NovAtel SPAN™

Aerial Photogrammetry Test Flight Results

Precise thinking

NovAtel SPAN

NovAtel Inc.

Aerial Photogrammetry Test Flight Results

Abstract

This paper demonstrates how NovAtel's GPS/INS technology, SPAN (Synchronized Position Attitude Navigation), can be integrated into an aerial photogrammetry application, with the Inertial Explorer® software package, providing post-processing capability. Flight tests were conducted using a Northrop Grumman LN200 IMU, which is one of four IMU types available for use with SPAN. Attitude accuracy is derived by comparison to an aerotriangulation (AT). Accuracy of ground points is verified by comparison to ground control points. Although this paper is primarily concerned with a photogrammetric application, LiDAR users can expect similar attitude accuracies.

Test Overview

This mission was undertaken to demonstrate the data flow through NovAtel's SPAN and Waypoint's Inertial Explorer products to complete an aerial photo mission. For this test, SPAN hardware was integrated into a camera system. The camera was then installed inside an aerial survey plane. Data was collected over two flights collected on consecutive days. Data collected included raw GPS measurement data, raw IMU data, SPAN real-time GPS/INS solution data, camera exposure times, and photo exposures. Imagery was digitally processed using BAE SocketSet™ software. Using ground control points in the data from the first flight, boresight angles were computed with an internal bundle adjustment software. These boresight angles were then used on the data from the second day's flight to evaluate the accuracy of the inertial navigation solutions from SPAN and Inertial Explorer. Attitude accuracy and ground coordinate accuracy are analyzed in the results section.

Equipment Overview

NovAtel's SPAN technology was used to collect the GPS and IMU data during the flight mission. Post processing of the raw data was done using NovAtel's Waypoint products group's Inertial Explorer package. The following two components provide a complete GPS/INS solution:

1. A high quality real-time solution with superior signal tracking performance and simultaneous raw data and event logging capability.
2. A powerful data processing package including forward and reverse processing, boresight angle computation and a solution smoother.

The tightly coupled architecture of SPAN achieves reciprocal aiding between the GPS and INS. This results in a significant improvement to the signal reacquisition and integer resolution capability of the receiver or subsequent software. After signal blockages, SPAN reacquires the lost GPS signals in less than 2 seconds, 95% of the time. This is significantly faster than a stand-alone GPS receiver, which takes approximately 11 seconds to reacquire all GPS signals, 95% of the time.

SPAN and Inertial explorer also utilize GPS information in the measurement domain, using carrier phase measurements to aid the INS filter whenever a position domain update is not available or is of questionable quality. This feature is useful during banked turns in the air and in urban canyons on the ground.

SPAN currently supports the following four tactical-grade IMU choices:

1. Northrop Grumman LN200
2. Honeywell HG1700 AG58
3. Honeywell HG1700 AG62
4. iMAR FSAS.

The LN200 IMU was used for this survey and is the IMU referenced throughout this paper.

Test Set-up

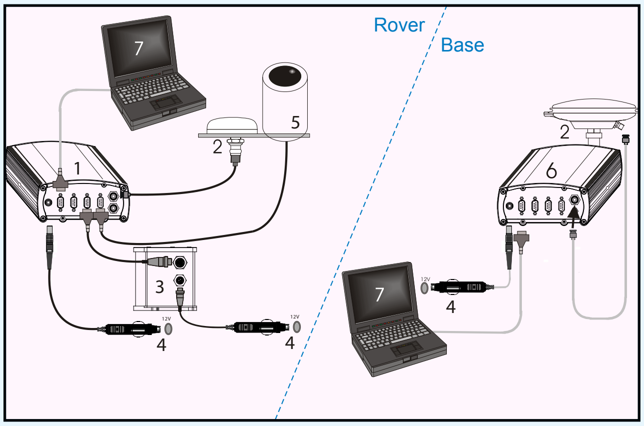


Figure 1: SPAN set-up

Reference Number & Description

1: A ProPak-V3 receiver connected to a laptop for data storage
2: User-supplied NovAtel GNSS antenna
3: LN-200 and IMU interface cable to AUX
4: User-supplied power supply
    ProPak-V3 SPAN (1): +9 to +18 V DC
    ProPak-V3 base (6): +9 to +18 V DC
    LN-200 IMU (3): +12 to +28 V DC
5: User-supplied camera device to I/O
6: User-supplied base station OEMV Family receiver
7: User-supplied PC or laptop, for setting up and monitoring, to COM1

