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ESA ESTEC
Keplerlaan 1
2201 AZ Noordwijk
The Netherlands

SCIENTIFIC READINESS LEVELS (SRL) HANDBOOK

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1. PURPOSE OF THE DOCUMENT

This document serves as a "Scientific Readiness Levels (SRL) Handbook". Its purpose is to establish an objective measure for the maturity of science with respect to a mission/instrument concept, satellite mission, or satellite instrument activity (from this point on satellite missions and satellite instruments are referred to synonymously as "the mission"). This SRL Handbook provides definitions of the nine SRL levels and of guiding questions that should be addressed in a Scientific Readiness Assessment (SRA). In addition, guidance on appropriate evidence is provided for the individual SRLs. The SRLs are not linked to a specific scientific discipline or space mission programme, and SRLs cannot be used to compare the importance or relevance of one particular scientific discipline or its value to another.

The structure of this handbook and the description of the SRAs follow the "Technology Readiness Level Handbook" [RD-1]. This second issue of the SRL handbook takes feedback from users into account.

This handbook can be used as guideline for several purposes, e.g.:

- To carry out an SRL self-assessment as a science team (e.g. Scout team, proposer to an Earth Explorer call, at Project milestones during mission implementation of R&D or operational missions);
- To set criteria and required evidence and establish the Terms of Reference (TOR) for an SRA;
- To prepare the Science Plan for an ESA mission (by the ESA mission and campaign scientists in conjunction with a Mission Advisory Group);
- To provide informed feedback after the SRA.

It is noted that this handbook can only provide a general framework for advancing and assessing scientific maturation during a mission's lifetime. Procedures and documentation for individual missions can be vastly different and therefore, this handbook provides general descriptions rather than definitions whenever possible. Appendix A contains a basic set of descriptions underpinning the terminology used in this document.

Earth Observation (EO) missions commonly deal with remote (or indirect) measurements of the geophysical quantities of interest, and are often intrinsically linked to inverse problems. Consequently, a lot of the terminology adopted in this handbook originates from remote sensing concepts. Nevertheless, the framework is general enough to encompass other types of missions, for instance such relying on direct in situ measurement techniques.

2. REFERENCES

RD-1 TRL Handbook - Technology Readiness Levels Handbook for Space Applications, TEC-SHS, TEC-SHS/5551/MG/ap, Version 1, revision 6, September 2008

RD-2 ECSS-S-ST-00-01C, Glossary of Terms (2012/10/01), online glossary: https://ecss.nl/glossary/

RD-3 ECSS-M-ST-10C Rev.1, Project Planning and Implementation (2009/03/06), https://ecss.nl

3. ABBREVIATIONS

AO	Announcement of Opportunity
ATBD	Algorithm Theoretical Baseline Document
Cal/Val	Calibration and Validation
CEOS	Committee on Earth Observation Satellites
DPM	Detailed Processing Model
E2E	End-to-End
ECSS	European Cooperation for Space Standardization
EE	Earth Explorer
EO	Earth Observation
ESA	European Space Agency
ICD	Interface Control Document
L0/1/2	Level 0/1/2
MDD	Mission Definition Document
MRD	Mission Requirement Document
R&D	Research and Development
SRA	Scientific Readiness Assessment
SRD	System Requirement Document
SRL	Scientific Readiness Level
TDS	Test Data Set
TOR	Terms of Reference
TRL	Technology Readiness Level

4. DEFINITIONS

Calibration	The process of quantitatively defining the system responses to known, controlled signal inputs (CEOS).
Commissioning	Verification and validation activities conducted after the launch and before the entry into operational service either on the space segment elements only or on the overall system (including the ground segment elements) [RD-2]
E2E Simulator	An end-to-end simulator is a computational tool which simulates the mission from a representation of the true environmental state, with the geophysical quantities of interest, to the final retrieved parameters contained in the mission data products. It represents the Space Segment and the Ground Segments, including the payload (instruments or sensors) and the processing and/or retrieval algorithms, respectively. More details are provided in Annex A.
Goal / Aim (Science / Research)	A *broad* purpose that is part of a larger strategy or is related to a scientific challenge or (set of) question(s). A mission will make progress towards the goal(s).
Level 1 (Data Product)	Reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters (e.g., platform ephemeris) Typically Level-1 products have further levels (e.g. Level-1a, Level-1b, Level-1c …) depending on the level of processing. Level-1a data are typically equivalent to Level-0 data products in terms of content whereas Level-1b data have been calibrated and are the traditional interface to further processing to Level 2 geophysical products.
Level 2 (Data Product)	Geophysical variables (e.g., ocean wave height, soil moisture, ice concentration) derived from Level 1 data.
Level 3 (Data Product)	Variables mapped onto uniform spacetime grid scales, usually with some completeness and consistency (e.g., missing points interpolated, complete regions mosaicked together from multiple orbits, etc.).
Measurement	The process or set of operations to determine the value of a quantity (the measurand).
Measurement Data	Data produced *directly* by a measurement process. Measurement data are all scientific data generated by an instrument containing information on the geophysical variable(s) of interest or are needed for the interpretation of the geophysical variable(s).

