Airborne Kinematic Positioning and Attitude Determination Without Base Stations

Mohamed M. R. Mostafa and Joseph Hutton

Applanix Corporation
85 Leek Cr., Richmond Hill
Ontario, Canada L4B 3B3
Phone: (905) 709-4600 ext 274
e-mail: mmostafa@applanix.com

BIOGRAPHY

Mohamed Mostafa is responsible for Research and Development in Airborne Systems at Applanix Corporation and is the Chair of the Direct Georeferencing Committee of the American Society of Photogrammetry and Remote Sensing. He obtained a Bachelor of Science and a Master of Applied Science from Alexandria University in 1991 and 1994, respectively and a Ph.D. from The University of Calgary in 1999. His research interest is mapping using multi-sensor systems.

Joseph Hutton is the Product Manager of Airborne Systems at Applanix, and has been with the company since its inception in 1991. He obtained a Bachelor of Applied Science in Aerospace Engineering and a Master of Applied Science in Aerospace Control from the University of Toronto in 1989 and 1991, respectively. He has over 10 years experience in the areas of inertial/GPS integration, Kalman filtering, airborne photogrammetry and LIDAR. His research interest is optimal design of airborne GPS/inertial systems for mapping by multi-sensor systems.

ABSTRACT

One of the limitations of using integrated inertial/GPS systems to Directly Georeference airborne sensor data (c.f., Mostafa and Hutton, 2001), is the necessity of using a GPS base station or stations in order to obtain the positional accuracy required to meet the accuracy standards of certain mapping products. In some precise large-scale aerial survey applications having to place a number of GPS base stations in a remote or inaccessible location becomes quite problematic.

In some other occasions, such as in a real production environment, the GPS base station data is lost. In this paper, the potential of using GPS with no base station for aerial survey applications is discussed. The NGS CORS network stations are processed in conjunction with the airborne GPS raw observables to determine the aircraft position which is then used to aid the inertial data processing in a closed loop fashion to end up with a full resolution of the trajectory parameters, namely position, velocity and attitude, which are then used to generate Exterior Orientation data to support aerial mapping. Flight test data were collected in January 2001 using the Applanix POS/AV™ system (S/A is off). Test results and analysis are presented in some detail.

1. INTRODUCTION

Aerial survey industry has been using airborne GPS as a standard procedure to assist map production for the past decade. More recently, GPS-aided inertial systems such as Applanix POS/AV™ have been successfully used to provide the full resolution of trajectory parameters, namely position, velocity, and attitude. This way, the entire set of translational, and rotational parameters of any airborne acquired image or laser scan line can be measured with respect to some mapping frame.

Data acquisition procedure plays a role in the success of this method. Separation between the airborne and base station GPS receivers, satellite geometry as reflected by the Position Dilution of Precision (PDOP), signal multipath and many other parameters must be considered in order to achieve the maximum possible GPS positioning accuracy. Many times it is difficult or not practical to optimize these parameters.

For example, since the sun angle required for aerial photography and the PDOP required for strong geometric positioning by GPS do not necessarily occur at the same time, aerial flight missions sometime inadvertently compromise the GPS PDOP in order to get a good sun angle.

Hence for high accuracy mapping applications where the highest GPS positioning accuracy is required, careful mission planning is therefore mandatory. A usual outcome of this is the requirement for a series of GPS base stations to be deployed in order to support the project. In inaccessible regions this can be very difficult.

In other applications such as corridor surveying where the accessibility is usually quite good and the positional accuracy is often relaxed, a major problem is the cost of laying out base stations at regular intervals along the corridor, which can often be thousands of km in length. In some other occasions, (as often is the case in a real production environment), the GPS base station data may simply be lost due to equipment problems or human error.

Therefore, the focus of this paper is on the accuracy that can be obtained using the NGS CORS (c.f., www.ngs.noaa.gov/CORS) stations as base stations for airborne GPS positioning, and the possibility of using these stations to supplement, back up, or even replace the base stations usually deployed for a given project.

2. THE NGS CORS

The CORS (continuously operating reference station) system is run by The US National Geodetic Survey (NGS). CORS comprises a network of 219 sites, (as of April 2001), containing geodetic quality GPS receivers.

