MISSUS EXPERIMENT ONBOARD BEXUS 15: AN INNOVATIVE INTEGRATED SENSORS SUITE FOR METEOROLOGICAL MEASUREMENTS IN LOW PRESSURE ENVIRONMENTS AND FOR ATTITUDE RECONSTRUCTION

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ABSTRACT

This paper describes the MISSUS experiment (Meteorological Integrated Sensor SUite for Stratospheric Analysis), developed at CISAS (Center for Studies and Activities for Space "G.Colombo") with the aim to characterize the most significant environmental parameters of thin atmospheres and fully reconstruct attitude and trajectory. MISSUS flew onboard the BEXUS15 ESA/SSC/DLR stratospheric balloon in September 2012 and it has been designed to collect meteorological and attitude data and validate the atmospheric models during the ascent, cruise and descent phases. The flight provided an unique opportunity for testing the onboard innovative instrumentation, which has been designed basing on CISAS previous know-how on balloon flights and space missions. In particular, MISSUS temperature sensor is the prototype of the MarsTem, the instrument which will be part of the DREAMS suite (Dust characterization, Risk assessment, and Environment Analyser on the Martian Surface) onboard ESA Mission Exomars 2016.
The design and the results are presented.

1. INTRODUCTION

The role of meteorological instrumentation is central for planning a surface mission on a planet because the study of the atmosphere allows to go deeply into the dynamics of the atmosphere formation and to investigate the evolution processes of the whole Solar System. The recent ESA programs have focused on Mars for 2012-2016 and beyond, to investigate the environment of the planet, in particular on the research of present and past life traces and demonstrate new technologies for future missions and landings.
From this starting point the need of realizing a meteorological package conceived for applications in Mars-like environments arose. MISSUS experiment, composed of several sensors for the measurement of temperature, pressure, humidity, velocity, magnetic field and attitude, gives a useful contribution in the development of integrated multi-sensors packages for harsh atmospheres exploration. At an altitude of 20-30 km, Earth atmosphere is similar to Mars ground environment concerning the pressure and the thermal exchange mechanisms, whereas differences respect to Mars atmosphere are related to the thermal conductivity and thermal capacity of Carbon Dioxide and the presence of dust [1].
At the moment, CISAS is involved in the design and realization of DREAMS package, which will be part of the payload on Exomars 2016 Mission [2].
MISSUS results constitute a useful input for the mission: the innovative temperature sensor onboard is the prototype of the sensor which will be used to directly measure the temperature profile of Mars atmosphere on the Entry Descent and Landing Demonstrator Module (EDM, Exomars 2016). From the detailed analysis of the acquired data and the sensor behavior during flight, some useful improvement and modifications have been introduced in the design of the Flight Model of the sensor.
In addition, thanks to the collected data during flight, the BEXUS gondola attitude and trajectory (not presented here) have been determined and atmospheric models have been validated.

2. MAIN OBJECTIVES

MISSUS planned to reach both scientific and technical goals.
The scientific goals are:

- Characterization of the environment up to 20-30 km altitude.
- Validation of the atmospheric mathematical models, thanks to the data acquired by the sensors onboard.

- Comparison between Earth thin atmosphere at 20-30 km altitude and Mars atmosphere on ground (this objective will be reached once data from Mars will be available).
- Reconstruction of the attitude and the trajectory of the gondola, on which MISSUS is mounted.

Strictly related to the previous scientific goals, the technical goals consist of:

- Design and realization of an integrated multi-sensors scientific payload.
- Design, development, calibration and test of an innovative temperature sensor, able to measure fast temperature fluctuations.
- Design and development of a system for the impact detection of the gondola with ground.

3. EXPERIMENT DESCRIPTION

As described above, MISSUS experiment is able to provide both meteorological measurements and attitude and trajectory measurements.

The innovation of the experiment is based on the integration of all the sensors and on data-fusion, which has been managed in post-processing: every measurement has been cross-correlated with the others to increase the accuracy of the results, based on a synergic approach.