Objective (Mission)	A *focused* purpose that must be achieved by a mission, and that can be part of a larger strategy to address the science or application goal(s) and objective(s). It generally spells out a specific and/or quantified contribution.
Objective (Science)	A *focused* (scientific) purpose that is part of a strategy to address the (science) goal(s).
Observable	The quantity targeted by the observing system, i.e. a geophysical parameter.
Observation	The process of quantification of an observable through measurements by an observing system.
Observation Data	Data produced by the observing system.
Parameter	A measurable or derived variable occurring in the physical or digital world (CEOS).
Processing Levels	The data Processing Levels correspond to successive steps in processing from raw instrument data (Level-0) to higher-level mission data products (Level-1, 2, 3, 4). Processing Levels specified herein follow the generic CEOS definition. Many observation and measurement requirements are associated with and specified for different Processing Levels.
Requirement	Specifies a critical condition, parameter, or capability that ***shall*** be fulfilled to achieve the mission aim and objectives. It ***shall*** be possible to verify and validate every requirement using a practical approach.
Requirement, Mission	A requirement related to the overall mission specification. This includes observation and measurement requirements.
Requirement, Observation	A requirement related to an observable, an observation, or observation data.
Requirement, Measurement	A requirement related to a measurand, a measurement or measurement data. A measurement requirement may be needed to fulfil an observation requirement.
Requirement, Science	A requirement related to a scientific question and/or a science objective, generally associated with the highest-level requirements of a mission.
Requirement, System	A requirement related to any hardware or software of the Observation or Processing System.
Validation	Validation is the process of demonstrating that a requirement has been achieved based on independent and traceable evidence.
Verification	Activity aiming to confirm that requirements and specifications are actually achieved/met. A verification process is designed to confirm that the output(s) of a process are correct and consistent with the process specifications.

5. INTRODUCTION

Earth Observation missions that address new science objectives inevitably face four major scientific challenges during preparation, implementation and operation phases:

1. Building a theoretical understanding of the relationship between the measured quantity and the geophysical parameter to be observed;
2. Collecting observational evidence that this relationship between measurement data and geophysical parameter exists;
3. Growing the readiness of a scientific user community to process and exploit the measurement / observation data obtained from the new observing system;
4. Demonstrating the impact of a new measurement / observation data type for science, applications, and society.

Critical in the process of advancing the scientific maturity of a mission during its lifetime is the consistency of objective assessment of the SRL status. Evidence-based, regular, and well-timed ‘Scientific Readiness Assessments’ (SRAs) are therefore important for the cost-effective, time-efficient, and traceable management of advanced scientific R&D projects. The ability to make informed and objective decisions concerning the selection of new mission concepts, implementation choices, and (preparatory) scientific studies is essential.

The SRLs support a traceable maturation of science and provide a foundation for minimising the scientific risks that may prevent achieving the science objectives pursued by the mission. SRLs enable consistency of this process throughout the various phases. A formal SRA also ensures a process by which to evaluate the maturity of a mission at specific milestones, and constitutes fair input to any selection process for missions in competition.

Phases of a Mission

A mission generally spans a life cycle which is divided into 7 standardised phases [RD-3], see Figure 1:

- Phase 0 – Mission analysis and needs identification
- Phase A – Feasibility
- Phase B – Preliminary Definition
- Phase C – Detailed Definition
- Phase D – Qualification and Production
- Phase E – Utilization (where E1 refers to the commissioning period)
- Phase F – Disposal

From a scientific perspective, phases 0, A, and B mainly revolve around identifying and defining science goal(s) and objective(s), mission objectives and related requirements, accounting for technical and programmatic constraints (feasibility). During phases C and D, space and ground segments that comply with the top-level objectives are developed and qualified, leading to launch, commissioning, exploitation and maintenance in phase E, and a safe disposal in phase

F. Formal technical reviews (see Figure 1) provide recognised milestones over this life cycle, in particular towards the end of each phase.

The standard project timeline in Figure 1 has been augmented with a scientific maturation timeline. Whilst SRL milestones are not formally included in the project life cycle, their assessment could be conventionally coupled to, or synchronised with, project reviews or other programmatic milestones.

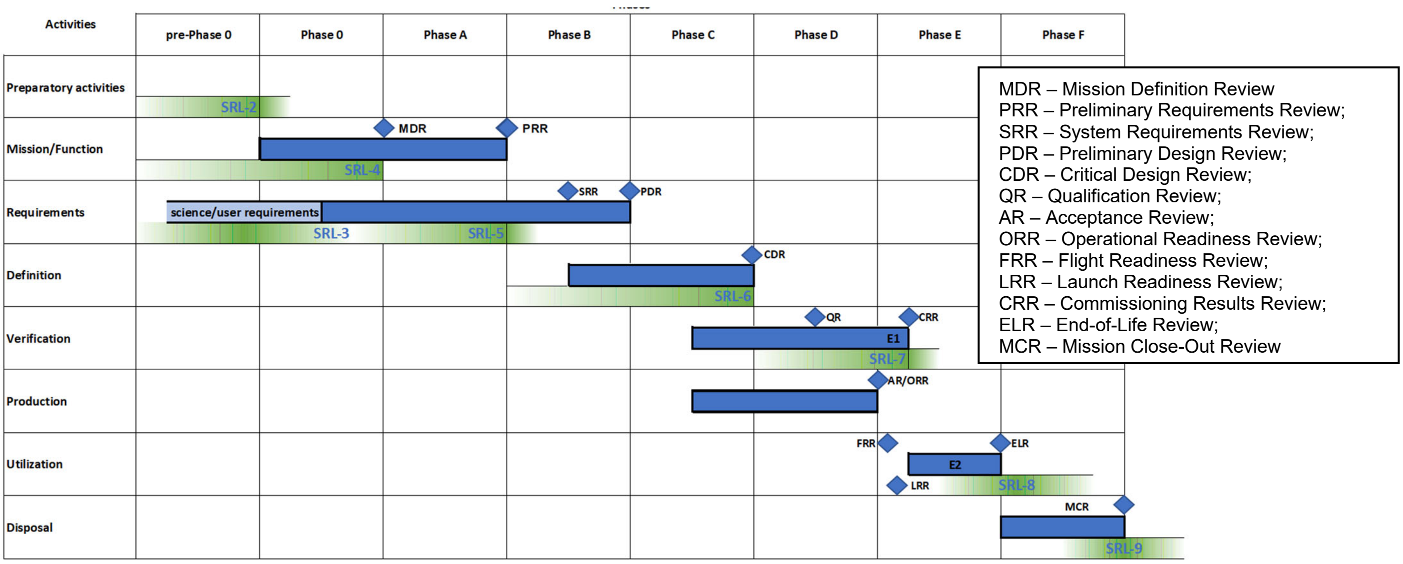

Figure 1: Typical project life cycle of a space mission with project reviews (*adapted* from [RD-3]).

