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Static and dynamic GNSS attitude function testing of airborne equipment

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Summary

In the future reliable and accurate GNSS based attitude measurement equipment will be developed for application in aviation. Since aviation application requires reliable attitude determination the newly developed attitude measurement equipment must be tested thoroughly. In this paper a two step method for testing the GNSS attitude function is presented. The first step is static testing, using a static angular reference system. The second step is performing ground and dynamic flight tests using a test aircraft. This test scenario has been practiced successfully at the NLR. Example test results are presented.

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1 Introduction

In the past it has been demonstrated by researchers (Ref. 1 through 4), that the attitude of an aircraft can be determined by measuring the relative positions of multiple GPS antennas mounted on an aircraft structure.
Advantages in using GNSS based attitude determination by means of two or more antennas on board an aircraft, are: low cost, low weight, small volume and low power consumption as compared to the classical gyro/inertial navigation attitude function. Therefore it is to be expected that in the future reliable and accurate GNSS based attitude measurement equipment will be developed for application in aviation. Aviation requires reliable attitude determination in terms of accuracy, availability, integrity and continuity. For this reason there is a requirement to be able to test newly developed attitude measurement equipment thoroughly.
In this paper a two step method in testing the GNSS attitude function is presented. The first step is static ground testing, using a ground based test rig, and the second step is performing ground and dynamic flight tests using a test aircraft. This test scenario has been practiced successfully at the NLR.

2 Description of the test method

Testing the GNSS attitude function has to be done by comparing this measurement method with results obtained from an independant measurement method based on different physical principles.
The first part of the tests will be the static tests using a ground based test rig. These tests are based on comparing the GNSS attitude measurements with an electronic inclinometer for the pitch attitude. The heading is to be verified by comparison with directions determined by two accurately surveyed locations.
The second part of the testing is ground and flight testing using an aircraft. As reference for pitch, heading and possibly roll an accurate ring laser gyro IRS (Inertial Reference System) is installed in the aircraft.

2.1 Static angular reference system

A test rig (see figure 1) has been developed for static laboratory testing such that it is possible to place the test rig at any arbitrary location on a stable ground surface, such as:

- in open field at an ideal location (free line-of-sight down to a mask angle of a few degrees),
- at an airfield, e.g. in front of an hangar simulating less satellites in view and a multipath environment, and
- near an helicopter underneath the rotor.

A disadvantage is that some weather conditions (like rain and strong winds) are unacceptable during these measurements.

Figure 1:Static angular reference system.

2.1.1 The static angular reference system

The two antennas together with ground planes are fixed on a straight rigid beam of a length of 2 m (see figure 1). The actual diameter of the groundplanes is 20 cm but can easily be resized up to a diameter of 1 m. The baseline length of the two antennas can be selected (1200 mm, 1500 mm and 1800 mm). The beam can rotate around a two-axis hinge being fixed at the top of a tripod. This tripod is accurately positioned using a plummet above a surveyed point. The orientation of the rigid beam is measured with an absolute accuracy of 0.1^o in pitch and heading. Generally this accuracy is sufficient to verify if the pitch and heading satisfies the accuracy requirements of the attitude sensor. The true heading calibration is based on the known positions of two accurately (±1 cm) surveyed locations: one at the two-axis hinge and the second one at a certain distance (50-200 m) from the test rig. The true heading of the straight rigid beam is calibrated by aligning this rigid beam to the second surveyed location applying telescopes fixed to the rigid beam. Because two of these telescopes have been installed on the rigid beam, two headings opposite to each other ($\pm 180^o$) can accurately be measured. More heading directions can be measured applying a third, fourth, and so on, accurately surveyed locations at a distance of 50-200m from the test rig. The pitch angle is measured with a combination of a water level and an electronic inclinometer

2.1.2 Measurement sites

There are two measurement sites: (1) M1 with free line-of-sight down to a few degrees above the horizon (see figure 2), and (2) M2 in front of a building of metal (wind tunnel building of NLR; see figure 3) simulating a hangar resulting in less satellites in view and a multipath environment. The multipath environment has been checked (see figure 4). To determine the reference heading directions, a number of reference positions have been surveyed in the surrounding of M1 (figure 2) and a number of points in the surrounding of M2 (figure 3). All these locations have accurately (horizontal position ±1 cm) been surveyed by a third party. To validate these positions a theodolite has been placed on M1 and M2 respectively in order to measure the relative angles between the reference points in its surrounding. A comparison has been made between these angles and the angles computed from the accurately measured positions. It could be concluded that the accuracy is well within the requirement of 0.1^o absolute (rms of all the checked angles is 0.05^o and the maximum error found is 0.08^o).

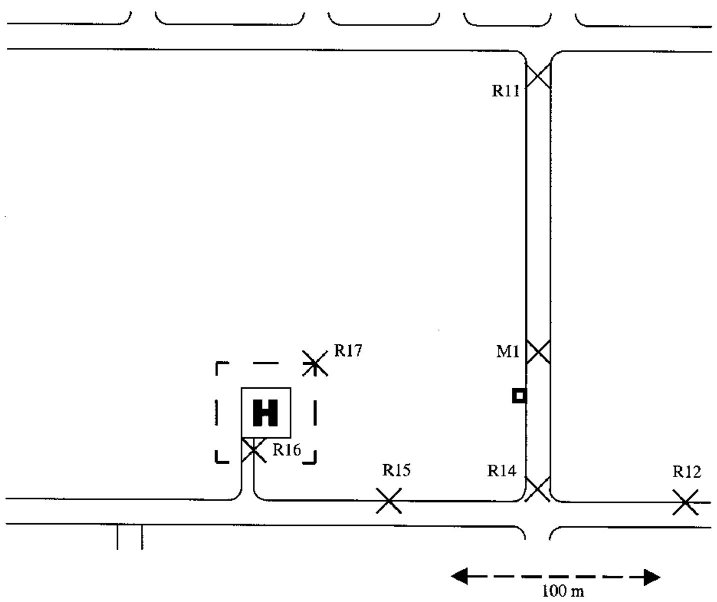

Figure 2: The open field measurement site M1 with free line-of-sight with the reference points R11, R12, R14, R15, R16 and R17.