The experiment is split in two parts: some sensors have been placed outside the gondola, on a 1.2 meter length Aluminum mast attached to the gondola rails, for the meteorological measurements; the other sensors have been placed inside the gondola, together with the electronics, which controlled the sensors, the batteries and the PC104, for the data-sampling, data-handling and transmission to ground station. Power supply for all the sensors has been provided by two Lithium - ion batteries through the electronics. Data conditioning and telemetry subsystem collected data coming from sensors and sent part of them to the ground station through BEXUS E-link unit, while the whole data volume has been stored in a solid state memory.

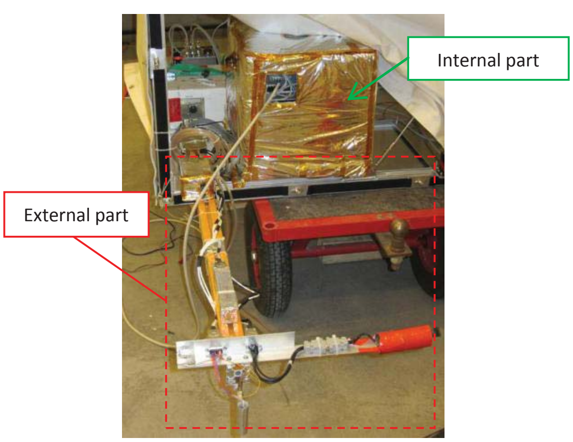

Figure 1. MISSUS experiment onboard the gondola

All internal components (sensors, electronics and batteries) have been mounted inside an edged box, (380x360x364) mm^3 volume, close to the external side of the gondola, easily accessible (in order to recharge batteries) and close to the boom (in order to minimize the length of the external cables).

The experiment has been provided with the following sensors:

- An innovative resistance temperature sensor, placed on the tip of the external mast, on an Aluminum support, in order to get the temperature of the external environment as a function of the altitude. This sensor is a home-made platinum resistance thermometer with a thin platinum wire wrapped around a PEEK support.
- A second temperature sensor (a Resistance Temperature Device commercial sensor), used as a reference sensor for the innovative temperature sensor and for redundancy reasons; it has been placed near to the innovative temperature sensor.
- A humidity sensor (Honeywell HIH-4000 series), placed on the mast, used for the measurement of humidity during the ascending and descending phases.
- Two USB cameras (Logitech), for the monitoring of the experiment (e.g. to assess the position of the Sun by the observation of the shadows) and for public outreach contribution.
- A fluxgate tri-axial magnetometer (Bartington Mag-03MS1000) for the measurement of Earth magnetic field; it has been placed on the mast, far from the gondola in order to minimize spurious effects due to the magnetic field of the gondola and its subsystems: it gave a contribution to completely reconstruct the gondola attitude.
- An absolute pressure sensors (Freescale MPX-2200 series) and a gage pressure sensor (Honeywell 060MG), placed inside the gondola, near to the electronics, to get the absolute pressure as a function of the altitude.
- A differential pressure sensor (Vaisala PDT101), placed inside the gondola, and connected to the external Pitot tube, placed on the tip of the mast, in order to obtain the descending velocity measurements by the measure of the differential pressure.
- An IMU (XSENS MTi-G), provided with GPS receiver, in order to reconstruct the gondola attitude and trajectory;
- A tri-axial accelerometer (Dytran7523A5), specific for shock measurements.

Combining the signals provided by the tri-axial accelerometer, able to measure shocks, and the absolute pressure sensor, a system has been developed to detect the probe impact with the ground. The aim of the system was to demonstrate the feasibility of this technology since one of the most critical issues in

stratospheric balloon missions is the separation of the payload from the parachute after probe landing, considering that parachute may drag the payload for long distances before being recovered, with consequent damage of the instrumentation. The absolute pressure sensor signal is fundamental to measure absolute pressure on ground, avoiding accidental separation during the flight (e.g. when parachute is deployed).
A housekeeping system (e.g. additional temperature sensor) and active thermal control system have been used in order to monitor and control the experiment respectively.
Fig. 2 and Fig. 3 show the internal and the external parts of MISSUS with all the sensors integrated.

