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# MEMS based inertial navigation systems onboard balloons

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**Abstract.** Performances of low-cost inertial navigation sensors, usually poor, can often match different mission requirements by means of a careful signal and data processing and/or an augmentation by means of different observables. The paper presents the LOWCOINS navigation experiment, intended to fly onboard BEXUS balloon mission in late 2008. LOWCOINS has as the main component a low-cost three-axes inertial unit, integrating three accelerometers and three gyros. The slow dynamic typical of a balloon flight is deemed as an ideal test to verify the performances of the unit and to improve the knowledge on the data processing needed to obtain an accurate final navigation solution. In order to enlarge the set of available data, a cluster of magnetometers and a pressure sensor, always belonging to low-cost instrumentation range, are hosted on board. Measurements are both stored on board and downlinked to a ground station. Position and velocity components (both the onboard computed first guess and the post-flight calibrated solution) will be compared with the data gathered by a GPS receiver, which is a standard component of BEXUS balloon avionics. Substantial attention to thermal aspects has been requested in order to cope with environmental conditions prior of and all along the flight. The requested navigation unit case design is shortly reported.

**Key words.** Inertial Navigation Systems – MEMS – INS augmentation – Balloon Navigation – Ballooning Thermal Issues

## 1. Introduction

The appearance of low-cost inertial sensors, like the ones belonging to the Micro-Electro-Mechanical Sensors (MEMS) class (Helvajian 1999), has the potential to change the navigation scenario in several applications. Their limited impact in volume, mass and power requirements, their capability to match modern strap-down architectures without constraints on accomodation or vibration insulation, together with extremely reduced procurement costs due to the manufacturing techniques typical of ICs mass production, opened to inertial navigation new possibilities. The drawback of these sensors is their limits in performances, still far from navigation grade at least for commercial part. However, additional effort in signal conditioning, and above all in data processing and filtering can improve the situation. This additional effort is strictly application de-

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*Send offprint requests to*: G.B. Palmerini pendent, and only knowledge and experience in the field lead to exploit the sensors at their best. Furthermore, in many projects there is the option to augment the inertial measurements by means of complementary sensors, based on different observables. This additional effort is again application specific, and the validation of a meaningful aerospace-oriented project therefore require real flight tests.

Within this frame, it was deemed of great interest for graduate engineering students to work on a complete navigation unit based on MEMS components and possibly augmented by pressure and magnetic sensors. The chance was given by the European Space Agency (ESA) Balloon EXperiment for University Students (BEXUS) initiative, promoting a call for student payloads at the beginning of 2008. The (successful) entry of a team from Università di Roma La Sapienza was a navigation unit labelled LOWCOINS, standing for LOW COst INertial System. The main component of the navigation unit is a three axis MEMS inertial unit, which measurements allow for the determination of the kinematic state of the balloon. LOWCOINS effort has been primarily motivated by the possibility to acquire hands-on experience on MEMS application and measurements exploiting in a operative yet favourable - due to balloon slow dynamics - environment. Furthermore, BEXUS balloons offer the chance of a benchmark solution for position and velocity by means of GPS data provided by a receiver which is a standard part of the flight avionics. To improve the capabilities of the LOWCOINS unit, a pressure sensor and complete set of magnetometers (a single axis and a two axes unit) were added. Even these sensors have been selected within the frame of the low-cost $components-off-the-shelf$ (COTS) philosophy, deemed as the most suitable to student projects.

In the next paragraphs, BEXUS characteristics are briefly recalled, followed by a general description of the LOWCOINS experiments and of the selected sensors. The proposed housing, and the way to satisfy, by means of a temperature-conditioned case with active heaters, the operational requirements of the sensors, are then discussed.

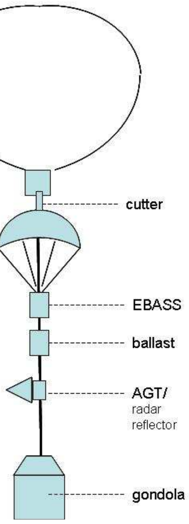

**Fig. 1.** A sketch of the BEXUS platform.

## 2. The BEXUS platform

BEXUS initiative is based on a platform (BEXUS 2007) including the $12000m^3$ balloon, the cutter/parachute release system, the avionics bay dubbed EBASS, the AGT compartment hosting transponder and GPS receiver and the gondola with the payload. The gondola sizes $1.42m \times 1.42m \times 1.2m$ for a total experiment mass up to $100Kg$. Different mechanical fixings and accommodations on the gondola are possible, to be selected on the basis of the specific payloads flying together. Each experiment should provide its own power supply, if requested.

