COMPASS: A STUDENT EXPERIMENT FOR MAGNETIC FIELD MEASUREMENT ON STRATOSPHERIC BALLOON BEXUS-9

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ABSTRACT

This paper describes the COMPASS experiment, designed and realized by a team of four students of the Space Robotics Laboratory of the II Faculty of Engineering of the Alma Mater Studiorum University of Bologna, successfully launched on the stratospheric balloon BEXUS-9 from ESRANGE (Kiruna, Sweden) in October 2009. The scientific aims of this experiment are the measurement and analysis of the geomagnetic field and solar flux, in particular to verify the accuracy of the standard IGRF model at a local scale; a secondary objective is the balloon gondola attitude determination. The experiment sensors are a magnetometer for the magnetic field measurement, an Inertial Measurement Unit, two cameras and a Sun sensor for the gondola attitude determination. The COMPASS experiment subsystems are described in the paper and the data analysis is discussed. Optimum results have been obtained in every application field of the experiment.

1. INTRODUCTION

The COMPASS experiment, successfully launched on BEXUS-9 (Balloon Experiment for University Students) in October 2009, is a project designed and realized by a team of four students of the Space Robotics Laboratory of the II Faculty of Engineering Alma Mater Studiorum University of Bologna.
The main scientific aim of COMPASS (Calculating & Observing Magnetic Polar field At StratoSphere) experiment is the study of the Earth magnetic field at local level. In particular the mission consists of measuring the intensity and the direction of geomagnetic field and comparing these data with the international standard model IGRF (International Geomagnetic Reference Field), in order to point out possible gaps. The reason of this research is the importance of the geomagnetic model in the aerospace applications, from the airplane navigation to the satellite attitude determination. Besides, another objective of the project is measuring the solar flux in a wide range of altitude. Considering the link between geomagnetic field and solar flux, these data provide a motivation of possible anomalies in the magnetic measurements. Moreover, the experiment opens the possibility of testing and validating the sensors and components behaviour, in order to use them in subsequent missions. In order to obtain its purposes, the experiment needs to have an ADS (Attitude Determination System), which is a secondary target of the mission.

2. COMPASS DESIGN OVERVIEW

In Fig. 1 a diagram of the general overview of the experiment is shown.
The main instrument is a three-axial magnetoresistive magnetometer (Honeywell HMR 2300 [1]) which provides an array containing the geomagnetic field components in BRS (Body Reference System). The IGRF data are given in a TRS (Topocentric Reference System), so it is necessary to rotate them to obtain the magnetic field values in the same reference system.
For this reason the experiment is equipped with an ADS composed by three sensors. An IMU (Inertial Measurement Unit), a MEMS (Micro Electro Mechanical System) component (MicroStrain 3DM-GX2 [2]) made up of three accelerometers and three gyros, supplies accelerations, angular rates and rotation matrix. A Sun sensor, designed and realized by the team, provides the direction of the Sun in the gondola's reference system (BRS) and the solar flux intensity. It is an analog sensor, that uses the currents generated by five solar cells, placed on the faces of a cubic structure as shown in Fig. 2, to obtain its outputs. Finally, a horizon sensor that is composed by two cameras pointed parallel to horizontal plane of gondola and placed at 90° by each other. With this configuration it is possible to determine the inclination of the sensor relative to the LTP (Local Tangent Plane).

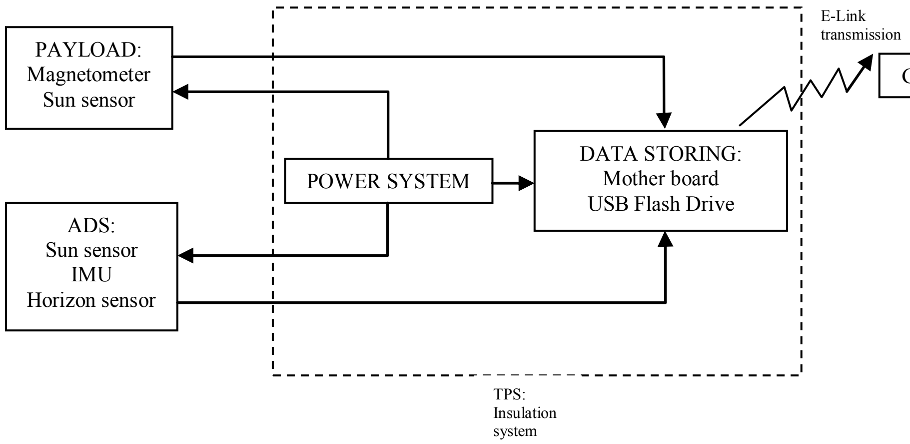

Figure 1. COMPASS experiment layout

The data storing is performed by an embedded computer PC/104 connected by serial ports to all components and by Ethernet connection to E-Link telemetry system of BEXUS-9, in order to monitor the experiment behaviour during the flight. The size of the memory of OBDH (On Board Data Handling) is extended to a total of about 5 GB with the support of an USB Flash Drive.

