Airborne DGPS Without Dedicated Base Stations for Mapping Applications

A.M. Bruton, M.M.R. Mostafa, and B. Scherzinger, *Applanix Corporation, Ontario, Canada*

BIOGRAPHIES

Dr. Alex Bruton recently joined Applanix Corporation where he works in the Advanced Technology Group. He holds a Ph.D. in geomatics engineering and a B.Sc. in surveying engineering from the University of Calgary. His research interests include modeling and estimation for inertial navigation, and the development and use of integrated systems for applications in mapping and geodesy.

Dr. 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 B.Sc. and a M.Sc. 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.

Dr. Bruno Scherzinger obtained a B.Eng degree from McGill University in 1977, and M.A.Sc. and Ph.D. degrees from the University of Toronto in 1979 and 1983, respectively. He is a founding partner and the Chief Scientist at Applanix Corporation.

ABSTRACT

This paper evaluates the potential of deriving reliable and accurate estimates of the position of a survey aircraft without the establishment of dedicated GPS base stations. Although there are several approaches to doing this, the concept studied herein is to make use of data available from existing permanent GPS reference systems to estimate the position of the aircraft. While such stations have been established to support static or low dynamic land based GPS surveying and can be at a considerable distance from the survey area (e.g. 100 to 500 km), they are often large in number and their data is usually freely available. In this research, position is determined using data collected as part of the NGS CORS network in conjunction with the measurements made by the receiver on the survey aircraft.

The success of the approach is evaluated empirically based on data collected using the Applanix POS/AV^{TM}. Analyses of the test results show that when using five network stations at average distances between 160 and 420 km, it is possible to achieve an accuracy of 25 cm (RMS) in 3D position while not deviating from the dedicated solution by more than 42 cm at any time during the survey. It is also seen that when the network solution is augmented to include three stations at average distances of between 40 and 90 km, the quality of the 3D positioning information can reach the level of better than 12 cm (RMS) while never deviating from the dedicated solution by more than 28 cm. It is then observed that when positioning information from any of these scenarios is used (in place of that coming from dedicated GPS base stations) as an update to the IMU in the POS/AV^{TM} system, the maximum differences in roll and pitch can reach the level of 3 arc seconds and the maximum difference in heading can be as low as 10 arc seconds. Finally, comments are made regarding the application of this method in practice.

1. INTRODUCTION AND METHODOLOGY

Positioning information derived from GPS measurements has become a reliable component of many of today's aerial mapping systems. However, one of the logistical limitations commonly faced when using GPS for airborne mapping is the need for continuous data collected by a GPS receiver at one or more base stations in the area of the survey (e.g. having a station within 30 km of the aircraft at all times). While the use of such data is a means of meeting the accuracy requirements of today's most demanding applications, the establishment of the base stations is often a difficult task when surveys take place over remote or inaccessible terrain. Further, even when dedicated base stations are established, the continuity of the data is not always guaranteed as a result of environmental effects, receiver error, or human error.

With these comments in mind, this paper contributes to research being carried out at Applanix Corporation to evaluate the accuracy with which the position of an aircraft can be estimated in post-mission for scenarios in which dedicated GPS base stations are not available within the immediate vicinity of the survey. Specifically, the objective is to explore the capabilities of a method that estimates position via an optimal combination of solutions obtained from the stations in an existing permanent GPS reference system. The method is evaluated empirically using data collected by an Applanix POS/AV™ 510 system and data made available by the United States (US) National Geodetic Survey (NGS) as part of their Continuously Operating Reference Stations (CORS), see Snay (2000) and Spofford and Weston (1998). The utilities and batch processing options available within the Applanix POSPac™ software (version 3.0) are used to do the data processing, and the resulting solutions are evaluated by comparing them to a reference solution that has been validated against ground control points (GCP) using aerial triangulation (AT), and that is considered to have an absolute accuracy of 10 cm in position and between 20 and 30 arc seconds in attitude.

This research is intended to complement the analysis carried out in Mostafa and Hutton (2001) in which a network of NGS CORS stations (with an average distance from the aircraft of 216 km) was used to estimate position and attitude of an aircraft in a different survey. Comments about that survey, the survey presented herein, and the consistency of the two surveys will be discussed in section 5.

