A LOW COST INERTIAL NAVIGATION EXPERIMENT ONBOARD BALLOONS

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ABSTRACT

The paper presents a navigation experiment, successfully flown onboard BEXUS 6 balloon mission on 8th October 2008 from ESRANGE Space Center in Kiruna. Northrop Grumman Italia (NG Italia) according to multi-year collaboration plan with University of Rome "La Sapienza" has provided support to the students' team that proposed, designed and operated the LowCoINS (Low Cost Inertial Navigation System) experiment. LowCoINS has as the main component a low-cost three-axes inertial unit, integrating three accelerometers and three gyros, together with temperature sensors, three-axes magnetometer and a pressure sensor for augmentation purposes. Measurements from the sensors are both stored onboard and downlinked to a ground station making them available for a successive post-processing. Several tests have been exploited to verify the effectiveness of the choices operated in the design phase of the unit and its capability to withstand to all the environmental requirements. The data processing included the development and execution of different sensor fusion algorithm to obtain attitude, position and velocity data throughout the entire flight. An overview of the LowCoINS design philosophy, the extensive set of environmental test performed to validate the unit and a description of the algorithm used together with the results obtained are reported hereafter.

1. INTRODUCTION

MEMS (Micro Electro Mechanical Systems) is an enabling technology allowing the development of new sensors, opening to a multitude of users and applications. A growing number of inertial systems currently benefits of the MEMS technology allowing for inexpensive, small and lightweight inertial systems. The drawback of these sensors is their limits in performances, still far away from navigation grade, at least for commercial part. However, additional effort in signal conditioning, and above all in the data processing and filtering can improve the situation. This additional effort is strictly application dependant, and only knowledge and experience in the field lead to exploit the sensors at their best. Furthermore, in the project there is the option to augment the inertial measurements by means of complementary sensors based on different observables, i.e. earth magnetic field and atmospheric pressure. This additional effort is again application specific, and the validation of the meaningful aerospace-oriented therefore project require real flight tests. LowCoINS experiment started answering a call for proposal made by the European Space Agency (ESA) within the frame of the BEXUS (Balloon-borne Experiments for University Students) programme.
BEXUS platform consists in a stratospheric balloon able to carry approximately 100 kg of payloads which is launched from ESRANGE space center in Kiruna (Sweden).
The slow dynamic typical of a balloon flight does not stress too much the sensors' requirements, however clearly expose all the components to extreme temperature variations leading to the implementation of an active thermal control system to limit temperature changes. Inertial data alone are not sufficient to provide a reliable and stable navigation solution and this is particularly true when low cost inertial sensors are used as in the case of LowCoINS. To damp the errors of the inertial measurement unit (IMU) the system implements a three-axes magnetometer and a pressure sensor for aiding. Moreover, also GPS data from the BEXUS avionics can be used to improve the overall system accuracy as it acts as an aiding and as a reference at the same time. It is thereby necessary to implements sensor fusion algorithms, such as Kalman filters, to mix and to put together different data from different sensors. In the following paragraphs, after an overview of the LowCoINS experiment's characteristics and requirements, will be shown the algorithms used to compute the attitude, the position and velocity of the BEXUS 6 gondola during the entire flight.

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2. SYSTEM OVERVIEW

The heart of the system is its inertial measurement unit (IMU). The IMU implemented in the experiment is a low cost commercial-off-the-shelf sensor produced by ANALOG DEVICES type ADIS16355. This piece of hardware is an highly-integrated digital inertial sensor containing three accelerometers and three gyros mounted along three orthogonal axes realizing the typical strap-down mechanization [1]. Accelerations and turn rate data are made available from the sensor through a serial SPI interface with a resolution of 14 bit. Moreover, the sensor hosts all the signal conditioning and conversion circuitry providing an excellent and easy-to-use all-in-a-box solution. The three-axes magnetometer outputs provide aiding in the attitude determination and it is obtained joining a two-axes magnetometer FGM-2 to a single-axis FGM-1 sensor. The sensors provide a digital output with 16 bit resolution. The pressure sensor is used as a barometric altimeter, leading to an accelerometers-independent system for the vertical position determination and together with the temperature sensors, is the only analogue sensor present in the project. The wide use of digital-output sensors allowed for an easy circuit design avoiding all the signal conditioning and conversion circuitry to be present in the PCB as they are embedded in the sensor packages. Power supply is provided by an embedded battery pack and regulated to the correct operational voltages by the use of switching regulators to increase the efficiency.

