New Developments of Inertial Navigation Systems at Applanix

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ABSTRACT

GNSS-Aided Inertial Navigation for Direct Georeferencing of aerial imagery and other sensors such as LIDAR is a well accepted technology that has been in use since the mid 1990's. Position accuracies of 10 cm RMS horizontal and 15 cm RMS vertical are routinely achieved using post-processed kinematic ambiguity resolution (KAR) differential GNSS along with specific operational restrictions that are necessary due to the nature of the airborne environment. These include: flying turns of less than 25 deg bank angle, flying less than 30 km from a reference GNSS receiver in order to correctly fix integer ambiguities, and keeping the maximum baseline separation to less than 75 km once the ambiguities are fixed. This paper introduces a new patent pending post-processed GNSS-Aided INS development at Applanix that promises to not only eliminate or reduce these restrictions, but improve the overall accuracy that can be achieved with airborne differential GNSS positioning.

1. INTRODUCTION

This section provides an overview of the GNSS positioning technology that is currently being used in Aided Inertial Navigation Systems for Airborne mapping and surveying, highlighting both its capabilities and restrictions. A novel development in then introduced that promises to reduce if not eliminate most of the restrictions.

1.1. Positioning via RTK GNSS

The use of real-time kinematic (RTK) GNSS using integer carrier phase differential processing to achieve centimeter level positioning in support of land-based surveying and construction applications is now common practice. This is usually achieved by setting up a dedicated reference GNSS receiver (also called a reference station) with a real-time radio link to correct the roving GNSS receiver used by the surveyor within 10 km of the reference station. The 10 km restriction rover-reference baseline separation is driven by errors introduced through propagation delays of the GNSS signals through the atmosphere. The further the roving receiver is from the reference station, the less these errors are correlated and hence cannot be cancelled out in the rover's RTK processing, resulting in potential loss of accuracy and reliability of an RTK position solution. Within a 10 km baseline separation, RTK performance is typically 1 cm plus 1 ppm of baseline separation RMS horizontal, and 2 cm plus 1 ppm of baseline separation RMS vertical (Trimble 2005).
More recently this single reference station approach has been replaced with a Virtual Reference Station (VRS) solution. A VRS solution uses a network of continuously operating reference stations to compute a set of corrections for the roving receiver anywhere within the network. The corrections are computed by a VRS server and then sent to the rover in real-time via a radio link or cell phone. The VRS corrections appear to come from a virtual reference station located close to the rover receiver, thereby providing compatibility with older single-baseline RTK-capable GNSS receivers. A single VRS network can provides accurate corrections over a large area such as a major city using 4 reference stations on the area perimeter. A single VRS network can service several rover receivers, and thereby eliminates the need for surveyors operating in this area to set up their own reference stations (Landau H., 2002). The network approach has the advantage of RTK positional accuracy over large areas using relatively few reference receivers by continuously using the reference receivers to calibrate spatially correlated atmospheric errors within the network. Real-

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

1.2. Robust Positioning via Inertially-Aided RTK GNSS

Inertially-Aided RTK (IARTK) is a method of RTK GNSS processing where the integer ambiguity resolution is aided by information from the inertial system in a GNSS-Aided INS (Scherzinger B. 2006). Unlike a classical GNSS-Aided INS architecture where the GNSS processing is performed separately and the position is then fed into aid the inertial solution as one of the aiding sensors, IARTK is part of an approach that processes the raw GNSS observables from the rover and reference receiver directly in a single processing step (Figure 1). This approach is often referred to as a *Tightly-coupled* processing, while the former is often referred to as *Loosely-coupled* processing.

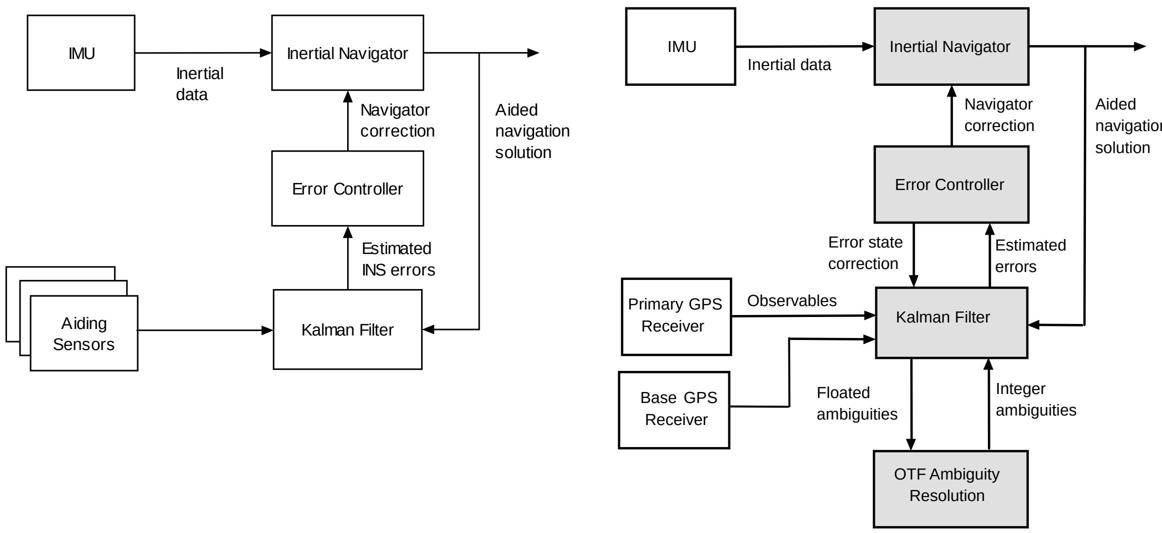

Figure 1: *Loosely Coupled* Aided Inertial Architecture (left),
Tightly Coupled GNSS-Aided Inertial Architecture (right)

In the *Tightly coupled approach*, a single Kalman filter is used to estimate both the inertial errors and the GNSS floated ambiguities, and then a kinematic ambiguity resolution (KAR) algorithm is used to fix the ambiguities as integers to obtain centimeter level positioning.

The IARTK method has the clear advantage over standard RTK processing when loss of GNSS signals occur due to full or partial obstruction of the sky. The IARTK method maintains the inertial position accuracy at the decimeter-level during the outage, so that at the end of the outage the ambiguity search space converges immediately to a small volume and rapid ambiguity resolution can occur. Depending on the quality of the inertial sensors and the duration of the outage, this can occur within seconds (Scherzinger B. 2006). With standard RTK processing, a recovery after loss of lock will take as long as an initial RTK convergence, from 15 seconds to several minutes, depending upon the distance to the reference station.

