A Different Approach to System Tests

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At the European Space Agency, validation of the interface between the control center and the spacecraft is traditionally achieved by means of so-called System Validation Tests (SVTs). They consist of typically three test slots with the spacecraft flight model for a total of 15-20 days, spread within 1.5 years from launch, for validation of telemetry/telecommands database and flight procedures. In practice, the flight model schedule is very busy prior to launch and getting the required slots for these tests in appropriate time frames w.r.t the rest of the ground segment development is difficult. As a work-around, it has become quite common on several missions to revert to spacecraft Engineering Models or Avionics Test benches to perform part of the SVT tests. In addition to reducing the criticality of the SVT, this approach has the advantage of more relaxed schedule costraints and formalism in the test set-up and execution. In some cases it also allowed early familiarization of the team with the spacecraft, early validation of critical spacecraft interfaces, and early debugging of operational aspects of the on-board software. For the ESA interplanetary missions currently in development (BepiColombo, Solar Orbiter, Exomars), it has been decided to include in the project baseline from the very beginning control centre test slots on the engineering model, in addition to the traditional SVT slots on the flight model. The required test time is of the order of four to six weeks, the tests are planned to start two years before launch and to concentrate on software, AOCS close loop testing and system operations validation by the operations team. This paper recalls the traditional approach to system validation tests, and the programmatic difficulties and limitations that are normally experienced with it. The approach gradually developed for recent missions is presented and lessons learned are discussed. The benefits expected from the early adoption of the new approach on the future missions in preparation are described.

I. Introduction

This paper discusses the approach to ground segment system validation tests adopted recently by the interplanetary missions of the European Space Agency (ESA). Each mission is operated by dedicated Flight Control Teams (FCT) located at the European Space Operations Center (ESOC), an ESA center located in Darmstadt, Germany.

At ESA, the ground segment testing and validation is performed in several steps:

- Unit testing normally performed by each company developing a ground segment element
- Acceptance testing performed by the ground segment and operations team on each element individually
- Spacecraft interface testing, which consists of two distinct families of test:
    - The Radio Frequency Compatibility Test (RFCT), to verify the interface between the spacecraft transponder and the ground station
    - The System Validation Tests (SVT), to verify end-to-end the proper generation of spacecraft commands and processing of spacecraft data by the ground segment. These tests are the subject of this paper.
- Finally, System Operations Validation tests exercise specific mission scenarios, involving all elements of the integrated ground segment.

The SVTs are the only tests which involve the spacecraft.

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In this paper, different approaches to SVTs will be discussed, referring to two specific ESA interplanetary missions to illustrate the discussion. The first mission is Rosetta[3], the ESA comet chaser, launched in March 2004. The second mission is BepiColombo, the ESA-JAXA mission to Mercury, due to launch in August 2015[1].

II. The Traditional Approach to SVTs

At the European Space Agency, the interfaces between the ground and space segments are traditionally validated by means of dedicated tests called System Validation Tests (SVT). The space segment under test is the spacecraft Flight Model. The tests are split into three slots:

- SVT0 – 2 days at L (Launch) -18 months
- SVT1 – 10 to 15 days at L-9 months – the exact duration depending on the spacecraft complexity.
- SVT2 – 5 to 10 days at L-4 months, when the spacecraft is at the launch site, for close-out of the anomalies detected in the previous slots. Again, the exact duration depends on the spacecraft complexity and amount of retesting necessary.

A. SVT Scope

The traditional objective of SVTs is to confirm the correct processing by ground of all telemetry generated by the spacecraft, and the correct encoding of all telecommands. This is achieved by constructing test procedures maximizing the coverage of spacecraft database elements for each sub-system / instrument, in order to manually check that each telecommand has the expected effect. However, as spacecraft get more complex, the scope of the SVT increases accordingly.

In the area of Orbit and Attitude Control (AOCS), the operators are required to implement specific data processes, e.g. to command the spacecraft attitude profile, or propulsion manoeuvers. These processes are validated in SVT by running AOCS close-loop tests, where the space environment, sensor and actuator signals are modeled by specific test equipment.

Ground applications have also been developed to support memory maintenance operations. Such applications provide the capability to save software images as references, to generate memory patch telecommands by comparing a memory image with a stored reference, to generate dump request telecommands over user-defined areas, and to compare received memory dump telemetry packets with a stored reference.

In addition, since the late 90's, increasingly complex applications are being deployed on the space segment, requiring the implementation of mirror applications on the ground to use them.