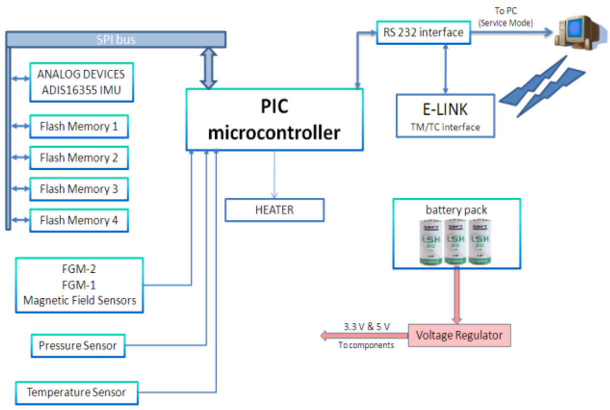

Figure 1.Functional block diagram

2.1. Data handling

The sensors are read by a Microchip PIC® microcontroller which is also responsible for all other tasks required by the system. These includes to store all the data gathered from the sensors into four serial SPI flash memories. Even though the recovery of the gondola is most likely to occur, it is not granted to be able to recover the experiment. This is the main reason why the same data stored onboard are continuously downlinked to the ground by the use of the telemetry interface E-link made available to experiments as a standard avionics of the BEXUS flights. The use of a Telemetry/Telecommands interface allows to continuously monitor the unit operations during the mission and also allows to reconfigure the system in flight if necessary.

The overall amount of information to be stored onboard and downlinked to ground is a data frame 24 bytes long. The data frame is generated every 50 ms, leading to an update rate of 20 Hz for the most critical inertial and magnetic data. Other data such as pressure and temperatures measurements are gathered, together with ancillary data as system status and diagnostics, at a lower rate (2 Hz) defining the Cyclic data bytes. Thus, the total data rate is 3840 bit/s that is well within the maximum telemetry channel capacity of 9600 bps. The onboard memories adopted make available a total capacity of 128 Mbit allowing for 10 hours of data recording.

2.2. Thermal control and mechanics

In the unit is present an active thermal control to keep the system temperature within components' operational temperature ranges. The thermal control is also demanded to the PIC that acquires the system temperatures and control the switching of an heating plate placed above the electronics.

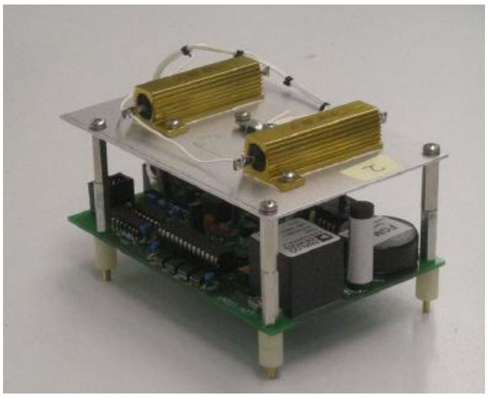

Figure 2. System overview

A temperature sensor is placed on the heater for feedback purpose. The power required to the thermal conditioning (10 W) is largely dominant with respect to the amount needed for the electronics (<1W), leading to the inclusion of three SAFT LSH20 Lithium cells with nominal capacity of 13 Ah.

The electronics, together with the battery pack is hosted in an housing safely constrained to the gondola. The case provides mechanical protection to the unit as well as a primary thermal protection to maintain the components' operational temperature range. Data from previous flights leads to extend the temperature range down to -90°C, which is definitely out of the operational region for all the components. Moreover, the mission profile is extremely demanding on this aspect, as the pre-launch time can last several hours at an external temperature to be conservatively assumed as quite low. These issues suggested to insulate the box with foam to provide both vibration protection and poor conductivity to the external environment.