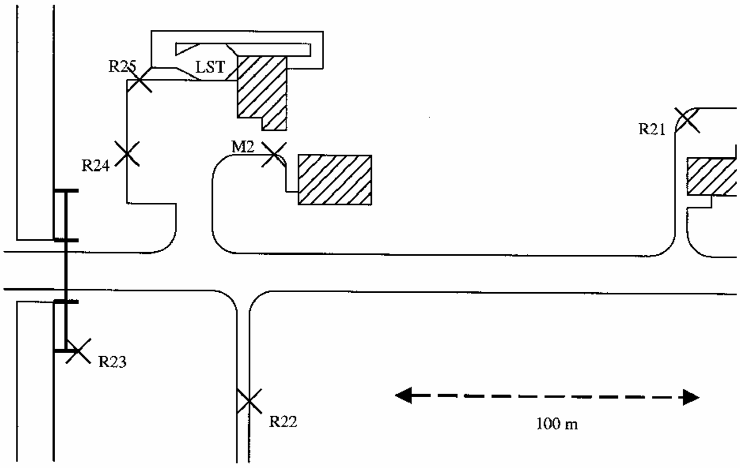

Figure 3: The measurement site M2 in front of a building of metal and the reference points R21, R22, R23, R24 and R25.

2.2 The laboratory aircraft

Flight tests can be conducted either with the NLR research aircraft Fairchild Metro II, PH-NLZ (a transport type aircraft equipped with two wing mounted turbo prop engines, see figure 5), or with the Cessna Citation II research aircraft (a business type aircraft equipped with two fuselage mounted jet engines). A measurement system is standard available.

2.2.1 Instrumentation

Figure 7 shows a scheme of the aircraft with measurement equipment installed. ARINC 429 data are stored on tape. All relevant parameters are available as time series based on UTC time. The data collection system is a fully certified aircraft instrumentation system. At the upper section of the aircraft’s fuselage a number of antennas can be installed on an antenna box (see figure 6). Output of the GPS antennas for the attitude function will simultaneously be measured with the GNSS attitude function prototype equipment under test. An additional GPS antenna (L1 + L2 frequencies) is connected to a geodetic-quality dual frequency Trimble MS750 GPS receiver enabling the accurate determination of the flight trajectory (several base stations are available to support these measurements) which feature, although not required for attitude determination, is standard available.
The angular reference system installed in the aircraft is a Honeywell IRS HG1050 GG1342 ring laser gyro, having a proven accuracy of 0.1^o in pitch and heading.

2.2.2 IRS misalignment check

To check the angle of pitch and angle of roll misalignment of the IRS the aircraft was placed on jacks. After the aircraft was carefully leveled, the IRS output was recorded and analyzed later on. An angle of pitch of 0.03^o and an angle of roll of $-.86^o$ was measured by the IRS. These deviations from the ideal alignment of the IRS were taken into account during the performance analysis.

Prior to each ground and flight test the IRS heading was checked. Therefore the aircraft was slowly moved and directed towards a tower at Schiphol Airport. The direction towards the tower was monitored continuously applying a telescope placed on top of the aircraft's fuselage (see figure 8). The position of the tower and of the aircraft are known and once the tower is visible through the telescope the heading of the aircraft is identical the computed heading from the two positions. The results are listed in table 1.

Table 1: Results of IRS heading check

Flight number	IRS heading – Reference (tower)
9013 (ground test)	0.865°
9014 (ground test)	0.853°
9015 (ground test)	0.843°
2637 (flight test)	0.852°
2638 (flight test)	0.815°