1.3. Current Use of Differential GNSS for Aerial Mapping and Surveying

GNSS positioning in support of aerial mapping and surveying is now well into its second decade of acceptance, most often used in conjunction with an aided-INS to produce both position and orientation of an aerial sensor such as a camera or LIDAR (Mostafa M.M.R. et al, 2001). However the challenges of establishing a real-time radio link to the aircraft, the high dynamics of the aircraft, and keeping the flight lines within 10 km of a reference station have meant that RTK GNSS has never been practical for airborne applications. Instead, post-processing of the logged GNSS data in the aircraft and at the reference station is used, allowing optimal smoothing to improve the accuracy of the post-processed position and orientation solution. Furthermore, restricting flight lines to within 10 km from a reference station is simply not practical, so the standard practice is to resolve the integer ambiguities when the aircraft is close to the reference station, and then carry these fixed ambiguities through the mission to baselines of up to 75 km. This typically allows a position accuracy of better than 10 cm RMS horizontal and 15 cm RMS vertical (assuming a 1 to 2 ppm error), however the aircraft must be restricted to flying bank angles less than 25 deg ("flat turns"). This is required to avoid phase lock loss and cycle slips that result from excessive tilting of the aircraft-mounted GNSS antenna in a turn. If a cycle slip occurs when the aircraft is more than about 20 - 30 km distant from the reference receiver, re-resolving the correct cycle ambiguities becomes more difficult due to the de-correlation of atmospheric propagation delays experienced by the rover and reference receivers. Furthermore, if the number of satellites tracked drops below five, the KAR algorithm must completely re-initialize, and at such a distance it may simply not be possible to resolve the correct integer ambiguities.

In order to reduce this problem and extend the efficiency of aerial survey, the use of multiple reference station processing has been introduced. The multiple reference stations may either be deployed specifically for the survey, or be part of an existing continuously operation reference station (CORS) network (Bruton A.M. et al, 2001). The multiple reference stations must be positioned such that the aircraft initially flies less than 30 km from at least one reference station to allow correct ambiguity resolution. The aircraft must also still be flown using flat turns with less than 25 deg bank angle to minimize carrier phase lock loss among the receiver channels. Flat turns increase the time required to fly the survey, and are problematic in restricted flight zones where there may not be enough room to safely maneuver. They also increase the stress level on the crew, which leads to fatigue and potential operational errors. The ideal scenario would be to fly standard turns with 30 to 40 deg bank angles and have the option of banking over 50 deg when necessary without worrying about the GNSS receiver.

1.4. A New Novel Approach to Differential GNSS for Airborne Mapping and Surveying

Applanix Corporation, in conjunction with the GNSS Center of Excellence at Trimble, has developed a new approach to KAR differential GNSS for aerial mapping and surveying that eliminates the need to start close to a reference station to initialize ambiguities, eliminates the need to fly flat turns, and increases the accuracy and reliability of positioning in an airborne environment. This novel patent pending approach, which has been implemented in POSPac Air Version 5, combines the technology of both VRS and IARTK and extends it to airborne mapping and surveying.

The Trimble VRS™ technology has been adapted to work in post-processing and to use longer distances between reference stations in order to calibrate the atmospheric errors within a network of GNSS receivers. The Post-Processed VRS (PPVRS) corrections are then applied to the observables from the rover receiver and processed in an Inertially-Aided Kinematic Ambiguity Resolution (IAKAR) mechanization similar to the IARTK algorithm shown in Figure 1.

The PPVRS corrections significantly reduce the atmospheric delays in the rover GNSS observables, so that reliable kinematic ambiguity resolution can occur anywhere within the network and decimeter-level position accuracy is maintained. The IAKAR approach ensures that the correct integer ambiguities can be re-established within a few seconds after a large bank-angle turn that causes some or all of the GNSS satellites to be masked.

The ability to accurately correct the atmospheric errors within the network will of course depend upon the amount of atmospheric activity during the survey, and the density of the reference stations. Tests conducted by Applanix have shown that it is possible to achieve better than decimeter RMS accuracies with a sparse network of only 4 reference stations separated by over 100 km, but the results are highly dependent upon the particular data set. However for existing dense networks such as the CORS network in Ohio State, the GSI network in Japan, or in the SAPOS™ network in Germany, where the there are literally 10's to 100's of stations separated by distances of typically 50 – 70 km, the robustness improves tremendously and the area that can be flown is virtually limitless. The PPVRS can process up to 50 reference stations at a time, with a separation to the farthest reference station limited to 400 km. Furthermore, the processing time when adding more reference stations to the PPVRS is not adversely affected, as it is when using the standard KAR multibase approach in POSGNSS. POSGNSS can only process a maximum of only 8 reference stations in mulitbase mode, with typical processing times of about 12 minutes. In contrast, even with double the number of reference stations (16), POSPac Air V5 takes only 5 minutes to process (times to not include QC on base stations).

The PPVRS includes a rigorous adjustment of all the reference station antenna positions within the selected network over a 24-hour period. This quality control function ensures that all the reference station data and coordinates are correct and consistent before the rover data is processed. Such a concept is done routinely in land survey as part of best practices, but has been a weak point in the aerial mapping and survey industry. Too often data from a single reference station or a CORS network are used without proper quality control. Quality failures can include incorrect published antenna coordinates, incorrect datum or poor observables, any of which can result in accuracy and reliability failures in the final product.

2. TEST RESULTS

This section presents some typical results and capabilities of the new POSPac Air V5.

2.1. Sparse Reference Station Network Processing

Figure 2 shows the trajectory of a typical airborne survey of a section of a corridor project using a POS AV 410 GNSS-Aided Inertial system for Direct Georeferencing. This particular project was chosen for the following three reasons: i) it used a less accurate inertial system, ii) it contains turns with bank angles of up to 40 deg, and iii) it was flown in California where many CORS GPS reference stations are located. The lower accuracy inertial data is useful for studying the dependency on the quality of the inertial data to bridge GPS outages using IAKAR. The non-flat turns and the large availability of CORS stations allows for experimentation on PPVRS-IAKAR configuration. As seen in Figure 3, the pilot attempted to keep the bank angle below 25 deg, however during this particular mission, flight restrictions and winds forced the pilot to execute some of the turns with 40 deg bank angles. The typical banked turn duration was 30 to 50 seconds, and the time to complete the turns was typically 1.5 to 2.5 minutes.

