J³:

CubeSats as a Platform for In-Orbit Verification of Scientific Instruments for Interplanetary Missions

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Abstract

The commercial availability of CubeSat components with flight heritage makes it possible to perform fast and relatively cheap flight tests of space instruments or their subsystems. The J³ mission aims to test the performance and reliability of several radiation detectors for the Particle Environment Package (PEP) for ESA's Jupiter Icy Moon Explorer (JUICE) mission. Unlike in conventional mission design, where most parameters can be varied continuously, the use of already available components for CubeSats restricts the possible design solutions that can be made. On the other hand this also enables to perform trade-offs on the mission level utilizing the complete discrete space of possible configurations.

The paper describes this design process of selecting mission and spacecraft configurations based on their impact on the science output predicted by simulation. To achieve this, multiple variable parameters of a CubeSat system are considered and simulated to determine their impact on the instrument activity profile. These profiles are then related with the measurement characteristics determined from radiation simulations of the relativistic electrons in the Earth's magnetic field. This method makes a rapid mission design within the tight time schedule of instrument development and verification feasible. The techniques presented here provide an approach which can be adapted by other CubeSat missions for optimizing their scientific return.

1. Introduction

The aim of this paper is to present a new design methodology that can be used for CubeSats. This methodology has been implemented in the form of design software tools. The tools that have been developed provide an automated configuration generation which selects components from a pool of available subsystems based on the requirements of the payload. Together with these generated configurations, the mission profile is subsequently put into a mission simulation which shows the performance of the complete system for each configuration. The simulation output, which includes a science score can later be used to facilitate the trade-off between different sets of components.

This technique is demonstrated in the case study of the J³ mission, which aims to verify the performance of components planned to be used in an instrument for an interplanetary mission.

2. Verification Missions Becoming Feasible

In the recent years, the usage of CubeSats has experienced a strong growth. This has lead to the availability of commercial of the shelf (COTS) subsystems. While these products typically use non-radiation hardened components, they are tested for space conditions and have gained flight heritage since their release. Furthermore the increase in CubeSat activities has lead to the availability of reports covering nano-satellite operation. These factors have lowered the entry barrier into designing a CubeSat-type mission significantly and

consequently lead to the feasibility of conducting such a mission for verification activities for components of space instruments destined to fly on interplanetary missions.
The feasibility of such a verification activity depends foremost on the cost and probability to succeed. First time CubeSat missions tend to have a high rate of failure, which can often be attributed to a lack of verification of newly developed components [1]. The availability of COTS CubeSat subsystems with flight heritage reduces the risk inherent in the design of a subsystem, therefore increasing the probability of success.

3. Description of the J³-Mission

3.1. Mission Objective

The J³ mission is an example of the use of CubeSats as a platform for verification of instrument components for interplanetary missions. The goal is to test radiation mitigation approaches for the Particle Environment Package (PEP) currently being developed by the Swedish Institute of Space Physics (IRF) to fly on the Jupiter Icy Moon Explorer (JUICE) mission to Jupiter. The J³ mission will determine the characteristics of the electron amplifying elements of the instrument. To characterize the response of the amplifying elements to energetic electron events and to determine the efficiency of the anti-coincidence system, IRF has developed the Radiation Test Experiment for JUICE (RATEX-J) experiment, which is the payload of the J³ mission. multi-channel plates (MCP) and ceramic channel electron multipliers (CCEM) are optimized to detect electrons in the range of hundreds of electron Volts but will encounter much higher energies in the vicinity of the Jovian radiation belts. These high energy electrons can penetrate the instrument wall and create erroneous signals in the amplifying elements. To detect the events and filter them from the measurement results an anti-coincidence system is used which detects if an electron enters the measurement volume by placing solid state detectors (SSD) behind surfaces sensitive to penetrating radiation. If an electron penetrates the surface and also enters the SSD, the latter gives a signal which can be used to discard the measurement.

3.2. The Payload RATEX-J

The RATEX-J payload is an experiment consisting of two detector stacks, a high-voltage supply needed by the detectors and the measurement electronics integrated into a common container. It has a form-factor of approximately half a CubeSat unit and requires the exposure of two circular apertures to the space environment which occupy one of the smaller sides of the experiment almost completely. A model of the experiment can be seen in Figure 1.
When active, the predicted power consumption of RATEX-J is approximately 2.3W of combined electrical power via its 3.3V, 5V and 12V rails. The experiment can be controlled by the On-Board Data Handling system (OBDH) over a serial interface which is also used to retrieve the measurement results for storage and transmission to the ground.
The attitude control requirements for the instrument aperture normal have been determined in [2] to be 32° relative to the magnetic field line with an accuracy +-15° in order to make sure that a sufficient number of electrons gyrating around the field lines are entering the detector stack and create a signal.

