.

These problems are solved via the Applanix IN-Fusion™ technology, which implements an Inertially-Aided Kinematic Ambiguity Resolution (IAKAR) algorithm to compute the GNSS ambiguities. In this approach the inertial data and raw

GNSS observables (phase and range measurements) are processed in a single tightly integrated Kalman filter, which allows the inertial data to be used to solve for the integer ambiguities. The IAKAR architecture is illustrated Figure 1.

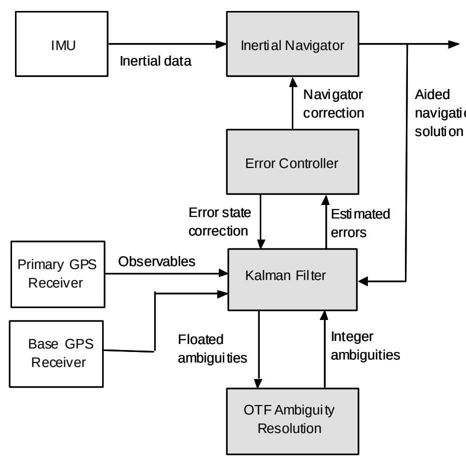

Figure 1. Applanix IN-Fusion IAKAR Architecture

With IAKAR, if there is a cycle slip or outage in the GNSS data, the inertial data keeps a "memory" of the ambiguity, allowing the correct integer ambiguity to be quickly re-established immediately after the outage. For airborne applications this means there is no longer any need to fly flat turns to avoid signal outage. Flying a turn at 15 deg bank angle at a typical survey speed of 150 knots, gives a turn rate of about 2 degs/sec and a turn radius of about 2.3 km. The time to compete a 180 deg turn will take minimum of about 1.5 minutes. In contrast, if the aircraft bank angle is not restricted, the same turn can be made in approximately half the time and radius, simply by banking at 30 degs instead of 15 degs. This savings means the mission can be flown in less time (reducing fuel costs), or more lines can be flown per mission. Furthermore, the smaller radius of the turns also allows more flexibility for flying missions in restricted airspace.

1.2 Applanix SmartBase

At distances greater than 20 to 30 km from a reference station, the residual ppm error caused by the atmosphere delaying the GNSS signals reaches a magnitude such that the correct carrier ambiguities can no longer reliably be estimated. Hence with traditional KAR differential GNSS processing, it is always necessary to be within 30 km of a reference station sometime during the mission in order to resolve the ambiguities. Once the correct ambiguities are resolved, the aircraft can fly up to about 75 km from the nearest reference station before the magnitude of the ppm error exceeds level required for high-accuracy applications. For land-based applications a significant productivity improvement in Real-Time Kinematic (RTK) positioning has been achieved using the concept of a "Virtual Reference Station" or VRS (Landau H., 2002), illustrated in Figure 2. Here observables from a dedicated network of GNSS reference stations are processed to compute the atmospheric and other errors within the network. These are then interpolated to generate a complete set of GNSS observations as if a reference station was located at the rover.

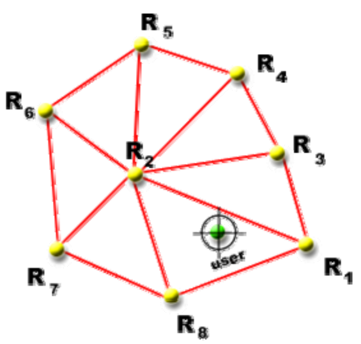

Figure 2. Virtual Reference Station (VRS) Concept

There are a number of significant benefits to a VRS approach:

- the distance to the nearest reference station can be extended well beyond 30 km
- the time to fix integer ambiguities is significantly reduced
- the overall reliability of fixing integer ambiguities in increased
- the cost of doing a survey is reduced by eliminating the need to set up dedicated base stations.
- no special processing is required in the RTK engine, as it is the case for a centralized multi-base approach

Real-time positional accuracies using a VRS approach are at the cm RMS level anywhere within the network (Hakli P., 2004).

