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Online and Offline Monitoring and Diagnosis of Spacecraft and Space Weather Status

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Abstract Spacecraft control teams in the European Space Agency lack assistance for monitoring and diagnosis of space weather conditions related to spacecraft status in real-time. This paper discusses the Monitoring Tool of a Decision Support System that provides Flight Control Teams with useful Space Weather information (past, current and forecasted) to increase their ability to protect spacecraft components from hazardous events. The Monitoring Tool (MT) is a sub-module of the system's Monitoring and Diagnosis module. It provides real-time spacecraft data visualization, real-time spacecraft alarms and recovery suggestions inference, through real-time data loading. The Monitoring Tool, which is still under development, will also provide users with real-time graphical visualization of space weather parameters, user-defined alarms and events (e.g. solar flares, geomagnetic storms).

Keywords: Decision Support, OLAP, Neural Networks, Knowledge Base Systems, Space Weather

1 Introduction

Space Weather is a phenomenon caused by radiation and atomic particles emitted by the Sun and stars. The sun, solar wind and solar and galactic solar rays largely determine the Space Weather and its effects, while the state of Earth's magnetosphere, ionosphere and thermosphere also bear an influence. Space Weather can influence the performance and reliability of space-borne and ground-based technological systems as well as endanger human life or health [6-8]. Space Weather can cause several problems to spacecraft components, such as degradation of sensors, degradation of solar arrays and changes in on-board memories caused by Single Event Upsets[1] (SEU). The final effect is degradation of the spacecraft overall performance and, in extreme cases, complete unavailability of services. When certain alarm conditions are reached, risk avoidance procedures may be invoked, e.g. switching off high voltages/biases/filters etc, and transition to protected operating modes. Better prediction of radiation conditions and more accurate

[1] *A Single Event Upset is a bit-flip on an electronic memory device.*

information could greatly improve these operations.

This paper concentrates on the Monitoring and Diagnosis module of the Decision Support System (DSS), being developed in the project "Space Environment Information System (SEIS)", for the European Space Agency (ESA), by UNINOVA and DEIMOS [4]. In particular, we will discuss in detail the characteristics and functionalities of the Monitoring Tool (MT), which is a sub-module of the Monitoring and Diagnosis module.

SEIS is a multi-mission project whose main goal is to support the spacecraft operators in taking decisions about how to react to space weather conditions possibly causing spacecraft degradations. In addition the system will facilitate the awareness and understanding of how space weather affects satellite performance, paving the way to possibly prolong mission lifetime and increase the quality of services and the safety of the payloads.

The paper is organized as follows. The second section describes the data and the missions addressed within the system and the third section briefly presents the SEIS system's architecture. The fourth section discusses in detail the real-time SEIS Monitoring and Diagnosis Module, focusing on the Monitoring Tool key functionalities. Finally, the conclusions and future work can be found on the fifth section.

2 Spacecraft and Space Weather Data

The SEIS system will extract and integrate spacecraft and space weather data from various sources.

The Space weather data is extracted from scientific research institutes such as: NOAA/SEC, Lomininckу's Peak and WDC in Kyoto University. Space weather data is classified in parameters and events. Space weather parameters comprise but are not limited to: proton, electron and neutron fluxes, ionosonde data, radio bursts, solar activity indexes, solar wind and magnetic field disturbances values. Space weather events include geomagnetic storms, solar flares and coronal mass ejections, among others.

The spacecraft data is extracted from existing data of three distinct on-going spacecraft missions, hosted by the European Space Agency. The three addressed missions are INTEGRAL (INTErnational Gamma-Ray Astrophysics Laboratory) [2], ENVISAT (ENVIronmental SATellite) [1] and XMM (X-Ray Multi-Mission) [3]. Each mission will have a specific purpose in terms of usability and demonstration of involved concepts, and therefore the data collected from them varies according to their goal [5]. For the reference mission, INTEGRAL, which will be responsible for the system's performance and utility assessment, the SEIS project will provide even more services that will be deployed in the flight control room.