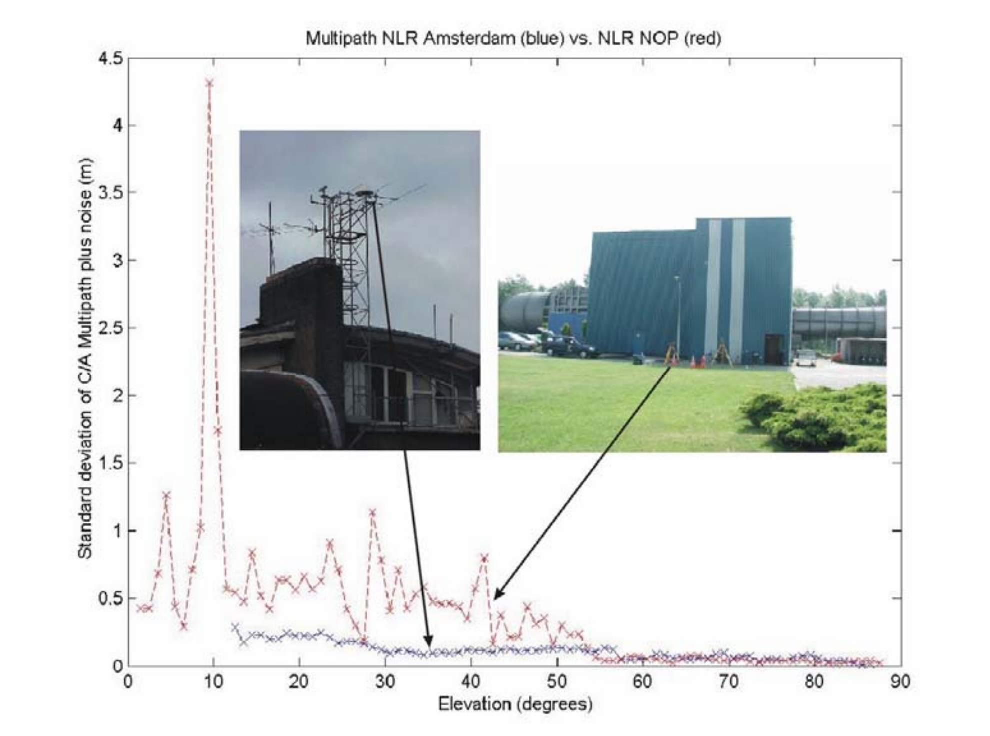

Figure 4: Multipath at site M2 compared to a nearly multipath free environment.

The difference between the IRS heading and the reference shows a mean value of 0.85^o and a standard deviation of just 0.02^o. The obtained mean value is of a too large magnitude to be interpreted as IRS heading error and therefore must be interpreted as misalignment of the telescope relative to the IRS x-axis. The standard deviation is small and indicates that the IRS heading measurement accuracy is well within 0.1^o. From these observations it is concluded that the IRS attitudes are of an overall accuracy well within 0.1^o and are to be seen as true reference for the GNSS attitude function.

3 Results

A number of example test results are discussed. The example results are taken from the SHINE (Smart Hybrid Integrated Navigation Equipment) project. As part of the EC (European Commission) project SHINE, the NLR was responsible for the testing of the basic SHINE prototype attitude sensor functions. The SHINE prototype is an airborne unit, designed to offer position and attitude parameters required by civil aviation and helicopters, with lower weight and cost than current equipment. The basic technical approach is the optimal integration of information from a GPS attitude sensor, based on L1 measurements only, with inertial data. Complementary sensor data fusion of inertial measurements (accelerations, angular rate) and GPS twin antennas (propagation time and phase) measurements will be utilized for the best estimate of position and attitude (pitch, yaw and heading) of the aircraft. A limited number of SHINE test results, as related to the GPS twin antenna measurements, are discussed in this paper.

3.1 Accuracy performance analysis of the test results obtained with the static angular reference system

3.1.1 Test matrix

The test rig has been placed in open field (see figure 1 and 2) with free line-of-sight down to a mask angle of 10^o.

Two parameters have been varied: nominal pitch (-40^o, -20^o, -10^o, -5^o, 0^o, 5^o, 10^o, 15^o, 20^o, 40^o) and nominal heading (0^o, 90^o, 180^o, 270^o).

These tests are repeated with the test rig located in front of a large building (see figure 3 and 4) simulating less satellites in view and a multipath environment.

3.1.2 Example test results

The figures 9 show representative samples of the observed attitude errors, each of these figures shows the heading error, the pitch error and the valid flag. The baseline length was 1.8 m; for other baseline lengths the errors will decrease in ratio with the inverse of the baseline length. From figure 9 it has been concluded the heading performs well during these tests, however, the pitch error was larger than expected (note that the attitude determination was based on L1 measurements only as required for civil aviation).

Figure 10 shows a measurement sample of a test performed in front of a metal building. Gaps in the data mean that data outages occurred. Obviously multipath can prevent acceptable results. Note that the valid flag was equal 0 most of the time which means that the attitude sensor output may not be trusted.

Figure 5: NLR research aircraft Fairchild Metro II, PH-NLZ, in front of hangar during multipath tests.

3.1.3 Discussion of results

On the basis of test results (example figures 9) obtained with the static angular reference system it is possible to verify the static performance of the GNSS attitude function in open field (the overall performance was observed to be: 95% pitch error 1.7^{o}; 95% heading error 0.8^{o}).

The multipath effect on the performance in front of a metal building can very well be checked and can be dominating as illustrated in figure 10.

3.2 Accuracy performance analysis of the test results obtained with the laboratory aircraft

3.2.1 Test matrix

<u>Ground tests</u>

The aircraft has been positioned into different nominal headings 90°, 180°, 270°, 360° on the runway. No buildings were in the neighbourhood.
These tests have been repeated in front of an hangar (see figure 5) simulating less satellites in view and a multipath environment.

<u>Flight tests</u>

The manoeuvres performed are:

1- turns of 360° with nominal bank angles of 15°, 30°, 45°, 60°.

2- level flight with nominal headings 90°, 180°, 270°, 360° (low speed and high speed).

Figure 6: Antenna box on the Metro II research aircraft. The first and the last antenna are used for attitude determination. The antenna in the middle (L1 + L2) has been used to determine the trajectory of the aircraft accurately.

3.2.2 Example test results

The figures 11 show the observed attitude errors, each of these figures show the heading error, the pitch error and the valid flag (flag equals –1 means: no data). Gaps in the data mean that data outages occurred. The baseline length was 1.45 m. From figure 11 it has been concluded, the heading as well as the pitch perform well, except during turning manoeuvres with large bank angles.

