INTELMOD: ARTIFICIAL INTELLIGENCE IN SUPPORT OF MISSION OPERATIONS TASKS

Alessandro Donati
ESA/ESOC, Robert-Bosch-Str. 5, D-64293 Darmstadt, Germany,
tel. +49 6151 902574, fax +49 6151 902135, e-mail adonati@esoc.esa.de

Enrico Romani
Dataspazio S.p.A., Via Laurentina 756, I-00143 Rome, Italy,
tel.: +39 06 50097 24, fax: +39 06 5022331, e-mail enrico.romani@dataspazio.it

Mark Aynsley
Science Systems (Space) Ltd. 1st Floor, 12 The Parks, Newton-le-Willows, Merseyside, UK,
tel: +44 (0)1942 270 060, fax: +44 (0)1942 270 049, e-mail: mark.aynsley@scisys.co.uk

ABSTRACT

This paper presents the results of a project aimed to deliver an advanced pre-operational Artificial Intelligence (AI) system to support visual monitoring, diagnostic processing and resource management of a spacecraft during its operational lifetime. The tool can also be used during mission preparation for training of flight controllers and as an assistant during operational procedures development and validation.

The INTELligent MODeller (INTELMOD) toolkit has been developed using a COTS knowledge based system and object-oriented techniques. Initially, it will assist the flight controllers in the generation and maintenance of spacecraft models, providing a user friendly man-machine interface to collect engineering and operational knowledge directly from the experts. The models will then be used by the INTELMOD inference engine to support the flight controllers in the following tasks: monitoring, anomaly detection and anticipation, failure detection, isolation, diagnosis and recovery, failure propagation analysis and on-board resource management.

The generic tool has been then demonstrated for the Cluster mission, with the modelling of the Cluster AOCMS and power subsystems and with customized interfaces for the Cluster mission database and SPEVAL [1] system, providing processed telemetry (and telecommand) retrieval.

1. INTRODUCTION AND BACKGROUND

The European Space Operations Centre (ESOC) of ESA, as a centre of excellence in delivering flight operations services to spacecraft user community, has often made the effort to pursue constant improvement in its own processes, methods and tools to guarantee an outstanding record of successful mission operations.
In this framework INTELMOD represents a pioneering activity in understanding and exploiting, at prototype level, the potential benefits offered by mature knowledge based system technology and applied to flight operations processes.

Previous studies [2] have already offered indications of the possible use of artificial intelligence in the spacecraft operations domain; the INTELMOD toolkit now provides a user-friendly modeling environment directly usable by operations and spacecraft experts for two purposes:

- to transfer and organize their own knowledge of the spacecraft system, mission phases, and diagnostic rules into a knowledge database;
- to use the stored "know-how" during mission operations to advice operations staff when and, possibly, just before anomaly occurrences.

2. OPERATIONAL CONCEPT

INTELMOD is not intended to replace any existing Mission Control System (MCS); it will be interfaced to existing MCS with the objectives of expanding and extending the current MCS supported functions.

To support the different stages of model development and implementation, three classes of INTELMOD user have been identified:

Spacecraft Component Developer (SCD)- responsible for the creation of spacecraft components (modules, subsystems and units) which are then inserted into a Component Library to be used later during a model definition phase. Component Developers are expected to have a high level of knowledge concerning typical spacecraft "building blocks".

Spacecraft Model Developer (SMD) - creates a mission specific model representation by selecting and configuring items created by the Component Developer. Models are progressively assembled and configured to provide a physical, functional and mission-related representation of the spacecraft in question.

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INTELMOD User - interacts with the models created by the Model Developer during Mission operations / training scenarios.

The toolkit has been conceived to be used in two distinct phases of the spacecraft operations lifecycle:

- during *mission preparation*, the users will access the toolkit as SCD, to create, modify or augment the models of the "terminal" elements of the hierarchical representation of generic spacecraft, to be then stored in a library. In the very same phase, the user will access also as SMD to model selected subsystems, down to the end item, the related mission modes, the diagnostic and failure propagation rules, the contingency procedures and the trend analysis rules belonging to a specific spacecraft and mission;
- during *flight execution* phase INTELMOD will be connected to the existing Mission Control System (MCS), to receive telemetry (and telecommands). The user will access as INTELMOD User. This time the toolkit will provide operational advisory services to the flight control team.

