IAC-18-A2.5.4x44337

Using onboard data fusion of IMU and GNSS for improvement of scientific rocket flights

Josef Ettl[a], Alexander Schmidt[b]*

[a] *Mobile Rocket Base (MORABA), Institute for Space Operations and Astronaut Training , DLR – German Aerospace Center, Muenchenerstrasse 20 82234 Wessling, Germany, josef.ettl@dlr.de*
[b] *Mobile Rocket Base (MORABA), Institute for Space Operations and Astronaut Training , DLR – German Aerospace Center, Muenchenerstrasse 20 82234 Wessling, Germany, alexander.schmidt@dlr.de*

* Corresponding Author

Abstract

Quite often scientific sounding rocket missions, such as the microgravity-mission MAIUS in 2017, require an as accurate as possible attitude determination. Up to now, GNSS and IMU data have mostly been used separately on sounding rocket flights. IMU data have been used for attitude determination solely, while GNSS data provided position and velocity vector of the rocket with a high accuracy but low sample rate. Normally, this data have so far been combined only during post processing.

In a recent sounding rocket flight program, the atmospheric physics mission PMWE, MORABA, the Mobile Rocket Base of DLR – German Aerospace Center, was responsible for trajectory and attitude determination as well as for the live data handling on board and the communication with the ground stations. During this mission, a newly implemented algorithm, running on the onboard computer, performed the combination of the highly sampled, but drifting IMU data and of the very accurate, but low sampled GNSS data. Although the GNSS only delivers position and velocity vector, the attitude data could be improved with the help of this fusion algorithm. The used algorithm is based on Kalman filtering and was used for the first time on a MORABA sounding rocket flight. Furthermore, during post-flight processing a data fusion with the measurements of a second GPS-receiver was made. The results show that this technique can also be useful for missions, which require advanced guidance and control. For example, the inclination and orbital accuracy of satellite launchers could be improved as well.

In this paper we present on the basis of the flight data of the PMWE sounding rocket mission the results of the on-board as well as of the post-processing fusion, and the improvements which have been gained with this new technique.

Acronyms/Abbreviations

ACS	Attitude Control System
DLR	Deutsches Zentrum für Luft- und Raumfahrt – German Aerospace Center
DMARS	Digital Miniature Attitude Reference System
GNSS	Global Navigation Satellite System
GSOC	German Space Operations Center
IAP	Institute for Atmospheric Physics
IMU	Inertial Measurement Unit
MAIUS	Materiewellen Interferometrie unter Schwerelosigkeit (Matter Wave Interferometry in Weightlessness)
MORABA	Mobile Rocket Base
PMWE	Polar Mesospheric Winter Echo
RCS	Rate Control System
SHEFEX	Sharp Edge Flight Experiment

1. Introduction – Sounding Rocket Flights

Sounding rocket flights provide an interesting platform for scientific missions in many areas such as material science, atmospheric physics and hypersonic research. During the last 51 years MORABA gained extensive experience during more than 500 rocket launches to support the investigation of scientific questions within a huge spectrum of research fields. [1]

Besides providing a full launch service, for many of these missions MORABA also develops new launch vehicle systems to meet the scientists' requirements. This can be the development and qualification of new kinds of launchers combining various rocket motors but includes also the steady improvement of the mechanical and electrical flight systems. To the last category belong systems for RCS, ACS and navigation. MORABA gained a lot of experience with this topic, for example during the SHEFEX II flight in 2012, where a precession maneuver was conducted [2] or the MAIUS mission in 2017 which required a very accurate attitude control for the generation of the first Bose-Einstein-Condensate in space. [3]

The needs for such type of missions include also accurate correlations of time, position and attitudes given by the sensors during flights. This is necessary for valuable and reliable scientific data. Therefore, MORABA continously works on the improvement of the accuracy of the experiment's state vectors and the related time basis. As a first step, a post-processing analysis was done for some flights using data fusion methods, e.g. [4]

2. Data Fusion

There are several methods for data fusion algorithms including stochastic methods, classification methods, fuzzy-logic and others. Sensor Fusion or data fusion based on Kalman filtering is a very well-known method to combine information from more than one data source [5]. The sources used in MORABA's sounding rocket mission are twofold: IMUs, and GNSS receivers. Considering these two different data sources, on one hand we have accurate data on instant position and velocities but with a low sample rate, without drifts and low noise levels from the GNSS systems and on the other hand we have sensor data sampled with high rates but afflicted by drifts and errors. The on-board combination of the different data sets with different attributes and uncertainties was conducted by Kalman fusion technique.