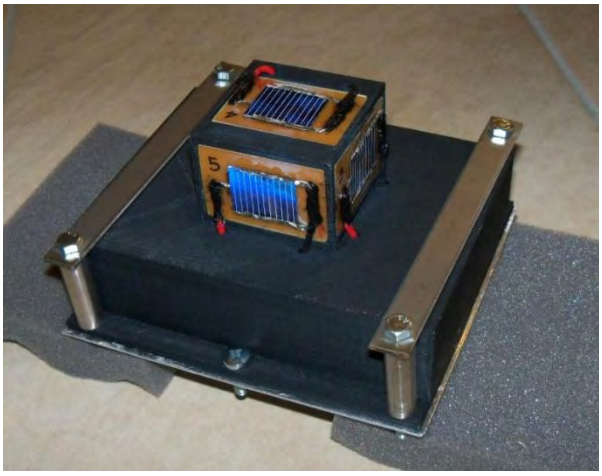

Figure 2. Sun sensor in flight configuration

All these components are powered by an electronic board that supplies them by a 28V lithium battery pack. The system has telemetry of temperatures, currents and voltages and these data are stored in a waterproof EEPROM (Electrically Erasable Programmable Read-Only Memory), in which also magnetometer and Sun sensor data are collected as backup. The experiment setup in flight configuration is represented in Fig. 3 and Fig. 4. The mechanical structure is composed by three subsystems: a case inside gondola containing the embedded computer, the electronic board and a battery pack protected by a thermal insulation system; outside the gondola other two cases are placed with the payload and attitude sensors. This configuration is necessary to avoid magnetic disturbances to the sensors, due to electronic components and iron-magnetic materials, and to permit Sun exposition and horizon visibility. The external cases are fixed on a folding boom in order to make easy the sensors power-on and possible inspections.

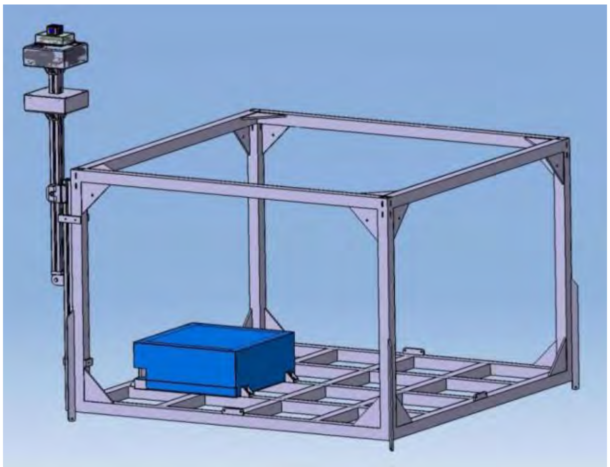

Figure 3. 3D CAD model of COMPASS flight configuration

3. FLIGHT PERFORMANCES

Concerning the mission assessment, different considerations can be pointed out. Regarding the hardware, a positive conclusion can be drawn, given that no failures were noticed. All the sensors behaved correctly, the mechanical structure bore the loads without any damage and no anomalies were found in telemetry data. Relating to the payload measurements, the same conclusions can be highlighted: all data are consistent and reasonable results about geomagnetic field and solar flux were obtained, as it is presented in following paragraphs.

Figure 4. COMPASS experiment into the gondola

3.1. Real Time Attitude Determination

During the flight the algebraic method was used to determine the attitude of the gondola in real time. Any couple of unit vectors $\hat{u}$, and $\hat{v}$ (if not parallel) define an orthogonal coordinate system with the basis vectors, $\hat{q}$, $\hat{r}$, and $\hat{s}$ given by the algebraic system Eq. 1.

$$\begin{cases} \hat{q} = \hat{u} \\ \hat{r} = \dfrac{\hat{u} \times \hat{v}}{|\hat{u} \times \hat{v}|} \\ \hat{s} = \hat{q} \times \hat{r} \end{cases} \quad (1)$$

At a given instant, two measured vectors in the gondola body coordinates (denoted by the subscript B) $\hat{u}_B$ and $\hat{v}_B$, determine the body matrix, M_B as in the Eq. 2.

