PREDICTING THE ATMOSPHERIC RE-ENTRY OF SPACE DEBRIS THROUGH THE QB50 ENTRYSAT MISSION

Y. Prevereaud(1), F. Sourgen(2), D. Mimoun(3), A.Gaboriaud(4), J-L. Verant(5), and J-M. Moschetta(6)

(1)ONERA - The French Aerospace Lab, 31 055 Toulouse, France, Email: Ysolde.Prevereaud@onera.fr
(2)ONERA - The French Aerospace Lab, 31 055 Toulouse, France, Email: Frederic.Sourgen@onera.fr
(3)ISAE - Institut Supérieur de l'Aéronautique et de l'Espace, 31 055 Toulouse, France, Email: david.mimoun@isae.fr
(4)CNES - Centre National d'Étude Spatial, 31400 Toulouse, France, Email:Alain.Gaboriaud@cnes.fr
(5)ONERA - The French Aerospace Lab, 31 055 Toulouse, France, Email: Jean-Luc.Verant@onera.fr
(6)ISAE-Institut Supérieur de l'Aéronautique et de l'Espace, 31 055 Toulouse, France, Email: jean-marc.moschetta@isae.fr

ABSTRACT

ISAE's EntrySat student satellite is one of the 10 QB50 In-Orbit Demonstration (IOD) satellites. The scientific objectives have been defined in collaboration with ONERA and are the following : to refine the atmospheric modeling between 120 and 350 km and to refine the aerodynamic coefficients modeling. Aerodynamic forces and associated kinematics (position, attitude motions) will be evaluated. EntrySat will perform these measurements during orbit decay phase and destruction phase. This paper presents the EntrySat mission, in board instrumentation and pre-flight analysis.

Key words: Space debris; Atmospheric re-entry; EntrySat mission; QB50.

1. INTRODUCTION

1.1. Context

Since 1957, the number of space debris has significantly grown, not only due to the increase of satellites launch but also to the rise of in-orbit collisions. Soon, the atmospheric re-entries will be more and more numerous due to both in-orbit collisions increase and afterwards to atmospheric drag, leading to involuntary de-orbiting process. During the last forty years, around 16,000 tons of space debris entered the Earth atmosphere. Between 10 and 40% of this mass has impacted the Earth surface, representing a serious threat for goods and persons [1]. Since 2008, the French Space Operation Law (LOS) proceeds to control the National space activity, especially to limit risks linked to orbital space debris. Meanwhile, ONERA has developed a new 6-degree of freedom trajectory code called MUSIC/FAST that couples aerothermodynamic loads as well as ablation and fragmentation to flight mechanics, in order to improve the accuracy of atmospheric trajectory computations. To date, physical models used in MUSIC/FAST have only been tested and calibrated for a series of larger controlled vehicles and objects entering the atmosphere. The real-world validation strategy proposed is based on a specific satellite reentry mission called EntrySat, set up for collecting flight data. The EntrySat mission is a students collaborative project between the Institut Superieur de l'Aeronautique et de l'Espace (ISAE), the Office National d'Etudes et de Recherches Aerospatiales (ONERA), and the Centre National d'Etudes Spatiales (CNES) to fly a 3-U CubeSat under the QB50 mission scheduled for launch in 2015. The primary objective of the mission is to return data from the hypersonic air environment around such a small object that behaves like an orbital debris after de-orbiting. As a matter of fact, the EntrySat mission will be a unique occasion to record temperature and drag force data during such re-entry event aiming at validating re-entry models especially to small sized debris, presently questionable. Although most of the mission duration will be devoted to orbital operations, the last seconds into atmosphere focus attention. Data collection from GPS, absolute attitude, magnetometer, and satellite dynamics via on-board IMU will allow correlation between temperature data and drag force data to the satellite orientation and real-time trajectory until destruction. Communication provisions will be made through the use of alternative networks such as the Iridium constellation, in addition to UHF/VHF radio to ensure data. This project is intended to fly as an In-Orbit Demonstration (IOD) satellite for the QB50 constellation.

