Comparison of Attitude Performance for Multi-Antenna Receivers

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This article covers ambiguity validation aspects for two types of single-board attitude determination GNSS receivers. With the single-frequency attitude receiver, the PolaRx2@, the attitude of the antenna array is computed based on L1 carrier phase measurements from three antennas. With the dual-frequency attitude receiver, the PolaRx2HD, the heading and pitch are computed using two dual-frequency antennas. The ambiguity fixing performance is discussed in detail for the receivers of both types. It is shown that the PolaRx2HD has excellent ambiguity fixing characteristics even when no assumption about the antenna array is made. With a single-frequency attitude receiver, similar performance can be achieved if the antenna array is rigid, and if this information is used for the validation process of the integer ambiguity candidates. Single-frequency attitude determination with the use of the geometric constraint was successfully used in a city-driving test and on a fixed-wing aircraft.

Introduction

Attitude determination using GPS is based on carrier-phase differential processing of GPS measurements from multiple GPS antennas firmly affixed to the body of a vehicle. Existing GPS-based attitude determination systems rely on duplication of existing hardware and typically include several high-end OEM receiver boards and additional processor boards. Hence, these devices are bulky and expensive, which is quite restrictive, e.g. for small-size UAVs.

An alternative approach is to design single-board multi-antenna receivers, such as the PolaRx2@ and the PolaRx2HD. The characteristics of these two attitude receivers, discussed in this paper, can be summarised as follows.

- The PolaRx2HD is a dual-antenna, dual-frequency receiver, which is able of computing only heading and pitch angles. This receiver benefits from fully dual-frequency ambiguity fixing and consequently shows high efficiency of ambiguity fixing even if no assumptions about the antenna geometry are used.
- The triple-antenna, single frequency attitude receiver (PolaRx2@) can compute a complete set of attitude angles (heading, pitch, roll) and it shows equally efficient ambiguity resolution when the geometry of the antenna array is rigid and known.

The purpose of this article is to compare the availability, reliability and accuracy of the attitude determined using both receivers, and to demonstrate the importance of the a-priori knowledge of the antenna array in different field tests. The availability of an attitude solution depends on the combination of the re-acquisition time of phase measurements and on the validation time of integer ambiguity candidates. From a performance perspective the single-frequency attitude determination can be as good as dual-frequency attitude determination if the known antenna geometry is exploited.

Hardware Design

The architecture of our multi-antenna receivers is similar to the architecture of the single-antenna Septentrio's receiver, the PolaRx2, which is a fully software-configurable receiver. The hardware layout of attitude receivers is different from the layout of a single-antenna PolaRx2 only in the RF front-end part. For the two types of attitude receivers, different combinations of front-end modules are mounted onto the RF part of the board. The base-band DSP and the CPU are the same as in PolaRx2. The CPU determines the real-time position and attitude solution, and performs controlling functions and other computations. Figure 1 and Figure 2 show the architecture of the PolaRx2@ and the PolaRx2HD, respectively.

With PolaRx2@, the position is computed using the single- or dual-frequency measurements of the main antenna. The PolaRx2@ can be connected to up to three antennas and the single-frequency auxiliary antennas are used for attitude determination, which is based on L1 code/phase measurements. The PolaRx2HD has a similar design, but is able of providing a dual-frequency heading/pitch solution.

As mentioned before, the channel matrix in the Greco (baseband DSP) is fully configurable through software, hence there exist multiple channel configurations with a different total limit of tracked satellites. Some possibilities are presented in Table 1 and show that the receiver configuration can be optimised to suit the needs of various user applications.

The PolaRx2@ shall typically be used in an open sky environment with low multipath, such as agriculture and maritime applications. The PolaRx2HD shall