With the POSPac MMS software, Applanix has introduced a post-processed version of VRS called the Applanix SmartBase™. Based upon the industry leading Trimble© VRS™ technology, the Applanix SmartBase software has been optimized for large changes in altitude by the rover, and extended to work with reference stations separated over very large distances. With this approach it is only necessary to be within the network and at least 70 km to the nearest reference station to initially resolve the correct ambiguities. Once resolved, the aircraft can then fly up to 100 km away from the nearest station within the network, while still achieving positioning accuracy at the 10 - 15 cm RMS level (Figure 3).

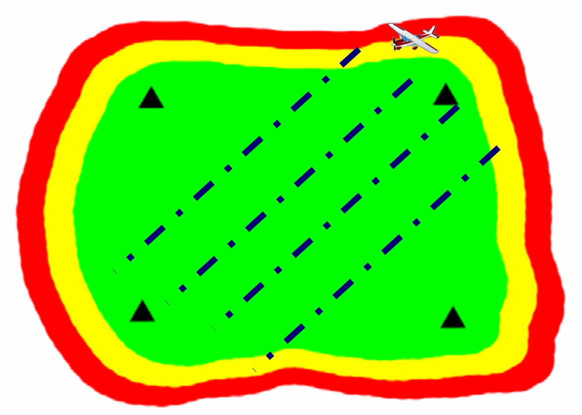

Figure 3. Applanix SmartBase Concept

The ability to accurately correct the atmospheric errors within the network will of course depend upon the amount of atmospheric activity during the survey, and the density of the reference stations. Tests conducted by Applanix have shown that it is possible to achieve better than decimeter RMS accuracies with a sparse network of only 4 reference stations separated by over 100 km, but the results are highly dependent upon the particular data set. However for existing dense networks such as the CORS network in Ohio State, the GSI network in Japan, or in the SAPOS™ network in Germany, where the there are literally 10's to 100's of stations separated by distances of typically 50 – 70 km, the robustness improves tremendously and the area that can be flown is virtually limitless. The Applanix SmartBase includes a rigorous adjustment of all the reference station antenna positions within the selected network over an 18-24 hour period. This quality control function ensures that all the reference station data and coordinates are correct and consistent before the rover data is processed. Such a concept is done routinely in land survey as part of best practices, but has been a weak point in the aerial mapping and survey industry. Too often data from a single reference station or a CORS network are used without proper quality control. Quality failures can include incorrect published antenna coordinates, incorrect datum or poor observables, any of which can result in accuracy and reliability failures in the final product.

The Applanix SmartBase module together with the Applanix IN-Fusion technology enables missions to be flown with bank angles above 20 degs, with the only restriction that the turns be less than about 70 km from the nearest reference station (Hutton, J. et al, 2007).

2. TEST RESULTS

This section presents results from a number of studies into the new capabilities of POSPac MMS.

2.1 BLOM Case Study

Using data collected from a LIDAR calibration flight conducted in April 2007, BLOM Geomatics AS of Norway performed a study on POSPac MMS to investigate the accuracy using existing reference stations, and the potential for flying sharp turns.

2.1.1 Accuracy Using Existing Reference Stations: In order to test the accuracy of the Applanix SmartBase module, an existing set of 27 reference stations located throughout Norway, Denmark and Sweden was used to create four separate Applanix SmartBase networks, with baselines 60, 110, 200 and 300 km apart respectively (Figures 4 and 5).

