

ESSOPE: TOWARDS S/C OPERATIONS WITH REACTIVE SCHEDULE PLANNING

J Wheadon

N 9 4 - 2 3 8 9 6

ESA/ESOC European Space Operations Centre
Darmstadt, Germany

ABSTRACT

The ESSOPE is a prototype front-end tool running on a Sun workstation and interfacing to ESOC's MSSS spacecraft control system for the exchange of telecommand requests (to MSSS) and telemetry reports (from MSSS). ESSOPE combines an operations Planner-Scheduler, with a Schedule Execution Control function. Using an internal "model" of the spacecraft, the Planner generates a schedule based on utilisation requests for a variety of payload services by a community of Olympus users, and incorporating certain housekeeping operations. Conflicts based on operational constraints are automatically resolved, by employing one of several available strategies. The schedule is passed to the execution function which drives MSSS to perform it. When the schedule can no longer be met, either because the operator interferes (by delays or changes of requirements), or because ESSOPE has recognised some spacecraft anomalies, the Planner produces a modified schedule maintaining the on-going procedures as far as consistent with the new constraints or requirements.

1. INTRODUCTION

Many modern spacecraft, particularly those for science missions or experimental technology missions, are characterised by carrying payloads comprising a number of subsystems which will be employed on a variety of tasks or experiments. Recent examples of such ESA spacecraft are ERS-1, EURECA, and in the field of telecommunications, OLYMPUS.

The operation of such a spacecraft is a complex undertaking; there are usually many constraints which have to be respected. Such constraints may prohibit the simultaneous or concurrent operation of two or more given payload subsystems in certain specific modes, for example because of interference or disturbances caused by one to another, or because of the shared use of some resource, e.g. a

transponder, or a supply of electric power, or some available bandwidth in a downlink signal.

Whereas it has been the traditional practice to operate spacecraft following rigidly pre-defined and pre-tested Flight Control (procedural) Timelines, and indeed this practice is generally continued for spacecraft platform operations, for complex missions such as those mentioned above a more flexible approach to defining the activities of payload operations is needed. Not only must the "on-board" constraints be respected, but also the temporal requirements of the satellite users, e.g. Principal Investigators or Experimenter Institutes, have to be accommodated. For example, an Earth observation satellite's payload will be constrained to operate in one or another mode at different times according to the nature of the target areas (sea, land, ice...) which the satellite is passing over. As another example, users of a telecoms satellite may wish to schedule use of a given payload at times when they can have the use of specific ground station equipment for the performance of a communications experiment.

Because of this need for flexibility in defining the activities of day-to-day operation, there is much interest in having the use of automated planning systems to generate operational timelines or schedules which define the actual activities in detail. Such systems can generate the sequences of telecommands which have to be uplinked to the payload at given times, or which alternatively will be loaded into an on-board Master Schedule for automatic on-board execution later when required.

Automated "mission planning systems" have already been developed and put into daily operation for example for EURECA and ERS-1, where the schedules are prepared several hours in advance of their execution.

It was decided to investigate the possibility of linking more closely the planning/scheduling function with a ground-based automatic schedule

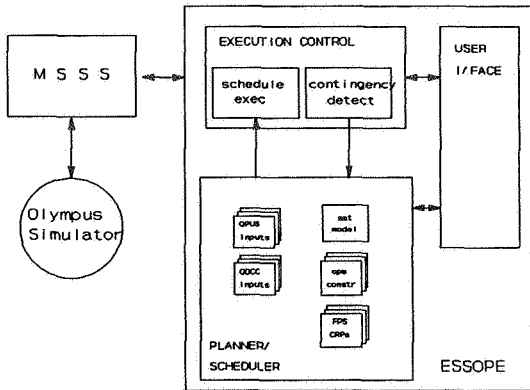


Figure 1: System Overview

execution function. It was also decided to attempt to introduce an element of "reactive planning", i.e. fast revision of an existing currently executed schedule in the event of new constraints or user demands arising more or less in real time, or of on-board or other anomalies being detected during the operation and preventing some of the scheduled activities.

In order to be able to demonstrate the concept of closely-coupled reactive planning and execution of operations, the Olympus geosynchronous telecommunications satellite was chosen as a "test case", and a demonstration system architecture was conceived which made use of existing ESOC infrastructure, namely the Multi-Mission Support System (MSSS) and ESOC's real-time operations simulator of Olympus. The MSSS was augmented by the ESSOPE, which provides an "intelligent front-end" for the user, performing detailed schedule planning of the operations activities, and online step-by-step control of their execution.