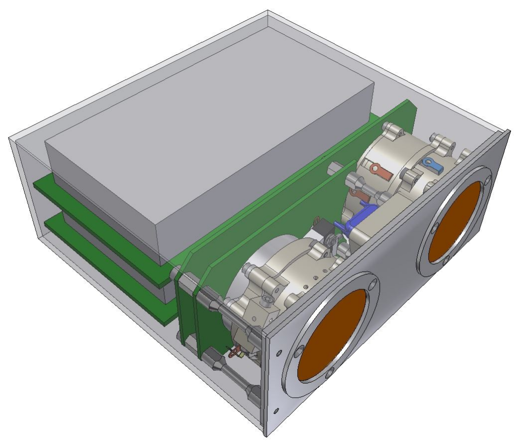

Figure 1: Model of the Radiation Test Experiment for JUICE (RATEX-J)

3.3. Mission Profile

To achieve the mission goal, RATEX-J has to be exposed to high energy electron radiation of sufficient flux to make the results comparable with the conditions expected in the Jovian environment. A study showed that the most favorable conditions for measurements with RATEX-J in LEO are to be found during the crossings of the northern and southern radiation belt [2]. Therefore the active periods of the instrument are focused to these sections of the orbit. To be able to reach the radiation belts, the orbit inclination has to exceed 63°, hence making sun synchronous orbits a good candidate for this mission. Therefore the further design process assumed a sun synchronous orbit.

3.4. Design Constraints

In order to make the J³ mission feasible from a funding perspective, the size is constrained 1U. This poses a challenge due to the payload already occupying half of the available volume. Furthermore the small size of the CubeSat also limits the power which can be collected by solar panels mounted on its exterior due to the limited cross section. As will be shown, this can limit the instrument duty cycle.

Most CubeSat missions are launched into Low Earth Orbit (LEO) and an analysis of regularly offered launch opportunities showed that from the orbits which comply with the life-time limits for CubeSats (between 500km and 800km altitude), the precise orbit altitude does not impact the expected measurement results significantly [2].

4. Design Process and Workflow

To facilitate future design activity, a workflow was conceived which reduced the amount of manual design decisions to be made. While the market for CubeSat components has grown to a point where spacecraft designers have a variety of solutions to choose for each subsystem, it is still small enough to consider automatic evaluation of all feasible CubeSat configurations. A possible configuration is defined here as a set of CubeSat components, which form a spacecraft fulfilling the functional and interface requirements imposed on the design by the payload and mission profile.

The design workflow has been divided into several steps also illustrated in Figure 2. From the data gathered for the available COTS components and the requirements of the payload and mission profile, a series of all possible configurations is generated. These are then used as input to a mission simulation, where also other characteristics of the components of a configuration are taken into account. The mission is then simulated with respect to several aspects, especially the science data collected by the payload from which a score is computed. This score and the simulated satisfaction of operational requirements are then taken as input into the final trade-off deciding on the CubeSat configuration. The individual steps are being described in the following paragraphs.