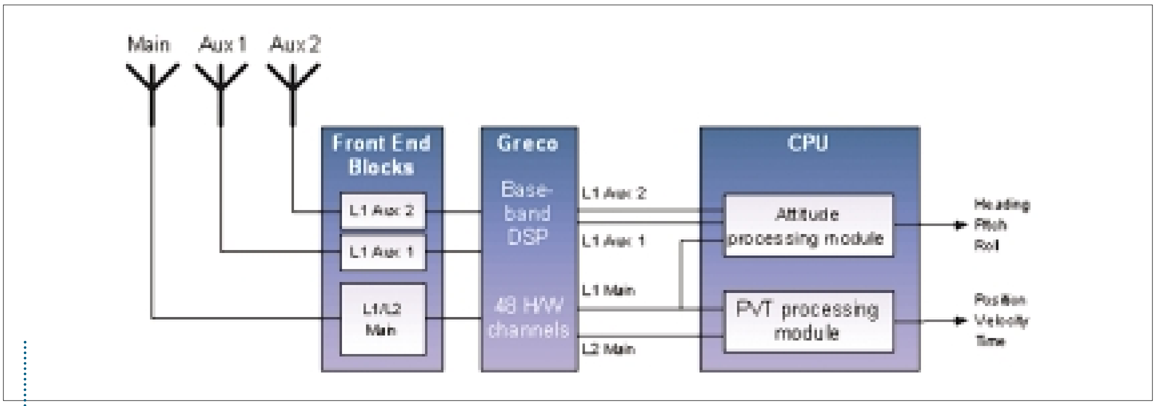

Figure 1 - Single-board triple-antenna PolaRx2@ GPS receiver.

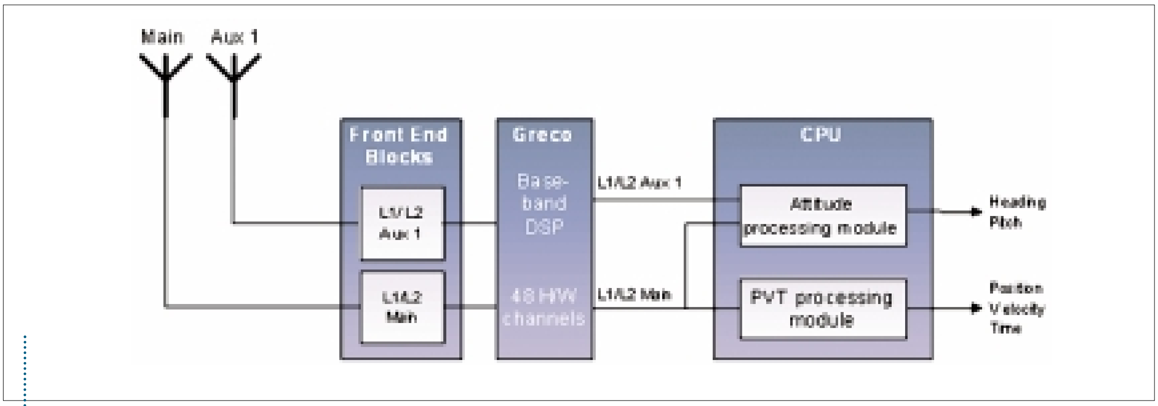

Figure 2 - Single-board dual-antenna PolaRx2HD GPS receiver.

Receiver	Channel setup	Total antennas	Total satellites available for position/ attitude
PolaRx2@	- Position: single-frequency - Attitude: single-frequency	3	16
PolaRx2@	- Position: dual-frequency - Attitude: single-frequency	3	9
PolaRx2HD	- Position: dual-frequency - Attitude: dual-frequency	2	8

Table 1 - Examples of receiver channel configurations.

typically be used as optimal alternative in environments with considerable masking and reflections. Less hardware channels can be foreseen due to masking. The fix performance is improved, compared to single-frequency attitude determination, due to the longer L2 wavelength.

Attitude Determination

Different Kalman filter-based algorithms have been presented to determine attitude from GPS observables (VanGraas, 1991), (Cohen, 1994), (Cohen, 1996), (Cannon, 1992), (Axelrad, 1993), (Lu, 1995). They are all based on the use of precise carrier-phase measurements and some of the solutions are using additional aiding from gyroscopes. The algorithms used in the Septentrio attitude receivers are discussed in (Simsky, 2005) and (VanderKuylen, 2005).

For attitude determination using carrier-phase measurements, it is necessary to resolve the double-differenced carrier-phase ambiguities to their integer nature. For the estimation of these ambiguities, the LAMBDA method, developed at the Delft University of Technology, is used (Teunissen,1994). This method has become the default method over the last decade mostly due to its efficiency. The LAMBDA method also has the advantage that it uses a mathematical description of the boundary of the search space, which avoids incorrect fixes if a correct stochastic model is used.

