TRL GUIDELINES - PROPOSED ANNEX FOR DETECTORS

Background:

This document has been prepared to clarify the assessment of Technology Readiness Level for detectors. The effort has been initiated by ESA, and developed within the Detector Working Group (DWG), which has representatives from all relevant stakeholders (from ESA member states) pertaining to the development and use of detectors in space applications, namely; agencies, primes, system integrators, manufacturers, and test houses.

Once endorsed by the DWG, it is intended to submit the content below to be added as an Annex in the existing handbook ESCC-E-HB-11A 'Technology readiness level (TRL) guidelines', as a change request which will be subject to usual ECSS review process. Existing annexes in the handbook cover software (Annex A), EEE components (Annex B), and materials and manufacturing processes (Annex C). [*Update: this Change Request has been submitted 17/07/2024, based on the Issue 2.0*]

Reaching a consensus on a TRL definition for detectors has been challenging, even within a group dedicated to detector technologies and applications. This has further highlighted the need for a harmonized understanding of TRL applied to detectors, and the below work is considered a valuable achievement of the DWG.

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CHANGE LOG

Reason for change	Issue	Revision	Date
Version 1 Prepared by ESA, and distributed to the DWG for first review	(draft)	1	November 2021
Version 2 Feedback collected from Detector Working Group in the period up to Feb 2022, and discussed via teleconference on 09/02/2022 (MoMs reference ESA-TECEDC-MIN-2022-000500) Main changes in the content: • Introduction re-written • For TRL4 and TRL5 there is a separate consideration of 'active element' and 'detector assembly'	(draft)	2	June 2022
Issue 1 Feedback collected from Detector Working Group on Version 2 showed convergence on technical topics, however it was highlighted that the document is missing the connection between the TRL progression in the frame of a project schedule. Main changes in content: • Included a specific section to address relation of detector development with project timelines • Minor updates to table.	1	0	October 2023
Issue 2 Further minor refinements in the TRL table (for TRL4, 5 and 6) based on Detector Working Group review of issue 1. Additional paragraph in Section 3 to further elaborate the typical relation between TRL of a detector within a project schedule (i.e. not just TRL6, but also noting timelines for TRL4 and 5).	2	0	July 2024

Annex D
TRL considerations for Detectors

1. Introduction

The definition of a detector (or synonymously a 'detector assembly') which is the subject of this Annex is a device converting incident electromagnetic radiation, ranging from thermal infrared through to X-ray wavelengths, into a measurable electrical signal. A detector includes a packaging to provide a mechanical, electrical, optical and thermal interface for next-level assembly.

Detectors for space applications are often non-recurrent products developed for specific applications, in many projects forming the very core of an instrument and having correspondingly challenging performance and reliability requirements. They vary significantly in materials and complexity; for example a CCD sensitive in the visible wavelengths, or a mercury-cadmium-telluride photodiode array hybridized to a silicon read-out-integrated circuit for sensitivity in the infrared wavelengths. Packaging may be hermetic or non-hermetic, and operating temperatures can vary from cryogenic (e.g. for a long-wave infrared detector) up to room temperature.

Detectors are an atypical technology in the sense that they are not categorised as a unit/equipment, and neither are they considered as a EEE component. This has some significant implications in terms of development programs for space missions, such as;

- The usual EEE approach regarding evaluation/qualification is not feasible due to the generally low numbers of devices manufactured and high recurring cost. There may be complex assemblies and atypical packaging solutions having various add-ons, and production of a 'set' of devices can sometimes span across many months or even years. The concept of a 'lot' or 'batch' is often not applicable.
- The usual approach for unit/equipment development is also not suitable. For unit/equipment, the progression through TRL is based on low quantities but they are constructed from well understood building-blocks which are themselves evaluated and qualified. This is not the case for detectors, where the 'active element' is the fundamental building-block of the detector being concurrently developed.

Furthermore, for custom detectors which are intended for a specific space application, there is a close connection between the development of the detector and the mission development phases. This imposes some programmatic challenges in both directions; for instance some outcomes from the detector development, largely performance related measurements, determine the instrument design. These aspects may not always be predictable at the outset and rely on measurements of at least the 'active element' part of the detector, sometimes with new test benches also specifically developed for the application. On the other hand, the instrument design needs to be sufficiently progressed before the interfaces to the detector are well defined and until then the 'packaging' part of the detector cannot be developed. This often results in a conflict where there is insufficient time between having a fully consolidated detector requirement specification (i.e. including packaging) and an instrument PDR to progress the detector through the intermediate TRL4 to TRL6 stages.