4.1. Configuration Generation

The configuration generation determines all

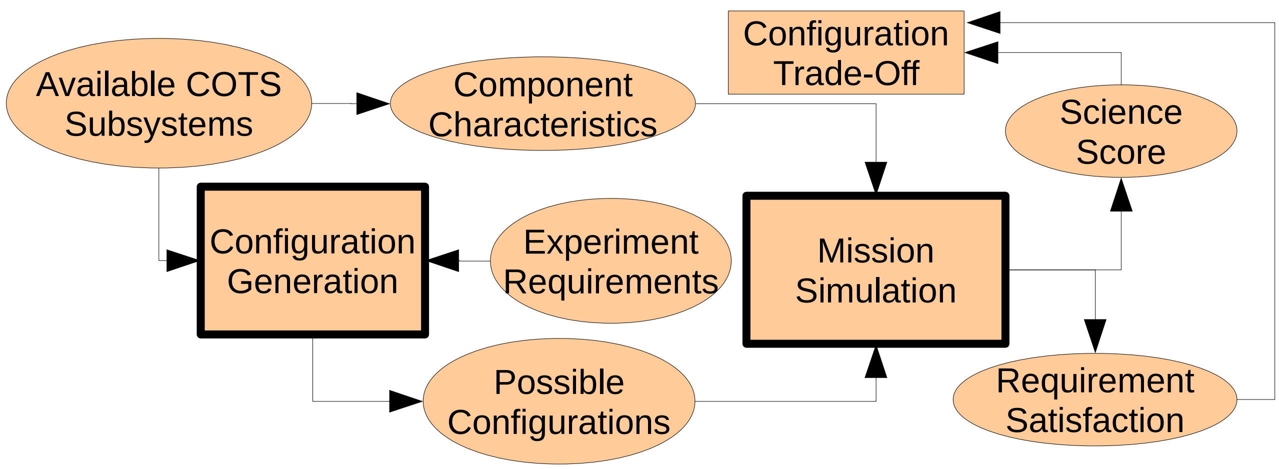

Figure 2: Workflow Diagram of the Design Process for J³

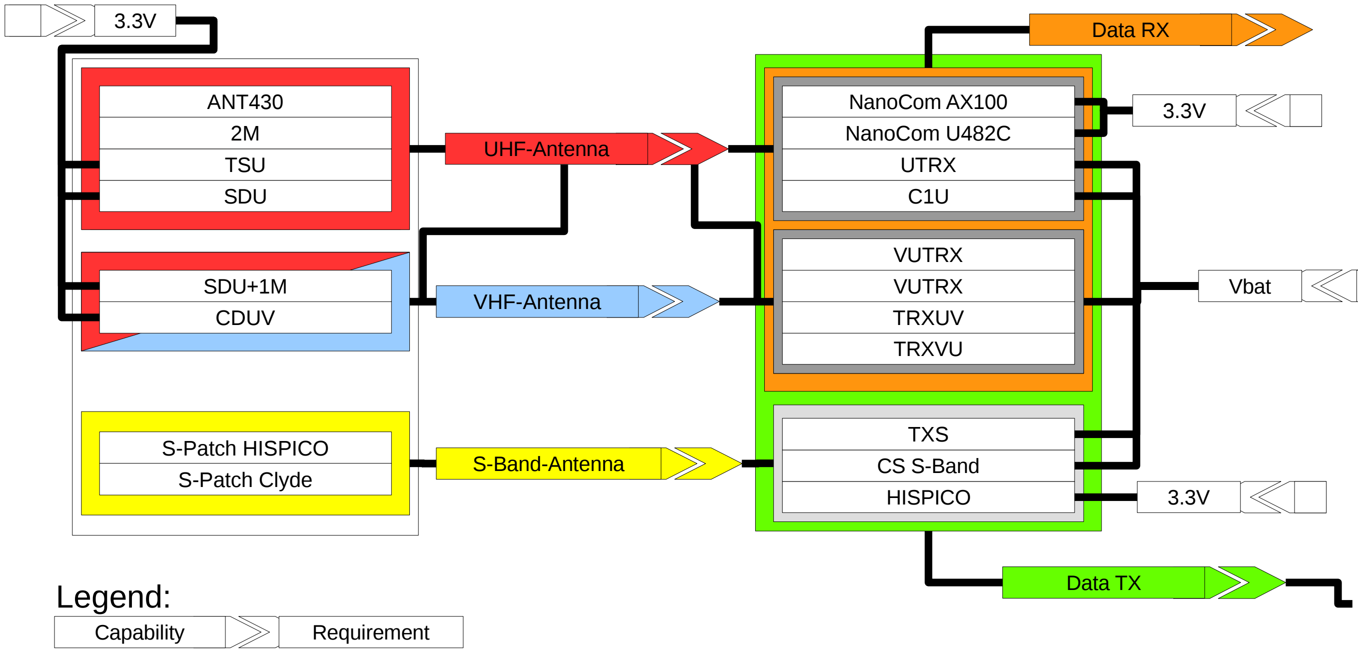

Figure 3: Diagram of Example Components, their Requirements and Capabilities.

possible configuration of CubeSat components which form a spacecraft bus for the payload. To achieve this, the characteristics of the individual components are mapped onto a respective set of abstracted requirements and capabilities. These requirements and capabilities can just represent a simple function, e.g. “Exterior Mounting Point” or “UHF-Antenna”, but can also be extended to more complex characteristics, e.g. “Power Rail providing 5V and up to 1 A”. Therefore it is necessary for the matching process to take into account if a capability may be used by a single requirement or by multiple requirements from different components and if so, by how many.

An example of this network of capabilities and requirements is illustrated in Figure 3 for a set of different antennas, transmitters and transceivers. Here different types of antennas with respect to the illustrated requirements and capabilities can be identified. Most importantly, the frequency capabilities vary between UHF-only, VHF and UHF and S-band only. These capabilities can be used to match the requirements imposed on the design by a selected radio component. These radio components on the other hand differ with respect to the provided capability of transmission and reception or transmission only as well as the required power supply. The latter has then to be matched with an electrical power supply (EPS) subsystem.