One example is the on-board time-tag queue or Mission Timeline (MTL). The contents of the MTL needs to be modeled on the ground for adequate monitoring by the operators. The ground applications offer the capability to generate maintenance commands (e.g. delete, time-shift) out of this ground model, or to compare the ground model contents with the on-board contents.

Another example is file transfer. Uplink file transfer applications have been implemented for the first time on the ESA interplanetary mission family Rosetta / Mars Express / Venus Express, launched between 2003 and 2005, and enabled the use of files for commanding[2]. This application supports the uplink to the spacecraft of telecommand files or of binary files. The telecommand files are then executed by a dedicated Telecommand Sequencer application on-board. The file transfer application provides the capability for the spacecraft to identify and request the retransmission by ground of elements of the files which have been lost on the ground to space link. This protocol is supported by dedicated ground applications, offering functionalities for the operator to create and store files in the ground archive, to initiate, manage and monitor transfers. The execution of telecommand files is then modeled on the ground to allow adequate monitoring by the operators.

All these ground applications are tested at unit-level, using ground segment test harness and the spacecraft simulator, a complex software tool which functionally and realistically models the spacecraft for operators training. The state-of-the-art simulators feature processor emulators allowing to run the actual on-board software in the simulator, which greatly enhances the representativeness of the whole system. However, ultimately, some of these on-board applications do not rely entirely on software, but also on hardware board-to-board interfaces, which are not representatively modeled on the spacecraft simulator. Test of these functions in SVT, interfacing to the actual spacecraft hardware, is therefore necessary for full validation of the tools supporting the protocol on both sides.

The spacecraft on-board autonomy is also getting more complex, with on-board functions to monitor and trigger action upon specific parameter values or packet reception (so-called parameter and event monitoring), or on-board control procedures (OBCPs), which are pseudo-code scripts to perform operations requiring telemetry checks in close-loop. A generic commanding interface to such functions is normally provided, which can easily be validated on a single example, but the operators are also interested in functionally validating the specific use cases implemented by Industry.

Finally, key system scenarios are run in SVTs, to validate the corresponding operations procedures. Such system scenario typically include:

- Execution of the automatic launch separation sequence and monitoring thereof by the operators
- Transitions to back-up modes and recovery thereof
- Execution of trajectory control manoeuvers end-to-end (simulating chemical and/or electric propulsion, as supported by the mission)
- Validation of any other specific spacecraft system mode: for example, for the Rosetta mission, , several very specific modes have been implemented on-board and required validation in SVT: a near-sun hibernation mode, a deep space hibernation mode, and an asteroid close-loop tracking mode.
- Execution of a representative set of routine operations, including instruments.

B. SVT Organisation

Because SVTs are such an important milestone for the ground segment and operations preparation, they are handled very formally.

Actual slot dates are negotiated with Industry. Then, for each slot, a test plan is being generated months in advance, for review and approval by Industry. The required spacecraft and checkout equipment configuration is agreed and properly documented. Detailed procedures covering every test operator action planned to be carried out are defined, reviewed and approved by Industry. A Test Readiness Review is performed a few days before the slot start. Each test day starts with a test briefing involving all actors involved in the test, on ESOC and industry side. After spacecraft hand-over to ESOC, the start and end of each procedure is announced on the voice loop. Any deviation to the procedures is first agreed between the ESOC test leader and his counterpart on Industry's side. Anomaly reports are generated for each detected anomaly. These reports are then converted into spacecraft non-conformances where relevant. Each test day ends with a test debriefing, wrapping up on the as-run status, making plans for the next test day, and agreeing on the handling of the detected anomalies.

A few weeks after completion of the test slot, a test report is generated.

Every SVT procedure is first validated on the ESOC spacecraft simulator. For SVT1 and SVT2, the reuse of flight procedures is maximized.

C. SVT Difficulties and Limitations

In practice, test time on the spacecraft Flight Model is very precious, and negotiation for test slots quite hard. The spacecraft integration may run into delays, making the schedule even more critical. In these conditions, the specified SVT schedule cannot be complied with.

Another problem is that the Flight Model activities normally concentrate on hardware integration and testing, which means that software versions tend to be frozen on the Flight Model to secure the schedule of other testing activities. While the use of "older" software versions is certainly acceptable to support hardware integration and overall spacecraft thermo-mechanical qualification, most of the SVT objectives involve the use of software, and executing them on old versions of software does not allow proper validation of the related functions. Furthermore, the SVTs are taking place in parallel to the preparation of flight procedures, which relies on the latest software version and associated database made available by Industry. The parallel management of two different software versions by the ground segment and operations team is very challenging. It results in extra workload and increase risk for configuration mismatches.

