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Using Data Fusion of DMARS-R-IMU and GPS Data for Improving Attitude Determination Accuracy

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The Mobile Rocket Base (MORABA), a division of the Space Operations and Astronaut Training Department of the German Aerospace Center, has developed and flown sounding rocket rate and attitude control systems since 1972. For determining position and attitude, some of the past missions have used a DMARS-R (Digital Miniature Attitude Reference System) roll stabilized platform produced by the Inertial Science Company. The DMARS-R is a high-precision, roll-stabilized IMU (Inertial Measurement Unit) comprising accurate angular rate and acceleration sensors and mounted on a roll-stabilized platform. Standard IMUs are inherently subject to drift in inertial position, velocity and attitude. By the fusion of GPS and with DMARS-R data, one can achieves a long-term drift-corrected IMU enabling for longer duration flight applications, such as satellite launchers, spin stabilized rockets and balloons. The main experiment of the MAIUS mission, initially planned for autumn 2015, requires accurate pointing to the Earth's gravitational center.

The required accuracy will be obtained by the fusion of DMARS-R and GNS data to produce "drift free" attitude data for the cold gas attitude control system of the payload. The attitude correction and control algorithm will be implemented in the DMARS-R processor.

I. Introduction

Operation execution of sounding rocket missions often requires high accuracy attitude control of the vehicle to provide proper conditions for the scientific objectives. To achieve these conditions, cold gas control systems are used which process navigation data from various sources in real-time. The Mobile Rocket Base (MORABA) at the German Aerospace Center (DLR – Deutsches Zentrum für Luft- und Raumfahrt) has developed and flown rate and attitude control systems on its sounding rockets since the early 1970s.

The MAIUS mission should test the equivalence principle with the help of Bose-Einstein-condensates[1,2]. The MAIUS rocket was planned to be launched in fall 2015 but has been delayed to the second half of 2016. Therefore, the original intention of this paper, to describe the attitude control mechanism and algorithms as well as the results after data post-processing can no more be achieved in this document. Instead of this, we describe the current progress as well as experiences with previous flights and tests. The main idea presented in this paper is the use of GNS data for correction of sensor drift of the inertial sensors. Using the corrections necessary to align the position and velocity vectors, one can also generate correction for the attitude parameters.

After a short introduction to MORABA and a presentation of the sensors flown in the past, we describe the DMARS-R platform, which is the current inertial platform used for our purposes. A description of the SHEFEX-II (Sharp Edge Flight Experiment) mission and the post-processing of its flight data, where data fusion was performed post-flight, giving some insight for data improvements. Finally, we describe the new data fusion concept as well as the tests done so far with the new data fusion algorithms and give an outlook for possible future developments.

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A. MORABA - A Brief Overview

Mobile Rocket Base (MORABA) was founded in 1967 as part of the Max Planck Society. MORABA was later integrated into the DFVLR, now DLR and is based in Oberpfaffenhofen, Germany.

One of MORABA's main tasks is the support of the national and international research communities in the preparation and operation of sounding rocket- and balloon-borne experiments. These cover a variety of scientific fields, such as atmospheric physics, astronomy, microgravity, hypersonic research, technology testing and education. By providing and operating mobile infrastructure (telemetry, tele command and RADAR stations as well as rocket launchers), it is possible to perform complex scientific missions at almost any location that might be required by the experiment. Most frequently, launches are conducted from Esrange (Sweden), Andøya Rocket Range and Spitzbergen (Norway), Natal and Alcântara (Brazil) as well as Biscarosse (France), but remote locations like Antarctica or Woomera (Australia) have also been used. Minimal local infrastructure is required to establish a launch site at other desired locations.

The development of new launch vehicle systems, to meet the scientific requirements of the various missions, constitutes a key capability of MORABA. This also includes the continual evolution of attitude and rate control systems as well as guidance, navigation and control algorithms, coinciding with the further objective of MORABA to develop, test and build commercially unavailable mechanical and electrical components and systems for sounding rockets and balloons as well as for short duration satellite missions.

The key work areas of MORABA are shown in Figure 1. In accordance with these work areas, MORABA is structured into four groups covering telemetry and RADAR for status and trajectory information, electronic and mechanical flight systems as well as launch services and flight dynamics. Development and operations of rate and attitude control systems and GNC algorithms is performed mostly by the electrical and mechanical flight system groups.