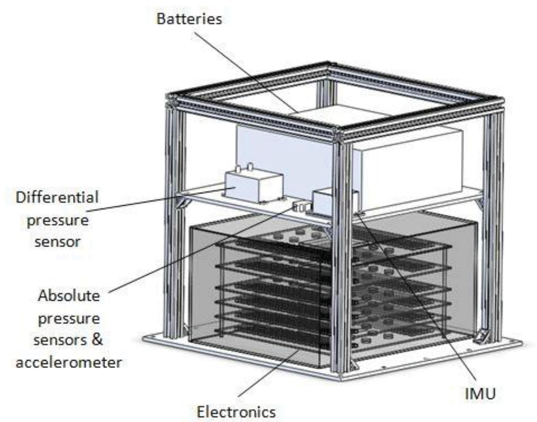

Figure 2. Internal components of MISSUS experiment

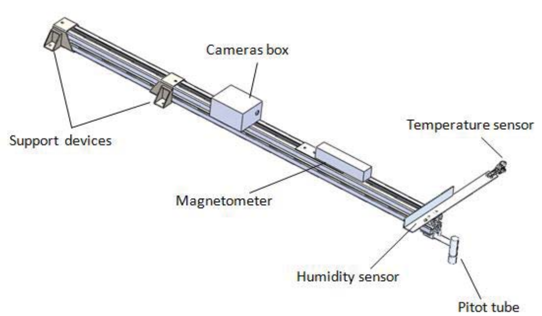

Figure 3. External components of MISSUS experiment

3.1 The Innovative Sensors

MISSUS is equipped with two innovative sensors, entirely designed, developed, calibrated and tested at the University of Padova: the temperature sensor and the Pitot tube.
The temperature sensor, which constitutes the prototype of the sensor that will land on Mars ground in 2016 (MarsTem), has been conceived to measure fast temperature fluctuations and has been placed on the tip of the experiment boom.

The main structure of the sensor consists of two titanium arms internally hollow in order to accommodate and shield the electric cables. At the tips of the arms two rings support 3 PolyEther Ether Ketone (PEEK) bars (450GL30); the platinum sensitive wire is wrapped around them and fixed thanks to glue (resistant at low temperatures). The edges of the structure are smoothed, in order to reduce fluid perturbations due to the stem. Two holes per ring allow the connections between the sensitive platinum wire with the electric cables.
Thanks to the platinum net, the exchange surface between the wire itself and the air flux is maximized. Conductive thermal exchange between sensitive element and Titanium structure is negligible considering PEEK insulating properties.
Fig. 4 shows the innovative temperature sensor and the coarse temperature sensor attached on the titanium structure.

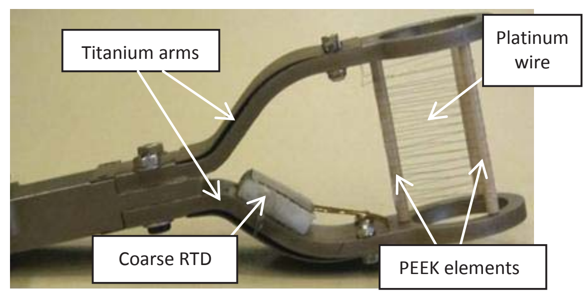

Figure 4. Innovative temperature sensor

The Pitot tube, realized in Aluminum Alloy (AA 6061-T6), has been designed to detect the flow velocity of the gondola during the descending phase: it can be estimated once the static pressure and the total pressure on the Pitot tube are measured by the differential pressure transducer (Bernoulli law, Eq.1).

$$v = k\sqrt{\frac{2(p_{tot} - p_s)}{\rho}} \qquad (1)$$

v is the flow velocity, coefficient k has been estimated by the calibration process, p_{tot} and p_s are the total pressure and the static pressure respectively, ρ is the air density obtained by the atmospheric models.
The Pitot tube has been placed on the tip of the external boom, not far from the temperature sensor, and connected to the internal differential pressure sensor through plastic tubes. The special configuration has been conceived in order to avoid possible issues arising from the misalignment between total pressure probe axis and flow direction. The total pressure probe is inside a cylindrical cover, which consists of a tube with a convergent-divergent section.