Eventually, the operators are placed in front of a dilemma whether to reduce the scope of a test slot to adjust to the available Flight Model configuration, or to run the activities as planned at a much later date. Delaying SVT1 is often no feasible, since there needs to remain enough time to resolve the potential SVT1 anomalies prior to SVT2 and launch.

Finally, the level of risk acceptable for tests with the Flight Model is much lower than with other spacecraft models. Test activities that may endanger the hardware, such as operation on redundant interfaces or use of specific telecommands, will simply not be approved for a run on the Flight Model.

In a nutshell, if the operations team has to rely only on the Flight Model for SVT execution, the test scope is accurately scrutinized and compressed to the essentials. Keeping the overall ground segment and operations schedule is also very demanding, asthe operations team is under great pressure to prepare, execute and post-process SVTs in parallel to all other ground segment validation and operations preparation activities taking place within 9 months from launch.

III. Working-around SVT Limitations

Faced with the difficulties highlighted in sect.II, most teams adopt pragmatic workaround solutions, using alternative spacecraft model.

Most ESA missions share a similar model philosophy. First a Structural and Thermal Model (STM) is being built. This model focuses on providing representative thermo-mechanical properties. Then an Engineering Model (EM) is built, focusing on electrical and data interface representativeness. Some missions do not implement an EM, but they need a test bench for Functional Verification, which shares many characteristics with an EM, in terms of data handling interfaces between subsystem and Avionics/data handling representativeness. Finally, the Flight Model (FM) is built.

Whilst some of the SVT objectives can only be achieved by testing on the Flight Model, in particularin case of tests involving hardware interfaces, which are only implemented to the full extent on the Flight Model, many of the SVT objectives address mainly on-board software applications. Because the Engineering Model focuses on electrical and data interfaces, it normally features a fully representative data handling network, composed of on-board computer, mass memory and data buses, as well as the electronic boxes of all sub-systems and instruments. Industry increasingly uses this model to validate on-board software increments, while the software version on the Flight Model remains frozen to support hardware-driven tests.

The EM programme starts before the FM programme, so that lessons from the EM programme can be retrofitted into the FM programme. This means that by the time the FM programme starts, the schedule pressure on the EM programme is normally decreasing.

On some missions, the immediate work-around to SVT scheduling difficulties therefore consists in executing some of the slots on the Engineering Model instead of the Flight Model – typically SVT0 and part of SVT1. All SVT activities involving on-board software applications can normally be run on the EM, provided the adequate on-board software version is available. Since the EM mainly serves as test bench for on-board software, on-board software installed on it is by definition always up to date, i.e. installed and tested as soon as released by the software contractor. Because the schedule pressure is usually lower on EM by the time the software is in a mature state for SVT, SVT slot negotiation is less conflictual.

During the Rosetta mission preparation, delays in the readiness of the on-board software were threatening the readiness for the fixed launch date of the mission. The Project decided to decouple the software system level verification on the EM from the FM programme, where an old but stable version of the software was kept throughout most of the testing activities. Towards the end of the FM test campaign, when the on-board software was mature, it was installed on the FM spacecraft and a relatively short series of confidence tests were run to confirm the solidity of the software also on the FM.

Also driven by the schedule pressure, and by the non-availability of up-to-date software for the traditional SVTs on the FM, also the ESOC test approach had to be modified, by introducing the use of the EM for early software validation tests[4]. A first test with the Engineering Model(SVT0 Part 1) took place 21 months before launch. The test duration was one day. It concentrated on exercising the COP-1 protocol, verifying basic telemetry management functions on the Avionics subsystem, as well as storage of data on the mass memory. It was followed by a second slot of one day 18 months before launch. This slot exercised the Mission Timeline and uplink file transfer functions, and uncovered a number of problems with the implementation of these functions on-board.

The experience with the quick informal tests with the ground segment and the EM spacecraft was so successful, both from the ground and the space segment, that the Project granted several additional slots on the Engineering Model, : one day at L-16 months, one day at L-13 months, six days at L-8 months. Nine months before launch, interface tests with the Flight Model (SVT1) started, for a total of 11 days between L-9 months and L-5 months. Finally, 5 days of final testing took place at L-3 months with the Flight Model at the launch site.

The early test slot on the Engineering Model had several advantages:

- It uncovered very early some fundamental anomalies in the spacecraft on-board software, in areas that Industry had actually already functionally tested. This is because the tools used by Industry for testing of the Mission Timeline and File Transfer applications are limited compared to the tools developed at the control center for flight.
- The tests with the Engineering Model resulted in a thorough validation at an early stage of the mission control system at the control centre, in highly representative flight conditions and in particular incoming telemetry load. The same level of validation could have been achieved with the simulator, but at a later time.

