Eurostar E3000 Satellite On-Board Software Development of a product line towards multiple system needs

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Abstract:
The present paper describes how the on-board software for the telecommunication satellites family Eurostar E3000 contributes to the successful story of the product line. It encompasses a synthetic description of the platform and the on-board software functions and major requirements to support the different options and variants, how this generic software was efficiently developed and verified, how each instantiation for each new satellite program could benefit from the overall industrialization process.

Keywords: Reusability, Evolvability, Product line

1. Introduction

On one side main space programs are considered for avionics and on-board software as a new prototype every time. On the other side the commercial market pressure has forced satellite manufacturers to improve drastically their cost and their time to market. These market constraints are particularly true for the commercial telecommunication satellite market.
To achieve such goals EADS ASTRIUM has decide to develop a very generic telecommunication satellite platform named Eurostar E3000 able to be customised for all major telecommunication application domains and missions.
A new powerful and modular avionics was developed to be compatible with the performance range and the functional set of variants and options. The on board software running in the main computer was defined, developed and validated as a generic product line with a major objective to reduce as far as possible cost and schedule for each program instantiation and qualification.

2. Eurostar 3000 Telecommunication Platform

2.1 From Eurostar 1000 to Eurostar 3000

The latest version Eurostar E3000 inherits from the large development and in-flight experiences of the two first versions Eurostar E1000 and E2000 with 21 operational in-orbit satellites.

All the family was developed with a very modular design for efficient customised solutions covering a broad range from medium size (3 KW to 6 KW payload power) for E1000/2000 platform to large size (up to 12 kW) for E3000 platform.

- E2000+ characteristics
  - Highly efficient for missions in the 40 transponders range
  - Launch mass : up to 3.4 tons, compatible with all launch vehicles
  - Payload power : up to 6.2 kW
  - Payload : up to 48 installed high-power amplifiers, large and multiple antenna configurations
  - Satellite manoeuvre life : 15 years
  - CCSDS telemetry / telecommand protocol
- E3000 characteristics
  - Modular architecture provides for a wide range of high power missions, flexible payload accommodation
  - Launch mass : up to 6.4 tons, compatible with all commercial launch vehicles
  - Payload power : up to 12 kW
  - Payload :up to 120 installed high-power amplifiers, large and multiple antenna configurations
  - Satellite manoeuvre life : 15 years
  - Multi-standard telemetry/command protocols

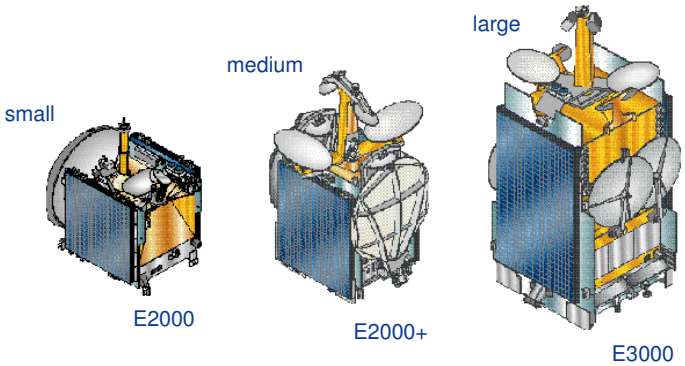

Figure 2.1 - Eurostar satellite

2.2 The latest generation Eurostar E3000

The latest Eurostar version, the E3000, already chosen by satellite operators Eutelsat, Hispasat, Inmarsat, Intelsat, SES Astra, Paradigm and Telesat and successfully introduced in orbit in 2004, is setting new standards.

The following improvements have been introduced in the EUROSTAR 3000 platform:

- Increase launch mass, by designing a scale -up structure of the heritage design, which is capable of up to 6 tons launch mass with conservative design margins.
- Improve critical platform performance such as pointing by implementing a 2 DOF AOCS system, propulsion performance by implementing the flight proven plasmic propulsion technology.
- Improve operability and autonomy by using additional computer capacity to implement user friendly system interface and a complete and comprehensive FDIR approach.
- A design for manufacture and test approach has been followed with extensive participation of manufacturing and AIT during all phases of the design.