For reliable attitude determination, integer ambiguity candidates must be validated in order to avoid incorrect fixing, which in its turn may lead to incorrect attitude. The total duration of time needed to fix integer ambiguities is a sum of the time needed to estimate integer ambiguity candidates, and the time needed to validate these candidates. For attitude determination, the validation process takes more time than ambiguity estimation and drives the total time-to-first-fix. This is especially the case when only L1 phase measurements are used due to the short wavelength compared to multipath range errors. Therefore, it is important to speed up the validation process without decreasing the reliability of the fixed integer ambiguities.

Ambiguity Validation for Non-Rigid Antenna Arrays

The Chi-square and ratio statistic tests have been in use for some time but they lack mathematical proof and are typically empirically used. For single-frequency attitude determination, the code multipath and L1 wavelength are in the same order of magnitude. In these situations, it becomes difficult to distinguish between integer ambiguity candidates due to the distortion of the float estimate. Consequently, the ratio test will fail, which will result in long fix times.

Dual-frequency ambiguity fixing based on the use of wide-lane phase observable is a well-known way to significantly improve the ambiguity fixing performance due to the increase of the carrier cycle. Hence, when L1 and L2 phases are both used, the reliability and the time to fix are improved.

Ambiguity Validation for Rigid Antenna Arrays

To reduce the time-to-first-fix without compromising the reliability of the fixed integer ambiguities, a rigidity constraint can be used at the stage of the validation of the ambiguity candidates. This constraint can be exploited in two ways.
- It can be used at the stage of the estimation of integer ambiguities. With this method, the constraints on the antenna geometry are transformed into the ambiguity search space (Mönikes, 2005).
- It can be used during the validation process of the first N integer ambiguity candidate sets in the position domain. This method has been suggested in (Park, 2003).

This latter approach is used in the current PolaRx2 firmware for attitude determination. In order to take advantage of the antenna geometry constraint, the user must provide the antenna positions in the vehicle reference frame with sub-centimetre level accuracy. The rigidity constraint is used for integer ambiguity validation if the relative antenna position of at least one auxiliary antenna is provided. Although the main purpose of this method is to improve the single-frequency ambiguity resolution, it works the same way for the dual-frequency case.

Currently, the PolaRx2@ and the PolaRx2HD both use the user-provided antenna geometry exclusively for the validation of integer ambiguities. After the ambiguities are fixed, the attitude determination is based on phase measurements only.

Performance Analysis

In this section, the main quality indicators for attitude determination are discussed for the PolaRx2@ (single-frequency attitude determination) and for the PolaRx2HD (dual-frequency heading/pitch determination):
- the time to a first attitude solution with fixed ambiguities
- the attitude accuracy
- the robustness of attitude determination in masked and high-multipath environment.

The time-to-first-fixed-attitude and the attitude accuracy are determined from several static test campaigns and are discussed for both receivers. In the discussion of the city-driving test, the performance of single- and dual-frequency attitude determination is compared. The results of the flight test will show the improvements that can be achieved by using the rigidity constraint for single-frequency attitude determination.

	TTFFA					Wrong fixes
	1-epoch	< 30 sec	<150 sec	< 420 sec	> 420 sec	
Single-freq (rigid)	97.5%	1.0%	0.5%	1.0%		0.3%
Single-freq (non-rigid)	2.5%	5.0%		37.0%	55.5%	3.0%
Dual-freq (non-rigid)	97.1%	2.4%	0.5%	0%		0%

Table 2 - Test results for TTFFA for single- and dual- frequency attitude determination.

Time-to-First Fixed Attitude

The Time-To-First-Fixed-Attitude (TTFFA) is defined as the period of time from the restart of the attitude algorithm until the epoch when phase ambiguities for all the auxiliary antennas are fixed. Figure 3 shows the antenna array on the rooftop of the Septentrio building. This environment suffers from multipath due to surrounding buildings.