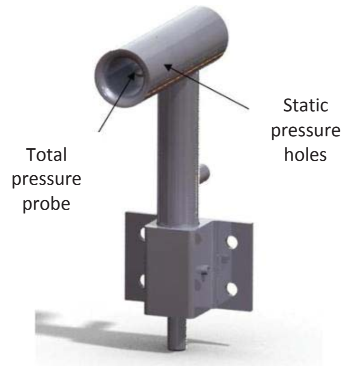

Figure 5. Pitot tube

The static holds are around the external cylinder and their position has been optimized thanks to fluid-dynamics analysis in order to compensate the overpressure due to the stem by the depression due to the leading edge of the tube.

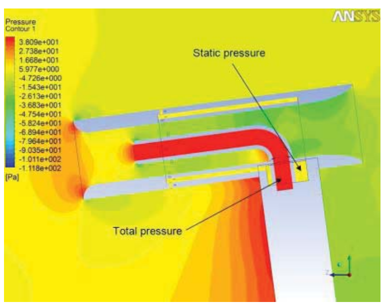

Figure 6. Pitot tube, CFD analysis

3.2 Mechanical Design

MISSUS mechanical structure has been designed in order to withstand the worst static load condition (-10 g in the vertical direction, ±5 g in the horizontal direction), according to BEXUS user manual. Starting from analytical considerations, in the earlier stages of the project, then the design process focused on FEM verification, which has been extended on the main structure and on all home-made elements (temperature sensor and Pitot tube).
A minimum safety factor of 2 has been guaranteed.

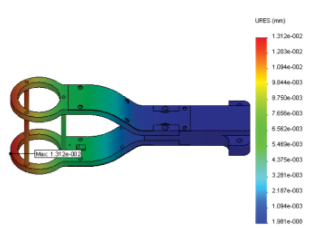

Figure 7. Temperature sensor, FEM analysis

In order to reduce the weight of the experiment and maintain an acceptable cost, aluminum has been extensively used where possible. The boom, the box structure, support plates of the internal systems and the Pitot tube have been realized in Aluminum 6061-T6, whereas the support devices which fix the boom to the gondola structure have been realized in AISI304 steel. The temperature sensor, being the prototype of DREAMS temperature sensor, has been realized in the same material, titanium.

3.3 Thermal Design

A detailed thermal model has been developed in order to estimate the temperature of components and eventually implement thermal control techniques (passive and active) on the experiment. All environmental thermal fluxes (solar, albedo, planetary flux) and internal generation (electronics and batteries self-heating) have been considered; the external temperature of the atmosphere has been treated as a boundary condition. Fig. 8 shows the temperature of sensitive components as a function of time, as a result of the thermal model.

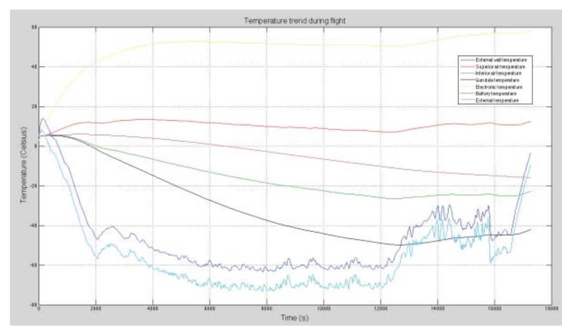

Figure 8. Temperature of MISSUS components

In order to keep the temperature of the internal units and sensors within their operative limits, polyurethane-foam walls and MLI have been used to cover MISSUS box; in addition heaters have been placed on the batteries and on Pitot tube, with the aim to avoid ice formation inside the static pressure holes during flight.

3.4 Electronics

The experiment main electronics has been designed to acquire, supply sensors and heaters, detect impact with ground. All electronics boards have been mounted inside a rack placed on MISSUS box, inside the gondola.
Main electronics is composed of the following elements:

- A logical unit (PC104) which provides: (1) experiment monitoring; (2) data acquisition management; (3) telemetry management by means of Ethernet bus; (4) data storage (IDE Solid State Disc – 32 GB memory).
- Signal sampling (ADC) unit.