$$M_B = \begin{bmatrix} \vdots & \vdots & \vdots \\ \hat{q}_B & \hat{r}_B & \hat{s}_B \\ \vdots & \vdots & \vdots \end{bmatrix} \quad (2)$$

During the flight, these two measured vectors were the Earth's magnetic field vector from the magnetometer, and the acceleration vector g from the IMU accelerometers. Moreover these vectors could also be obtained in the TRS (denoted by the subscript R) from the models. The reference matrix, M_R, is constructed from $\hat{u}_R$ and $\hat{v}_R$ as it is shown in the Eq. 3.

$$M_R = \begin{bmatrix} \vdots & \vdots & \vdots \\ \hat{q}_R & \hat{r}_R & \hat{s}_R \\ \vdots & \vdots & \vdots \end{bmatrix} \quad (3)$$

The attitude matrix A is given by the coordinate transformation, by solving the Eq. 4.

$$A = M_B\, M_R^T \quad (4)$$

The ease of the Eq. (4) made it particularly adapt for the experiment on board processing, because, in this way, the computation requirements were minimal [3].
During the flight, the attitude obtained as result of this analysis was plotted in real time 3D graph, as it is presented in Fig. 5. The picture contains two different representations of the attitude:

- the left one is obtained by the algebraic method;
- the right one instead is given by the IMU rotation matrix.

Three different colors were used to represent the body frame: the x-vector is colored by blue, the y-vector in red, while the z-vector in green. The reference frame is represented by the black axis.
During the post analysis phase, an analysis upon this algebraic method (TRIAD) and IMU data were done to confirm the feasibility of this methods to represent the attitude. The angle between x-vectors, taken at the same instant from the reference systems generated respectively by the algebraic method and by the IMU data, was calculated. The same analysis was applied to the y-vectors and z-vectors, too. The results are presented in Fig. 6, where it is possible to see, for a generic time interval of about 10 minutes, that the standard deviation for the angle between the two x-vectors and the y-vectors is the same and its value is near to 7°. The maximum of these difference angles is near 15°, while the angle between the two z-vectors is very close to zero degrees. The reason of these results are better described in the paragraph 4.3, where the disagreement between the measured magnetic field vector and the IGRF model is discussed, in particular in the horizontal plane of the gondola. However this analysis proves the goodness of the attitude determination system used.