BEXUS launch campaigns are based at the Esrange in Kiruna (Sweden), and typical flights last 2 to 5 hours, with final gondola recovery. Maximum altitude is between 25 and $35km$, depending on the payload mass and the resulting ballast computation. Acceleration experienced by the gondola is expected to be in the $\pm 10$ and $\pm 5$ along vertical and horizontal directions respectively, while nominal landing velocity is in the order of $8m/s$. BEXUS balloons maintain a continuous bi-directional link, via UHF telecommand-telemetry channel and high data rate S-band Esrange Airborne Data Link (2Mbps).

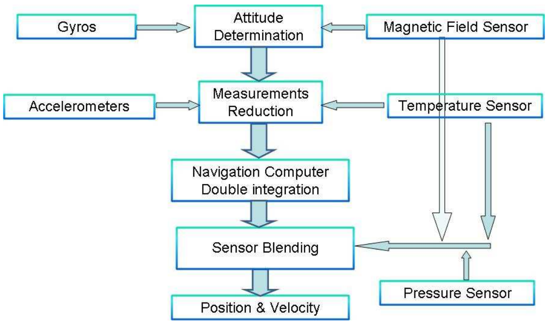

**Fig. 2.** Functional skecth of the LOWCOINS tasks.

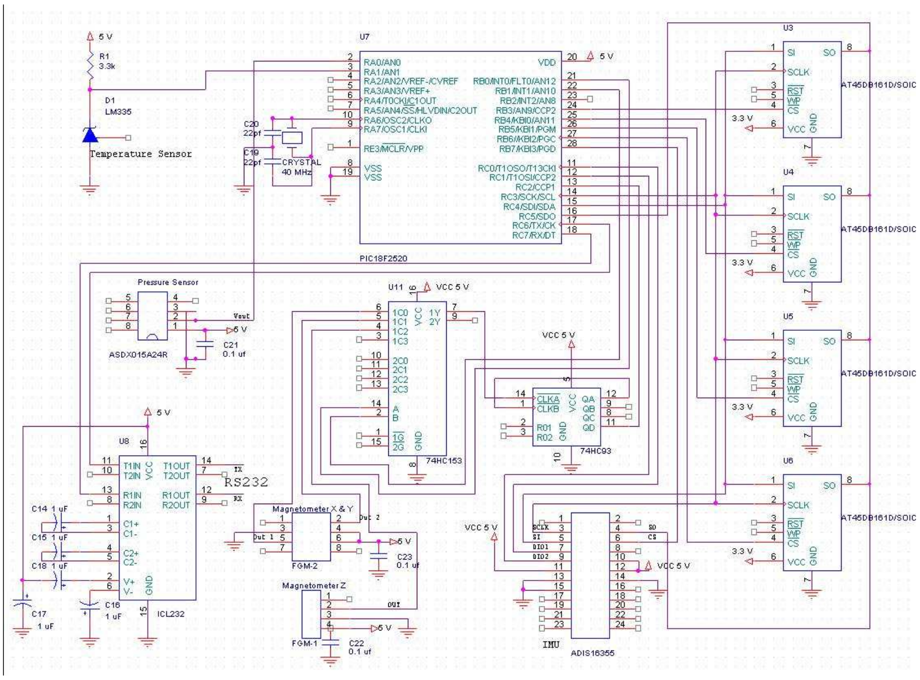

**Fig. 3.** Scheme of the main LOWCOINS PCB.

## 3. LOWCOINS experiment

Figure 2 reports a flow chart for LOWCOINS tasks. The core is represented by an inertial measurement unit realizing a typical strapdown mechanization (Titterton, & Weston 1997), with sensor readings in body frame, followed by accelerometers measurements translation in navigation axes by means of the attitude matrix computed with gyro outputs. The navigation computer carries out the double integration, together with the g-loop and the apparent forces evaluation, so producing the basic INS solution. The augmenting sensors help in different ways: the cluster of two magnetometers primarily allows for attitude update; the very same information can be considered at a later stage as an auxiliary

**Table 1.** Amount of data gathered

| Measurement | Number of meas. per step | Resolution (bits) | Memory occupation (bytes per sample) | Sampling frequency Hz |
|---|---|---|---|---|
| accelerations | 3 | 14 | 2 | 20 |
| angular rates | 3 | 14 | 2 | 20 |
| magnetic field | 3 | 16 | 2 | 20 |
| temperature | 1 | 12 | 2 | 1 |
| pressure | 1 | 10 | 2 | 1 |

information on position (even if plagued by the poor accuracy in the representation of the magnetic model). Also the pressure sensor acts as an augmentation source for the position solution, precisely with respect to the vertical channel which is disrupted at the foreseen flight duration (longer than Schuler period) by the g-loop instability. The temperature sensor included in the INS unit allows for calibration, entering the computation before data reduction. Furthermore, the output of other temperature sensors, external to LOWCOINS and referred to the environment, can be used in connection with pressure data to acquire information about the atmospheric vertical profile, as an augmenting source.