Fig.1 shows a principle diagram for data fusion based on Kalman filtering. The state and the process co-variance matrix, the Kalman gain and the measurement of the state are the most important parts of the process.

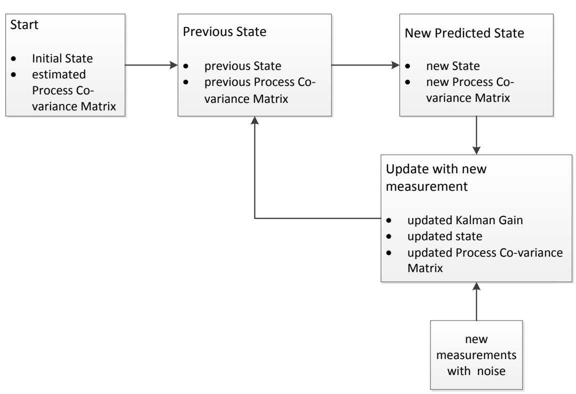

Fig. 1: Principle of Data fusion

In parallel, a data fusion, based on DLR GPS and IMU data sets, has been performed in post-processing but this time with a different technique. This data fusion technique uses control loops to minimize drifts in the attitude and position determination of the vehicle.

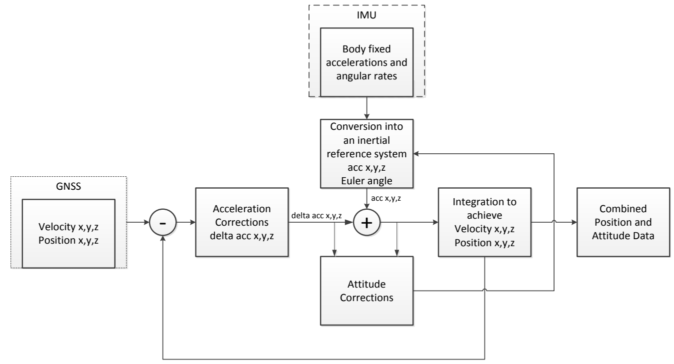

Fig. 2: Principle Scheme based on Control Loops

This technique includes control loops for the alignment of the GNSS and the IMU position, and in parallel an attitude correction is conducted on the basis of the measured and corrected acceleration vectors. As each control loop has a filtering behaviour, high frequency noise is dampened and drifts are compensated. Fig.2 gives a schematic overview of the method used.

Both data sets, the first achieved on-board during flight and the second done in post-processing, have been compared to each other. The results of the comparison will influence the decision which technique will be used in future sounding rocket missions. The comparison is illustrated in the graphs of this paper.

3. PMWE flight and used IMU and GPS receivers

The PMWE 2 flight launched at Andøya Space Center on April the 14th, 2018. The goal of this flight was to investigate so-called Polar Mesospheric Winter Echoes (PMWE's), an up to now not very deep investigated phenomenon in the higher atmosphere. The principal investigators for this mission are from the IAP in Kühlungsborn [6], Germany.

The flight was nominal, and the water tight payload could be recovered by ship approximately one hour after lift-off. The scientists requested a comprehensive navigation data set, which allowed an accurate determination of the angle of attack over the flight time. Therefore, different navigation system sensors had been installed in the payload to achieve a certain redundancy in case of a sensor failure. Also, in the post-flight processing in addition to the on-board data fusion experiment, a sound investigation of the data was made to gain as lot of information as possible out of the sensors' data.

3.1 DMARS Inertial Platform

DMARS-R is an inertial platform used by MORABA for measuring acceleration, velocity and position flight data as well as angular rates and rockets attitude, given in Euler angles or quaternions. The attitude determination is based on dynamically tuned rate gyros sitting on an inertially roll-stabilized platform. This ensures very high accuracy with 0.2 deg/hr non-g sensitive bias in attitude determination, even for launch vehicles with a spin rate about the longitudinal axis up to 20 Hz. One advantage of the platform is its capability of gyro-compassing which makes it completely independent of external references.