3.2.3 Discussion of results

The sigma of the pitch and heading error is relatively small during the high speed straight level flights (sigma pitch error: 0.24^{o}, sigma heading error: 0.09^{o}) and increases during all other type of manoeuvres including the ground tests. The most likely explanation of this phenomenon is the presence of ground multipath during ground tests and the rapidly changing Doppler effect due to the acceleration during turning flight manoeuvres. During the turns with bank angles equals or larger than 30^{o}, the valid flag did often show an invalid value while data outages occurred; this effect increases with increasing bank angle.

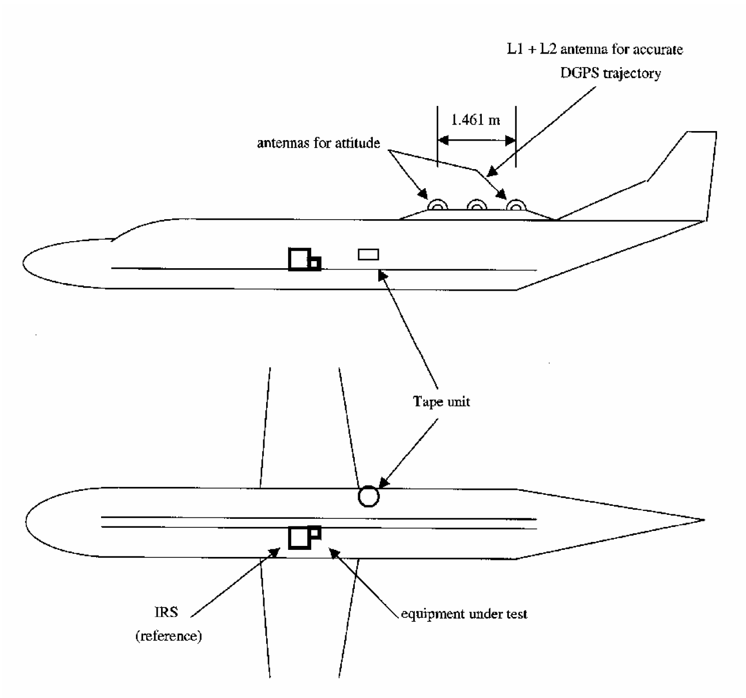

Figure 7: Fairchild Metro II aircraft with measurement equipment.

Figure 8: Telescope at the top of the aircraft for IRS heading check.

4 Conclusions

The two step testing method, described in this paper, is a logical way in GNSS attitude function testing since the static tests, using a ground based test rig, are cheap and don’t need much preparation. This way the initial static testing saves a significant amount of money for two reasons: firstly the static tests don’t need an instrumented test aircraft making this part of the tests much cheaper while test results become quickly available and secondly the flight testing will only be undertaken once the static tests did show results in accordance to the expectations avoiding troublesome outcome of the flight testing.
The accuracy in attitude of the ground based static test rig as well as the IRS in the test aircraft was proven to be better than 0.1^{o} being sufficient for reference purposes.
The presented flight test results did show a degraded performance of the GPS attitude function during the turns with bank angles equal and larger than 30^{o}, the valid flag did often show an invalid value and in addition data outages occurred; these effects increase with increasing bank angle.
The multipath effects observed were most severe in front of the hangar.

5 References

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2. C.E. Cohen, B.W. Parkinson. Aircraft Applications of GPS-Based Attitude Determination. ION GPS-92, Albuquerque, NM, 1992.
3. C.E. Cohen, B.W. Parkinson, B.D. McNally. Flight Tests of Attitude Determination Using GPS Compared Against an Inertial Navigation Unit. Journal of the Institute of Navigation Vol. 41, No. 1, Spring 1994.
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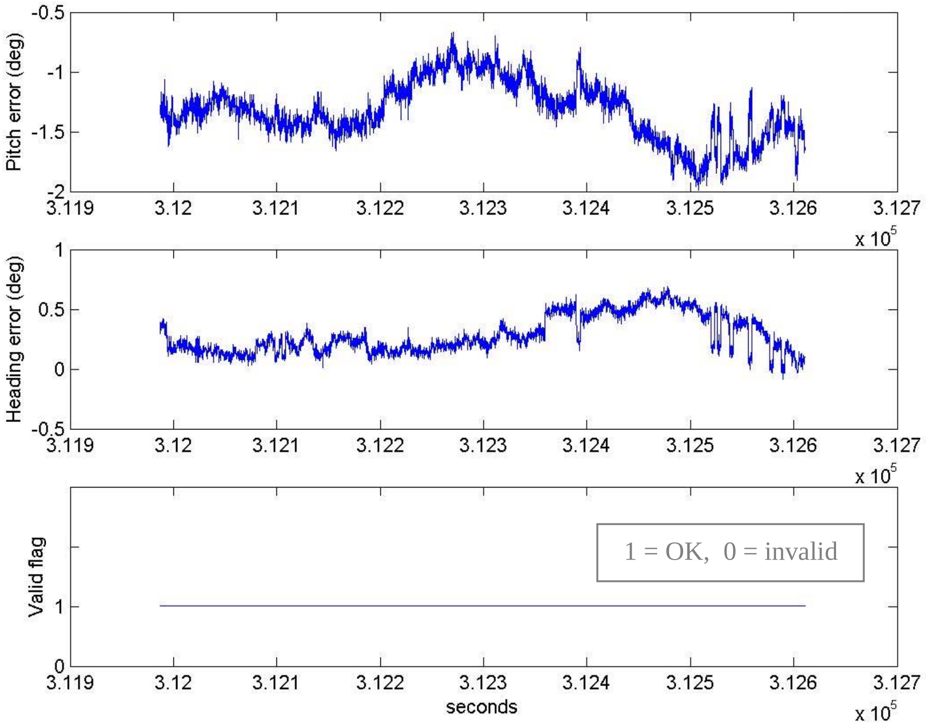

Figure 9a: Heading error, the pitch error and the valid flag. Condition: open field pitch = 0^o, heading = 255^o.