In the next section of this paper, the data set used in the analyses is described, and the method used to derive the reference for the position and attitude estimates is outlined. This is followed in section 3 by an evaluation of the position estimates that are obtained via various combinations of the CORS network solutions, and in section 4 by an assessment of the corresponding attitude estimates. As mentioned above, the results obtained herein are compared in section 5 to refined results based on the data that were presented in Mostafa and Hutton (2001). Comments are also made in section 5 regarding the general applicability of the method. Finally in section 6, the paper is summarized and conclusions are drawn in light of the use of this method in practice for a variety of applications.

2. THE FIELD TEST, THE CORS DATA, AND THE REFERENCE SOLUTION

The new analyses presented in this research are based on data collected by HJW GeoSpatial Inc. using an Applanix POS/AV™ 510 system during a survey that took place on June 21 2000 between Oakland and San Jose California in the US. As shown in Figure 1, a dedicated base station (labeled TOMS) was established directly below the centre of the flight track and a CORS reference station (labeled CHAB) was available at a location very close to the airport. Local cities are labeled for reference, but GPS data are not available at those sites. The flight took place between approximately 14:30 and 18:30 local time and the ellipsoidal flying height was 1155 metres for approximately one third of the flight lines and 995 metres for the remainder.

The CORS stations that were operating on June 21 2000 are shown in Figure 2 for the area within 400 km of the flight track. Notice that there are many CORS stations in the California area; five within 90 km of the survey site and eight others between 160 and 420 km of the site. The data collected at the stations marked by an unfilled square are all subject to 2 to 5 minute periods of missing data immediately after 18:00 and are therefore not used in these analyses. As shown, there are therefore three useable stations within 90 km of the survey site and five useable stations between 160 and 420 km of the site. With the exception of the CHAB station, those marked with a solid circle are used in the combined network solutions that are discussed later in section 3. Note again that the cities are only shown for reference. Also note that although other California CORS stations exist for the area shown in Figure 2, they are not shown because data are not available for them on June 21 2000.

As mentioned above, the results obtained in the following sections are evaluated by comparing them to a reference trajectory. That trajectory was derived from differential GPS solutions obtained by using the TOMS and CHAB stations in a dedicated fashion. Specifically, both stations were used independently to estimate the trajectory of the aircraft using fixed integer carrier phase techniques. These estimates were then combined using the POSGPS™ component of POSPac™ and used as an update to the IMU in the POS/AV™ system, resulting in a smoothed best estimate of the trajectory (SBET). Under the conditions of this survey the absolute accuracy of the POS/AV™ 510 system is at the level of 10 cm RMS for position and 20-30 arc seconds RMS for attitude. This is documented in Cramer (1999) and Mostafa and Hutton (2001), for example. The absolute accuracy of the solution in this specific case was established by comparing it to the position and orientation derived from a set of photogrammetric data using aerial triangulation. The accuracy was confirmed to be 10 cm RMS for position and 20-30 arc seconds RMS for orientation. Thus validated, this solution is considered to be the ideal solution and the objective of the research is to consider how closely it can be approximated using the solutions based on the other CORS stations.

Although data processing was done using the whole data set in all cases, the analyses presented in the following only consider the time period during which the aircraft was at survey altitude (i.e. all maneuvers are considered except during the periods of ascent and descent).

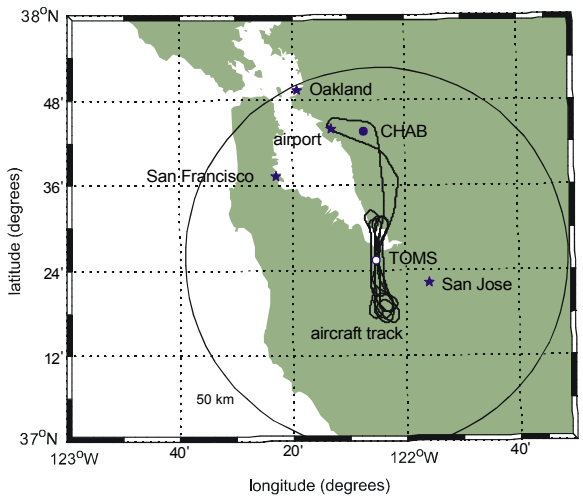

Figure 1: The trajectory and the dedicated base stations used to generate the reference solution