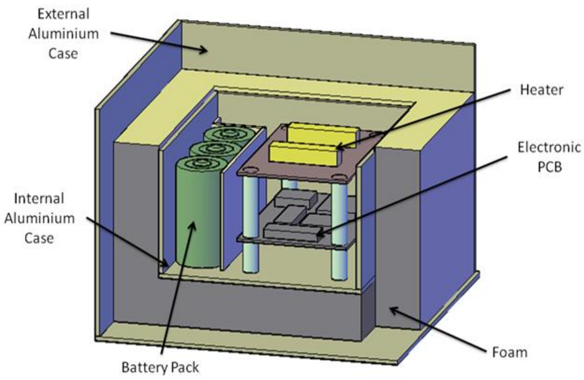

Figure 3. Mechanical design

2.3. Pre-flight tests

Data from previous BEXUS missions points out some variability on typical thermal loads that experiments withstand during the flight. It depends upon several different aspect and may vary upon day or night flight or the kind and location of equipment that can be seen as additional thermal loads nearby the experiment. Evidently worst case conditions should be considered as a guideline for the thermal design. Environmental tests are required to validate the thermal aspect of LowCoINS. All the tests have been performed in Northrop Grumman Italia S.p.A. that kindly made their equipments available to the team, and particularly the thermal-vacuum chamber needed. The typical experimental setup foresees the following conditions:

- Temperature to -70 °C
- Pressure to 5 mBar

Even though the lowest temperature set point is not -90°C, test conditions are close enough to the worst case to be able to successfully validate the system. Moreover, it is much easier for the thermal chamber to lower the temperature to the set point before to decrease the pressure to the near vacuum when conduction/convection heat transfer is inhibited. This fact, together with the descent rate for the temperature and pressure adopted for the tests well above to the real rates of a typical ascent phase, make the experimental setup to be harder than the expected actual flight. The experimental setup is completed by the use of several thermocouples placed in different locations to monitor:

- Internal chamber temperature
- Internal and external case temperatures
- Experiment internal temperature

The test results shown in Fig. 4 is about the final validation test that lasted 8 hours and demonstrated that the unit succeeded to keep the system temperature near the set point of 10 °C independently to the external temperature. The temperature set point chosen proved to be a good trade-off between overall thermal dissipations and acceptable battery de-rating, besides compliant with all components involved.

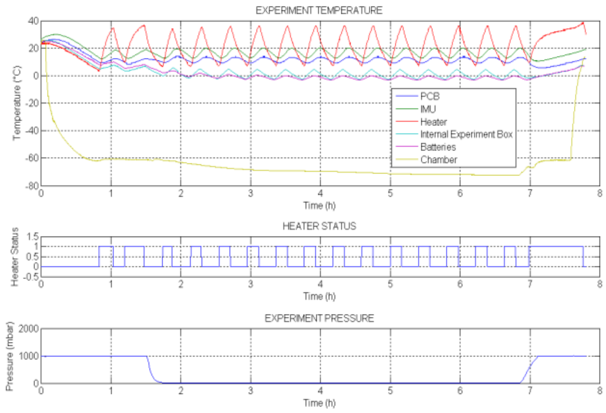

Figure 4. Thermal-vacuum test

Heater intervention has been constantly monitored and proved the power supply to be well dimensioned to cope the entire flight.

Besides the environmental tests, the collaboration with Northrop Grumman Italia S.p.A. allowed also to perform a precise calibration of the inertial measurement unit and the magnetometer as well.

3. FLIGHT RESULTS

3.1 LowCoINS INS/GPS performance

Given the ability to measure the acceleration, it is possible to calculate the change in velocity and position by performing successive mathematical integrations of the acceleration with respect to time. In order to navigate with respect to an inertial reference frame, it is necessary to keep track of the direction in which the acceleration are pointing. Rotational motion of the body with respect to the inertial reference frame is sensed using gyroscopic sensors and used to determine the orientation of the accelerometers at all times. Given this information, it is possible to resolve the accelerations into the reference frame before the integration process takes place. By combining the two sets of measurements, it is possible to define the translational motion of the vehicle within the inertial reference frame and so calculate its position within it. Moreover, inertial navigation systems do rely upon the availability of accurate knowledge of vehicle position at the start of navigation. The inertial measurement are then used to obtain estimates of changes in position which take place thereafter. [1]

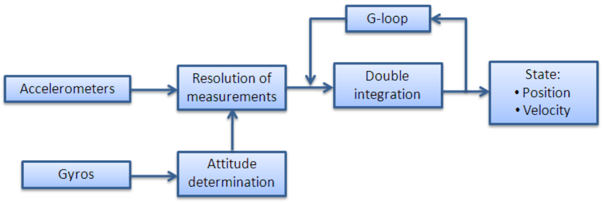

Figure 5. Inertial navigation process

Inertial navigation is a dead-reck process, meaning that calculated position will sooner or later diverge from the true position due to accumulation of errors. It is than necessary to have a reference that does not rely upon the integration of inertial measurements to dump position and velocity errors. This reference is represented by GPS data available from the BEXUS standard avionics. Then information from the inertial system and GPS are fused together by the use of a classic Kalman filter.
The Kalman filter estimates a process by using a form of feedback control: the filter estimates the process state at some time and then obtains feedback in the form of (noisy) measurements. As such, the equations for the Kalman filter fall into two groups: time update equations and measurement update equations. [2]
The Fig. 6 shows the whole process of the Kalman filter.