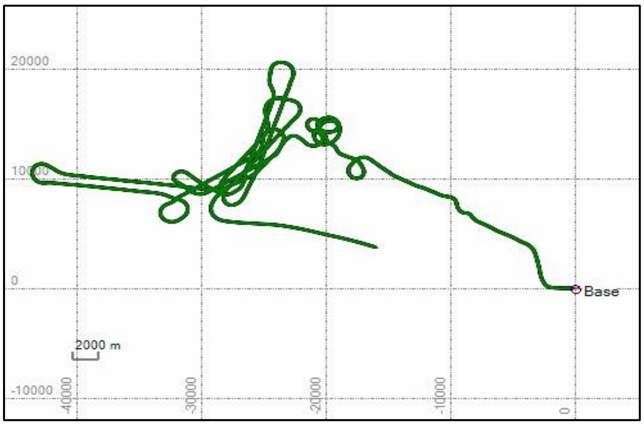

Figure 2: Trajectory

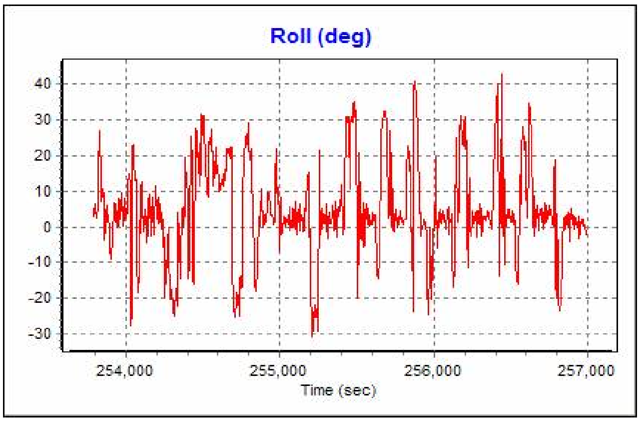

Figure 3: Aircraft Roll

The trajectory was generated using POSPac Air V4.4, which uses a loosely-coupled approach described previously. Here the KAR solution using a dedicated reference station was first generated by POSGNSS, and then run through the Aided-Inertial processing. Since the reference station was located at the airport, the correct integer ambiguities were easily computed and carried through the rest of the mission. Figure 4 shows that the POSGNSS solution remains in integer fixed mode for the entire flight, and the expected accuracy is less than 10 cm RMS, as indicated by the forward reverse separation plots (Figure 5). The maximum base-line separation using the dedicated base was 45 km (see Figure 2). Although there were relatively large bank angles during the flight, the number of satellites in view remained greater than 5 ensuring the KAR results were accurate and reliable.

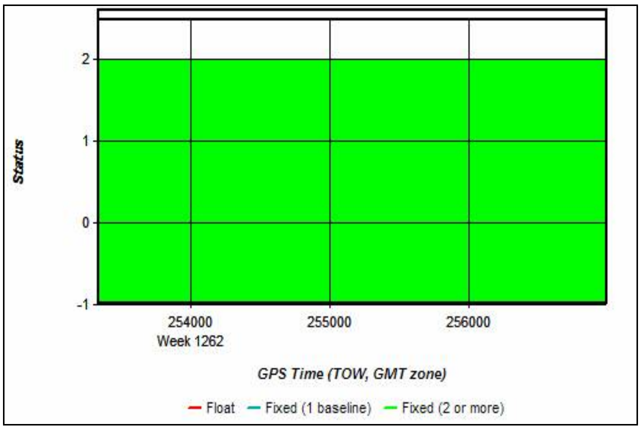

Figure 4: Solution Status, PP V4.4, Dedicated Base

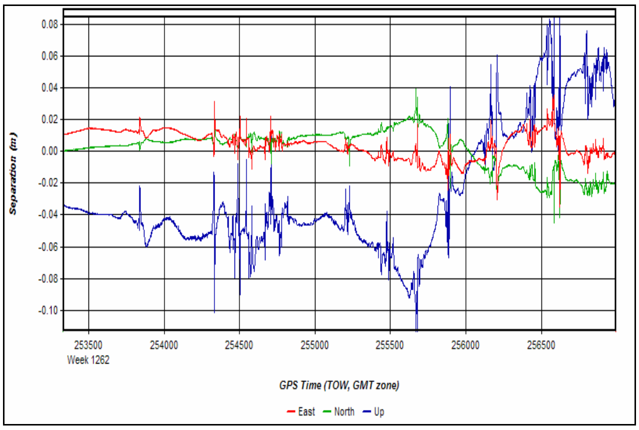

Figure 5: Forward-Reverse Separation, Dedicated Base

The same trajectory was then processed using POSPac Air V5, which incorporates a version of PPVRS called Applanix SmartBASE (or ASB™), and tightly coupled IAKAR Aided-INS processing. In this case, four reference stations were used in the ASB solution with a separation between the reference stations from 80 km to over 200 km, and with the distance to the nearest reference station ranging from 77 km to over 95 km during the flight (Figures 6 and 7). The dedicated reference station in the project area was *not* used in this experiment.

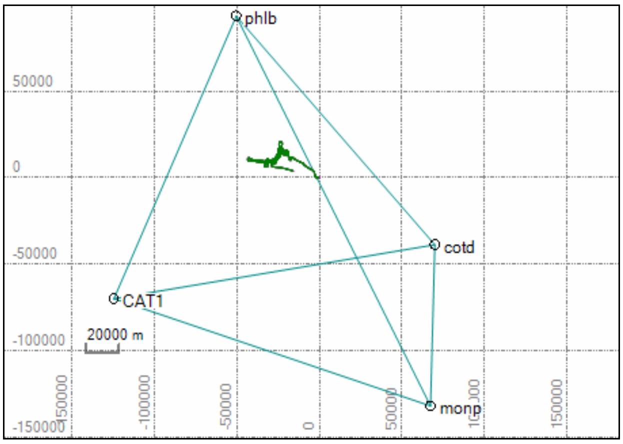

Figure 6: Reference Station Configuration

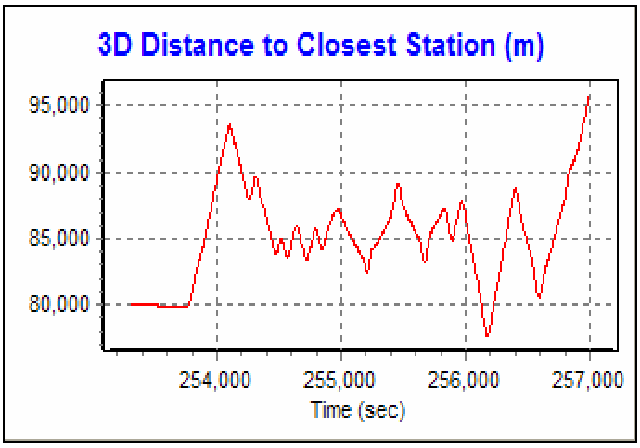

Figure 7: Distance to closest station, PP V5

Figure 8 shows that the IAKAR processing in POSPac 5 remained in integer fixed mode for the entire solution. The difference between the POSPac Air V5 solution and the POSPac Air V4.4 solution using the dedicated base is shown in Figure 9, with associated statistics in Table 1.