Figure 1 shows the combined configuration, and its operation is described later in this paper. But first follows a summary of the Olympus planning and execution problem domain, in order to give the reader an appreciation of the technical motivation for the choice of Olympus as the "test case" for the ESSOPE study.

2. THE PROBLEM DOMAIN

Note: The description given below relates to Olympus as it was being operated at the time when ESSOPE was being developed (1989-1991). In early 1991 Olympus suffered a solar array failure which has resulted in a significant reduction in the available power supplied to the payload.

Olympus is a large geostationary telecommunications satellite which was launched in July 1989. It carries a multipurpose experimental payload to test future telecommunications flight hardware and provides an opportunity for communications and broadcasting experiments throughout Europe, and also in Canada.

There are four quite separate payloads on Olympus-1, each with its own antennas:

- the Direct Broadcast Service (TVP) Payload
- the Specialised Services Payload (SSP)
- the 20/30 GHz Advanced Communications Payload (CMP)
- the Propagation Payload.

The exploitation of these payloads in orbit is co-ordinated under an overall Olympus Utilisation Programme, which encompasses all aspects of the satellite's use.

The TVP payload operates at 18 GHz for uplink and 12 GHz downlink and there are two channels each with a pair of redundant high-power TWT amplifiers feeding two separately-steerable antennas which can beam down over different regions of Europe, Scandinavia and North Africa. A wide-beam uplink antenna can be accessed from anywhere in Europe. The TVP payload supports experiments in direct sound and TV broadcasting for domestic reception, education and training, and interactive information services, as well as technical tests of various kinds (TV standards, HDTV, antenna measurement techniques), for more than 20 user organisations.

The Specialised Services Payload (SSP) offers bandwidths of 18 or 36 MHz, and operates in frequency bands between 12.5 - 19.3 GHz. Its antennas provide an array of five circular overlapping beams in a fixed pattern steerable over a very wide area. The SSP supports four up- and downlink signals which can be switched between the five beams, either in static mode, or dynamically allowing satellite-switched TDMA experiments to be made.

Experiments cover a range of applications and technical tests, including SS-TDMA, tele-education, high-quality document image distribution, compressed video, news-gathering and frequency diversibility for many user organisations.

The Advanced Communications Payload (CMP) provides two 40 MHz bandwidth channels operating in the 30 GHz (uplink) and 20 GHz (downlink) regions. An alternative wideband capability of 700 MHz is supported. There are two spot beams independently steerable over a very wide area. Three output amplifiers provide one-for-two redundancy.

A large range of technology and applications experiments are supported by the CMP for more than 30 user organisations. Worthy of special note is the Inter-Orbit Communications experiment in space data relay being successfully performed by ESA. This involves continuously steering on of the Olympus 20/30GHz payload antennas to track and communicate with EURECA, ESA's low-orbit Retrieval Carrier satellite, which has an orbit inclination of about 27° and a period of about 90 minutes.

The Propagation Payload just generates three signal beacons. Its operation is very simple, and was not sufficiently interesting to be considered in the ESSOPE study.

On any typical day, many user institutes (here called "experimenters") are able to make use of Olympus services, however, not all can be accommodated simultaneously. ESA therefore performs scheduling of all operations, nominally about a week in advance. However, it quite often happens that adjustments to the schedule have to be made at quite short notice: a few hours is not uncommon. The scheduling is done using simple spreadsheet and database tools, with resource conflicts being resolved manually. In fact this system is quite adequate for normal weekly scheduling, but at the same time the Olympus scheduling problem is sufficiently complex to make it interesting as the "test case" for ESSOPE, especially for demonstration of "reactive planning" which cannot be achieved to anywhere near the same degree of real-time reaction by manual methods.

Scheduling takes into account requests for specific Experiments (characterised by Experimenter, payload and its configuration) to be supported during given time windows. It must also take account of certain platform operations which can affect the availability or usability of certain payload configurations.

Platform operations, which are essential to the health of the spacecraft, take priority over experiments which may conflict with them. Such platform operations include: Eclipse operation (reduced power available), station-keeping, attitude manoeuvres, and certain AOCS (Altitude/Orbit Control System) gyro calibration checks; the resource conflict created by the latter is not on-board, but on-ground: It keeps the spacecraft controller fully occupied for half an hour, so that he is not able to spend time configuring payloads ready for the next customer.