Latitude 51.048985584° ±0.612m
Longitude -114.025541971° ±0.470m

CDU_DEMO - Position (Read-only)

Latitude	51.048985584° ±	0.47m
Longitude	-114.025541971° ±	0.61m
Hgt. (Ell.)	1037.798m ±	0.69m

Solution type: Single Ins
Iono correction: Unknown
AdVanced RTK status: N/A
Solution age: 0 second
Differential age: 0 second
# of satellites: 9
Used in solution: L1 L2 L5 / L1 L2
Solution Status: Computed

Fri Apr 21 17:35:46 2006 GMT
Fri Apr 21 11:35:46 2006 Local

Roll	Pitch	Azimuth
1.6585°	3.5083°	283.68°
±0.01	±0.01	±0.11

Latitude	51.048985584° ±	0.470m
Longitude	-114.025541971° ±	0.612m
Hgt. (Ell.)	1037.798m ±	0.686m
Velocity	8.6153m/s ±	0.067m/s
North	1.9798m/s ±	0.043m/s
East	-8.3724m/s ±	0.050m/s
Up	0.4554m/s ±	0.012m/s
X Offset	0.000m	
Y Offset	0.000m	
Z Offset	0.000m	
ZUPT	Off 0	

COM3
INS_SOLUTION_GOOD (Ready to use)
Fri Apr 21 11:35:46 2006 Local

```
[COM1]
<OK
[COM1]
```

Figure 2: CDU during data logging

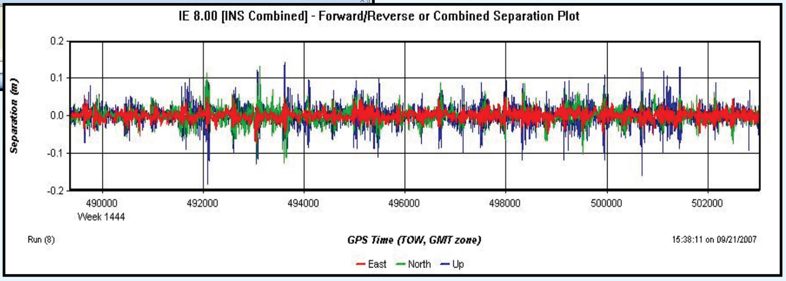


Figure 3: Example of Inertial Explorer Forward-Reverse Separation Plot

Test Set-up

SPAN COMPONENTS: DATA COLLECTION AND REAL-TIME NAVIGATION SOLUTION

For real-time single point operation, communication between the base station and rover 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) and can also accept the SBAS trajectory to aid the IMU processing.

Configuration of the SPAN system (that is, GPS to IMU offsets, SBAS configuration) and data logging can be done through NovAtel's **CDU** software. A screen capture of **CDU** during data logging is shown above in Figure 2.

WAYPOINT 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) at longer baselines.

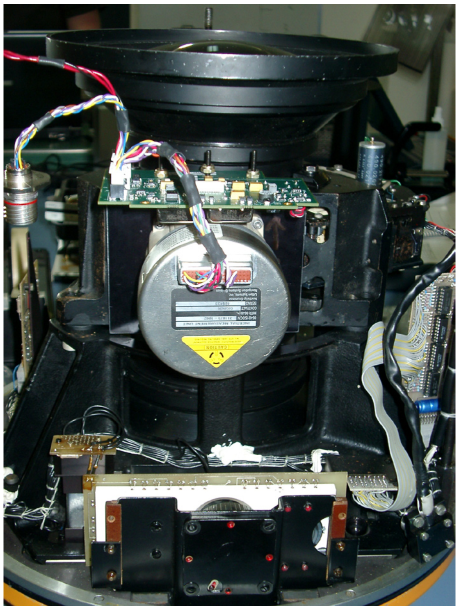
The GNSS data can be processed forwards and backwards and combined for an optimal solution.

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-Strïebel (RTS) smoother is implemented to offer optimal minimization of errors during GNSS outages.

Plotting functionality is built in, with many analysis tools to help you confirm the quality and accuracy of your results. For example, you can plot GPS/INS misclosures or the separation between the forward and reverse solutions. Many people find the forward-reverse separation plots useful to verify that a good solution was obtained. If there are major differences or trends in the forward-reverse separation, it can indicate problems with the processing, such as incorrect GPS to IMU offset vectors or poor initial alignments. Figure 3 on page 2 shows an example of the forward-reverse separation plot in the position domain, as exported from Inertial Explorer.

