Assembly, Integration & Verification of Systems-of-Systems – Simulation capability applied to the Galileo Mission Segment

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ABSTRACT

Simulation has a major role to play in supporting integration, qualification and maintenance of complex systems. This paper focusses on the approach adopted for the Galileo Mission Segment (GMS). The GMS comprises a number of distinct and complex components (or elements), developed by many companies, and delivered over a range of time and at differing stages of maturity. This presents a challenge to the systems integrator, who must work efficiently to accept and integrate each new element, as interface specifications and schedules evolve. The GMS Assembly, Integration and Validation Platform (AIVP) has been developed to address this challenge, by providing interface and behavioural simulation of the GMS elements allowing one-for-one replacement of real elements with emulators in a highly configurable and scalable manner. The capabilities of the AIVP approach are described, from early system integration to through-life maintenance support. Potential for re-use of the AIVP approach in other large scale integration programmes is discussed.

INTRODUCTION

Integrating complex systems

The integration of large, complex data systems (and 'systems of systems') presents a range of challenges. Those challenges are both technical and managerial.

Each contributing element can be assumed to have been tested with a reasonable degree of completeness against its own requirements and interface implementations prior to integration. Nevertheless, combining those 'finished' elements will give rise to issues including: Differing interpretation (and implementation) of interface specification; Conflicting behaviour where interface specification is incomplete or hard to interpret; Conformance to differing interface specification versions; Unexpected dynamic behaviour; Previously undetected faults in element implementation.

Elements will also become available for integration at differing times and at varying degrees of maturity and completeness (with regard to both interfaces and function). The integration process is thus subject to a large degree of schedule coupling between interfacing element pairs. Work can only begin once both sides of the interface are available for testing against each other – and may then be constrained by the completeness of each element's internal functionality.

In large systems, a reduced 'core' system may be available a long time in advance of the completion of the system as a whole. Under these circumstances, the behaviour and performance of the completed system remains unconfirmed until the last element (or instance of it) is integrated.

Even with all components delivered complete and correct, it can remain difficult or impossible to generate the right system conditions for verification of specific system behaviours.

Galileo Mission Segment (GMS)

This paper discusses the specific case of the Galileo Mission Segment. The GMS is a purpose-developed system delivering the core navigation data products of ESA's Galileo Global Navigation Space System (GNSS). The GMS monitors Galileo spacecraft signals and generates data tables distributed (via spacecraft) to Galileo receivers for the calculation of position and time.

The GMS comprises approximately 15 different element types. Each element implements a specific and complex function and is developed by a different contractor. Interface definitions are under the control of the segment prime contractor, supported by the element developers. The number of instances of each element type in the complete system varies from two (e.g. for the segment archiving facility, the GACF), to a maximum expandability of 152 (for the remote sensor stations).

The primary management and data processing capabilities are implemented in a redundant pair of control centres (GCCs), each with its own internal 'hot' redundancy. Galileo Sensor Stations (GSS) and UpLink Stations (ULS) are globally distributed, with multiple instances and redundancy on each site. The sites are linked to the GCCs via a global Wide Area Network (WAN).

For integration purposes, the elements of the GMS can be represented as computer systems communicating over Ethernet via standard transport and application protocols (e.g. UDP, TCP/IP, FTP, SNMP). System messages and signals are defined and encoded in a combination of a GMS-specific binary formatting and common formats such as XML or ASN.1. GMS-specific exchange protocols are defined on top of the basic transport protocols, to support (e.g.) authentication, retry and query mechanisms. Time synchronisation is performed using both NTP and IRIG-B signals. Messages conveying real-time navigation information are carried on a separate network to those for near-/non-real time flows. Interface definitions include specifications of the time at which messages must be generated, ranging from one per second to (e.g.) weekly. For per-second messages, phase offset is defined at the millisecond level.

ASSEMBLY, INTEGRATION & VERIFICATION PLATFORM (AIVP)

The Galileo GMS AIVP has been developed by Telespazio VEGA UK to support integration and qualification of the GMS.

The main aims of the GMS AIVP are: To support testing of GMS Elements on delivery to GMS Factory; To support integration and testing of multiple GMS Elements and processing chains; To support performance / load testing of GMS; To support qualification of the GMS against segment requirements; To support fault investigation of GMS Elements.

The system meets these aims by providing an environment and tool set which allows the user to: Design and configure test scenarios; Prepare test data; Execute and manage test scenarios; Analyse test output data (e.g. interface flow recordings); Monitor data flow between elements in real-time; Change data flows between elements in real-time (injecting test values or errors). All scenario definitions and test data (inputs and outputs) are stored in a manner that supports strong configuration control and traceability, ensuring that the conditions under which a test was run are known, recorded and reproducible.