Concerning payload resource constraints: Apart from the need to direct the required signal beams to the right places, and the need to allocate channels to users, some mutual resource constraints exist between payloads; for example, both the SSP and CMP share the 20/30 GHz transponders for some experiments. There are also power availability constraints to be respected, which become more severe in eclipse.

Concerning payload configuration, the time to arrive at a desired new configuration will depend on what configuration was used immediately beforehand, and this must be taken into account by the scheduler. The number of intermediate states, through which the payload must be switched, directly affects the time to go from state A to a different state B. Usually each intermediate step is effected by a single telecommand (or block-command), and these must each be verified (verification delay 20-30 seconds per command) before proceeding to the next intermediate state. In certain cases longer delays and pauses have to be planned in the intermediate states. For example, the TWT amplifiers are normally kept warm either by active heating, or by the processing of signal traffic, but it is sometimes necessary to switch them off completely to conserve power. Subsequent pre-warmup to bring them back into use can take half an hour or so.

However, because most of the possible payload reconfigurations can proceed at a rate limited only by the telecommand verification process on the ground (send command, await verification by MSSS on next arriving TM format... nominal delay 18 seconds), and because such step-by-step operations (on the real Olympus, without ESSOPE) effectively tie up the spacecraft controller full-time, it the practice in those cases to avoid concurrent reconfiguration of more than one payload at a time.

This is one more "operating constraint" applied by ESSOPE, which is otherwise capable of scheduling and also executing reconfigurations of the payloads in parallel. In cases involving intermediate step delays, multiple payload reconfigurations actually do proceed in parallel.

In addition to operating constraints imposed by the satellite itself, some ground-based factors have to be considered during scheduling, mainly related to the need to coordinate the activities of the experimenters in real time. This last point basically requires the ESA Olympus operations coordination function to contact experimenters by phone to ensure that they will be ready to use their allocated time slots, and that they do not transmit to Olympus outside those slots. This coordinator is also a schedulable resource; basically the available staffing allows phone calls to only one experimenter at a time.

3. OPERATIONS WITH ESSOPE

The ESSOPE has been developed to run on a SUN workstation, and is linked via a specially designed interface protocol to the MSSS software. The spacecraft operator is served through an ESSOPE user interface on the SUN, in addition to his normal MSSS operations interface screens/keyboard.

ESSOPE provides two main operating functions to the user: A Planner/Scheduler which generates a schedule of Olympus operations, and a schedule implementation function ("Execution Control") which controls the execution of the schedule, coordinating it with the state of the spacecraft telemetry and with the activities of the spacecraft operator. The Execution Control function is served by the MSSS to perform the basic control functions on the spacecraft (simulator !).

ESSOPE also provides appropriate knowledge acquisition functions, to configure it off-line (eg to allow the definition of procedure steps). These knowledge acquisition functions are not further described in this paper. For an exhaustive account of the design and functioning of ESSOPE, see (Refs. 1,2).

ESSOPE Execution Control effectively takes over some of the low-level mechanical tasks of the spacecraft operator. Thus he no longer has to transcribe manually into MSSS the telecommands

described in paper-based procedures or timelines; instead, ESSOPE reads these directly off the schedule generated by its planner/scheduler, and sends the appropriate telecommand requests to MSSS via the interface. In return, MSSS provides ESSOPE with reports confirming the uplink of the telecommands, and subsequently also their verification based on simple direct responses observed in the spacecraft telemetry.

In normal MSSS operation (without ESSOPE), the operator is required to perform visual checks of spacecraft status at each step of the procedure, by viewing displayed groups of telemetry parameters on the MSSS screens. He has to compare the displayed values with an equivalent hardcopy sheet of required values, included in the standard procedures handbook: The "Flight Operations Plan". ESSOPE is able to make these additional checks automatically for him, at the same time advising him which MSSS displays to call up to monitor the same information. The required telemetry parameters for these checks are specified to MSSS by ESSOPE directly over the interface, and MSSS responds by sending regular messages containing the latest values, back to ESSOPE.

MSSS performs continual limit checks on a large number of telemetry parameters, and when out-of-limits are detected, raises out-of-limit alarms on the MSSS user displays. When ESSOPE is in use, the out-of-limit information is sent to it by MSSS, and ESSOPE is able to perform some simple "first-level" evaluation of the anomaly, and propose to the operator an appropriate Contingency Recovery Procedure (CRP).

