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Galileo System Verification: Approach, Methods and Tools

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ABSTRACT
This paper gives an overview on the approach applied for Galileo system verification.
It also describes the methods and necessary tools for the verification on system level.

Background:
The high level Galileo mission requirements, which capture user requirements, have been translated into the Galileo system requirements. These system requirements have formed the basis for specifying the Galileo system, segments, and elements.
Thus, for the verification of the Galileo system it is necessary to verify the Galileo system against the system requirements.
This paper addresses the approach for system verification and elaborates on methods and tools to be applied throughout the various system development phases up to full deployment and operational readiness of the Galileo system.
These methods and tools to be used for each phase of system verification have been integrated into the System Verification Plan [RD 4].

This paper focuses on:
The verification methods (advantages and overlapping) that will be applied to achieve a high level of confidence in the design and implementation, already in early phases of the development, by providing plausibility and proof for system requirements to be met by the design and applied technology, in an incremental fashion.
Completeness of verification reached at different stages during the development of the system (i.e. what is feasible to verify and/or demonstrate with deployed architecture and analysis of difficulties and limitations).
Identification of tools required in support of the verification methods and activities.

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Galileo System Verification: Approach, Methods and Tools

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Summary

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- Completeness of verification reached at different stages during the development of the system (i.e. what is feasible to verify and/or demonstrate with deployed architecture and analysis of difficulties and limitations).
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Contents

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1 Approach for System Acceptance

1.1 Galileo System Description

For a better understanding the Galileo system is shortly described below (see also [RD 1]).

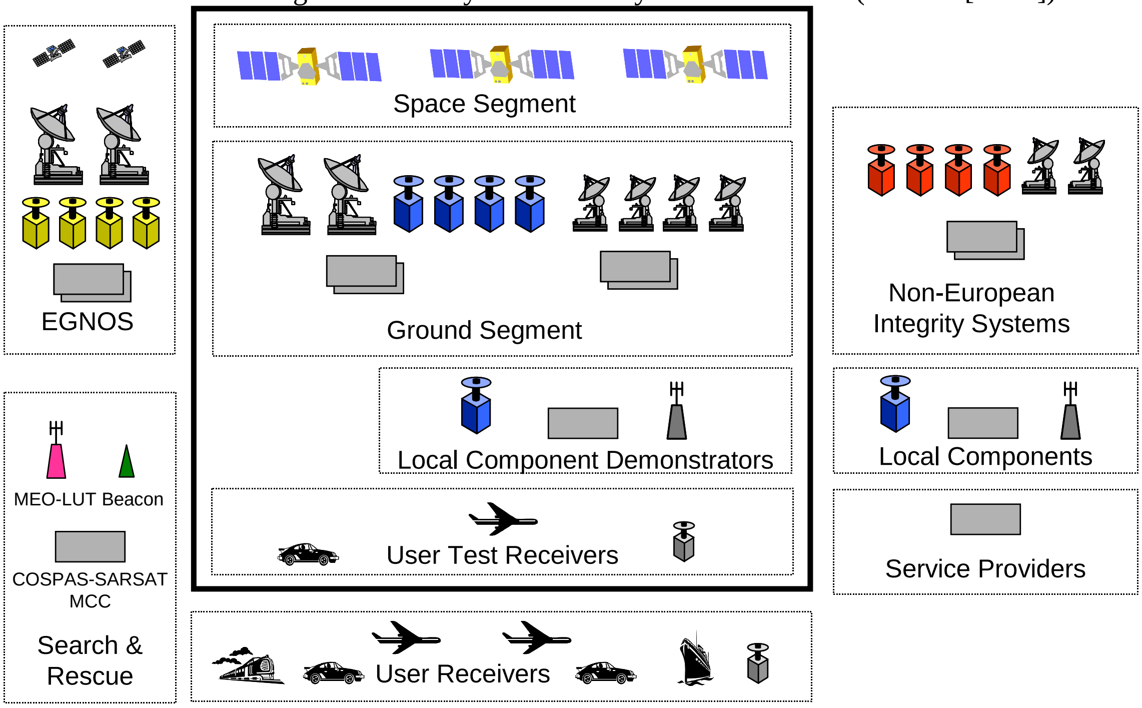

Figure 1: Overall GALILEO System

The overall Galileo System is illustrated in Figure 1. The components to be considered within the Galileo System for the purposes of the Galileo Phase B2 Study are those within the solid line.

