International Global Navigation Satellite Systems Society
IGNSS Symposium 2007

The University of New South Wales, Sydney, Australia
4 – 6 December, 2007

GPS/INS Integration in Real-time and Post-processing with NovAtel's SPAN System

Sandy Kennedy (1)
NovAtel Inc., Canada
Phone: (403) 295-4937 Fax: (403) 295-4501 Email: Sandy.Kennedy@novatel.com
Darren Cosandier (2)
NovAtel Inc., Canada
Phone: (403) 295-4500 Fax: (403) 295-4501 Email: Darren.Cosandier@novatel.com
Jason Hamilton (3)
NovAtel Inc., Canada
Phone: (403) 295-4953 Fax: (403) 295-4501 Email: Jason.Hamilton@novatel.com

ABSTRACT

NovAtel offers a GPS/INS solution with a uniquely robust architecture. The SPAN (Synchronized Position Attitude Navigation) system builds on the OEMV receiver, by integrating inertial measurements to provide a high-rate, continuous navigation solution. The integration is tightly coupled with access to the GPS receiver core, with both the GPS and inertial processing benefiting from the integration. Typically, GPS measurements are used to aid the inertial solution, providing update measurements to model IMU errors and control error growth during GPS outages. With SPAN, GPS performance is also improved. A SPAN enabled receiver features rapid signal requisition and a faster return to fixed integer carrier phase status (RTK) after signal outages. By improving the quality and availability of the GPS signals, the INS solution is also improved since there are more updates available. Post-processing functionality comes with Inertial Explorer, a software package featuring a fixed interval smoother to minimize errors during GPS outages.

To demonstrate the performance of the SPAN (real-time) and Inertial Explorer (post-processed), results from real world applications will be presented. Data sets collected in an aircraft and in a land vehicle will be presented. The airborne data set illustrates how SPAN can be incorporated in a aerial photogrammetry application. The land vehicle data set is very similar to an urban mapping application. Test results will show SPAN system performance with various levels of GPS aiding, demonstrate the benefits of a tightly coupled system, and the accuracy improvements possible with post-processing.

KEYWORDS: GPS/INS, tightly coupled, smoother, signal reacquisition, photogrammetry

1. INTRODUCTION

This paper outlines the architecture of the SPAN GPS/INS system. System capabilities in real-time and post-processing are described. Performance is verified in two different environments: airborne and land. In the airborne data, SPAN was integrated into an aerial photogrammetry system at the board level. Attitude accuracy provided by SPAN and Inertial Explorer is evaluated with respect to the photogrammetrically derived attitude estimates. In the land data, SPAN was mounted in a mini-van and driven through downtown Calgary, Alberta, Canada, which is a severe urban canyon environment. The real-time and post-processed performance is demonstrated using georeferenced imagery and comparison to a navigation grade IMU (Inertial Measurement Unit). These evaluations provide guidance for reasonable performance expectations.

2. SPAN TECHNOLOGY

SPAN stands for Synchronized Position Attitude Navigation. Combined with the post processing capability provided by Inertial Explorer, it is a complete GPS/INS solution: a high quality real-time solution with superior signal tracking performance, simultaneous raw data logging capability. A full navigation solution (position, velocity and attitude all precisely time tagged with GPS time) is continuously available at a maximum rate of 100 Hz or 200 Hz, depending on the selected IMU.

The tightly coupled architecture of SPAN achieves reciprocal aiding between the GPS and INS. This is shown graphically in Figure 1.

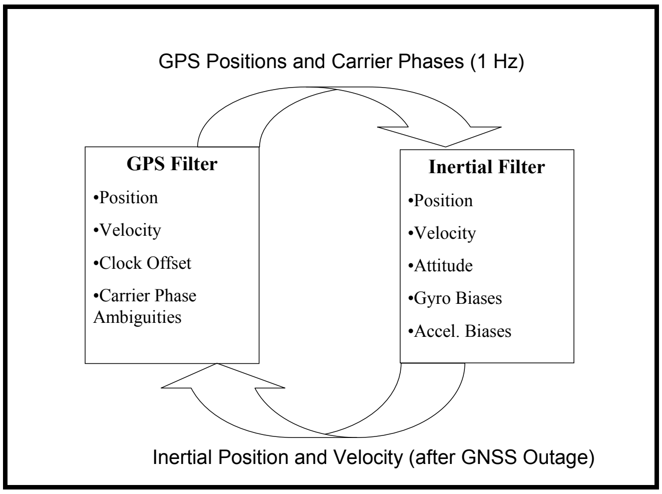


Figure 1. SPAN Tightly Coupled Architecture

In a typical GPS/INS system, the INS is aided by the GPS, with position updates being used to estimate the IMU biases and other errors. In this typical GPS/INS system, the GPS is unaffected by the addition of the IMU to the system. In SPAN, the GPS is improved by the addition of the IMU. Figure 2 shows the signal reacquisition histogram for a SPAN enabled receiver and a stand alone receiver.