3.2 Novatel GNSS receiver

For the PMWE flights, two independent GNSS-receivers have been used. The GNSS receiver chosen for performing the on-board data fusion with DMARS-R data during the flight was the NOVATEL GPS/GLONASS (OEM STAR 10 Hz D-G) receiver. This receiver has the capability for processing GPS as well as GLONASS satellite signals. Its data have been sent to the DMARS-R platform for on-board data fusion during the flight.

3.3 Phoenix GPS receiver

The second of the two GPS sources for the PMWE flights has been the Phoenix GPS receiver, an in-house development by the GNSS and navigation technology group at GSOC, DLR Oberpfaffenhofen. This receiver was flown on many missions, also by MORABA. The Phoenix receiver constituted a source independent from DMARS and the Novatel Receiver for position and velocity determination. A good overview of the activities with this receiver, involved in the former MAIUS mission, can be found in [7].

4. Analysis and Evaluation of the results

The DMARS and the Phoenix GPS receiver performed well during the flight, but the Novatel GNSS receiver didn't deliver navigation solutions after lift-off until the first T+120 seconds. After 120 seconds flight time, the data fusion on the base of DMARS and Novatel GNSS data sets started und performed successfully. It is assumed, that the Novatel GNSS receiver lost track during the boosted phase of the rocket, and it took a while until it delivered navigation data during the coast phase of the flight. After the GNSS's recovery, the data fusion on the basis of DMARS and the GNSS data sets performed well.

For the purpose to compare the different data sources, the raw DMARS data and the improved navigation data set by fusion, an additional data fusion on the base of the Phoenix GPS receiver and DMARS data set was conducted by post-processing. Furthermore, this data fusion was performed in order to improve the accuracy of attitude and flight vector data until the recovery of the GNSS receiver.

Note that both GNSS receivers use different reference systems. The Novatel GNSS receiver's height information is based on Sea Level measurements, while the Phoenix GPS receiver's data set is aligned to the WGS 84 reference system. This causes a difference of several dozens of meters depending on the receivers' position.

The following graphs illustrate the results of the data fusion, and compare DMARS original data sets without fusion with DLR GPS, GNSS data, merged data and with a merged data set done by post-processing.

4.1 Altitude Determination

The figures 3 to 8 show the performance of the different sensors and fusions in determining the altitude of the vehicle during the flight. During some important flight phases a more detailed image is presented in order to highlight the difference between the different data sets.

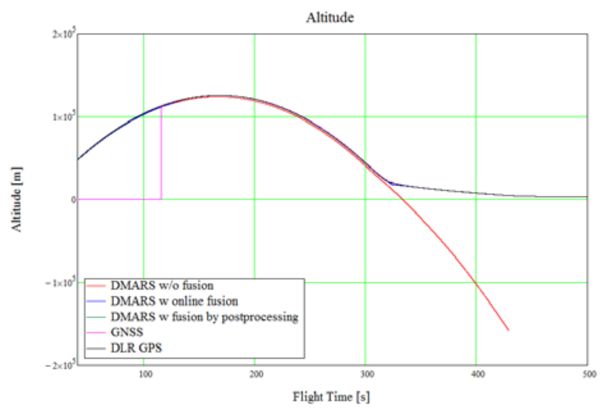

Fig. 3. Altitude, total flight time

Fig. 3 displays the altitude over the whole flight time. Two main aspects are obvious. First, the GNSS receiver recovered at approx. T+120 s, and later on the online fusion started. Second, during the re-entry phase the DMARS normally loses its orientation due to very high dynamics in this phase, and approaches ground without any deceleration without fusion.

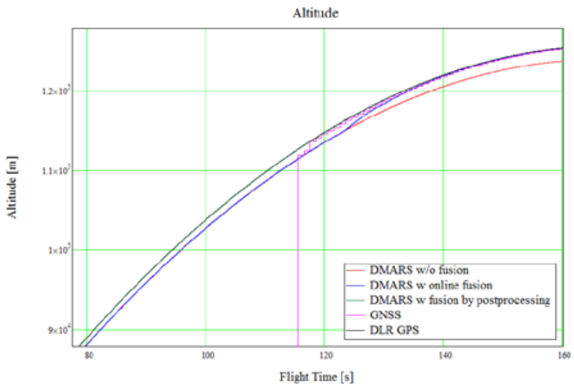

Fig. 4. Altitude at start of online fusion

Fig. 4 shows the start of data fusion and the combined altitude (DMARS with online fusion) following slowly the GNSS altitude. The DLR GPS receiver was able to determine the altitude over the whole flight time.