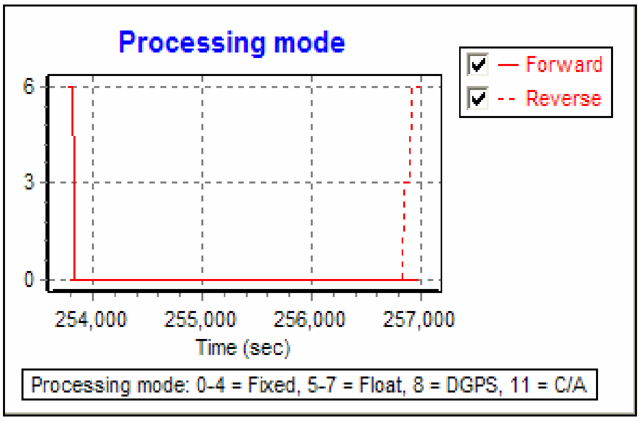

Figure 8: Solution Status, PP V5

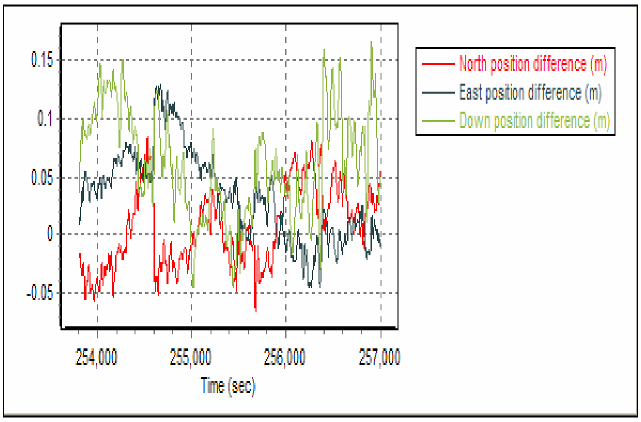

Figure 9: Differences with Reference, PP V5

Difference	RMS	Sigma	68%	95%	100%
North (m)	0.03	0.02	0.04	0.06	0.08
East (m)	0.05	0.04	0.05	0.11	0.13
Down (m)	0.08	0.04	0.08	0.13	0.17

Table 1: Statistics of Differences, PP V5 vs Reference, Sparse Network

The results shows that POSPac Air V5 using a sparse network of four reference stations can produce virtually the same RMS accuracy as a standard KAR solution using a dedicated reference station. It is important to note however that these are the results of only one test, and hence should not be interpreted as being a definitive specification on what can be reliably and consistently achieved using sparse networks. The performance with a sparse network is highly dependent upon the ionospheric activity at the time of survey, the quality of the reference station data, and keeping the turns flat in order to maintain carrier phase lock on at least 5 or more satellites. A definitive performance specification for sparse networks is being developed as part of a separate study.

For a comparison, the same four reference stations were processed in POSGNSS using the KAR multibase processing option. Figure 10 shows that, as expected, the integer ambiguities could not be reliably estimated since the trajectory exceeded 30 km from the nearest base, and the processing stayed in float mode for the entire trajectory. The associated differences with the reference and statistics are presented in Figure 11.

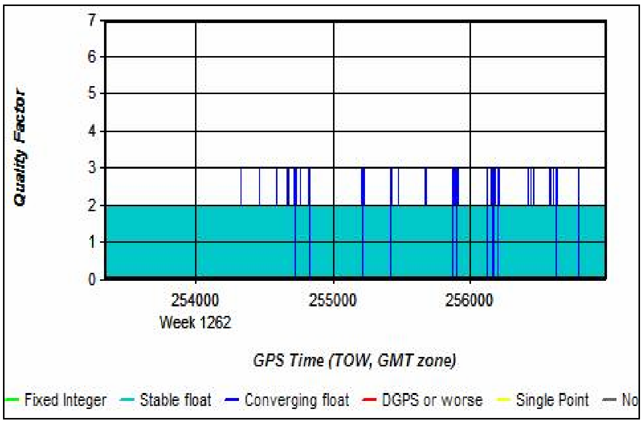

Figure 10: Solution Status, PP V4.4

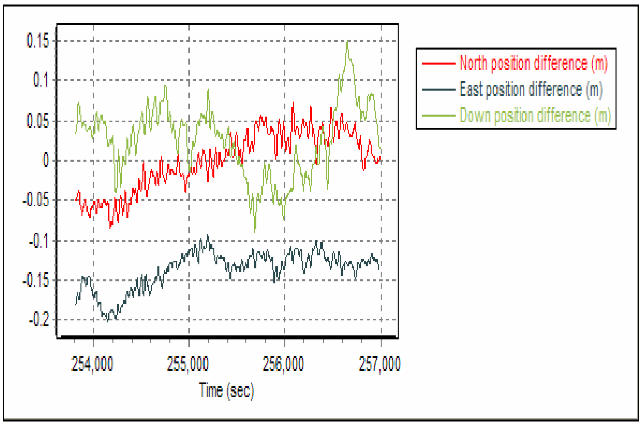

Figure 11: Differences with Reference, PP V4.4

2.2. Simulated Outages During Turns

This section investigates the ability of the new POSPac Air V5 software to correctly and quickly re-initialize the integer ambiguities to satellites that are blocked during banked turns. Here we look at two extreme cases: a partial outage for up to 60 seconds, and complete outages for 20 to 30 seconds. The partial outage assumes a worst case where a 40 deg bank might effectively reduce the total number of satellites being tracked to 3 or 4 for up to 60 seconds. This can occur if the aircraft needs to climb or descend in a spiral, or there are a series of right and left banks to bring the aircraft onto the next line. The complete outage assumes a worst case where the aircraft needs to bank by 50 to 60 degrees, and the number of satellites being tracked drops to zero for a maximum of 30 seconds.