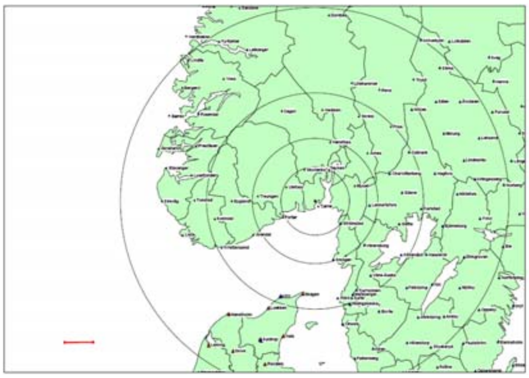

Figure 4. Reference Station Networks

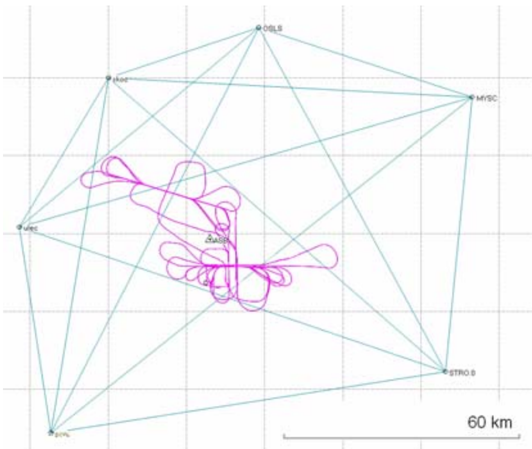

Figure 5. 60 km Network

The coordinates of each reference station were transformed from ETRS89 to ITREF 2000 epoch 2007.30 in order to place them in the same frame of reference and epoch as the GPS observables, and the SmartBase quality check adjustment was run. The adjustment detected that one of the reference stations was using an incorrect antenna model. This was subsequently fixed and the Smartbase solution was computed for each network, which were then used to generate 4 different SBET solutions using the Applanix IN-Fusion processing in POSPac MMS.

The SBET solutions for each network were then differenced with a reference or "truth" solution generated using the loosely coupled POSPac V4.4 processing and a network of 7 reference stations that included a dedicated base station directly in the project area. The accuracy of the POSPac V4.4 reference solution was estimated to be 4 cm RMS horizontal and 5-7 cm RMS vertical for position, and 20 to 30 arcsec for the orientation. The results revealed that once the solution had converged, the position differences with the reference for the 60, 110, and 200 km networks were all well below 10 cm, and the orientation differences were well below 30 arcsec (Figures 6 and 7). Only for the 300 km network did the differences start to grow as the software had trouble resolving the correct ambiguities (Figure 8).