The E3000 platform is characterised by its modularity:

- A common Service Module design
- A large level of modularity with generic elements
  - Communication module with one, two or three floors
  - Propulsion : chemical only or chemical + electric (Plasma), several tank capacities from 2.4 to 2.9 tons
  - Power : scalable solar array, NiH2 or Li-Ion batteries
- Satellite power up to 16 kW : solar array span up to 45 m

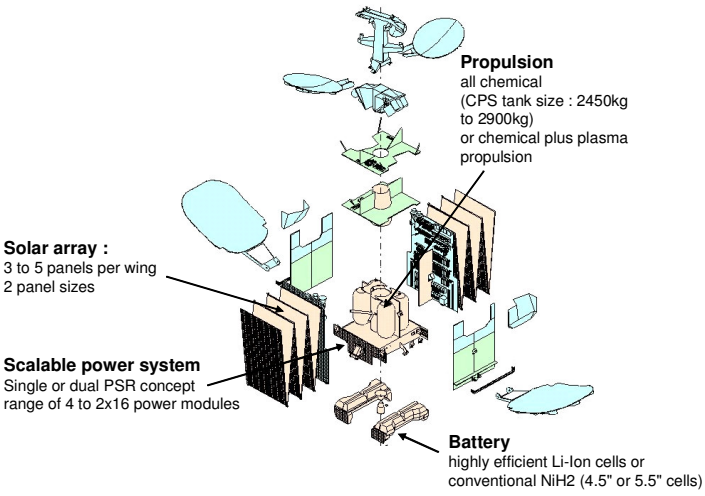

Figure 2.2 - E3000 Platform modularity

2.3 The Eurostar E3000 software product catalogue and alternatives

The E3000 new product development policy was established to meet various telecommunication program requirements:

- It leads to a Platform product catalogue with options,
- At Software level (definition and implementation) the driver was to make a generic product to the maximum extent and to customize this product through data (database to the maximal extent) in the frame of a dedicated program,
- This approach is the most effective in terms of planning and cost and enables strong heritage between programs
- The counterpart is:
  - The SW is not exactly tailored to a specific program needs but to a family of needs fulfilled by a set of SW alternatives
  - At SW generation, the generic product is customized to fit a program's needs (alternatives selection)
  - Customisation may lead to extra code (in the frame of a dedicated program)
  - This extra code is identified, made neutral and without side effects on board

The E3000 Software product catalogue has been prepared as an input to the E3000 platform product catalogue: the structure is derived from the structure of the E3000 platform product catalogue to allow an easy mapping of information between these two documents.

This SW catalogue is also a reference document for the "E3000 On-Board Software Alternatives Implementation" document which provides a detailed cartography of alternatives impacts in the E3000 SW and especially how the non selected alternatives are managed inside the SW (i.e. unused SW if any and in this case how its safety is ensured).

The Figure 2.3 summarises the position of the different documents.

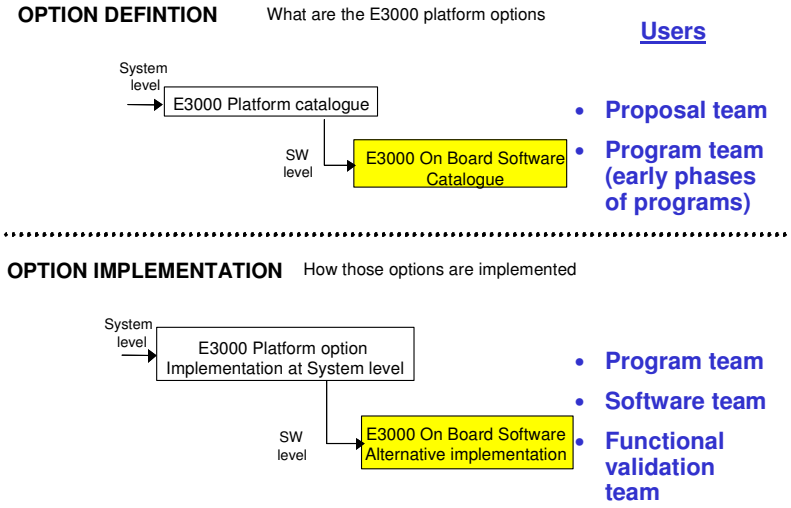

Figure 2.3 - Platform and OBSW product catalogue and alternative documents

Each alternative is described with the same structure:

