ON THE SIMULATION OF THE UPMSAT-2 MICROSATELLITE POWER

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ABSTRACT

Simulation of satellite subsystems behaviour is extremely important in the design at early stages. The subsystems are normally simulated in both ways: isolated and as part of a more complex simulation that takes into account inputs from other subsystems (concurrent design). In the present work, a simple concurrent simulation of the power subsystem of a microsatellite, the UPMSat-2, is described. The aim of the work is to obtain the performance profile of the system (battery charging level, power consumption by the payloads, power supply from solar panels…). Different situations such as battery critical low or high level, effects of high current charging due to the low temperature of solar panels after eclipse, DoD margins…, were analysed, and different safety strategies studied using the developed tool (simulator) to fulfil the mission requirements. Also, failure cases were analysed in order to study the robustness of the system. The mentioned simulator has been programed taking into account the power consumption performances (average and maximum consumptions per orbit/day) of small parts of the subsystem (SELEX GALILEO SPVS modular generators built with Azur Space solar cells, SAFT VES16 6P4S Li-ion battery, SSBV magnetometers, TECNOBIT and DATSI/UPM On Board Data Handling –OBDH–…). The developed tool is then intended to be a modular simulator, with the chance of use any other components implementing some standard data.

1. INTRODUCTION

Currently, when designing and developing new satellite missions, is common to run some simulations in order to predict, or at least get some information, about the performance of on situation impossible or too expensive to recreate on Earth [1–3]. More precisely, simulation of the Electrical Power Subsystem (EPS), performed over the whole subsystem or some of its different parts, is a good practice for the optimization of the system architecture, as it mostly integrates non-linear systems [3,4]. On the other hand, reliability and troubleshooting analysis are important aspects covered by EPS simulations [5–7]. Reliability of each satellite subsystem during the mission has become increasingly relevant within the last decades, as insurance fees are normally around 50% of the satellite cost. Accordingly, special attention should be addressed to the EPS, as problems regarding this subsystem are translated into a big percentage of the total number of insurance claims regarding satellite failures [8]. Finally, leaving aside the EPS reliability it should be pointed out that simulations of this subsystem allow the satellite users to limit the number of possible configuration adjustments once on orbit [1].

Simulations, even if they are calculations based on simple formulae [1,2,9–11], or assumptions based on interpolation from other mission data [12–15], are performed in all steps of a satellite EPS design. EPS simulations are normally performed based on two different criteria [9]:

- Energy balance simulation, it allows to monitor solar array output voltage/current, battery State of Charge (SoC), bus voltage. These simulations are based on balance the average power requirements of the satellite and the EPS power supply on a certain interval (one orbit, one day…).
- Voltage quality simulation. It is used to analyse transient behaviour of the electronics. Therefore, the time interval is much smaller than the one from the energy balance simulation.

In the present work the simulation of a typical microsatellite EPS is proposed. The main goal of the simulator is to test and check that the EPS, and especially the battery, performance gets no damage and is always within the operative limits set by both manufacturers and the mission requirements.

The modelling is adapted to the UPMSat-2 microsatellite, which is being now developed at the IDR/UPM Institute (*Instituto Universitario de Microgravedad "Ignacio Da Riva"*). This microsatellite represents one more step within the space science and technology carried out at the Polytechnic University of Madrid (UPM - *Universidad Politécnica de Madrid*).

Finally, the pedagogical aspects of the UPMSat-2 should be mentioned. Since 2012, more than 20 final project works of students from the Aeronautics & Space Engineering School of UPM have been completed and marked with good results. Besides, 5 PhD thesis related to the UPMSat-2 design and development are being carried out at present at the IDR/UPM Institute.

2. THE UPMSAT-2 MISSION

The UPMSat-2 is a 50 kg microsatellite developed for a 2-year LEO mission, orbiting in an sun-synchronous orbit at around 700 km altitude [16], see Figure 1. This satellite mission is preceded by a former one, the UPMSat-1, launched in 1995 by the same team at (UPM) [17]. The general characteristics of UPMSat-2 satellite and the list of payloads on board are respectively summarized in Tables 1 and 2. Also, the power consumption of the different subsystems has been summarized in Table 3.