Figure 1. MORABA Operation, Research & Development Fields

During MORABA history there was quite often a need to use special sensors and equipment to meet the scientific requirements of sounding rocket missions. Consequently, some evolution can be seen which we will described in the next chapter. More information about MORABA can be found in [3,4,5].

B. Attitude Control of Sounding Rockets Payload flown by MORABA

The first requirements for attitude control of sounding rocket payloads concerned solar and stellar astronomy. The solar pointing systems in the British and German programs were initially based on two axes pointing using a combination of coarse and fine sun sensors, which could achieve pointing accuracy of *2-3 arcmin* to the photometric center of the sun. The roll axis control of the payload used a three axis magnetometer which required calibration and compensation to minimize the effects of the payload magnetic field. The actuators consisted of cold gas thrusters. The lateral accuracy of such systems was in the order of ± *2 arcmin* and limit cycle of *5 arcsec* RMS on the sun, and ± *3°* in roll. A considerable number of such systems were used for stellar X-ray astronomy in daylight, where the experiment detector could be physically offset to the payload axes. In the British program, a variant of this system comprising moon plus magnetic field pointing system, coupled to a strap down inertial maneuver and star tracker fine pointing, was developed and successfully flown but the complexity and acquisition time indicated that for night flights, a more convenient coarse sensor was required.

The solution to coarse attitude pointing independent from the presence of the sun or moon was provided by roll stable inertial platforms. The first systems comprised two twin axis free gyros on a motor driven roll stable platform which isolated the gyros from the rocket spin during the burn phase. The MIDAS (Miniature Inertial Digital Attitude Sensor) analog platform from the Space Vector Corporation provided inertial accuracies in the order of *2-3°* depending on the maneuver. The advantages of this platform were that one could provide pointing measurement and control in practically any direction independently from time of day. The elevation and azimuth of the vehicle in the launcher were measured in the launcher by clinometer and laser return to a payload mirror from a surveyed point to obtain the reference attitude prior to uncage of the platform. The only limitations were the gimbal lock condition of a three gimbal platform, which could be avoided for the desired targets by optimizing the rotation of the platform relative to the experiment.

A later development of roll stable platforms resulted in the DMARS (Digital Miniature Attitude Reference System) platform from Inertial Science Inc. This platform contains two tuned rotor gyros and three accelerometers on a roll stable platform. In addition, the DMARS contains a microprocessor and all the electronics for signal processing of the rate and acceleration sensors and production of attitude and position data. A significant advantage is the feature which, with input of the latitude, longitude and elevation of the platform in the launcher and initiation of the self-alignment mode, the DMARS rotates its roll stable platform in 4 quadrants, compensates the sensor offsets and scaling and determines its attitude to true north and its elevation angle. This removes the need for external elevation and roll attitude measurements. Although the DMARS provides accurate inertial attitude and navigation data during flight, the possibility of combining its in-flight navigation data with GPS led to the development of this feature, which offers a considerable improvement in attitude and navigation performance and is the subject of this paper.

The next logical step is now to improve the accuracy of the flight data in real time using a data fusion of GNS (Guidance and Navigation System) and IMU (Inertial Measuring Unit) data. With the help of the GNS data, possible drifts, resulting from sensor inaccuracies or other effects in the platform measurement, can be corrected to achieve the most accurate position and attitude data from the vehicle throughout the flight.

II. Detailed Description of the DMARS-R Inertial Platform

The DMARS-R is an autonomous inertial guidance, navigation and control sensor, specially designed for scientific sounding rockets, produced by Inertial Science Inc. (ISI) in California, USA. It comprises 2 dynamically tuned gyros and 3-axis of precision pendulous accelerometers, mounted on a roll-axis rotating gimbal. The roll isolation of the platform allows up to 25 r/s, and therefore the platform is ideal for use on spinning rockets. It is designed with a single gimbal. With an unlocked gimbal the platform operates in a mode with two axes in strap-down mode and one axis in gimbal mode. The gimbal can also be locked, such that the platform could be operated in a full strap-down mode.

The platform has the capability to find its orientation via a self-alignment process, which significantly reduces the sensor biases. The accuracy of the self-alignment is better than *0.1°* in horizontal axes and *0.3°* in vertical axis. In addition, transfer alignment using external sources is also possible. The instruments (gyros and accelerometers) are mounted on the gimbal.