INTEGRATION INTO THE AERIAL CAMERA SYSTEM

To demonstrate the performance of SPAN and Inertial Explorer in an aerial photogrammetry application, aerial photography data was collected. The LN200 and SDLC card were mounted onto the lens cone casting of an LMK camera, a few centimeters from the optical centre of the camera. See a picture of the installation below.



The power and data cables visible in the upper left of the picture were inserted through an existing access hole in the shroud. The data cable was connected to the OEMV-3 and the power cable was connected to a 28V DC source. The LMK camera was then placed into its mount, as shown in the picture below (aerial camera is in the photo foreground).

Produced at the mid-point of the photo exposures, Transistor-Transistoro Logic (TTL) pulses generated triggers that were precisely timed by the OEMV. The times generated by the MARKTIME log were correlated with the flight management system output to assign the correct annotated photo identifier to each event.

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.

Test Methodology

Overview

Test flights were flown in the vicinity of Toronto, Ontario, Canada.

Two flights were flown on consecutive days. The first day's flight was used to compute the boresight angles. The second day's flight was used to evaluate the accuracy of the inertial navigation solution by 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 4, below, shows the flight pattern, photo points and control points.

Like all NovAtel OEMV receivers, SPAN can obtain SBAS corrections (WAAS, EGNOS, OmniSTAR, or CDGPS) for better accuracy than single point positioning.

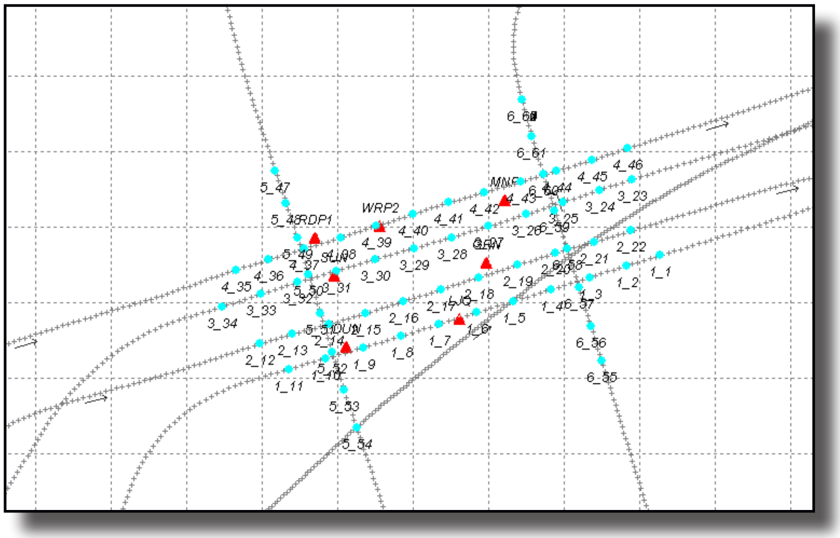


Figure 4: **Flight Lines, Photo Points (cyan dots) and Ground Control Points (red triangles)**

Test Methodology

Workflow

Airborne mapping applications typically deal with very large volumes of data and numerous projects are being dealt with in a short amount of time. This requires a very streamlined workflow. Inertial Explorer is very much geared to this application and many years of development have gone into optimizing the processing flow, which is shown in Figure 5.

In real-time, the aerial camera notifies the SPAN system of each mid-point exposure. A flight management system was also used but is not shown here.

Once the mission is completed, the navigation processing begins using Inertial Explorer (shown on the right of the flow chart). In a one step process, the raw IMU and GPS data are decoded to Waypoint's proprietary file formats using the GPS Data Converter. At this stage, the base station data may also need to be converted or downloaded from the internet.

For GPS processing, base station coordinates, antenna model and a processing profile are specified. Once processed, the forward and reverse trajectories are automatically combined. At this point, the operator is advised to review the position separation between the forward and reverse trajectories.

For inertial processing, the IMU to GNSS antenna lever arm vector must be entered. Several minutes of static data was collected at the start and end of the survey in order to process a static coarse alignment in forward and reverse. A kinematic alignment can also be processed in either direction by choosing the appropriate start/end processing times that correspond to straight and level portions of flight. Both directions are then processed, smoothed and combined producing a final trajectory containing position, velocity and attitude at 200 Hz.