The Attitude Control and Determination Subsystem (ACDS) is based on Earth magnetic field interaction. It is composed by magnetic torquers by ZARM (ZARM Technik AG) and magnetometers by SSBV (SSBV Space & Ground Systems). The On Board Data Handling (OBDH), representing the on board computer is designed by TECNOBIT and DATSI/UPM. The Telemetry, Tracking and Command subsystem (TT&C) integrates an EMXYS board. The Electrical Power Subsystem (EPS) is composed by the solar panels, the battery, and the Power Distribution Subsystem (PDS).

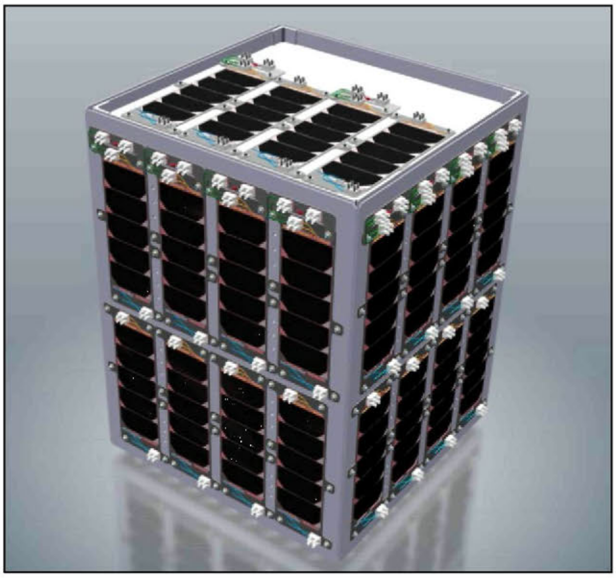

Figure 1 Sketch of UPMSat-2. The solar panels built with SPVS-5S solar modules by SELEX GALILEO can be observed. Solar panels are disposed in lateral faces +X, –X, +Y, –Y and the top one, +Z.

Table 1 General characteristics of the UPMSat-2 satellite.

Characteristic	Description
Mass	< 50 kg
Dimensions	0.50 x 0.50 x 0.60 m^3
Orbit Type	Sun-synchronous / Noon
Orbital Altitude	700 km (approx.)
Period	≈ 98 min. (eclipse: 36 min.)

The power consumption of every subsystem and all the payloads is limited by the available power obtained from the sun radiation. The UPMSat-2 will be orbiting in a sun-synchronous noon orbit, with the Z-axis perpendicular to the orbit plane, see Figure 2. Other possible attitudes were also studied (indicated in Figure 2), but they were not selected due to its lower efficiency in terms of power absorption from the sun radiation.

The UPMSat-2 has four solar panels disposed at the lateral sides plus one more located at the top side (see Figure 1). The lateral solar panels are built with 8 SPVS-5S solar modules by SELEX GALILEO, whereas the one on the top is built with 4 SPVS-5S solar modules. The battery of the UPMSat-2 is made by SAFT, being built on the new Li-Ion technology represented by the VES-16 cells. More details concerning the solar panels and the battery are included in Section 3.

Table 2 Payloads on board UPMSat-2.

Company / Component	Power Requirements
IberEspacio / Micro thermal switch	5 W (10 min. at start) 40 W (max.)
ESTEC / SCT Solar Cell Technology	-
Bartington / Magnetometer	0.525 W (max.)
TECNOBIT/STRAST / MRAD Monitoring the Radiation Effects	-
Arquimea / Pin Puller	26 W (max., 3.5 s)
SSBV / Reaction Wheel	16 W (max.)
UPM / Solar Sensors for Attitude Determination	-
IDR/UPM / CTM Thermal Control	1 W
IDR/UPM / Boom	-
IDR/UPM / MAC Attitude Control	3.96 W (max.)

Table 3 Subsystems power consumption on UPMSat-2.