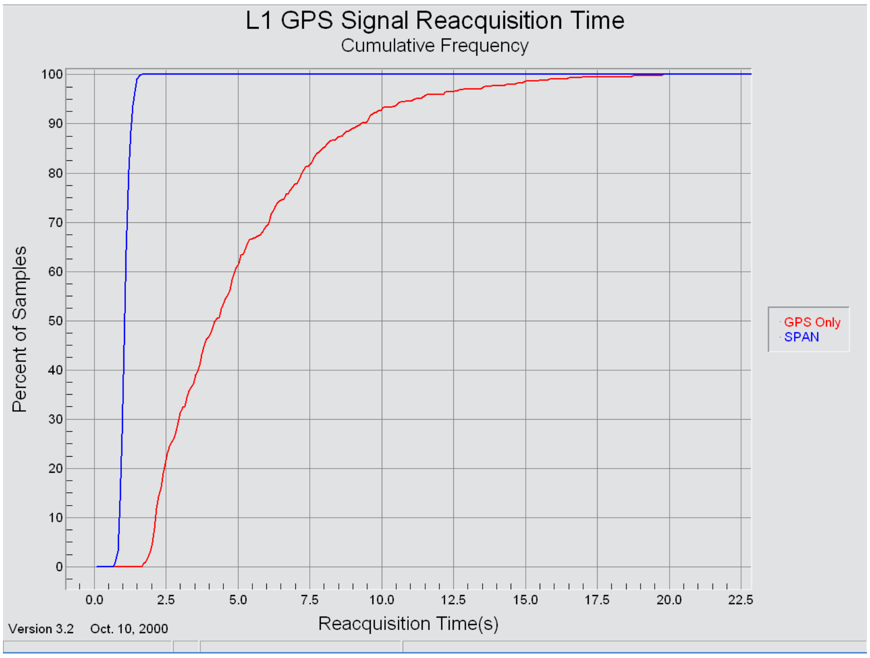


Figure 2. L1 GPS Signal Reacquisition with and without SPAN

After a complete signal blockage for 10 s, SPAN reacquires all GPS L1 signals in less than 2 seconds (95% of the time). A stand alone GPS receiver will take approximately 11 seconds to reacquire all GPS L1 signals, 95% of the time. This provides more GPS measurements to aid the INS side of the system. In obstructed signal environments, there may only be a short window of opportunity to obtain any GPS measurements.

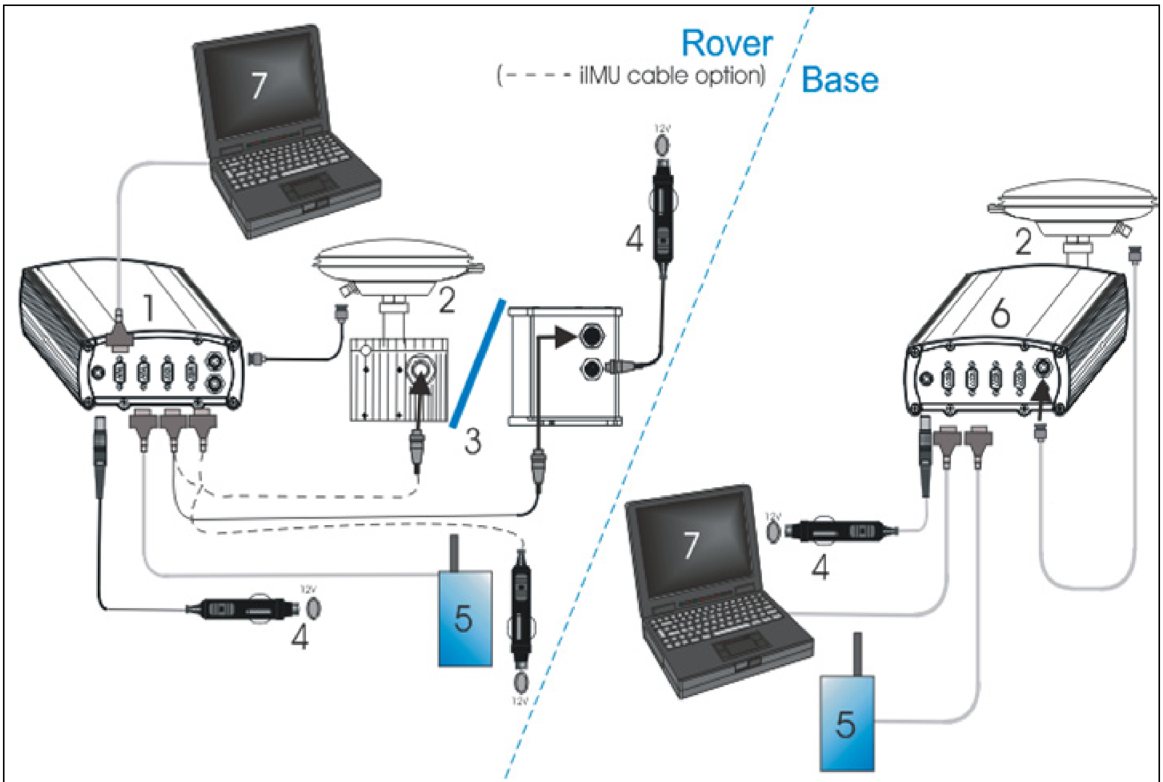
SPAN also uses GPS information in the measurement domain, using carrier phase measurements to aid the INS filter whenever there are less than 4 satellites available. As long as 2 satellites are in view, SPAN is updating the INS filter, controlling error growth until a full constellation is available. Kennedy *et al.* (2006) provides an analysis of how effective the carrier phase updates are during partial GPS outages. This feature is useful during banked turns in the air and in urban canyons on the ground.