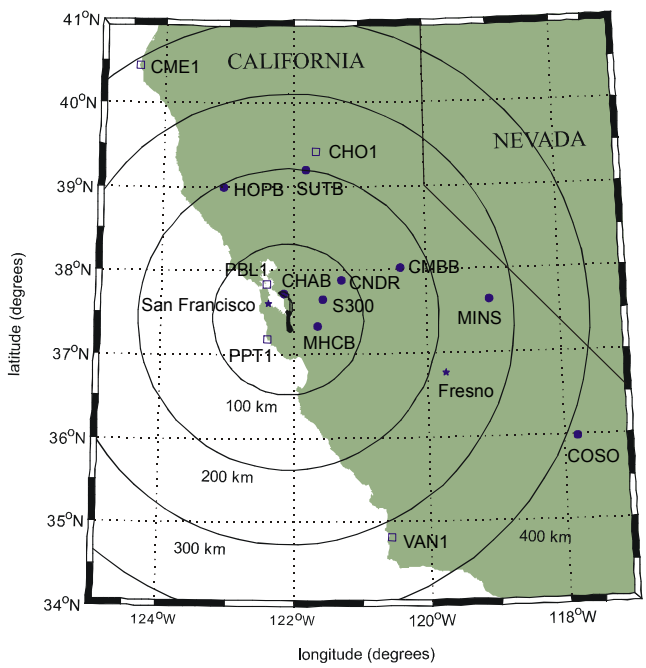

Figure 2: The CORS base stations for which data is available during the survey

3. EVALUATION OF THE ESTIMATED POSITION SOLUTIONS

The goal of this section is to evaluate the position estimates coming from various combinations of the estimates that were in turn obtained by processing between each of the CORS stations and the aircraft. In all cases, differences in position are evaluated by comparing an estimated position to the one given by the reference solution that was described in the last section.

As a starting point, briefly consider the individual solutions between the CORS base stations and the aircraft that are discussed in the Appendix. It is seen therein that as expected, the differences are generally smaller for stations closer to the aircraft, and that they can be quite large for longer baselines. Notice from Table A1 (also in the Appendix) that the RMS of the observed differences in the 3D position vector varies between 9 and 51 cm, and that the maximum observed difference varies between 25 and 87 cm, depending on the station used.

Next, consider Figure 3 and Table 1 that show the differences between the reference trajectory and trajectories obtained via three different combinations of the solutions to the individual CORS stations. The top plot in Figure 3 and the first entry in Table 1 show the differences between the reference trajectory and estimates of position obtained using all eight of the CORS stations available. The agreement for the 3D position vector is at the level of 12 cm RMS and the largest difference at any point in time is 28 cm. This is clearly very good and implies that estimates of position derived from such a network can be used to estimate position at or near the noise level of those derived from dedicated GPS base stations.

The differences shown in the other plots of Figure 3 and the other entries in Table 1 were computed in order to assess the role that stations close to the survey area play in such a combined solution. The middle plot shows the differences in position for a solution that is based only on the three CORS stations closest to the survey area (MHCB, S300 and CNDR), and the bottom plot shows the differences for the solution based on the remaining five CORS stations. The usefulness of having stations close to the survey areas is clear. Because it is likely that surveys will take place in areas with no GPS reference stations within 90 km of the survey area, it is important to note the quality of the combined solution that is based on the five stations further than 160 km: the agreement for the 3D position vector is at the level of 25 cm RMS and the largest difference at any point in time is approximately 42 cm.

Before concluding this section, note that for this data set, the solution obtained using only the three CORS stations closer than 90 km is slightly better than the solution obtained using all eight CORS stations. This implies that if such stations are available, then the inclusion of others does not help. Unless that level of proximity to the aircraft is available for a number of CORS stations, however, it will be desirable to process all available stations in the vicinity of the flight area.

4. ACCURACY WITH WHICH ATTITUDE CAN BE DETERMINED

The goal of this section is to evaluate the differences in attitude estimates made by the POS/AV^{TM} 510 system when positioning information from the solutions discussed in the last section is used in place of that coming from dedicated GPS base stations.