This network is currently growing at a rate of about 3 sites per month. NGS collects, processes, and distributes data from these sites in support of high-accuracy 3D positioning activities throughout the United States and its territories. For details about CORS, see Snay (2000) and Spofford and Weston (1998). Figure 1 shows a number of CORS stations in southern US, some of which were used in the analysis presented here.

3. REFERENCE TRAJECTORY

To establish a reference trajectory for comparison purposes, a set of photogrammetric data was collected. The photogrammetric data included a number of overlapped photographs acquired over the mapping area and a number of land-surveyed ground points that appear in the acquired images.

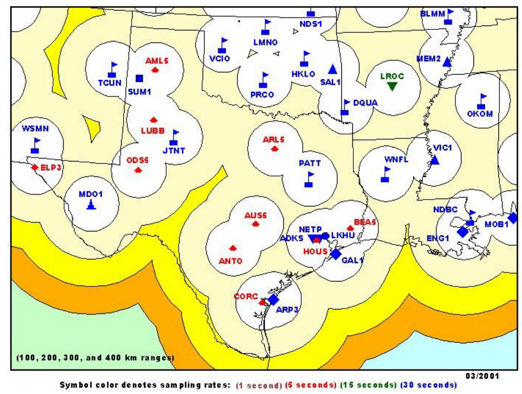

Figure 1 The CORS Stations in Texas/Oklahoma Area (courtesy of CORS website)

The ground point coordinates used together with their measured locations on the imagery, allow for the determination of each photo centre position. Although they only provide a discrete version of the trajectory, the photo centre positions establish a reference trajectory determined by a technique completely independent from GPS.

The resulting photo centres were compared to a 200 Hz Smoothed Best Estimate of Trajectory (SBET) determined by POSPac^{TM}, which is produced using GPS/inertial data and a base station at the airport.

The resulting position differences at the photo centres were about 15 cm in horizontal and about 20 cm in height. Having validated its accuracy in this manner, the SBET, computed using the GPS base station located at airport, (shown in Figure 2), is taken as a reference for the remainder of the paper. For details on the subject; see Hutton, et al (1997); Mostafa and Hutton (2001); Scherzinger (1997).

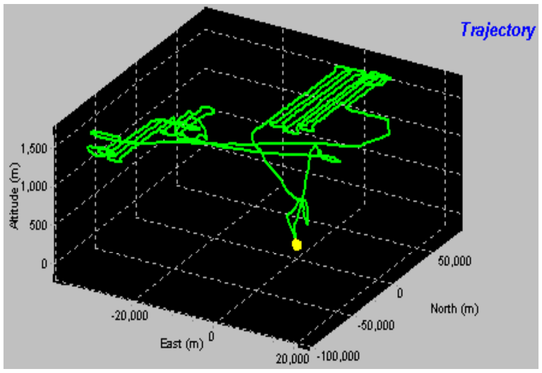

Figure 2 Smoothed Best Estimate of Trajectory (SBET) derived by GPS/inertial Data and a Base Station at Airport for Jan 26 Flight in Texas

4. GPS DATA PROCESSING USING DIFFERENT CORS STATIONS

As Shown in Figure 3, six CORS stations were independently used as base stations to allow for differential GPS positioning. Each of the derived trajectories was then compared to the reference SBET trajectory (see Section 3). In the following the, results of these comparisons are presented in some detail.

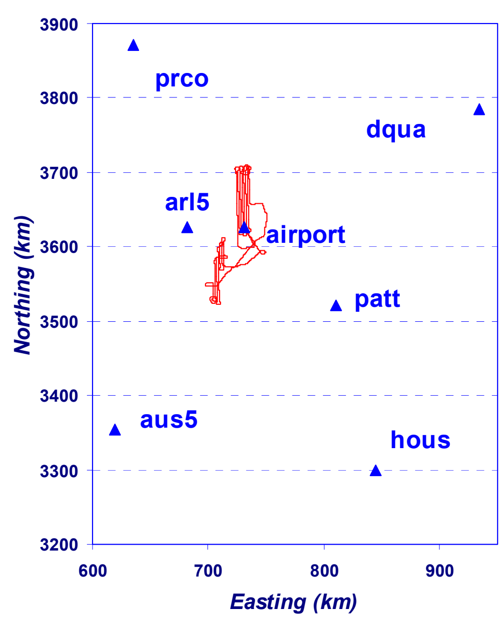

Figure 3 Aircraft Trajectory and six Surrounding CORS Stations

4.1 DGPS PROCESSING USING ARL5

The ARL5 station, which data is collected at 5-second intervals, was used as a base station to determine the trajectory of the aircraft. The master-to-rover separation varied from 30 to 110 km as shown in Figure 4. For details on ARL5; see Texas/texas_arl5.html under the CORS website listed in Section 1.