2.1 SPAN Components: Data Collection and Real-time Navigation Solution

SPAN is made up of three main components: OEMV3 GPS receiver, IMU (Nothrop Grumman LN200, Honeywell HG1700 AG58 or AG62, or the iMAR FSAS) and SDLC card (for the LN200 and HG1700 only).

The OEMV3 in a SPAN system is the same as any other OEMV3. All that is required to use it in a SPAN system is an appropriate authorization code and firmware version. The IMU choice depends on the customer's preference. The LN200 and FSAS feature FOG technology, while the HG1700s have RLG technology. The FSAS is German manufactured, and is not considered a controlled good which eases export restrictions. The SDLC card is used with the LN200 and HG1700, where it serves as the interface between the IMU and the OEMV. For the LN200 and HG1700, the SDLC and the IMU are normally housed inside an enclosure. However, board level integration is also possible with the IMUs.

In addition to these main components, cabling, a GNSS antenna and logging computer are also required for complete SPAN operation. See Figure 3 for a diagram of the SPAN setup, with differential corrections being sent from a base station.



Reference	Description	
1	A ProPak-V3 receiver connected to a laptop for data storage	
2	User-supplied NovAtel GPS antenna	
3	LN-200, HG1700, or iIMU-FSAS IMU and IMU interface cable to the port labelled AUX on the Propak-V3. With the iIMU, you must also plug in the interface cable to the ProPak's I/O port and to power.	
4	User-supplied power supply	
	ProPak-V3 SPAN (1):	+9 to +18 V DC
	ProPak-V3 base (6):	+9 to +18 V DC
	Separate supply for IMU (3):	see Table 3 on Page 23
5	User-supplied radio device to COM2	
6	User-supplied base station OEMV Family receiver	
7	User-supplied PC, for setting up and monitoring, to COM1	

Differential Set-Up

Figure 3. SPAN Setup with Differential Corrections

For signal point operation, the base station setup is not required. Like all OEMV receivers, a SPAN receiver can receive SBAS corrections (WAAS, EGNOS, Omnistar, or CDGPS) for better accuracy than single point positioning. In post-processing, Inertial Explorer offers PPP (precise point positioning).

2.2 Inertial Explorer: Post-Processing

Inertial Explorer is an extension of the popular GrafNav GNSS post processing software. GrafNav is a high-precision GNSS post-processor, supporting multiple base stations and featuring very reliable on-the-fly (OTF) kinematic ambiguity resolution (KAR) for single and dual frequency data. The GNSS data can be processed forwards and backwards and combined for an optimal solution.

After the GNSS trajectory is created, Inertial Explorer processes the inertial data. The GNSS and inertial processing share the same user interface. Inertial Explorer supports SPAN data, automatically recognizing the data format, and has a predefined error model for each SPAN supported IMU. A Rauch-Tung-Striebel (RTS) smoother (Gelb, 1974) is implemented to offer optimal minimization of errors during GPS outages.

Plotting functionality is built in, with many analysis tools to help the user confirm the quality and accuracy of their results. For example, the user can plot GPS/INS misclosures or the separation between the forward and reverse solutions. The output can be defined by the user, allowing him to choose the reference frame, coordinate system, angle convention, and data elements.

3. TEST SETUP AND METHODOLOGY

3.1 Airborne Test Setup

To demonstrate the performance of SPAN and Inertial Explorer in an aerial photogrammetry application, real world data was collected. The LN200 and SDLC card were mounted onto the lens cone casting of an LMK camera, a few centimetres form the optical centre of the camera. See the installation in Figure 4.