The spacecraft data consists of: spacecraft's orbital positions for all addressed missions; ENVISAT mission's SEUs historical database of occurrences [13]; and the XMM satellite's radiation sensors telemetry data. For the reference mission,

INTEGRAL, the SEIS system will extract real telemetry (from several instruments such as the INTEGRAL Radiation Environment Monitor and the Imager on-board INTEGRAL), operational data (e.g. current ground-station coverage), and environmental data (e.g. eclipse passage times) in near real-time.
The expected results for each mission vary according to its scientific purposes and available data. All three described missions want to correlate telemetry and/or anomalous occurrences (such as SEUs) with space weather phenomena and space positions. They also would benefit from the availability of automatic report generation that can correlate such parameters and establish cause-effect relationships.
In addition, SEIS will enable the INTEGRAL mission team to monitor, in real time, its telemetry parameters along with some critical space weather parameters. Moreover, the team will benefit from the existence of a on-line alarm generation and diagnosis tool, that can assist them in the decision making process in case of spacecraft anomalies or space weather hazardous conditions [5].

3 SEIS Architecture

The SEIS (Space Environment Information System) envisaged solution consists of extracting and collecting historical, real-time and forecasted spacecraft and space weather data. The system design was inspired by traditional business oriented Decision Support Systems, based on Data Warehousing storage techniques [9].
Figure 1 depicts the SEIS Decision Support System overall architecture.

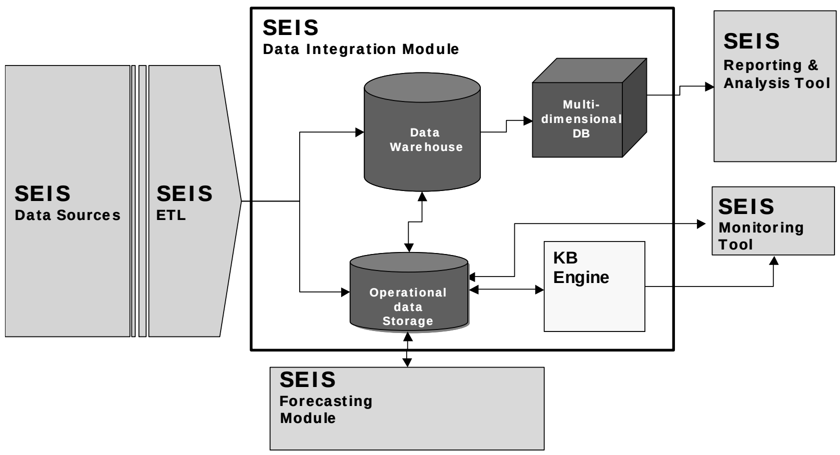

Figure 1: SEIS system architecture.

Considering that all relevant data sources have been identified, along with the data retrieval mechanism (most of the data sources are accessible through ftp or http), then by applying ETL (Extraction, Transformation and Loading) mechanisms the system is able to process, transform and store all relevant data.
The Data Integration Module (DIM) is responsible for storing all loaded and internally generated data (i.e. generated by the Forecasting Module and Knowledge

Based Engine). It is composed of several logical databases according to their purposes. The main storage repository is a data warehouse that contains all historical (at least 10 years of historic data will be loaded), present and forecasted data. The multidimensional database is an OLAP [10] database used to re-structure the data warehouse data in order to provide fast querying response times to the Reporting and Analysis Tool module (also OLAP-based).

The Operational Data Storage (ODS) is a real-time database implemented to address the Monitoring Tool's high performance demands, which will be explained in more detail in the next section.

Closely related with the DIM module, one may find the SEIS Forecasting Module. This module provides forecasting capabilities for space weather and spacecraft data, based on well-established physical models, as well as generic time series prediction based on Artificial Neural Networks (ANN). In addition, the Forecasting Module also comprises orbital propagator models.

The physical models are static models that cannot adapt to unpredicted events (with space weather or spacecraft origin). Predicting what may happen, based upon information regarding the sun's activity, is a complex task and may not always be possible with the existing physical models. To suppress this gap and enhance the system's predictive capabilities a plug-in application for ANN models is available. The goal is to allow any kind of model (MATLAB based), created and trained outside the system to use the data available in the DIM and to produce forecasts that will be afterwards included in the databases and made available to all tools.

The purpose of the Reporting and Analysis Tool (RAT) module is to allow exploration of all stored data in the DIM module, through the use of OLAP [10] analytical querying. Additionally, report creation, which correlates different data types, as well as various data visualization options, will also be available in the same tool.

Finally, the Monitoring Tool of the Monitoring and Diagnosis module, which is the focus of this paper, is an on-line-oriented tool that, in addition to the visualization of real-time space weather and spacecraft telemetry data, also displays the resulting inference produced by the Knowledge Based Engine. The KB Engine, which includes the implicit domain expert's knowledge, will run a continuous spacecraft diagnostic in order to infer possible spacecraft/space weather alarms and suggest appropriate recovery actions to minimize damage on the spacecraft instruments.