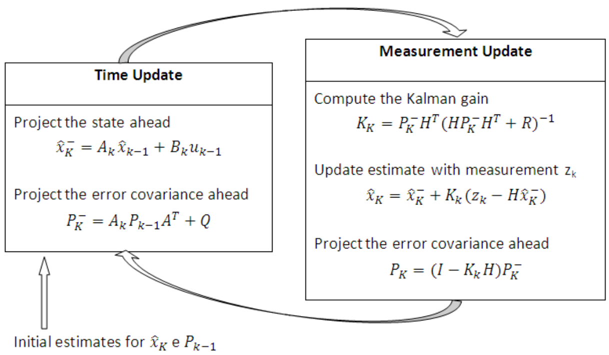

Figure 6. Kalman Filter

The time update equations are responsible for projecting forward (in time) the current state and error covariance estimates to obtain the a priori estimates for the next time step. The measurement update equations are responsible for the feedback, i.e. for incorporating a new measurement into the a priori estimate to obtain an improved a posteriori estimate. [2]

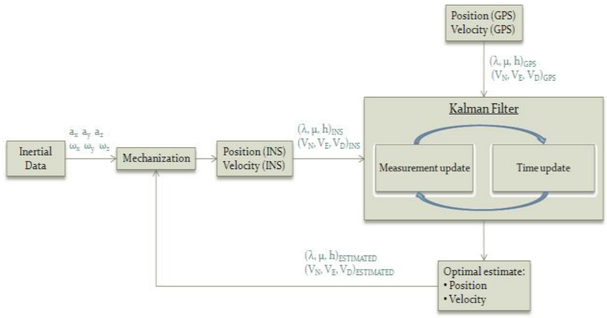

Figure 7. INS/GPS integration

The integration mode used for the Kalman filter is a loosely-coupled. This configuration envisages a first Kalman filter in which GPS raw measurements are analysed to determine the GPS positions and velocities in a geographic coordinate system; then, in a second Kalman filter, these data are combined with the analogous INS measurements in order to calculate more reliable positions and velocities.

This method allows to calculate the BEXUS 6 trajectory during the entire flight, as shown in the Fig. 8 and Fig. 9.

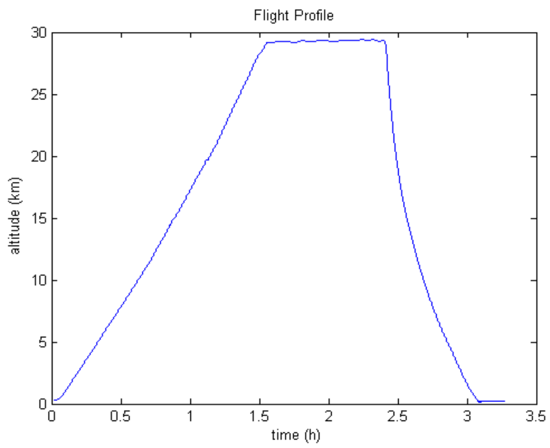

Figure 8. Flight profile

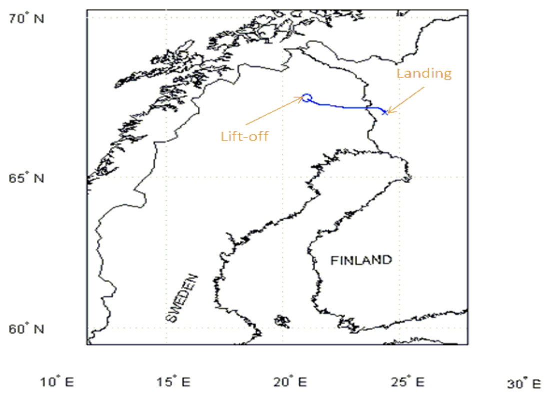

Figure 9. Trajectory

RMS errors between positions and velocities obtained from the Kalman filter and the analogous measurements from the GPS are shown in the Tab. 3.