The power and data cables visible in the upper left of Figure 4 were run through an existing access hole in the shroud. The data cable was connected the Propak-V3 and the power cable was connected to a 28V DC source. The camera system was mounted in the floor of the aircraft, as shown in Figure 5.

The GPS antenna to IMU vector was precisely measured and input to SPAN and recorded for use in post-processing. SPAN was configured to log the real time navigation solution at 10 Hz, raw IMU data at the full data rate of 200 Hz, and GPS pseudorange and carrier phase data at 1 Hz. Photo exposures generated triggers received by the OEMV to time correlate the photos to the navigation data.

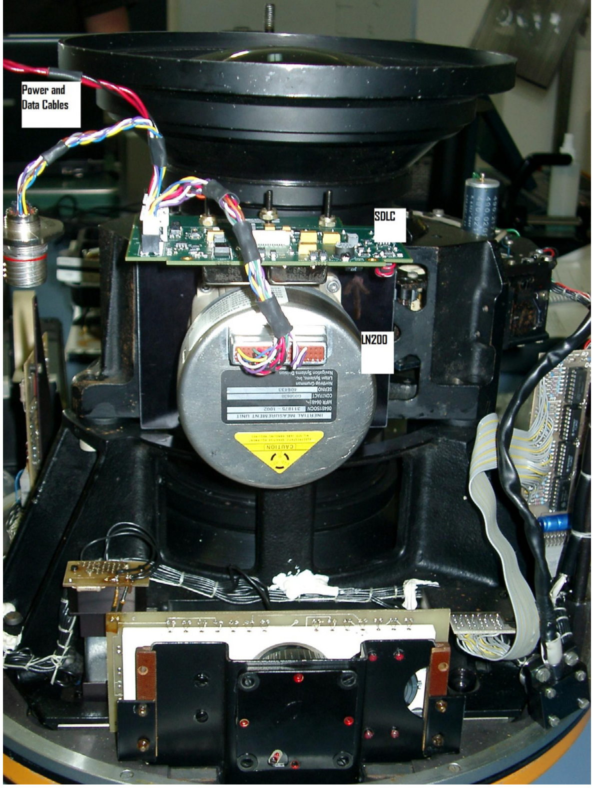


Figure 4. Board Level Integration of SPAN into LMK Camera

Figure 5. LMK Camera System Mounted in Aircraft

Test flights were flown in the vicinity of Toronto, Ontario, Canada. Two flights were done on consecutive days. The first day's flight was used to compute the boresight angles. The second days' flight was used to evaluate the accuracy of the inertial navigation solution, applying the boresight angles as determined on the first day. The flying height was 900m, giving a photo scale of 1:6000. A total of six photo identifiable control points were used for ground control comparisons. Figure 6 shows the flight lines, photo points and ground control points. Figure 7 shows the processing workflow for an aerial photo mission, using SPAN and Inertial Explorer.

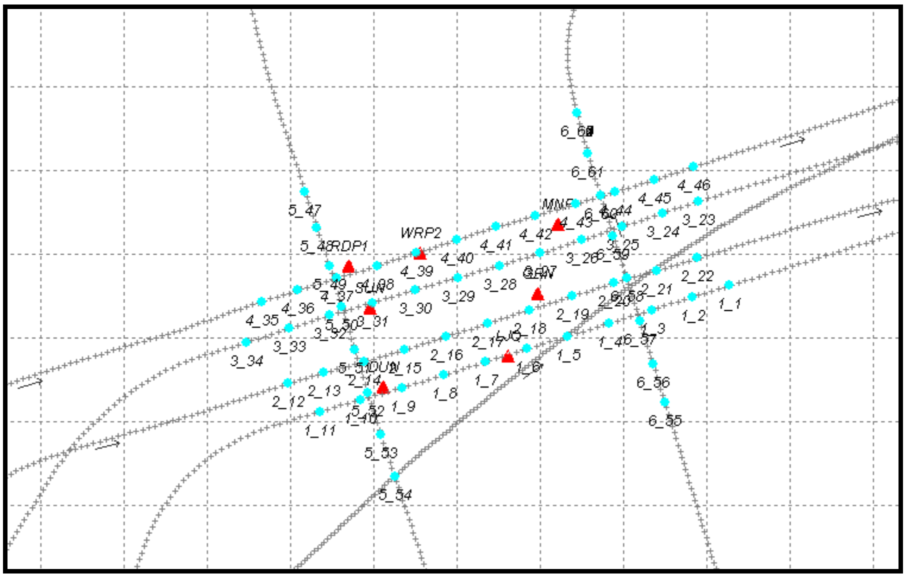


Figure 6. Flight Lines, Photo Points (cyan dots) and Ground Control Points (red triangles)