4 The Monitoring and Diagnosis Module

As previously mentioned, the SEIS Monitoring and Diagnosis Module will provide users with real-time spacecraft data visualization, space weather parameters and events (e.g. solar flares, geomagnetic storms), real-time spacecraft alarms and recovery suggestion inference, through real-time data loading as well as inferred alarms.

The Monitoring and Diagnosis Module is composed by the Monitoring Tool, the KB Engine and the ODS database, as depicted in Figure 2. The Monitoring Tool is directly supported by the ODS and the KB Engine.

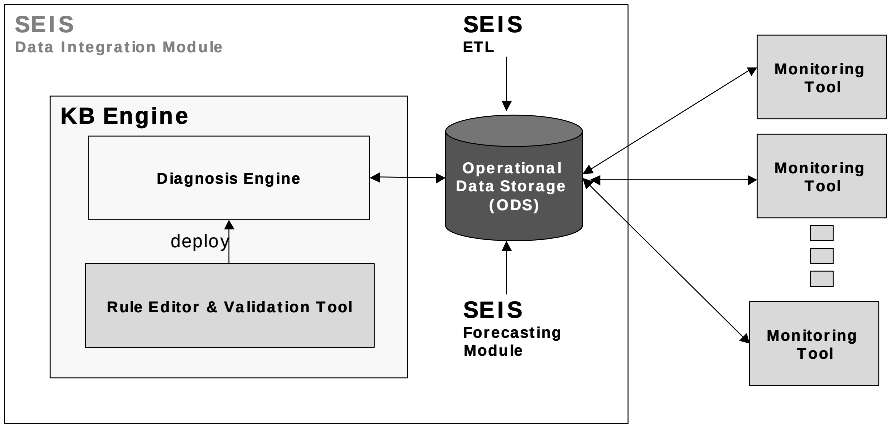

Figure 2: The monitoring and diagnosis module diagram.

4.1 KB Engine: Diagnosis Engine

In general, the Diagnosis Engine evaluates the current alarm rules, using the real-time available data in the ODS database, storing the results back into the same database. The rules are evaluated at every flux of new data inserted into the ODS.

A spacecraft may suffer several problems during its lifetime. These problems affect one or more spacecraft subsystems and/or sensors. Telemetry data assesses the spacecraft subsystems status and can be used to identify possible problems. The detection of these problems is reported as spacecraft alarms. However, alarms can also be related to space weather conditions. These alarms are detected by a rule-based system.

Each alarm is defined by a rule that contains the logic to detect an anomalous situation, i.e. it defines when the alarm should be triggered. An alarm may also contain associated suggested recovery actions to be performed in order to minimize spacecraft instruments' damage. These recovery actions define the (human) action to be undertaken when the alarm is triggered.

Each rule is composed of one or more parameters along with constrains on those parameters' values. In this context, a rule is the combination of parameters and their values' constraints (called expressions). Expressions are related to each other through Boolean operators (e.g. and, or). Each of these expressions defines a constraint on spacecraft or space weather parameters. A parameter can be restricted by a raw value, a calibrated expression (e.g. ON, OFF, WAIT, RESET) or another parameter (see Figure 3).

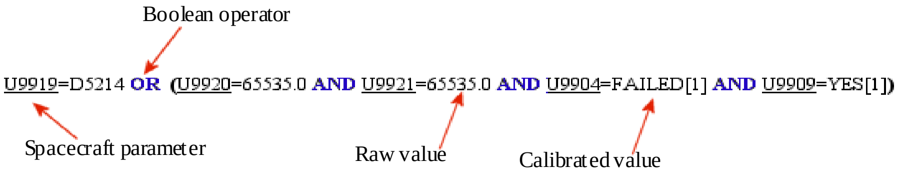

Figure 3: Simple alarm rule example.

The expressions are evaluated at a specific moment in time, and use only the last (most recent) available values. However, due to non-trivial constraints that require more complex logic such as “parameter must hold a value for x seconds” or “parameter’s value must not increase for x seconds”, special functions were created to address these cases. These special functions are composed by expressions as for example “K5119>=20000, 8s”. This particular function will return TRUE if the parameter K5119 is greater or equal than 20000 during 8 consecutive seconds. To evaluate such expression, the function must use not only the parameter’s current value but previous values as well. If we name the previous function F1, we can use it as a normal parameter in any expression (e.g. F1=FALSE).
Since the KB Engine is based on real-time spacecraft telemetry parameters, it has to be robust enough to deal with possible missing values, i.e. in the absence of some values necessary to evaluate a rule, the system must be able to produce the result based on a pre-defined behaviour. It is the user that pre-defines this behaviour for each expression in a rule. The possible values for each expression are: TRUE, FALSE or IGNORE.