A guiding schedule linking the SRLs and the implementation phases is provided in Figure 3. Formal SRAs could be linked to the major mission reviews, for instance at SRR (SRL 5), CDR (SRL 6), CCR (SRL 7), or SRL 8 and 9 for ELR and MCR, respectively.

Scientific Maturation Process

The scientific challenges and problems that need to be addressed for advancing the SRLs during the life cycle of a mission change throughout the different phases. During the early phases, the focus is on the theoretical understanding of the scientific problem and collection of observational evidence. Later, the focus shifts towards establishing and refining goals, objectives and requirements, and the traceability ("flow-down") between them, as well as assessing the performance of the proposed observing system, often in a "bottom-up" performance assessment. From this foundation, the operational processors for the geophysical quantities, including realistic uncertainty estimates, are developed. Once measurement and observation data sets become available, the quality of the data products needs to be assessed, and the data need to be exploited addressing original and new science objectives. However, independently of the actual scientific tasks that need to be addressed, the SRL step-increase follows a general process (Figure 2).

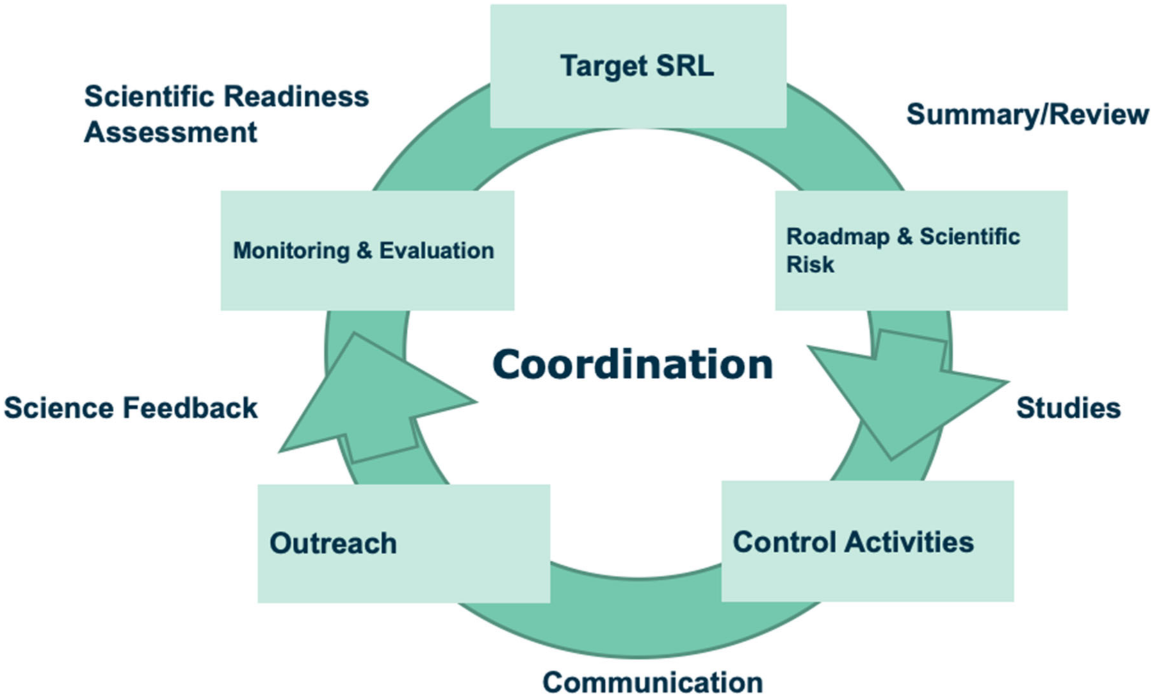

Figure 2: Scientific maturation process, typically associated with a step-wise increase in SRL.

Each SRL development cycle comprises the following steps (Figure 2):

- A roadmap detailing the mission-specific scientific challenges and the associated scientific risks is prepared.
- Studies including campaigns are defined and implemented to address the open scientific tasks, reducing and/or eliminating the identified risks.
- Progress and scientific results are documented and communicated in reports, scientific publications, and conference presentations.
- Scientists are encouraged to actively seek feedback from the wider community, e.g. through the peer-review process, and/or by holding regular, mission-specific workshops obtaining independent advice and evaluation.
- The resulting feedback from independent expertise as well as the monitoring activities themselves, e.g. study outcomes, should be collected as input to a subsequent SRA.

6. SCIENTIFIC READINESS LEVEL DEFINITIONS

SRLs are a set of metrics that enable the classification of the maturity of a mission or mission concept and a consistent comparison of maturity between different types of scientific disciplines — all in the context of an EO mission. There are 9 steps in the SRLs and Figure 3 provides a high-level illustration of the SRL scale in the context of the progression from basic research to matured science in (operational) applications, in relation to the phases of an EO mission.