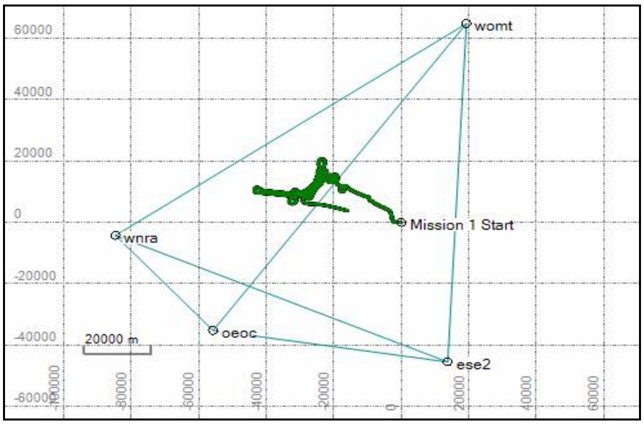

Figure 12: Reference Station Configuration

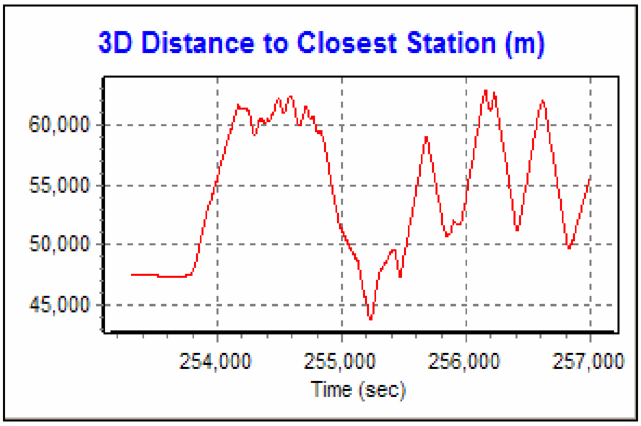

Figure 13: Distance to Nearest Station

For these tests, four reference stations were chosen such that each turn of the trajectory always remained within 63 km from the nearest reference station (Figure 9). This restriction was added to ensure that the residual ionosphere error in the PPVRS solution during the times of the outages was minimized to ensure faster and more robust ambiguity re-initialization after GPS outages. Note that this is still twice the 30-km restriction required for standard KAR processing. As in the previous section, a minimum of four reference stations is required to ensure redundancy for maximum reliability. Figures 14 and 15 show the number of satellites tracked during the partial and full outages tests.

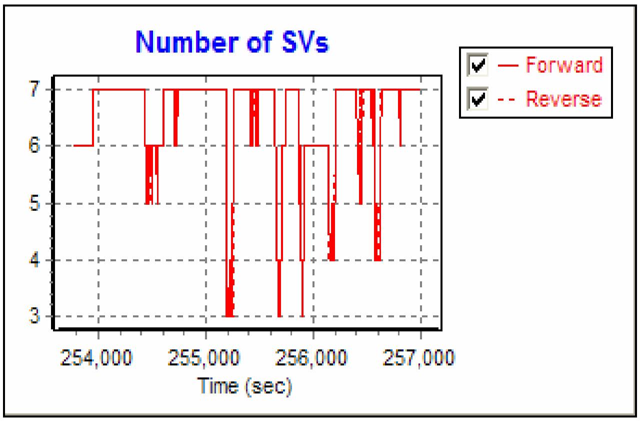

Figure 14: Number SV's, Partial Outages

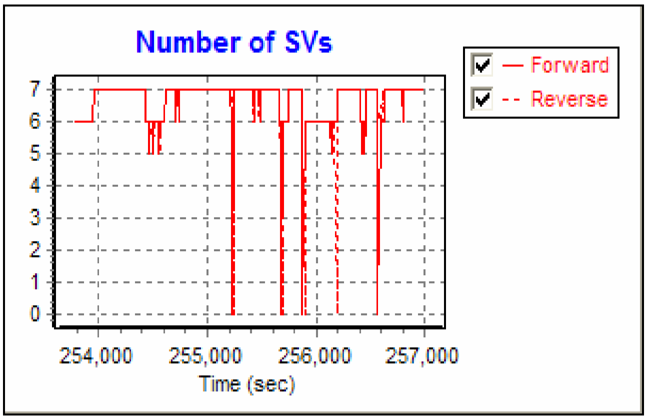

Figure 15: Number of SV's, Full Outages

Figure 16 shows the POSPac Air V5 solution status for the partial outage test, while the differences against the POSPac Air V4.4 reference using a dedicated base station are plotted in Figure 17.

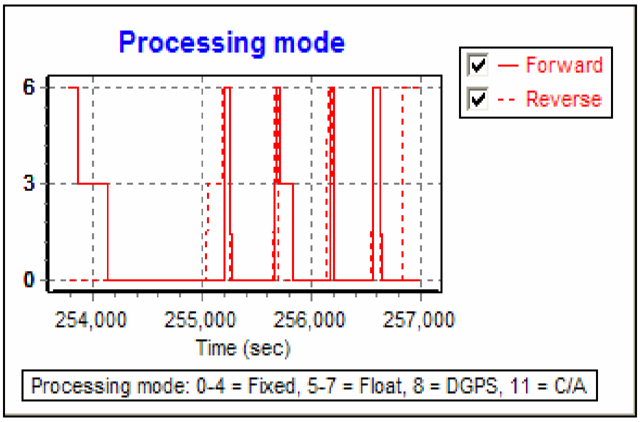

Figure 16: Processing Mode, PP V5, Partial Outages

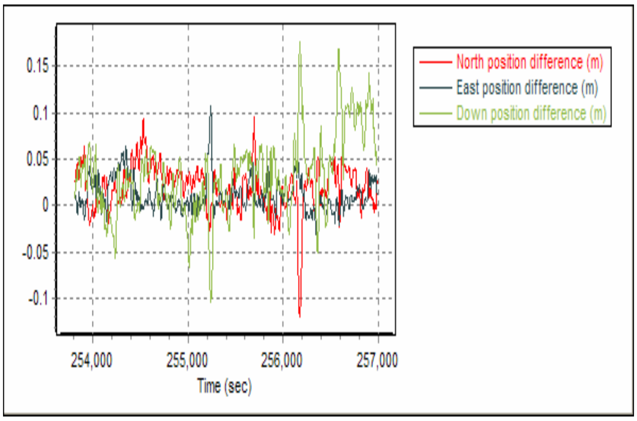

Figure 17: Differences with Reference, Partial Outages

The results show that POSPac Air V5 switches to floated ambiguity mode during the partial 60 second outages when the number of satellites drops below 5, but very quickly returns to fixed integer mode after each outage. The differences show that even with the partial 60 second outages during the turns, POSPac Air V5 is able to produce the same decimeter level accuracy during each flight line as a standard KAR solution using a dedicated base *without* partial outages.

Figure 18 shows the POSPac Air V5 solution status for the full outage test. Even with full GPS outages of 20 to 30 seconds, POSPac Air V5 is able to quickly return to integer mode within seconds after each outage. The difference of this solution with the POSPac Air V4.4 reference using the dedicated base is show in Figure 19. Again, even with full outages, POSPac Air V5 is able to produce the same level of accuracy as the reference. It is interesting to note that the performance during the turns is actually slightly better than the partial outages test since the duration of the full outages was only half of the partial outages (30 seconds vs 60 seconds).