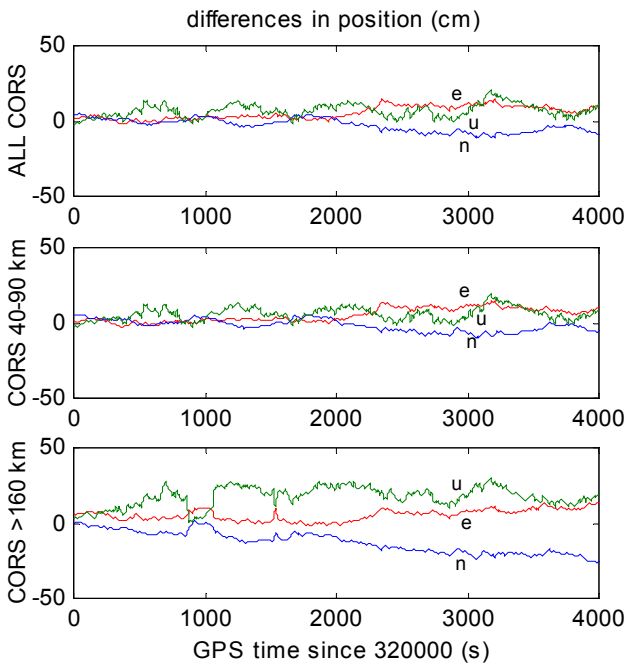

Figure 3: Differences in position for various combined solutions

Table 1: The statistics for differences in position for the combined solutions (cm)

station	statistic	component of difference north	east	up	3D
All CORS stations	RMS	5.0	6.8	8.1	11.7
	largest	11.2	14.4	21.0	27.8
3 CORS stations (40-90 km)	RMS	4.2	6.8	7.3	10.9
	largest	9.7	15.0	19.9	26.7
5 CORS stations (>160 km)	RMS	14.4	6.5	18.8	24.5
	largest	26.4	13.5	30.0	42.2

Differences in attitude are evaluated by comparing estimated attitude values to those given by the reference solution that was described in section 2.

Processing was carried out using four different position estimates as updates to the IMU in the POS/AV^{TM} 510 system; the three combination solutions that were treated in Figure 3, and the single baseline solution that was obtained by processing between the MINS CORS station and the aircraft. Because the latter exhibited the largest differences in position (see the Appendix), it is considered a worst-case scenario. The differences in attitude corresponding to these processing instances are shown in Figure 4 and Table 2.

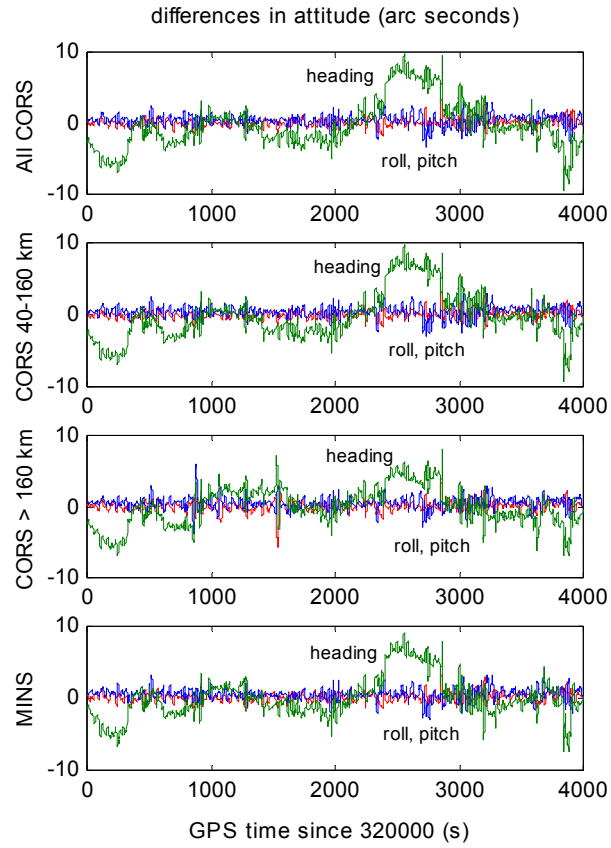

Figure 4: Differences in attitude for various combined solutions and for the MINS solution

Table 2: The statistics for differences in attitude for the combined solutions (arc seconds)

station	statistic	component of difference roll	pitch	heading
All CORS stations	RMS	0.60	0.87	3.32
	largest	3.45	3.35	9.74
3 CORS stations (40-90 km)	RMS	0.60	0.89	3.27
	largest	3.22	3.11	9.74
5 CORS stations (>160 km)	RMS	0.71	0.97	2.68
	largest	5.83	5.97	8.20
MINS (268 km)	RMS	0.63	0.94	2.84
	largest	3.20	3.28	9.06

In all of these cases, the differences in attitude are at the level of just under 1 arc second (RMS) in roll and pitch and approximately 3 arc seconds (RMS) in heading. Clearly then, the effect of the various position solutions on attitude is within the noise level of the reference solution. Further, there are no visible long-term (drift-

like) differences in attitude for this data set, implying that the observed differences are due to short and medium-term differences in the position solutions. In turn, these may be due to the fact that the solutions based on dedicated GPS base stations use fixed ambiguity carrier phase observables, while all of those based on the CORS stations use ionospheric-free carrier phase observables.