The raw data was interpolated to 1-sec intervals and then processed in differential mode. The derived trajectory was compared to the reference SBET. Figure 5 shows the differences in east, north, and down position components. Table 1 shows the RMS values.

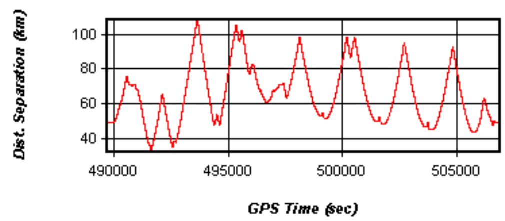

Figure 4 Distance Separation between ARL5 Station and Aircraft

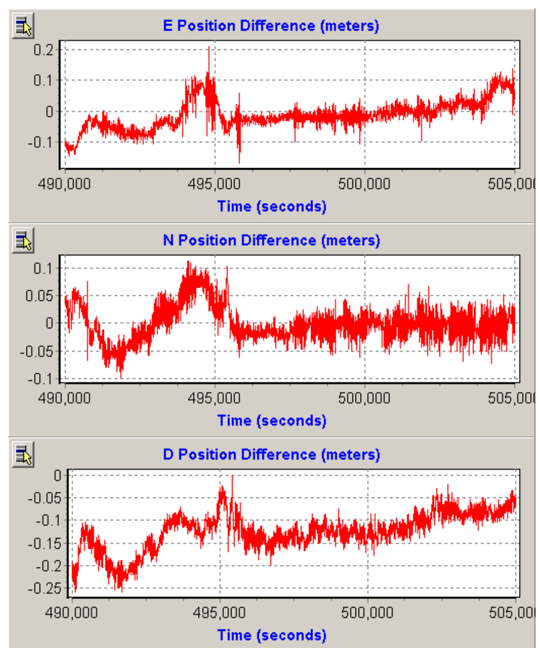

Figure 5 Position Difference in East, North, and Height Between Reference SBET and GPS-derived Trajectory using ARL5

Table 1. Position Difference Statistics ARL5 solution

Position Component	Max (m)	RMS (m)
Easting	0.21	0.11
Northing	0.11	0.12
Height	0.29	0.25

4.2 DGPS PROCESSING USING PATT

The PATT station, which data is collected at 30-second intervals, was used as mentioned above. For details on PATT; see Texas/texas_patt.html. The master-to-rover separation ranged from 100 – 200 km, as shown in Figure 6.

The raw data was interpolated to 1-sec intervals and then processed in differential mode. The derived trajectory was compared to the reference SBET. Figure 7 shows the position difference, while Table 2 shows their statistics.

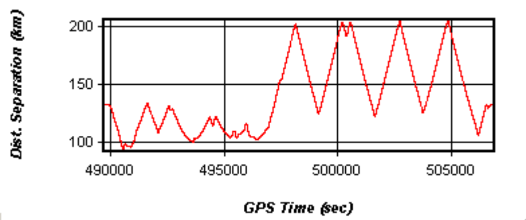

Figure 6 Distance Separation between PATT Station and Aircraft

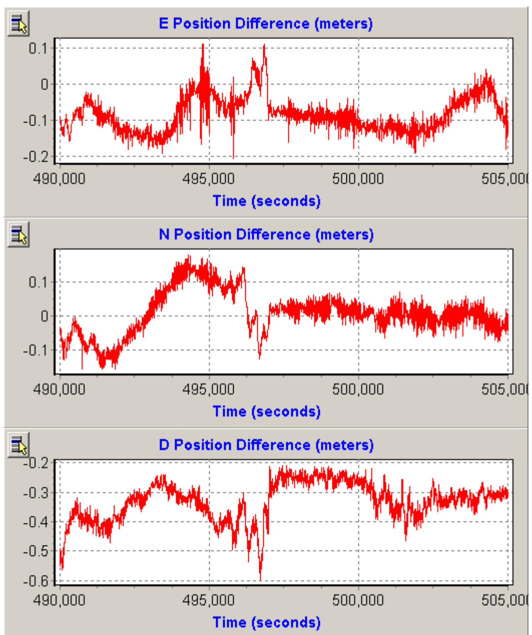

Figure 7 Position Difference in East, North, and Height Between Reference SBET and GPS-derived Trajectory using PATT

