Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

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From simulations to operations: Developments in Test and Verification Equipment for Spacecraft

TNG-GEN-TP-002

L.J. Timmermans, T. Zwartbol, B.A. Oving, A.A. Casteleijn
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Abbreviations

AIV	Assembly, Integration and Verification
AOCS	Attitude and Orbit Control Subsystem
ASI	Analog Stimuli Interface
BSI	Bi-level Stimuli Interface
CCS	Central Checkout System
CE	Checkout Environment
COTS	Commercial Off-The-Shelf
DASIA	DAta Systems In Aerospace
ECSS	European Cooperation for Space Standardization
EGSE	Electrical Ground Support Equipment
EMCS	EGSE and Mission Control System
ESA	European Space Agency
ESOC	European Space Operations Centre
ESTEC	European Space Research and TEchnology Centre
FDIR	Failure Detection, Isolation and Recovery
FE	Front-end Environment
GTM	General Timing Monitor
IEEE	Institute of Electrical and Electronics Engineers
INTEGRAL	International Gamma-Ray Astrophysics Laboratory
IRIG	InterRange Instrumentation Group
MACS	Modular Attitude Control Systems
MCS	Mission Control System
MDL	Mission Definition Language
MIL	Military
MOI	MOnitor Interface
NCTRS	Network Control and TM/TC Router System
NL	Netherlands
NLR	National Aerospace Laboratory NLR, Nationaal Lucht- en Ruimtevaartlaboratorium
OBC	On-Board Computer
OBDH	On-Board Data Handling
PC	Personal Computer
PLUTO	Procedure Language for Users in Test and Operations
PSS	Procedures, Specifications and Standards
PTB	Project Test Bed
PUS	Packet Utilisation Standard
R&D	Research and Development

RE	Routing Environment
SCOE	Special Check-Out Equipment
SCOS	Spacecraft Control & Operation System
SDB	Satellite DataBase
SE	Simulation Environment
SHAM	Simulation Handling Module
SMS	Simulation Model Software
STD	Standard
SUT	System Under Test
SVF	Software Validation Facility
TC	TeleCommand
TM	TeleMetry
TM/TC	Telemetry & Telecommand
TMTP	TVE Message Transfer Protocol
TNG	TVE Next Generation
TOS	Technical and Operational Support
TPM	TVE Protocol Message
TVE	Test and Verification Equipment
UCE	Unit Checkout Equipment
VME	Versa Module Eurocard
XMM	X-ray Multi Mirror

FROM SIMULATIONS TO OPERATIONS: DEVELOPMENTS IN TEST AND VERIFICATION EQUIPMENT FOR SPACECRAFT

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ABSTRACT/RESUME

Supported by Research and Development programs of the European Space Agency (ESA), simulation and test tools are being developed to improve the life cycle cost efficiency of spacecraft development. Standardisation and rationalisation, use of (C)OTS products, reuse of both software and hardware are some of the lines along which schedule optimisation and cost reduction is pursued.

Based on experience with the development, production and use of test equipment for scientific satellites such as XMM-Newton and INTEGRAL, the National Aerospace Laboratory NLR is developing a next generation of Test and Verification Equipment (TVE) for spacecraft avionics systems, such as Attitude and Orbit Control Subsystems (AOCS). Starting points for these developments are the application of existing relevant technologies, modularity, scalability, commonality and reuse of tools, equipment and results during the various phases of the spacecraft life cycle.

This paper will focus on the interface between TVE and ESA's latest generation Spacecraft Control & Operation System, SCOS-2000, as important element of the next generation TVE to enable reuse of technologies from simulations to flight operations.

1. INTRODUCTION

During spacecraft development, a number of simulation and test facilities are used to support different activities like mission analysis, design and development, Assembly, Integration and Verification (AIV) and flight-operations preparation and training. Simulation is used extensively in design verification and operations preparation, but simulation is also required for test benches involving real flight hardware. Electrical Ground Support Equipment (EGSE) is used to verify the spacecraft's functionality on ground, by stimulating it with test signals and telecommands (TC), and analysing its responses via monitoring interfaces and telemetry (TM).

From past spacecraft programs, a number of important issues for the optimisation of the spacecraft life cycle have emerged, e.g.:

- Need to reuse simulation environments and simulation model software, not only during the development and verification phases, but also during commissioning and in-flight operations.
- Need for early on-board software prototyping and validation. Historically much simulation effort was spent on the verification of control algorithms functionality and performance, before implementation in the On-Board Computer (OBC). Experience has shown that it is equally important to exercise the (often very complicated) Failure Detection, Isolation and Recovery (FDIR) functions implemented in on-board software of autonomous spacecraft, and possibly associated operational control procedures in an early stage of the development. The use of a simulation facility, possibly coupled to an OBC emulator, will enable early prototyping and validation of control algorithms and autonomy functions.
- Need for the development of operational flight control procedures as early as possible, such that the on-board software and operational procedures are exercised to the greatest possible extend on the ground. The developed operational procedures shall be usable during system level integration and test, commissioning and operations.
- Need to use a (central) spacecraft database (SDB) throughout the life cycle. As the life cycle consists of several phases with activities taking place at different locations, it shall be possible to interface to, build up and use the SDB in the different phases and at different places. This requires compatibility and import/export capabilities of database tools used.

Based on experience with production and use of test systems for satellites such as XMM-Newton and INTEGRAL, NLR is developing a new generation of Test and Verification Equipment (TVE) for spacecraft avionics systems. Starting points for the developments are: the existing TVE technology, lessons learned from XMM-Newton and INTEGRAL, application of relevant technologies developed in ESA -R&D- programs, commonality, modularity and scalability, reuse during the various phases of the spacecraft life cycle, use of COTS products.

2. INTEGRATION OF RELATED ESA TECHNOLOGIES

Among the related technologies being developed under ESA programs, are the Project Test Bed (PTB), the Spacecraft Control & Operation System (SCOS), the Software Validation Facility (SVF), and the TVE itself. These technologies are independently used in different phases of the spacecraft life cycle. By reuse of these technologies, the next generation TVE bridges the spacecraft life cycle [2].

The Project Test Bed is intended to be used as a single test platform, based on real-time simulation, that is able to provide support to the different phases of a project, and be reused across projects [3]. The core of the test bed is the real-time simulator that includes libraries of both spacecraft subsystem models and environment models. The simulator is based on the real-time simulation environment EuroSim [4], which provides support for model development and integration, simulation execution and analysis of results.

SCOS-2000 is the latest generation Spacecraft Control & Operation System [8], based on long-time experience, developed and used at the European Space Operations Centre (ESOC). The system is scalable in order to suit different mission requirements, budgets and/or mission phases and provides the essential functions to monitor and control a satellite both in orbit and during testing.