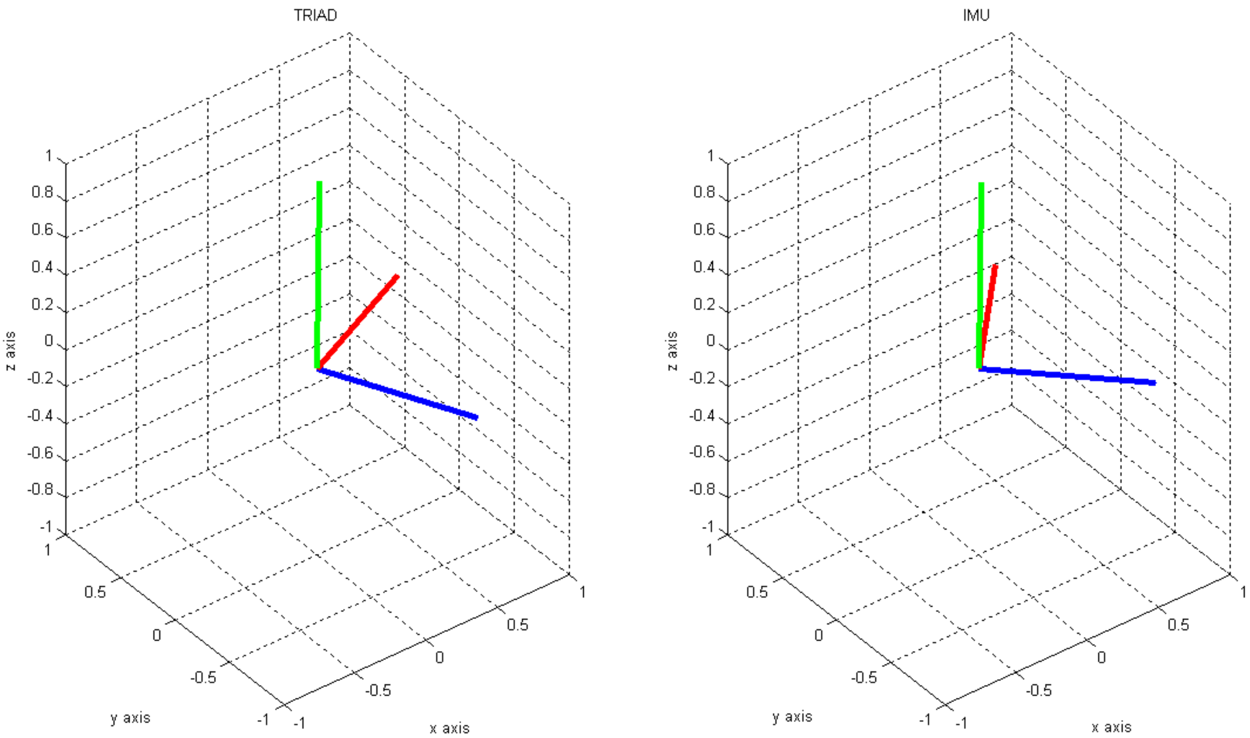

Figure 5. Attitude representation

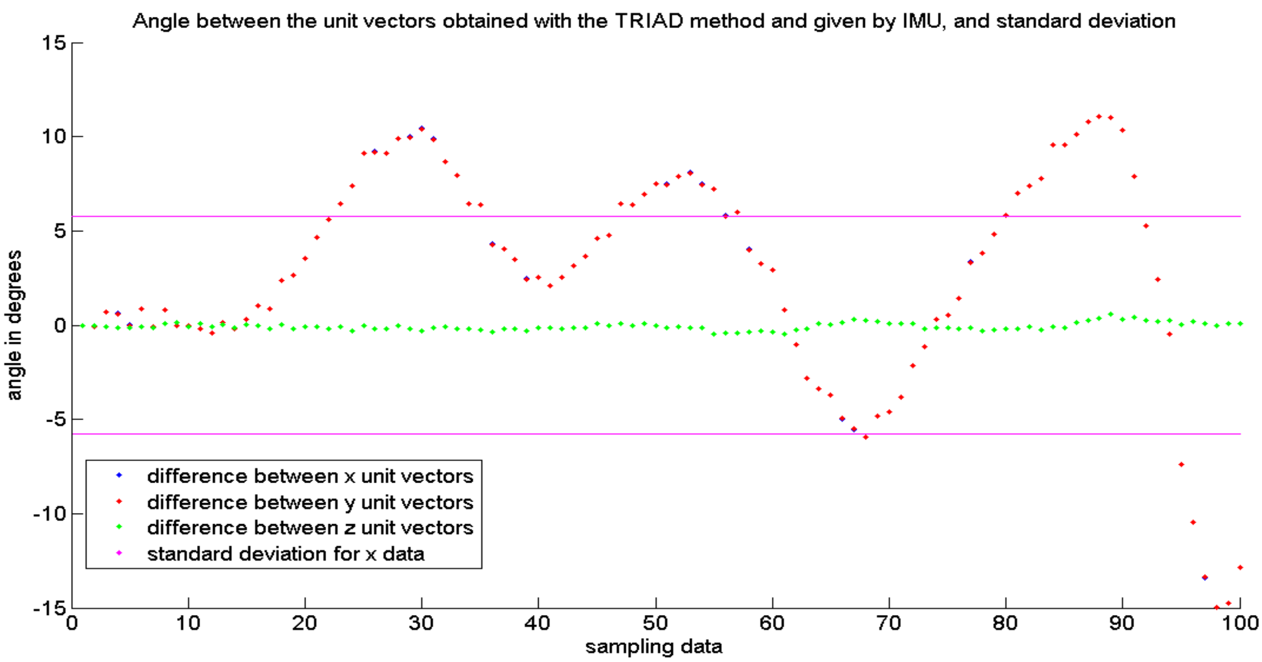

Figure 6. Angle between the unit vectors obtained with the TRIAD method and given at the same time by IMU. The standard deviation is also indicated

4. EXPERIMENT RESULTS

In order to reach the scientific aims expected for the experiment, it was necessary to proceed to different data analysis operations. After some preliminary adjustments like synchronization and data import, the attitude determination was necessary to permit subsequent analysis phases. In parallel the Sun sensor measurements were examined, providing solar flux intensity and Sun direction. Adding these data with the BEXUS-9 GPS (Global Position System) ones, it was obtained the measured geomagnetic field in the right reference system. The last operation was the comparison between these results and IGRF model.