The AIVP provides multiple GMS Element interface emulators, all of which can be operated in parallel and managed through a single user interface. Each AIVP Emulator type reproduces the network data interfaces of the real GMS Element of the same type. One Emulator type is provided for each GMS Element type e.g. Galileo Sensor Station (GSS), Message Generation Facility (MGF), Precision Timing Facility (PTF), etc. As configured for GMS, the AIVP supports approximately 200 independent emulator instance (of ~15 different types).

The AIVP Emulators incorporate a 'Behavioural Model' which is developed to reproduce the behaviour of the real element. The fidelity of reproduction is tailored to suit each element. Message format is exactly reproduced; Timing is accurately reproduced (+/-10ms); Data content of messages can be based upon functional models, recorded (replayed) data or operator-provided values. The test interface traffic is carried on physical networks matched to the target system. These networks are separate from the AIVP's own internal management network.

When executing at full capacity, emulators are distributed across a number of physical host servers – but managed from a single 'Master Kernel' Server which also provides the main user interface.

Test Scenario definitions, test input data, test output logs and recorded interface traffic are all stored on a central RAID-based storage system.

Simulated 'test' time is provided by a dedicated COTS Time Server. This permits real elements under test to synchronise to the test scenario's simulated time. Reference current (actual) time is maintained by a second Time Server, used to synchronise AIVP server clocks.

Although designed primarily for use on a rack-mounted multi-server system (inc. RAID and Time Servers), the AIVP can also be operated from a single laptop (with performance constraints) for use as a portable test tool. The distribution of emulators across multiple servers or a single machine (acting as both Master Kernel and Emulator Server) is fully configurable.

AIVP Development & qualification

The GMS AIVP system was first produced to support the In-Orbit Validation (IOV) phase of the Galileo programme, and is now being upgraded to support Galileo's Full Operational Capability (FOC) phase. It has been developed by Telespazio VEGA UK Ltd, under contract to Thales Alenia Space Germany, as Integration partner for the Galileo GMS.

It is built upon ESA's SIMSAT simulation technology, originally developed for spacecraft operational simulators at the European Space Operations Centre (ESOC) in Darmstadt. The original, non-distributed architecture of SIMSAT was modified by Telespazio VEGA to allow management of many emulators, distributed across a network, from a single, central 'Master Kernel'.

As with many integration and test tools, schedule was a key driver for the AIVP. The system was required to be available, with accurate reproduction of GMS Element behaviour and interface formats, *before* those real elements were available. To achieve this, rapid interface development was essential. An auto-generation process was developed to meet this need. The main GMS interface message formats were specified by the Element developers using standard encoding such as ASN.1 or XSD schemas. Telespazio VEGA developed a software system to auto-generate SIMSAT-compatible (SMP2) encoder / decoder modules from these schemas. These modules where then used as a common resource by each Element Emulator (either as a source or a sink). Extensive testing was performed on this auto-generation process to ensure that the messages created by the auto-generated code were compliant to the original message definition.

All new software has been developed and qualified in accordance with the Galileo Software Standards (GSWS), which are derived from standards used in the aviation industry. The AIVP is categorised at Delivery Assurance Level (DAL) E, meaning that it cannot directly contribute to a safety-critical failure of the GMS.

Although originally conceived as an integration tool only, the AIVP will now be deployed as part of the operational GMS system. The AIVP will be used to support long-term maintenance and evolution of the GMS.

ESA Perspective on AIVP Development

This section of the paper presents ESA's own perspective on the GMS AIVP.

> "A software-based test tool is a rather broad concept. It can be something as simple as a shell script developed ad-hoc for a specific purpose such as test stub, format converter, etc. or as complex as a simulator modelling a spacecraft. Regardless of the complexity and purpose, several factors are typically sought after from a test tool, for instance early availability (the test tool shall be available *before* the system under test) and configurability (for reusability throughout the whole test phase).
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> The AIVP (AIV Platform) developed by Vega for the Galileo Mission Segment Programme (GMS) satisfied those needs. But on top of that, the GMS required, from a customer perspective, something that is not always considered: <u>formality</u>; the AIVP plays an important role on GMS qualification during the Galileo In-Orbit Validation phase (IOV). GMS has almost 3000 customer requirements, and the AIVP was used in approximately 70% of the verification tests executed in the GMS Factory, in Pforzheim (Germany).
>
> The GMS is responsible for managing the Galileo services, and builds the content of the different signals which are broadcast by the Galileo satellites. GMS is mainly composed of unmanned elements which perform real-time processing of the data received from the spacecraft; hundreds of signals are exchanged between the different subsystems (or Elements, in Galileo terminology). For this reason, the verification of these GMS functions relies heavily on two aspects: a) the ingestion of

simulated data as if coming from the Galileo constellation, and b) the offline analysis of data, which typically requires extensive data format conversions. Both functionalities are provided by the AIVP.