The electronics of the platform contains Sigma–delta analog to digital converters with 16-bit resolution and a digital processing module. The new data fusion concept uses an unique adaptive algorithm (yet to be published) to detect and correct unhealthy GPS signals, often caused by highly dynamical vehicles such as faults or dropouts. It also employees a conventional loosely coupled 12-state-variables Kalman filter. The algorithm is able to process 10 frames per second. This coincides with the update frequency of the GNS.

The GPS used onboard the rocket is a NOVATEL GPS/GLNSS (OEM STAR 10 Hz D-G) receiver . This choice was made because it provides a discrete hardware signal of position-fix which interrupts the fusion process prior to erroneous calculation. This hardware signal is also used in the adaptive algorithm. It also has a capability of processing GPS and GLNSS. The receiver is integrated into the DMARS-R platform as a subsystem and connected via RS232 interface. The second channel of GNS data can also be used independently from the DMARS-R data.

Figure 2. DMARS-R Inertial Platform

III. SHEFEX II Mission – Description and Results of Post Flight Processing

An interesting example of data fusion, but in post processing, is given by the SHEFEX II mission. For the interested reader a much more detailed description of the mission and its precession control maneuver is presented in the paper [6].

A. Mission Description

The SHEFEX II mission was launched from Andoya rocket range on June 22nd 2012 at 19:18 UTC. The mission's purpose was to test and improve new techniques for future reentry vehicles and their interaction with the atmospheric environment during a hypersonic flight. Part of the mission was a maneuver for repointing the second stage prior to its ignition, thereby providing a suppressed trajectory to achieve greater horizontal velocity and a flat atmospheric reentry angle. The second stage was spun up in order to minimize the effects of thrust misalignment. The prediction of the pointing vector for the precession maneuver was performed on the basis of the data from the DMARS-R platform. Despite the fact that the main goal of the mission was the atmospheric reentry and therefore navigation with very high precision was not the main objective, a detailed analysis of the data was made after flight.

Four different control systems using cold gas were used for rate and attitude control:

- Roll Rate Control
- Two-Axes Precession Control
- Three-Axes Attitude Control
- Three-Axes Rate Damping Control

The control system of the SHEFEX II rocket included a DMARS-R platform as well as a GNS system. Both systems were used independently. However, in the post processing of the flight data a data fusion was made showing up some interesting features, the results of which we describe in the next section.

B. Post Flight Processing of the SHEFEX II Navigation Data

Subsequent to the flight, all the data have been evaluated and a comparison of the data of different sources was made to get a better idea of the accuracy of the different data sets used. Several effects during the post-flight analysis were discovered which had to be considered for further data processing.

The DMARS's rate sensors have been affected by the singularity of the navigation algorithm close to the North Pole (wander azimuth), and therefore, these wander azimuth calculation errors caused a deviation between the GPS and DMARS data. By further investigation, the contributions of different error sources have been identified. The position, velocity and inertial lateral angles of the payload experienced a drift, which is displayed by the following graphs (Fig.3 , Fig4):

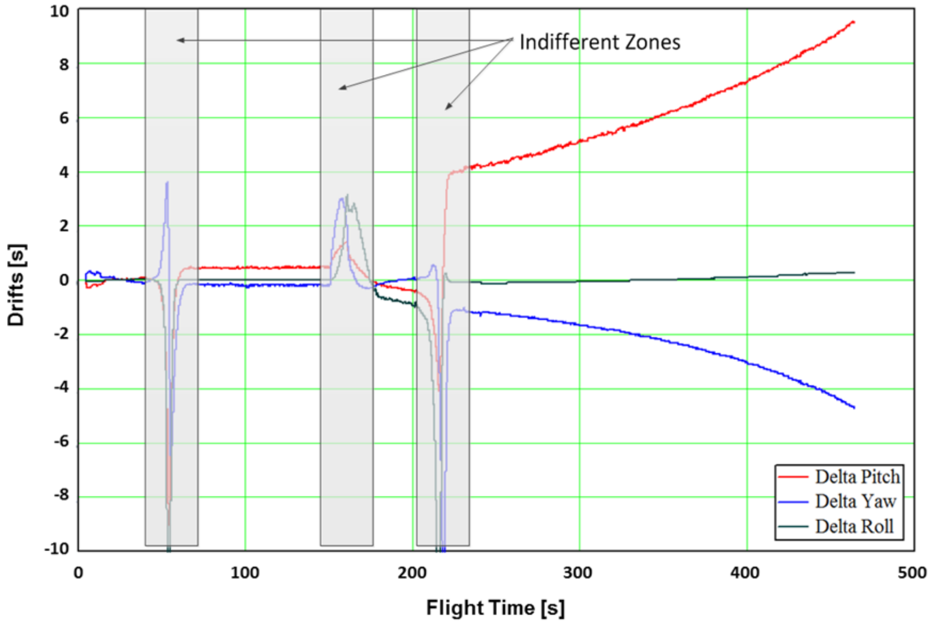

Figure 3. DMARS Drifts as Functions of Flight Time.