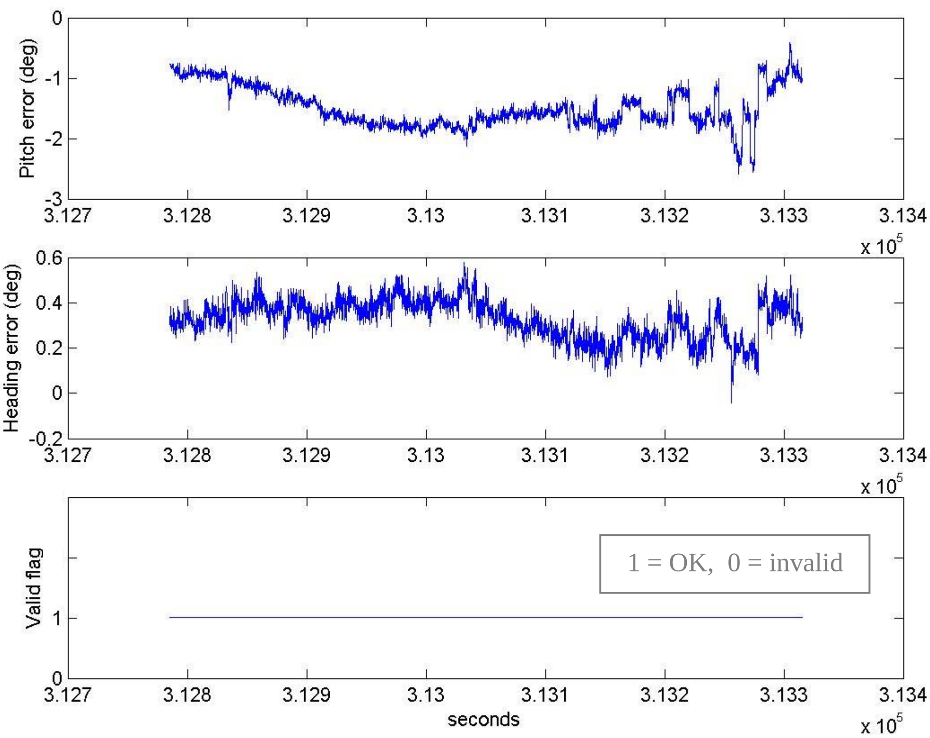

Figure 9b: Condition: open field, pitch = 10^o, heading = 255^o.

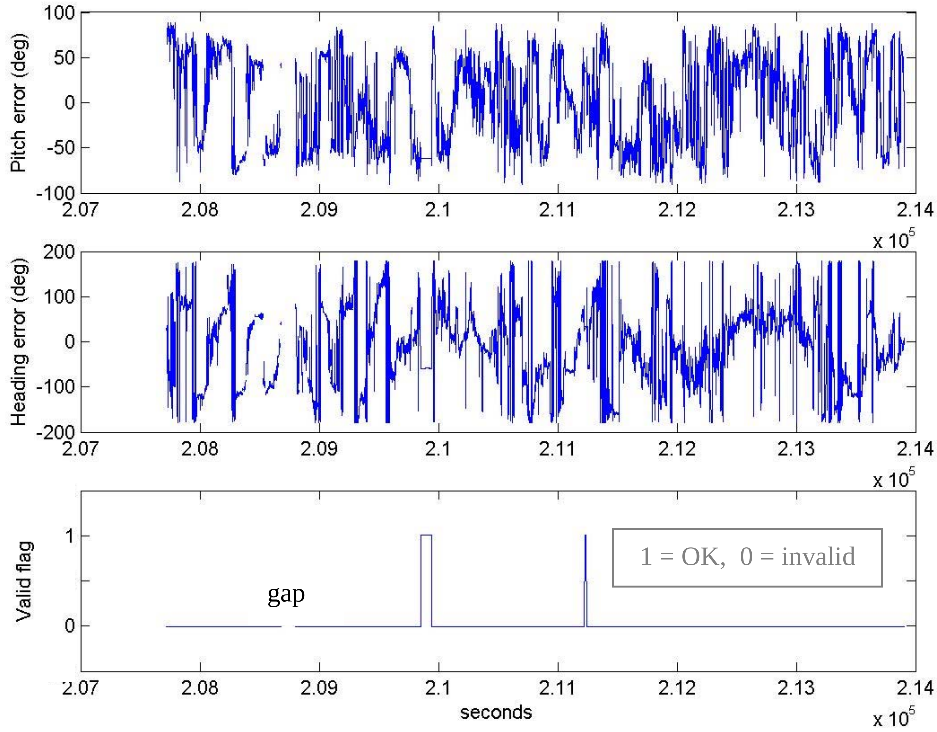

Figure 10: Measurement result of test in front of metal building. Condition: pitch = 0^o, heading = 292^o.