Subsystem	Power Requirements (averaged per orbit)
ADCS	Magnetic torquers: 1.2 W Magnetometers : 0.6 W
OBDH	Boards: 3 W
TT&C	Receiver: 1 W (*) Transmitter 5 W (*)

(*) To Be Confirmed

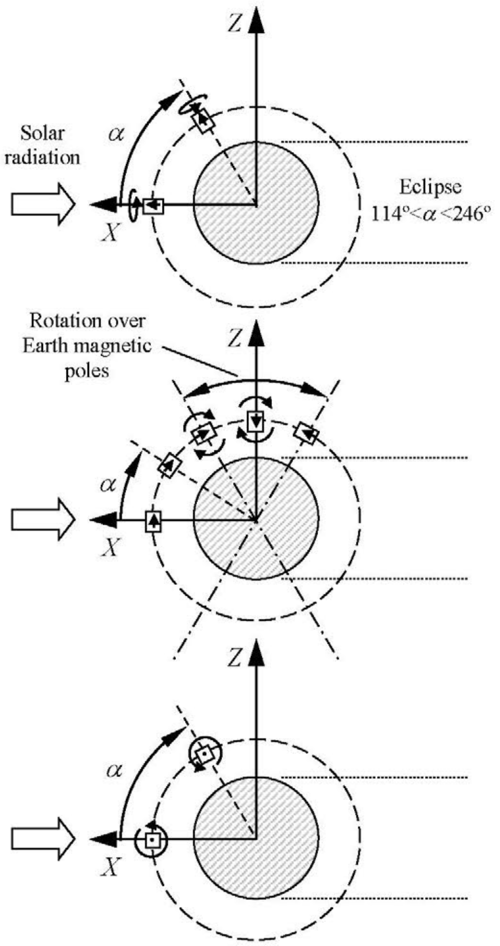

Figure 2 Sketch of three different attitudes on the noon sun-synchronous orbit studied for the UPMSat-2. Top: satellite with Z-axis aligned with the vector direction to the Earth; Middle: satellite with Z-axis aligned with the Earth magnetic field lines; Bottom: satellite with Z-axis perpendicular to the orbit plane. The last attitude (bottom) was the selected one for the UPMSat-2 mission, as the calculations respectively indicated 12% and 25% increase of average-per-orbit available power with respect to the other attitudes.

3. MODEL DEVELOPMENT

The model simulates differently three parts of the EPS, each one modeled in a different way. These parts are: batteries, solar cells, and loads (payloads and other subsystems). In the following sub-sections a description of the batteries and solar panels used in the UPMSat-2 satellite is included, together with the considered modelling methodologies and the selected one.

3.1. Batteries

As previously said, the EPS of the UPMSat-2 satellite integrates a 6S4P VES16 modular battery designed and built by SAFT (see Figure 3), the battery being built with Li-Ion VES16 cells. See respectively in Tables 4 and 5 the main characteristics of both the VES16 cells and the 6S4P VES16 battery.

Figure 3 Top-right: SAFT 6S4P VES16 battery of the UPMSat-2 built with VES16 Li-Ion cells; Top-right: SAFT VES16 cell; Bottom: Testing of the UPMSat-2 battery at the IDRUPM laboratories.

Table 4 Electrical characteristics of SAFT VES16 Li-Ion battery modules.

Nominal capacity	4.5 A·h (4.1 V, 20ºC)
Nominal energy	16 W·h (4.1 V, 20ºC)
Specific energy	150 W·h/kg (C/3, 20ºC)
Voltage range	2.7 V - 4.1 V (*)
Operating temperature	10ºC - 40ºC (**)
Maximum charge current	0.09 A (C/50) at –20ºC 0.15 A (C/30) at 0ºC 0.9 A (C/5) at 10ºC 2.25 A (C/2) at 20ºC 2.25 A (C/2) at 30ºC
Maximum discharge current	9 A (2C)

(*) Safe limits: 2.5 V, 4.2 V.
(**) Optimal range: 15ºC – 25ºC. Safe limits: –20ºC, 70ºC (less than 6 hours).