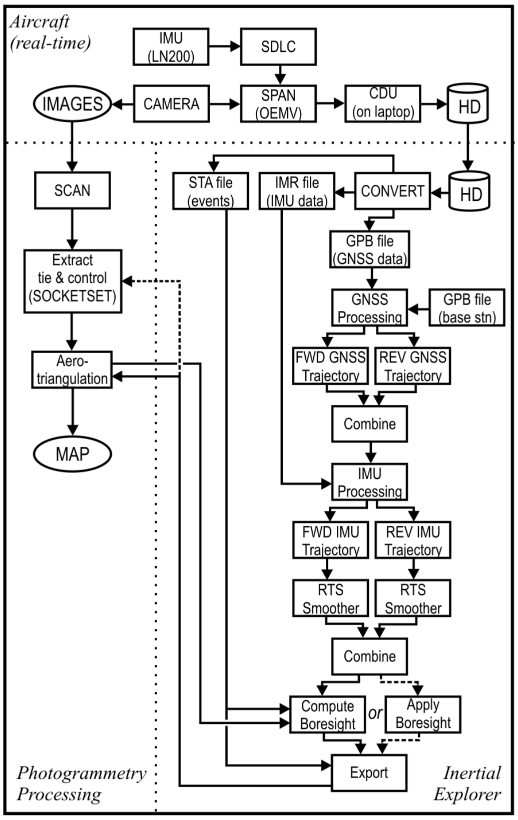


Figure 7. Workflow for Aerial Photo Mission Using Inertial Explorer and SPAN

The aerotriangulation (AT) was performed with NovAtel's internal bundle adjustment package. The photos were digitally processed with BAE SocketSet™ software. The auto-correlation was noisier than usual, due to the use of higher speed film which results in grainier images. The higher speed film was chosen so that the ground would e readily visible in a highly urban environment. Figure 8 is a photo taken from the cockpit during the airborne survey.

Figure 8. Aerial Survey Area

3.2 Airborne Test Methodology

To compare the photogrammetrically determined attitude to the attitude provided by the inertial navigation solution, some intermediate data processing is required. The inertial navigation solution reports roll, pitch and heading (RPH). The photogrammetric system uses omega-phi-kappa (WPK) angles. These two angular systems differ in several ways, summarized in Figure 9.

WPK angles describe the rotation from the ground to the aircraft; whereas, RPH describe the rotation of the aircraft with respect to the ground. In the photogrammetric system, WPK are generally applied in that order (though PWK can be used). In SPAN and Inertial Explorer the order of rotations is RPH, which is about z, about x, and then about y. The convergence of meridians angle must be applied to the WPK angles, as they are referenced to grid (map) north rather than true north. The inertial navigation solution (RPH) is referenced to ellipsoidal height, while the WPK solution is referenced to the geoid. This requires the application of deflections of the vertical, to account for geodetic assumption of a uniform gravity field. The WPK angles describe the orientation of the camera, while the RPH angles describe the orientation of the IMU. To compare WPK to RPH, the boresight angles must be applied. Finally, the WPK system uses the coordinate frame with x forward, y to the left and z up. The RPH system using x to the right, y forward and z up.

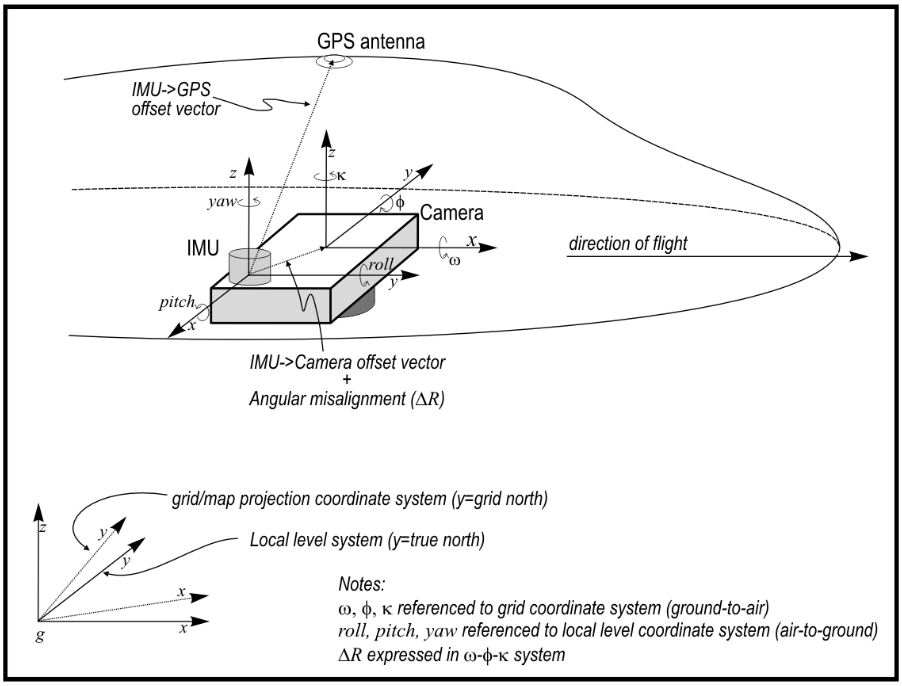


Figure 9. Relation of Omega-Phi-Kappa (WPK) to Roll-Pitch-Heading (RPH)