Although the behaviour of the attitude estimates made based on all four of these position solutions is similar, the following observations follow from Figure 4 and Table 2:

- The maximum differences in roll and pitch for the solution that is based on only on the three closest CORS stations (MHCB, S300 and CNDR) are very slightly smaller than those for the solution based on all of the CORS stations. This is to be expected from the last section, where it was seen that the differences in position are also slightly smaller for the solution based on the three closest stations.
- The maximum differences in attitude for the solution that is based on the five farthest CORS stations are different from the others; the differences in roll and pitch are larger and the differences in heading are smaller. It is possible that this is due to different quality factors being assigned to the position estimates by the batch processor in the POSGPS™ component of the POSPac™ package. In turn, this could imply that different weights (i.e. confidence levels) are being assigned to the position updates.

5. DISCUSSION OF THE APPLICABILITY OF THIS METHOD

This section of the paper is included for completeness with the goal of commenting on the applicability of this method in general. For this purpose, the analysis using a different POS/AV™ 510 system that was presented in Mostafa and Hutton (2001) is briefly recalled. It will be referred to as the Dallas project. Consider Figure 5 in which the flight path and the locations of the CORS and dedicated GPS base stations are shown for that data set. One dedicated GPS base station and six CORS stations were considered in the area. As in the analysis presented in this paper, the dedicated GPS base station was used to generate a reference position trajectory, and the five CORS stations marked with solid circles were used to generate a combined estimate of the position. The ARL5 solution was not included in the combined solution because it was considerably closer to the survey area than the others and would therefore dominate that solution. As such, the average distance between the aircraft and the five remaining stations is 216 km. These were then each used as an update to the IMU in the POS/AV™ system to compute the corresponding SBETs.

Figure 6 and Table 3 are included so that the results from that analysis can be directly compared to those of the analyses presented so far in this paper; they show the differences between the reference trajectory and selected solutions obtained using the CORS stations for the period of time during which the aircraft was at survey altitude during that flight test. The top plot in Figure 6 and the first entry in Table 3 show the differences between the reference trajectory and estimates of position obtained using all five CORS stations. The agreement for the 3D position vector is at the level of 23 cm RMS and the largest difference at any point in time is 42 cm. This is clearly consistent with the results presented in the current research and supports the conclusion that estimates of position derived from such a network can be used to estimate position near the noise level of those derived from dedicated GPS base stations. The second plot in Figure 6 and the second entry in Table 3 are included for completeness to show the differences obtained when using the furthest CORS station alone (HOUS which is 347 km away on average).

In Figure 7 and Table 4, the plots and statistics can be found for the attitude estimates that correspond to the position solutions in Figure 6 and Table 3. Note that the attitude results for the Dallas project have been refined since they were presented in the earlier publication. As such, these attitude results are also consistent with the results presented in the current research.