For this test, two dual-frequency PolaNt and one single-frequency PolaNt_SF antennas are used. The PolaRx2@ and PolaRx2HD are connected to the same antennas. The tests are performed over an 8-hour period to expose the receivers to a varying constellation and multipath environment. During the test period, the receivers are continuously reset. The presented TTFFA, shown in Table 2, does not include re-acquisition time. When the receiver is unable to fix ambiguities within a predefined time-out period, the attitude filter is reset as well. For the PolaRx2@ with rigidity constraint and for the PolaRx2HD, these time-out periods are set to 2 min. For the PolaRx2@ without rigidity constraint the time-out period is set to 7 min because worse fix performance is expected.

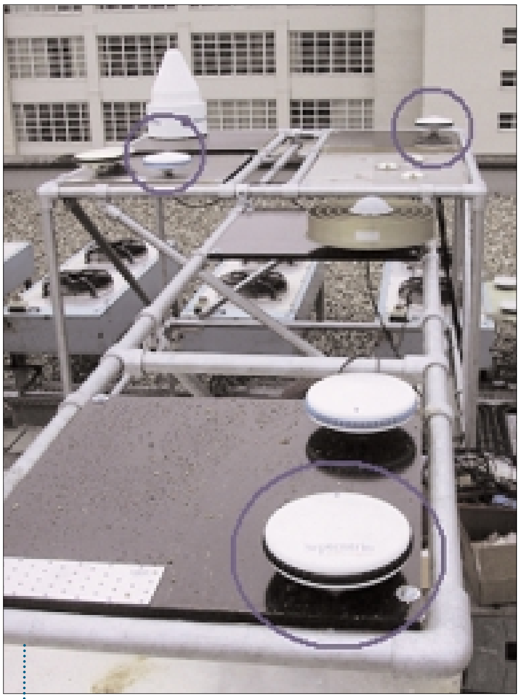

Figure 3 - Antenna setup on roof of the Septentrio building.

Table 2 shows that the fix performance for the single-frequency receiver becomes comparable to the performance of the dual-frequency attitude receiver, if the rigidity constraint is used for single-frequency attitude determination only. The probability of one-epoch fixes for the dual-frequency attitude receiver will also increase when the rigidity constraint is used for the PolaRx2HD as well.

The single-frequency attitude determination with rigidity constraint still shows some incorrectly fixed integer ambiguities (0.3%), which is undesired. The reliability of the fixing process can be further improved by adjusting the validation thresholds. However, with more stringent thresholds the TTFFA will increase and the validation thresholds shall be optimised to suit actual conditions of the user application.

The availability and reliability of a fixed attitude solution is the worst for single-frequency attitude determination without rigidity assumption used. These results demonstrate that the Chi-squared and ratio test are not acceptable for the validation of the integer ambiguities in single-frequency attitude determination algorithms in the presence of significant code multipath.

Attitude Accuracy

The accuracy of the computed attitude is mostly contaminated by phase multipath and can be anticipated based on the known accuracy of a short-baseline RTK positioning. The geometry of the antenna array has a profound impact on the attitude accuracy. The baseline length between the main and auxiliary antennas is inversely proportional to the accuracy of attitude. The accuracy of the roll is also influenced by the separation angle between the baselines. Since the roll is determined by the projection of the main-auxiliary 2 baseline onto a plane perpendicular to the main-auxiliary 1 baseline, this projection is the effective baseline to be taken into account for the accuracy of the roll angle.

Table 3 provides typical accuracy of each Euler angle for various baseline lengths and separation angles. No distinction has to be made between the accuracy of the PolaRx2@ and the PolaRx2HD since they both have the same attitude accuracy. The L2 measurements only improve the integer ambiguity resolution process. It can be noted that heading has a higher accuracy than roll and pitch because it is computed primarily from the horizontal components of the baseline, which typically have higher accuracy than the vertical component.

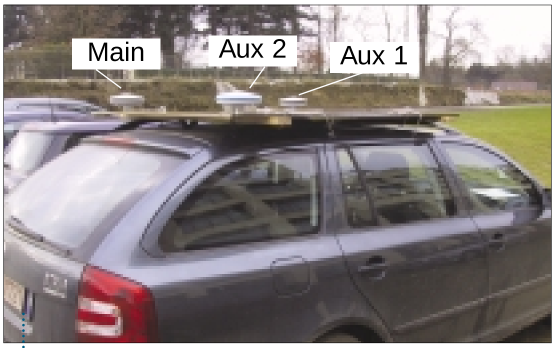

Figure 4 - Antenna installation on car.