- Two Power management boards, provided with DC/DC converters (one to supply power at 5V, the other one at ±15 V).
- One power digital board to activate heaters, provided with 8 configurable digital channels.
- Four analog conditioning boards, with 6 analog channels for each board. Only 21 channels of the conditioning boards are used.
- One additional board, also called separation system simulation board, devoted to the impact detection system and implementing vector sum of 3 acceleration components and critical parameters (acceleration and pressure) threshold setup.

The following figure is a representation of the electronics functional overview.

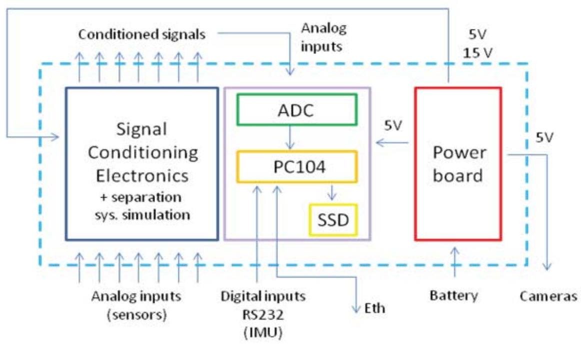

Figure 9. Electronics functional diagram

Fig. 10 shows electronics rack assembled.

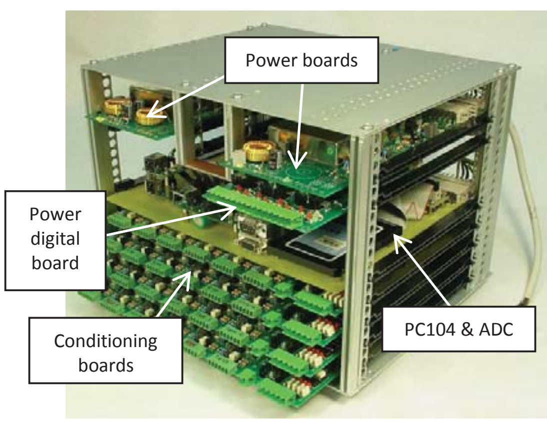

Figure 10. Electronics rack

3.5 Software Design

MISSUS on board software has been designed to record data sampled from the ADC continuously during flight, save data and transmit a subset of the sampled data through the ethernet interface. Software is real time (every function has to be run within a fixed amount of time) and has been designed to run on a Unix-like operating system (Linux), in order to increase both reliability and performance. It is subdivided in 2 different layers: operating system layer (Linux layer) and MISSUS layer (data logging, telemetry management, monitoring, power management); all software has been written in C++.
The onboard software is able to send data to the Ground Support Equipment (GSE) using UDP through BEXUS E-link system to the GSE. Every data packet contains start and end codes (0x0010, 0x9000). The start code is followed by a sequence number, a timestamp and all the sampled data. In case of packet loss from gondola to ground, the packet is not retransmitted.
The Ground Support Equipment is a GUI client program that allows to: (1) log data received from the MISSUS board, (2) display sensors data during flight, (3) display house-keeping data (temperature of the batteries and electronics, batteries voltage and current), (4) switch on and off the sensors, (5) send telecommands onboard (e.g. to activate heaters). The client has been written in C++, using Qt4.8 and KDE marble library, and runs on Linux.
Experiment status has been monitored by the GSE thanks to dedicated control packets; in addition onboard software was able to accept commands packets from the GSE using UDP and consequently to send an acknowledgment packet as reply to every command.

4. CALIBRATION

Both innovative temperature sensor and Pitot tube have been calibrated at University of Padova premises.

4.1 Temperature Sensor Calibration

Using an Ethanol thermal bath (Ultra Low Temperature Bath 7380, Hart Scientific) at controlled temperature, the output of the secondary sensor (to be calibrated), in other words the resistance of Platinum wire, has been compared with that of a primary calibrated sensor. Given the resistance of the sensors as a function of the temperature of the bath (that is an input), interpolating curves, which represent resistance as a function of temperature, have been obtained within the calibration range (from -80°C up to +40°C). Interpolation laws are reported in Eq. 2 and Eq. 3.

$$T = AR^3 + BR^2 + CR + D, T < 0 \qquad (2)$$

$$T = AR^2 + BR + C, T > 0 \qquad (3)$$

Calibration coefficients *A*, *B*, *C*, *D* have been experimentally estimated.
The result of the calibration is reported in Fig.11, which represents the correlation between resistance (x axis) and the temperature (y axis), both for the reference sensor (blue curve) and for the innovative sensor (red curve).