Finally, the link between a detector and application implies that many of the environmental requirements for the detectors are known early in the TRL progression, for instance at TRL5 and TRL6 some mission specific levels can be applied. This is one reason that detector developments tend to follow a validation process (where assembly and performance aspects are 'validated' against an expected mission requirement with sufficient margin) rather than a more conventional evaluation process (where the technology is characterized with respect to its limits of use and behaviour, in EEE domain typically involving step-stress approach to test to destruction in order to define limits, de-rating, screening etc.).

Therefore, this Annex intends to provide a guide for a detector's TRL assessment with these technological and programmatic peculiarities taken into consideration[1]. Most notably, at TRL4 and TRL5 there is a separate consideration of the 'active element' part of the detector. This intends to alleviate the package definition conundrum described above. In a development program, this would allow the 'active element' to advance as far as TRL5 and secure the critical performances for the proposed application, while the package development remains at a lower maturity as long as the instrument and interface definitions are not fixed.

In case there is heritage of some element or process in the detector assembly, then, as for any technology, this can be used in place of testing as the basis of a TRL assessment, provided the relevance and applicability can be justified accordingly.

Section 2 below gives the performance achievement and reliability considerations for detectors at each TRL. This represents the maturity of the technology itself at a given point in time. The programmatic perspective is emphasized in Section 3, discussing how the development itself progresses with respect to a project timeline.

[1] Note that there are many detectors for which a EEE approach for TRL assessment (i.e. Annex B of ECSS-E-HB-11A) would be more relevant and existing ESCC standards can be applied. For example such devices include quad photodiodes or other single/low pixel-count sensors. Some relevant ESCC standards include: ESCC 2269000 Evaluation test programme for integrated circuits, ESCC 2265000 Evaluation test programme for discrete non-microwave semiconductors, and ESCC 5000 Generic Specification for discrete semiconductor components, hermetically sealed and die. Furthermore for CCD and CMOS image sensors there is the ESCC 9020 Generic Specification for photosensitive CCDs and CMOS Imaging Sensors with hermetic and non – hermetic packages, which is relevant for the higher TRL levels addressing qualification.

2. TRL Table for Detector Assemblies

Table X-1: Performance and reliability considerations for detectors

TRL 1	Performance achievement: Concept for a detector is formulated, basic principle of operation is observed.
TRL 2	Performance achievement: Basic test structures exist and were used to support the detector concept. Potential applications are known. Possible constituent materials, design rules and tools, processes, and manufacturing tools exist. Reliability considerations: Qualitative reliability aspects have been considered based on proposed materials and processes.
TRL 3	Performance achievements: Design library and special functions for the intended application and environment exist for the active element of the detector. Representative test structures are produced and used to demonstrate functionality. This proof-of-concept model can be applied to benchmark the technology potential and feed into application requirement definition for further development. Reliability considerations: Potential failure modes derived from the semiconductor technology and its processing are known, including radiation resistance. Hardware example: A reduced pixel-array size, or building-block elements (pixel, ADC, variants thereof) compared to final target device, but allowing for critical or novel performance aspects to be measured and validate the design, such as spectral response, quantum efficiency, read-out speed, dark signal, cross-talk, etc. Packaging concept sufficient to allow necessary performance demonstration (e.g. probe-testing, chip-on-carrier).

<table>
<tr><td rowspan="2">TRL 4</td><td><u>Active element part of the detector:</u>

<u>Performance achievements</u>:

Prototypes or representative test vehicles were produced and tested to demonstrate compliance with functional and performance requirements, including the operating temperature and biasing sequences from preliminary application requirements.

<u>Reliability considerations</u>:

TID and DD impact has been tested to validate the design and EOL performance prediction. SEL effects (if applicable) are known (by design) or tested. The relevant electro-optical failure modes and associated early degradation indicators are identified. Acceleration factors needed to define evaluation and qualification test programs are known or determined by test.

<u>Hardware example</u>:

Full sized or reduced pixel array with representative read-out circuitry (e.g ROIC), and interfacing allowing for quantitative performance measurements. Radiation aspects can be based on representative test structures. Packaging concept sufficient to allow necessary performance demonstration (e.g. probe-testing, chip-on-carrier).</td></tr>
<tr><td><u>Complete detector (in addition to the TRL4 for active element):</u>

<u>Performance achievements</u>:

A draft detailed specification exists for the complete detector assembly. Potential flight suitable package and interfaces (electrical, thermal, and optical) as well as the major materials and processes for the assembly are defined. The test benches and the test methods for the assessment of the (understood) performances are described.

<u>Reliability considerations</u>:

Possible failure modes related to materials and processes needed to build flight suitable package and interfaces are known. The expected package-related failure modes are identified and associated with early degradation indicators, such as leak rate for hermetic detectors.