	Latitude	Longitude	Altitude
RMSE	2.1 m	2.3 m	15.8 m

Table 1. Position Root-Mean-Square Error

A detail of the flight trajectory is in Fig. 10, where appears evident the gap between the filtered solution from the "true" solution represented by the GPS data.

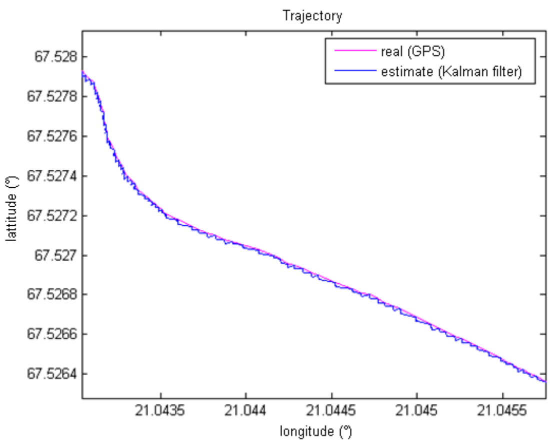

Figure 10. Flight trajectory comparison

3.2 LowCoINS AHRS performance

In order to have an acceptable navigation performance, LowCoINS needs to be integrated with a GPS receiver and it is not able to navigate for long time periods without periodic re-initialization.

However, there is an application where the system alone is able to provide acceptable results. An Attitude and Heading Reference System (AHRS) that uses inertial data to compute the system orientation in space is an example. The attitude of the gondola can be very useful for a wide range of balloon borne experiments, and it is an information that is not available from the BEXUS standard avionics. The working principle of the LowCoINS used as AHRS is to integrate the angular velocity from the gyros to determine the attitude, while bounding the unavoidable drift of the attitude, mainly due to gyros biases, using the magnetometers and/or accelerometers as an auxiliary system for the attitude determination. The fusion of the attitude data computed from the integration of the gyros output with the one from the manipulation of the information from accelerometers and magnetometers is achieved using a sensor fusion algorithm such as a Kalman filter.

It is therefore necessary to define a process model and a state vector associated with it. In the formulation of the Kalman filter the state is defined by 7 parameters: 4 components of the attitude quaternion and 3 gyro's biases (Eq. 1).

$$x = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \\ b_x \\ b_y \\ b_z \end{bmatrix} \qquad (1)$$

Quaternion-based attitude representation has been preferred because of the absence of singularity, even though the dynamic of the balloon itself avoids to reach conditions close to singularity.

$$\begin{aligned}
\dot{q_1} &= -\frac{\left(q_2(\omega_x-b_x)+q_3(\omega_y-b_y)+q_4(\omega_z-b_z)\right)}{2\sqrt{q_1^2+q_2^2+q_3^2+q_4^2}} \\
\dot{q_2} &= \frac{\left(q_1(\omega_x-b_x)-q_4(\omega_y-b_y)+q_3(\omega_z-b_z)\right)}{2\sqrt{q_1^2+q_2^2+q_3^2+q_4^2}} \\
\dot{q_3} &= \frac{\left(q_4(\omega_x-b_x)+q_1(\omega_y-b_y)-q_2(\omega_z-b_z)\right)}{2\sqrt{q_1^2+q_2^2+q_3^2+q_4^2}} \\
\dot{q_4} &= \frac{-\left(q_3(\omega_x-b_x)-q_2(\omega_y-b_y)-q_1(\omega_z-b_z)\right)}{2\sqrt{q_1^2+q_2^2+q_3^2+q_4^2}} \\
\dot{b_x} &= 0 \\
\dot{b_y} &= 0 \\
\dot{b_z} &= 0
\end{aligned} \qquad (2)$$

The process model identifies the dynamic of the system (Eq. 2). The dynamic of the quaternion is well known [1], while for the biases it is assumed a null dynamic. This assumption is not completely true, as biases of the gyros vary with time constant of the order of hundreds of seconds, but it can be taken into account acting on the error process covariance matrix that defines how close is the process model to the true dynamic.