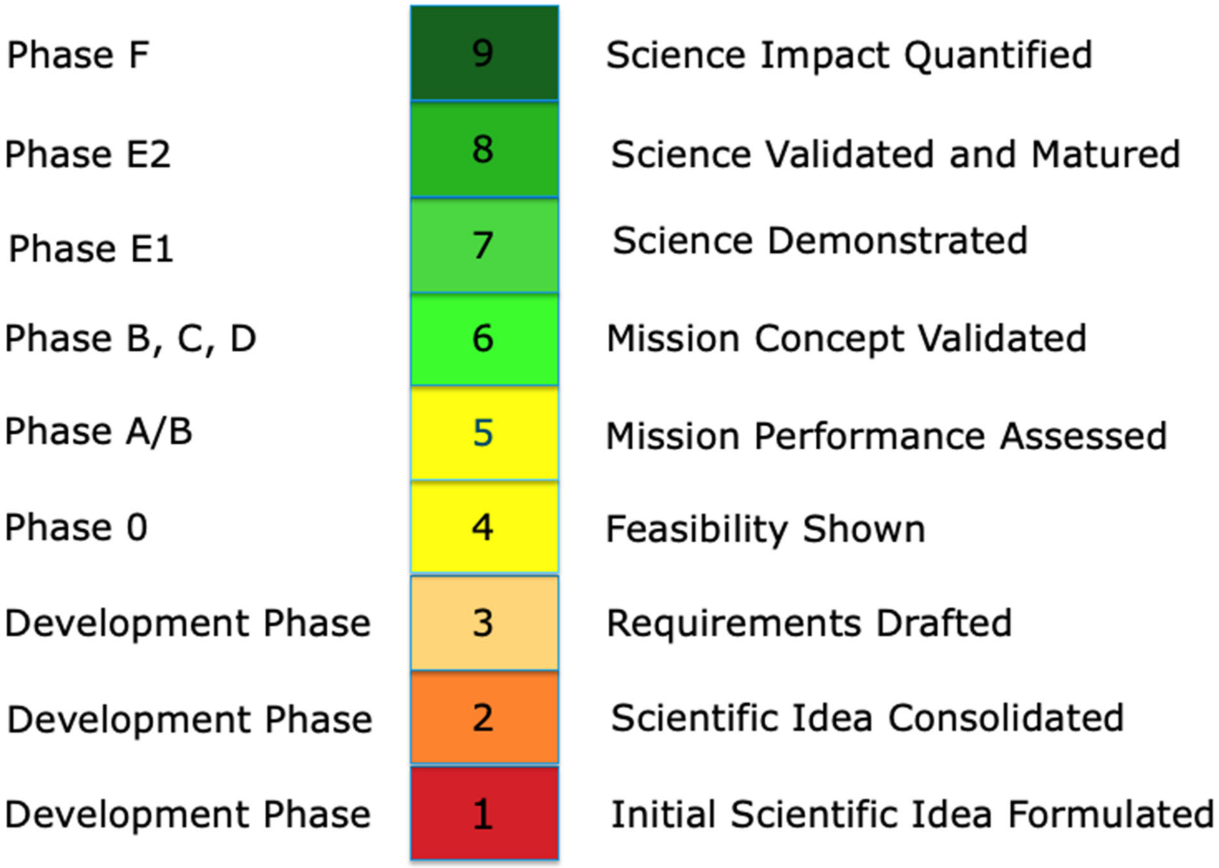

Figure 3: High-level illustration of the SRL scale in the context of the progression from basic research to matured science and/or (operational) applications, in relation to the phases of an EO mission

The definitions of the SRLs and guidance for an SRA are presented in the next section. Each paragraph provides:

1. a general definition or description of the respective SRL;
2. high-level guiding questions for the definition of qualification criteria for an SRA;
3. notional and/or specific examples of the type(s) of accomplishments (evidence) that would satisfy an SRA.

It shall be noted that:

- a single mission may have more than one science objective and it may be necessary to establish more than one line of SRL, especially if multiple instruments are being implemented;
- the SRA is mission-specific in the sense that the high-level guiding questions shall be complemented by more detailed questions addressing the specific scientific risks;
- if a guiding question is not considered relevant for a mission, then this shall be indicated and justified;
- it is the responsibility of the *SRA Chair* (see Figure 4 and Chapter 6) to ensure that scientific risks identified in a previous SRA are properly addressed.

SRL 1: Initial Scientific Idea Formulated

An idea combined with a general *science objective* is stated and / or a *scientific hypothesis* is presented. In parallel, an interest from users has been expressed and high-level user requirements are created. A scientific community can be a user, as well as an operational agency or society in general. The scientific idea can still be decoupled from specific mission objectives or a specific measurement concept.

Assessment

Guiding high-level questions to establish qualification criteria:

- Is the idea stated?
- Has a sound scientific hypothesis been formulated?
- Is there an interest from a user community?
- Have science / user requirements been formulated?

Evidence required:

- Scientific idea and / or hypothesis established, documented and discussed.
- Expression of interest from user community documented (e.g. Letters of Support, User Surveys, White Papers, etc.).
- High-level science / user requirements drafted, documented and discussed, e.g. in a technical report or a first version of the Mission Description Document (MDD).
- Roadmap for scientific advancement to the next SRL.

Targeted for any point in time but before Phase 0.

SRL 2: Scientific Idea Consolidated

Scientific evidence and supporting scientific theories are established answering to one or more scientific ideas. This could for example be shown on theoretical grounds or through laboratory experiments. Observations and theories are linked to the consolidated science / user requirements and / or the problem statement. The strategy to address the scientific challenge and the open questions is defined.

Assessment

Guiding high-level questions to establish qualification criteria:

- Is a set of high-level mission science / user requirements established and are missing requirements identified?
- Are science goal(s) and objective(s) formulated?
- Is the scientific theory behind the idea drafted?
- Has an appropriate descriptive and / or theoretical model been established?
- Has the phenomenon been observed and / or are supporting field/laboratory data available?
- Are the observation data and / or measurement data and their characteristics (e.g. type, their accuracy, spatial or temporal resolution, coverage) discussed?

Evidence required:

- Scientific Literature review
- Critical assessment of requirements documented and discussed, e.g. in a revised version of the MDD.
- Statement(s) from user community.
- Clear roadmap of activities to be pursued
- SRL-2 technical report addressing key questions

Targeted for any point in time but before Phase 0.

SRL 3: Science, Observation, and Measurement Requirements Drafted

A first iteration of observation and measurement requirements, e.g. product accuracy and precision and temporal and spatial sampling, is performed and mapped against the science / user requirements. Traceability between requirements is established and the corresponding evidence can be provided. During this process a justified selection of the conceptual measurement technique(s) is developed, based upon observational requirements.