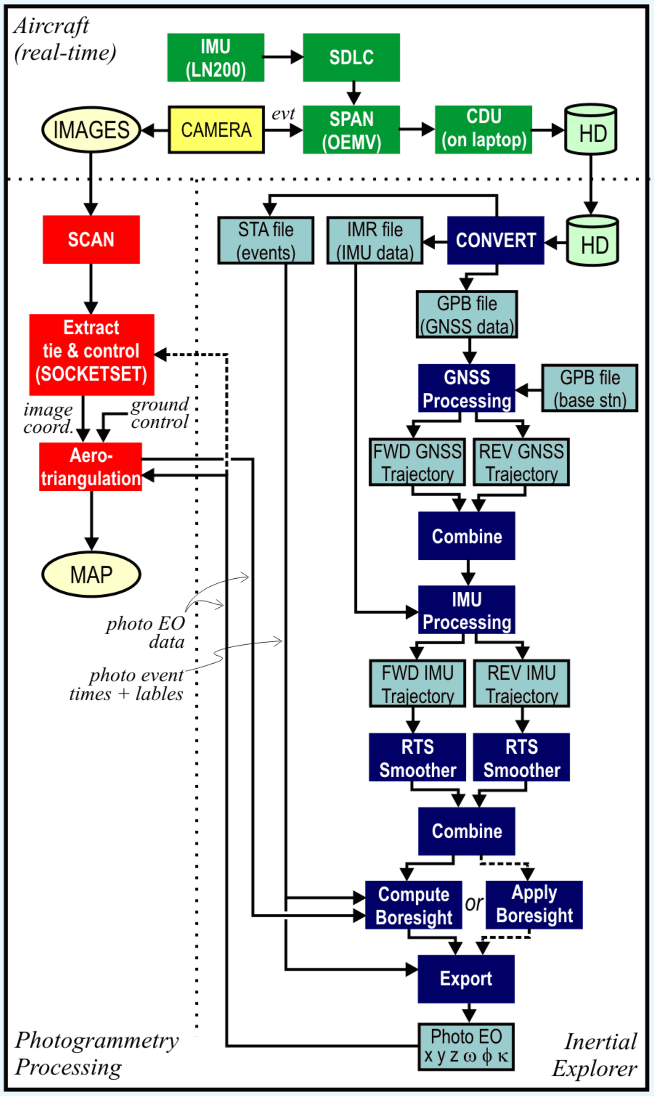


Figure 5: Workflow for Aerial Photo Mission Using Inertial Explorer and SPAN

While the navigation data was processed, the photos were scanned and AT points were extracted automatically from the digital imagery with BAE SocketSet™ software (shown on the on the lower right in Figure 5). The auto-correlation was noisier than usual due to the use of higher speed film which resulted in grainier images. The higher speed film was chosen so that the ground would be readily visible in a highly urban environment. The images below are photos taken from the cockpit during the airborne survey.

Test Methodology

Comparing Attitude Solutions

To compare the photogrammetrically determined attitude to the attitude provided by the inertial navigation solution, some intermediate data processing was 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 6.

WPK angles describe the rotation from the ground to the aircraft, whereas RPH angles describe the rotation of the aircraft with respect to the ground. In the photogrammetric system, WPK are generally applied in that order, although PWK can also be used. In SPAN and Inertial Explorer, the order of rotations is RPH, which is about z, about x, and then about y. The meridian convergence angle must be applied to the WPK angles, as they are generally 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. To account for the geodetic assumption of a uniform gravity field, the application of deflections of the vertical was required. 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 were applied. Finally, the WPK system uses a coordinate frame with x forward, y to the left and z up, whereas the RPH system uses x to the right, y forward and z up.

This rather complex conversion was performed within Inertial Explorer's boresighting module. For this conversion, the only thing to be concerned with was the grid system used and verifying the order of WPK required by the image processing system receiving the output.

Once all the differences between the WPK and RPH angles were accounted for, a comparison was made. Special care was taken during processing to decorrelate the position from the attitude in the bundle adjustment. To do this, a low standard deviation was applied to the airborne GPS coordinates. To insure that the attitude angles from the INS did not "aid" the AT, a very large standard deviation was assigned to the INS angles.