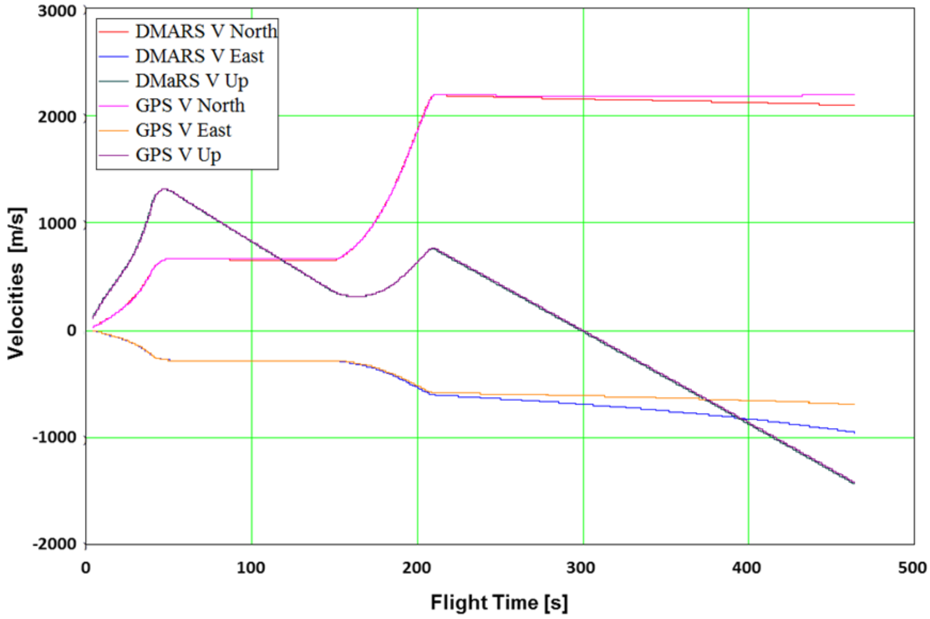

Figure 4. DMARS and GPS Velocities as Functions of Flight Time.

The indifferent zones indicate time periods where the effective acceleration, composed of accelerations induced by air drags, gravitation and motor thrusts, is about *0 g*. During these periods a determination of drifts is difficult to perform. These periods occurred during the burn out phase of the first and second stage and shortly after the ignition of the second stage. After *200 s* of flight time a jump of about *4°* in the pitch axis is visible. This wander azimuth effect was not considered up to this point, because the main intention of the mission was the aerodynamic reentry, and a very accurate pointing direction was not a main requirement. The main goal of the re-entry mission was to obtain a stable re-entry with a low angle of attack. This was achieved by a rate damping rather than attitude control mode. However, a recalculation, including the wander azimuth effect was made, resulting in a much better precision of the vehicles position and attitude (see graph Fig. 5).