4.1. Attitude Determination

During the post-analysis phase, two different ways of attitude determination were applied in order to have a double verification of the analysis method correctness. These methods are similar to the ones depicted in paragraph 3.1, but with some differences specifically studied for the following geomagnetic field comparison. The first was based on the IMU rotation matrix: the relative rotation of BRS in a generic instant was obtained utilizing rotation matrix between that instant and the initial one (t_0); the attitude in the TRS was determined assigning to t_0 the initial conditions obtained from the Sun sensor (azimuth) and the horizon sensor (inclination), getting the angles between the x-axis of the BRS and the North axis of TRS. In order to avoid the possible IMU drift, five different t_0 were chosen, in particular at minute 0, 11, 40, 70 and 110 of the analysis time interval. Using these data, the attitude evolution was simulated with STK™ software; adding this animation to videos taken by the cameras, it was noticed a maximum inclination angle of the horizontal plane of 5°. With this consideration, the second method of attitude determination used was based only on the Sun sensor measurements. Approximating the flight to an horizontal one, the rotation of the body around z-axis was obtained calculating the difference between the Sun direction azimuth angle measured by Sun sensor and the one obtained by Sun ephemeris. These analyses permitted to obtain the rotation matrix between the TRS and the BRS in every instant of the flight. The two different attitude analyses performed gave very similar results, proving the accuracy of the model. Moreover, by importing the attitude data into STK™ software and comparing the simulation with the cameras videos, a second confirmation of the validity of attitude determination is given. In Fig. 7 a screenshot of the attitude simulation with the software is shown.

4.2. Sun Sensor

Sun sensor measurements were used to reach two different objectives: the solar flux intensity at various altitudes and the direction of the Sun in BRS. The sensor is equipped by five solar cells disposed in cubic configuration. By evaluating the difference of current

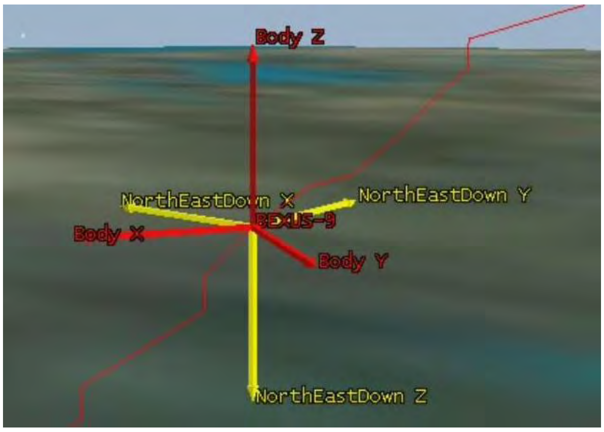

Figure 7. STK attitude simulation screenshot

generated by every cell, it is possible to determine the direction cosines of the unit vector of Sun direction. To obtain this, the algebraic system (Eq. 5) was solved.

$$\begin{cases} I_1 = I_0 \cos\alpha_1 \\ I_2 = I_0 \cos\alpha_2 \\ I_3 = I_0 \cos\alpha_3 \\ \cos{\alpha_1}^2 + \cos{\alpha_2}^2 + \cos{\alpha_3}^2 = 1 \end{cases} \quad (5)$$

With these results Sun elevation and azimuth angles in BRS were found out. Utilizing the semi-empiric equations (Eqs. 6-7) [4], the same angles were calculated in TRS: α is the elevation angle, γ the azimuth angle, δ the declination angle, φ is the latitude in which TRS is centered and ω is an angle that take the time zone into account. Comparing the two unit vectors obtained, and approximating the flight to an horizontal one, the attitude was determined.

$$\alpha = \sin^{-1}(\sin\delta\ \sin\varphi + \cos\delta\ \cos\varphi\ \cos\omega) \quad (6)$$
$$\gamma = \sin^{-1}\left(\frac{\cos\delta\ \sin\omega}{\cos\alpha}\right) \quad (7)$$

The total amount of power produced by all cells gives the measurement of the energy received from the Sun. Besides the variation of solar flux during the flight, the solar constant was calculated by considering atmospheric absorption evaluated through the use of the Air Mass coefficient depending on the altitude.
In the Fig. 8 it is presented the trend of solar flux combined with the atmospheric pressure to show the reliance on the altitude.
In the first part of the graph (about the first 15 minutes), corresponding to the period in which the gondola was held in the launch pad, the intensity of solar flux slightly increases because of the natural rise of the Sun. In the next part of the flight, when the gondola was in the

ascent phase, the curve increases reaching a value double of the initial one, due to the thinner atmospheric layer above the sensor. In the following floating phase, corresponding to an almost constant altitude, the solar flux maintains the previous reached value. The median value measured in this last phase is 1215 W/m^2, whereas the calculated solar constant at the external atmosphere boundary is 1340 W/m^2.