Table 2. Position Difference Statistics PATT solution

Position Component	Max (m)	RMS (m)
Easting	0.22	0.10
Northing	0.19	0.07
Height	0.61	0.34

4.3 DGPS PROCESSING USING DQUA

The DQUA station, which data is collected at 30-second intervals, was used as previously mentioned. For details on DQUA station; see Arkansas/arkansas_dqua.html.

The master-to-rover separation was 210-350 km, as shown in Figure 8. The derived trajectory was compared to the reference SBET. Figure 9 shows the position difference, while Table 3 shows their statistics.

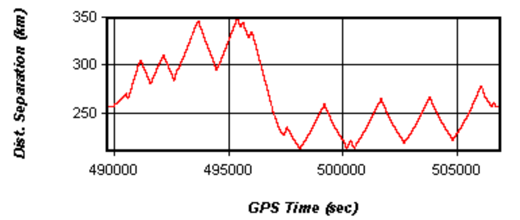

Figure 8 Distance Separation between DQUA Station and Aircraft

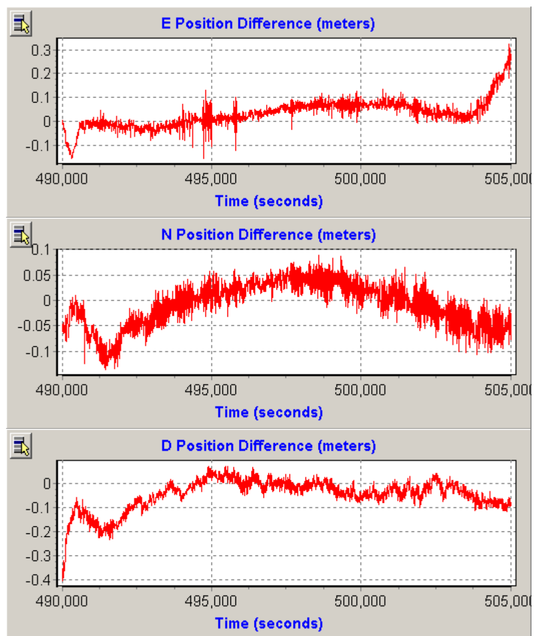

Figure 9 Position Difference in East, North, and Height Between Reference SBET and GPS-derived Trajectory using DQUA

Table 3. Position Difference Statistics DQUA solution

Position Component	Max (m)	RMS (m)
Easting	0.35	0.18
Northing	0.14	0.05
Height	0.42	0.09

4.4 DGPS PROCESSING USING AUS5

The AUS5 station, which data is collected at 5-second intervals, was used as previously mentioned. For details on AUS5 station; see Texas/texas_aus5.html.

The master-to-rover separation was 190-370 km, as shown in Figure 10. Figure 11 shows the position difference, while Table 4 shows the statistics of the difference.