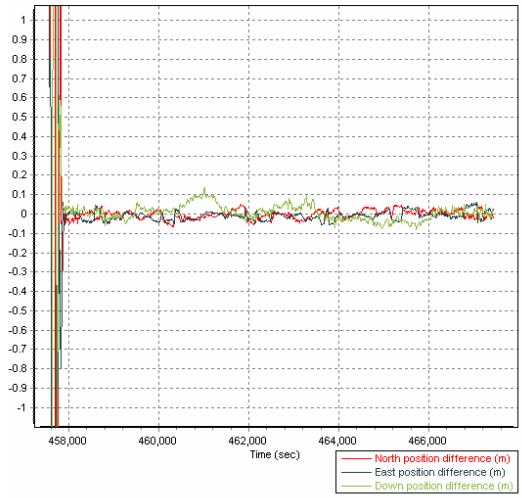

Figure 6. Position Differences, 200 km Network

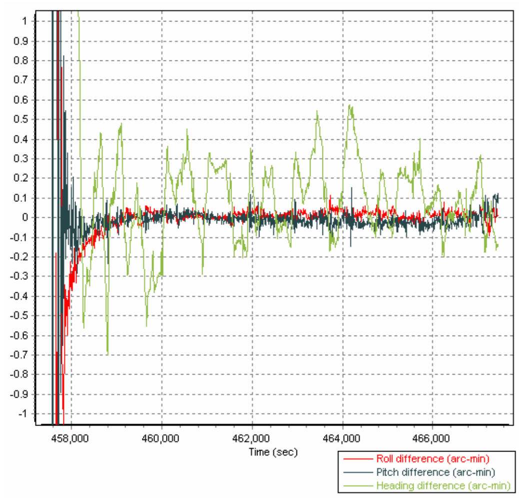

Figure 7. Orientation Differences, 200 km Network

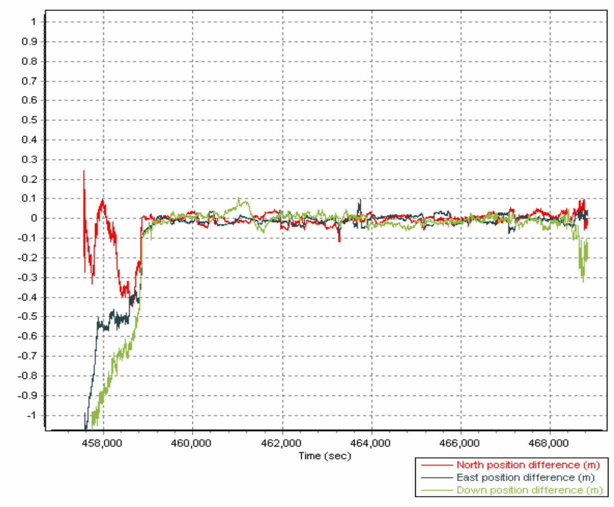

Figure 8. Position Differences, 300 km Network

2.1.2 Simulated Satellite Outages Due to Large Roll Angles: In order to study the effect of satellite outages that might occur during a high banked turn, two types of outages were simulated. This was done by turning off the raw GPS observations for some of the satellites in the processing at the centre of the trajectory. The first case reduced the number of satellites being tracked to only 2 during a period of 30 seconds, while the second case reduced the number to 2 for 75 seconds. In each case the SBET was re-generated using the 60 km SmartBase network and then differenced with the POSPac V4.4 reference solution that did not have any satellite outages.

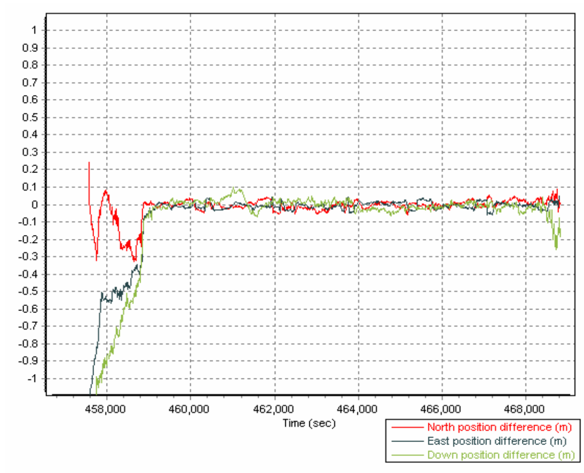

Figure 9. Position Differences 30 sec Outage

Figure 9 shows the position differences for the simulated outage of 30 seconds, while Figure 10 shows the differences for the 75 second outage. In both cases, once the solution has converged, the position differences remain below 10 cm, and are virtually unaffected before and after the outages.

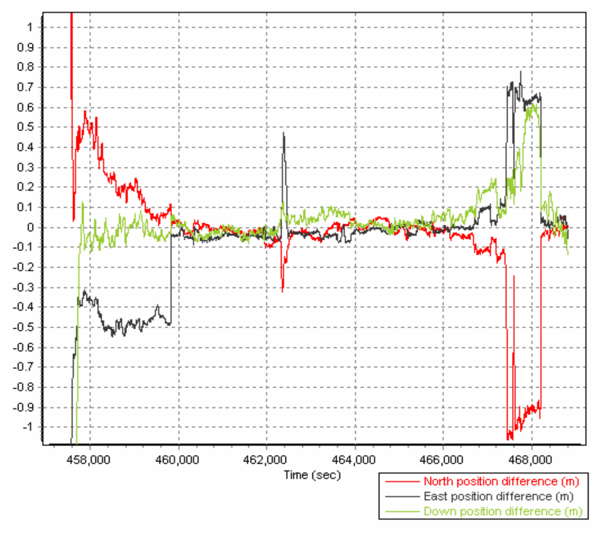

Figure 10. Position Differences 75 sec Outage

2.2 Applanix DSS Case Study

As part of the USGS certified manufacturing process for the Applanix DSS, a directly georeferenced medium format camera system, each DSS undergoes a final acceptance test in the form of a flight test over a geometric test range. The acceptance test involves validating the calibration of the DSS and the accuracy of the embedded POS AV 410 solution against a series of ground control points.

As of October 2007, Applanix began using POSPac MMS and flying sharp turns on all DSS acceptance tests. This section presents a summary of the geometric analysis results for 8 of the test flights, plus an analysis on the associated savings attained.