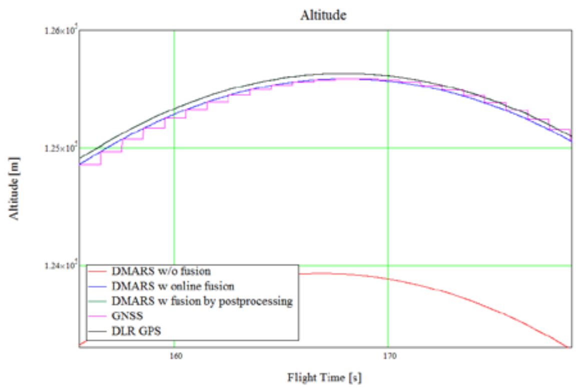

Fig. 5. Altitude at apogee

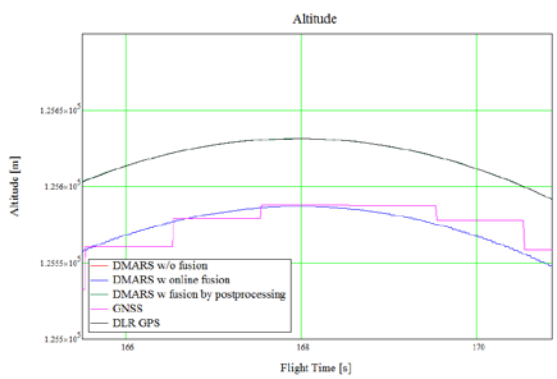

Fig. 6. Apogee zoomed in

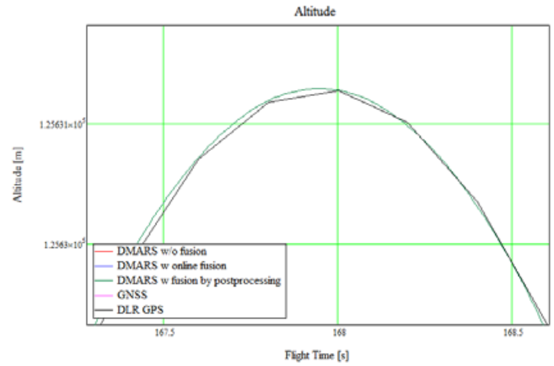

Fig. 7. Apogee zoomed in, DLR GPS and post-processed data

Fig. 5, 6 and 7 demonstrate the accuracy of the determination of the apogee by the different means. The difference between the DLR GPS and the GNSS is obvious and can be explained by the different origins of the altitude reference system at sea level and the WGS 84 system, which is expressed by a difference of about 80 m. The data fusion, on the base of the DLR GPS and the DMARS data set done in post-processing, points out a very high coincidence with the DLR GPS data set (see Fig. 7).

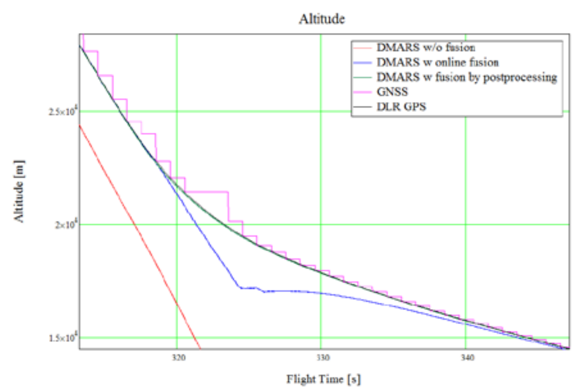

Fig. 8. Altitude at re-entry phase

During the re-entry phase, where the payload tumbled and finally entered a flat spin motion, the DMARS lost its orientation, because their lateral rate sensors went into saturation. This lack of orientation led to an almost movement to ground with nearly no deceleration while the other sensors recognised a deceleration in the altitude. The online fusion first followed the original DMARS altitude and later on it aligned to the GNSS altitude after 325 s.