The Software Validation Facility is an onboard software test environment, which provides representative behaviour for a target system, based on the Simulation HAndling Module (SHAM), an onboard computer (OBC) emulator, developed by Chess Engineering B.V. [5]. SVF also comprises a software environment for a/o TM/TC handling and simulation. The SVF/SHAM concept has widely been used the last few years for several ESA scientific satellites.

The Test and Verification Equipment has been developed by NLR for integration and testing of spacecraft avionics systems. Next to a real-time simulator, TVE features a generic front-end with a modular, VME based, architecture, containing hardware interfaces to the spacecraft data buses and to the avionics units for stimulation and monitoring.

While PTB is currently mainly used in the first phases of the spacecraft life cycle, SCOS is used in the final phase. TVE is typically used in phase C/D, see Fig. 1. The next generation TVE bridges the life cycle by integrating a/o the EuroSim and SCOS-2000 technologies. Integration of SHAM, used for both software development and software maintenance, is taking place. The integration of these technologies will stimulate the reuse of simulation and test tools and project results from the early simulations phases (A/B) to the final operations phase (E).

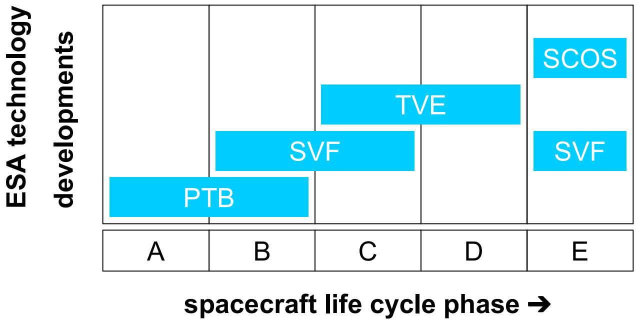

Fig. 1. Overview of TVE related ESA technologies in the spacecraft life cycle

3. THE TVE CONCEPT

TVE was originally developed for ESA, and is (being) used for testing of the AOCS of the XMM-Newton and INTEGRAL scientific satellites, at AOCS subsystem and spacecraft system level [1].

TVE is a closed loop test bench facility (no real motion) for avionics systems. A complete avionics system, together with dynamics and environment can be considered as a loop, which is actively closed by the Attitude Control Computer (ACC) or, more general, an On-board Computer (OBC). The OBC cyclically reads out the sensors, performs the control and other tasks (e.g. FDIR, TM/TC) and issues the resulting commands. The spacecraft dynamics and environment are simulated. The sensor electronics are stimulated by the simulation such that they produce the measurements for the

OBC. The OBC will command the actuators to control the spacecraft dynamics. The relevant signals from the actuator units are acquired by monitoring interfaces and routed back into the simulation. The dynamics simulation runs at a fixed simulation cycle rate, which generally is a multiple of the OBC sample frequency.

During the Assembly, Integration and Verification activities in phase C/D, the avionics subsystem is gradually built up, depending on the schedule of incoming units. Hardware units not yet present are to be simulated. The functional behaviour of these units is simulated in software, while the units physical interfaces are simulated by a hardware unit simulation interface. In this way verification can be performed with any combination of real and simulated units; starting from pure software simulations, via integration of a single OBC, gradual replacement of software models by hardware units, up to a fully integrated subsystem.

Four main elements can be identified in test and verification of spacecraft, see Fig. 2:

1. The System Under Test (SUT), which is (part of) the spacecraft avionics systems that needs to be tested as if it is in its operational environment; an important unit is the OBC that controls the spacecraft
2. Front-end Environment (FE). The Front-end electronics consist of two parts:
   - stimulation and monitoring equipment, which electrically or physically stimulates sensors and electrically monitors actuator units
   - data bus interfaces, which are able to:
     - simulate missing units (address, data interface)
     - monitor all traffic (data, instructions) on the bus
     - simulate the bus controller
   - perform fault injection
3. Simulation Environment (SE), which hosts the Simulation Model Software (SMS) to simulate the spacecraft dynamics and space environment, to calculate stimuli values, and to simulate avionics units
4. Checkout Environment (CE), which contains the knowledge about the SUT (e.g. procedures and TM/TC database) and from which automatic test procedures are executed and AIV activities are controlled

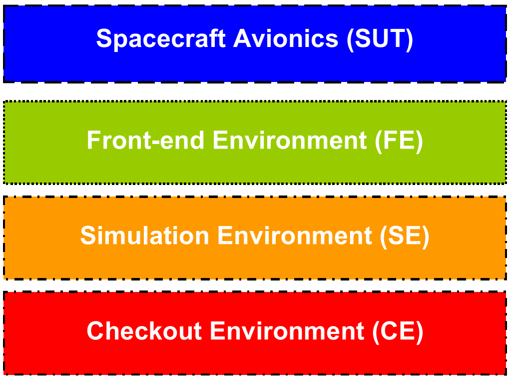

Fig. 2. Main elements in test and verification of spacecraft avionics

The term environment is used as a combination of software and hardware.

Front-end Environment (FE)

For the current TVE FE, data bus interfaces are available for Modular Attitude Control Systems (MACS) and On Board Data Handling (OBDH). For the next generation TVE, new developments are test interfaces for the MIL-1553 bus, the new PSS-04-255 standard OBDH bus, and the SpaceWire (upgraded IEEE-1355) data link. TVE's electrical stimulation and monitoring equipment interface comprises a set of low level boards. For stimulation, NLR has developed Analog Stimuli Interface (ASI) and Bi-level Stimuli Interface (BSI) boards which provide configurable, high-resolution current/voltage stimuli channels. These channels have fully isolated test interfaces with overvoltage and overcurrent protection. For acquisition of data to be monitored, Monitoring Interface (MOI) and General Timing Monitor (GTM) boards have been developed. With the MOI board analogue and bi-level values can be acquired. The GTM board provides timers for the measurement of time duration with 1 ms resolution. For the next generation TVE also features an IRIG-B timer board. Furthermore, dedicated, manufacturer supplied, Units Checkout Equipment (UCE) can be integrated in the FE, e.g. for operation, stimulation and monitoring of star tracker or sun acquisition sensor units.

Simulation Environment (SE)

The current TVE is based on ProSim, a general purpose simulation tool and ancestor of EuroSim. For the next generation TVE, EuroSim will be used, which is a configurable simulator tool that is able to support all phases of space and non-space programmes through real-time simulations with a person and/or hardware-in-the-loop. For PTB, the simulator is also based on the EuroSim real-time simulation environment. TVE-specific tools and interfaces will be developed as extensions to EuroSim. EuroSim has the possibility to interface with other processes via the so-called external simulator access.