2.2.1 Accuracy Results, Sharp Turns: To evaluate the DSS a small block of photos consisting of 12 flight lines is flown. Ten of the flight lines are flown at a Ground Sample Distance (GSD) of 15 cm, while 2 of the flight lines are at flown at either 18 cm or 25 cm GSD, depending upon the focal length (60 mm vs 40 mm). Each line contains 6 photos, and they are flown in a cross pattern for strong geometry. Endlap and sidelap is 60% and 40% respectively. For this analysis only the 15 cm GSD flight lines were used in order to allow a direct comparison on accuracy between flights. Geometric accuracy was assessed by running the block of photos in the POSPac Calibration and Quality Control (CalQC) module along with the Exterior Orientation computed from the POS AV 410. The CalQC automatically generates a set of tie points from the imagery, then runs a block adjustment holding the EO, camera model and boresight angles fixed to see how everything "fits" against surveyed Ground Control Points (GCP). The RMS accuracy against the GCP gives a direct indication on the quality of the EO from the POS AV.

A total of 2 to 8 GCP's were used to evaluate each flight, depending upon what could be identified in the imagery due to weather conditions (ie snow coverage). The average number of measurements per GCP ranged from 10 to 15 (although only 2 GCP is not ideal, since the imagery was flown with such high overlap the same GCP could be viewed in multiple images, hence the high number of measurements).

The SmartBase network used for the processing is comprised of 5 reference station; four from the Can-Net VRS network (www.can-net.ca), and one CORS station. Figure 11 shows the trajectory and layout of the network. Figure 12 shows a plot of the distance to the nearest base station for one of the flights. As indicated by the peaks and valleys, the turns are anywhere from 36 to 49 km from the nearest station.

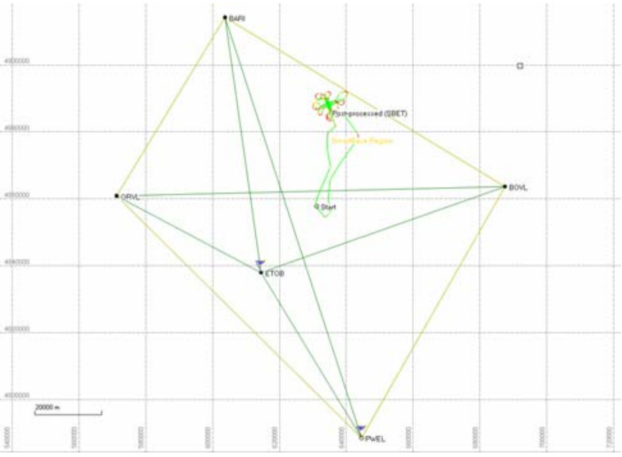

Figure 11. Test Flight Trajectory and SmartBase Network

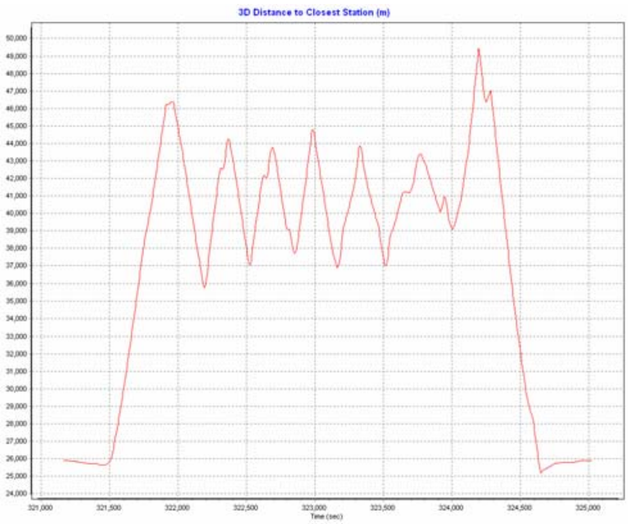

Figure 12. Distance to Nearest Reference Station

Two of the DSS flight tests were flown with maximum bank angles of 25 deg. The remaining 6 were flown with maximum bank angles of 30 to 40 degrees. In all cases the Applanix IN-Fusion technology was able to remain in fixed integer ambiguity mode, even during the turns.