A complete exploiting of gathered data, with all functions depicted in Fig. 2, will be performed only off-line, after the flight. In particular, a sequence of re-alignments of the inertial unit will be attempted, using as a benchmark the navigation solution independently provided by the BEXUS GPS receiver.

Note that the customary strapdown mechanization is extremely critical as far as it concerns the update of the rotation matrix, and the complete band - in the order of hundreds of Hz - provided by sensors is typically used in inertial units. Such a complete exploitation is out of reach with the foreseen LOWCOINS computation architecture, and, even if attained, should not be considered as the end of the navigation task. In fact, the availability of the augmenting sensors calls for a refined filtering of any different possible input, and for their optimal blending, requiring even more resources to the logical unit. Based on these consideration, the focus has been intentionally placed on the data gathering (to have the most complete data set available for later analysis and processing) instead of on the real time computation, and the tasks assigned accordingly.

## 3.1. Sensor selection

The main issue in LOWCOINS is the selection of the inertial unit, which has been identified in the Analog Devices ADIS16355 model, providing all-in-a-box three orthogonal acceleration and angular rate measurements, completed by temperature data close to the sensors, which are useful to calibrate the sensor behavior. Measurement ranges are ± $3g$ and ± $300\,\deg/s$, with 14 bits (13 plus the sign bit) resolution. The output interfaces to a serial bus, leading to an easy solution for the logic architecture.

Selected miniature magnetometers are from Speake and Co., FGM-2 (2 axes, on the nominal horizontal plane) and FGM-1 (aligned to the nominal vertical) model; both the components output a 5V rectangular pulse with a period depending on the field strenght.

The pressure sensor is the Honeywell ASDX015A24R, measuring the absolute environmental presure in the range from 0 to 15 psi, with a 0.267 V-psi scale factor.

## 3.2. Data Handling

The main Printed Circuit Board (PCB) accommodates the inertial sensor, the two magnetometers, the pressure sensor and the hardware to control these sensors, handle the data flow and interface with the datalink (see Fig. 3 for the relevant scheme). The logic is a PIC (Microchip 18F2620), with the companion crystal, which polls in a programmed sequence all sensors and handles on a SPI bus the gathered data, storing them in the four flash memories present in the PCB. This is considered the main task, as BEXUS flight history makes the soft landing a likely option, and post-flight accurate data exploiting a real possibility. Table 1 gives the amount of data from different sensors to be handled per step, leading to a minimum volume of 2912 bps, and to about 6.4 hours of continuous recording with the presented architecture. As its second task, the PIC controls the downlink of the most significant part of the data, to provide a back-up in case of impossible recovery of the memories. Any remaining computation capability is left to a preliminary, uncalibrated navigation solution obtained directly onboard.

A second, simpler board hosts the regulators that make available the range of stabilized voltages required by different sensors and handles the heaters.

## 4. Housing, power and thermal considerations

The sensors and the printed circuit board need a case to safely constraint them to the gondola and protect from vibration. Furthermore, this accommodation should include the power supply for the unit, and take into account the thermal protection needed to maintain the components' operational temperature range. Data from previous flight leads to extend the temperature range down to $-90\,^{\circ}C$, which is definitely out of the operational region for all the sensors. 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, and to install active heaters to maintain the sensor-accepted thermal range. Switching of the heaters is demanded to the PIC, and approximate thermal analysis and extensive thermal vacuum tests helped to correctly seize the batteries. As expected, the power request for thermal conditioning is largely dominant with respect to the amount needed by electronics, leading to the inclusion of three SAFT cells LSH20 with an effective capacity of 7 Ah.

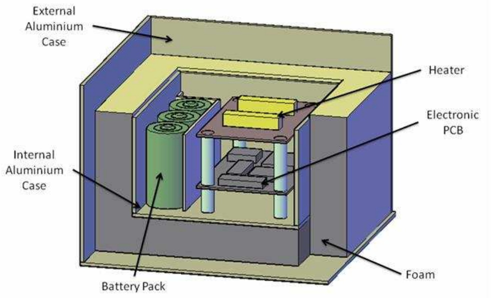

**Fig. 4.** LOWCOINS housing, highlighting the attention to thermal issues.

## 5. Final remarks

The ESA call for payloads to fly onboard BEXUS balloons has been deemed of relevant interest for a student project aiming to evaluate the performances of low cost MEMS inertial sensors. A cluster including a three-axes complete inertial unit, augmented by pressure sensor and magnetometers, has been proposed to and accepted by ESA. The unit provides for both first guess uncalibrated solution on board as well as for real time downlink and back-up storage of the measurements gathered. In addition to test all-the-way long the sensors and data processing issues, with the solved for kinematic state to be validated through balloon standard GPS navigation solution, the experiment can provide the previously unavailable attitude data for the gondola. BEXUS flight hosting LOWCOINS unit is foreseen in October 2008.

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