Assessment

Guiding high-level questions to establish qualification criteria:

- Are the science / user requirements complete?
- Can the science / user requirements be verified and justified?
- Are the science / user requirements adequately traced to the science goal(s)?
- Are observational requirements derived from science / user requirements?
- Are the Mission Objectives drafted?
- Has a viable observation / measurement concept been identified?
- Have alternative solutions been analysed?
- Has a quantitative theoretical understanding between measurement data and observation data been established?

Evidence required:

- Supporting statement from user community;
- Clear roadmap of activities to be pursued;
- Peer reviewed scientific literature;
- Observational gap analysis;
- SRL-3 technical report addressing key questions or consolidated version of the MDD.

Targeted for any point in time prior to initiating Phase 0.

SRL 4: Mission Concept Feasibility Shown

The measurement concept is established e.g. through a model linking geophysical parameters and measurements. Sensitivity of the measurement data to the targeted geophysical parameter(s) is demonstrated through extensive analyses by means of dedicated experiments, through numerical simulations, or both. The underlying geophysical processes affecting the geophysical parameters and the corresponding co-variances are discussed.

Assessment

Guiding high-level questions to establish qualification criteria:

- Are the science goal(s) translated into mission objectives, mission requirements and system requirements in a fully traceable way?
- Is a model (software package) available that allows the computation of measurement data based on geophysical input data?
- Is the model technically and scientifically adequate and has it been independently reviewed?
- Has the sensitivity of the measurement data to the targeted geophysical parameter been demonstrated based on representative measurement data (e.g. campaign data) or in any other way?
- Has an information content analysis been performed and have the geophysical parameters contributing to the measurement data been identified?
- Has a scientific risk analysis been performed?
- Has a demonstration data set of measurement data been produced?
- Has the mission concept been discussed with respect to complementary and / or alternative missions?

Evidence required:

- Draft MRD.
- Software code for the model and documentation.
- Peer reviewed scientific literature.
- SRL-4 technical report addressing key questions.
- Clear roadmap of activities to be pursued.
- Scientific risk register.

Targeted by the end of Phase 0.

SRL 5: Mission Performance Assessed

The key modules of an end-to-end performance simulator are available. This comprises as a minimum a scene generator providing the stimuli entering an instrument module, and a processing chain generating measurement data and observation data. All modules represent critical elements in the development of the mission which also pose a scientific risk.

The E2E simulator retrieval capability is developed, tested and validated using realistic simulations and / or proxy data from actual measurement data. These measurement data could for example be provided through targeted campaigns or existing observing systems approximating the mission. The performance evaluation is applied to a predefined range of conditions (including representative variabilities of natural and observational origins) and can be used to address the needs originating from the science/user requirements in an end-to-end manner. Performance simulations applicable for a realistic range of uncertainties (both geophysical and technical) are traced through the system and are compared against a pre-defined performance metric (or set of metrics) reflecting observation and measurement requirements.

The objective is to quantify performance and to verify the mission concept rather than delivering a software tool. Ideally, modules are chained resulting in a first version of the end-to-end performance simulator.

Assessment

Guiding high-level questions to establish qualification criteria:

- Is a performance simulator in place and are the most important and significant processes and input parameters (including sources of uncertainty) properly represented?
- Is an error propagation model in place allowing the rigorous computation of uncertainties (e.g. accounting for co-variant error effects) for measurement and observation data?
- Has a set of realistic and representative test scenarios and input scenes been established and are they scientifically justified?
- Is the simulator tested, verified / validated and applied for the predefined set of scenarios?
- Are all assumptions of the performance simulator documented and critically discussed?
- Has the robustness of the simulator been demonstrated against independent observations (e.g. campaign data)?
- Is a draft mission calibration and product validation strategy available and properly described?
- Is there a demonstrated interest of users?
- Is there a first evaluation of (simulated or measured data) in applications?

Evidence required:

- Clear roadmap of activities to be pursued.
- Consolidated draft version of the MRD (for acceptance and signature at the end of Phase B1).

- Draft ATBDs describing the generation of measurement data and observation data and their uncertainties.
- E2E simulator software modules and documentation as first version.
- Peer reviewed scientific literature.
- SRL-5 technical report addressing key questions.

Targeted for mission selection at end of Phase A(/B1).

SRL 6: Mission Concept Validated

To validate the mission concept, a full E2E simulator is used to assess the performance regarding the requirements specified in the MRD. In the ideal case, the status of the development of all E2E simulator modules should be reported at the Critical Design Reviews of the instrument and the system. The algorithms for data product Levels 1 and 2, together with their uncertainties, are in place and the corresponding documentation is available.

In addition, the scientific data products need to be specified and communicated. Based on the E2E simulation a first assessment of key characteristics, e.g. data volume, product generation time, is provided and discussed together with algorithm implementation options and trade-offs with respect to the expected and required uncertainties.

In parallel, the validation activities need to be addressed. This includes the development of measurement devices providing independent data sets, and the preparation of infrastructure as well as measurement protocols.

Assessment

Guiding high-level questions to establish qualification criteria:

- Has the performance been assessed with respect to the mission requirements using the E2E simulator?
- Is the E2E simulator representing the latest system and instrument developments?
- Is the E2E simulator sufficiently documented allowing a scientific assessment of the critical components?
- Have comprehensive test data sets been made available for the scientific user community?
- Have the results from the E2E simulator been used to address higher level product performance or mission impact (traceability to science objectives)?
- Is the documentation describing the L1 and L2 processors available and does it allow to start developing operational processors for the ground segment?
- Are the mission's data products specified and documented?
- Are measurement devices providing data for an independent product validation available?
- Are calibration and validation plans established for measurement data and observation data products at Level 1 and Level 2, respectively?
- Have scientific studies been performed using simulated data or measurement data collected through e.g. airborne campaigns?