4.2 KB Engine: Rule Editor & Validation Tool

The Rule Editor & Validation Tool (REV Tool) purpose is to help the user to create and edit alarm rules. It can then be used to validate and deploy these rules into the system.
The REV Tool has two main areas: an alarm rule edition area and an alarm validation area. The edition area provides a simple interface with a list of available spacecraft and space weather parameters to ease the rule creation process. It also provides a list of previously defined alarm rules to be edited or created.
To complement this, the validation area allows the user to load a set of parameter values and simulate the alarm triggering process. The result consists in the alarm status for each loaded parameter value allowing a complete validation of the created alarm rule.
The rules defined or edited within this tool will be deployed into the diagnosis engine.
Figure 4 illustrates the REV Tool validation area after loading a set of parameters values.

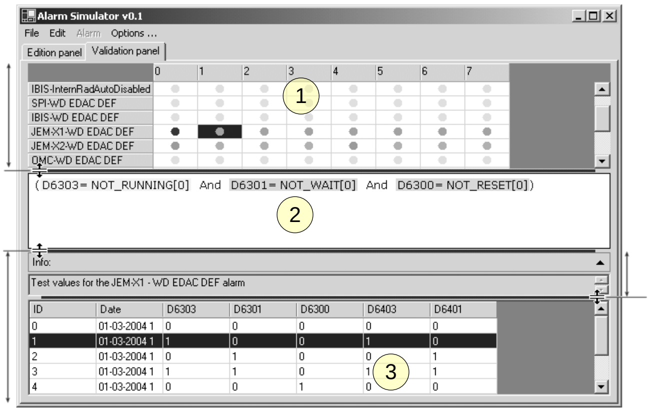

Figure 4: The validation area loaded with spacecraft parameter values.

The validation area is divided in three main sections. The section identified with 1 is the triggered alarms section where the alarms statuses are displayed. Each cell represents the value of an alarm (row) in a given instantaneous point in time (column). Number 2 identifies the rule area where the rule of a selected alarm, in a given moment in time, is displayed. Each expression is highlighted in red (the expression was satisfied) or in green (the expression was not satisfied). Finally, section 3 contains the loaded parameter values where the parameter values are displayed.

4.3 The Operational Data Storage

The ODS is a relational database designed to behave as a time sliding window of approximately 168 hours (84 hours of real data and 84 hours of forecasted data).
This database stores spacecraft parameters and alarms (generated by the diagnosis engine), spacecraft orbital positions, space weather parameters, events and alarms (also generated by the diagnosis engine). The ETL process uses advanced scripting to load this data into the ODS, with the exception of the alarms generated by the diagnosis engine, ensuring continuous data availability. The update period of the database is approximately 5 minutes.
This database plays a central and crucial role in the system's on-line component. The ETL process is constantly targeting it to load new data (at every 5 minutes) and to delete obsolete old data. The Diagnosis Engine is also constantly accessing it to load any triggered alarm and to get newly available data. Further, all instances of the Monitoring Tool will be directly connected to the ODS to retrieve requested data for visualization.

4.4 The Monitoring Tool (MT)

The SEIS Monitoring Tool is an advanced multi-user visualization application that allows the proper visualization of all data stored in the ODS database, at near real-time rate. Furthermore it provides triggered alarms warnings through an intuitive graphical interface, as well as details about those triggered alarms.

The Main Window Interface

Figure 5 depicts the Monitoring Tool main window, with its areas properly identified.