1.2. QB50 Flight Opportunity

QB50 is a network of 50 Cubesats that is planned to be launched together in the first half of 2015 into a circular orbit at 320 km, inclination 79°. This project was created by the Von Karman Institute (VKI) for Fluid Dynamics in Brussels, Belgium, to fulfill both scientific and educational purposes. Indeed, the conception and fabrication

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phases can be performed by students, giving them valuable experience to later work in the aerospace sector.
The QB50 project uses satellite designs based upon the standard developed by Stanford University and California Polytechnic Univeristy. This small satellite design enables students and research teams to gain access to space for a much lower price than large national missions. The standard, known as CubeSats, are satellites with very small dimensions (typically $10 \times 10 \times 10$ cm for a 1U CubeSat), low power and mass-budgets (1W, 1 kg). Due to electronics miniaturization, complex instruments can now be used even aboard small platforms. Combined with a coupled desire to utilize commercial-off-the-shelf (COTS) components, these satellites typically require less funding.

Given the area of expertise of the VKI, the scientific objectives are clearly linked with fluid dynamics: obtaining reliable in-situ and globally spread data on the upper-layers of the atmosphere. Given the remaining friction forces at the altitudes considered (90 to 320 km) the lifetime of an orbiting object is quite limited. Most national agencies study the upper atmosphere with balloons, sounding rockets, or the occasionally satellite in a highly elliptic orbit. As a consequence, very few global, simultaneous, in-situ measurements have been performed by national agencies with limited data collection amounting to a few minutes. The data does not allow scientists to have an overview of an entire atmospheric layer at one time. The 40 double unit ($10 \times 10 \times 20$ cm) CubeSats will carry sets of standardized sensors for multi-point, in-situ, longduration measurements of key parameters and constituents in the largely unexplored lower thermosphere and ionosphere before their reentry and destruction. In addition to the 40 atmospheric double Cubesats, 10 double or triple ($10 \times 10 \times 30$ cm) CubeSats for science and technology demonstration will be selected.

The EntrySat proposed by ISAE is one of the 10 double or triple CubeSats for science and technology demonstration. The deadlines for this project are the Preliminary Design Reviews (PDR) on the 29th of March 2013, the Critical Design Reviews (CDR) on the 1st of November 2013, the Flight Readiness Review (FRR) on the 27th of February 2015 and the launch in mid-April 2015. The collected data will be made available to the scientific community. Concerning the overall development strategy, an electrical breadboard will be realized and tested for the CDR. Afterwards a flight model will be built, tested and delivered in the beginning of January 2015.

2. ENTRYSAT SCIENTIFIC OBJECTIVES AND PAYLOAD

The EntrySat experiment consists of inserting a nanosatellite, in the form of a 3U CubeSat similar in principle to a debris, into low-Earth orbit. A science module operating during the reentry phase will be able to perform in-situ measurements of the CubeSat environment as well as integrity up to its destruction. Acquired data will be sent in real time through the Iridium constellation back to the ground segment. This In-Orbit Demonstration (IOD) CubeSat is to be injected into a trajectory representative of an uncontrolled atmospheric reentry with both very low slope and high orbital velocity. Fig. 2 presents the overall mission profile.