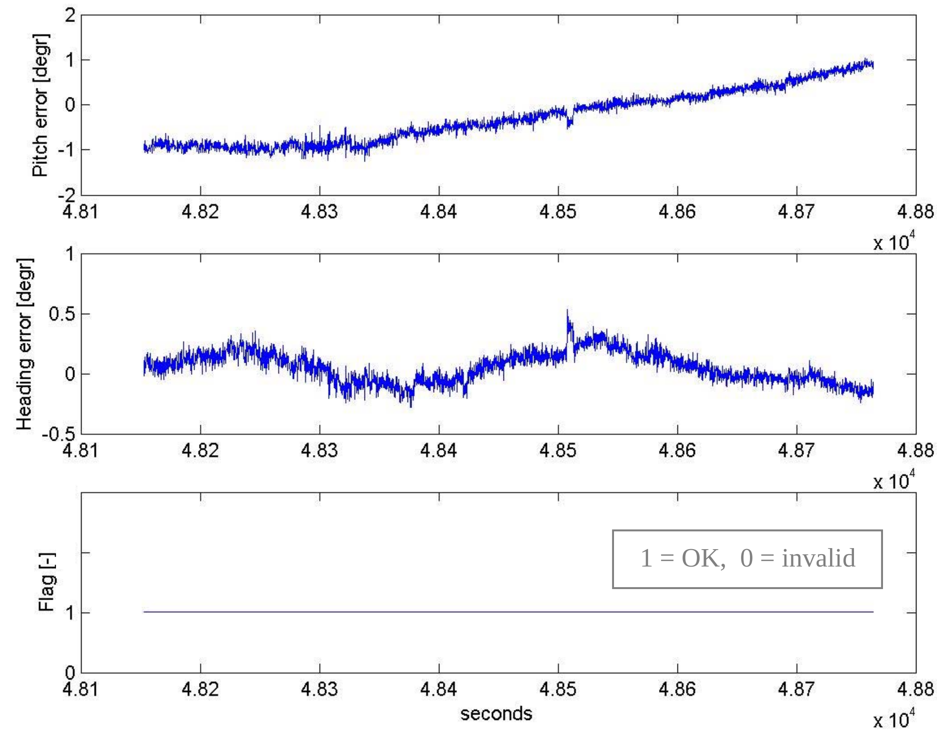

Figure 11a: Heading error, the pitch error and the valid flag. Condition: aircraft on runway, heading = 268^o.

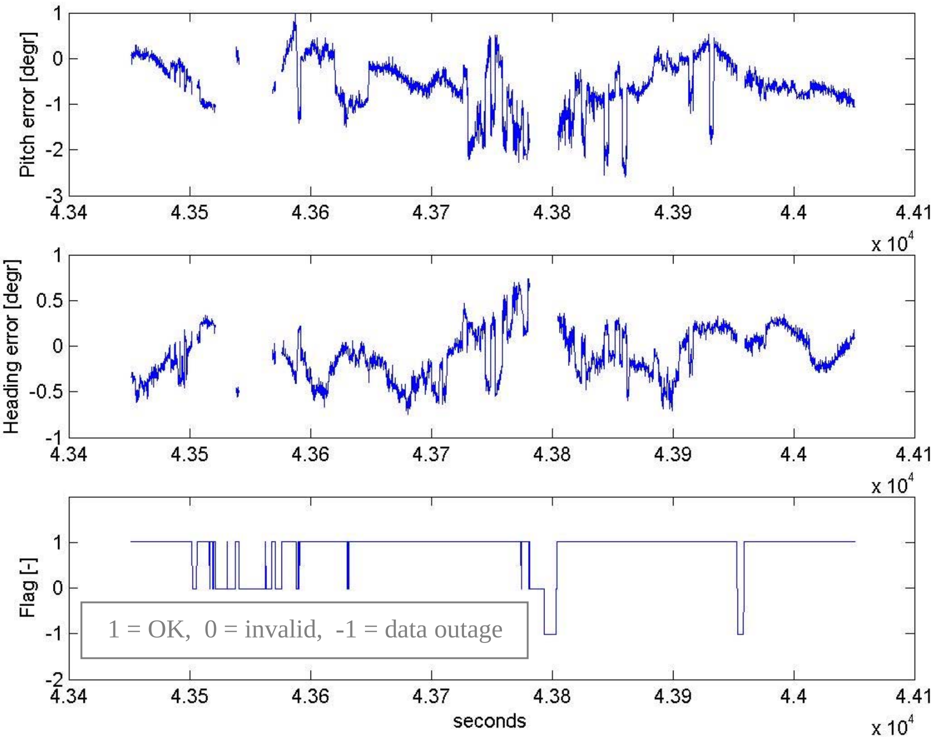

Figure 11b: Heading error, the pitch error and the valid flag. Condition: aircraft in front of hangar, heading = 130^o (parallel hangar).