The Galileo Space Segment will comprise a constellation of a total of thirty satellites in medium-Earth orbit (MEO), so that at least ten satellites will normally be visible from any point on the Earth’s surface. Each satellite will broadcast precise time signals, together with clock synchronisation, orbit ephemeris and other data. A user equipped with a suitable receiver will be able to determine his position to within a few metres when receiving signals from just four Galileo satellites.

The Galileo Ground Segment will control the whole Galileo constellation, monitoring satellite health and up-loading data for subsequent broadcast to users. The key elements of this data, clock synchronisation and orbit ephemeris, will be calculated from measurements made by a world-wide network of stations.

Galileo will provide an interface to Service Providers. These Service Providers will give users a point-of-contact to the Galileo system, will provide a variety of value-added services and will play a role in collecting fees. This interface may also include provision of specialist data, such as clock and ephemeris history and predictions to specialist scientific users.

External components, such as GPS, GLONASS, LORAN-C, may be interfaced to Galileo receivers to provide combined navigation services. However, this Document places no specific requirements on such operation.
Galileo will thus provide a range of guaranteed services to users equipped with receivers meeting Galileo specifications.

1.2 System and Segment Differentiation

The Galileo system requirements document (GSRD [RD 1]) lists requirements for the final operational capability of the Galileo system.
The requirements consist of the following requirement groups:

- Service Requirements
- Functional Requirements
- Implementation Requirements
- Operational Requirements
- Security Requirements
- Safety Requirements
- Verification Requirements
- Signal-in-Space Requirements
- External Interfaces Requirements

These requirements can be divided into three categories:

- Category 1: Requirement has to be verified on system level, since more than one segment (i.e. space, ground mission, ground control, and user segment of Galileo) is involved .
- Category 2: Requirement can and will be performed on segment level, since the functionality specified is related to a segment. In this case in the system verification reference is made to segment tests or verifications.

According to this differentiation, the verification of requirements may be performed either on system level or on segment level. Only requirements of category 1 have been considered in this paper, i.e. requirements of direct system relevance.

1.3 Phasing of Verification Activities

The verification methods for system verification and acceptance are ([RD 5]):

- Test/Measurement
- Analysis
- Review of Design
- Simulation
- Inspection

These verification methods are applied – as far as applicable and possible – for the following three milestones:

- System Critical Design Review (S-CDR)
- In-Orbit Validation Review (IOVR)
- Final Validation Review (FVR)

S-CDR

During the System CDR (Critical Design Review) the verification methods proposed at the beginning of the Phase shall be reviewed and accepted in order to be used for the IOV phase. Subsequently the test procedures and all the necessary verification tools for the IOV Phase have to be written or established.

At the System CDR some of these principle methods are already addressed, especially w.r.t.

- Analysis: where applicable first analysis for verification of system requirements could be made available.
- Review: At CDR the design of the System shall be reviewed and accepted. First verification of requirements by review shall be possible at this time.
- Simulation: some simulations are needed to demonstrate the adequacy of the design to met the system requirements.

IOVR

The IOV (In Orbit Validation) phase is characterised by the fact, that in this phase the system configuration to be accepted is not complete in the sense of the GSRD. The selected IOV configuration is a compromise fulfilling schedule and budget constraints on one hand and providing an acceptable technical platform for verification of system parameters on the other hand.

Despite of the limited IOV configuration compared to FOC (Final Operational Capability):

- 4 satellites instead of 27+3 satellites
- limited ground segment (with reduced number of GSS, ULS, TT&C Station, Control Stations and no redundancies)

the GSRD remains the baseline for the system requirements. It is the objective of the IOV phase to verify and demonstrate at an early time, that the system finally implemented at FOC will meet the GSRD requirements. A major prerequisite of system verification for IOV is the adaptation of those GSRD requirements to IOV requirements which a specifically applicable for the IOV system configuration.