Figure 13 shows a plot of the roll for one of the flights that had bank angles up to 40 deg, with the exposure times indicated by the blue squares. Figure 14 shows the number of SV's tracked during the same flight. During the turns this drops to as low as 5. Figure 15 shows the solution status for the same flight, which always remains in fixed integer even as SV's come in and out of the solution. Table 1 provides a summary of the checkpoint residuals for the 8 flights. In each case the RMS accuracy is well within the DSS system accuracy specification of 1.2 X

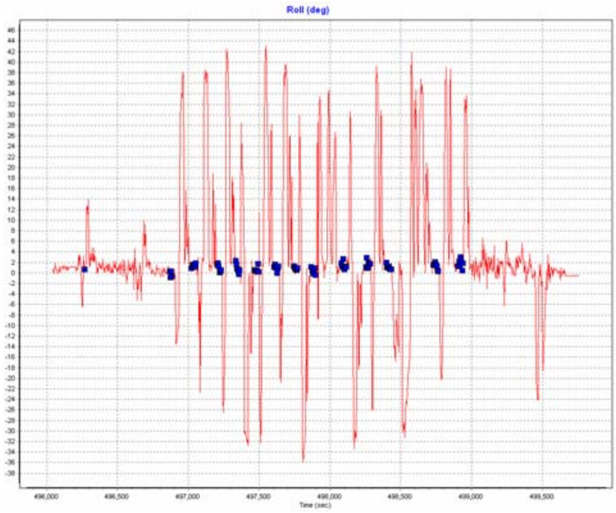

Figure 13. Roll angle

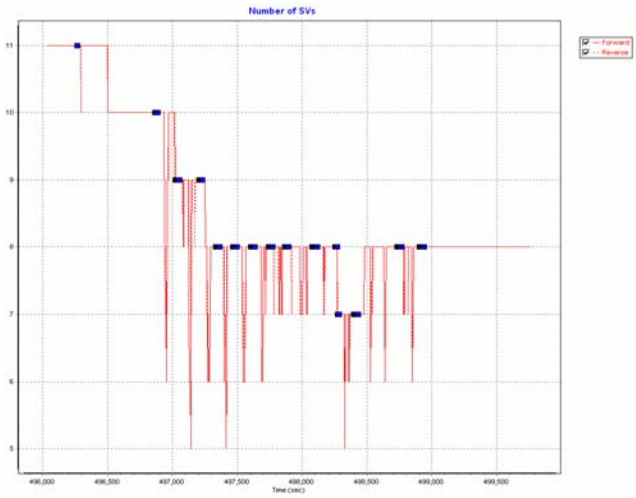

Figure 14. SV's Tracked

effective GSD RMS horizontal and 3 X effective GSD RMS vertical (approximately 20 cm and 50 cm RMS respectively). The average RMS over the 8 flights is 11 cm and 12 cm horizontal, and 13 cm vertical.

This indicates that the accuracy of the EO produced by the POS AV 410 is well within its specification and completely unaffected by flying sharp turns with distance to the nearest base station as large as 49 km.

#	**Lens (mm)**	**Max Roll (deg)**	**RMS E (m)**	**RMS N (m)**	**RMS H (m)**	**# GCP**
1	60	25	0.17	0.19	0.07	8
2	60	25	0.16	0.17	0.15	7
3	60	40	0.06	0.14	0.09	3
4	60	30	0.13	0.12	0.23	4
5	60	40	0.12	0.13	0.15	4
6	40	30	0.07	0.09	0.19	2
7	60	30	0.08	0.08	0.07	2
8	60	35	0.12	0.07	0.07	2
		Avg	**0.11**	**0.12**	**0.13**	