Evidence required:

- Validation of prototype processor and algorithms.
- Documented Algorithm Theoretical Baseline Documents (ATBDs), Interface Control Documents (ICDs), Detailed Processing Models (DPMs) etc.
- E2E simulator and documentation.
- Performance assessment report.
- Measurement devices providing independent data.
- Test Data Sets from campaigns and / or E2E simulations.
- Draft instrument calibration strategy.

- Draft data product validation strategy including draft measurement protocols.
- Peer-reviewed literature.
- SRL-6 technical report addressing key questions.
- Clear roadmap of activities to be pursued.

Targeted for Mission CDR (end of Phase C or early Phase D).

SRL 7: Science Demonstrated

Retrieval algorithms are applied and assessed using real mission data. Uncertainties are provided and the satellite data products are validated using independent measurement data obtained for limited temporal and spatial domains. The estimated performance is mapped against the measurement and observation requirements of the mission. Based on this assessment, a strategy for the evolution of the processing algorithms is established and the infrastructure for a long-term validation is put in place. This SRL step increase goes hand in hand with the IOQAR and CRR.

Assessment

Guiding high-level questions to establish qualification criteria:

- Are retrieval algorithms implemented and tested using real satellite measurement data?
- Are the resulting retrieval products validated against independent measurement data?
- Has a first mission performance analysis been undertaken and are the results matched against specifications?
- Are first uncertainty estimates for the measurement / observation data available?
- Has user feedback been collected and analysed?

Evidence required:

- Clear roadmap of activities to be pursued
- Cal/Val reports for Level 1 and Level 2 (first version summarising the Commissioning Phase)
- Results published in peer reviewed literature
- SRL-7 technical report addressing key questions

Targeted for end of Commissioning Phase E1 as part of the CRR.

SRL 8: Science Validated and Matured

Data products have been systematically generated and disseminated. The mission's science goal(s) and objective(s) are tested and evaluated. Science linked to the mission is advancing, leading to a growing scientific community, new applications, and new scientific insights.

Assessment

Guiding high-level questions to establish qualification criteria:

- Is a systematic quality control and performance analysis for measurement data and observation data in place?
- Is there evidence that the scientific community uses the mission's geophysical products?
- Are the primary science objective(s) and mission objectives fulfilled?
- Has a consistent reprocessing been performed to generate one or more stable data sets (Level 1 or Level 2 or both)?
- Is the mission performance evaluated against the mission objectives?
- Is there an outreach effort towards growing the user community and producing new scientific insights?
- Do ideas for new application areas exist?

Evidence required:

- Clear roadmap of activities to be pursued
- Stable and consistent data sets
- Peer-reviewed publications.
- Summary and recommendations from dedicated workshops.
- Documented scientific benefits and impact or from key applications.
- SRL-8 technical report addressing key questions

Targeted for Phase E2.

SRL 9: Science Impact Quantified

The measurement data and observation data have been re-processed ensuring validated high-quality data sets with fully described uncertainties. The science goal(s) and objective(s) of the mission are evaluated, and a summary of the mission's achievements is available. The end-to-end scientific impact across the mission with respect to the science / user requirements is assessed and quantified, e.g. through a mission extension review.
The requirements are revisited with the corresponding user community and a set of new requirements for an extended period of mission operations or future mission concept is established.

Assessment

Guiding high-level questions to establish qualification criteria:

- To what degree is the science community exploiting the products?
- Have the initial intended science goal(s) and objective(s) been met?
- Have clearly identified research questions based on the geophysical products been answered (for science missions) / operational targets been met (for operational missions).
- Has the impact on science and/or in user applications been quantified?
- Have the reprocessed dataset been curated in relevant reputable data centre and distributed widely to the relevant international user community?
- Has an evolving set of requirements been established and / or a lessons learnt exercise been performed?

Evidence required:

- Peer reviewed scientific literature.
- Summary and recommendations from dedicated workshops.
- Requirement analysis and evolution.
- SRL-9 technical report addressing key questions.

Anytime during or after Phases E2 or F.

Table 1: Overview of the Scientific Readiness Levels (SRLs) in a matrix structure

SRL	Name	Associated documents	Theory	Experiments	Users & Requirement	Targeted Time
1	**Scientific Idea Formulated**	Scientific Report	- A scientific challenge is identified. - The scientific objective is formulated. - A scientific hypothesis is established.	No observational evidence is required.	- The application area is defined. - Interest of the users is identified. - High-level scientific requirements are identified.	any
2	**Scientific Idea Consolidated**	Scientific Report, Peer-reviewed Publication	- A scientific theory is formulated. - The physical principle behind the hypothesis is outlined (at least qualitatively).	- Experimental / Observational evidence supporting the scientific hypothesis exists.	- Scientific objective is formulated. - Consolidated scientific requirements are established.	any
3	**Scientific, Observation & Measurement Requirements Drafted**	Mission Description Document (MDD)	- Theoretical understanding of link between measurement and observation (no software required) is established and described.	- Initial capability assessment performed. - Conceptual measurement technique is identified.	- Mission Objective(s) are drafted.	any
4	**Mission Concept Feasibility Shown**	Draft MRD / Report for Assessment	- Measurements are simulated based on geophysical parameters (e.g. numerical forward model).	- First measurement device approximating the instrument is available. - Sensitivity of measurements wrt observation is demonstrated.	- Mission objective(s) confirmed and translated into mission requirements and system requirements	Phase 0
5	**Mission Performance Assessed**	MRD, Report for Mission Selection	- Retrieval Algorithms are available and documented. - Mission performance is assessed - Computational Models describing the mission elements are available.	- Demonstrator (e.g. airborne instruments) provides/simulates representative measurements with uncertainty budgets, - Draft calibration and validation strategy available.	- First evaluation of observations and / or measurements in applications, - Higher-level products approached.	Phase A/B1
6	**Mission Concept Validated**	Final ATBD's, DPMs, Cal/Val Plan	- Operational processor developed and ready for implementation (Level t0 Level 2) - Performance assessed using the E2E simulator.	- Test data and sampled data processing - Validation data sets collected - Validation instrumentation tested - Cal / Val Strategy under consolidation	- User studies with simulated or pre-cursor data;	Phase B2/C/D
7	**Science Demonstrated**	Commissioning report	- First uncertainty analysis - Performance assessed - Algorithms improved	- Cal/Val conducted (L1 and L2) - Early release of first data / demonstrational data are provided - Characterisations of measurements and observations; - Performance vs. specification	- User feedback collected, - Feedback from beta-users received.	Phase E1
8	**Science Validated and Matured**	Science feedback, peer reviewed publications	- Full uncertainty analysis - Enhancing scientific understanding	- Systematic validation and quality assurance performed - Operational / nominal processing of measurements and observations	- Science impact quantification, - first performance assessment wrt mission objective - scientific goal evaluated	Phase E2
9	**Science Impact Quantified**	TBD	- advancing scientific understanding and addressing its impact for scientific and societal applications	- Generation of long-term data sets - Data fusion	- User impact quantification, - Final performance assessment wrt mission objective - Final performance assessment wrt science objective	Phase F