The major verification method for space infrastructure systems “Test/Measurement” [RD 5] is not directly applicable for the incomplete IOV configuration. To overcome this problem other verification methods have to complement the ones mentioned above:

- Simulation
- Test/Measurement plus Simulation, including extrapolation from measured results

FVR
The FOC phase is characterised by the fact that the system to be accepted at FVR is now complete, in the sense of the GSRD.
The FOC configuration consists of:

- 27+3 satellites
- full ground segment (with complete network of GSS, ULS, TT&C Stations, Control Stations, and redundancies)

The GSRD is fully applicable and FOC performance and design has to meet the GSRD.
The major verification method for space infrastructure systems “Test/Measurement” shall be applied as far as possible. Simulations shall be used as a comparative tool and for parameters, which are difficult to measure (e.g. integrity risk). Another aspect is to use simulations for extrapolation of measurements or should be extended to an area (e.g. in case measurements are performed at a limited number of points, but the compliance with a requirement requesting world-wide coverage should be shown).

The verification policy applied is to prove as soon as possible, that the systems already established or planned will work properly to minimise the risk. This implies that the verification process runs in parallel to the development process in each of the development stages/phases, which will be finalised not before FOC (i.e. when full system deployment is achieved).

2 Completeness of Verification

439 requirements on system level (i.e. category 1) of the GSRD have been investigated. For each of these requirements the verification method has been given for the S-CDR, IOVR, and FVR.
The verification of a requirement is considered to be complete at a milestone (i.e. S-CDR, IOVR, FVR), when no more verification activities with respect to this requirement are needed after this milestone.
If the verification of a requirement is not complete at a certain milestone a justification has been provided.

The completeness of verification reached at CDR is 3%, at IOV 11%, and at FOC 99.8%.

A completeness of verification of 100% can not be obtained for FOC as the requirement 8.4.1 (“The Full Operations shall provide the Galileo services at the required level of availability and reliability, continuously for the full-specified service duration.”) requests verification activities after FOC. The requirements request continuously on-going activities over the full-specified service duration.
A preliminary verification at FOC can be obtained by using analysis and simulations following the approach described above.

A detailed view for each requirement group is given in Appendix A.

3 Verification Tools

3.1 Approach

The system verification methods for each phase have been used as the starting point for the specification of the requirements for the verification tools, and to map these tools requirements to the existing tools, i.e. checking if the requirements are adequately covered by tools as available/planned today.

The analysis of system verification tools has allowed the selection of the most suitable tools to be used for the verification process, taking into account also the validation status and the quality standards followed by the tools (in view of the future certification of the Galileo system).

The analysis of system verification tools also suggests possible updates to existing tools, in case some of the requirements were not adequately covered by existing tools, or recommended the procurement of new tools with detailed specifications.

The main goals of applying the system verification tools change with the system development phases and their corresponding verification objectives:

- Up to S-CDR the tools will be used to simulate the system performances and to give proof that such performances are compliant to the specifications. Also, until CDR the GSTB (Galileo System Test Bed) [*RD 7*] will be used to make early tests and experimentation on the system.
- Up to IOVR, the tools will be mostly used to combine simulations with measurements performed with the limited IOV system configuration. Whereas the system performance at this stage is much degraded w.r.t. FOC, extrapolations to the performances of the full system can be computed by interfacing the deployed elements to the simulators. At this

stage, thanks to the real measurements, this allows for simulators algorithms to be refined and calibrated in order to better model the system.
- At FVR, the importance of simulation tools is minor because at this stage the verification can be performed essentially by test based on the FOC system configuration.

3.2 Considerations on the Selection of Tools

It is important, in view of the system certification, that the selection of the tools to be used for verification considers the following issues:
- Independence of the tools used for the design from the ones used for the verification
- Concerning the quality standards for the software, the ECSS-E-40A [RD 6] will be tailored and applied for the Galileo System
- Validation status of tools
- The criticality of the requirements to be verified. For requirements with a higher level of criticality it will be necessary to have high confidence in their verification. In this case it is reasonable to verify those requirements by means of more than one tool.
- The tool stability: some of the tools listed above have been developed using office tools, which may be intrinsically unstable or unable to reliably handle large amounts of data. For this reason their use for verification purposes has to be carefully evaluated considering that it may slow down very much the process and it could be more convenient to use other tools.
- Minimisation of the number of used tools: in order to reduce the need of interfaces and to simplify the whole verification process.

3.3 Selection of Tools

A number of existing tools have been identified and described including essentially the tools that have been used for the definition and preliminary design phase. The tools considered are listed in [RD 3]. Anyway, whereas this list is long, the primary tools that have been taken into account for the verification activities (see [*RD 7*]) are the
- Galileo System Simulation Facility (GSSF)
- Galileo Signal Verification Facility (GSVF)
- Galileo System Test Bed (GSTB)

The justification for this choice remains in the fact that the three tools together give a good coverage of the verification needs and are a good starting point in case the verification needs require updates to the tools.
Moreover the other tools have been used for the design, so it is advisable to use different tools for the verification (if suitable, industry tools may be used as support, to give more confidence in the results, but it is important to have independent tools for verification).