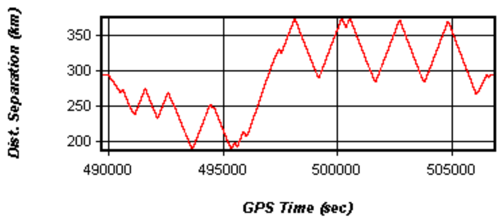

Figure 10 Distance Separation between AUS5 Station and Aircraft

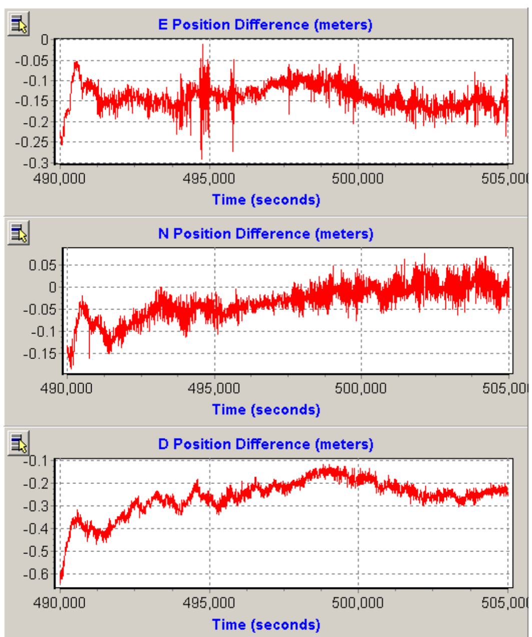

Figure 11 Position Difference in East, North, and Height Between Reference SBET and GPS-derived Trajectory using AUS5

Table 4. Position Difference Statistics AUS5 solution

Position Component	Max (m)	RMS (m)
Easting	0.30	0.18
Northing	0.21	0.07
Height	0.67	0.28

4.5 DGPS PROCESSING USING PRCO

The PRCO station is used as described previously. The GPS raw data was collected at 30-second intervals. For details on PRCO station; see Oklahoma/oklahoma_prco.html.

The master-to-rover separation was 190-360 km, as shown in Figure 12. Figure 13 shows the position difference, while Table 5 shows their statistics.

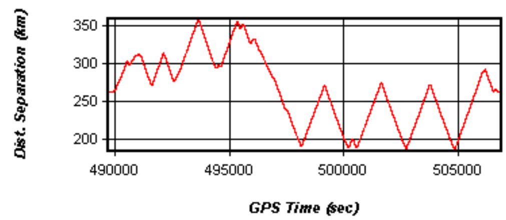

Figure 12 Distance Separation between PRCO Station and Aircraft

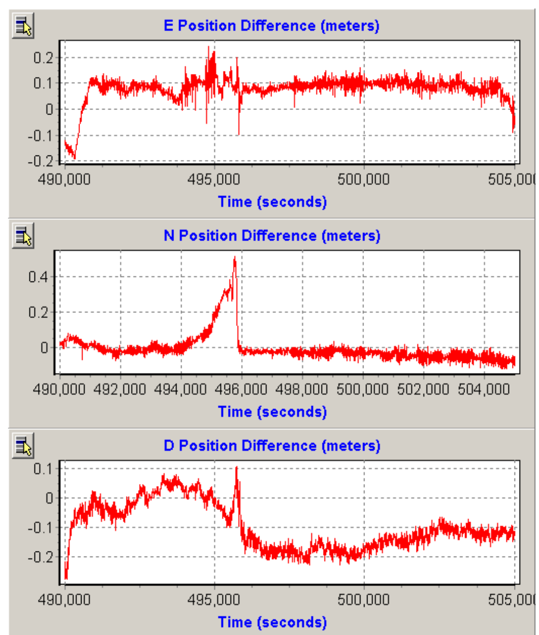

Figure 13 Position Difference in East, North, and Height Between Reference SBET and GPS-derived Trajectory using PRCO

Table 5. Position Difference Statistics PRCO solution

Position Component	Max (m)	RMS (m)
Easting	0.22	0.10
Northing	0.47	0.08
Height	0.29	0.13

4.6 DGPS PROCESSING USING HOUS

The HOUS station is used as described previously. The GPS raw data was collected at 5-second intervals. For details on HOUS station; see Texas/texas_hous.html. The master-to-rover separation was 260-420 km, as shown in Figure 14. Figure 15 shows the position difference, while Table 6 shows their statistics.