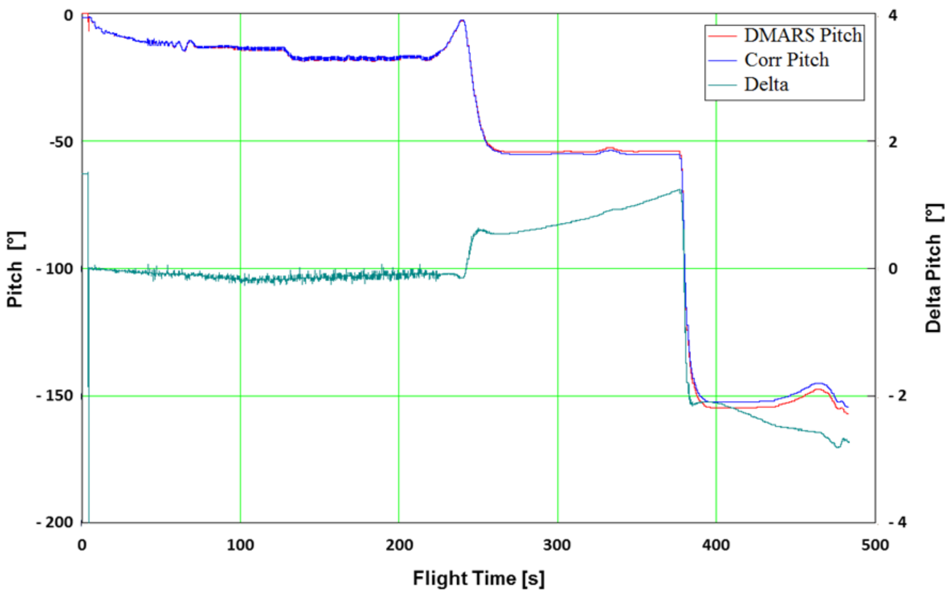

Figure 5. Attitude Angles related to Pitch as Functions of Flight Time.

Another observed effect was that the velocity vectors obtained by the GPS receiver and the DMARS differ dramatically after the flight time of *200 s* (see graph Fig. 3) The drifts before *200 s* are related to drifts introduced by the DMARS's sensors. After the correction of the data, considering the wander azimuth effect, the angle drifts show normal behavior and lie within the specification of the DMARS. The second step was to build up a data fusion of DMARS and GPS data to eliminate also the remaining drifts. The results of this data fusion are visible in the following graphs. The fusion was performed with the algorithm mentioned in the previous section.

Assuming that the acceleration axis of the rocket is parallel to the longitudinal axis of the rocket an alignment of the DMARS's velocity and position vector to the according GPS data was performed by adapting the attitude of the rocket's longitudinal axis and by varying the acceleration along the rocket's longitudinal axis. This procedure was done by Kalman filtering.

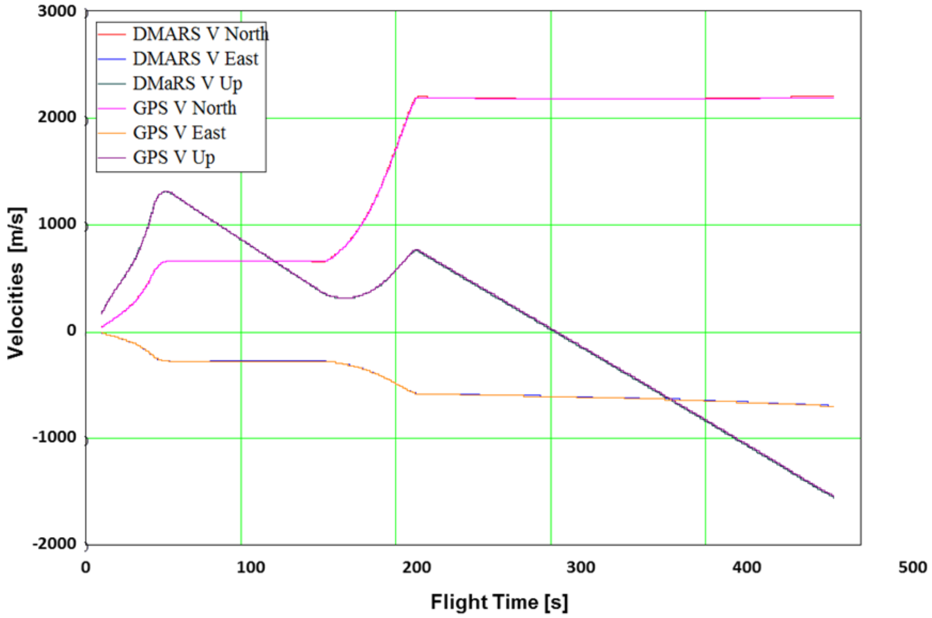

Figure 6. DMARS and GPS Velocities as Functions of Flight Time.