Table 5 Electrical characteristics of SAFT 6S4P VES16 battery. Dimensions of the battery have been also included in the table.

Nominal capacity	18 A·h
Nominal energy	384 W·h
Voltage range	18.75 V – 24.6 V
End of Charge Voltage (EoCV)	24.3 V
Dimensions	240 mm x 175 mm x 90 mm
Weight	3.65 kg

The output data from battery models integrated in EPS simulators consist normally in two parameters: the State of Charge (SoC) and the voltage working point (Vbat).
Currently, there are two approaches to Li-Ion battery modelling [18]:

- electrochemical models, and
- electrical circuit models.

The first ones take into account all about the chemical reactions that occur inside the battery, being especially useful when studying temperature performance or ageing. On the other hand, the second approach uses a more practical method for electrical engineers. Without being based on any physical parameters they propose an electrical circuit that reproduces the battery performance, generating useful information about SoC and Vbat.
Within the second approach, there are three main ways to estimate SoC. The first approach simply integrates the amount of current that flows in or out the battery, so, having an initial SoC, it is possible to calculate that variable at any moment. The second one takes the Open-Circuit Voltage (OCV) to estimate the expected SoC form experimental data. Finally, the last of the three approaches consists in Artificial Intelligence (IA) predictions through neuronal networks or Kalman Filters (KF) [19].
In the present work, a current integrator approach has been selected for estimating the UPMSat-2 battery SoC [20], and after that it obtains the battery voltage and other electrical parameters using equations extrapolated from experimental data of the manufacturer. The main advantage of this method is its easy implementation and short calculation time within the whole simulator [19].
Furthermore, this method can be easily implemented later on the satellite and it is also so easy to reproduce for other kind of batteries, repeating the experiments for the new battery.
A common characteristic that makes coulomb counting methods unusual is the lower accuracy compared to other methods, due to accumulated errors, and that is impossible to real-time estimation [20]. In this work, both of these disadvantages are not critical: there's no need to have a perfect accuracy and it is a simulator, so it's not expected to work in real-time problems.
Bus voltage, which depends on battery voltage, should be between 18V and 24V, approximately. Furthermore, the selected battery has its own balancing system to assure that voltage differences between highest and lowest cell stays on the appropriate margin. Nameplate energy is 384 W·h.

3.2. Solar Cells

The photovoltaic satellite panel implemented in the simulation has four body-mounted panels with 40 Azur Space 3G28C cells each one, joined in 4 strings per panel (10 cells per string, see Figure 1). The fifth half-panel, located on the top face does not receive any Sun radiation in the stabilized attitude, see Figure 2 The power obtained from them varies mainly because of two causes: first, the common solar cells parameters, which change with temperature, and second, satellite's attitude makes orientation respect to the Sun change constantly.
UPMSat-2 will have a sun-synchronous 700 km height noon orbit. This is translated into a 98 minutes orbital period, with less than 36 minutes of the total period corresponding to eclipse. Therefore, two sudden temperature changes are expected within each orbital period. Furthermore, the selected satellite's attitude has a spin around +*Z* body axis (perpendicular to the orbital plane, see Figure 2), which causes dark-light cycles on each panel. Early stage calculations indicate no huge temperature oscillations (–8°C and 27°C for lateral faces and 26.5°C, almost constant, for the battery) at the UPMSat-2, since thermal inertia is big and the expected stabilized rotation speed (around 0.1 r.p.m.).
The approach to the solar cell's model was quite simple. Instead of the typical knee-shaped curve, a two-straight-line approximation was selected**,** see Figure 5. For each temperature, the panel behaviour is simulated with 2 lines, the first one from the short circuit point to the maximum power point, and the second one from the maximum power point to the open circuit point. As said, the panel behaviour was simulated for a wide range of temperatures, based on the temperature variations of the three characteristic points (short circuit, maximum power, and open circuit) from the manufacturer's datasheet (see Table 6).

Table 6 Solar cells operating points.