4.2 Latitude Measurements

Figures 9, 10 and 11 display the latitude over the flight time. At approx. T+120 s flight time the fusion started and led to a slow alignment of the DMARS latitude towards the GNSS latitude. At the re-entry phase the fusion showed an overshoot in the determination of the latitude (fig. 10), but later on it aligned to the GNSS latitude determination. This overshoot is also aligned with the GNSS loss of track and the lack of capability to correct the DMARS latitude for a short while at re-entry at approx. T+320 s.

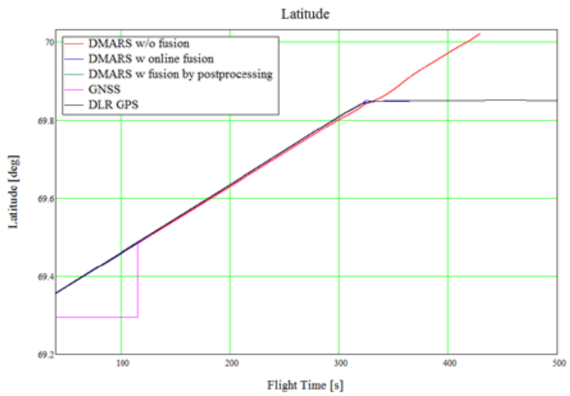

Fig. 9. Latitude over the whole flight time

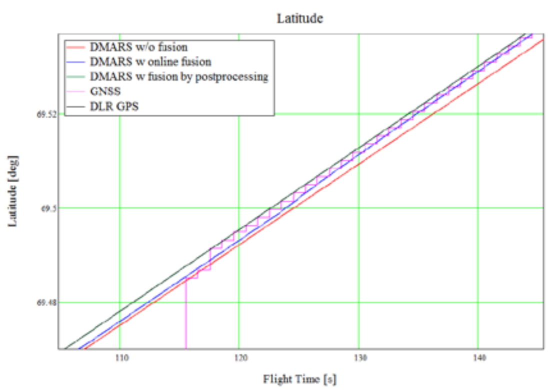

Fig. 10. Latitude at start of fusion

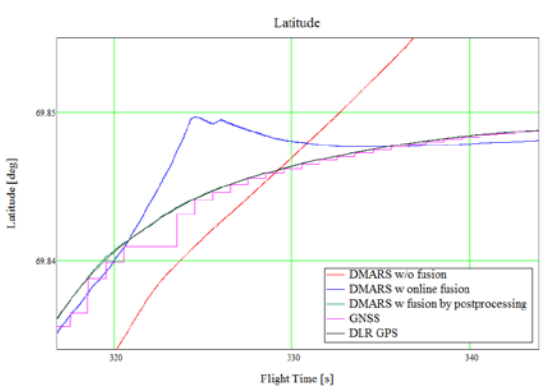

Fig. 11. Latitude at re-entry phase

4.3 Longitude Measurements

Figures 12 to 14 present the longitude determinations over time by the different sensors and means. The longitude curves show a similar characteristic as the latitude curves. At approx. T+120 s the fusion started, and at re-entry phase at about T+320 s the fusion could not follow the GNSS longitude determination and produced an overshoot of the longitude, too. In both cases it is obvious, that the data fusion by post-processing showed more accurate results.

The raw DMARS longitude and latitude determination showed that the DMARS sensors went into saturation as expected and therefore, DMARS lost its orientation, which is illustrated by an almost un-decelerated lateral movement during and after the re-entry phase.