Using the requirements of the payload as a starting point, the system searches for possible matches of capabilities within the set of available COTS components. Since a selected component also has requirements of its own, this process is repeated until all possible configurations are found. The search depth and therefore the amount of components which form a possible configuration, is limited by global capabilities that cannot be matched by other components. In the J³ configuration generation for example, the available height in the 1U stack limits the amount of components which can be placed within.

This system shows its impact directly in the resulting set of configurations. From these, three have been selected to illustrate the dependency resolution in Figure 4. When type A of OBDH and Telemetry and Command (T&C) subsystem is chosen, the low profile of the solutions permits the usage of a wider variety of EPS types. When on the other hand type B is chosen for the T&C system, the usage of space in the subsystem stack narrows the solution space of EPS systems and EPS type A is not possible any longer. Furthermore T&C type B also requires a different antenna type, which further requires a different type of solar panel for mounting reasons.

The set of possible configurations generated by this process is used in the mission simulation.

4.2. Mission Simulation

The mission simulation has several goals: Most

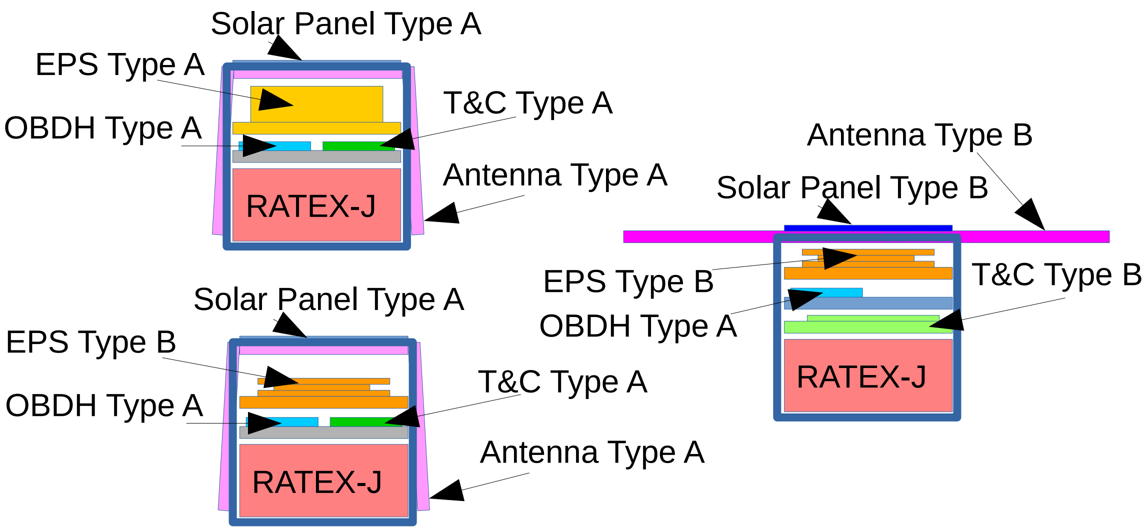

Figure 4: Examples for J³ Configurations

importantly, to reduce the criteria for the trade-off between different subsystems by predicting the mission output for all possible configurations. Thereby it is not necessary to define separate trade-off criteria for individual subsystems, which then influence the mission output. Furthermore, the simulation partially verifies the feasibility of the configuration with respect to some operational requirements, e.g. the limit on the depth-of-discharge on the battery system.
The aspects of the mission which are simulated for the design process are described in the following paragraphs.

4.2.1. Science Score

The science score is defined to be the main trade-off criterion for the mission configuration. Therefore it has to be designed in such a way that the outcome represents the mission success thoroughly. Obviously the criteria and the ease with which it is definable is strongly dependent on the type of mission. For the J³ mission, the score was defined as the amount of electron events which are predicted to be registered by the detectors, recorded in on-board memory and finally transmitted to the ground. The influences on this value are the instrument operating time, the position relative to the Earth's surface and the attitude relative to the magnetic field. The last influence has not yet been included in the simulation and is planned for a later revision. The count rates predicted based on these influences are then integrated and the average over one year is taken as the science score.