4.3. Geomagnetic Field

The analysis of the Earth magnetic field involved all the experiment sensors and previous attitude results. IGRF data were obtained by inserting the geodetic coordinates of BEXUS-9 trajectory provided by the GPS in the appropriate Matlab™ routine. The comparison of the geomagnetic field size between the model and the sensor measurements permits to evaluate the magnetometer behavior without involving the other sensors. In the Fig. 9 this difference is pointed out.
The first evaluation that can be highlighted is the different oscillation frequency between the model and the sensor measurements. In the first 20 minutes, when BEXUS-9 was in the launch pad, it can be noticed an anomalous behavior of the magnetometer respect to the rest of the flight. This can be linked to disturbances due to iron-magnetic materials of the launch site and of the gondola holder. In the next minutes, in particular in the floating phase, there is a settlement of sensor measurements toward the nominal value of IGRF, with a difference of about 3%. This aspect is related to the higher altitude so to the greater distance from the Earth surface disturbances.
By using the rotation matrix obtained with the two ways described at paragraph 4.1, the geomagnetic vector was rotated from the BRS to the TRS and vice versa to obtain the arrays in the same reference system. In this way the difference in direction was evaluated by determining the angle between the two vectors, pointing out a mean value of 6.1° and a median of 3.8°.
A more accurate analysis was followed out determining the vectors components value along the axes of the considered reference system. In particular in the Fig. 10 it is shown the graph of the second components in BRS for 50 minutes of the flight. For every component can be noticed a small difference between the magnetometer data and the IGRF, according to the magnetic field size considerations. Where the difference of modulus is higher it is possible to notice a bias between the curves like in the first part of the Fig. 10. Whereas, when this discrepancy is moderate, the curves are almost overlapping, proving an accurate attitude determination.