Checkout Environment (CE)
Within the current TVE, the checkout environment to control the tests is strongly coupled with the ProSim. For system level testing, there are two ways to develop and operate the avionics subsystem related tests:

- use TVE, and request a Central Checkout System (CCS), also referred to as core EGSE, to send telecommands to the spacecraft. In this case, both by the CCS and TVE must process telemetry.
- use the CCS, and remotely control the TVE simulation environment and test interfaces.

For XMM-Newton, TVE was used as Checkout Environment. All tests have been developed in the ProSim/EuroSim Mission Definition Language (MDL), a C-like language with access to (part of) the simulator. Because MDL is an interpreter language, test scripts could also be changed during a test. Also flight procedures have been implemented in MDL, for verification.
For INTEGRAL the CCS is used to perform all system level tests, which has the advantage that telemetry only needs to be processed once, and all AIV engineers use the same checkout environment. On the other hand, tests developed at subsystem level with the TVE (and also the system level tests from XMM) can not fully be reused.
Since SCOS-2000, with its EGSE capabilities, will be used as Checkout Environment for the next generation TVE, test procedures can be reused at avionics subsystem, spacecraft system, and spacecraft operations level.

The next generation Test and Verification Equipment will improve life cycle cost efficiency of spacecraft development, especially of ESA scientific spacecraft. Reuse of existing technologies and standardisation will bridge the spacecraft life cycle from the early simulation phases (A/B) to the final operations phase (E). These technologies include SCOS-2000 for checkout and operations, EuroSim for simulation such that models developed with PTB can be reused, and the TVE front-end to interface with the flight hardware. Furthermore Chess BV (NL), supported by NLR, is developing an interface between the SHAM and EuroSim [12], which will facilitate the reuse of the SVF/SHAM technology. The reuse of these technologies is shown in Fig. 3.

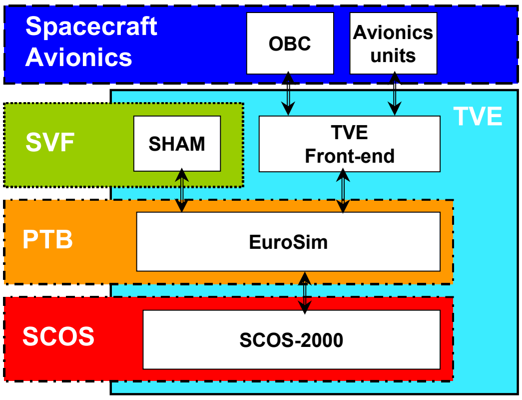

Fig. 3. Reuse of existing ESA technologies for main elements of the next generation TVE

4. COMMONALITIES BETWEEN SPACECRAFT CHECKOUT AND OPERATIONS

Systems for spacecraft checkout and spacecraft operations have a large degree of commonality. The system used to perform spacecraft checkout is traditionally called Electrical Ground Support Equipment (EGSE) and is used for Assembly, Integration and Verification (AIV) at both spacecraft system level and spacecraft subsystem level (like AOCS). During system level tests the EGSE controls a number of Special Checkout Equipment (SCOE), which are similar to the subsystem EGSE but with different functionality. The EGSE enables to control behaviour of spacecraft equipment under test by sending (tele)commands and acquiring signals and telemetry through specific interfaces. The system used for mission preparation and spacecraft operations is called Mission Control System (MCS). As for the EGSE, the MCS has to deal with spacecraft monitoring and commanding.

ESA has a long-standing objective of having a common system to be used as an EGSE and later on as an MCS [6, 7]. From a technical viewpoint it is obvious that for those systems many functions are similar, if not the same. However the necessary harmonisation had not in practice been possible, since these two systems are used in different phases of the mission and, moreover, under different responsibilities; the spacecraft prime contractor for the EGSE and ESA/ESOC for the MCS. This problem is essentially of a managerial and a contractual nature. By merging the Technical Directorate of ESTEC with the Directorate of Operations at ESOC into a single Directorate Technical and Operation Support (TOS) the EGSE support and operation support (including MCS) are now under the same technical responsibility. The combined system is called generically "EGSE and Mission Control System" (EMCS). The ESA Scientific Directorate is strongly pushing the spacecraft primes to propose systems that are common to EGSE and MCS. The data used by an EGSE and a MCS are very similar, see Fig. 4. Both the EGSE and the MCS must have knowledge about the spacecraft and its behaviour. This is described in a database that is often called the Mission Information Base

(MIB). The core information in the MIB is the Telemetry and Telecommand characteristics. By using the ESA Packet Utilisation Standard[1] (PUS), missions can easily reuse the same EGSE or MCS infrastructure.
Both the EGSE and the MCS are operated using procedures. During checkout, activities are described using a formal test language. During operation one has flight operation procedures which could also be defined using an operation language. By using a common language, like the Procedure Language for Users in Test and Operations (PLUTO) as defined in the ECSS-E-70-32 standard [10], test and operational procedures can easily be reused.
The last type of data needed by both an EGSE and a MCS are display data, especially TM/TC related mission representation, which can be alphanumeric displays, graphics or synoptic/mimic displays. By using the same representation, people involved in the AIV phase can easily provide support during the (early) operations, and vice versa, resulting in a better knowledge transfer and improved operations.

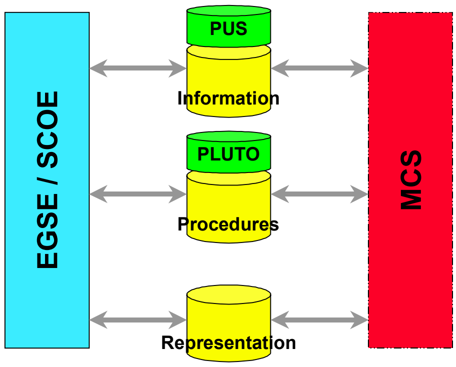

Fig. 4. EGSE / SCOE and MCS systems use common data

An important difference with a MCS is that the EGSE needs to control Special Checkout Equipment (SCOE), which can in essence be treated like spacecraft TM/TC. Note that TVE can be used both as standalone EGSE during subsystem level tests, and as SCOE during system level tests. Another important difference is that the EGSE/SCOE tries to uncover weakness (e.g. through error injection and checks) of the spacecraft, whereas the MCS has to work around such faults in order to keep the spacecraft alive.

From a system level, however, the interface of the (core) EGSE with the several spacecraft SCOEs can be compared with the interface of the MCS with the several ground stations. In both cases an interface is necessary to exchange the data in a standard way. In case of SCOS as MCS, the Network Control and Telemetry Routing System (NCTRS) is used as interface, see Fig. 5.