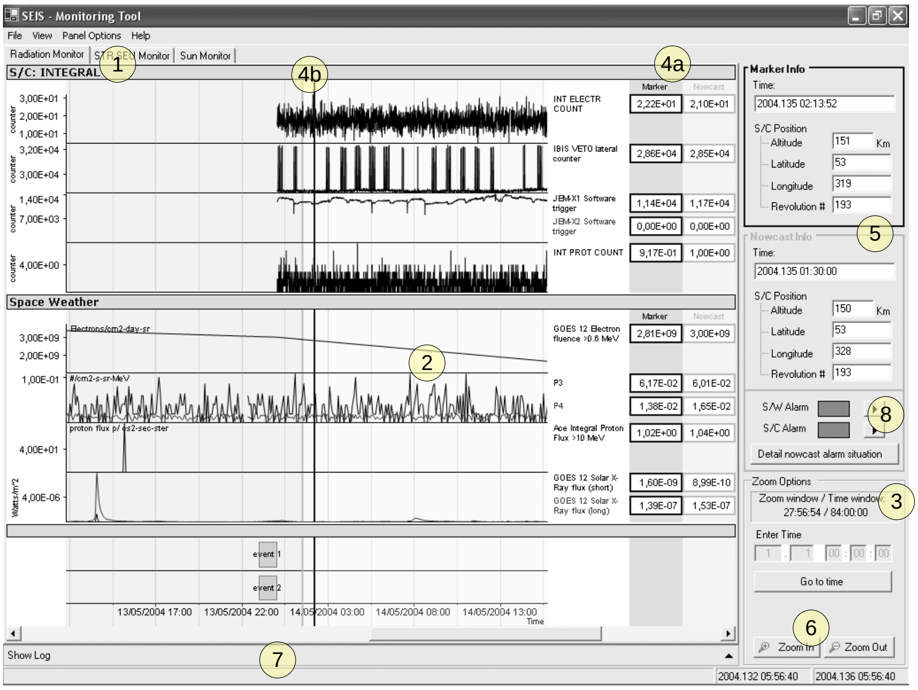

Figure 5: SEIS Monitoring Tool main window.

The monitoring tool is composed by a set of user-defined panels, which are always available to the user, one at a time (point 1). Each panel defines a set of spacecraft and space weather parameters to be plotted in several charts (point 2). Each chart can be customized according to the user's preferences.

Each panel contains data for a specified time window (point 3), which can be divided in past and future data (in each chart the darker area is the past data and the lighter area contains future data).

In point 4a are displayed the values for the nowcast (current) moment (lighter column) and the sliding marker (darker column). The sliding marker is the dark vertical line identified in 4b, and allows the user to visualize a specific time moment by moving it freely. In point 5 is displayed the INTEGRAL spacecraft position and revolution for the nowcast and sliding marker time positions.

Each panel also has zooming capabilities (point 6) by using the available "zoom in" and "zoom out" buttons or by clicking and dragging the mouse over the charts.

The log window is accessible from every panel and shows all occurred user-actions, application-activities and alarms triggered (point 7). The log window is equipped with filtering capabilities that can be defined individually for each panel.

Finally, there is an alarm area (point 8) composed by two flashing buttons (one for space weather and other for spacecraft alarms) that indicate the existence of triggered alarms. By clicking on the "detailed alarm" button, a new window will open, where the user can visualize the specific triggered alarms, the triggering rule and the suggested recovery actions, when applicable.

Characteristics

As mentioned, the Monitoring Tool is a multi-user application. Each instance of the application communicates directly with the ODS database to collect the necessary data to display in each panel (spacecraft and space weather parameters, orbital positions and alarms). Each panel contains a list of charts that plot values in a user-specified time window. This data is collected approximately every 5 minutes or whenever necessary, to update the panel being visualized by the user. In order to optimise the performance of this process, the panels in the application are controlled by one single entity whose purpose is to control the access to the database and decide what kind of data each panel requires as well as to monitor the passage of time. This entity is responsible for updating each panel in the following manner:

a) Removes unnecessary data from every panel (i.e. data that is no longer inside the panel's time window);

b) Requests from the database the values relative to the panel being visualized taking into account the data already loaded into this panel.

This process is activated whenever a panel is selected by the user, through the passage of time or even by an external process.

Another issue of concern is the fact that a large number of instances of the Monitoring Tool, being used at the same time, would impose a considerable amount of stress over the ODS database and therefore will reduce the system's performance. To deal with this problem another process will control the communications, between the Monitoring Tool instances and the database, acting as a caching service and reducing, significantly, the amount of accesses to the database.

5 Conclusion and Future Work

The real-time Monitoring Tool under development is showing great benefits for the users and will increase the mission's lifetime by decreasing the instrument's degradation, through a real-time spacecraft and space weather monitoring and diagnostic, along with its recovery actions and forecasting features. This project also aims to prove that the space domain can benefit by the application of business oriented techniques and artificial intelligence technologies.

For future work, we intend to extend the project to other spacecraft missions, and transform the Monitoring Tool into a multi-mission monitoring tool. The complexity of this task resides, mainly, in the data acquisition strategy since the Monitoring

Tool itself can be easily adapted to other spacecraft missions, as long as the data is stored in the Operational Data Storage (the supporting Monitoring Tool's database).

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