- The tests provided at an early stage a very large representative data set, that could be used as reference for activities with the simulator.
- The debugging of on-board software functions by ESOC contributed to consolidate the relationship and build trust between Industry and the Flight Control Team. To the extent that ESOC was formally involved in the system validation by Industry of the latest on-board software version generated by Industry, due for load on-board after launch. A number of test cases were agreed to be defined and executed directly by ESOC, with the support and approval of Industry.
- The cumulated test time on the Engineering Model was 10 days, to be compared with a required SVT0 duration of 2 days. This greatly enhanced the level of familiarity of the flight control team with the spacecraft.

This experience was overall so positive that it was decided to formalize it for the new generation of interplanetary missions after Rosetta.

IV. A New Approach for System Validation Tests

A. Spacecraft Access Requirements

On BepiColombo, the following requirements for spacecraft access for the purpose of ground segment interface testing have been defined:

1. Engineering Model access shall be provided to ESA/ESOC as from 2 years from launch for a cumulative total of about 6 weeks on a non-interference basis. We refer to these tests as Integrated Ground Space function Tests (IGST). The test scope includes:
   - The validation of software and its compatibility with the Mission Operations Centre (MOC);
   - The validation of the integrated ground/space functions (e.g. File Transfer, Mission Timeline, OBSM Interfaces;
   - Testing and validation of specific operations scenarios.

2. In addition, the traditional Flight Model access requirements for SVTs have been placed:
   - SVT-0 allowing for basic commanding on 2 consecutive working days at L-18 months;
   - SVT-1 comprising a 10 hours shift (effective test time) on each of 15 consecutive working days at L-9 months;
   - SVT-2 comprising a 10 hours shift (effective test time) on each of 10 consecutive working days at L-4 months.

B. IGST Organisation

There are a lot of similarities between the organization of an IGST and the organization of an SVT. The main differences are:

- The principle of maximizing reuse of flight procedures for IGST remains, however, it is accepted that procedures may not be validated on the simulator beforehand. Review of the procedures by Industry is performed to ensure their correctness.
- A SVT normally consists of 10 hours effective test time per day, complemented with briefing / debriefing time around the test activities each day. For IGSTs, the test time per day is limited to 8 hours, also complemented by briefing / debriefing time.
- For SVTs, the presence at ESOC of a Project and/or Industry representative is normally required, and a FCT member normally supports the test from the spacecraft location site, liaising with the industrial test team. This is waived for IGSTs.
- SVT procedures are formally approved by Project and Industry prior to the test start. For IGST, procedures are provided to Project and Industry for review before the test, and their concurrence confirmed in the test briefing. However, no formal approval statement is requested.
- There might also be some differences in the formal processing by the spacecraft manufacturer of the anomalies raised by the FCT. While in SVTs, all anomaly reports related to space segment anomalies are converted by industry into spacecraft Non-conformance Reports (NCR) for further tracing and resolution, IGSTs may perform early tests on functions which are not yet fully validated by Industry. In this case, the handling of anomaly reports will depend on whether the anomaly relates to a function which is already declared validated / qualified by the unit provider, in which case an NCR will be raised. If the function

has not yet been fully validated by its provider, then the anomaly report will be directly provided to the provider for direct resolution prior to the formal delivery of the unit flight model to the Prime contractor.

C. IGST Impact on the Ground Segment Development

The first IGST slot is required at L-24 months, while SVTs normally start at L-18 months. At the control centre this IGST requirement becomes the driver for the procurement of the Mission Control System, Network Data Interface Unit (NDIU) and Portable Spacecraft Simulator (PSS). The NDIU is used to interface the Mission Control System with the spacecraft EGSE. The PSS is used to perform data flow test with the ground station in operations. During ground segment development, it is also used to test the MCS before the spacecraft simulator becomes available, and it is integrated in the NDIU to support NDIU acceptance testing and data flow test with the control centre. At ESOC, MCSs are largely based on existing infrastructure. This allows to concentrate in the first delivery on any new function required on a mission specific basis, because the core TM/TC processing system is known to be reliably available. Early IGSTs can then be used to further validate the MCS mission specific functionalities, which can then be fully relied on to test the spacecraft simulator once it becomes available.