Note that for EGSEs and MCSs, one can distinguish two types of commonality: the horizontal commonality where the same system is reused between different missions, and the vertical commonality where for a same mission the same system is reused between the AIV phase and the operations phase.

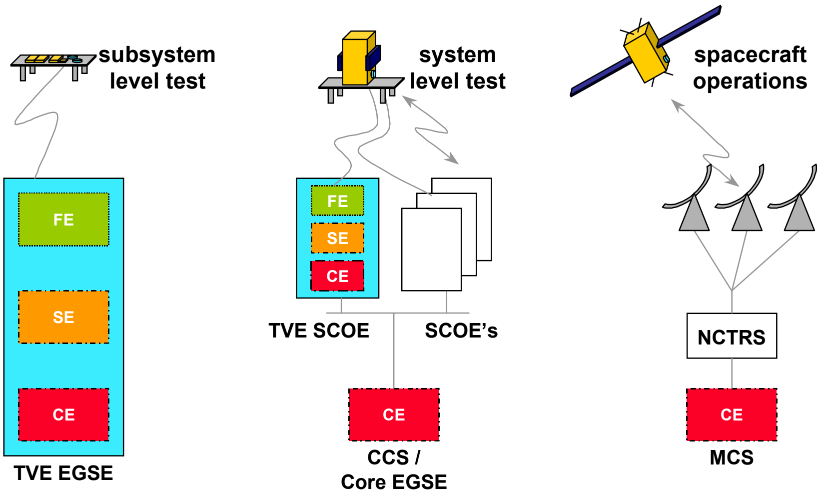

Fig. 5. System commonality for avionics subsystem level tests, avionics tests at system level and spacecraft operations

5. THE INTERFACE BETWEEN SCOS-2000 AND TVE

During operations, the SCOS-2000 has the role of MCS and as such controls the spacecraft via TM/TC. During checkout, SCOS-2000 has the role of CE, controlling both the SUT and the TVE (and other EGSE/SCOE equipment). The interface between SCOS-2000 and TVE will be TM/TC based, such that for SCOS-2000 a common interface is maintained.
Internally, TVE components communicate via the TVE Message Transfer Protocol (TMTP). The TMTP is mainly used for communication between CE/SE and FE. The TVE Protocol Messages (TPM) contain e.g. data for the electrical and data interfaces, status info and error/warnings.

[1] The PSS-07-101 standard will be replaced by the ECSS-E-70-41 standard [11]

The conversion between the TM/TC based (external) SCOS-2000 communication and the TMTP based (internal) TVE communication will be provided be a Routing Environment (RE). Telecommands from SCOS-2000 to TVE will have an embedded TPM, which is passed by the RE. The RE will put data from TVE in telemetry packets, to be read by SCOS-2000. All communication with the SUT will be passed through the RE in an appropriate format. Effectively, the data stream coming from SCOS-2000 is split into a TPM stream for the TVE and a TM/TC stream for the SUT. The conceptual architecture is shown in Fig. 6.

Since SCOS-2000 in the role of MCS interfaces with the NCTRS, an RE has been developed that implements the NCTRS ICD [9] on CE side, thus acting as an NCTRS simulator during checkout. On SE side, the EuroSim External Simulator interface has been implemented. For further reuse the RE should be able to connect different types of CE and SE, other than SCOS-2000 and EuroSim.

The TVE related TM/TC includes:

- control and monitor of the simulator state
- control and monitor of the real-time simulator test environment (Mission Definition Language actions)
- control and monitor of the simulation model variables (data dictionary)
- any TPM to TVE internal processes, e.g. to perform error injection
- error and warning messages

The user is provided with dedicated displays to command and monitor the TVE from the SCOS-2000 checkout environment.

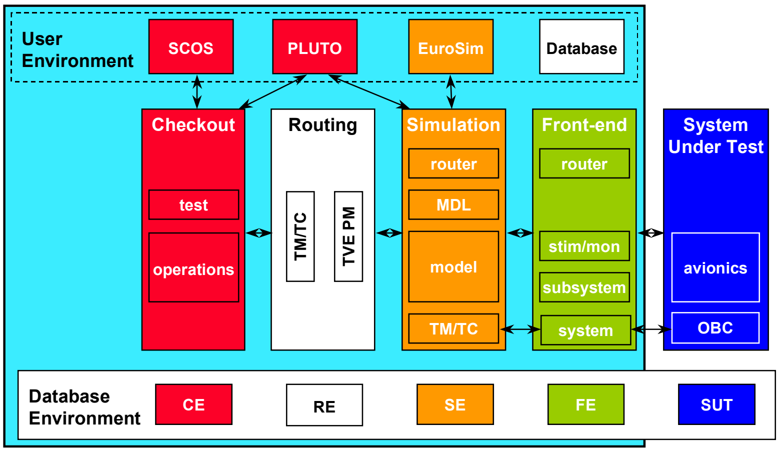

Fig. 6. Conceptual architecture of the next generation Test and Verification Equipment, showing the main elements and interfaces

6. CURRENT STATUS

The next generation Test and Verification Equipment at NLR operates in the following configuration:

- SCOS-2000, release 2.0, running on a Sun platform, as Checkout Environment
- EuroSim Mk2, running on a Linux PC, as Simulation Environment
- TM/TC based interface between SCOS-2000 and TVE, with a NCTRS simulator implementation as Routing Environment

For the target configuration TVE, a Linux version of SCOS-2000 will be used. The Linux version will become available in the next months.

Fig. 7 shows a screen snapshot that reflects the current development status, with part of the CE, RE and SE operational with the Point-Mass Controller (PMC) test case. The PMC-case is developed by Chess as case study for the development of On-Board Software [12]. A point-mass is commanded to a certain position with the OBS controlling two thrusters (in opposite directions and unequal forces). In the NLR configuration the OBS is running in the FE. Newton's law is simulated in EuroSim, which provides only the acceleration data as sensor for the PMC. The graph shows the position of the point-mass in time. The target position is set with a telecommand from the SCOS-2000 Manual Stack window, which shows two telecommands for the TVE system. The NCTRS simulator window shows the connections to SCOS-2000 and a hex dump of a raw telecommand.

7. CONCLUSIONS

NLR is actively contributing to the trend of maximising reuse of software and hardware throughout the spacecraft life cycle. It is developing modular and scalable Test and Verification Equipment, which integrates PTB/EuroSim, SVF/SHAM and SCOS-2000 technology, such that it can be (re)used for simulation and verification from the early simulations to final operations. Standardisation of tools is pursued.