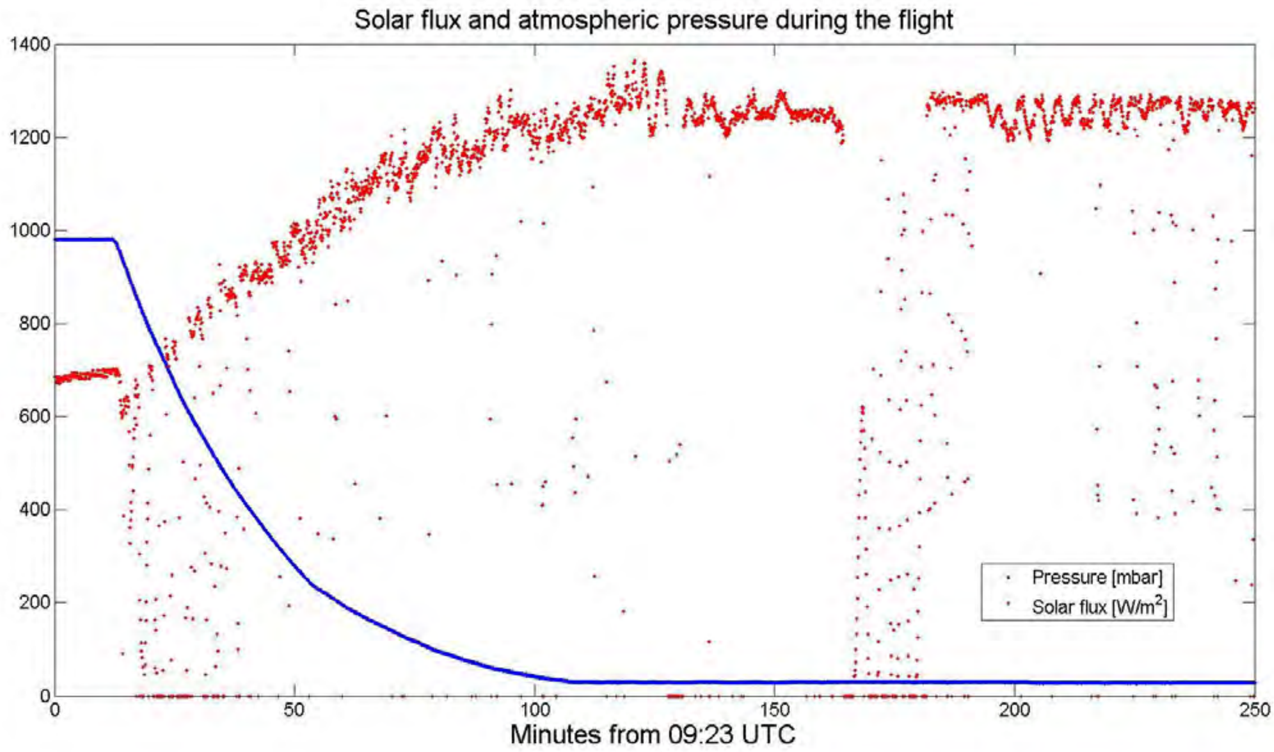

Figure 8. Solar flux and external pressure during the flight

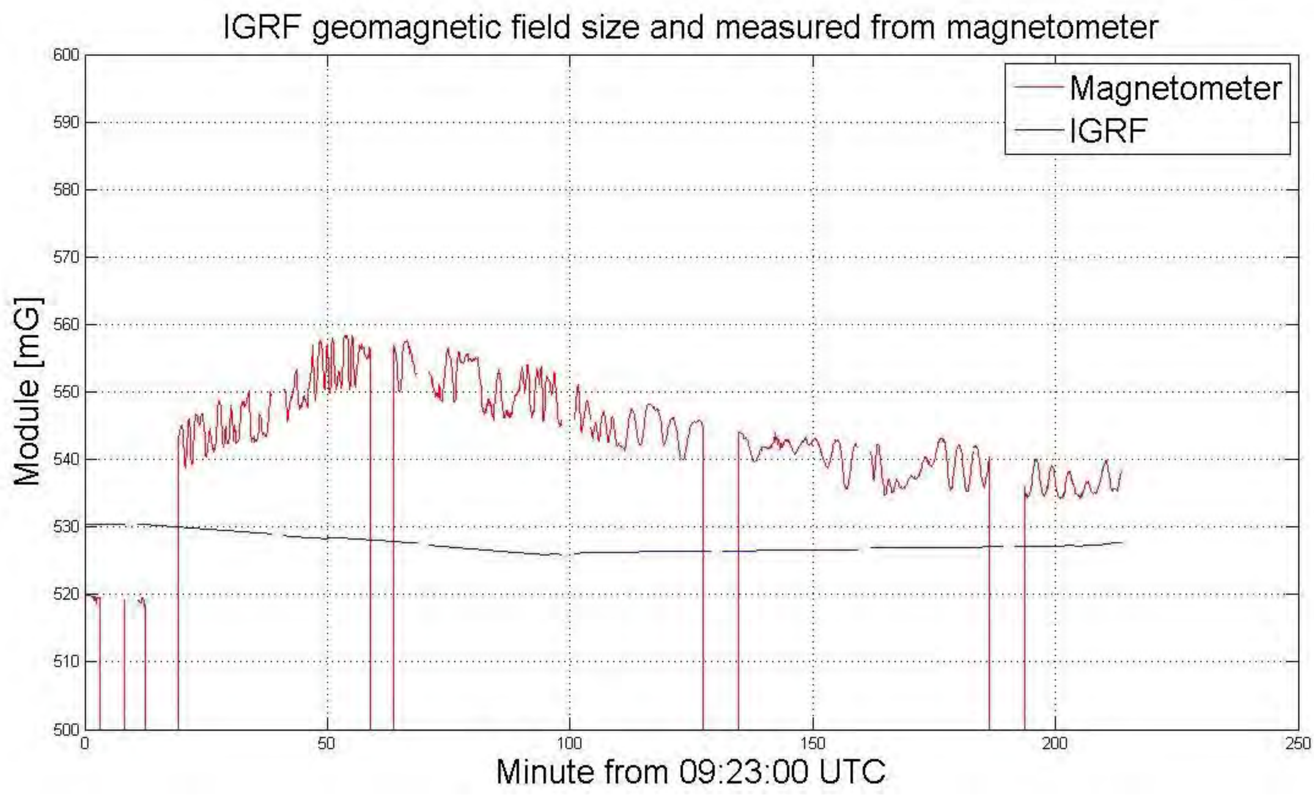

Figure 9. Geomagnetic field size: magnetometer measurements and IGRF data

All the previous considerations mean that a tiny gap among the measurements and the IGRF model is present. This difference can be attributed to various causes: the sensors error but also the intrinsic imprecision of the model, in particular in proximity of the Earth surface where the high frequency harmonics are more relevant.

5. CONCLUSIONS

The objective scheduled for the COMPASS experiment can be considered achieved. The system worked as expected, without anomalies during the flight and giving consistent results. The electronics and mechanics behaved correctly; in particular the Sun sensor structure, made of a polymeric experimental material ABS (Acrylonitrile Butadiene Styrene), didn't present any failure after the recovery, although the intense solar flux acting on it during the flight. With this positive test it is possible to assert that the material can be used in high altitude flights and space missions.

Concerning the ADS all the methods employed revealed themselves correct. The TRIAD algorithm is appropriate to evaluate the attitude in real time. The procedures applied in the post-analysis gave accurate and agreeing results, showing the applicability of the system to future experiments and spacecrafts.