4.2.2. Energy Budget

This part of the simulation predicts the performance of the electrical systems on the CubeSat, from the solar panels to the consumers.
The sun vector is used to calculate the power collected by the solar panels, thereby taking into account different strategies of attitude stabilization and states of rotation. This generated power is then simulated as being transformed by the battery charge controller and subsequently used by the separate power rails or stored in the battery. If the combined load of the power rails exceeds the generated power, especially during periods of eclipse, the battery is discharged in the simulation and the power fed together with the power produced by the solar panels into the power rail converters.
It is important to take the varying load profile on the separate power rails into account as the EPS efficiencies strongly depend on the load. Therefore the load on the power rails are computed in every time step and the drain of charge from the battery is calculated accordingly.
The battery state of charge is taking into account by the simulated on-board controller software, which tries to maximize the available instrument run time while keeping the depth-of-discharge below 20%. Here also the capacity of the battery system defined in a specific CubeSat configuration is taken into account.
In the design of the J³ mission, the efficiencies of the power rails varying with load have shown to be an important factor for the possible

instrument runtime. In Table 1 the variation of the power converter efficiency is shown for two states, one describing typical bus standby operation and the other when the instrument is active additionally. The resulting potential instrument runtimes are shown in Figure 5 as percentage of the orbital period. As mentioned before, these values are limited by the allowed depth-of-discharge of the battery system. It can be seen that for EPS 1 it is not possible to cover the whole region of interest consisting of the radiation belts and therefore approximately 20% of the orbit [2]. When reviewing this EPS, it has been found that the operation at the lower end of the EPS output power dramatically decreased the efficiency, significantly more than for other models.

	Instrument Off			Instrument On		
Rail	3.3 V	5 V	12 V	3.3 V	5 V	12 V
EPS1	56%	-	-	75%	41%	76%
EPS2	93%	-	-	93%	94%	80%
EPS3	91%	-	-	93%	62%	87%

Table 1: Change in efficiency due to change in load for different EPS

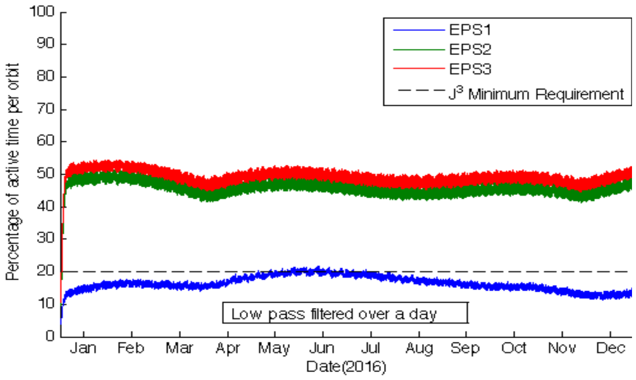

Figure 5: Impact of EPS efficiency on available instrument measurement time

4.2.3. Communication and Data Handling

The communication with the ground is simulated for the mission as well as the state of on-board data handling memory.

For the communication the periods of contact with the ground station are determined as well as the link conditions imposed by the relative geometry between ground station and the satellite. Kiruna was chosen as the location of the simulated ground station, as there is already a small satellite ground station available on the space-campus of the Luleå University of Technology (LTU).

The state of the OBDH memory is simulated to determine whether there is the possibility of overflowing the memory during periods in which there is no ground contact.

During our simulation several important results have been found: For the J^3 mission, no need for a data rate higher than 9.6kbps could be identified.. This limit is significant sine most available COTS CubeSat communication systems are providing this data rate as a result from amateur radio regulations.

This was analyzed and identified as an effect mostly of the frequent ground station contacts for sun synchronous satellites due to the high latitude location north of the polar circle and the low data production rate consisting of only approximately 22 kbyte per orbit of science data and additional house-keeping data.

4.3. Trade-off

The outcome of the simulation is taken into account in the final trade-off for the configuration of the satellite. While most influences of the components can be reduced to the science score in the mission simulation, some design aspects still remain to be judged manually. These include for example the expected software development effort for OBDH systems which have different hardware architectures, e.g. based on a microcontroller or a field-programmable gate array (FPGA). Furthermore if the initial configuration generation included component variants of COTS hardware which would require some modification, these also pose a development effort which has to be included in the trade-off.

Otherwise the cost of a configuration is the remaining trade-off criteria, which as a numerical value is easy to classify compared to more abstract qualities as the development effort.

5. Summary

In this paper a new methodology to facilitate the design process of CubeSats was presented within the case study for the J³ mission. The mission profile and requirements were presented which serve as input to the design software tools. These tools were able to identify critical differences in mission performance for different satellite configurations. Therefore the tools demonstrated their usefulness in the design process and may be adapted for future CubeSat developments.

6. References

[1] M. Swartwout, *The First One Hundred CubeSats: A Statistical Look*, Journal of Small Satellites, Vol. 2, No. 2, 2013

[2] F. Wolff, *On the Suitability of CubeSats in Earth Orbits for Radiation Testing of Interplanetary Payloads*, iCubeSat Conference, 2015