8. ACKNOWLEDGEMENTS

NLR thankfully acknowledges the fruitful discussions with the ESA Technical Operations and Support Directorate, especially the Mission Control System Division, the Test and Operations section, and the Modelling and Simulation section. Also the useful feedback from the current TVE users - Astrium Friedrichshafen for XMM-Newton and Alenia Turin for INTEGRAL – for their suggestions in improving the Test and Verification Equipment is much appreciated.

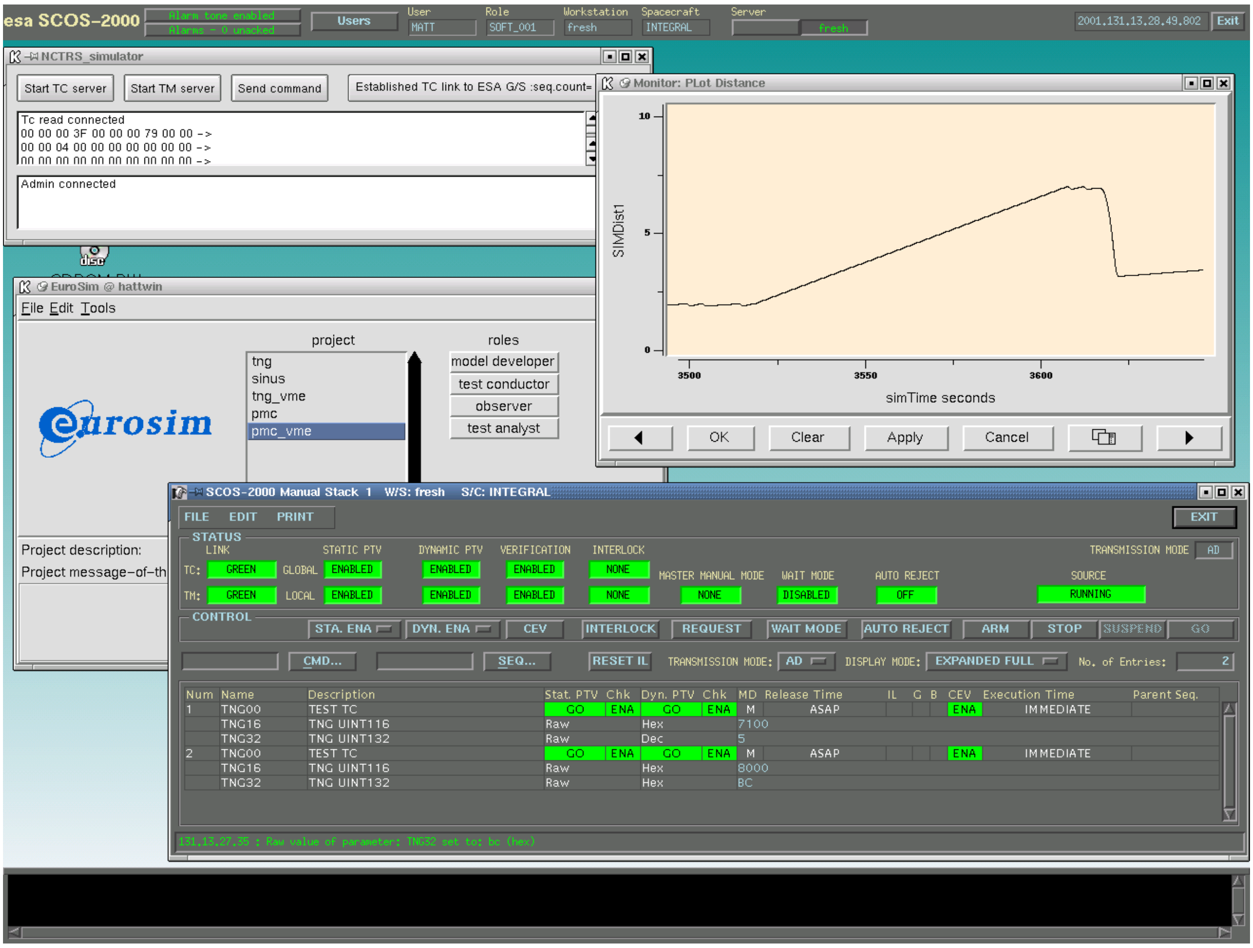

Fig. 7. Screen snapshot reflecting the development status for the next generation TVE, with user interfaces of SCOS-2000, NCTRS simulator and EuroSim operational in the Point-Mass Controller test case.

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From Simulations to Operations:

Developments in Test and Verification Equipment for Spacecraft

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National Aerospace Laboratory NLR

Presentation overview

- **Introduction**
- **Related ESA technologies**
- **TVE developments overview**
- **EGSE and MCS commonality**
- **SCOS-2000 interface with TVE**
- **Current status**
- **Conclusions**

DAta Systems In Aerospace, DASIA 2001, 28 May - 1st June 2001, Nice, France

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Test and Verification Equipment (TVE)

- **Standard ESA tool for AOCS test and verification**
- **Used at subsystem (EGSE) and system level (SCOE)**
- **Simulation (dynamics, units, environment)**
- **Electronic and data interface (HIL)**
- **Combinations of simulated and real units**

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TVE used during XMM AIV in Kourou

DAta Systems In Aerospace, DASIA 2001, 28 May - 1st June 2001, Nice, France

Test and Verification Equipment

- Successful applied for XMM-Newton and INTEGRAL
- Next generation TVE currently under development

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Main elements

Spacecraft Avionics (SUT)

Front-end Environment (FE)

Simulation Environment (SE)

Checkout Environment (CE)

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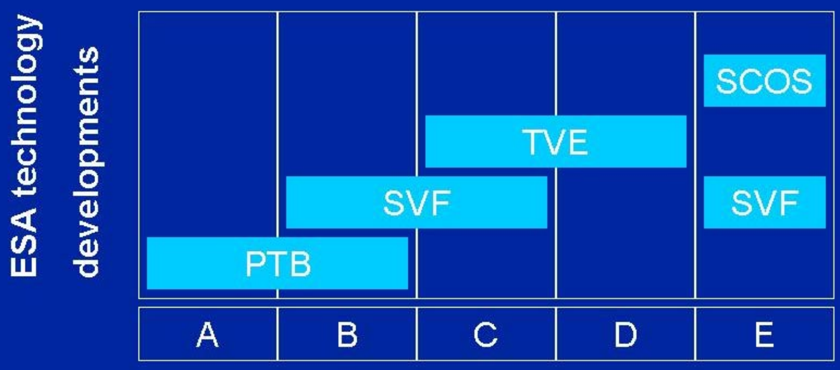
Related ESA technologies



spacecraft life cycle phase

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Technology integration

- Currently no easy transition between ESA tools
- In phase C/D both *simulation* (phase A/B) and *operation* tools (phase E) are needed
- NLR tries to facilitate reuse by integrating ESA tools with TVE