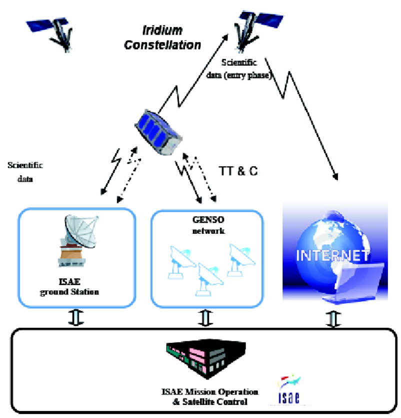

Figure 1. EntrySat System Overall architecture

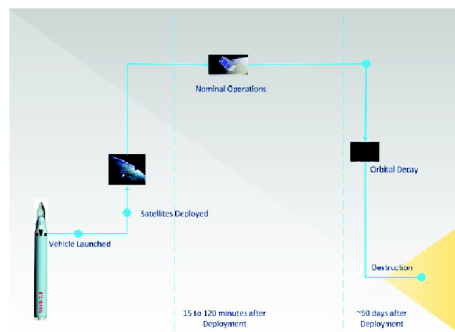

Figure 2. EntrySat Mission Profile

Furthermore, no propulsion or re-entry protection subsystems will be utilized during the destructive phase of flight thus the satellite will respond to the atmosphere in a similar manner as some orbital debris. The Orbital Debris Atmospheric Entry Experiment EntrySat CubeSat will be suitably equipped in order to relate the kinematics and the encountered aero-thermodynamic environment through aerodynamic forces and temperature data. Primary scientific objectives of the experiment are summarized in Fig. 3. In verifying the aero-thermodynamic models used in atmospheric re-entry codes, the EntrySat will help to increase the accuracy of predictions for known space debris and other small orbital objects. Especially, the collected data will be compared with the predictions obtained from MUSIC/FAST, a new 6-degree of freedom trajectory code, developed at ONERA, that couples aerothermodynamic loads as well as ablation and fragmentation to flight mechanics. The system architecture outline is described in Fig. 1. EntrySat CubeSat will be controlled by ISAE ground station, through the local ground station or via the Global Educational Network for Satellite Operations (GENSO) network. Raw science data shall be sent to the ground station via UHF/VHF (during nominal decay phase) or the Iridium network as necessary through Short Burst Data (SBD) transmission.

ISAE mission operation and satellite control will be linked to the main QB50 network through the internet. Expected mission duration is between 2 and 3 months, depending on the atmospheric state.

3. EXPERIMENT DESCRIPTION AND REQUIRED RESOURCES

3.1. In Orbit Demonstration Science Case

The proposed in-orbit experiment can be divided between two phases, as can be the natural atmospheric entry of orbital debris.

Phase 1) The first part of the experiment deals with accurate prediction of orbital decay, especially with respect to time remaining before entry, typically a few weeks or months. At the atmospheric entry point, the slope angle suddenly increases and the object must be destroyed before 70 kilometre. The atmospheric re-entry part will spend only few second. Accuracy of the trajectory simulation during orbit decay depends on the accuracy of several physical models:

- Atmospheric modeling (between 120 and 300 km): the whole QB50 project contributes to increase knowledge of the thermosphere since this is its first goal.
- Aerodynamic coefficients modeling in the rarefied and transitional regime.

To refine these models, aerodynamic forces and associated kinematics (position, attitude motions) should be available; EntrySat will perform these measurements during orbit decay phase.

Phase 2) During the second part of the experiment, the destruction phase, EntrySat will melt and break up. The expected velocity value is about 7 km/s and the break-up altitude and onboard conditions changes can be only determined if the CubeSat is suitably equipped to send information during re-entry. This kind of information is of primary importance to improve the multi-physics modeling during atmospheric re-entry as well as to improve the prediction of the survivability of satellite or launch vehicle elements.

While the first part of the experiment (measurements in the rarefied and transitional regime) can be performed with an excellent level of confidence, the data transmission during the second phase, in spite of the blackout expected to occur, will be a true challenge. During the early entry phase, data transmission will be achieved using two Iridium antennas (on both sides of the satellite). However, the exact technological choice for data transmission during the second part of the experiment remains under consideration because they will need further computations and experimental validation in phase A of the project.

The entry profile will be used thanks to the following tools:

- A 6 degree of freedom code will be used by ONERA to simulate the trajectory of the CubeSat. This code is coupled to physical models accounting for the real 3D geometry of the CubeSat, the aerodynamics forces and heat fluxes occurring in the rarefied, transitional and continuous regimes as well as the multi-physics phenomena (ablation and break-up). An integrated Monte-Carlo method allows the quantifying of uncertainties of models (and observations) along the trajectory. That advanced tool, called MUSIC/FAST, already used successfully for complex atmospheric re-entry of space vehicles will allow to validate the choice of materials (and their thickness) equipping the CubeSat as well as to accurately define the scientific instrumentation. In particular, the ablation of the CubeSat could be simulated.
- An aero-thermodynamics tool will be built by ONERA and Rtech in order to validate the above mentioned tool at some flight points using DSMC simulations for the transitional regime and Navier-Stokes computations (chemical disequilibrium) for the last part of the trajectory.
- The scientific instrumentation, especially heat flux sensors, piezoelectric sensors and thermocouples will be tested in a realistic heat loads environment by CNRS.