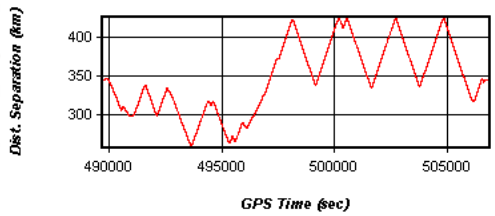

Figure 14 Distance Separation between PRCO Station and Aircraft

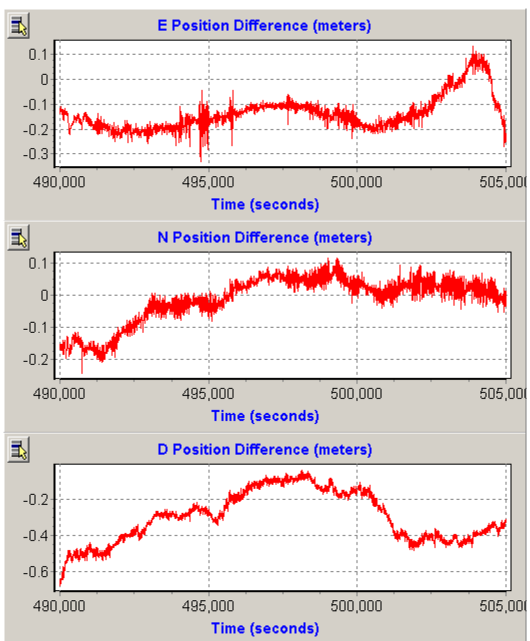

Figure 15 Position Difference in East, North, and Height Between Reference SBET and GPS-derived Trajectory using HOUS

Table 6. Position Difference Statistics HOUS solution

Position Component	Max (m)	RMS (m)
Easting	0.30	0.23
Northing	0.21	0.08
Height	0.67	0.38

5. COMBINED DGPS PROCESSING USING MULTIPLE CORS STATIONS

All six CORS stations were used to produce a combined GPS profile using POSGPS™ Batch Processing utility. The resulting GPS profile was then compared to the reference SBET. The position difference showed a similar pattern and magnitude to that shown when ARL5 station was used individually as a base station. This is due to the fact that the combined solution is mainly dominated by the ARL5 station since it is the closest to the airborne vehicle, as shown in Figure 4.

Therefore, only the five other CORS stations were combined to produce a GPS profile which when compared to the reference SBET resulted in the differences shown in Figures 16.

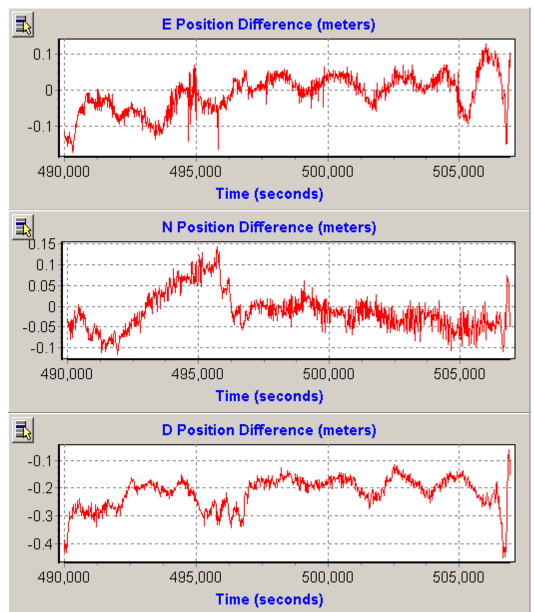

Figure 16 Position Difference in East, North, and Height Between Reference SBET and Combined GPS-derived Trajectory using Multiple CORS Stations

Table 7. Statistics of Position Differences The Combined solution

Position Component	Max (m)	RMS (m)
Easting	0.16	0.05
Northing	0.21	0.05
Height	0.46	0.22

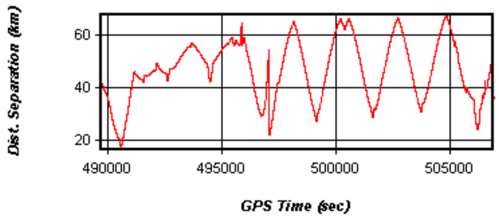

Figure 17 Virtual Mater-To-Rover Separation Using The Combined CORS Base Stations

Note that the CORS stations are well distributed around the flight trajectory. Consequently, they provide a geometrically strong combined solution, which can be considered as creating a single virtual base station closer to the rover than any of the CORS station used in the combined solution. For instance, using the combined solution, the resulting master-to-rover separation, shown in Figure 17, varies only between 18 and 65 km, while the closest CORS station to the airborne vehicle was 100 km away (PATT station; see Figure 6). Therefore, the combined solution provided the best solution when compared to the reference trajectory. Table 7 shows the statistics of the differences.