The flight operators will be supported by INTELMOD for visual monitoring and alarming, diagnostic support, including failure detection and anticipation, failure isolation, diagnosis and recovery and failure propagation analysis, resource evaluation and assessment.

The toolkit has been developed taking into account the following requirements:

- support multi-mission environment;
- user-friendliness of the interface for the operations and spacecraft experts during modeling and flight operations phases;
- minimal software customization effort when applying the toolkit to a specific mission, limited to interface adaptation.

3. THE PROJECT

INTELMOD has been developed using a RAD-style approach, based upon the Dynamic System Development Method (DSDM), which is a non-proprietary method that is becoming a de-facto standard within the UK [3]. This approach was partially adopted in this study to help ensure that the system could be developed in a much shorter timescale, and that the final system was more closely matched to ESA's real needs.

DSDM employs an iterative approach to development with heavy emphasis on end-user involvement and a project management philosophy which focuses on *products* rather than the activities needed to achieve them. Timeboxes were used to control the development process, whereby a fixed amount of time was allocated to complete a given area of functionality. Figure 1 below shows the DSDM development process, although this required some modification to comply with ESA's particular project control requirements and to overcome the challenges associated with the development team and end users being located in geographically distant locations.

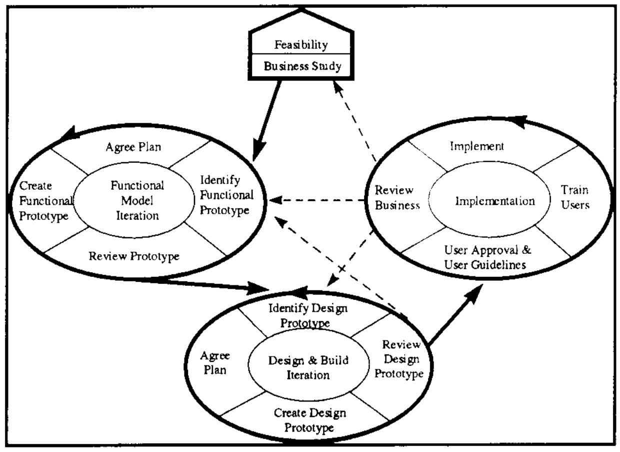

Figure 1. DSDM Development Process

INTELMOD has made extensive use of commercial off-the-shelf (COTS) software products, including:

- G2
- GDA
- G2-Weblink
- ODBC Bridge
- Space UNiT (Universal Intelligent Toolkit)

INTELMOD has primarily been developed using G2 (Gensym Corporation). This provides an object oriented environment for building and deploying mission-critical, intelligent applications. It is typically used to represent knowledge captured from operations experts performing complex tasks in real-time situations and has a broad range of potential application areas. GDA (G2 Diagnostic Assistant) is a layered application product for G2. It provides an integrated visual development and execution environment for modelling application logic / diagnostics. The major strength of GDA lies in its intuitive Graphical User Interface ??? GUI, allowing faster development of complex systems models required for INTELMOD.

G2-Weblink enables users to access G2-based applications via Web browsers. This allows the distribution of intelligent decision support information to intra/internet users throughout an organisation. Gensym also provides bridges for all ODBC-compliant databases. In the current INTELMOD study, a Microsoft Access copy of the CLUSTER database was used. Finally, INTELMOD also incorporates Space UNiT (Science Systems Space Ltd). This has been developed in a partnership programme for ESA to provide a component based suite of graphical products for procedure execution, schedule execution, monitoring and event handling [4]. Space UNiT enables INTELMOD to automatically execute contingency procedures following the detection of anomalies by one or more of the functional models described in section 4.

These products were used in order to provide the rapid delivery of functionality required. In addition, the industrial partnership approach made possible for the project to remain within budget.