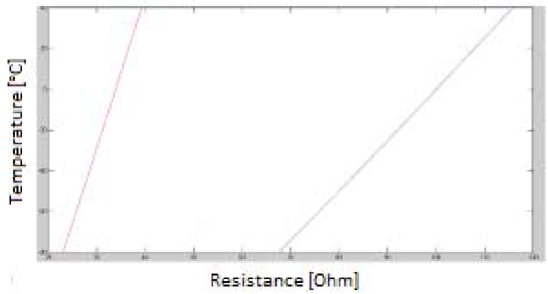

Figure 11. Temperature sensors calibration curves

4.2 Pitot Tube Calibration

The calibration process allowed to estimate *k* coefficient (see Eq. 1). The Pitot tube has been mounted inside a wind gallery (a duct of constant section) by means of a devoted flange (Fig. 12) and has been subjected to a flow of known velocity.

Figure 12. Pitot tube calibration set-up

The flow speed inside the duct has been regulated by means of a fan (UNI 10531) and the stable mass flow (stabilized thanks to a honeycomb structure) has been measured by means of an orifice plate. Then, known the velocity of the flow, the relative pressure has been measured by means of MISSUS relative pressure sensor. Several measurements have been performed, in order to evaluate the dependence of the output as a function of the attack angle: in particular yaw and pitch angles have been varied thanks to the gimbaled support of the Pitot tube flange. Fig. 13 represents the result of the calibration, the flow velocity as a function of relative pressure variation.

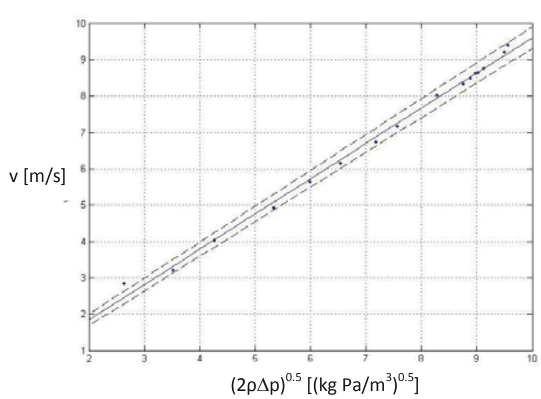

Figure 13. Pitot tube calibration curve

5. VERIFICATION AND TEST

Test campaign involved all the system and different subsystem, during the development of the experiment and at qualification/acceptance level, in order to guarantee the performance of the experiment in space-like environment, assessing readiness for flight.

Development tests involved electronics and software: (1) debug procedures have been implemented on the flight software, step by step at first, verifying different functionalities separately, and then on the whole software; (2) electronics have been extensively tested using oscilloscopes, spectrum analyzers, signal generators (each board has been tested separately, then the whole system has been verified). Qualification tests have been performed on the whole experiment: (1) Thermal vacuum tests have been performed on mechanical and electronics components, in extreme pressure and temperature conditions (from -80°C up to +40°C) for 6 hours continuously (that is the nominal duration of the flight); (2) Vibration tests have been performed on the experiment, subjecting the structure on random vibrations; (3) Some mechanical parts (e.g. sensors for detection of impact with ground) have been subjected to shocks.

At the end, functional tests have been performed to verify the general behavior of the system after all other tests, both in Padova and during launch campaign preparation at Esrange, before final integration on the gondola.

In general all test results have been successful and all experiment requirements have been fulfilled.

6. LAUNCH CAMPAIGN

MISSUS has been launched onboard BEXUS15 on 25th September 2012 from Esrange base in Kiruna, after 5 days of preparation activities, such as: check of components integrity and functionality (electronics and sensors check out), mechanical assembly, calibration and synchronization operations (for IMU and magnetometer), software and communication functional tests, radio frequency interference tests.