7. SCIENTIFIC READINESS ASSESSMENT (SRA) IMPLEMENTATION GUIDELINES

Science maturation should be complemented by independent reviews validating the results presented for a scientific readiness assessment. This chapter outlines the ideal set up for such an independent review and examples for practical implementations.

The Scientific Readiness Assessment

The most general set up for an SRA comprises three entities: An Applicant, an independent Board, and an independent Assessment Panel (Figure 4). The assessment shall follow good scientific practice in that the evidence shall be traceable, available to the public, and results shall be reproducible.

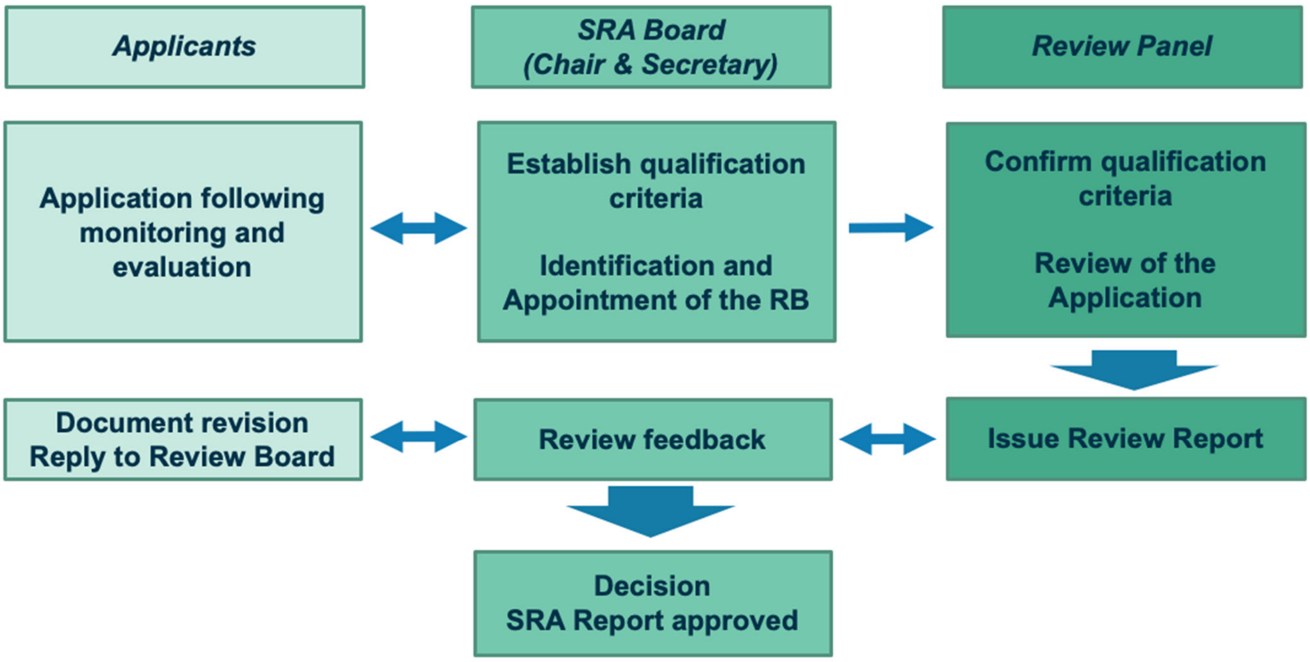

Figure 4: Schematic overview of the SRA process.

As an example, this approach has been largely followed for the SRL assessment of ESA Earth Explorer proposals entering Phase 0, where the proposing team is the *Applicant.* Here, the SRA Board comprises ESA Mission Science Division secretaries and external Advisory Committee members as Chair(s). The Review Panel consists of independent scientists appointed to represent the interests of their respective communities. The demonstrated scientific competence of the review panels allows for a thorough scientific review of the inputs for the SRA.

The assessment produces Scientific Evaluation Reports, which are then used by ACEO in the candidate mission selection. The same approach is applied for the down-selection of Earth Explorer Candidate Missions where the Review Board and Panel are external to ESA and the missions are still in the early stages of their life cycle.

Self-Assessments

A self-assessment is the lightest version of an SRA, where the reviewers are not independent and the *Applicant* and the *Review Panel* are identical. However, to ensure a certain degree of formalism and transparency, it is suggested to have an independent SRA chair representing the *Board* who confirms the extended set of questions, counter-checks the evidence and approves the SRA.