The present experiment is very complementary to the VKI Re-EntSat experiment. The latter satellite aims to collect data during a controlled atmospheric re-entry of vehicle or debris, while the ISAE experiment focuses on natural uncontrolled reentry of orbital debris and specifically on the prediction of trajectory and understanding of the reentry environment.

3.2. Mission Analysis

3.2.1. Contact with Iridium constellation during reentry

An important part of the mission design relies on the contact between the satellite and the Iridium constellation during re-entry. It is necessary that:

Scientific Question	Required In-Flight Measurements	Required Minimum Accuracy		Proposed Instrumentation
		Orbiting Phase	Destruction Phase	
What is the kinematics of space debris during reentry?	-Position -Attitude -Velocity	- 1 km, 1 day - 1°, 1 day - 1 Hz	- 10 m, 0.1 s - 1°, 0.1 s - 10 Hz	- GPS - Inertial Measurement Unit (IMU)
How do the aerodynamic pressures vary during reentry?	-Drag force -External temperature	N/A	95%	-Piezoelectric element to measure pressure on panel -Type K thermocouples
How does the integrity of the satellite vary during reentry?	Temperature of constituent materials	N/A	95%	-Thermocouples

Figure 3. EntrySat Mission Science Objectives

1) There is actually an Iridium satellite in visibility during re-entry to get the data back,

2) The Iridium system can compensate for the Doppler shift of the carrier due to the speed difference between EntrySat and the Iridium relay.

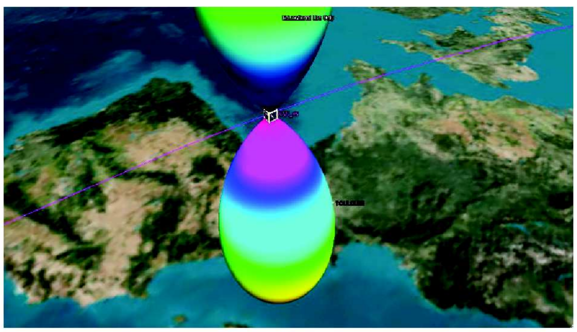

Figure 4. EntrySat Iridium antenna radiative patterns

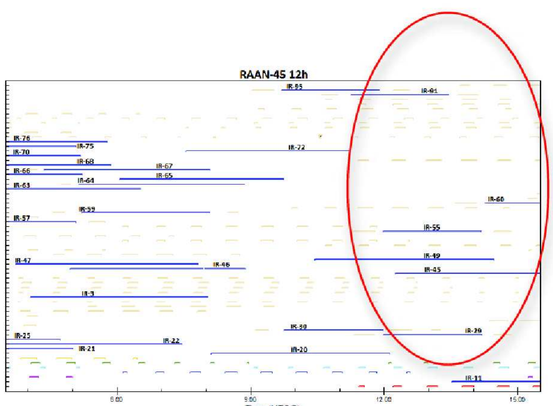

Figure 5. EntrySat - Iridium Access is possible with several satellites during the last 15 hours of predicted orbit

A preliminary study (see e.g Fig. 4, Fig. 5) has been done to establish the access properties between the Iridium constellation and the EntrySat in the last hours of the EntrySat life. Preliminary results indicate a probability of over 95% to have a link with ad-hoc properties during the re-entry phase.

3.2.2. Aerothermodynamic re-entry analysis

An analysis of the uncontrolled atmospheric re-entry of the EntrySat satellite has been carried out. The question of the EntrySat survivability during the re-entry phase is crucial for two reasons: first, according to the project requirements, the satellite must be destroyed before reaching the ceiling of 70 km. Secondly, the trajectory and life time duration specification are essential for the instrumentation acquisition.

Fig. 8 displays the stagnation point convective heat flux and dynamic pressure encountered during the EntrySat re-entry.
The convective heat flux is given by the Detra formulation [2] :

$$\Phi_{conv} = \frac{11030}{\sqrt{R_n}} \sqrt{\frac{\rho_\infty}{1.225}} \left[\frac{V_\infty}{V_{co}}\right]^{3.15} \quad (1)$$

Where V_{co} is the orbital velocity at the considered altitude (m/s), R_n is the nose radius (m), ρ_∞ and V_∞ are respectively the freestream density and velocity.