When all these differences between the WPK and RPH angles are accounted for, a comparison can be made. Special care still must be taken during processing to decorrelate the position from the attitude in the bundle adjustment. This is accomplished by applying a low standard deviation to the airborne GPS coordinates. Also, one must insure that the attitude angles from the INS are not "aiding" the AT. To insure this, a very large standard deviation is applied to the INS angles – 1 degree in this case.

Coordinate computations were done in UTM, zone 17. The coordinates provided by Inertial Explorer are compensated in the height direction with the map scale factor. Due to temperature and tropospheric effects, there may be a residual bias term in the height. For this data, this bias correction amounted to -7cm and -10cm, for day 1 and day 2 respectively.

Again, special care must be taken that the photogrammetry is not "aiding" the camera exterior orientation (position and attitude). This is handled by applying a large standard deviation to the image measurements. In this case, 100 μm was used instead of the more typical 5-15 μm.

Because photo identifiable points were used instead of photo targets, it is expected that the height component will be more accurate than the horizontal. An error in picking the ground control point location in the image will not result in much vertical error due to minimal topographic variations in the survey area.

Finally, the results of the comparison to the photogrammetric control can be compared to the quality measures Inertial Explorer reports, to see if these statistics are overly optimistic or pessimistic.

3.3 Land Vehicle Test Setup

To verify SPAN performance in urban canyon environments, data was collected in downtown Calgary, Alberta, Canada. The selected SPAN IMU was the iMAR FSAS. It was mounted on the floor of a mini-van, along with a navigation grade Honeywell CIMU IMU. The vectors to the GPS antenna on the van roof were accurately measured with a total station. The van was driven through downtown Calgary, which is a difficult environment for GPS with its many tall, reflective buildings and pedestrian overpasses. Figure 10 is a picture taken from the van during the test run.

Figure 10. View during Testing in Downtown Calgary

Optical encoder wheel sensor data was available for the offline processing, and was applied to the Inertial Explorer iMAR FSAS results. The real-time SPAN solution did not use the wheel sensor.

3.4 Land Vehicle Test Methodology

The accuracy of the position solution provided by SPAN (real-time) and Inertial Explorer (post-processed) was evaluated in two ways. Firstly, the estimated trajectories were plotted on georeferenced imagery of downtown Calgary. The image coordinates are accurate to approximately 50cm – 1m. This was purely a visual check to see that the computed trajectory was on the streets that were actually driven, and on the correct side of the street.

The second evaluation was done with respect to the post-processed trajectory computed with the navigation grade CIMU data. Both the CIMU solution and the iMAR FSAS solution were output at the antenna location for comparison at the same point. The solutions were then differenced. The CIMU is a navigation grade IMU, with specifications two orders of magnitude better than the iMAR FSAS. Differences between the CIMU and iMAR FSAS trajectories will be dominated by the iMAR FSAS errors. The specifications of both IMUs are given in Table 1.

Specification	Honeywell CIMU	iMAR FSAS
Gyro Rate Bias	0.0035 deg/hr	0.75 deg/hr
Gyro Rate Scale Factor	5 ppm	300 ppm
Angular Random Walk	0.0025 deg/√hr	0.16 deg/√hr

Accelerometer Range	± 30 g	± 5 g
Accelerometer Scale Factor	100 ppm	300 ppm
Accelerometer Bias	0.03 mg	2.0 mg

Table 1. Honeywell CIMU and iMAR FSAS Specifications

The CIMU data was post-processed with Inertial Explorer, using the GPS range measurements collected by the SPAN OEMV receiver.

4. TEST RESULTS

4.1 Airborne Test Results

The agreement between the photogrammetrically determined attitude and the attitude solution provided by Inertial Explorer and SPAN is given in Table 1 below. The boresight angle was computed with Day 1's data, and this same boresight was used to correct Day 2's data.