Because the IGST preparation does not rely on the simulator (procedures are effectively directly validated with the spacecraft Engineering Model), this approach allows to delay the start of the simulator development, which becomes essentially driven by the SVT dates. This is very beneficial, because it allows to wait with the start of the simulator procurement until the spacecraft design has become mature, thereby avoiding inefficiencies, cost and schedule delays on the simulator development due to unavailability of spacecraft design information.

On the Flight Dynamics side, the earliest time at which Flight Dynamics commanding interfaces would be validated using the traditional approach would be SVT1, i.e. as late as 9 months before launch. In this new approach, and keeping in mind that new on-board software versions are normally installed for system validation on the Engineering Model as soon as available, tests of the Flight Dynamics functions become possible as soon as the corresponding software version is available. This drives the Flight Dynamics implementation schedule, but again allows early validation of critical functionalities.

D. The BepiColombo Example

On BepiColombo, the ground segment procurement was initiated at a time when the launch was July 2014. A launch shift to August 2015 was announced at the beginning of 2012, at a time where the development of the Mission Control System and Simulator had already been kicked off.

For the 2014 launch, Industry had already communicated difficulties to implement the SVT slots in the required timeframe, and a possible cancellation of SVT0 with corresponding increase of the SVT1 duration was already under discussion.

The first IGST with a duration of three days had been agreed end of 2011 to take place in June 2012, in line with the L-2 years requirement. The spacecraft manufacturer agreed to keep the slot despite the launch delay.

The spacecraft Engineering Model currently includes the engineering model of the on-board computer, running version 1.2 of the central software, which is complete in terms of data handling functionality (including Mission Timeline, Uplink File Transfer and Telecommand Sequencer) thanks to large reuse from another ESA science mission, GAIA. These functions have not yet been functionally verified by the Prime contractor, but they are considered validated by the software supplier. It also includes the engineering model of the mass memory, running all telemetry storage and retrieval services, as well as a downlink file transfer application, which is a new development for BepiColombo. Even though the unit is installed on the Engineering Model, the downlink file transfer application is not yet fully validated by the unit provider.

One of the ground segment test objectives is early validation of the mission timeline, uplink and downlink file transfer applications, which are complemented by complex modeling applications on the Mission Control System. The MCS development was therefore required to concentrate on these applications for the first delivery required in March 2012. This development also benefits from a large re-use from GAIA. The main mission specific requirements consisted in the implementation of an additional application which models on-board commanding files on-board, of modeling functions to support additional Telecommand Sequencer on-board functionalities wrt GAIA, and of modeling and processing applications supporting the downlink file transfer. The first delivery was installed at ESOC on the 10th April 2012.

The PSS testing could be successfully completed in February 2012, using a pre-delivery of the MCS (possible thanks to the large GAIA and infrastructure re-use) allowing to acceptance test the NDIU in March, and to test the MCS first delivery in April. The infrastructure used for implementation of the PSS supports extra functional modeling of telemetry and telecommand packets. This capability was exploited to model the downlink file transfer telemetry and telecommands, thereby allowing to enhance the quality of the MCS tests performed in this area prior to the IGST.

This allowed to delay the kick-off of the simulator development to January 2012, at a time where most spacecraft unit Critical Design Reviews have been completed. The first simulator delivery is due in September 2012, which would have been 5 months prior to SVT0 for the 2014 launch. This version will include processor emulators allowing to run the Avionics and mass memory on-board software, and part of the platform (no AOCS). For the 2014 launch, the second delivery was then planned for April 2013, 6 months prior to SVT1, which was considered feasible though rather tight. With the launch delay, this delivery has moved to September 2013, which is more than a year prior to SVT1. This delivery will include the complete simulator functionality. By the time the simulator will be delivered, the MCS D1 acceptance testing will be completed and partially validated against the spacecraft in IGST1.

Central Software version 2, which includes a few AOCS modes, is already available. Industry plans to run AOCS close-loop tests in the first half of 2012. This will enable such tests to be performed by ESOC in IGST2. The slot for this test remains to be negotiated, but is expected to take place towards the end of 2012. This is driving the Flight Dynamics development and the implementation of the Flight Dynamics operational interfaces.

V. Conclusion

This paper described the traditional approach adopted in ESOC for validation of ground segment interfaces with the spacecraft, the limitations of this approach, and the new approach - addressing these limitations – adopted on the new generation of ESA interplanetary missions, starting with BepiColombo.

The impact of this new approach on the ground segment development was explained. The clear benefit of the new approach being:

- early validation of critical space-ground interfaces
- decoupling of the development and testing of two of the main ground segment elements (Mission Control System and Simulator)
- early familiarization of the operations teams with the spacecraft.

The same approach is being adopted for Solar Orbiter and Exomars.

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