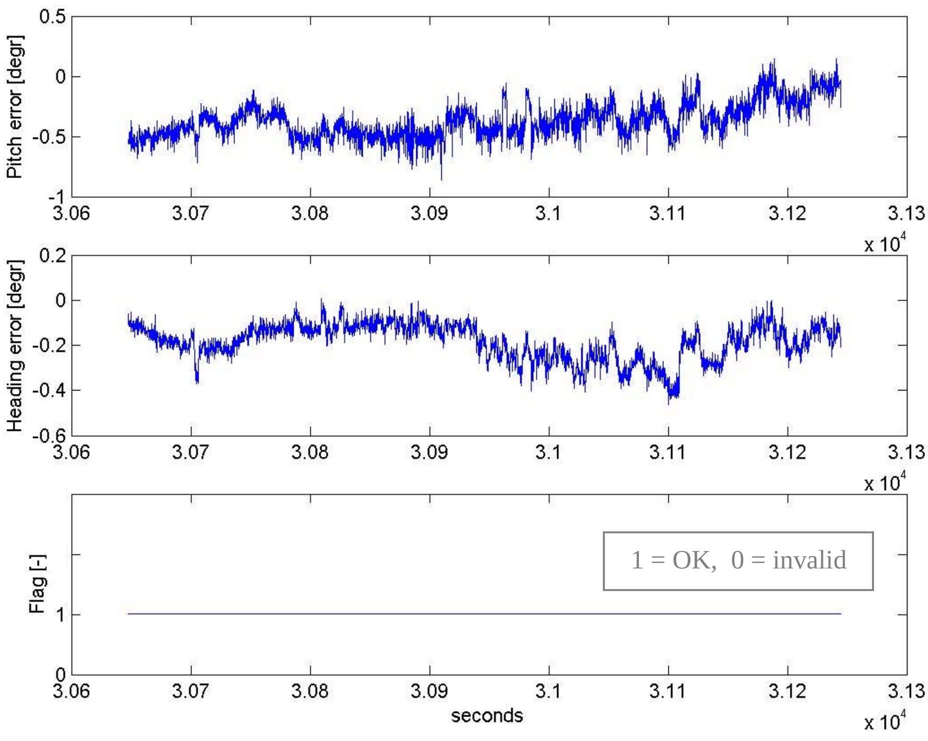

Figure 11c: Condition: straight level flight, high speed, heading = 157^o.

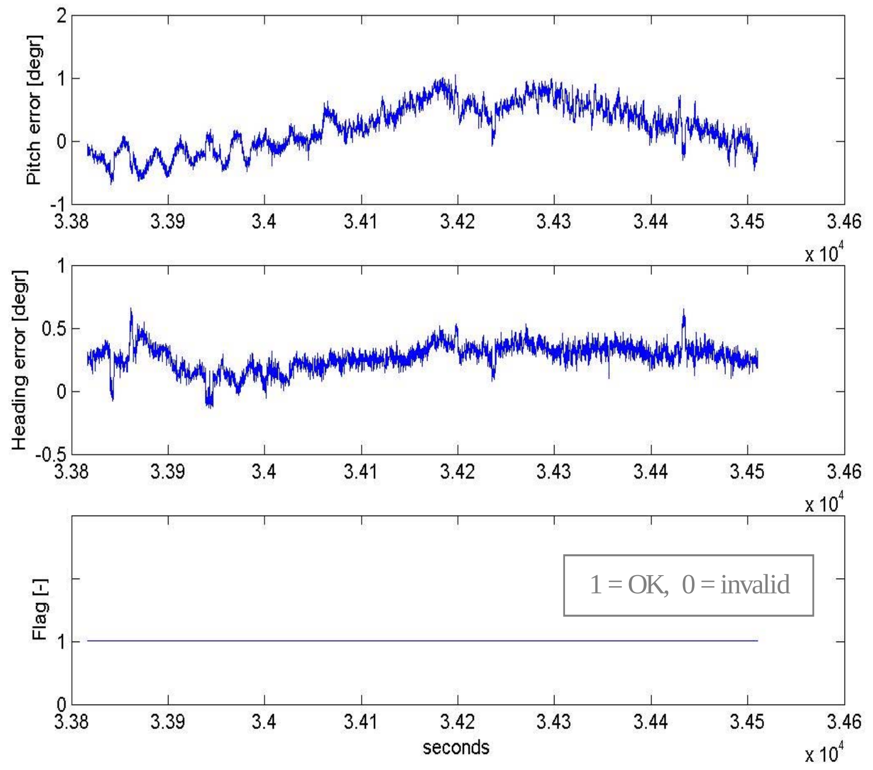

Figure 11d: Condition: straight level flight, low speed, heading = 281^o.