DAta Systems In Aerospace, DASIA 2001, 28 May - 1st June 2001, Nice, France

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DASIA'2000 High Level consideration #1:

- *Necessity for Europe to adjust to the evolution of the ground segment software market*
  - trend to more general use of COTS
  - individual software selections for easiest solutions (= better advertised (= US)) …
  - attempts to curb this trend, like e.g. SCOS-2000, have to be encouraged

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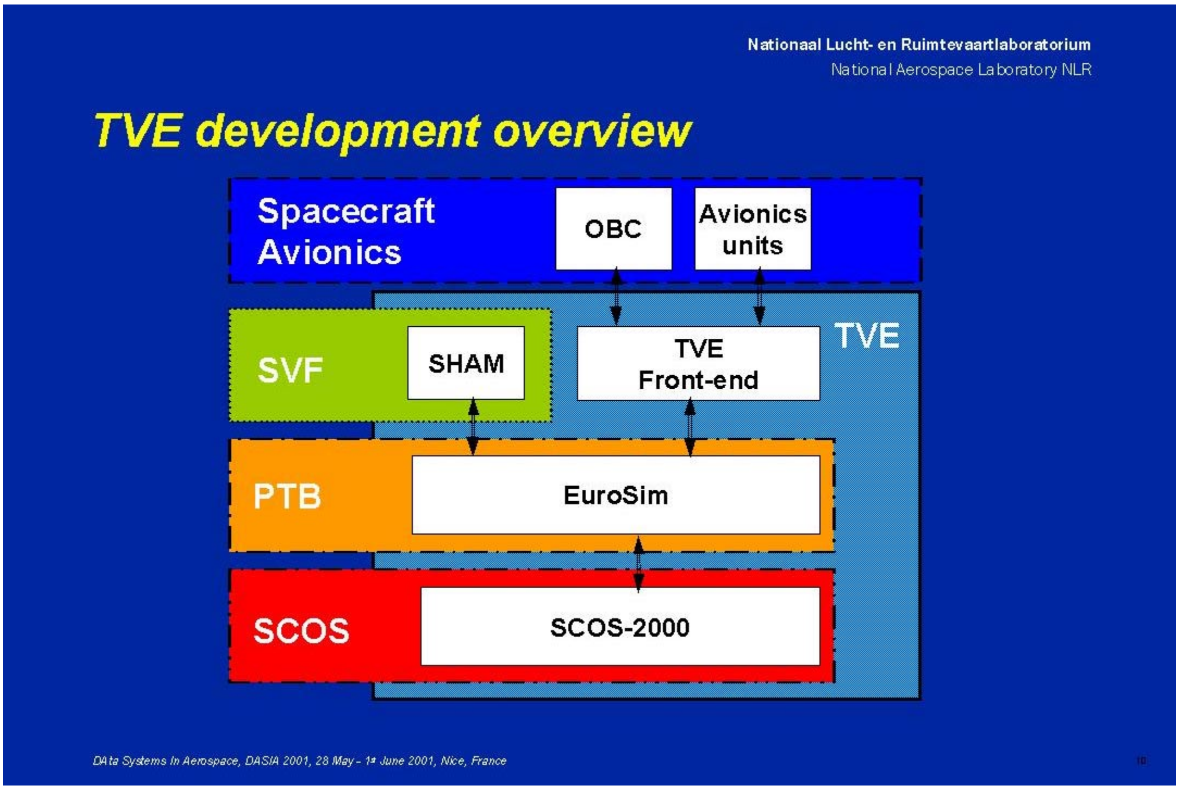
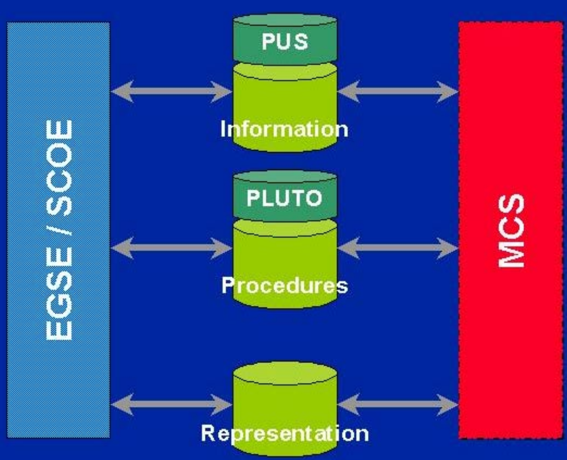
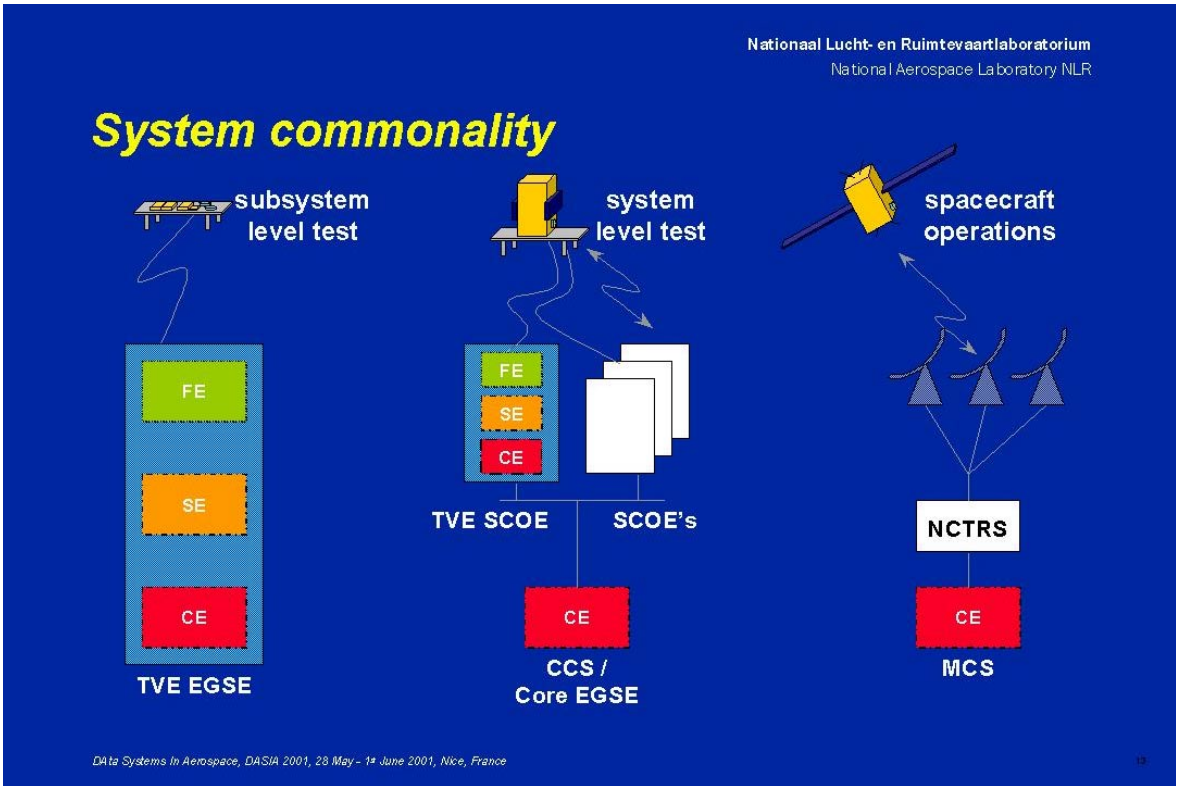