- **Description**: a summary of the functionality introducing the configurability provided by the alternative
- **Categorisation**: whether it is linked with a platform option or it is a functional alternative. When it is a system option, its relevant name is provided.
- **Justification**: an explanation of the reasons that caused that feature to be optional.
- **Reference**: a list of the User Requirements Documents referring to this alternative.
- **Compatibility**: a description of the compatibility issues associated with the alternative (i.e. compatibility with other OBSW alternatives).
- **Alternative selection**: a description of what has to be done to select the alternative in terms of software (i.e. Database, numerical data, requirements documents …) after the alternative has been elected (i.e. all the system analyses has been carried out). In the process for recurrent E3000 OBSW, all the alternatives will be selected at user level through the "Alternative Inputs Table" in the program specific GURD.
- **Improvement** : a list of proposed improvement dealing with the alternative management (specification, design, selection …)
- **Development status**: the level of the definition/development of the alternative. A description of the work to be performed to finalise the production of the software.
- **Maturity**: the level of verification / validation of the alternative. A description of the work to be performed to finalise the verification.

About twenty platform options are defined and available at system level spread over all sub-systems:

- TM/TC options (Sub-carrier, bit rate, protocols, authentication or not)
- Payload Configuration
- Power system configuration (Solar arrays, Battery, Number of modules, Single or Dual)
- Actuators configuration (Chemical and Plasmic propulsion, thrusters, CPS tank size, number of wheels)
- GNC modes (Inverted attitude, Transfer orbit, Orbit inclination)
- Thermal loops configuration (Number, frequency, monitoring, thresholds)

This OBSW catalogue allows many spacecraft configurations. Nevertheless, some OBSW alternatives are linked together and some configurations are not recommended or even not allowed. In order to provide to proposal managers a quick overview of all sets of alternatives which have already been designed and validated together in the frame of programs, the document includes table presenting a mapping of selected OBSW alternatives in existing Satellite configurations: sets of alternatives that have proven their compatibility and preferred configurations (i.e. already developed).

3. Eurostar 3000 On Board Software product line

From an On Board Software (OBSW) production view point, Eurostar E3000 Spacecraft family represents a particular challenge:

- The development approach shall live for more than 15 years and support the production of On Board software versions for tenths of satellites involving various alternatives combinations. (Software versions have already been produced for more than ten different Satellites. Satellite integration and avionic validation activities may typically involve four satellites in parallel)
- The Eurostar E3000 family OBS production shall cope with evolution needs (for correction or enhancement purpose).
- EADS Astrium shall provide operational satellite customers with a maintenance/expertise capability.

Eurostar E3000 On board Software product line was settled to achieve these objectives. E3000 OBSW product line encompasses source code objects, data, tests scripts, tools and processes that allow maintenance, production and validation of OBSW versions for E3000 family satellites in an optimized way.
The next chapters develop how each of these components contributes to achieve this goal through the basement of E3000 OBSW product line: architecture, source code and data management.

3.1 OBSW Architecture

OBSW architecture is organised in hierarchical layers with modular components and standardised interfaces.
This layered architecture is common to all application programs and is illustrated in term of layers and major components on next Figure 3.1.
This modular architecture allows isolating each specific component dedicated to an equipment management or a service: when an alternative is needed, generally it is implemented within only one component:

- Battery choice
- Number of wheels
- Telecommand protocol

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Another interesting feature is the existence of Interpreted Program (IP) allowing late or even in-flight evolution with a large capacity to adapt code or data to a specific alternative need.

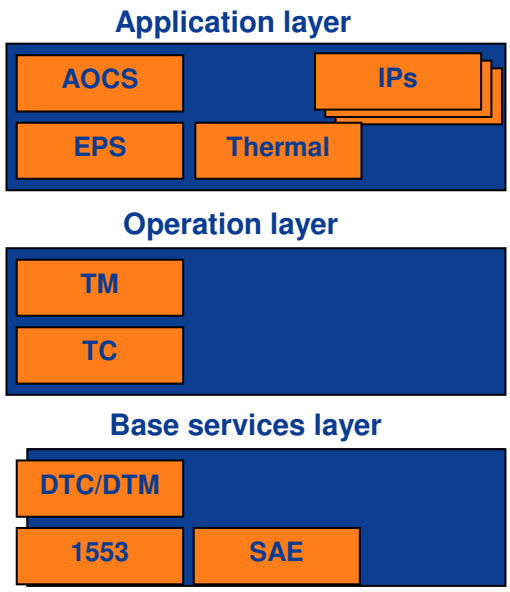

Figure 3.1: E3000 OBSW architecture

3.2 OBSW source code management

Alternative management in source code mostly relies on two methods: use of distinct objects or conditional compilation in a shared object. These two methods avoid the presence of unused software parts in the on board software.
In some cases however, option management may lead to unused OBSW parts in the final on board software binary file. Dedicated analyses are then performed to make sure that such unused part of OBSW (that have anyway been validated at component level) cannot nominally be reached and that they do not include any action that could interact with hardware.
More generally, for each alternative in the E3000 catalogue, a dedicated so-called Alternative Implementation Document describes how alternative is managed in source code and justifies the innocuousness of any unused validated Software part.