The choice of focusing on GSSF, GSVF, GSTB has also been driven by the fact that the number of tools to be used for verification should be minimised and that the GSSF, GSVF, and GSTB will be used anyway as minimum set of tools.

In those cases where the verification needs are not covered by the abovementioned set of tools, it has been evaluated whether it is better to extend their functionality, to use other existing tools or to develop new tools.

Among the tools that have been identified as currently missing is the Galileo User Test Receivers (GUTR), required as a tool capable of receiving the Galileo Signal-In-Space and analysing associated performance characteristics.

3.4 Requirements for Verification Tools / Facilities

The System Verification Tools Requirements (SVTR) have been produced according to the verification methods.

The verification tool requirements (VTR) have been issued either as use cases or as explicit requirements (that may also be derived from previous use cases). The tool requirements can be traced to the relevant verification method, are linked to the development phase in which they are applicable, and give a mapping to the applicable type of tool.

3.4.1 Example

5.2.2 Coverage (from System Acceptance Criteria [*RD 2*], i.e. GSRD)

Verification for all phases:
The approach followed is a combination of test and simulation. The following requirement can be derived for the simulators:

Table 1: Requirement for verification / facility- Example

Phases	Tool/Facility	VTR ID and Title	SVTR Text	Comment
CDR, IOV, FOC	Service Volume Simulator	VTR-SRV-0020 Grid of users	In order to evaluate the services coverage, the simulator shall be able to evaluate the system performances for a grid of users (the grid can be from global to local scale).	

3.5 Mapping of Requirements to Tools

The following table gives an example for the mapping of the Verification Tools Requirements (VTR) and the Use Cases (UC) to the existing tools. This example shows that the GSSF should be used as a simulator for Search And Rescue (SAR) functionality to verify return link delivery time of the SAR system. The example also shows the default toolset does not cover a SAR distress radio beacon.

Table 2: Mapping of requirements to tools – Example

Phase	**Tool/Facility Category**	**VTR ID and Title**	**GSSF**	**GSTB V1 / V2**	**GSVF**	**Other**	**Not Covered**
	SAR						
CDR	SAR simulator	VTR-SAR-0030 SAR Return Link Delivery Time	X				
IOV, FOC	SAR Distress Radio beacon	VTR-SRV-0010 SAR Beacon Type					Suitable SAR beacons to be procured

3.6 Tool Selection per Phase

In the next step the tools were selected for each phase and missing tools were identified according to the tool selection as mentioned in section 4.2. The table below shows an example where GSSF is proposed as tool to be used in all phases (tool requirement UC-ACC-0010), while a variety of tools is proposed to for another tool requirement (UC-CC-0020).

Table 3: Tool selection per phase – Example

VTRs and Ucs	CDR	IOV	FOC	Missing/ Comment
UC-ACC-0010 Verification of Services Accuracy Performance	GSSF	GSSF	GSSF	Uses results from UC-ACC-0020
UC-ACC-0020 Pseudorange error (UERE) characterisation	GSSF & GSTB-V1	GSSF& GSTB-V2/ TRSF / GUTR	TRSF / GUTR	For CDR & IOV: Interface GSTB -> GSSF assumed present, as needed for the measurement-based UERE components characterisation. (see GSSF SRD Vol1 section 8.1.1). For IOV: Interface TRSF / GUTR ->GSSF needed for same reason. Assumed to be the same interface definition as GSTB->GSSF.

3.7 Requirements for missing / upgraded Tools per Phase

In the next step the missing features / tools were described for each tool requirement per phase. The following table is exemplary for the GSSF.

Table 4: Requirements for missing / upgraded tools per phase - Example

UC-ACC-0020 Pseudorange error (UERE) characterisation	GSSF shall provide an interface to GSTB
VTR-OP-0080 Special Operations simulation	GSSF shall cover simulation of all special operations
VTR-SAR-0006 SAR Forward Link Service capacity VTR-SAR-0015 SAR Forward Link Service Detection probability VTR-SAR-0020 SAR Return Link Message rate VTR-SAR-0030 SAR Return Link Delivery Time	GSSF shall support updates of SAR payload model

Primary tools planned to be used for Galileo verification are:

- Galileo System Simulation Facility (GSSF)
- Galileo Signal Verification Facility (GSVF)
- Galileo System Test Bed (GSTB)

Additional features have been identified for both GSSF and GSVF for all phases (Design, IOV, and FOC).