The principal regions of the ESSOPE operator interface for Ops Execution Monitoring are shown

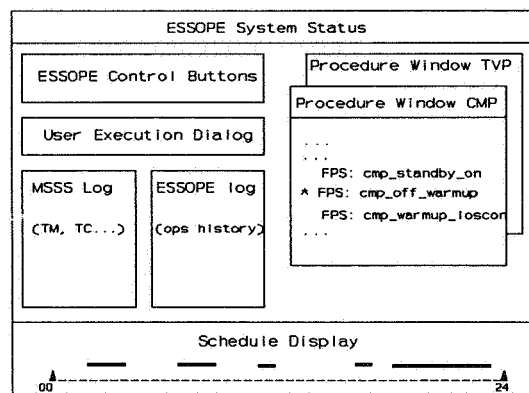
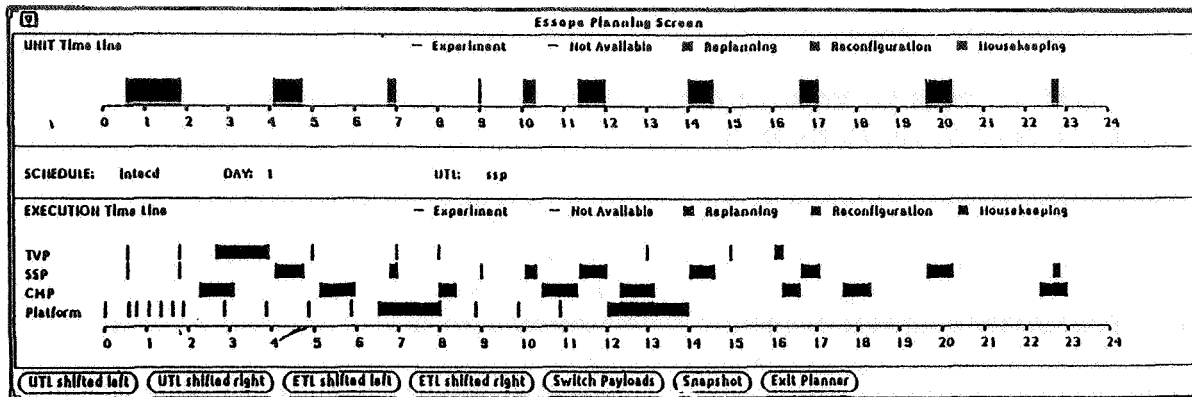


Figure 2: Execution User I/F



1Figure 3: Planner Screen with Schedule Display

schematically in Fig. 2. An overview of the schedule and of the steps of each active "procedure" in execution are displayed, with markers at the current position in each case, so the operator can follow the progress exactly. Note that a payload "procedure" in ESSOPE terms is not exactly equivalent to a Flight Control Procedure (FCP) in the traditional sense meaning a predefined, documented and validated procedure which the operator reads step-by-step out of a book on his console. A "procedure" for ESSOPE means a sequence of actions needed to change one of the payloads from one operating mode to another, *in the context of the current schedule*. This point is elaborated later under "Planning/Scheduling".

The schedule display shows a planned timeline for each payload and for the platform. Each payload timeline defines a series of "procedures" for switching the payload configuration, chained together with the periods of steady-state payload operation where the actual experiments are performed. ESSOPE is not able to build all possible platform timelines, but a representative set of procedures for the platform can be generated.

At any time, more than one procedure may be active concurrently, according to the progress along the individual timelines. of the schedule. The operator is no longer required to enter the required telecommands (or call up the TC sequences) manually on MSSS; instead, the appropriate commands for each procedure step are sent automatically into MSSS by ESSOPE. The operator can thus retain a higher-level view of the operation with less distraction, and still has at his disposal all standard MSSS information displays.

Due to the modular architecture of the MSSS software, virtually no changes to it were necessary to accommodate ESSOPE, apart from the addition of a special interface server module. In fact the MSSS is essentially unaware that part of the operator's normal (low-level) functions have been taken over by ESSOPE.

4. PLANNING/SCHEDULING

Fig 3 shows the schedule as displayed to the user. There are basically four parallel timelines, three for the payloads and one for the platform.