The maximal dynamic pressure and convective heat flux are respectively reached at about 55 km and 70 km.

The flight analysis is supported by Navier-Stokes computations to build EntrySat aerothermodynamic data base (Fig. 6 and Fig. 7). Fig. 6 shows the iso-Mach field around a double CubeSat for an identified flight point ($Z = 70\ km$ and $V_\infty = 6692\ m/s$) and EntrySat position according to the flow. The shock is detached from the wall because of the stagnation area geometry. Fig. 7 displays the heat flux for a catalytic wall at $T_w = 1000$ K, $Z = 70\ km$, and $V_\infty = 6692\ m/s$. The maximum heat flux is reached on the trailing edges (Fig. 7).

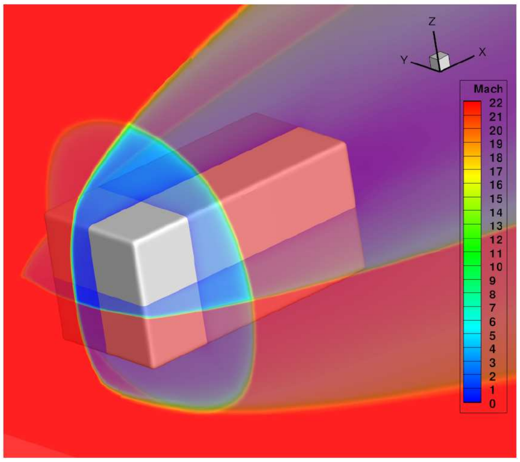

Figure 6. Navier-Stokes laminar numerical computation of a 2U QB50 at $Z = 70$ km and $V_\infty = 6692$ m/s

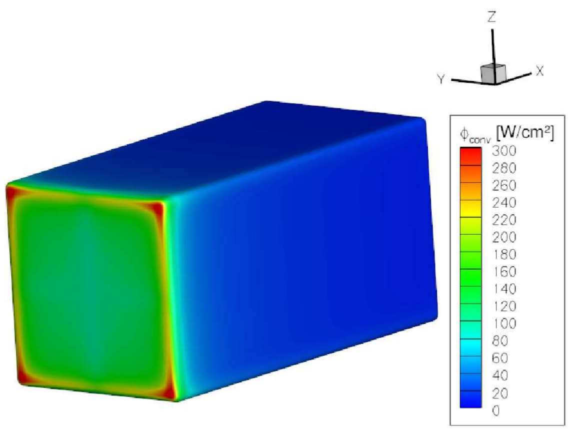

Figure 7. Heat flux for a catalytic wall at $T_w = 1000$ K, $Z = 70$ km, and $V_\infty = 6692$ m/s

4. SATELLITE DESIGN

4.1. Satellite Overview

The EntrySatdesign is a still on-going process. Current status is pictured in Fig. 9. Starting from payload requirements, a preliminary design mostly based on off-the shelf components bought from ISIS (Innovative Solutions In Space) provider has been built. The work has been initiated by producing high-level, subsystem, space systems, and ground systems requirements. The process of subsystem hardware selection for the EntrySat is a trade study where components are weighted most heavily by impact on the power budget, mass budget, and whether the component is space-grade or requires (simplified) qualification procedures.

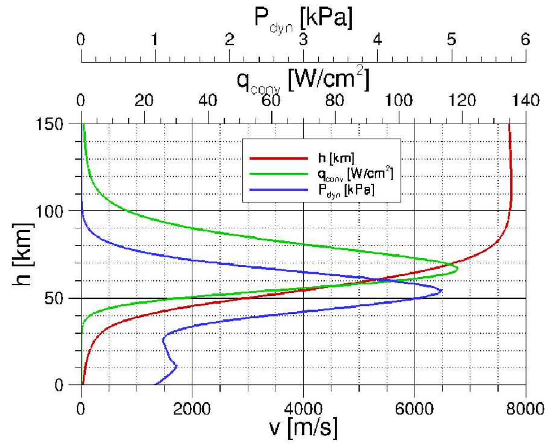

Figure 8. Stagnation point convective heat flux and dynamic pressure encountered during the EntrySat re-entry