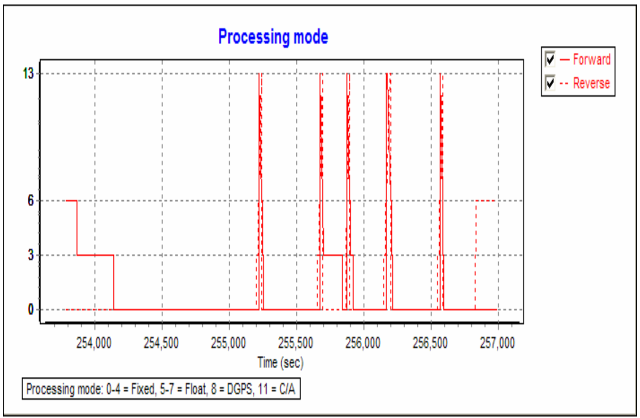

Figure 18: Processing Mode PP V5, Full Outages

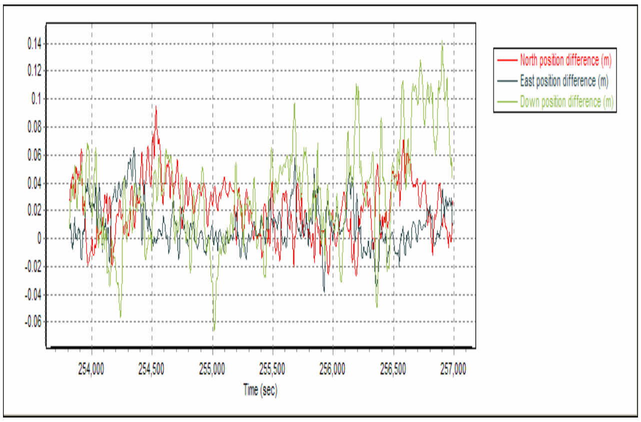

Figure 19: Diff with Reference, PP V5, Full Outages

For comparison, the POSPac Air V4.4 POSGNSS multibase KAR solution was also run with the same partial and full outages. As expected, the solution status stayed in float mode for the entire trajectory and the accuracy was quite poor. The differences with the reference trajectory are shown in Figures 20 and 21.

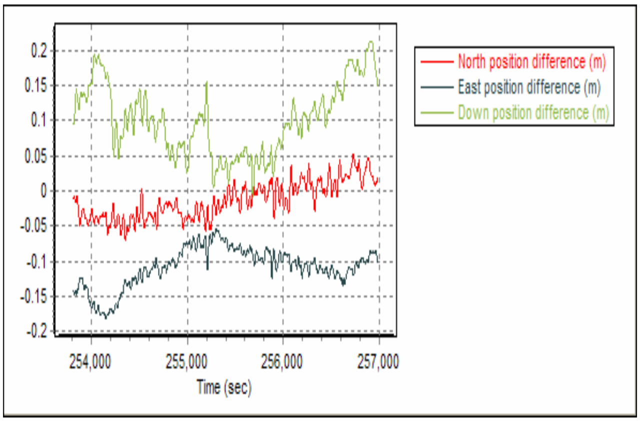

Figure 20: Diff with Reference PP V4.4, Partial Outages

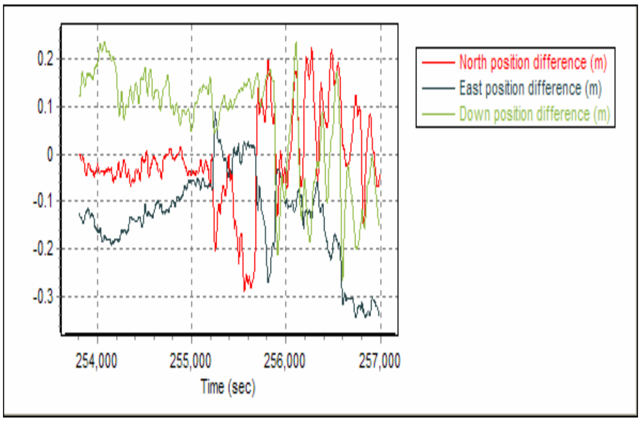

Figure 21: Diff with Reference, PP V4.4, Full Outages

In reality it will be quite rare that the number of satellites tracked will actually drop to zero or to below 4 during a high banked turn, especially with the introduction of GLONASS observables. However these tests show that the use of PPVRS with IAKAR is extremely robust and provides the complete assurance that sharp turns can be flown without concern.

2.3. High-Bank Angle Test Results

In this section we present the results for two flights that were flown with high bank angles. The first was an experimental flight where the same survey lines were flown 3 times using bank angles of 15 to 25 deg, 30 to 40 deg, and 50 to 60 deg respectively. The second flight was an actual survey flight flown where the pilot was required to fly at banks angles up to 60 deg due to flight restrictions. For each test only 4 reference stations were used.
Figure 22 shows the trajectory for the first flight, while Figure 23 shows the associated roll angles. Figures 24 and 25 show the number of satellites in view and the distance to the closest reference station. For this particular flight the reference station network happened to be quite sparse. As expected when the bank angle increases, the number of satellites in view dropped, but in this case never below 5.