The Planner/Scheduler generates schedule segments of 24 hours at a time, and can cover up to seven successive days. The starting state for each new day is automatically inherited from the final state at the end of the previous day. The operator specifies the requirements in the form of Platform Operations and times (these are considered immovable), and Experimenter requests. The latter specify nominal start and finish times, and acceptable variations on these, as well as some parametric data affecting settings for the required payload configuration.

Earlier in this paper, the concept of a "procedure" was briefly introduced. By "procedure" is meant a sequence of actions, or in the terminology of AI, "a goal-oriented plan" of actions which have to be performed *in the context of the current schedule* on one given hardware unit or subsystem, to change it from a starting state to the desired goal state.

The planning of each timeline is derived from knowledge of an internal state-based model of the

relevant spacecraft subsystem. Each procedure in the timeline is composed of "Flight Procedure Steps" (FPS), which are placed at the appropriate points on the timeline. These are the smallest schedulable unit of activity, are rigidly-defined "mini-procedures", and are classified according to their function; a "state-to-state" FPS will move the state of a payload subsystem from one node to an adjacent node in the model's state-space by sending telecommands. Other classes of FPS exist, eg a "wait" FPS can request and await some information from the operator, or can delay until some telemetry parameter has acquired a given value. Each FPS is given a unique name to indicate its function, and the sequence of FPS names for each active procedure is displayed by the Execution user interface in a "procedure subwindow".

The ESSOPE Planner/Scheduler builds the schedule in such a way that the timelines are only loosely-coordinated. And may be executed concurrently with no greater mutual synchronisation than is necessary. The scheduler respects all the operational constraints, and all conflicts discovered are automatically resolved by applying a number of strategies, eg shortening experiments or shifting them within specified time limits. Some of the factors which the conflict resolution takes account of are experiment priority, Experimenter priority, the proximity in time of experiments, the actual duration of the procedure required to switch each payload between the required modes. The user has the option to influence, during the scheduling process, the choice of strategy to be applied whenever there is a conflict, or he can leave the scheduling process to run automatically. Any redundant FPS are deleted. Production of a 24-hour schedule segment is quite fast, being done in about 2 to 3 minutes on a Sun SPARC-2.

The schedule is passed to the Execution controller as a set of parallel streams of FPS grouped into procedures, one stream per timeline. At the moment of execution, the operator has the choice of running any individual procedure in automatic mode, or in user-authorise mode where ESSOPE awaits his authorisation to commence each new procedure step. The schedule specifies an earliest and latest time for each FPS, and any FPS may be flagged with pre-conditions to block its execution, and post-conditions which it shall establish to affect the pre-conditions of other FPS (either subsequent FPS of its own thread or FPS of others); in this

way a dynamic and elastic coordination between the timelines is achieved.

5. REPLANNING

It is possible that accumulated delays in execution of a given thread result in an inability to meet the final deadline for the next FPS. Or it may be necessary to abandon the execution of a particular thread or prematurely terminate the execution of an experiment because of the need to execute a Contingency Recovery Procedure to deal with a spacecraft anomaly. Or an Experimenter may announce at short notice that his requirements for his service that day have changed (maybe his equipment has broken down, for example). These situations lead to the need for a re-planning operation which is performed by the Planner/Scheduler; this is done while allowing the continuation of all active timelines which do not have to be stopped due to the problem in hand. The Planner/Scheduler passes the new version of the schedule (new timelines) to the Execution Controller which adopts it for continued operations.

6. REFERENCES

1. Gusmeroli S, Pezzinga A, Barone S, Briatico D, Wheadon J. 1990. ESSOPE - Expert System for Spacecraft Operations planning and Execution. In *Proc Symp on Ground Data Systems for S/C Control*. Darmstadt, Germany. ESA SP-308.
2. Gusmeroli S, Monti M. 1991. A Knowledge Based Assistant for Olympus Spacecraft Operations. In *Proc Artificial Intelligence and Knowledge-Based Systems for Space Workshop*. ESTEC, Noordwijk, NL.

7. ACKNOWLEDGEMENTS

ESSOPE was created as part of an ESA-funded study. Thanks are due to: A Pezzinga, S Gusmeroli, and M Monti of FIAR, Milan (prime contractor) for problem domain analysis, architecture design, and the development of the Planner/Scheduler; also to D Briatico, and S Barone of INTECS, Rome, for the development of the Execution Controller and MSSS Interface. The knowledge acquisition editors were developed by both companies.