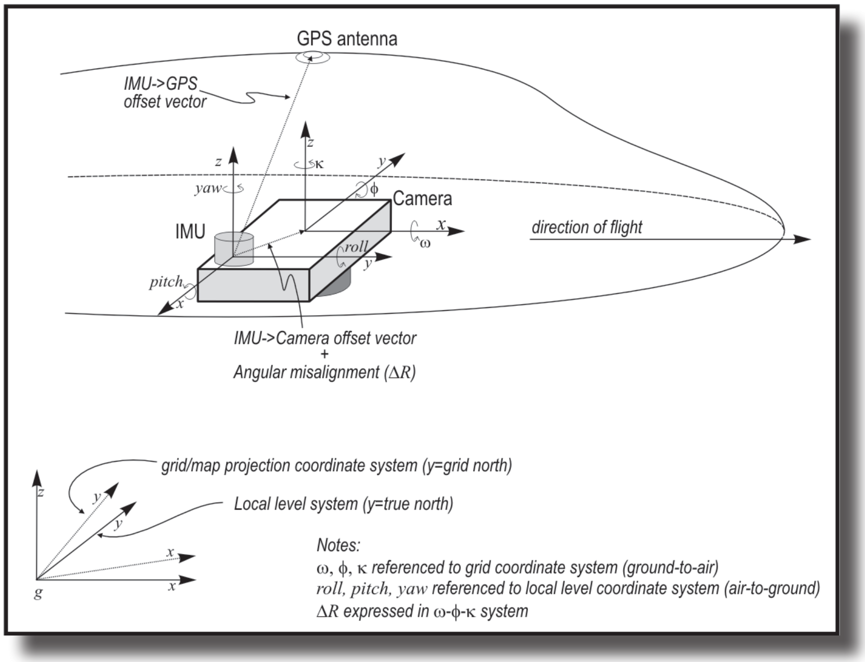


Figure 6: **Relation of Omega-Phi-Kappa (WPK) to Roll-Pitch-Heading (RPH)**

Comparing Ground Coordinates

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. This is necessary because horizontal coordinates are scaled by this same amount. Due to temperature and tropospheric effects, there may be a residual bias term in the height. For this data, the bias correction amounted to approximately 14 cm on both days. Removing the height bias is an important part of the processing methodology.

For ground comparisons, the image position and attitude should be determined by the values originating from the GPS-IMU and not aided by the photogrammetry. Ground errors will be a combination of exterior orientation and individual point measuring errors. Hence, tie points were not used to refine the exterior orientation.

The ground control points used are part of a privately maintained control network. The accuracy of their coordinates is considered to be on the order of several centimeters, but there were no targets laid. These are photo-identifiable control points and for this reason, it is expected that the height component will be more accurate than the horizontal component. An error during selection of the ground control point locations in the image will not result in much vertical error due to small topographic variations in the control point area.

Airborne mapping applications require a very streamlined workflow. Inertial Explorer is very much geared to this application and many years of development have gone into optimizing the processing flow.

Test Results

Attitude Comparison

The agreement between the photogrammetrically determined attitude and the attitude solution provided by Inertial Explorer and SPAN is given in Tables 1 and 2. The boresight angles were computed with the data from day 1, and this same boresight was used to correct the data from day 2.

Ground Control Comparison

The agreement between the ground control coordinates and the coordinates of those photo identified points as determined by Inertial Explorer is given in Tables 3 and 4.

Quality Control

Inertial Explorer provides two measures to evaluate the quality of a survey: the reported standard deviation and the RMS of the separation between the forward and reverse processing passes. Separations are available for position, velocity and attitude. In this analysis, of most concern is the attitude separation. The position separation is more meaningful in GPS solution analysis.

The RMS of the attitude separation is computed by differencing the forward and reverse trajectories. The variance of this difference is the sum of the variances of the forward and reverse trajectories. Therefore, the RMS of the separation of the forward and reverse trajectories is a pessimistic measure of the variance of the final trajectory produced by Inertial Explorer. The data in Tables 5 and 6 report these measures in RPH space for day 1 and day 2, respectively. For convenience, the WPK differences estimated photogrammetrically are repeated in Table 7.

Table 1: RMS Difference between Photogrammetrically Derived Attitude and Inertial Attitude in WPK (day 1)

Inertial Solution Source	Omega Arcsecs (degs)	Phi Arcsecs (degs)	Kappa Arcsecs (degs)
Inertial Explorer	15.0 (0.004)	16.2 (0.005)	15.1 (0.004)
SPAN Single Point	21.9 (0.008)	20.1 (0.008)	74.9 (0.027)
SPAN RTK	18.3 (0.005)	37.5 (0.010)	63.0 (0.018)

Table 2: RMS Difference between Photogrammetrically Derived Attitude and Inertial Attitude in WPK (day 2)