EGSE and MCS commonality

- Long-standing ESA objective
- Data commonality
- System commonality

Data commonality





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SCOS-2000 interfaces

- TM/TC interface with SUT
- TM/TC interface with TVE
  - control and monitor simulator state
  - control and monitor model variables (data dictionary)
  - perform error injection
  - error and warning mechanism

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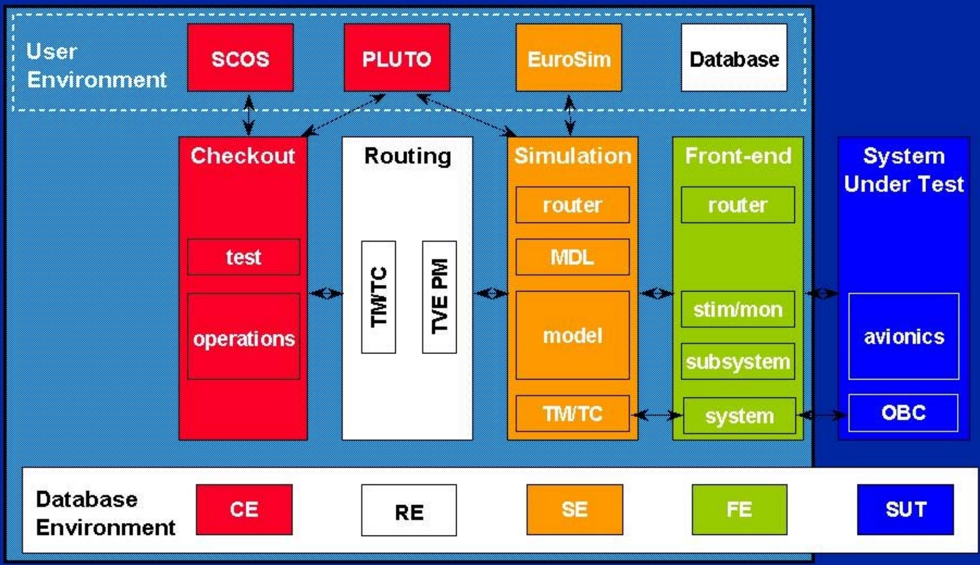
TVE conceptual architecture



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Current status

- Operational configuration
  - SCOS-2000, release 2.0 (SUN)
  - EuroSim Mk2 (Linux)
  - TM/TC interface between SCOS-2000 and TVE
- Interface between EuroSim and SHAM under development by Chess (NL), supported by NLR