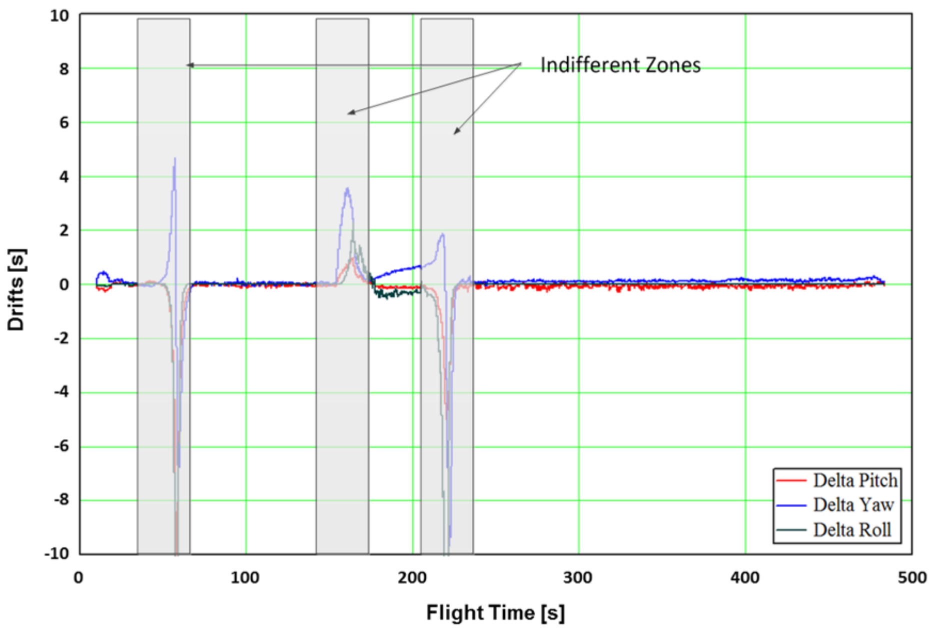

Figure 7. DMARS Drifts as Functions of Flight Time.

The indifferent zones indicate time periods where the effective acceleration, composed of accelerations induced by air drags, gravitation and motor thrusts, is about *0 g*. During these periods a determination of drifts is difficult to perform. It is evident that there occurred a drift during the burning phase of the second stage (S44), which can be explained by a misalignment of longitudinal axis of the vehicle and the longitudinal axis of the DMARS. This effect was also visible during the precession maneuver where a resulting nutation (~ *0.3°*) happened. After executing this procedure in the post flight processing, the integration of the corrected DMARS accelerometer and rate data produces almost identical velocity vector and position information compared with the information obtained by the GPS receiver. Therefore, the goal was achieved and also a drift correction for the attitude could be made. Furthermore, gaps in the data set were filled in by interpolated data in order to achieve a data set for the whole flight with a sample rate of *100 Hz* for the position, velocity vector and the attitude in space. After this post-flight processing it was possible to calculate the exact angles of attack of the SHEFEX II vehicle, which was a very important input for the scientists for their aerodynamic data set analysis, particularly during the ascent and re-entry phase of the flight.

IV. Current Test Status of the Improved GNC Concept.

Based on the experiences with the SHEFEX II mission described above, an improvement of the GNC procedure for future missions was considered. This mainly consists of a new data fusion concept for drift correction of the sensors. To get a first idea how the new algorithm could work, a first test of the new system was performed by Inertial Science, using a van for transportation. The van transported a DMARS-R platform as well as a Novatel GNS. A test route with the van was driven to see how the drift correction would work. The test loop route had a length of *21.6 km*, and included a local residential street and a freeway in Thousand Oaks, California. The route passed under four bridges which caused GNS signal blackouts for approximately *2 s*. Additionally, the route included about 1 mile of heavily shaded area with trees. The starting point was the same as the end point. Before starting the trip, several self-alignments with the platform were made. During this trip, whenever GNS was available, the drift correction was made. After the trip the attitude was compared with pre-surveyed data just after the vehicle test. The graphs in Fig. 8 show the van tests results.