Inertial Solution	Day 1			Day 2		
	Omega (arcsecs)	Phi (arcsecs)	Kappa (arcsecs)	Omega (arcsecs)	Phi (arcsecs)	Kappa (arcsecs)
Inertial Explorer	15.0	16.2	15.1	16.6	10.8	24.3
SPAN Single Pt	28.1	27.0	97.8	20.9	34.1	59.2
SPAN RTK	18.3	37.5	63.0	20.6	40.3	42.8

Table 2. RMS Difference between Photogrammetrically Derived Attitude and Inertial Attitude in WPK

The agreement between the ground control coordinates and the coordinates of those photo identified points as determined by Inertial Explorer is given in Table 3.

Ground Control ID	Day 1			Day 2		
	North (m)	East (m)	Height (m)	North (m)	East (m)	Height (m)
DUN	0.079	0.076	0.025	0.008	0.034	-0.075
GRN	0.046	0.005	0.082	-0.134	0.068	0.006
LJQ	0.315	0.299	-0.016	-0.209	-0.086	0.043
MNP	-0.029	0.023	-0.016	-0.149	0.161	0.009
RDP1	-0.037	0.030	0.026	0.010	-0.049	0.105
SUN	-0.016	-0.067	-0.024	0.072	-0.308	0.227
WRP2	0.058	0.131	0.043	-0.092	0.061	0.168
RMS	**0.135**	**0.137**	**0.042**	**0.118**	**0.153**	**0.125**

Table 3. Differences between Published Ground Coordinates and Cooridnates Determined by Aerial Survey

4.2 Land Test Results

The first evaluation of the land test results was performed by overlaying the SPAN and IE trajectories on georeferenced imagery. This is a qualitative evaluation. Figure 11 shows the overall trajectory taken though downtown Calgary. Some sections of the route were traversed more than once. The route repetition provides a consistency check, while the imagery provides an absolute error check.

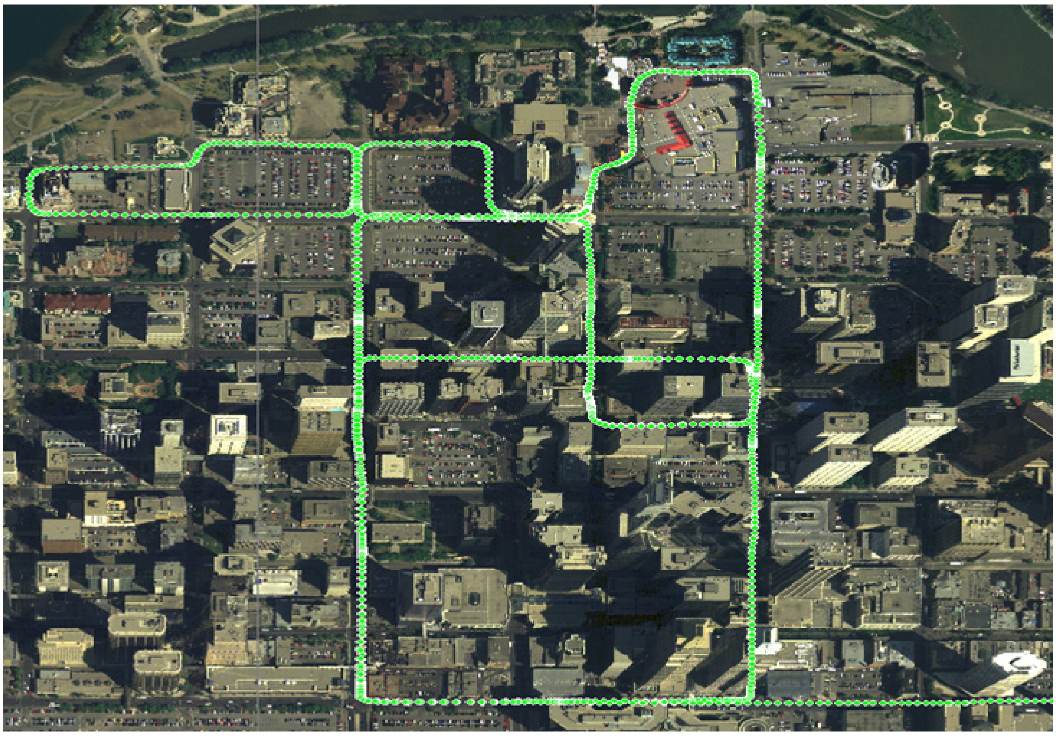


Figure 11. Inertial Explorer Trajectory Overlaid on Geoferenced Imagery (Imagery copyright Valtus Imagery Services, 2006)

Looking closer, Figure 12 shows a portion of the trajectory at finer detail. Note that the same street was traversed more than once, which accounts for apparent "zig-zag" in trajectory along the right hand side of Figure 12.

Figure 12. Detail of Inertial Explorer Trajectory Overlaid on Georeferenced Imagery (green dots are iMAR FSAS, red dots are CIMU)

For a more quantitative analysis of the data, the differences between the trajectory estimated with the CIMU data and the trajectory estimated with the iMAR FSAS data are given in Table 4.