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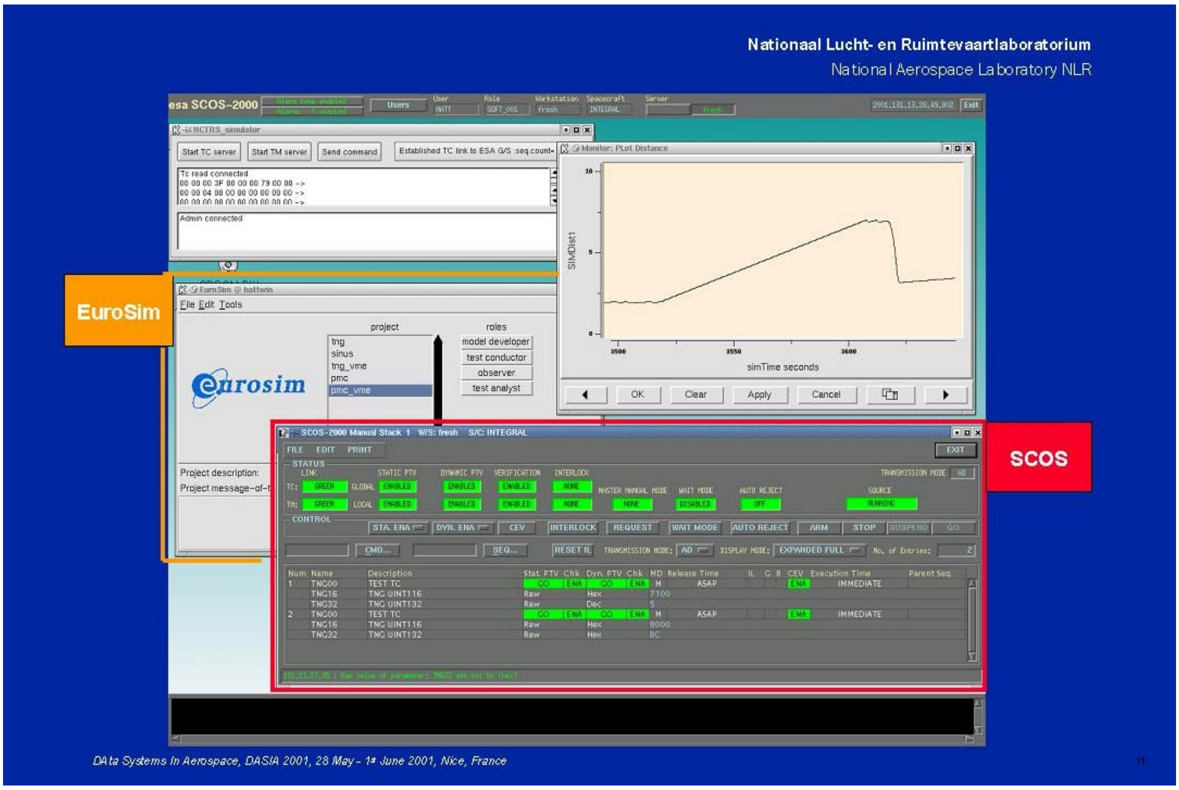
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EuroSim
SCOS
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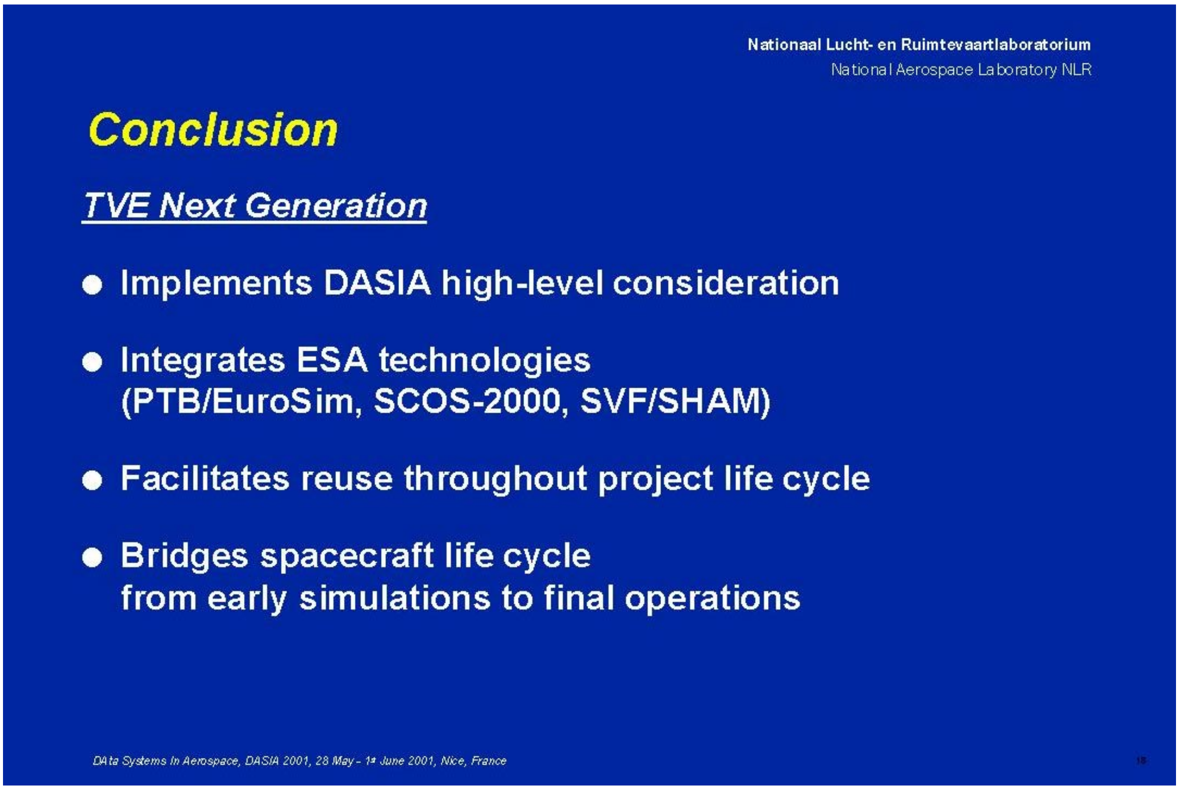
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Conclusion
TVE Next Generation
Implements DASIA high-level consideration
Integrates ESA technologies
(PTB/EuroSim, SCOS-2000, SVF/SHAM)
Facilitates reuse throughout project life cycle
Bridges spacecraft life cycle
from early simulations to final operations
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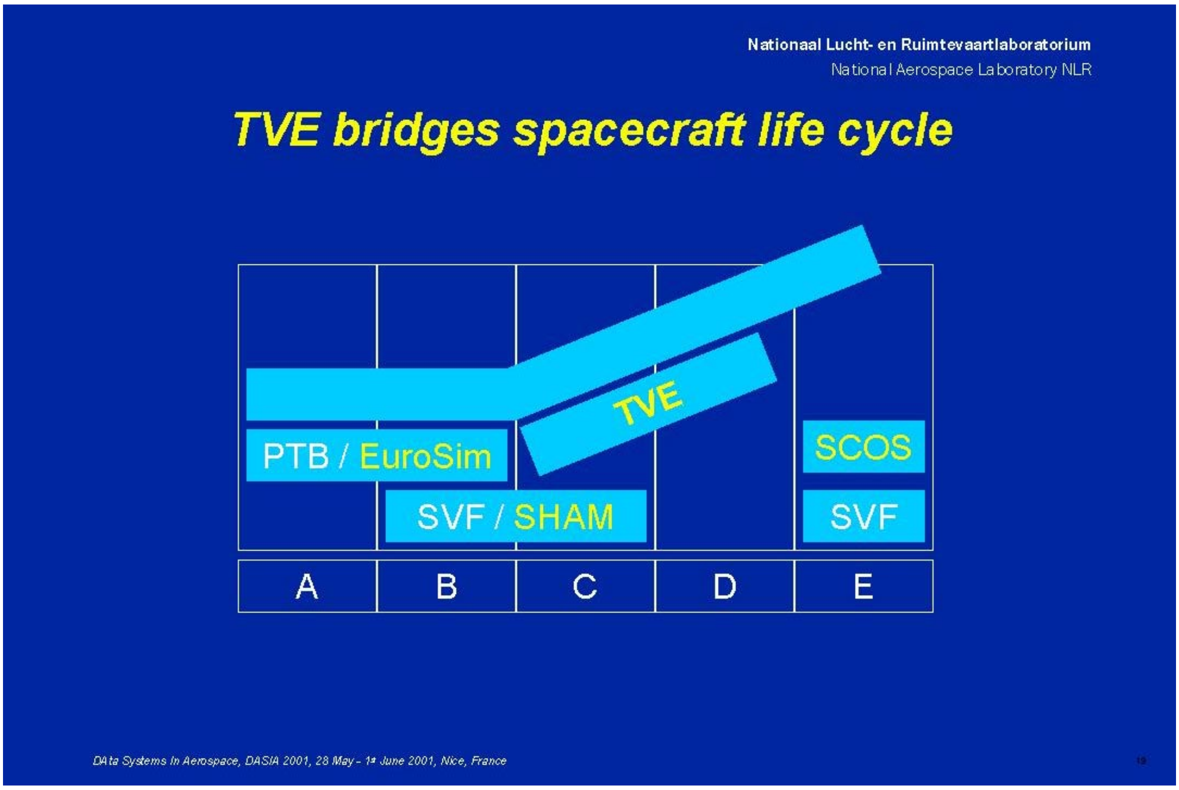
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TVE bridges spacecraft life cycle
TVE
PTB / EuroSim
SVF / SHAM
SCOS
SVF
A
B
C
D
E
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