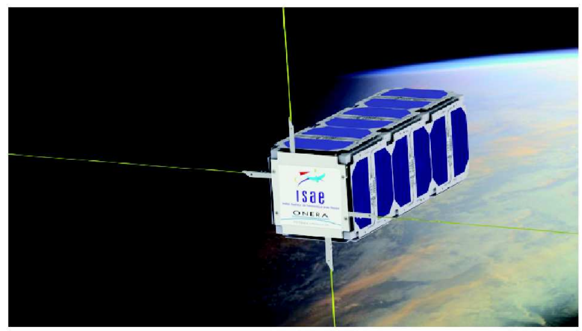

Figure 9. EntrySat CAD model

4.2. Bus Description

The EntrySat will have no propulsion unit, and the functional hardware otherwise representative of a spacecraft bus will be fully integrated with the satellite due to size. While CubeSats are modular in nature, the EntrySat mission does not call for a completely separate science module - rather, modularity will be reduced to the level of the printed-circuit boards (PCB) stacked within the CubeSat due to the distributed nature of the EntrySat sensors. Elements of a traditional spacecraft bus included in the EntrySat subsystems include the EPS (batteries, solar panels), ADCS [magnetic actuators, sun sensors, magnetometers, Inertial Measurement Unit (IMU)], and Global Positioning System (GPS). As can be seen in Fig. 10, these hardware elements are distributed throughout the length of the CubeSat and modularized by Printed Circuit Board (PCB) units. Attitude Determination and Control System (ADCS) components, under this proposal, will be revisited in trade study, isolated on the component level, and fully modularized into a separate area of the 3U satellite frame. Due to the strong heritage of the ISIS design, no specific thermal control is foreseen. However a preliminary thermal modeling shall determine the need of heaters, although there is no current Electrical Power System (EPS) baseline. The CubeSat structure claims heritage from ISIS CubeSat design.

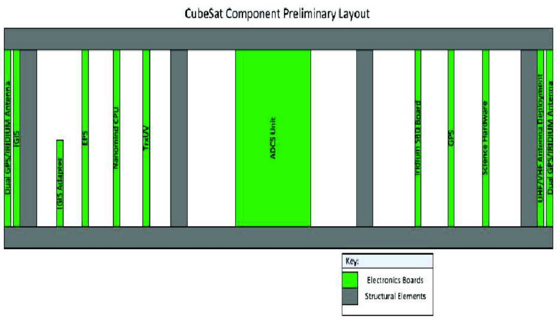

Figure 10. Satellite basic schematics

4.3. Payload Description

The payload for the purpose of accomplishing the EntrySat goals is the Iridium SBD (Short Burst Data) board, the GPS unit, and several sensors including: IMU with magnetometer, gyroscopes and gyrometers to determine the euler angles and their derivatives. Six washer type-k thermocouples are in the center of each of the six faces of the Cubesat to give an access to the external temperature. The thermocouple position is crucial to avoid side effects. The understanding of the drag force during the mission is also a scientific goal and six piezoelectric force sensors are therefore used in addition to accelerometers. Six heat flux sensors complete the in-situ measurements. A GPS sensor will be used to retrieve the EntrySat position and velocity. Ground testing will be necessary to validate and characterize the capabilities of two of these items namely, the Iridium SBD board and the piezoelectric force sensors. Specifically in the case of the force sensors, it is hypothesized that if piezoelectric sensors give adequate information on incident forces, then some atmospheric properties can be deduced based upon the understanding of drag force. This hypothesis, as well as methods of properly affixing the thermocouples and force sensors to obtain the desired data, will be tested and verified during phase B before finalization of sensor selection and construction of the flight model.

4.4. Avionics Architecture

Key to the avionics architecture are the system trade-offs - many of which have already been studied by students at ISAE. A Nanomind A702 CPU has been selected with its capability to communicate with hardware via the I2C protocol. Further trades remain in the selection of specific hardware for the conversion and interface of non-I2C devices with the Nanomind unit. Such conversion hardware, combined with the IMU, is labeled in Fig. 10 as the Science Hardware. GPS, Iridium, and Science hardware will be integrated with the PC/104 bus for delivery of data to the CPU. The Nanomind unit, upon receipt of data, will perform necessary computations, send commands, and store necessary data.