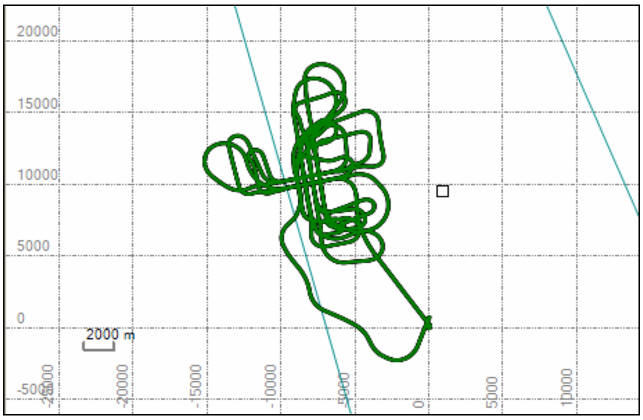

Figure 22: Trajectory, Sharp Turns Flt1

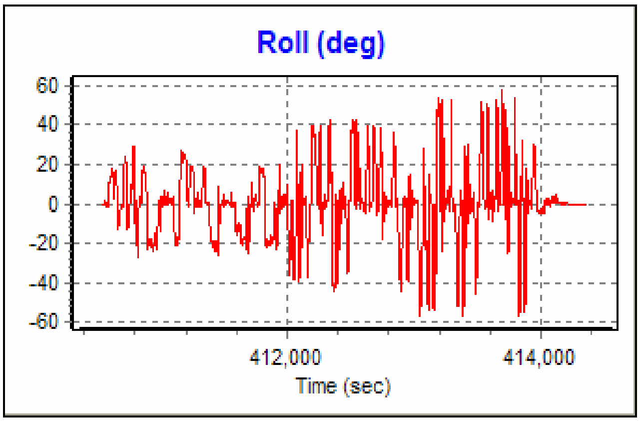

Figure 23: Aircraft Roll, Sharp Turns Flt1

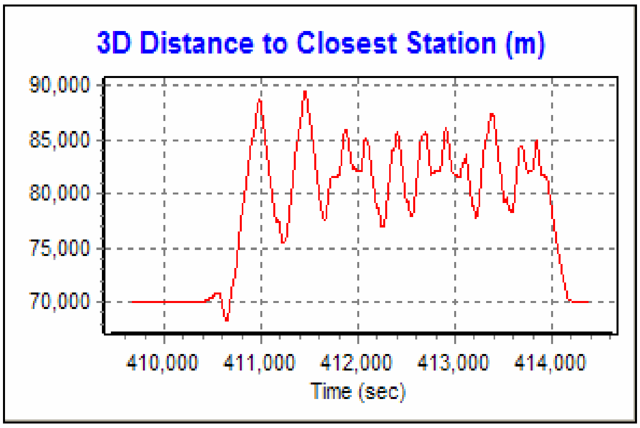

Figure 24: Distance to Nearest Station

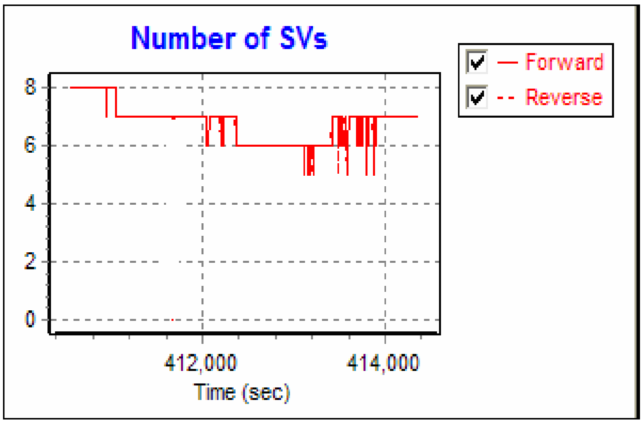

Figure 25: Number of Satellites Tracked

Figure 26 and 27 show the solution status of the POSPac V5 and POSPac V4.4 multibase KAR processing for the flight. Again, even during the sharp turns, the POSPac Air V5 IAKAR remains in full integer fixed mode for the entire the flight. In contrast the POSGNSS multibase KAR processing is completely unable to fix integer ambiguities due to the long baselines to the reference stations.

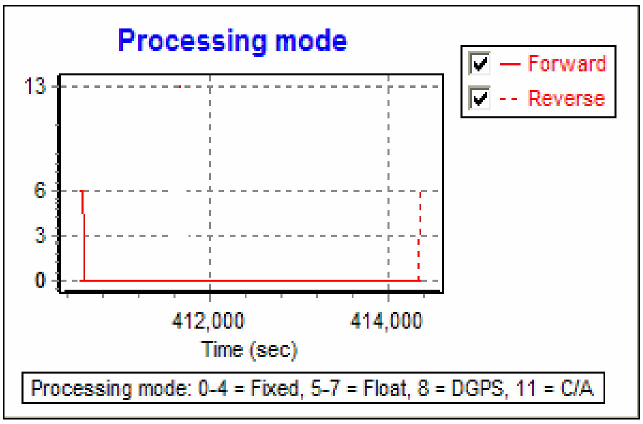

Figure 26: Processing Mode PP V5, Sharp Turns Flt1

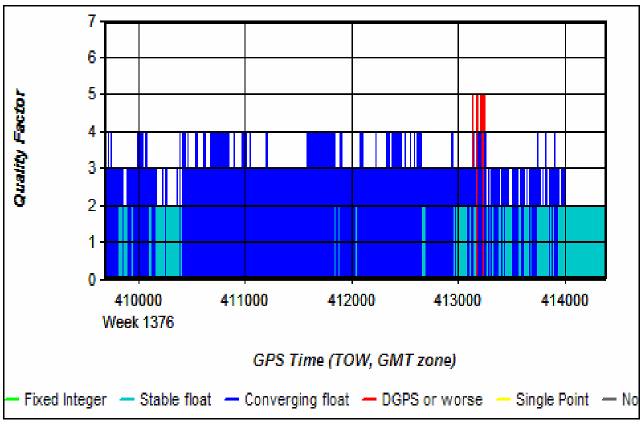

Figure 27: Processing Mode PP V4.4, Sharp Turns Flt1

Figures 28 and 29 show the trajectory and bank angles for the second test, while Figures 30 and 31 show the distance to the nearest reference station and the number of satellites being tracked