PC104 seemed to be defective before launch, provided that sometimes the communication between the experiment and the ground station had failed and MISSUS could not be switched on remotely. Problems seemed to be fixed before launch, MISSUS worked properly and, once switched on, the experiment logged data continuously as expected until 4 hours and 6 minutes after launch, when suddenly the ground station lost contact with MISSUS. After the recovery a detailed investigation has been performed in order to asses motivations which caused the lost of connection: the experiment has been carefully isolated from the gondola and each sub-system has been analyzed one by one. A preliminary data-analysis demonstrated no anomalies in the behavior of the components: as an example, voltage, current and temperature levels of sensitive items (such as batteries or DC/DC) have been considered; all values appeared normal, without peaks or discontinuities. In this phase the experiment has been completely rebuilt, finding out that it was still alive and properly working. During flight not only the connection had been lost but the PC104 did completely stop working, causing the lost of the data on the descending phase: both Pitot tube data and sensors system for impact detection data have not been acquired. However a great amount of data has been collected during the ascent and floating phase; such data have been then analyzed in detail and cross-correlated. In addition the prototype of the MarsTem has been successfully tested; the sensor resulted undamaged after impact with ground and is still available for further investigations.

7. RESULTS

The main objectives of the data analysis are here summarized: (1) BEXUS gondola attitude and trajectory reconstruction; (2) Meteorological data collection; (3) Atmospheric models validation.

First of all, it has been noticed that all analogical signals were affected by a systematic disturbance: peaks of 0.05 V were present in all analog channels signals with a non-constant frequency (from 1 Hz up to 256 Hz). Therefore some preliminary elaborations of the signals resulted necessary: Discrete Wavelet Transforms (DWT) have been applied to sampled signals; the noise has been mitigated, with a negligible phase delay. Fig. 14 shows the noise isolated from the signal, whereas Fig. 15 represents the temperature signal (V) as a function of time, acquired by the innovative thermometer, before (blue curve) and after (red curve) de-noising procedure.

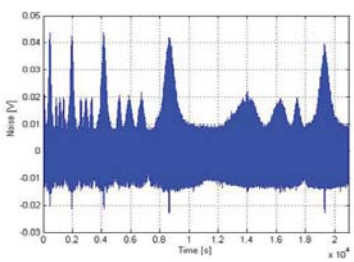

Figure 14. Noise isolated from the signal

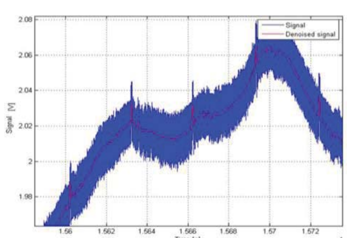

Figure 15. Temperature sensor signal before and after de-noising

After de-noising, analog signals resulted appropriate to be analyzed.

The attitude of the gondola have been reconstructed, basing on the GPS data and on the gravity vector and on the magnetic vector respectively. The following graphs show the resulting Euler angles (yaw, pitch and roll) in the North-East-Down frame.

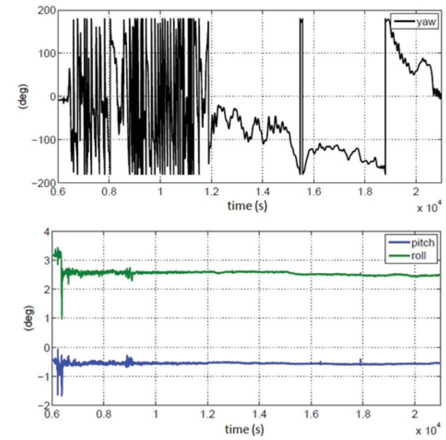

Figure 16. Euler angles as a function of time

Once Euler angles have been obtained, the yaw angle has been cross-correlated with the temperature signal provided by the thermometer, in order to deeply understand the influence of the direct solar radiation on the measurement at high altitudes, when heat exchange by convection is negligible. A thermal model has been developed, and, by the comparison between the yaw angle, the temperature provided by measurements and by the model, it resulted that the platinum wire is highly sensitive to the solar radiation: as the gondola turns and the thermometer is subjected to the direct solar flux, an increase of the measured temperature of about 30°C occurs. The understanding of this effect led to some original improvements and modifications on the design of the Flight Model of the MarsTem, which has been provided with special shields to prevent the direct illumination of the sensitive element.