4. ARCHITECTURE AND MODELS

4.1 Spacecraft Systems Model

This model provides a hierarchical representation of the spacecraft, its subsystems and individual components. For example, a spacecraft may be partially represented in terms of power, thermal and AOCMS subsystems. The power subsystem in turn may be composed of a power distribution unit, batteries etc. This knowledge is entered using a *breakdown editor* to interactively gather and structure knowledge related to the physical organisation of the spacecraft. The breakdown editor configures itself according to the user currently interacting with the system (SCD, SMD or generic user). Fig. 2 contains an high-level object-oriented diagram describing breakdown editor behaviour and user relationships

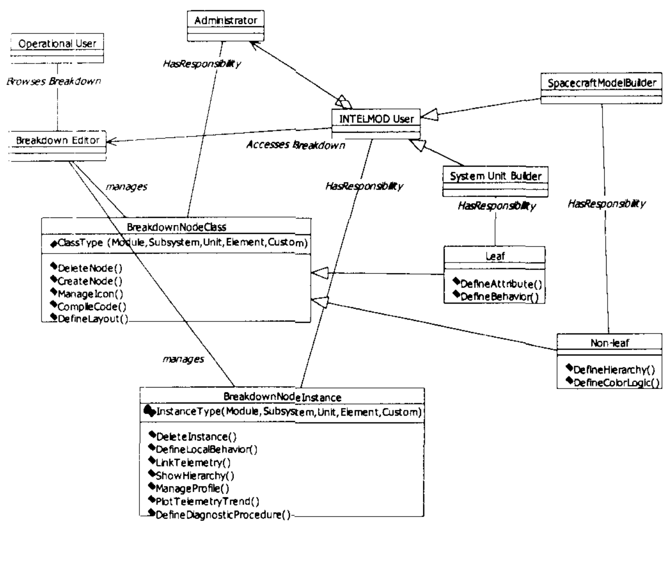

Figure 2. Breakdown Editor OO diagram

4.2 Mission Model

The Mission Model provides a hierarchical representation of the mission in terms of the various activities performed within various phases and modes, together with the expected configuration (i.e. status and resource consumption) for all the physical components defined in the physical spacecraft model. As with the physical model, a *breakdown editor* allows the Model Developer to gather and structure this knowledge.

4.3 Functional Model

The Functional Model uses a *graphical rule based language* to define knowledge related to the functions to be performed or assured during the course of a mission. This knowledge falls into the following areas:

- Spacecraft Behavioural Knowledge: Contains knowledge describing the behaviour of the spacecraft systems with respect to the interaction between the various components and subsystems. This knowledge enables the model to perform basic diagnostic functions including failure isolation and recovery.
- Mission Behavioural Knowledge: Describes the spacecraft behaviour exhibited during the execution of different mission phases and the activities performed during those phases. This model also uses the Flight Operations Plan (FOP) to enable INTELMOD to perform resource evaluation.
- Spacecraft/Mission Relationship Knowledge: This knowledge model captures the heuristics used by the Operations, Spacecraft and Payload engineers to identify and rectify problems that occur over the lifetime of the spacecraft. Once defined, the spacecraft/mission relationship knowledge enables INTELMOD to perform trend analysis, failure detection, diagnosis and prevention and to recommend recovery actions.
- Spacecraft/Mission Propagation Effect Knowledge: This model, available from the Flight Operations Plan and Mission specialists, describes the cause and effect knowledge, which relates sections of the spacecraft and mission models. A causal network allows the flight controllers to perform an analysis of process and hardware failures and predict the consequences of failure if no corrective action is taken. It also allows the controller to assess the mission impact in terms of unavailable hardware and lost functionality.

A summary of INTELMOD users and model types is shown in figure 3:

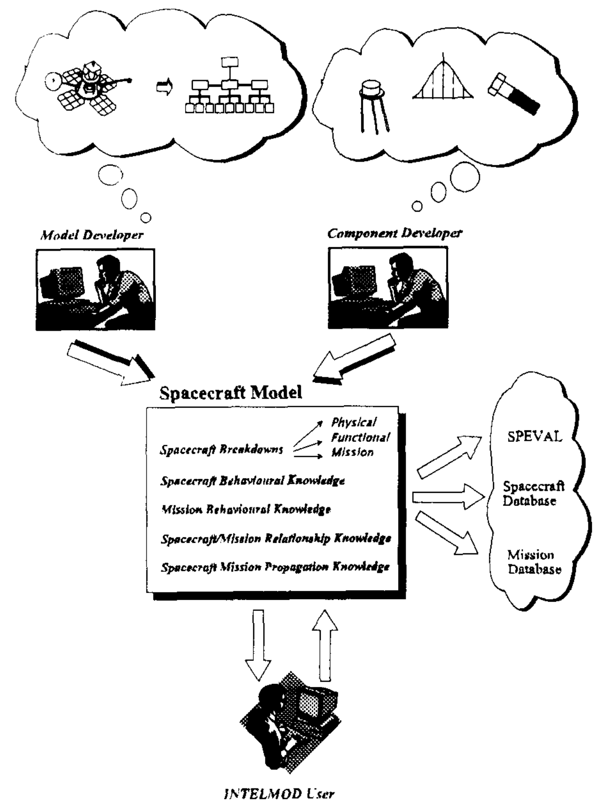

Figure 3. INTELMOD Users and Models

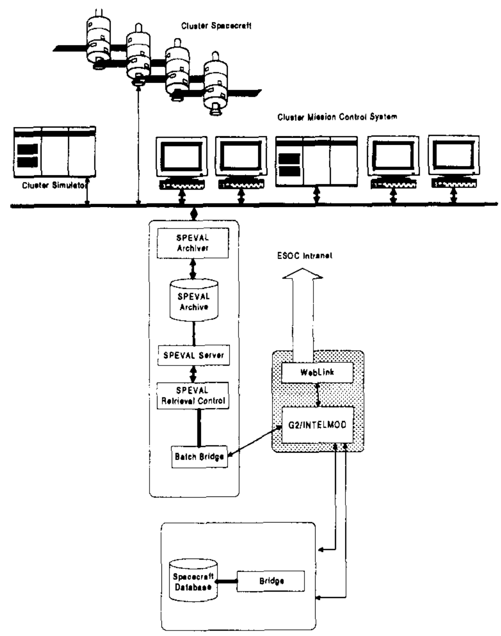

Figure 4. INTELMOD Interfaces

5. EXTERNAL INTERFACES

In order to demonstrate that INTELMOD could operate in a realistic manner and provide the support required to Mission Operations, the system must be provided with a high degree of connectivity. This was achieved using three separate interfaces:

- TM/TC bridge
- Spacecraft Database Bridge
- WWW Bridge (for message broadcast)

These interfaces are shown in figure 4 and described below.

5.1 TM and TC Bridge

The telemetry and telecommand bridge provides INTELMOD with the information required to perform its analysis. In a "live" implementation, this information would be supplied directly from the Mission Control System (MCS) software. However, in the time frame of the current study, data files were provided using SPEVAL (Spacecraft EVALuation tool), a client server application developed during a previous ESOC study [1]. SPEVAL maintains its own archive of data from the Cluster MCS, and this data can be retrieved batchwise using SPEVAL "Save Cases". The resulting data files are then read by INTELMOD, using a dedicated bridge.

5.2 Database Connectivity Bridge

The purpose of the database bridge is to connect the INTELMOD modelling environment to a satellite database containing information regarding the various parameters, command definitions and scaling / limit data that are specific to the particular spacecraft under study. This bridge enables INTELMOD to support the development of the models described in Section 4.

5.3 Message/ Alarm Broadcast Bridge

To provide a method for the distribution of alarms, warning messages and general information, G2 Weblink has been incorporated into INTELMOD. Whilst it would have been possible to provide a dedicated bridge to send messages as e.g. e-mail messages within ESOC, the use of Weblink provided a more generic COTS solution, enabling information to be accessed from the widest possible range of platforms.

6. INTELMOD FOR CLUSTER II

Within the scope of the current study, INTELMOD customization has been focussed on the AOCMS and Power subsystems of Cluster [5]. Taking the Power subsystem as an example, this has been decomposed using INTELMOD's Breakdown Editors into the following units:

- power control

- power distribution
- internal power dumpers
- external power dumpers
- battery regulation
- batteries
- pyro-electronics

Once these breakdown components have been identified attributes can be added, again using a dedicated editor e.g. a battery would typically be described using properties such as voltage, temperature, charge current and discharge current. This is shown in figure 5 below.