Parameter	Value at 28 °C	Variation
I_{sc}	0,5060 A	0.32 mA/°C
V_{mp}	2,3710 V	–6.1 mV/°C
I_{mp}	0,4870 A	0.28 mA/°C
V_{oc}	2,6670 V	–6.0 mV/°C

Although some accurate analytical approximations to the solar panel behaviour have been developed at the

IDR/UPM Institute [21,22], this bi-linear approximation was chosen in order to simplify the model and reducing the computational time.
The effect of the solar panel orientation with respect to the Sun was implemented using a factor that reduces current by the cosine of the angle between radiation and normal to the panel plane. This approach was taken for angles from 0 to 75 degrees; from that point factor is zero. See in Figure 4 a comparison of this approximation to the well know Kelly's cosine law.

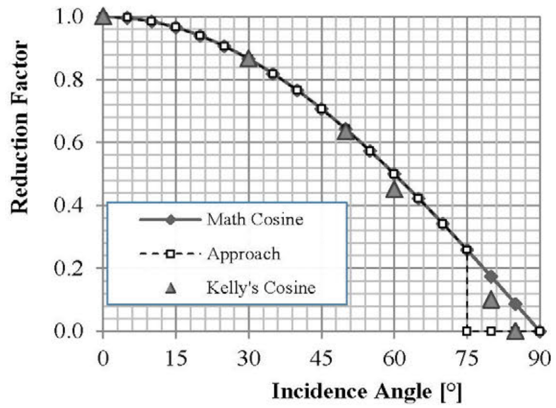

Figure 4 Comparison of Kelly's Cosine Law approaches.

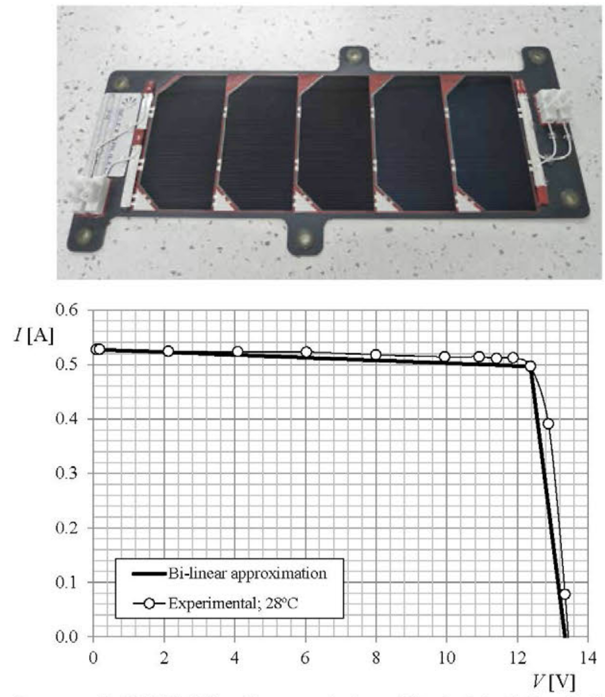

Figure 5 SPVS-5S solar modules (Fligh Model) of the UPMSat-2, see also Figure 1(top). I-V curve of the module measured at the IES/UPM, the bi-linear approximation is also included (bottom).

Another important effect is the degradation due to solar radiation. In the present work, it has not been implemented because the previous simulation showed that the amount of radiation was too low in the expected two year life, so it does not make a big difference.
The radiation is expected to be less than $5x10^{13}$ MeV [23], and the first data given by the manufacturer are referred to $2.5x10^{14}$ MeV, which is fairly above the expected radiation.

3.3. Subsystems

Subsystems energy consumption have great importance in the present work, as they are the main load of the whole electrical system, using the energy produced or "stored" by the previous components mentioned and, secondly, their working profile can be modified if required due to changes in the operational plans, so energy demanded changes too. The EPS simulations allow to create different power consumption profiles and evaluate which of them are feasible and which ones not. Thus, the load profile is one of the most important factors when designing a satellite power system [5].
The UPMSat-2 Power Distribution System (PDS) is designed following the Direct Energy Transfer (DET) scheme, as it is more reliable than the Peak Power Tracking (PPT) scheme. Also, DET has other advantages over PPT as higher total efficiency at End Of Life (EOL), lower mass, and less number of components [7,24,25].