Table 1. RMS Accuracy vs GCP, 15 cm GSD

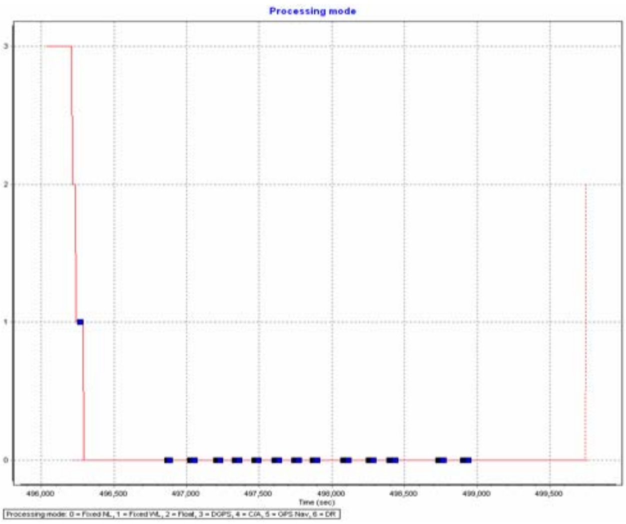

Figure 15. Solution Status

2.2.2 Time savings: Figure 16 shows an enlargement of one of the flight trajectories, colour coded by roll angle. In this case green indicates a roll of less than 10 deg, yellow is between10 to 20 deg, orange is from 20 to 25 deg, red is from 25 to 30 deg, and grey is above 30 deg. The plot clearly shows that the larger the bank angle, the tighter the turn, and the faster the aircraft is back on line.

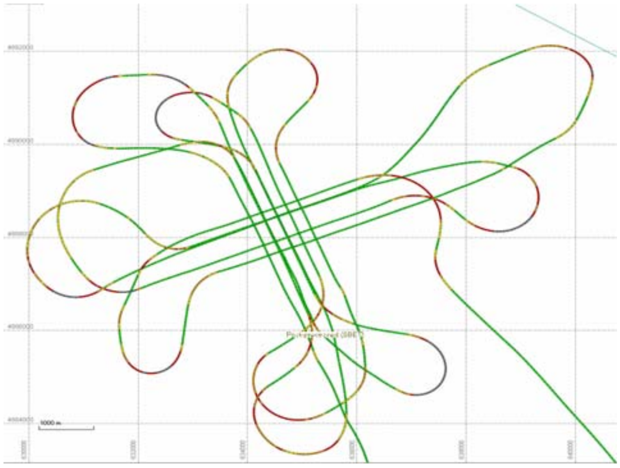
Figure 16. Sample Trajectory

Table 2 is a summary of the average turn times for the flights. The turn times are defined as the time between the last photo in a line and the first photo in the next line. The percent improvement is computed with respect to the flight having a maximum bank angle of 25 deg with170 sec average turn time.

#	Max Roll (deg)	Avg Spd (knot)	Avg Turn (sec)	% Improvement
1	25	105	170	n/a
2	25	97	150	n/a
3	40	97	110	35
4	30	97	120	29
5	40	116	110	35
6	30	116	140	18
7	30	116	130	24
8	35	127	120	29
			Avg	**28**

Table 2. Summary of Average Turn Times

The results show that simply by increasing the bank angle from 25 deg to 30 to 40 deg, the time to fly the turns was reduced by an average of 28%. Using the average time to turn of 170 seconds for the 25 deg bank angle flight, this translates to an average savings of 48 seconds per turn. With an average of 12 turns per flight, and an average of 50 flights per year, this translates to a savings in flight time of 12x44x48 = 28,800 seconds or 8 hours. Such a savings could easily be doubled or tripled for standard survey missions that have many more turns than a DSS flight test, especially if the turns are being flown at a bank angle less than 25 deg (say at 15 to 20 deg).

3. CONCLUSIONS

The new Applanix SmartBase and IN-Fusion technology implemented in the POSPac MMS software represents a paradigm shift in operational efficiency for aerial mapping:

- It can produce the same position accuracy as standard differential GPS with a dedicated reference station, but without the restriction of having to always fly less than 75 km from a reference station
- It can solve for the correct integer ambiguities without the need to fly within 30 km or less of a reference station
- It can eliminate the need to fly flat turns, which reduces the time to fly a mission, enables more flexible mission execution in restricted airspace, and reduces crew fatigue leading to fewer mistakes and increased safety.

Future work will focus on clearly defining the requirements for reference station location, density, and data quality in order to reliably and robustly meet the performance claims, especially during periods of increased ionosphere activity.

As a final note, performance results are only expected to improve as additional GNSS observables are added to the processing.

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REFERENCES

Hakli P., 2004, Practical Test on Accuracy and Usability of Virtual Reference Station Method in Finland, FIG Working Week 2004, Athens, Greece

Hutton J., Bourke, T., Scherzinger, B., 2007, New Developments of Inertial Navigation Systems at Applanix, Photogrammetric Week 2007

Landau H., Vollath U., and Chen X., 2002, Virtual Reference Station Systems, *Journal of Global Positioning Systems*, Vol. 1, No. 2, 2002