But beyond the AIVP features, the factor that allowed its use for GMS IOV qualification purposes is that the AIVP itself is *qualified*, that is, it has been developed and tested in compliance with the stringent Galileo standards, namely the Galileo Software Standard (GSWS) and the generic ECSS. Having a qualified tool is important not only in terms of product assurance, but also in terms of technical confidence: the results obtained in those tests can be endorsed by the customer as have been obtained with a qualified tool and therefore will not be put in question.

It shall be noted that the SIMSAT framework is also satisfactorily used in other areas of Galileo (in particular, the Constellation Simulator which is also qualified against the same standards as the AIVP). The AIVP will be used in the next phase of Galileo, FOC1 (Full Operational Capability) where it will continue playing an important role in the integration and verification."

David Ibanez (ESA), Galileo Mission Segment Integration Factory, Pforzheim.

AIVP FEATURES & BENEFITS

Scenario Definition & Configuration Control

The AIVP system was designed to provide a simple interface for designing and deploying test cases. A GUI-based tool is provided, allowing the user to select which GMS Elements (and instances) are included in the scenario. The user can further define which of these are real elements and which are to be emulated. Each interface is configured with default settings which may be overridden. Message content may be configured as dummy, modelled or replay data content.

Once a test case has been designed, it is then 'exported' to generate a unique test run. This process creates a record of the test design and ensures that outputs of the test are stored in a dedicated location for that test run instance. In this way, both the conditions of the test and the results are captured as evidence. The main benefits of this approach are traceability of system qualification results and repeatability.

Integration

The modular design of the AIVP system allows emulators to be created with a wide range of complexities. At the most basic level, an emulator can be created for early integration work with *no behavioural model* (known as 'Generic Emulators'). Message encoders and decoders can be plugged together creating an 'empty' emulator capable of sending and receiving messages under user control. This can be done as a configuration activity. At the opposite end of the scale, complex C++ models can be developed to reproduce detailed behaviour and timing. The user may choose between complex and simple models when designing a specific scenario.

The 'Generic Emulator' capability, combined with the rapid interface encoder / decoder generation process means that the AIVP can be available for use *before* the real elements. Hence, when the first real element arrives at the integration factory, it can already be tested against simple emulations of the other system elements. The configurability of the interface models also permits faults in the real element to be ‘worked around’ while waiting for corrective releases.

More complex behavioural models can be developed, as needed, in response to system test planning.

The primary benefit of this early availability is de-coupling of element development schedules for integration work. The Integration Team can begin their check-out and test planning work as soon as the first element arrives, without waiting for connecting elements to arrive from other suppliers and sub-contractors.

Verification & Validation

Due to its configurability and simplified behaviour (with respect to real system elements), V&V activities can be conducted more efficiently when using the AIVP than when using fully ‘real’ system. Element conditions which may take hours or days to achieve with real elements can be configured immediately on the emulator. Fault conditions and ‘rare’ element states / conditions can be reproduced on demand.

In general, the ability of the system to quickly and repeatedly reproduce specific test conditions and record test outcomes brings schedule and cost benefits to the test campaign.

Performance

The AIVP is able to represent the system under test at full scale deployment or maximum expandability. For example, while only a small number of real Galileo Sensor Stations (GSS) are available at the time of writing, the AIVP can emulate the presence of the full system deployment (100+ GSS). Test cases can also be configured to generate ‘worst case’ conditions, under full load.

The main benefit of this capability is risk reduction. The system integrator can demonstrate system performance in worst-case conditions, before placing orders for system completion. Faults in the system design can be detected early, reducing the cost of corrective work.

Analysis

Preparation of test messages and analysis of test results is supported by a single tool known as the Off-Line Analysis Tool (OAT). This is possible because the same format of files is used for test data (as inputs) and for test outputs (e.g. message recordings). Detailed information is stored, capturing message source and destination addresses, timing and fault conditions (e.g. incorrect checksums).