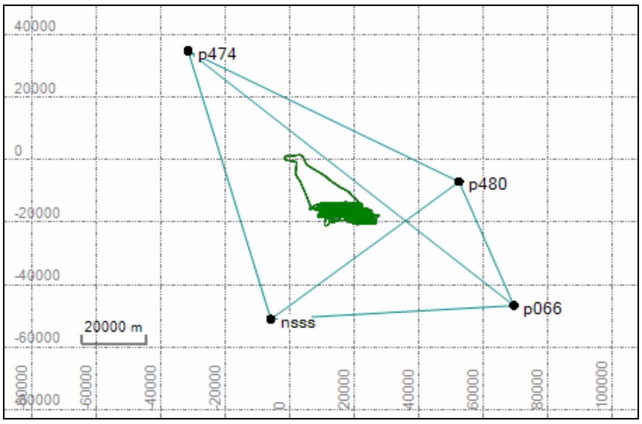

Figure 28: Trajectory, Sharp Turns Flt2

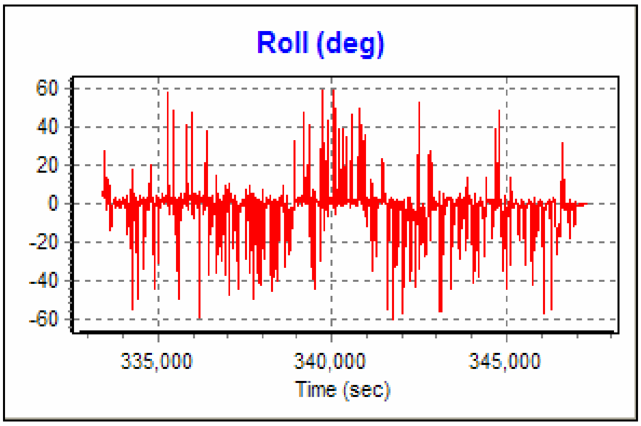

Figure 29: Aircraft Roll, Sharp Turns Flt2

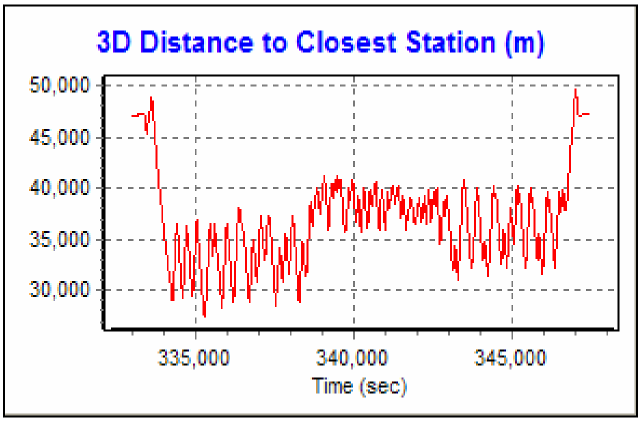

Figure 30: Distance to Nearest Station

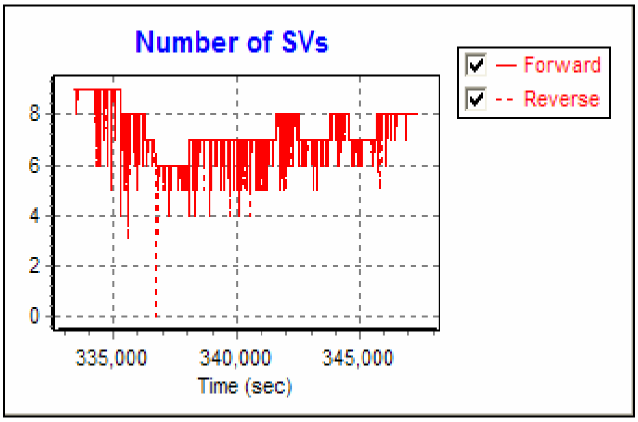

Figure 31: Number of Satellites Tracked

In this case the large bank angles caused the number of satellites being tracked to drop below 5 several times. Figures 32 and 33 show the solution status for POSPac Air V5 and POSPac Air V4.4 respectively. Consistent with the simulated outages test, POSPac V5 is able to quickly fix integer ambiguities before after the high banked turns while, POSGNSS using standard multibase KAR processing remains in float mode for the entire mission.

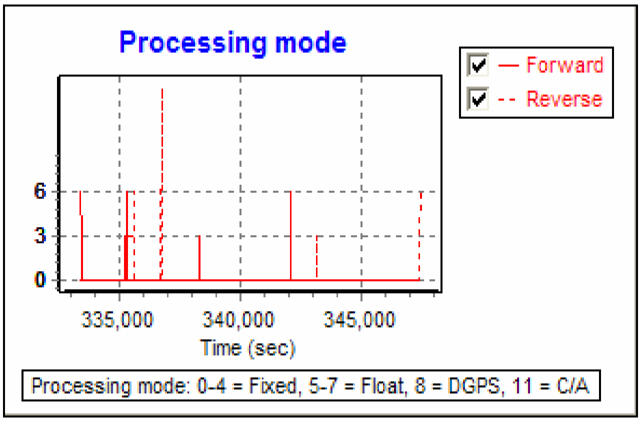

Figure 32: Processing Mode PP V5, Sharp Turns Flt2

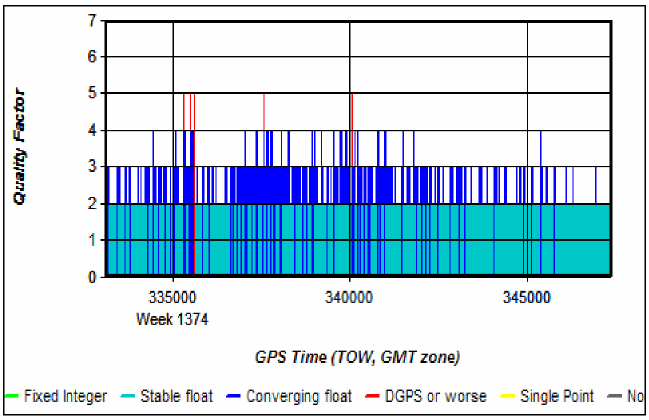

Figure 33: Processing Mode PP V4.4, Sharp Turns Flt2

3. CONCLUSIONS AND OUTLOOK

The new POSPac Air V5 software using combined PPVRS and IAKAR technology represents a paradigm shift in operational efficiency for aerial mapping and surveying by offering three new benefits over standard KAR processing:

- POSPac Air V5 can produce the same position accuracy as standard KAR with a dedicated reference station, but without the restriction of having to always fly less than 75 km from a reference station
- POSPac Air V5 can solve for the correct integer ambiguities without the need to fly within 30 km or less of a reference station
- POSPac Air V5 can eliminate the need to fly flat turns, which reduces the time to fly a mission, enables more flexible mission execution in restricted airspace, and reduces crew fatigue leading to fewer mistakes and increased safety.

Each of these claims has been validated in this paper through sample data sets. First, a typical mission with mostly flat turns was processed using four reference stations, with the nearest reference station ranging from 77 km to over 95 km during the mission. The results showed that POSPac Air V5 was able to correctly fix integer ambiguities, and produce position accuracy at the same level as using a standard short-baseline KAR solution with a single reference station. Secondly, a series of partial and full GPS outages was simulated during the turns. The partial outages reduced the number of satellites tracked by the aircraft-mounted GPS receiver to 3 or 4 for 60 seconds, and the full outages lasted for 20 to 30 seconds. In this case four reference stations were again used, but configured in such a way that the distance to the nearest reference station during each turn was no more than 63 km. In both cases POSPac Air V5 was able to recover fixed integers quickly before and after the outages and produce position accuracy at the same level as a short-baseline KAR solution using a single reference receiver without any outages. These tests were then followed by examples of two real flights that were flown with high-bank angles. The processing results for these flights were shown to be consistent with the results from the simulated outages.

The results presented in this paper are by no means an exhaustive study, and are not meant to be interpreted as definitive specifications for reliable performance. However they do provide an excellent illustration of what is possible using POSPac Air V5 with PPVRS and IAKAR technology. Future work will focus on clearly defining the requirements for reference station location, density, and data quality in order to reliably and robustly meet the performance claims, especially during periods of increased ionosphere activity.

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

4. ACKNOWLEDGEMENTS

The authors would like to thank the entire POSPac Air V5 team for the months of blood, sweat and tears they have put into this development. Edith Roy, Xeu-Fen Zhang, and Ian Murray are thanked for their help and guidance on the data processing. Thanks are also given to J.P. Barrier from Track'air for his useful input on optimal aircraft bank angles for survey missions.

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