Baseline Length	Heading Accuracy	Pitch Accuracy	Roll Accuracy For separations:		
			90°	60°	30°
1m	0.30°	0.60°	0.60°	0.70°	1.20°
3m	0.10°	0.20°	0.20°	0.23°	0.40°
10m	0.03°	0.06°	0.06°	0.07°	0.12°

Table 3 - Typical accuracies of estimated attitude angles.

During about 15% of the test, no attitude or position solution is available due to GPS outages caused by bridges and tunnels. Table 4 shows the fix performance during the remaining 85% of the test. Due to significant masking, only 5 satellites were constantly visible, which explains much lower availability of a fixed attitude solution during this test compared to the static test.

Single- and Dual- Frequency Attitude Determination During a City-driving Test

For the city-driving test, an antenna array was mounted on a car as shown in Figure 4. The environment in which the test is done suffers from frequent masking and high multipath (city of Leuven, Belgium). The goal of this test is to compare the performance of the single- and dual-frequency attitude receivers in this challenging environment. A rigid antenna geometry is assumed only for the PolaRx2@.

Figure 5 shows a part of the trajectory on a topographic map. In agreement with the results of the static tests, the data analysis has shown that the fix performance of single-frequency attitude determination with the geometric constraint is comparable to the performance of dual-frequency attitude determination. However, in the conditions of city driving the availability of the fixed attitude solution is still higher for the dual-frequency attitude due to larger code multipath.

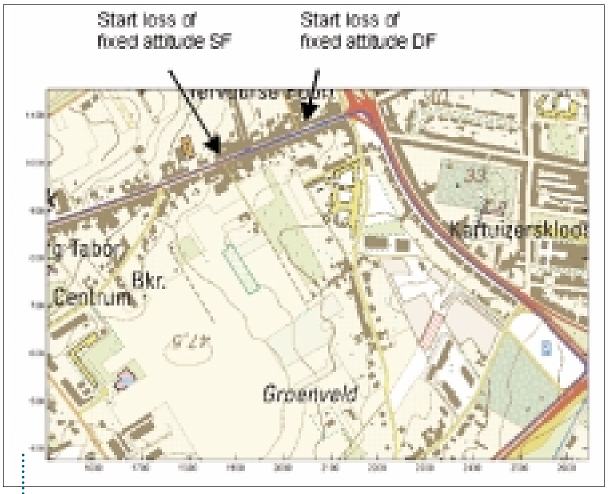

Figure 5 - Car test trajectory (driving direction from left to right).

	Availability of fixed attitude
DF (non-rigid)	79%
SF (rigid)	70%

Table 4 - Fix performance characteristics for single- and dual-frequency attitude determination.

Single-Frequency Attitude Determination during Flight

A flight test using aircraft laboratory of the Delft University of Technology was performed on 22nd April 2005. This laboratory is a twin jet Cessna Citation II aircraft with an array of three GPS antennas installed as shown in Figure 6. The main antenna is installed on the top of aircraft fuselage. The first auxiliary antenna (aux 1) is installed on a boom that is used to measure the angle-of-attack and the sideslip angle and which is located in front of the aircraft. The second auxiliary antenna (aux 2) is installed on the left wingtip. The goal of the test is to investigate the effectiveness of the rigidity constraint for single-frequency attitude determination of an aircraft, where wing flex due to the lift forces makes the main-aux 2 baseline not completely rigid.

Table 5 shows the availability of a fixed attitude solution from take-off to landing using the PolaRx2@ with and without rigidity constraint. The use of the rigidity assumption drastically increases the fix performance, regardless of the incomplete rigidity of the main–aux2 baseline. The post-processing of the flight data has shown that the variation of the baseline length during the flight was smaller than 1 cm.

The correctness of the ambiguity fixes in flight can be verified by computing the variation of baseline lengths during flight. The standard deviations of both baselines are shown in Table 6. It can be seen that the variation for the main-aux1 baseline is exactly as expected (less than 1 cm), while the variation of the main-aux2 baseline is larger than expected. Investigation has shown that at one point in flight, ambiguities were fixed incorrectly as indicated in Figure 8. If this part of the flight is excluded, the variation of the main-aux2 baseline length becomes smaller than 1 cm.