The early adoption of a standard, well specified message capture format, supports the development of further analysis tools. These can be designed and implemented independently of the main AIVP system, for specialised analysis tasks.

Through Life Support

Although originally conceived purely for integration and testing support during the commissioning of the GMS, the AIVP has now itself been integrated into the GMS, as a through-life support capability. This new role recognises that integration and testing continues throughout the operational lifetime of the system, as long as system upgrades (hardware or software) are being performed or fault investigations are needed. To support this new role the GMS AIVP has been upgraded, allowing it to be monitored remotely from the GMS' own monitoring and control facility, the GACF.

The AIVP will continue to be used throughout the Galileo mission lifetime to validate system upgrades and investigate faults. Using the AIVP means that these activities can be undertaken with minimal or no disruption to the operational system, reducing maintenance risks and costs.

The AIVP also provides a training capability for GMS maintenance and operations staff. The GMS will be operated for many years and new staff must be developed with the necessary system knowledge. The AIVP's detailed reproduction of GMS system design and its GUI-based configurability make it an excellent training infrastructure.

Modular interfaces

Modelled interfaces are supported through a modular system which separates the behavioural models of the GMS Element Emulators from the interface models through which they communicate. This allows interface modules to be changed in a range of ways without requiring changes to the behavioural model, and vice versa. Instances of the same interface module are used to send and receive a given message type by multiple Element Emulators. Interface modules are 'auto-generated' from the original ASN.1 or XSD specification using COTS generation tools. The outputs of these COTS tools are (automatically) modified for SMP2 / SIMSAT compatibility using post-processing tools developed by Telespazio VEGA.

The primary benefit of this approach is rapid upgrade of the system, responding to evolving interface definitions. A new interface module, compatible with existing emulators, can be available the same day. For Generic Emulators, this may be the case even where very extensive changes have been made to a schema. For more complex emulators, modifications to the behavioural model may be needed to ensure full compatibility.

The manner in which Emulators interact with their interface modules also allows for a significant degree of backward compatibility to be maintained, when interface specifications change. The system may be configured so that the user can select from multiple different versions of an interface definition, when designing a test case.

These features bring significant benefit from the AIVP's use as a through-life support system. The system supports maintenance activities based on both current (operational) and future (evolved) system specifications. The system operator can validate system upgrades before 'going live' on the real system.

FUTURE SYSTEMS

The approach adopted for the Galileo GMS AIVP is well suited to integration of systems with a medium to high degree of complexity. In particular, the distributable nature of the system enables it to reproduce the interface behaviour of a large number of diverse entities, such as those found on a spacecraft. An AIVP-based system could be developed to reproduce multiple payload modules and spacecraft platform sub-systems. Such a spacecraft AIV system could be used to benefit both payload developers (emulating the wider spacecraft) and spacecraft platform manufacturers (emulating the sub-systems and payloads' interaction with the On-Board Data Handling [OBDH] system).

'Hard' real-time accuracy (e.g. at microsecond level or below) is achievable by interfacing the behavioural models to peripheral devices, for example SpaceWire hardware test devices such as those produced by STAR-Dundee Ltd.

More generally, AIVP-based systems could be developed to support integration and testing of complex systems-of-systems in a wide range of engineering domains.

CONCLUSION

The Galileo GMS AIVP has been (and continues to be) a successful initiative supporting the integration, validation and continuing maintenance of a complex space system.

The AIVP gives the GMS integration team a powerful and flexible tool that de-risks the qualification process and improves its efficiency. Due to the strict qualification conditions met by the AIVP itself, results obtained when using it are trusted, both at the level of the integration team and by their customers (Thales Alenia Space France [GMS prime contractor] and the European Space Agency). The AIVP's strong approach to configuration management and capturing of test outputs allows auditing of test results by both system engineers and Quality Assurance teams.

The AIVP has been *widely* used in the qualification of the GMS (approx. 70% of all test cases). It is able to fulfil this central role due to the rapid-development modular approach adopted for interfaces, and due to the highly configurable nature of the system. Test scenarios are rapidly created, deploying only those components that are relevant to the aims of the test.

The architecture and core infrastructure of the AIVP is well-suited to deployment in support of other systems - in particular, those where multiple diverse elements with specialised behaviour are brought together.

While some test systems 'emerge' from ad-hoc developments of diverse tools, the AIVP has been *specified, designed and qualified* from the outset as a full system. As a result, it is able to take its own place within the deployed target system as a long-term maintenance platform. In this role, it will continue to reduce risk and cost for operation and evolution of the GMS system throughout the lifetime of the Galileo mission.