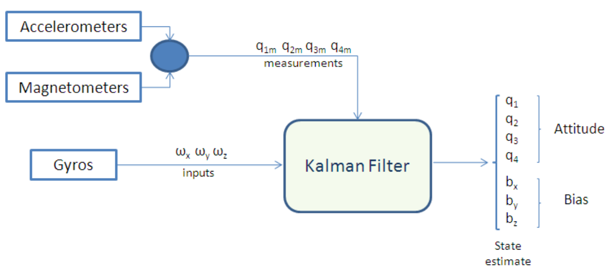

Figure 11. Kalman filter for AHRS

Several methods of attitude determination using accelerometers and magnetometers are available in literature [3] and they rely upon resolving gravity and

earth magnetic field components in body frame to determine attitude angles. The use of the gravity vector to determine the attitude is only possible when is the gravity the only acceleration sensed by the inertial sensor. Clearly this condition is not always verified, but it is valid for most part of the flight due to the slow dynamic of a balloon flight. The gyro-independent attitude obtained from accelerometers and magnetometer, in terms of quaternion, is used to update the system state with the measurements and more importantly, allow the output equations to be linear, which greatly simplifies the design of the filter.
Flight results are shown in Fig. 12 that represent the lift-off and early ascent phase.

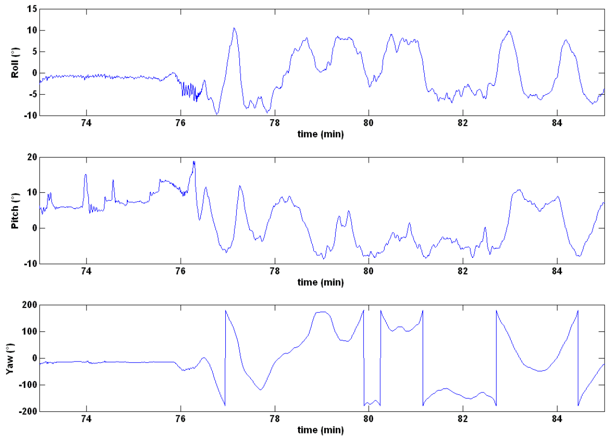

Figure 12. Attitude at liftoff

Once the experiment has been recovered, it has been possible to validate the performances of LowCoINS used as AHRS by the means of professional AHRS joined to it and acting as a reference. In order to provide a benchmark, LowCoINS has been compared to a NGI unit (the LISA-200) in a combined setup. Results, reported in Fig. 13, show a quite good agreement between units.

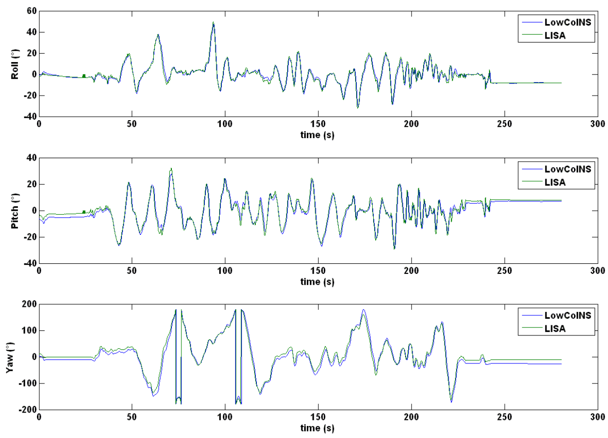

Figure 13. Attitude data comparison

Root-mean-square error reported in Tab. 4 shows the yaw error to be one order of magnitude larger with respect to the pitch and roll errors and this is primarily due to magnetometers used to damp that axis.

RMS Error		
Roll	Pitch	Yaw
2.20°	2.53°	13.35°

Table 2. Attitude Root-Mean-Square Error

4. CONCLUSIONS

An overview of the LowCoINS design philosophy, the extensive set of environmental test performed to validate the unit and a description of the algorithm used together with the results obtained have been reported. The environmental test held allowed to validate the system before the mission, and proved the unit was able to fulfill all the requirements. The flight has been successful, the unit worked as expected and no anomalies have been encountered. The big amount of data available after the flight enabled an extensive post-processing. Different filtering solution allowed to obtain attitude, position and velocity solution for the whole flight. The consequent results are in-line with the capabilities of the sensors involved. LowCoINS architecture will be used as a baseline structure to improve with other augmentation sensors. NG Italia will provide support to the university according to the student team collaboration.

5. REFERENCES

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