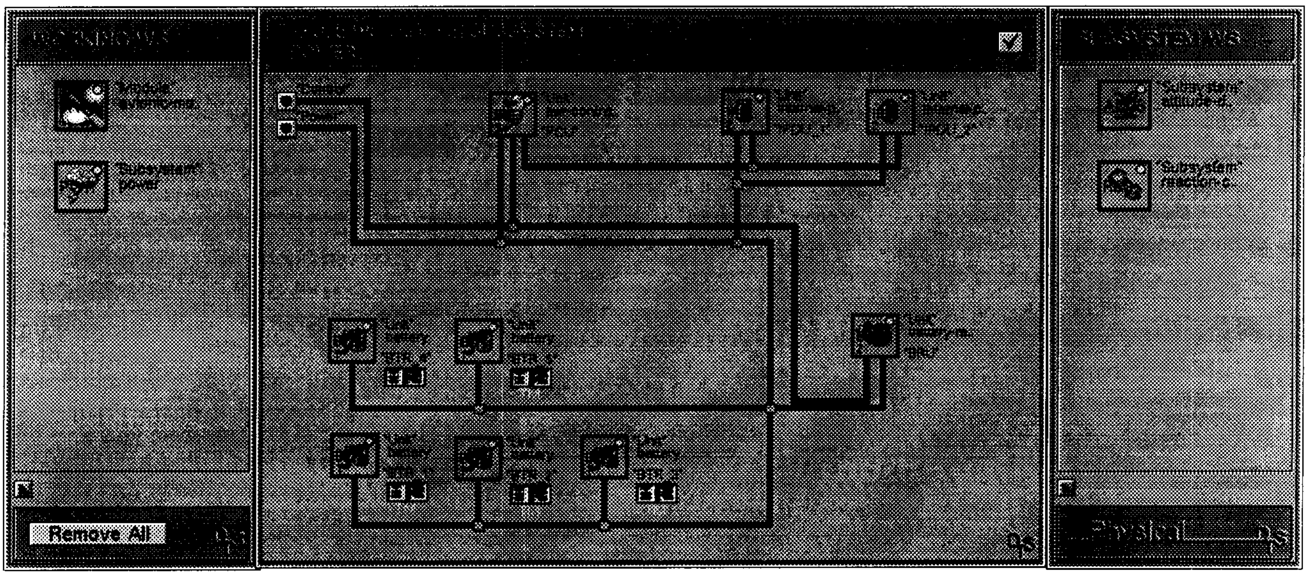

Figure 5. Screenshot of Breakdown Components

Having linked the INTELMOD breakdown components with their external counterparts (i.e. telemetries or groups of telemetries) by interactively querying the spacecraft database, it is then possible to construct the monitoring and diagnostic"*rules*".
Monitoring rules allows mapping status of breakdown leaves (as derived form the incoming telemetries) with a synthesis information: whenever the status of changes the color of the related component displayed in the breakdown mimics changed according to the following table:

1 - green:	OK
2 - red:	fault
3- yellow:	off-line
4- blue:	stand-by
5- orange:	redundancy lost.

This information travels upward in the hierarchy: once colors has been computed for all the components belonging to a specific level (e.g. units), the same colors are logically combined to derive the color representing the "assembling" component at upper level (e.g. subsystem). Color propagation and telemetry association logic is entered within INTELMOD via dedicated parsers which allow defining this logic in a '*natural language*' way.

Figure 6 shows a simple INTELMOD GDA-based diagnostic model (Spacecraft Behavioural). The blocks on the left of the diagram are "entry points", usually corresponding to a telemetry value which can be automatically created from the breakdown components. Signals are fed through various GDA logic blocks in an attempt to diagnose the cause of operational problems - in this case an internal power subsystem failure arising from a battery overdischarge. If all the logic paths entering the "AND" block on the left of the diagram are true, then a diagnosis can be made. A message will be sent to one of INTELMOD's message areas alerting operators to the cause of the problem. It should also be noted that the outputs/conclusions of one GDA diagram can pass information to other diagrams (via the connection post BTR1-CP1) and other INTELMOD model types. Customised GDA blocks are available to link diagnostic models with fault propagation models. In this way, operators are not only alerted to system failures and their potential causes, they can also be supported in assessing the likely knock-on effects, when these are expected to occur, and the impact on mission operations. In the example shown, the GDA model also incorporates a link to a UNiT procedure (shown by the block labelled "SL"). Consequently when the diagnosis is made, a contingency procedure will be automatically invoked to provide failure recovery .
All of INTELMOD's model types share a common mode of use. Model Developers use *pull-down menus and palettes* to select the building blocks that are required. These are then placed on a workspace, configured with any necessary information, then connected together. Such models are then immediately ready for use, allowing the developer to concentrate on the *expression of expert domain knowledge* rather than writing conventional programs.