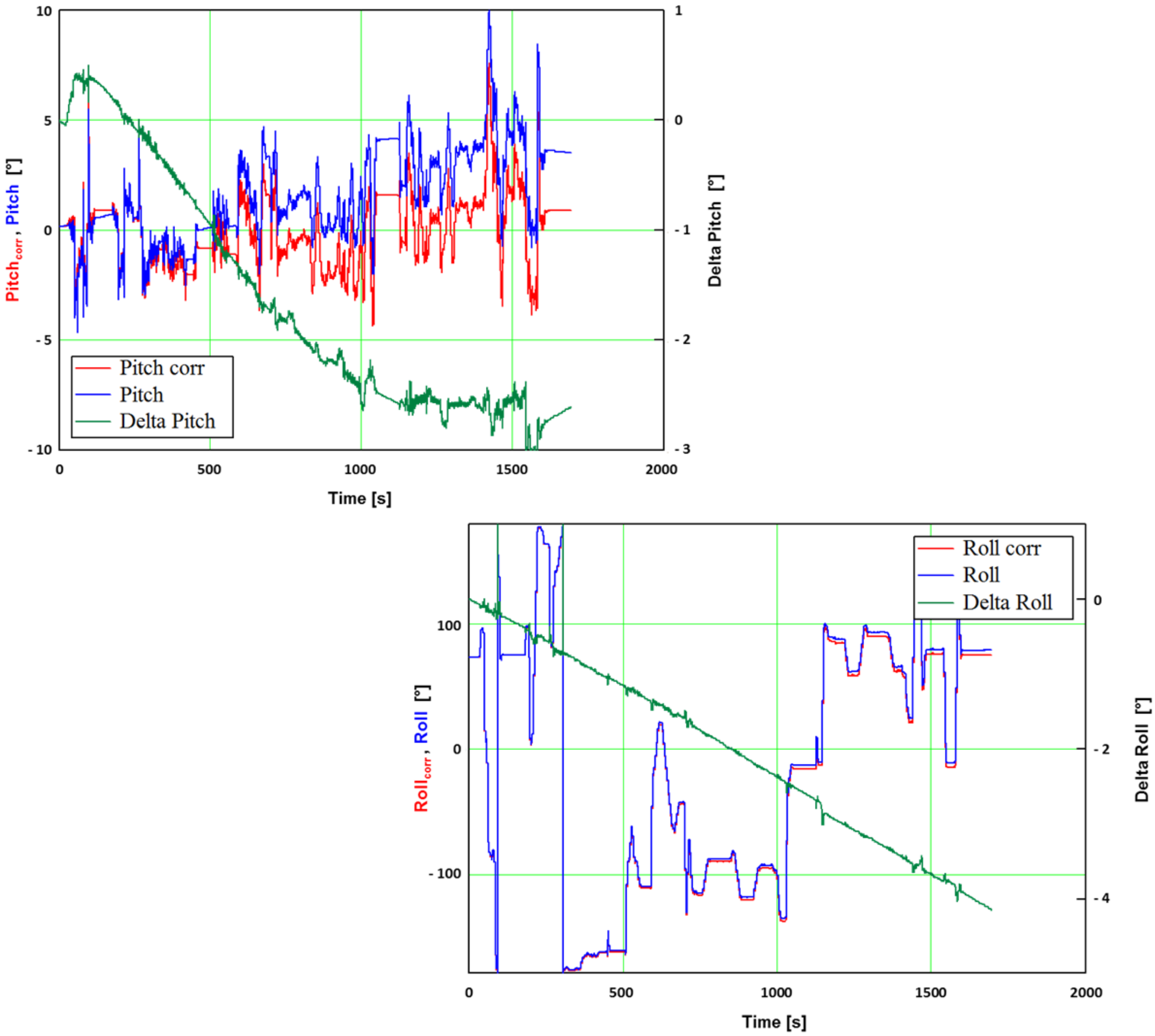

Figure 8. Attitude Angles related to Pitch and Roll as Function of Time.

The upper graph in Fig. 8 shows the drift corrections made for the pitch angle. One can see the measured pitch angle in blue as well as the corrected one in red. The lower graph in Fig. 8 shows the drift correction for the roll angle. The green line indicates the sensor drift showing a nearly linear behavior, especially for the roll angle. One can see from this first test data that the corrected values at the endpoint of the test are considerably closer to the values at the starting point than the original ones. Interruption of the GNS navigation data stops the data correction, but does not affect the operation of the platform and the drift correction resumes when the GNS navigation data is provided again.

V. Conclusion & Outlook

The precise control and measurement of attitude is a demanding requirement for scientific missions using sounding rockets as a carrier vehicle. In this paper we have described how MORABA tackles this challenge. We discussed the evolutions of sensors, described shortly the roll-stabilized platform, which we use for spinning rockets, and gave an overview of issues solved in the past and planned improvements of our systems and algorithms. The main feature of the new algorithms is the drift correction of the sensors by means of GNS-systems and to use it for the correction of the attitude parameters as well. We showed how these solutions can work for our purposes. Of course, further testing of the algorithm has to be conducted. Further tests with vans as well as tests with airplanes or even test flights on sounding rockets, if possible, are under consideration before using the system for a critical scientific mission. Possible flights for the application of the new system are the MAIUS mission and future rockets flown by MORABA.

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