In addition atmospheric models have been validated. As an example, Fig. 17 shows the temperature sensor signal (black curve), compared with the temperature curves provided by ISA standard atmospheric model from ICAO 1964 [3](red curve) and by NRLMSISE-00 model [4] (green curve). It can be seen that: (1) during the ascending phase the mean trends are compatible; (2) a temperature drop of about 10°C at 10-13 km occurs; (3) in the tropo-pause, over 12 km, an unexpected positive lapse rate takes place; (4) the measurement in the stratosphere layer is compatible with the models. In order to explain these anomalies, the atmosphere stability has been analyzed, taking into account the cloud profiles provided by CALIPSO satellite, buoyancy and potential temperature, revealing that the unexpected local variations are due to the presence of strong winds or cold layers.

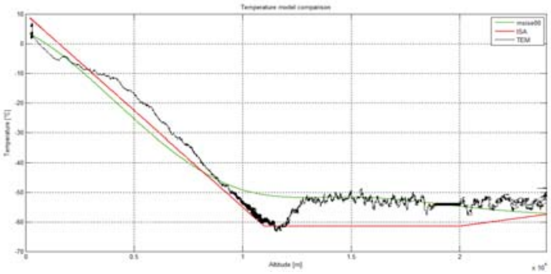

Figure 17. Measured and calculated temperature

8. CONCLUSIONS

Concluding, an integrated sensor suite for meteorological measurements and attitude and trajectory reconstruction has been conceived, designed and realized at University of Padova.
All primary scientific goals have been achieved, thanks to the great amount of data collected, available for the ascending and cruise phase: trajectory and attitude have been reconstructed and atmospheric models have been validated.
The prototype of the MarsTem onboard, the RTD which will fly on the EDM of ESA Exomars 2016 mission, has been developed and successfully tested during the flight; the acquired data allowed CISAS team to improve the design of the Flight Model of the sensor for the future planetary mission.
Since the temperature sensor resulted undamaged and undivided after impact with ground and perfectly operating, further tests will be performed in the near future to compare the thermal behavior of the prototype which flew on MISSUS and the Flight Model of the sensor. In particular thermal vacuum tests with solar simulator will take place at CISAS premises, in order to evaluate the effect of the direct solar illumination in vacuum conditions on the sensitive elements of the different sensors.

9. ACKNOWLEDGEMENTS

The experiment realization was possible thanks to the support by CISAS “G. Colombo”, Borgoverde S.r.L., Rotary Club International Valle dell’Agno and Ca’ Da Mosto S.p.A, Federmanager Venezia, which provided the team with funds needed to manufacture the experiment. In particular University of Padova provided also the facilities and premises needed for the realization and the verification. Professor Massimo Masi made available his expertise and the wind gallery for the calibration of the Pitot tube, whereas Alessio Aboudan and Michele Cesaro gave their constant and effective contribution in the software conception and development.
Antonio Selmo, electronics engineer and professor, designed, manufactured and tested the electronics board and the rack, making available his workshop and supervisioning the last phases of the experiment realization, also during the launch campaign.
Our gratitude goes to all ESA, SSC, SNSB, DLR staff for the great support during milestones and the launch campaign.

10. ABBREVIATIONS AND ACRONYMS

MISSUS	Meteorological Integrated Sensor SUite for Stratospheric Analysis
CISAS	Centro Interdipartimentale Studi e Attività Spaziali
ESA	European Space Agency
SSC	Swedish Space Corporation
SNSB	Swedish National Space Board
DLR	Deutsches Zentrum fur Luft-und Raumfahrt
DREAMS	Dust characterization, Risk assessment, and Environment Analyser on the Martian Surface
EDM	Entry Descent and Landing Demonstrator Module
PEEK	PolyEther Ether Ketone
RTD	Resistance Temperature Device
IMU	Inertial Measurement Unit
FEM	Finite Element Method
MLI	Multi Layer Insulation
ADC	Analogical Digital Converter
GSE	Ground Support Equipment
GUI	Graphical User Interface
DWT	Discret Wavelet Transform
GPS	Global Positioning System
ISA	International Standard Atmosphere
ICAO	International Civil Aviation Organization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations

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