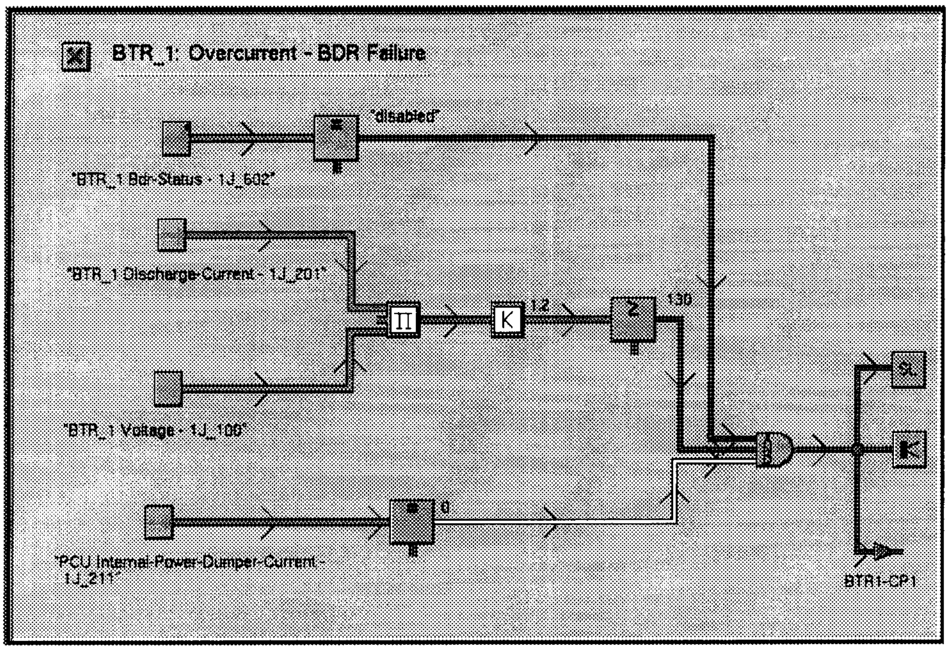

Figure 6. GDA-based diagnostic model

7. BENEFITS, LIMITS, FOLLOW-ON

INTELMOD is a generic satellite modelling toolkit that has been developed to offer faster, incremental development of spacecraft models. Thanks to its user-friendly man-machine interface, the system requires no formal programming expertise.

The use of AI techniques within INTELMOD has provided a significant enhancement in supporting operational tasks like monitoring, anomaly detection and anticipation, failure detection, isolation, diagnosis and recovery, failure propagation analysis and resource management.

The toolkit could also be exploited for assisting the training of new operations staff during simulated test case sessions, making use of the previously captured expertise.

Moreover it could potentially assist engineers during trade-off analysis, specifically to investigate alternative design solutions, alternative operational strategies and contingency recovery procedures.

The investment required in the modelling process has to have an economical return to be justified. From initial estimations, the toolkit should provide potential cost savings in the flight operations budget especially if applied to long duration missions (e.g. interplanetary missions) or recurrent/ repetitive missions (e.g. satellite constellations, meteorological satellites, etc.). Its applicability could also be of interest if focused on critical subsystem(s) of a specific spacecraft. INTELMOD can also support the automation of routine operational activities.

The results provided by INTELMOD will pave the road for an innovative operations concept where AI-based tools, integrated in an existing mission control system, will provide more effective and efficient support to the flight controllers during safety-critical and routine operations.

8. REFERENCES

[1] ESA (1994): *"SPEVAL Software Users Manual"*. ESA Internal Document. Ref. SUM/A18/0300. Vol. A.18, Issue 3.00

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[3] Stapleton, J. (1997): "DSDM: Dynamic Systems Development Method. The Method in Practice". Addison-Wesley Longman Limited.

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[4] DASA-Dornier (1995). "CLUSTER Users Manual - Vols. 1,4,5".

LIST OF ACRONYMS

AOCMS	Attitude, Orbit Control and Measurement Subsystem
COTS	Commercial Off-the-shelf Tool
DSDM	Dynamic System Development Method
ESOC	European Space Operations Agency
GDA	G2 Diagnostic Assistant
GUI	Graphical User Interface
INTELMOD	INTELligent MODeller
MCS	Mission Control System
FOP	Flight Operations Plan
ODBC	Open DataBase Connectivity
RAD	Rapid Application Development
SCD	Spacecraft Component Developer
SMD	Spacecraft Model Developer
SPEVAL	SPacecraft EVALuation system
UNiT	UNiversal intelligent Toolkit