The computed roll and pitch angles (with and without the rigidity assumption) are shown in Figure 9

	RMS baseline lengths [m]	
	Main-Aux1	**Main-Aux2**
Without rigidity assumption	0.007	0.05
With rigidity assumption	0.007	0.04

Table 6 - Reliability of fixed attitude during flight using the PolaRx2@.

Figure 6 - Antenna setup Cessna Citation II (Delft University of Technology).

	Availability of fixed attitude
Without rigidity assumption	65.5%
With rigidity assumption	96.5%

Table 5 - Availability of fixed attitude during flight using the PolaRx2@.

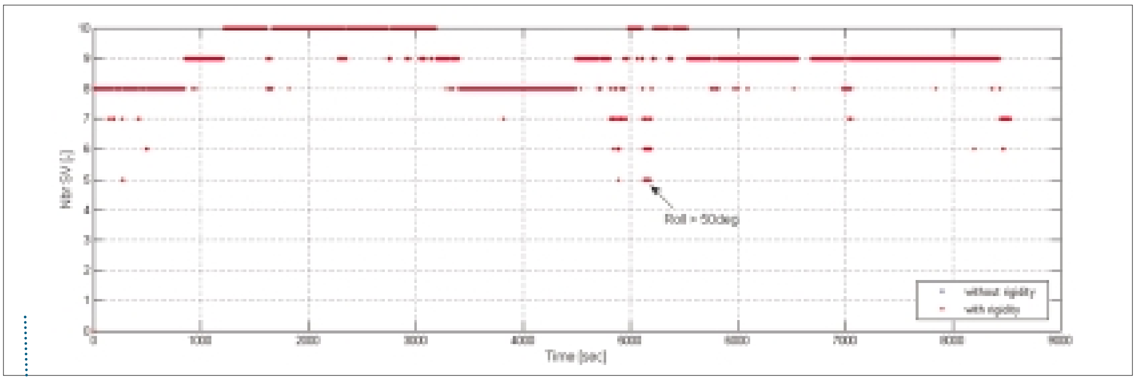

Figure 7 - Satellite availability during flight.

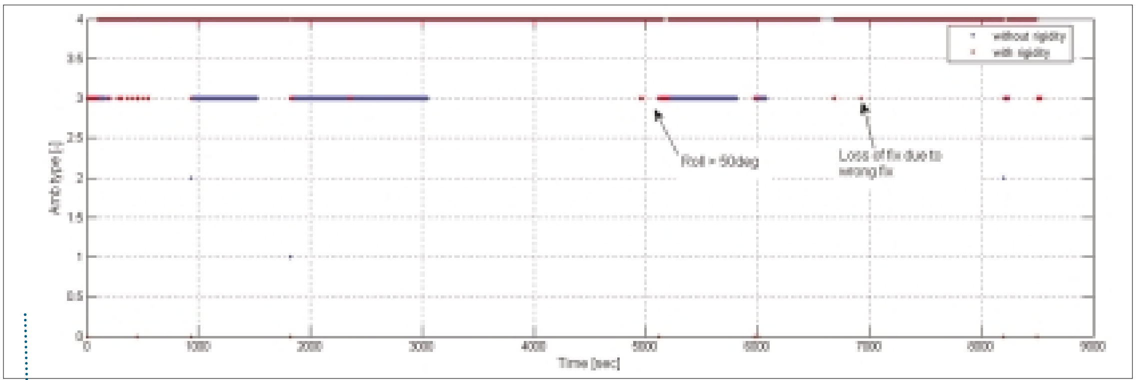

Figure 8 - Fix characteristics during flight (4: fixed, 3: float).