A complementary tool set has been specified, based on the tools requirements not expected to be covered by future versions of the baseline tools set. This complementary tool set includes the following:

- A tool capable to receive the actual GALILEO Signal In Space, either from the GSTB, the IOV satellites or the fully deployed GALILEO constellation, including an analysis environment in support of system verification. The tool includes a GALILEO User Test Receiver (GUTR) and is named Test Receiver Support Facility (TRSF).
- A tool in support of verification of requirements related to the susceptibility to interference, including jamming and spoofing: the Interference Generator Tool (IGT) as well as a related tool in support of the analysis of the signal spectrum as received by monitoring stations and users: the Spectrum Analyser Tool (SAT).
- A tool dedicated to the analysis and assessment of timing and frequency services as provided by GALILEO: the Time and Frequency Accuracy Measurement Facility (TFAMF).
- A tool capable to assess nominal and non-nominal operational conditions: the GALILEO Operations Simulator (GOS).
- A tool capable to assess and analyse requirements related to Search-And-Rescue functionality supported by GALILEO: the SAR Beacon and Support Facility (SBSF).
- A tool dedicated to security aspects in relation to signal encryption: the Encryption Test Facility (ETF).
- An environment providing the necessary interfaces between the various tools.

4 Conclusions

Starting from the Galileo system requirements all the requirements relevant to be verified on system level have been identified. For each of these requirements the verification method at each Galileo development stage has been described including the completion status.
From the verification methods the requirements for the verification tools have been derived. These requirements have been mapped to tools for each stage. The tools needed have been identified and missing tools, missing tools interfaces, and missing tool features have been described.

5 Biography

Klaus Strodl received the M.Sc. in Electrical Engineering from the Technical University of Munich in 1991. From 1992 to 1999 he worked in the SAR and image processing, digital signal processing, encoding techniques, SAR system layout and system performance, and flight campaigns at DASA and DLR. Since 1999 he is working in the field of verification & validation, system architecture, and security aspects for navigation systems.

Giovanni Naddeo graduated in Electronic Engineering from University of Rome (1992) and worked with GPS receivers for aeronautic applications. He was at ESA/ESTEC with a short time contract in radio navigation department (1994-95) and attended the postgraduate course in “Space System Engineering” at Technical University of Delft. In 1996 he joined Astrium GmbH working for satellite navigation programs and since 1998 he is mostly involved in verification, validation, and certification activities related to GNSS including security aspects.

Jaron Samson obtained a M.Sc. in Geodesy from Delft University of Technology, Faculty of Geodesy in 1996. He worked as GPS product manager for Topcon Europe. Since 1998 he is with NLR's Avionics division, involved in projects related to satellite navigation with focus on receiver assessment, developing of evaluation software, flight trials related to GPS and EGNOS, and GNSS performance validation.

Peter Dieleman was born in The Netherlands in 1959. After obtaining a M.Sc. in Electrical Engineering at the Delft University of Technology in 1983 he worked for several universities, research institutions, and industries. His work focussed on control engineering, and automated systems development with a focus on system design and software engineering. In 1999 he joined the Space Division of the National Aerospace Laboratory NLR where he has been involved in the definition of a GNSS performance monitoring facility and since 2000 in the definition of GALILEO with focus on RAMS and system verification in co-operation with European space industry.

Massimo Ferraguto received the M.Sc. in Aerospace Engineering from the University of Pisa in 1998. He works for Space Systems Finland Ltd. since 1999. He has worked at the development of COALA, an instrument for in-orbit ozone measurement using the stellar occultation principle, the development of orbit propagation software and other space-related software.

Hans-Joachim von der Hardt graduated in Electrical Engineering at Karlsruhe University (1992) and obtained his PhD at the Institut National Polytechnique de Lorraine (1997). He worked for three years (1998-2000) with Honeywell Regelsysteme on integrated navigation systems. In

2000, he joined the navigation systems engineering department of Astrium GmbH. Since 2001, he is seconded to Galileo Industries, where he is managing the Galileo System Verification and DDV Plan related activities.