A self-assessment is requested as part of an Earth Explorer proposal. The proposing team evaluates the scientific readiness based on the evidence collected and the SRL handbook. A scientist, who is active in the field and not listed as an author, could act as chair and be named in the proposal.

SRA Implementation for ESA missions under development / after launch

It can be convenient to link the SRA to an internal review during the mission's implementation phase, e.g. by making the assessment for SRL 6 part of the Mission Critical Design Review (M-CDR).
In this case, dedicated procedures need to be established, approved and authorised depending on the mission implementation phase.

8. APPENDIX A: TERM DESCRIPTIONS

In this Appendix, the reader can find a description of the most relevant terms for the SRL and SRA. These descriptions are not general definitions but provide further context to this document.

Mission/System Requirements Document (MRD/SRD) and traceability

- ESA Earth Observation mission requirements are maintained in a Mission Requirements Document (MRD), the customary structure of which is outlined in an internal procedure.
- Mission requirements are generated from mission objectives, whilst accounting for programmatic (and technical) constraints and assumptions. Mission requirements generally include a set of geophysical and observation requirements (at data product Level 2), including their quantitative description and justification, and associated measurement requirements (at data product Level 1), directly traceable to the geophysical needs.
- For Earth Observation missions developed by ESA, the conventional split of requirements between MRD and SRD is at the level of calibrated measurements (e.g., Level 1b data products).
- Traceability between requirements ensures each requirement is necessary to meet stakeholder expectations. A requirement traceability matrix can help to verify that all stated and derived requirements are allocated to system components (forward trace), as well as to determine the source of requirements (backward trace). At highest level, a Science Traceability Matrix (STM) can provide traceability between science goals/objectives, mission objectives, and mission requirements.

End-to-End simulator (E2E) and Performance Assessment

- Performance simulations generally aim at quantifying the performance of a system regarding its scientific and / or technical requirements, and supporting associated trade-off exercises.
- An ESA EO E2E simulator typically comprises a Scene Generator Module and a Satellite Geometry Module providing the input parameters for the Instrument Module generating measurement data at Level 0. These feed into a Level 1 Processing Module and a Level 2 Retrieval Model generating the Level 1 and 2 data products for the performance analysis, carried out in a Performance Evaluation Module.
- In early mission phases, the E2E simulator supports the definition and the verification of the Space Segment requirements, in particular 1) to predict system performance (based on Figures of Merit (FOM) - or metrics); and 2) to help implementing and improving the retrieval algorithms or processors (including L1 and L2 processors).
- Simulators (and particular s/w modules) evolve during Phases B/C/D towards supporting the development and validation of the on-ground data processing, and in particular, they can be used as 1) flexible tools for generating raw and test data sets to be used with (L1) Prototype and Operational Processors, 2) as prototypes for the actual ground processing, and 3) to support the assessment of the mission objectives.

- An E2E simulator should represent the most important processes and input parameters, be applied over well-defined, realistic, representative, and scientifically justified test scenarios, and be validated and demonstrated against independent observations. All assumptions and the output should be documented and critically discussed.
- For the purpose of science readiness, performance may further need to be assessed on the geophysical parameters targeted by the mission, as well as on higher-level mission objectives, science goals/objectives and/or user requirements, depending on how these are formulated.

Algorithm Theoretical Baseline Documents

- In the context of processor development, an Algorithm Theoretical Baseline Document (ATBD) describes the algorithms to be (or as) implemented.
- An ATBD describes for each function, systematically, the input, the output, and the mathematical algorithm to be used.
- For the scientific evaluation, the ATBD shall include a description of the scientific background with a full mathematical description and an evaluation of the sources of uncertainty. In the ideal case, traceability to the peer-reviewed literature or similar documentation is given.
- The ATBD is complemented by further documentation, e.g. the Interface Control Documents, the Algorithm Design Document, or the Detailed Process Model, which are generally not of scientific nature.

Scientific Risk

- In the context of this handbook, only individual risk items affecting the *scientific* maturity are to be identified and assessed. Ultimately, unresolved *scientific* risk items affect the overall scientific maturity, and provide an overarching scientific risk not to achieve the science objectives of the mission, which is captured by the SRL status.
- These individual risk items are typically of scientific nature and, for instance, could be linked to insufficient scientific knowledge or evidence; deficiencies in the scientific method or approach; lacking, untraceable or challenging mission requirements; unestablished measurement techniques; immature models or algorithms; challenging perturbances; insufficient means for verification and validation, lack of community interest, etc.

Campaigns

- In the context of SRLs and scientific advancements, campaigns comprise all activities in which data (measurement data and / or observation data) are collected and processed. Throughout the mission definition and development phases, these data can be used in multiple ways, e.g. to specify requirements, derive and validate algorithms, support and test an E2E simulator, etc.

Information Content Analysis

- In this handbook, information content analysis refers to the sensitivity of the measurement data with respect to geophysical parameters, e.g. radiance measurements at the top of the atmosphere can be influenced by aerosols, trace gases, water vapor, a reflecting surface, etc. The relative contributions shall be quantified.
- The objective of an information content analysis is to assess whether the targeted observable can be retrieved with the required uncertainty, and what requirements are necessary for the auxiliary and / or additional data products entering the retrieval.

Impact analysis

- In this handbook, the term refers to the impact of the measurement data / observation data on a certain application related to the mission objectives or the science goal(s) and objective(s).
- The impact analysis can be qualitative or quantitative depending on the nature of the mission and its implementation status.
- In the early Phases and low SRLs the guiding question could be: ‘What could we do and achieve if we had the measurements …?’ This question can be answered through a discussion, an Observation Simulation Experiment or Observing System Simulator Experiment, a dedicated campaign activity, etc.
- In the late Phases when real satellite data are available, the guiding question could be: ‘How large is the impact of this observation (compared to others) and what are we going to lose once this type of observation is no longer available?’ This question can be answered through, e.g. a data denial experiment.