Inertial Solution Source	Omega Arcsecs (degs)	Phi Arcsecs (degs)	Kappa Arcsecs (degs)
Inertial Explorer	16.6 (0.005)	10.8 (0.003)	24.3 (0.007)
SPAN Single Point	20.9 (0.006)	34.1 (0.009)	59.2 (0.016)
SPAN RTK	20.6 (0.006)	40.3 (0.011)	42.8 (0.012)

Table 3: Differences between Published Ground Coordinates and Coordinates Determined by Aerial Survey (day 1)

Ground Control ID	North Error (m)	East Error (m)	Height Error (m)
DUN	0.091	0.094	0.042
GRN	0.079	-0.099	0.214
LJQ	0.375	-0.344	-0.108
MNP	-0.035	0.032	-0.089
RDP1	-0.028	0.031	0.005
SUN	-0.011	-0.097	-0.010
WRP2	0.066	0.150	0.013
RMS	0.152	0.156	0.098

Table 4: Differences between Published Ground Coordinates and Coordinates Determined by Aerial Survey (day 2)

Ground Control ID	North Error (m)	East Error (m)	Height Error (m)
DUN	0.009	0.038	-0.150
GRN	-0.139	0.072	-0.062
LJQ	-0.213	-0.088	-0.008
MNP	-0.145	0.166	-0.067
RDP1	0.029	-0.076	0.081
SUN	0.073	-0.316	0.151
WRP2	-0.103	0.051	0.099
RMS	0.121	0.146	0.100

Discussion

The attitude results are of interest because 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) differences of 17 and 11 arcseconds respectively. This agreement is very good considering the photogrammetrically derived attitude also has errors due to tie point measurement noise. Assuming these are the real accuracies, these values would translate to photographic image errors of ~7-12 µm. While at this scale, attitude contribution to horizontal ground errors would be ~5-8 cm. Height would be further degraded by satellite geometry.

For kappa difference (which is approximately heading), 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. day 1 shows similar accuracies; further reinforcing the legitimacy of these estimates.

One would expect to see ground control errors reflect the above results. In height, this is roughly the case and for the most part, very good accuracies were observed. There were a couple of outliers on both days but with no real patterns. The ground control ID SUN (see Table 4) was heavily shaded on day 2. Airborne GPS normally does not have accuracies better than 5 cm. Hence, these values are typical given all of the error sources involved.

Horizontally, errors are larger solely due to the fact that photo identifiable control was used. Point LJQ was the worst on both days and the photogrammetric operator had trouble locating these points on the imagery. Again, SUN was shaded on day 2. Generally, the other points compared quite well and RMS agreements were on the order of 10 cm with these outliers removed.

Table 5: Day 1 Quality Measures from Inertial Explorer

	Roll Arcsecs (degs)	Pitch Arcsecs (degs)	Heading Arcsecs (degs)
Mean of Reported Std. Dev. at Photo Events	13.0 (0.004)	13.3 (0.004)	34.2 (0.010)
RMS of Fwd-Rev Separation	20.2 (0.006)	29.2 (0.008)	50.0 (0.014)

Table 6: Day 2 Quality Measures from Inertial Explorer

	Roll Arcsecs (degs)	Pitch Arcsecs (degs)	Heading Arcsecs (degs)
Mean of Reported Std. Dev. at Photo Events	13.0 (0.004)	13.0 (0.004)	32.4 (0.009)
RMS of Fwd-Rev Separation	20.2 (0.005)	29.2 (0.008)	50.0 (0.014)

Table 7: RMS of Differences between Photogrammetrically Derived Attitude and Inertial Attitude Estimated with Inertial Explorer

	Omega Arcsecs (degs)	Phi Arcsecs (degs)	Kappa Arcsecs (degs)
Day 1	15.0(0.004)	16.2 (0.005)	15.1 (0.004)
Day 2	16.6 (0.005)	10.8 (0.003)	24.3 (0.007)

Although many applications do not use the real-time solution, the attitude accuracy provided in real-time by SPAN is presented in Tables 1 and 2 to verify the accuracy of the solution with external control. This accuracy is available real-time and can be valuable for initial quality checks in the field.

SUMMARY

NovAtel's SPAN and Inertial Explorer products readily meet the demands of aerial photogrammetry. Both these products can be integrated into an airborne survey operation. Due to flexibility, the SPAN hardware is very easy to install in most airborne mapping environments. The post-processing capability of Inertial Explorer is available in its user friendly windows interface, or it can be automated for a specific workflow with the API interface.

For more information visit: http://www.novatel.com.