Franco Gottifredi received the M.Sc. in Aerospace Engineering in 1996. From 1996 to 2000 he worked on the design and development of GPS/GLONASS receiver for survey and space-born applications and in particular on the design and development of digital signal processing and of the navigation/RAIM algorithms. From 2000 he was responsible of the GSTB definition activities and from 2001 he is the responsible of the Galileo system verification activities in the Galileo project at Alenia Spazio.

6 References

Ref.	Title	Code	Version	Date
RD 1	GSRD	ESA-APPNS-REQ-00011	2 rev 1	01 Aug 2002
RD 2	SYSACC - System Acceptance Criteria	TNO-GAL-0095-GLI	4.0	25 Oct 2002
RD 3	SysVToolReq – System verification Tools Requirements	GAL-SSF-TN-001	3.2	07 Nov 2002
RD 4	SVP - System Verification Plan	PLN/GAL/0264/ALS	6	14 Feb 2003
RD 5	ECSS-Space Engineering; Verification	ECSS-E-10-02A		17 Nov 1998
RD 6	ECSS-Space Engineering; Software	ECSS-E-40A		13 Apr 1998
RD 7	Simulation and Experimentation in Galileo System Design and Verification;	E.J. Breeuwer et al., GNSS 2002, Kopenhagen		2002

7 Abbreviations

CDR	Critical Design Review
ECSS	European Cooperation for Space Standardization
ESA	European Space Agency
ESTEC	European Space Research & Technology Centre
ETF	Encryption Test Facility
FOC	Final Operational Capability
FVR	Final Verification Review
GOS	Galileo Operations Simulator
GSRD	Galileo System Requirements Document
GSS	Galileo Sensor Station
GSSF	Galileo System Simulation Facility
GSTB	Galileo System Test Bed
GSVF	Galileo Signal Verification Facility
GUTR	Galileo User Test Receivers
IGT	Interference Generator Tool
IOV	In-Orbit Validation
IOVR	In-Orbit Validation Review
S-CDR	System Critical Design Review
SAR	Search And Rescue
SAT	Spectrum Analyser Tool
SBSF	SAR Beacon and Support Facility
SLR	Satellite Laser Ranging
TFAMF	Time and Frequency Accuracy Measurement Facility
TSRF	Test Receiver and Support Facility
TT&C	Telemetry, Telecommand & Control
UC	Use Case
UERE	User Equivalent Range Error
ULS	Up-Link Station
VTR	Verification Tool Requirement
w.r.t.	with respect to

Appendix A

The following table is a matrix of methods to be used for the verification of compliance with requirements for the phases CDR, IOV, and FOC.

The following methods are taken into account:

- Test/Measurement (T)
- Analysis (A)
- Review of Design (R)
- Simulation (S)
- Inspection (I)

Main methods are identified using the symbol “M”, non-frequently used methods by the symbol “m”.

Table 6: Methods to be used for the verification of requirements (for the phases CDR, IOV, FOC)

Type of Requirement	Number of Requirements	CDR						IOV						FOC					
		T	A	R	S	I	Completion	T	A	R	S	I	Completion	T	A	R	S	I	Completion
Service	162		m	M	M	m	0% [2]	M	m		M		10%[1]	M	m		m		100%
Functional [3]	42		m	M	m		0%[1]	M	m		m		0%[1]	M	m		m		100%
Implementation[4]	95	m		M	m	m	8%[1]	M	M	m	M	m	21%[1]	M	m	m		m	100%
Operational	66		m	M	m		3%[1]	M	M	m	M	m	14%[1]	M	M	m	M	m	all except 1[5]
Security	18		m	M			6%[1]	M		m	m	M	0%[1]	M		m	m	M	100%
Safety	13			M			15%[1]	M	M	m	m		0%[1]	M	M	m	m		100%
Verification	15			M			0%[1]	m				M	7%[1]	M					100%
External interfaces	28		m	M		M	0%[1]	M	M			m	0%[1]	M	M			m	100%

[2] Main reason for incompleteness is the necessary fully deployed constellation for the verification of services
[3] Additionally, 1 requirement has to be verified on segment level here.
[4] Additionally, 60 requirements have to be verified on segment level, which is not covered here.
[5] All requirements except 1 are completely verified at FOC. The reason is that this requirement is verified after the full service duration.