4. RESULTS AND FUTURE WORK

Several simulations were performed within the present analysis. Averaged power loads in a day (16 consecutive orbits) were considered, as within this period two connexions with the Ground Segment will be programmed, one at noon and the other at midnight, in order to download data and upload possible control and housekeeping commands.
In order to consider the power losses the power transmission coefficients 0.85 and 0.65 were selected respectively for daylight and eclipse [26].
The first simulation was performed to obtain the available average power in order to supply the payloads, the results being 19.3 W. Once this figure was obtained the averaged values of the maximum Depth Of Discharge (DOD) and the charging and discharging rates were obtained (see Table 7).

Table 7 Battery charging and discharging parameters. Rates are approximate.

Parameter	Min. SoC	Max. Disc. Rate	Max Char. Rate
Value	94.6%	C/10	C/4

In order to go one step further the performance of the satellite was analysed taking into account two solar panel failure cases:

- failure of one lateral panel, and

- failure of two consecutive lateral panels.

The simulations which produce the results of Table 7 were repeated for this two new failure cases. In Figure 6 the charging/discharging rate is presented for one orbit, and it shows how discharging rates are higher for the failure case, but never reaching more than C/7, and C/5 when charging, so limits are not exceeded despite the failure.

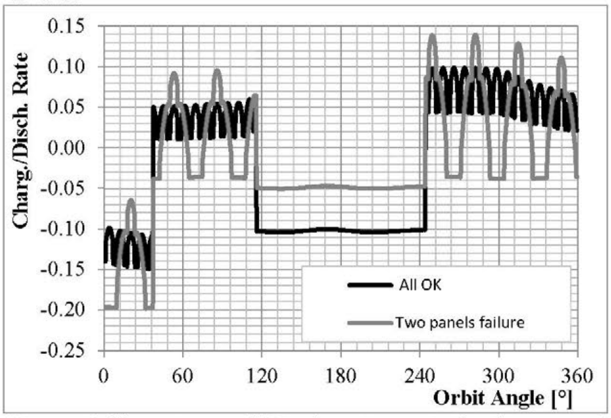

Figure 6 Charging and Discharging rate for the normal case and for failure of two contiguous panels. A rate value of one equals to C.

These calculations were carried out in two different power consumption modes:

- constant payload consumption equal to the available average power 19.3 W, and
- power consumption concentrated in 4 peaks of 5 minutes and 120 W along one day (15 orbits) with all the rest of the energy consumed steadily.

See in Table 8 the results of this simulation.

Finally, the recovery of the full-charge battery from a discharged situation was analysed. The UPMSat-2 will have 3 operational modes:

- normal mode,
- low battery mode, which implies that no payload will be operative, the different subsystems being under normal operational mode, and
- emergency mode, no load (payload or satellite subsystem) will be connected to the EPS.

The simulations carried out were programmed in order to estimate, once the battery is discharged and in emergency mode, the time required to restore the full-charge battery state with no solar panel failure, and also taking into account the aforementioned failure cases.

Table 8 Averaged consumption available for Payloads

	Constant Mode	Pulsing mode
All panels OK	19.3 W	17.6 W
One panel failure	12.8 W	11.2 W
Two panels failure	6.5 W	4.9 W

Table 9 Hours to recover SoC to 100% from 75%.

	All panels OK	One panel failure	Two panels failure
Low Battery	65.9 h	97.1 h	191.0 h
Emergency	56.0 h	75.7 h	120.2 h

5. CONCLUSIONS

The present work is a first analysis of the UPMSat-2 EPS. This analysis is based on the available power from the solar arrays, the battery characteristics, and the power consumption estimations of the different satellite subsystems.

The data resulting from the present work indicate a correct design of the UPMSat-2 EPS, the available power being able to ensure the correct performances of the different payloads on board the satellite.

Also, the battery maximum charging and discharging rates obtained in this study are below the safe limits indicated by the manufacturer.

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