In regard to the geomagnetic field and solar flux measurements, the results obtained are consistent and they permit to reach interesting conclusions. The Sun sensor data, used to determine the Sun radiation power at the external boundary of the atmosphere, provided a value very close to the nominal solar constant, $1367 W/m^2$ [4]. The IGRF is precise in particular at high altitudes, while near the Earth surface it doesn't present the local anomalies, as expected by a global model.

Taking into account the previous considerations, the presented system is suitable for future low cost experiments and researches about this kind of measurements. An improvement of the system can be obtained with an higher performance OBDH. Moreover, an accurate magnetometer calibration erases the external effects on the measurements, reducing the error. On the other hand, designing an ad hoc mission for these achievements, better results can be reached, since the involved variables are better defined.

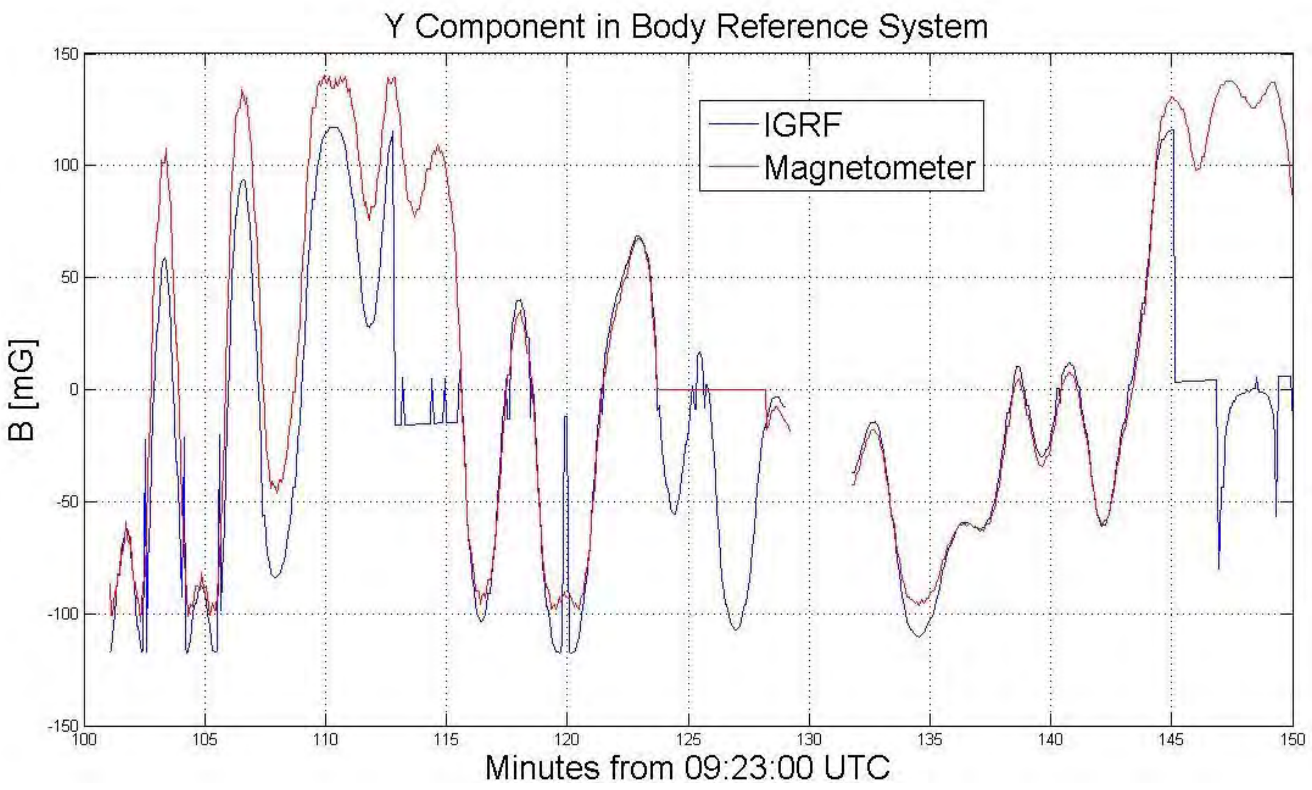

Figure 10. Geomagnetic y component: magnetometer measurements and IGRF data

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7. ACKNOWLEDGEMENTS

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EuroLaunch, a cooperation between the Esrange Space Center of the Swedish Space Corporation (SSC) and the Mobile Rocket Base (MORABA) of DLR, is responsible for the campaign management and operations of the launch vehicles. Experts from ESA, SSC and DLR provide technical support to the student teams throughout the project. REXUS and BEXUS are launched from Esrange Space Center in northern Sweden [5].