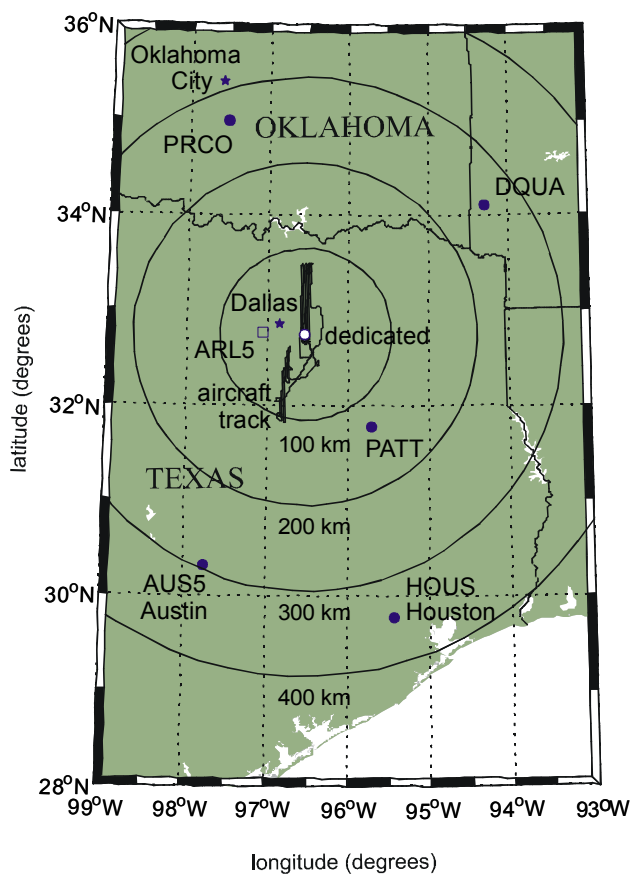

Figure 5: The trajectory and the GPS base stations used in the Dallas data processing

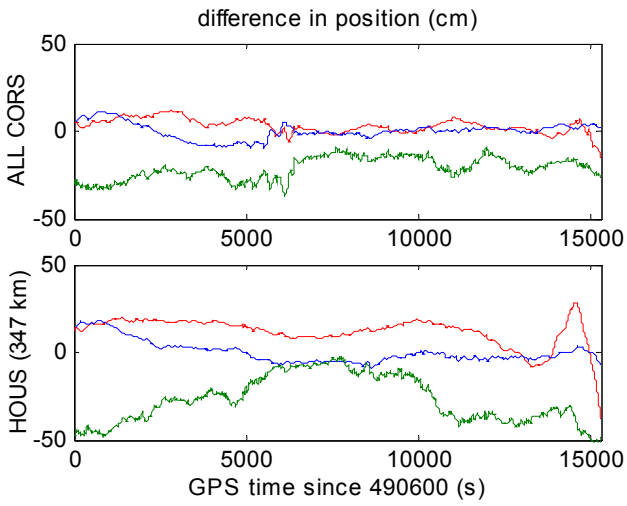

Figure 6: Differences in position for the combined solution and for the HOUS solution for the Dallas project

Table 3: Statistics for differences in position (cm) for the solutions in Figure 6

station	statistic	component of difference			
		north	east	up	3D
All CORS stations	RMS	5.0	5.1	22.2	23.2
	largest	11.6	15.2	37.8	42.3
HOUS (347 km)	RMS	6.4	14.4	30.2	34.0
	largest	18.1	37.8	52.4	67.1

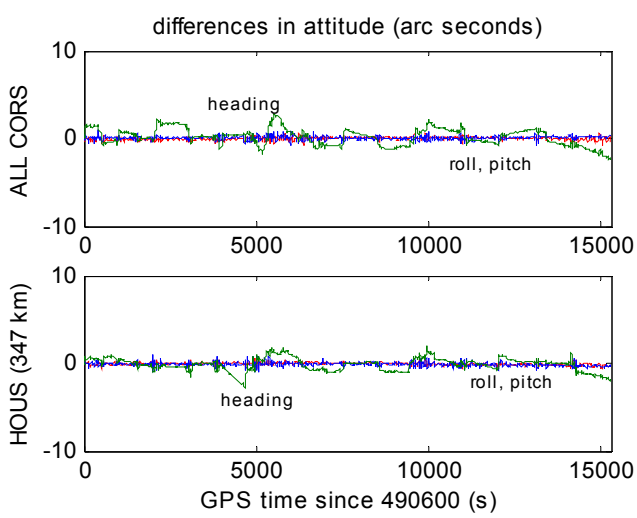

Figure 7: Differences in attitude for the combined solution and for the HOUS solution for the Dallas project

Table 4: Statistics for differences in attitude (arc seconds) for the solutions in Figure 7

station	statistic	component of difference		
		roll	pitch	heading
All CORS stations	RMS	0.18	0.20	0.97
	largest	0.85	0.95	2.89
HOUS (347 km)	RMS	0.16	0.22	0.76
	largest	0.67	1.07	2.73

Based on the high level of consistency that is observed between the results of these two studies, it is proposed by the authors that this method can provide a viable alternative for estimating the position of an aircraft in post-mission for scenarios in which dedicated GPS base stations are not available within the immediate vicinity of the survey.