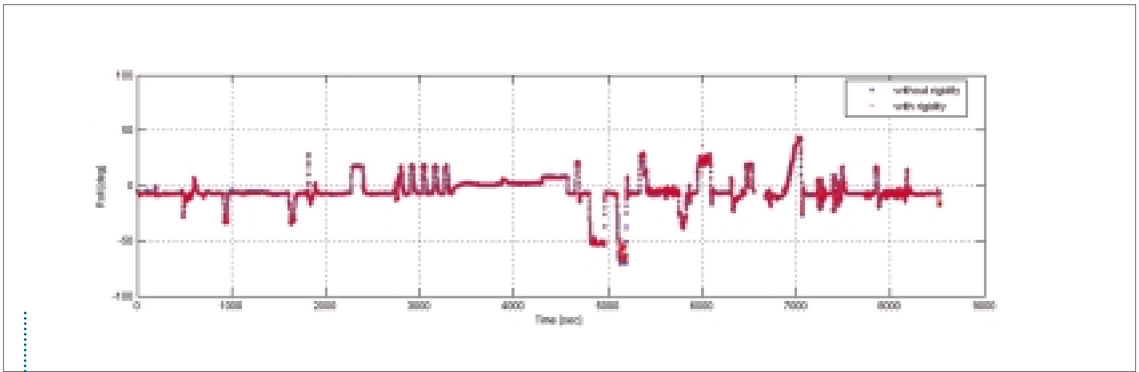

Figure 9 - Roll angle in the flight test computed by PolaRx2@.

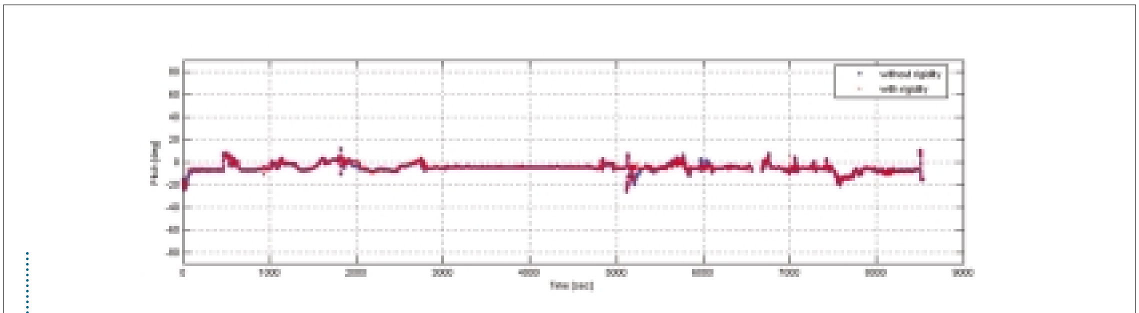

Figure 10 - Computed pitch during flight using the PolaRx2@ for single-frequency attitude determination.

Applications

and Figure 10 for the complete flight test. During the flight, the receiver is able to provide a fixed attitude solution for roll angles less than 50 degrees. At higher roll angles, the number of available measurements decreases, hence the receiver switches from a fixed to a float attitude solution.

These results show that the rigidity constraint can be applied even when one of the auxiliary antennas is installed on the wingtip. However, the wing flex may slightly reduce the roll accuracy.

Conclusions

The performance of a single-frequency, triple antenna attitude receiver, the PolaRx2@, and of a dual-frequency, dual-antenna attitude receiver, the PolaRx2HD is discussed with emphasis on the ambiguity fixing process. The validation of ambiguity candidates is critical for the overall performance of the integer ambiguity resolution process and has major impact on the availability and reliability of a fixed attitude solution.

With the dual-frequency attitude receiver, the validation of integer ambiguities is quick and robust due to the use of dual-frequency measurements. Traditional ambiguity validation methods, such as the Chi-squared and the ratio test, are sufficient to achieve an acceptable performance level. For the single-frequency attitude receiver, an advanced ambiguity validation method has been developed, which takes advantage of the knowledge of the rigid antenna array without any modification in the integer estimation process. The result is a performance level, which is comparable to dual-frequency operation where instantaneous (single-epoch) fixing is typical. The rigid antenna array constraint is demonstrated to be applicable for aircraft applications where the wing flex is not negligible.

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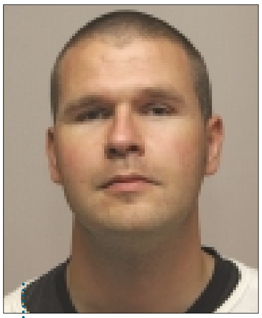

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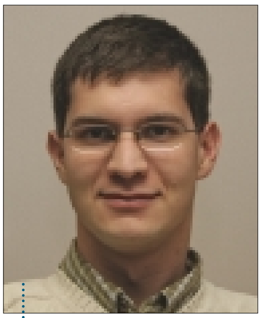

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