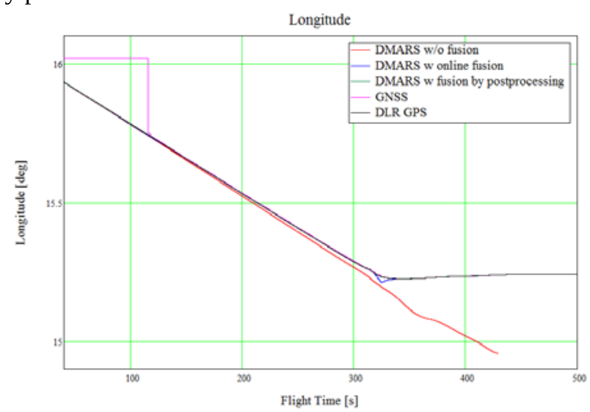

Fig. 12. Longitude over flight time

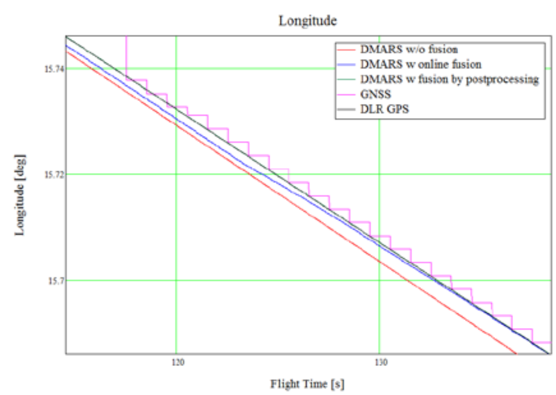

Fig. 13. Longitude at start of fusion

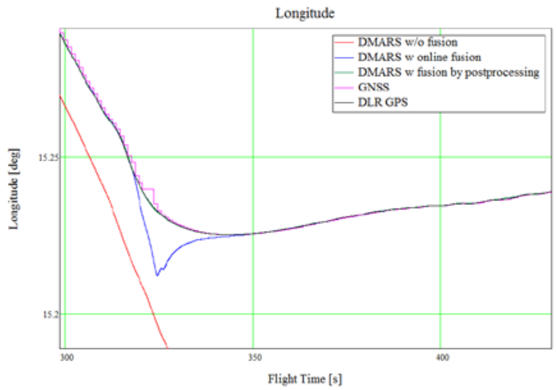

Fig. 14. Longitude at re-entry phase

4.3 Vertical Velocity Measurements

Figures 15 and 16 pick up the vertical velocity of the rocket over time. After the boosted phase, the DLR GPS receiver displayed an overshot in the determination of the vertical velocity (Fig. 15), which can be explained by the internal third order model of the GPS receiver and thus added inertial behaviour, which produces lag and lead times.

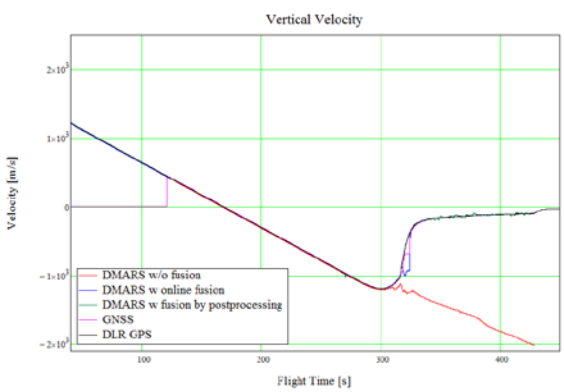

Fig. 15. Vertical velocity over flight time

It is also evident that, as mentioned before, the DMARS lost orientation and accelerated almost unbraked towards the ground (Fig. 15 and 16).

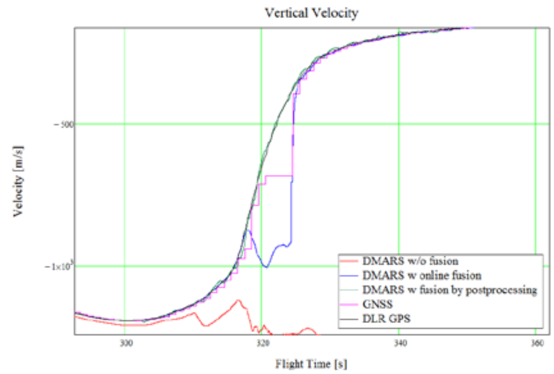

Fig. 16. Vertical velocity at re-entry phase

4.4 Attitude Corrections

During the boosted phase of PMWE 2 an attitude correction was performed by post-processing in order to compensate the initial attitude errors, which had been introduced by the Euler angle set up prior lift-off and during the drifts caused by the high spin, the acceleration, vibration levels and sensors' inaccuracies. The time for correction is short during the boosted phase, because the GNSS receivers are perturbed by several disturbances like multipath effects. Unfortunately, the attitude correction can only performed during measureable accelerations, like the boosted ascent and the re-entry phase. If one of the rate sensors experiences saturation it will be almost impossible to correct the achieved attitude by fusion.