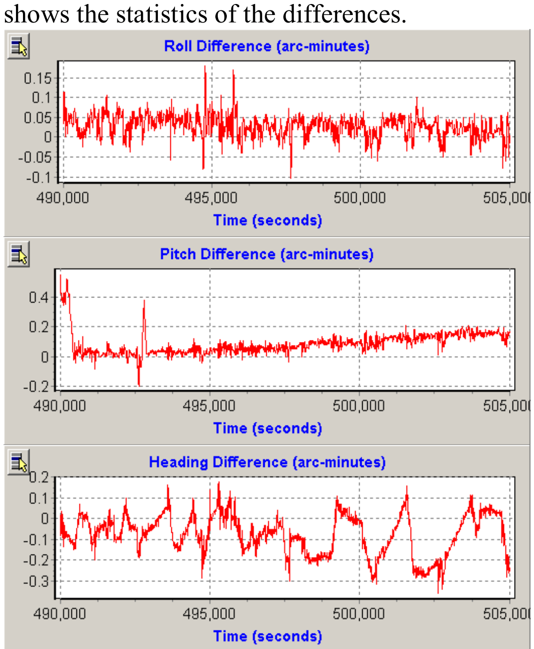

Figure 18 Attitude Difference

6. POSITIONING ACCURACY EFFECT ON ORIENTATION ACCURACY

Since airborne mapping depends on position and orientation accuracy, the effect of DGPS data processing using long baselines on the orientation accuracy is analyzed.

The GPS profile using farthest CORS station (HOUS) was used to generate another SBET file, which was then compared to the reference SBET.

Figure 18 shows the differences in roll, pitch and heading, while Table 8 shows their statistics. Note that the effect of GPS accuracy on the orientation accuracy is minimal and is well within the Applanix POS/AV^{TM} 510 accuracy specifications (c.f., Mostafa et al, 2001). Hence, the resulting mapping accuracy would not be affected.

Table 8. Attitude Difference Statistics HOUS SBET solution

Attitude Angle	Max (arcmin)	RMS (arcmin)
Roll	0.18	0.08
Pitch	0.47	0.07
Heading	0.37	0.14

7. EFFECT ON MAPPING ACCURACY

There are three ways of georeferencing airborne images to some mapping frame of reference. The first (traditional) is completely dependent on ground control points, which is obsolete. The second method is dependent on airborne GPS and minimal ground control using some aerial triangulation scheme and is, therefore, referred to as GPS-assisted aerial triangulation. The third method is referred to as direct georeferencing, which is completely dependent on GPS/inertial data that identifies the location and orientation of each aerial image at the moment of its exposure.

Using the CORS stations individually showed that the horizontal accuracy varies from 0.05 to 0.23 m RMS in east or north, while the height varies from 0.09 m to 0.38 m RMS. These accuracies are generally acceptable for either of the two new georeferencing methods.

In small-scale photography applications (high altitude photography), the GPS accuracy presented here is acceptable for both GPS-assisted aerial triangulation and for direct georeferencing, since positional accuracy requirement is generally relaxed. In large scale mapping projects (low altitude photography), the mapping error budget is dominated by GPS errors and, therefore, the accuracy shown in Section 4, is not good enough for direct georeferencing purposes, but acceptable for GPS-assisted aerial triangulation since in the latter case, the geometry of image networks together with the accuracy of ground control points improve the image positional accuracy, when all airborne, image, and ground information is processed simultaneously. For airborne remote sensing applications and resource mapping, the GPS accuracies presented using individual CORS stations are adequate.

Combined DGPS processing using multiple CORS stations, showed a significant accuracy improvement when compared to DGPS processing using individual stations, as shown in Section 5. A number of researchers showed similar results when operating in a multi-receiver configuration (c.f., Shi, 1994). For a complete list of references, see Raquet (1998).

SMMARY AND OUTLOOK

In this paper, the potential of using the US National Geodetic Survey (NGS) continuously operating reference stations (CORS) as base stations for airborne GPS surveys is studied. Six CORS stations were used individually and in combined configurations as base stations for an airborne GPS data set. All individual six GPS profiles were compared to an independent photogrammetrically derived reference trajectory, and the results were analysed. Generally speaking, the CORS stations have a great potential to serve the aerial mapping industry in USA, especially when the stations are densified and the data frequency is increased to 1-2 seconds interval instead of the 5-30 seconds intervals.

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