<u>Hardware example</u>:

As above.</td></tr>
</table>

TRL 5	***Active element part of the detector:*** Performance achievements: Prototypes were produced and tested to demonstrate compliance with functional and performance requirements in the relevant environment, including the operating temperature and biasing sequences from application requirements. Reliability considerations: Based on the failure modes, the most critical environmental aspects have been used to define and implement a preliminary evaluation test program. These tests shall target specifically the elements considered most at risk for the technology within the intended application. For instance, completing the SEE testing at the operating temperature, and an operating life test for detectors intended for cryogenic operation. Hardware example: Full sized pixel array with representative analogue and digital circuitry, and interfacing allowing for quantitative performance measurements. Packaging concept sufficient to allow necessary performance demonstration (e.g. probe-testing, chip-on-carrier).
	Complete detector (in addition to the TRL5 for active element): Performance achievements: A comprehensive detailed specification exists for the detector assembly. The detector is available in its intended flight package, manufactured according to a set of defined procedures aiming to provide a stable and repeatable process. The test benches and the test programs for the performance assessment are fully commissioned and suitable to validate the mission specific performance requirements. Flight packaged prototypes were produced and tested, the compliance with functional and performance requirements including the temperature range is demonstrated. Reliability considerations: Manufacturability of the final detector assembly is confirmed through engineering trials on assembly steps, with process controls defined and implemented. Construction analysis (CA) has been performed to verify that the material, design and workmanship used for the detector's construction, as well as the construction itself, meet the requirements of the relevant specification, are suitable for the intended application, and that the assembly can be reproduced with consistent results. A list of cosmetic defects and artefacts are catalogued and visual inspection criteria are defined. Hardware example: Detector assemblies, including packaging representative of intended flight package (e.g. ceramic package, flex-rigid PCB with electrical connector), and documented assembly materials and processes.

TRL 6	Performance achievements: A final detail specification exists for the detector assembly. The detector is available in its intended flight package, manufactured according to a stable and repeatable process. The test bench and the test program for the performance assessment is fully commissioned and calibrated for the mission specific performance requirements. Flight packaged prototypes were produced and tested, the compliance with functional and performance requirements at EOL including the temperature range is demonstrated. Reliability considerations: The detector or representative test vehicles have successfully completed reliability tests to confirm the suitability for the mission lifecycle. This evaluation testing includes for instance; shock, vibration, thermal cycling, humidity resistance, and high temperature storage, with test sequences including significant margin as compared to the expected mission requirements. Destructive physical analysis (DPA) has been implemented on the tested devices with satisfactory result. The manufacturer has established the yield for production of qualification and flight models. Screening test sequence for production of qualification and flight batches has been defined, as well as the qualification test program. Hardware example: Fully representative detector assemblies, including flight package (e.g. ceramic package, flexible PCB with electrical connector). In case of low yield, if some detector's performances are not fulfilling requirements, this can still be used as a part of the evaluation program (e.g. a device with excessive cosmetic defects in the package could still be used for mechanical tests).
TRL 7	*Note: This TRL level is suitable for recurrent detectors, such as in star trackers or other instruments suitable for multiple missions.* Performance achievements: The detector assemblies have been manufactured according to the successfully evaluated manufacturing process, and they have successfully completed the ESCC 9020 qualification tests or other applicable ESCC qualification which is relevant for the technology. Reliability considerations: QMs have successfully passed the ESCC 9020 qualification test program.

TRL 8	Performance achievements: The detectors have been manufactured according to the successfully evaluated manufacturing process, and they have successfully completed the mission qualification test program. Reliability considerations: QMs have successfully passed the mission qualification test program. Hardware example: Flight model Detectors
TRL 9	Performance achievements: The detector has achieved flight heritage of a typical duration of two years of nominal performance under nominal mission conditions.

3. Detector developments in the context of project implementation

As noted in Chapter 6 of this Handbook, it is typically desired to have reached TRL6 for a critical technology at the instrument PDR.

With increasingly compressed project development timescales, while maintaining novel and state-of-the-art detector technology, this TRL progression is becoming less feasible to obtain. It is more often the case to have the TRL6 maturity achieved sometime between the instrument PDR and the instrument CDR.

The level of risk to be accepted when taking this approach, not just for performances but for schedule and cost, is at the discretion of the project. A more tractable balance between technology maturity and schedule for instance could be to achieve TRL5 for the "Active element", and TRL4 for the "Complete detector" at the Detector PDR (following the instrument PDR). During the instrument PDR the relevant interfaces and environment are established to allow the definition of the evaluation test program. Then TRL6 for the "Complete detector" can be achieved at the Detector CDR (prior to the instrument CDR).

In the future, if there is more reliance on existing and proven detector technologies, then the TRL progression could be accelerated to match the project implementation timescales.