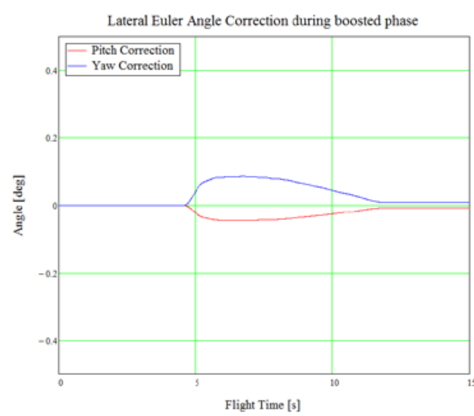

Fig. 17: Pitch and Yaw angle correction during boosted phase

5. Discussion

Although, the online data fusion during the PMWE 2 mission only partially worked properly, it showed promising results after the recovery of the Novatel GNSS receiver at about T+120 s. Further investigations and a closer contact to the manufacturer have to be performed to understand why the Novatel GNSS receiver lost track during the boosted phase after lift-off. Nevertheless, flight data have shown that the drifts of an integrating inertial measurement unit can be eliminated by the means of a GNSS system on board in time. Furthermore, it figured out, that especially uncertainties in the attitude set-ups at the launch pad prior lift-off could be also compensated by data fusion. This is a crucial issue, because the launch pad was close to the north pole, and the self-compassing capability of IMUs, which is based on measuring the earth rotation, is limited at very high latitudes. Additionally, it is a challenge to determine accurately the Azimuth of a launch beam at very high Elevation angles.

The PMWE 2 flight has shown that also GNSS receivers have a particular inertial behaviour, especially, when they experience highly dynamic flight characteristics. Most GNSS receivers are based on a third order model with an inherent inertia and producing lag and lead time, which can be compensated only in a limited dynamic range by prediction. Furthermore, induced by multipath effects of the received satellite signals, the accuracy of the GNSS's navigation solutions close to ground or launch pads is lower than expected. Performing a data fusion during this period, when multipath effects occur, lead to a degradation of the combined data sets of GNSS and IMU data. To overcome these effects it is advisable to evaluate the GNSS data before the fusion, and execute only a fusion, if the GNSS data is reliable.

6. Conclusions

The combination of the features of inertial measurement units and GNSS receivers will be standard not only in the field of sounding rockets but also in the aeronautical range. Especially, considering that more different GNSS constellations will be available in the future, this increases the reliability and accuracy. Additionally, cheaper inertial measurement units, based on MEMS, come into market, whose disadvantages of less accuracy can be compensated by accurate GNSS systems with higher sample rates.

Acknowledgements

We would like to thank the PMWE researcher and campaign team, as well as the team members from MORABA and GSOC, especially the GPS group, for their steady support. Furthermore, we would like to thank the manufacturing company of the DMARS platform, Inertial Science, Inc., California, for their steady support.

References

[1] R. Kirchhartz, M.- Hörschgen-Eggers, W. Jung, Sounding Rockets are unique Experimental Platforms, 69th International Astronautical Congress (IAC 2018), Oct. 1st –Oct. 5th , Bremen, Germany

[2] J. Ettl, J. Turner (2014) SHEFEX II Precession Control, SpaceOps 2014, May 5th -9th 2014, Pasadena, California, USA

[3] J. Grosse, S. Seidel et al., The MAIUS Sounding Rocket Missions – Recent Results, Lessons Learned and Future Activities, 68th International Astronautical Congress (IAC 2017), Sept 25th-Sept 29th Adelaide, Australia,

[4] J. Ettl, D. Kim, A. Schmidt, (2016) Using data fusion of DMARS-R-IMU and GPS data for improving attitude determination accuracy, Space Ops 2016, May 16th –May 20th, Daejion, Korea

[5] G. Giono, B. Strelnikov, H. Asmus, T. Staszak, N. Ivchenko und F.-J. Lübken, Detailed photocurrent characterization for meteor smoke particle detectors onboard the PMWE sounding rockets, Proceedings of the 23th ESA Symposium on European Rocket and Balloon Programmes and Related Research, 11 June-15 June 2017, Visby, Sweden, 2017.

[6] R. E. Kalman, A New Approach to Linear Filtering and Prediction Problems *(=* Transaction of the ASME, Journal of Basic Engineering*)*. 1960, S. 35–45

[7] B. Braun, A. Grillenberger, M. Markgraf, Performance Analysis of an IMU-Augmented GNSS Tracking System on board the MAIUS-1 Sounding Rocket, CEAS Space Journal. Springer, May 2018