4.5. Attitude Determination and Control System

The satellite can be under-actuated during the nominal orbital phase, and then not controlled during the entry-phase. For the ADCS, a study was conducted to determine the feasibility of a satellite attitude fine-control system using the interaction of the Earth's magnetic field with current-carrying coils to produce torque. The approximate intensity of the Earth's magnetic field was determined as a function of the satellite coordinates. Two systems for two-axis attitude control emerged from this study, one using three coils and the other using two coils. A magnetic controller was implemented in the equations of motion of the EntrySat satellite. Magnetic control laws were developed to bring the EntrySat to the desired equilibrium. This was accomplished by using a PID controller. The settling time to obtain a misalignment error of less than 3° is around 8 orbits which represents 1% of the total time of use of orbit.

4.6. Ground segment

ISAE will provide ground station facilities capable of UHF/VHF telecommunications. Two ground stations are available at this time, one in Toulouse and one in Cayenne. To maximize communications time, GENSO compatibility will be investigated. GENSO would enable internet communication of commands and data between QB50 ground stations so to optimize usage of visible ground stations. The EntrySat will also use the Iridium communications network however the use of this network will not be available to other teams. One of the biggest challenges of EntrySat is to successfully send measurement data during re-entry. The utilization of the Iridium network is intended for the final phase of satellite lifetime during re-entry to ensure that as much data as possible is returned, regardless of ground station visibility during the re-entry phase. An Iridium SBD is therefore embedded in the satellite. ISAE ground stations have proper licensing per French and International amateur radio regulations.

4.7. Software architecture

The satellite will be in several different modes during the whole mission, the most important ones will be the orbit mode in which measurements will be carried out with a low frequency and only UHF/VHF transmission will be used and the entry mode in which the measurement frequency will be high and transmission will be done using the Iridium constellation. The software architecture takes into accounts those modes. It is composed by :

- a main program block realizing a state machine,

- a communication block managing the UHF/VHF and Iridium communications,
- a measurements block carrying out the measurements,
- a housekeeping block assuring the satellite integrity,
- an ADCS block,

This architecture will be designed and implemented using TASTE. TASTE is a set of freely-available tools dedicated to the development of embedded, real-time systems. It was developed by the European Space Agency (ESA), together with a set of partners from the space industry. TASTE allows software designers to easily integrate heterogeneous pieces of code produced either manually (in C or Ada) or automatically by external modeling tools such as MATLAB Simulink, SCADE, or Real-Time Developer Studio.

4.8. Operations

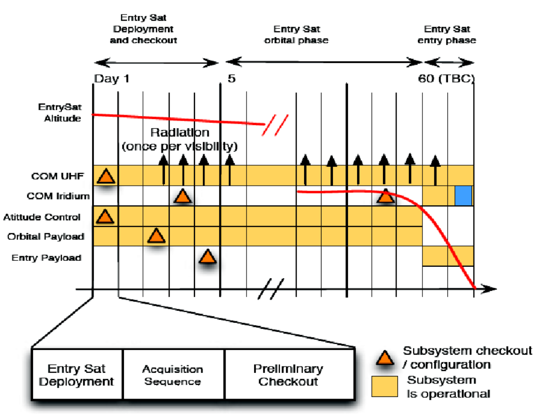

Figure 11. Prelimiray operations outline

EntrySat operation will be done from ISAE facilities, in close cooperation with the QB50 network. The EntrySat will commence operations upon deploy and will utilize two types of safe-modes to protect the functioning of the experiment one related to deployment and another related to low power-levels. Antennae will be deployed after a suitable wait time, and the satellite shall begin to attempt data link with a ground station. After successful linking with a ground station, the satellite will fully operational in a nominal sense and shall maintain system health in preparation for the re-entry event. Fig. 11 describes a preliminary outline of the proposed operation scheme.

Three main sequences are considered yet:

- Week 1: EntrySat deployment, first acquisitions and commissioning phase,
- Week 2 to 4: Orbital phase, monitoring of orbit decay,
- 2 last days: Entry phase, monitoring of satellite environment.

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