6. SUMMARY AND CONCLUSIONS

It was seen in this research that a combination of solutions from permanent GPS reference stations can be used very successfully in place of dedicated base stations for positioning a survey aircraft. Analyses of the test results show that when using five network stations at average distances between 160 and 420 km, it is possible to achieve estimates with a quality of 25 cm (RMS) in 3D position while not deviating from the dedicated solution by more than 42 cm at any time during the survey. It was seen that when the network solution is augmented to include three stations at average distances of between 40 and 90 km, the quality of the 3D positioning information can reach the level of 12 cm (RMS) while not deviating from the dedicated solution by more than 28 cm. It was also seen that if data are available from a sufficient number of GPS reference stations within 90 km of the survey area, then it is unlikely that data from stations further away than that will add anything to a combined solution.

It was observed with the data sets studied herein that the quality of attitude estimates is not greatly affected by the type of position solution being used (including single baseline solutions with position differences as high as 75 cm), as long as those position solutions are appropriately weighted when used as an update to the IMU in a mapping system such as the Applanix POS/AV^{TM}. The combination solutions considered here were observed to provide attitude solutions with maximum differences of 10 arc seconds in heading and 3-5 arc seconds in roll and pitch.

These observations are very encouraging for mapping applications taking place under conditions in which dedicated GPS base stations are not available in the area surrounding a survey. Immediate potential benefits of

this approach include precise positioning for aerial survey applications such as GPS-assisted aerotriangulation, and the generation of Exterior Orientation parameters for direct georeferencing for aerial film or digital cameras, LIDAR, and SAR.

As an example, this paper used data sets from the US, where data from the CORS reference network could be used in place of dedicated GPS base stations. Before concluding, the authors would like to point out there exist a number of other such networks throughout the world. As well as many permanent GPS reference networks existing at state or provincial levels, examples include many national networks. Among those are the Canadian Active Control System (CACS), the EUREF Permanent Network (EPN) in Europe, the Australian Regional GPS Network (ARGN), and two networks maintained by the Geographical Survey Institute of Japan.

Finally, in conclusion, the authors would like to point out that if a surveyor plans to use this method for estimating position, there exists a responsibility on his or her part to carefully plan the survey. For example, it is important to make sure that there is a sufficient number of baselines close enough to the survey area to ensure redundancy. The five CORS stations with periods of missing data discussed in section 2 are good examples of why this is so.

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APPENDIX: THE POSITION ESTIMATES FROM THE INDIVIDUAL CORS BASE STATIONS

This Appendix is included for completeness for two reasons. The first is to demonstrate the behaviour of the position solutions obtained by processing between each CORS station and the aircraft, and the second is to describe the important processing parameters that were used in generating each of them. As usual, the differences in position are evaluated by comparing a given estimate to the position given by the reference solution that was described in section 2.

Figure A1 shows the differences in position for the solutions obtained using the measurements for the five CORS stations that are at an average distance of greater than 160 km from the survey area. The average distances are shown on the left hand side of the figure (in brackets following each station name) and the differences are labeled with the letters e, n, and u to represent the east, north and upward components, respectively. The stations shown at the top of the figure are closer to the aircraft than those at the bottom. In all of these cases, processing was done using the batch processor in the POSGPS™ component of POSPac™. Default settings were used as a starting point for each processing instance. The basic approach was to use the ionospheric-free model and to process the data forward and backwards in time. Only minor changes to the default settings were made as necessary to minimize the differences between the forward and reverse solutions in each case. The solutions shown are based on an optimal combination of the forward and reverse solutions. Table A1 gives the statistics of the differences for each of these stations.

Figure A2 shows the data for the CORS stations that are at an average distance of less than 90 km from the survey site. The basic approach to processing these somewhat shorter baselines was also to use the ionospheric-free model and to process the data forward and backwards in time. For the two shorter baselines (MHCB and S300), it was also possible to aid the float ambiguity solution by initializing the processing with a “quick static” solution during the static periods at the beginning and end of the survey. Otherwise, only minor changes to the default settings were made as necessary to minimize the differences between the forward and reverse solutions

from each station. Table A1 gives the statistics of the differences for each of these stations.