3.3 OBSW data management

Data management is an important part of the industrial process that had to be settled in the frame of Eurostar E3000. Various kinds of data are used for the production of On Board Software: numerical values, 1553 acquisitions and commands lists, Telemetry format definition…

In the frame of E3000 OBSW product line, a data engineering activity was conducted. This activity first consisted in data categorisation. Several categories can be defined to sort out data: mission dependent data that do not depend on a software alternative (e.g. Attitude Control gains, sensor wedging), alternative dependent data that may or may not be mission dependent (typically the use of Proton launcher may require dedicated OBSW functions activated during Proton coast phase that require dedicated parameters), and other data that are not expected to be mission dependent (for example queue size parameters).

For each satellite application program, data are imported from system database or files into the source code at software generation by a dedicated tool called Production Program. Many OBSW functions do consume data that are expected to be mission dependent.

In the frame of E3000 OBSW product line that encompasses tenths of spacecrafts, the validation strategy for such functions is crucial. The industrial process that was settled for data management aims at fulfilling the following objective: data import into OBSW source code shall not question, to a

maximum extent, the OBSW validation of the concerned function.

To achieve this goal, the process impacts data population methods, code architecture, and validation. Mission dependent data are provided by the application program project team. Data population tools based on Excel file templates called Numerical Input Documents (NID). Macros have been designed in order to ensure that data are populated in a consistent way for all spacecrafts. These tools enable typically automatic population of alternative dependent data. The populated information is then automatically transferred to the system database (data of that category are called "data lists").

From a validation view point, the objective of the software validation for objects including data lists is to demonstrate the ability of importing and handling such data lists whatever their content is so that data list content evolution does not require the function OBSW re-validation. Data validation will be developed further in the next sections.
A dedicated document, called Mission Data Management documents (MDM), depicts the NID structure, population constraints, and the way to deal with data population for alternative dependent data.

Next Figure 3.2 summarizes the document structure that includes alternative management in Eurostar E3000 OBSW product line:

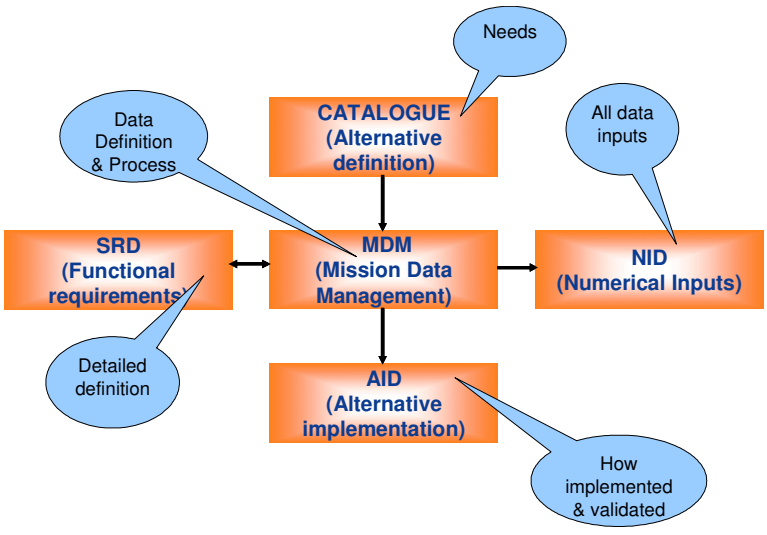

Figure 3.2 - Alternative management Documentation

4. Eurostar 3000 On Board software development and validation

4.1 OBSW Product line validation

The whole EUROSTAR 3000 OBSW product line has been validated according to a validation strategy that encompasses component tests and software integration tests on validation benches:

- Component tests are independent from mission data and focus on processing. (about 1600 component tests for 200000 lines of codes)
- Integration tests focus on components integration SW/database/Bus integration. The complete OBS validation campaign on validation benches encompasses about 400 integration tests. This validation campaign was thoroughly run for the four first E3000 application programs. These four first satellites contributed to cover all alternatives in E3000 catalogue and to demonstrate the ability of the software to accommodate various data values.