Statistic	Inertial Explorer (post-proc.) (m)			SPAN (real-time) (m)		
	North	East	Height	North	East	Height
Mean	-0.004	-0.085	-0.002	0.382	0.274	0.035
Std. Dev.	0.143	0.135	0.091	0.938	1.268	0.496
RMS	0.143	0.160	0.091	1.012	1.297	0.497
Maximum	0.648	0.495	0.270	6.130	7.240	1.987

Table 4. Differences between CIMU Trajectory and iMAR FSAS Trajectories

5. DISCUSSION OF TEST RESULTS

5.1 Airborne Test Result Discussion

The attitude results are of most interest. Overall photogrammetric system errors are directly attributable to errors in camera position and attitude. In the case of attitude, the Day 2 results show omega (~roll) and phi (~pitch) accuracies of 17 and 11 arcseconds respectively. On the photographic image, this translates into errors of ~7-12 μm. While at this scale, attitude contribution to horizontal ground errors would be ~5-8 cm. For kappa a very respectable 24 arcseconds was observed on Day 2. At photo scale, a maximum error of 12 μm would be produced translating to ~7.2 cm. Obviously, exact errors depend on geometry and are heavily influenced by image measurement errors. In addition, it is generally accepted the airborne GPS measurement errors will be on the order of 5-10 cm. Day 1 shows similar accuracies; although, the boresight was computed with this data.

Once would expect then to see ground control errors to reflect the above results. In height, this is the case and we observed for the most part very good accuracies. For Day 2, RDP1, SUN and WRP2 had worse than expected results and could be attributed to the grainier imagery. In the horizontal axis, errors are larger and due mostly to point measurement error. Matching the same point on the ground to the image can be difficult without a target. Such errors are quite normal for photo ID at this scale.

Although many applications do not use the real-time solution, the attitude accuracy provided in real-time by SPAN was evaluated to verify the accuracy of the solution with external control. This accuracy is available real-time to the user, and can be valuable for initial quality checks in the field.

5.2 Land Test Results Discussion

The tightly coupled nature of SPAN provides a distinct advantage in urban environments. The CIMU inertial data was collected in combination with a non-SPAN enabled receiver. When performing the data analysis, it became obvious that for the best reference possible the CIMU inertial data had to be combined with the GPS ranges collected by the SPAN receiver. Otherwise, the CIMU was deprived of external aiding information for extremely long periods of time.

The real-time SPAN solution represents the basic performance a user can expect from a SPAN system, with differential corrections but no additional equipment. The post-processed Inertial Explorer solution with the iMAR FSAS used wheel sensor data that was collected during the test run, but was not made available to SPAN. This solution represents the best accuracy a user could expect with the iMAR FSAS. SPAN and Inertial Explorer both use carrier phases as update information, whenever less than four satellites are available. The phase updates control error growth between position updates as effectively as a wheel sensor. A wheel sensor will be most helpful during complete GPS outages, like a tunnel or a parking garage.

The iMAR FSAS trajectory created from post-processing with Inertial Explorer agrees well with the CIMU, especially considering the difference in IMU specifications and price. The accuracy improvement gained by post-processing is also evident by comparing with the real-time SPAN solution. The smoother implemented in Inertial Explorer optimally combines the trajectories computed in forward time and reverse time. The smoothed error is generally about 10% of the error encountered in forward time (or real-time), a rule thumb which is supported in the results presented herein.

6. CONCLUSIONS

The SPAN system can be successfully integrated, at the board level, into an aerial photogrammetry application. Comparison to photogrammetric attitude and ground control coordinates verified that the Inertial Explorer post-processing package provides very respectable accuracies. Inertial Explorer can fit into the operational workflow of an aerial photogrammetry mission.

SPAN and Inertial Explorer also perform well in urban environments. The tight coupled architecture of SPAN insures that the maximum amount of GPS measurements are available for aiding in real time and post-processing. Qualitative comparison to georeference imagery and quantitative comparison to control trajectory computed with navigation grade IMU both showed accuracy the position trajectory generated by SPAN (real-time) and Inertial Explorer (post-processed). T

ACKNOWLEDGEMENTS

Hugh Martell of NovAtel's Waypoint Products Group is gratefully acknowledged for his assistance in the data processing and analysis.

REFERENCES

S. Kennedy, J. Hamilton, and H. Martell (2006) Architecture and System Performance of SPAN – NovAtel's GPS/INS Solution, *Proceedings of IEEE/ION PLANS 2006*, San Diego, USA, April 23-25, 2006.

A. Gelb (1974) *Applied Optimal Estimation*, M.I.T. Press, Cambridge, MA.