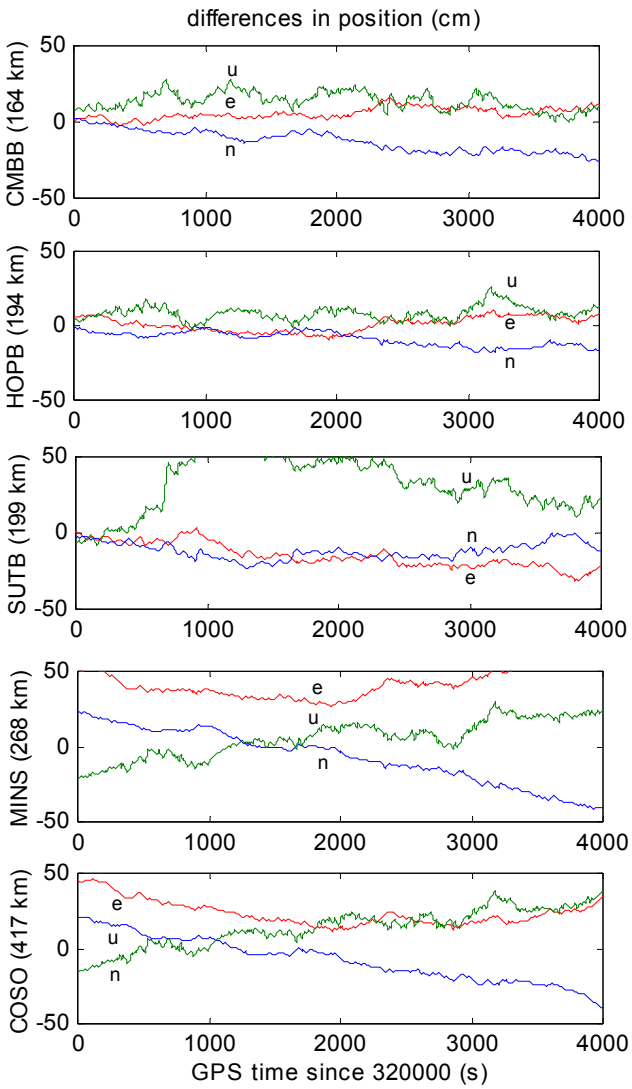

Figure A1: Differences in position for solutions from CORS stations more than 150 km from the aircraft

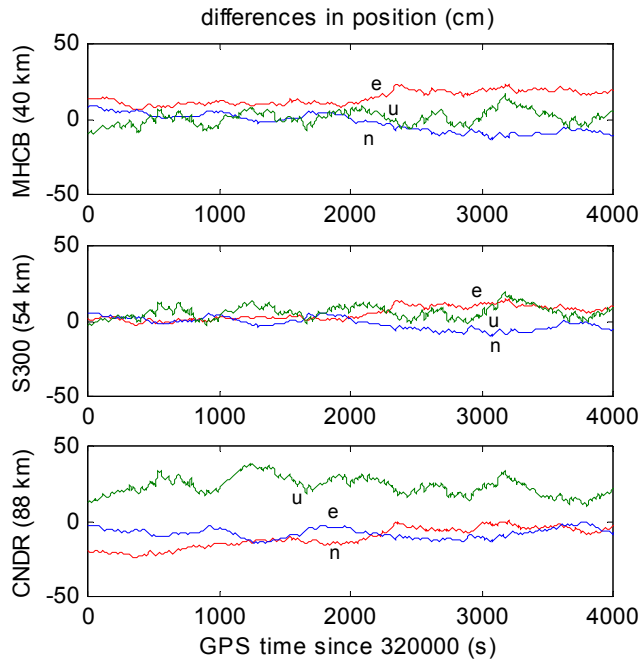

Figure A2: Differences in position for solutions from CORS stations more than 90 km from the aircraft

Table A1: The statistics for differences in position observed for solutions derived from each CORS station (cm)

station	statistic	component of difference north	east	up	3D
MHCB (40 km)	RMS	6.5	14.9	4.9	17.0
	Largest	13.3	23.5	16.7	31.7
S300 (54 km)	RMS	3.8	3.2	7.2	8.7
	largest	9.2	8.5	21.5	24.8
CNDR (88 km)	RMS	8.5	12.9	24.1	28.6
	largest	14.9	23.9	38.5	47.7
CMBB (164 km)	RMS	14.4	6.9	14.9	21.8
	largest	25.9	16.3	27.7	41.3
HOPB (194 km)	RMS	10.0	5.0	9.8	14.9
	largest	18.3	10.4	26.1	33.5
SUTB (199 km)	RMS	12.9	16.8	37.4	43.0
	largest	23.5	31.5	63.3	74.5
MINS (268 km)	RMS	19.3	44.6	13.5	50.5
	largest	41.2	70.3	29.7	86.7
COSO (417 km)	RMS	16.4	24.9	18.7	35.2
	largest	39.4	46.3	38.4	72.0