Anytime a software modification is performed (for product evolution or correction purpose), all impacted component and integration tests are updated and run before making the OBSW modification available for any application program.

4.2 OBSW validation for a "Recurrent" Program

Once the software product line is validated, the following spacecrafts OBSW validation strategy follows a so-called "recurrent" approach. Since source code has been validated in the frame of the available product line, the validation for recurrent programs shall mostly concern data validation.

The recurrent data validation strategy elaboration first consisted in reviewing all data and sorting them into several categories according to their origin, their functional meaning and at which level they shall be validated (OBSW or functional). OBSW level validation shall be covered by OBSW Validation Bench (SVB) tests, functional level validation may be performed on Avionic test bench or functional simulators as part of the satellite avionic test campaign. Figure 4.2 summarizes the data categories.

Data to be validated at functional level shall nevertheless be preferably exercised on SVB. It means that the SVB validation is performed with the data inputs which are contained in the SW image to be delivered (i.e. same data for SVB validation and for functional validation).

The validation strategy at OBSW level for EUROSTAR 3000 recurrent programs consists in performing a fixed subset of the SVB tests defined in E3000 product line validation plan. The corresponding test campaign is called “acceptance test campaign”. The acceptance test subset encompasses about one third of the complete EUROSTAR 3000 product line validation plan. (Note that the SVB procedures have been previously automated in the frame of the E3000 OBSW product development and that the validation on SVB is in fact a regression testing activity)

The validation of most data to be validated at OBSW level is ensured by the acceptance test subset. OBSW validation level Data not covered by acceptance campaign are clearly identified. An analysis that consists in checking the value of such data against the values already validated in the frame of E3000 product line is conducted in the frame of each recurrent program. Should an unprecedented value be encountered, the dedicated tests to be run in order to validate this new value are identified in advance in the Data Verification Control document. (That latter document identifies the tests that contribute to the validation of each OBSW data)

The acceptance test subset provides a large coverage of the OBSW functions for non regression / good health verification purpose. In particular these tests exercise as many functional level data as possible (though the responsibility of the validation of these data belongs to functional validation).The development plan for a recurrent program (that may involve unprecedented combination of alternatives and specific data) includes a unique OBSW version delivery. The production, the validation and documentation of this version is achieved in less than 1500 hours of manpower.

Data types	Type definition	Test level
TYPE 1 E3000 Study data	These data do not depend on any alternative but their value, provided by subsystem architects, may depend on the mission.	functional
TYPE 2A ALTERNATIVE Definition data	These data are the parameters used in software to define which alternative are involved in the mission.	software
TYPE 2B ALTERNATIVE Study data	These data depends on an alternative and are provided by functional subsystem architects for each mission.	functional
TYPE 2C ALTERNATIVE Operation data	This category gathers data such as Telemetry format definition.	functional
TYPE 2D ALTERNATIVE Unused data	Data imported in software that correspond to an alternative that is not used for the mission.	software
TYPE 2E ALTERNATIVE Software data	Alternative dependent data that are derived from software design (not functional data).	software
TYPE 3 E3000 Software data	Software non functional data that are derived from software design and may change between missions.	software
TYPE 4 E3000 Software constant	Software non functional constants that are derived from software design.	software
TYPE 5 ALTERNATIVE Database interface	Commands or acquisition definition that depend on alternatives or mission (e.g. list of command to be sent to configure equipments).	functional

Figure 4.2 - OBSW data types and associated validation

5. Conclusion

The on board software "recurrent" development efficiency and the in-flight successful operations are essentially due to:

- a well managed process starting from the system level to the avionics and software development level including definition, design, production and validation activities,
- a completely structured set of options and variants (so called alternatives) defined at system level in a catalogue and at software level by design, source and data management types definition with associated validation and verification objectives,
- a complete and powerful set of means at software level:
  - Source code and data configuration management,
  - Complete and modular documentation,
  - Automatised production of source product for each program,
  - Suite of integration and validation tests with minimised effort for "rerun" on a specific program instantiation.

6. Acknowledgement

The authors acknowledge the contribution of Mrs Dehaynain, Mr Gaullier and Mr Palous to this work.

7. Glossary

AOCS: Attitude and Orbit Control System

DOF: Degree Of Freedom

E3000: Eurostar 3000

FDIR: Failure Detection, Isolation and Recovery

IP: Interpreted Program

MDM: Mission Data Management

OBSW: On Board Software

SVB: Software Validation Bench