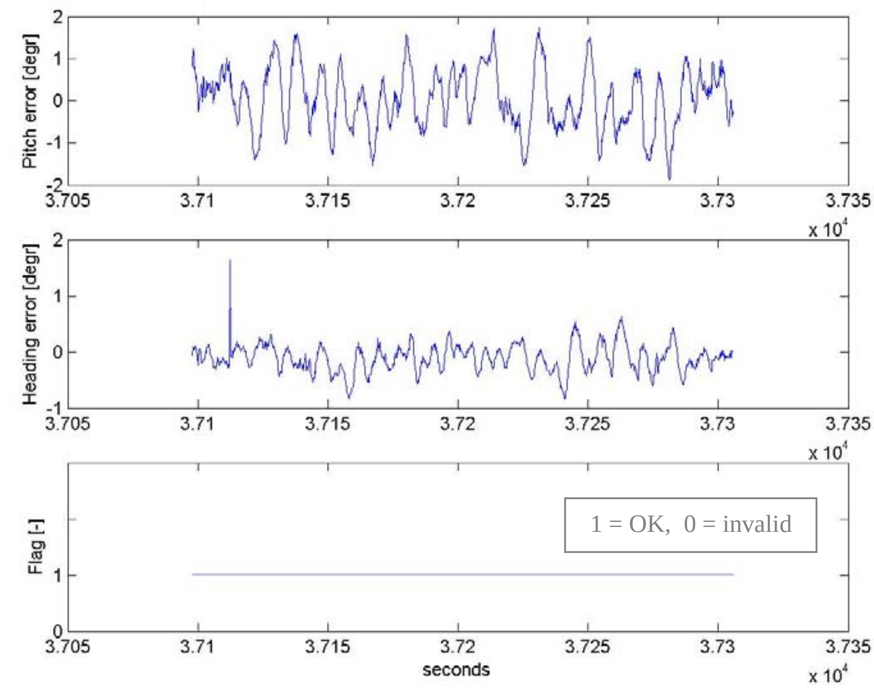

Figure 11e: Condition: aircraft is turning with a nominal bank angle of 15^o.

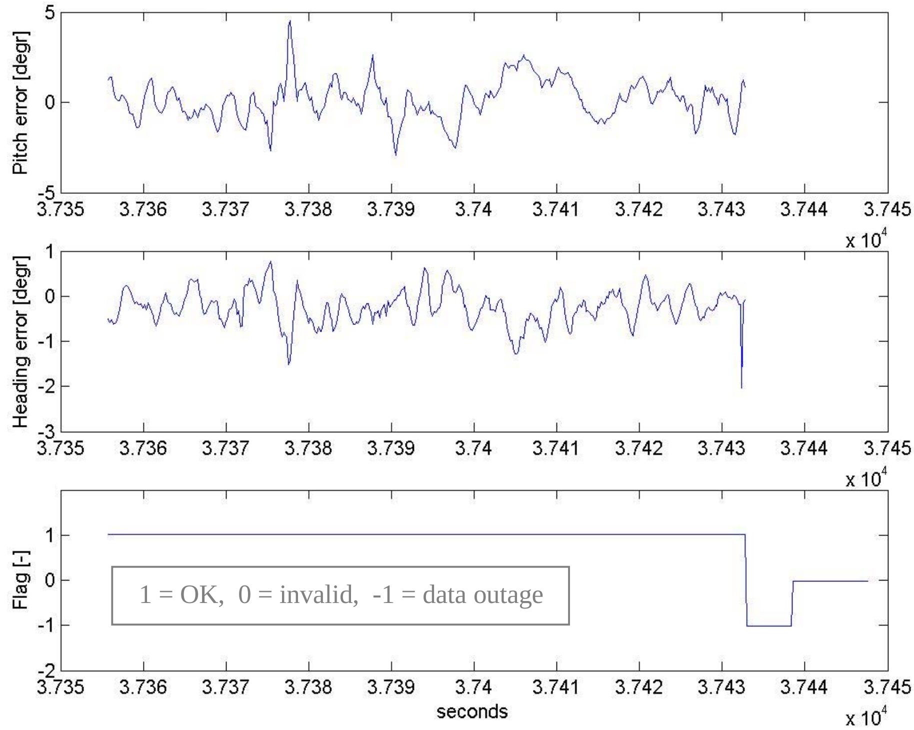

Figure 11f: Condition: aircraft is turning with a nominal bank angle of 30°.

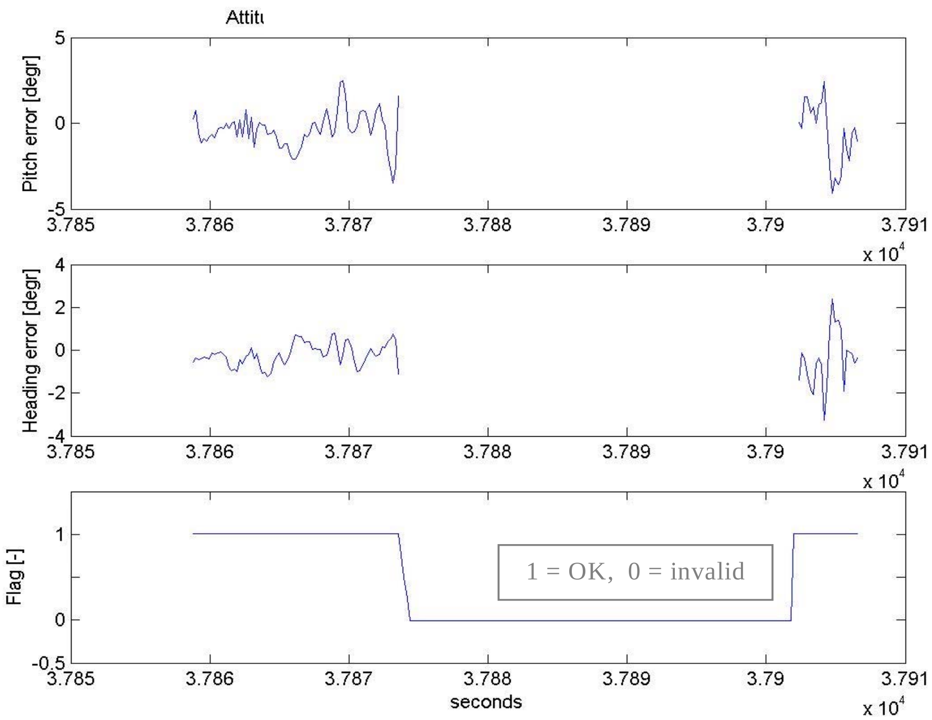

Figure 11g: Condition: aircraft is turning with a nominal bank angle of 60°.