Examples of Demonstrating TRL 6

30 December 2024

Foreword

The NASA Science Mission Directorate (SMD) Announcement of Opportunity (AO) for which this document is provided contains a requirement that states in part that "proposals that include a technology currently at less than TRL 6 shall include a plan for associated system maturation to TRL 6 by no later than PDR…". Satisfaction of the requirement is dependent on the nature of the proposed mission or investigation. *Satisfying this requirement does not necessitate a system-level test by default. However, having all components or even subsystems at or above TRL 6 does not automatically demonstrate an assembled TRL 6 system*.

The definition of TRL 6 is provided in NPR 7123.1, *NASA Systems Engineering Processes and Requirements*, Appendix E. The concept of combining the TRL values of components and subsystems to derive a full system TRL is discussed in the *NASA Systems Engineering Handbook* Appendix G [NASA/SP-2016-6105]. Measures for assessing technology maturity are described in the *Technology Readiness Assessment Best Practices Guide* [SP-20205003605]. Expert judgment is needed to apply the steps described in those references. This document illustrates these principles on practical examples of relevance to proposals submitted in response to AOs.

The intent of this document is to provide examples of assessing configurations that are not yet at TRL 6 and to provide possible scenarios in which system level TRL 6 can be demonstrated. This document provides methods to suggest how to get to TRL 6, but these are not requirements, nor do they define the specific steps to get to TRL 6. Proposing teams should address the requirement according to their mission or investigation's unique system considerations, including stages of development.

The examples in this document follow the flowchart provided in *Technology Readiness Assessment Best Practices Guide* so that there is a better understanding of how to assess whether components and subsystems are at or below TRL 6. Note that the term new technology covers a broad range from technology development to advanced engineering. The definition is meant only to identify where work still needs to be done in order to achieve TRL 6. The examples in this document are intended to differentiate between below TRL 6 and at TRL 6, not to assess other TRL levels. For further information on the details of TRL levels and TRL advancements, see the *NASA Systems Engineering Handbook* Appendix G.

TABLE OF CONTENTS

FIGURES

1. Definitions

The definitions below provide context for the terms used in the flowcharts used in this document:

New Technology – Any technology that does not have heritage in the manner of proposed use.

Engineering – The subsystem is at TRL >=6 for the proposed environment and lifetime, also typically referred to as "standard engineering."

Demonstrated Operationally – Demonstrated and performed as expected in space. Demonstrated operationally does not require the previous design to have been tested or used in a similar environment to the proposed design.

Demonstrated Capability – Tested in flight-like configuration in a relevant space environment to specific test levels. For example, testing the maximum data throughput of a device. Successful operational tests at these levels define the capability.

Bounded – The needed or required performance is within the levels of the demonstrated capability. For example, the required data throughput of a device is less than the throughput that has been tested to date.

Form and Fit – Mechanical and physical interfaces.

Interface – Electrical, software and signal interfaces.

Test – Verification test. Verification testing can be done via hardware test and/or validated simulations, modeling, and analysis with appropriate justification.

2. Examples

2.1. Example 1: New Detector in a Heritage Optical Instrument

2.1.1 Define the System

A new detector for an optical telescope on an orbiting observatory is being proposed. The optical telescope being proposed has heritage from a previous mission that was in the same orbit. The observatory will have the same lifetime and capture the same measurements as the previous mission. The imaging detector will have the same form factor as the one on the heritage mission; however, a different fabrication technique will be used to manufacture the detector in order to improve the detector quantum efficiency and reduce background noise. The Application Specific Integrated Circuit (ASIC) will require some modifications in firmware to interface with the new detector and support higher data rates. These types of firmware modifications have been performed for this ASIC on previous missions at data rates that exceed what is required for the proposed mission. A smaller form factor prototype of the new detector has been built and tested to show that the required performance can be met but has not gone through environmental testing. The interface from the detector to the electronics board is the same as that for the heritage instrument. There are no critical alignment considerations between the newly developed detector and the remainder of the system.

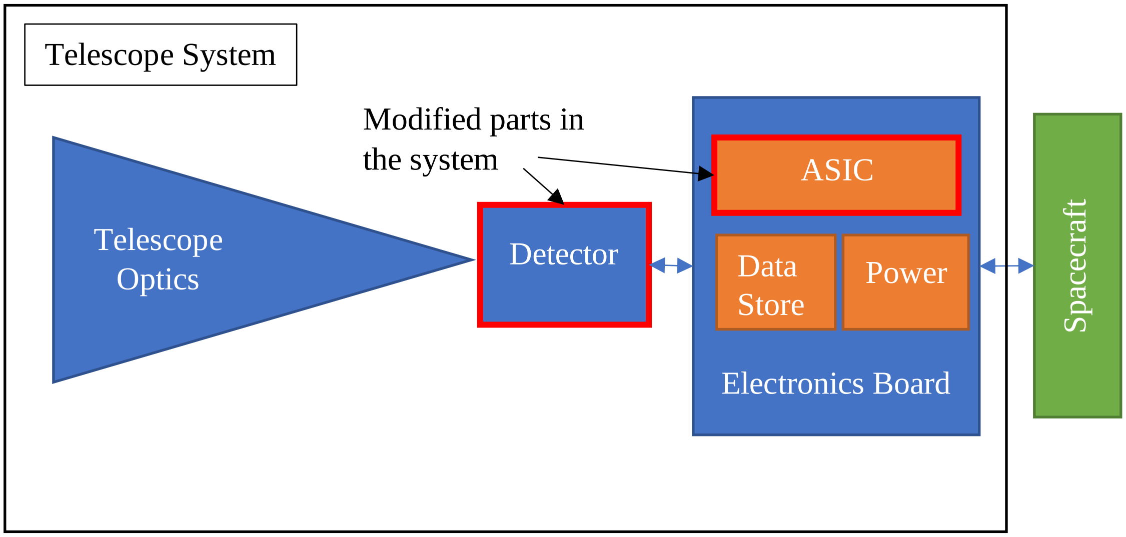

Figure 2.1-1. Example 1: New Detector in a Heritage Optical Instrument

2.1.2 Assess the Subsystem/Component TRLs

The existing TRLs for the relevant components/subsystems are assessed as follows:

Telescope Optical Subsystem (TRL >= 6) – The telescope optical subsystem maintains the same design as the heritage mission, including the same operational environment and lifetime. There is no plan to change the optics design or optical bench.

ASIC (TRL >= 6) – The changes to the ASIC are within the capabilities that have been demonstrated in flight.

Detector (TRL < 6) – The following flowchart from Technology Readiness Assessment Best Practices Guide can help assess whether the TRL level of the detector is below 6:

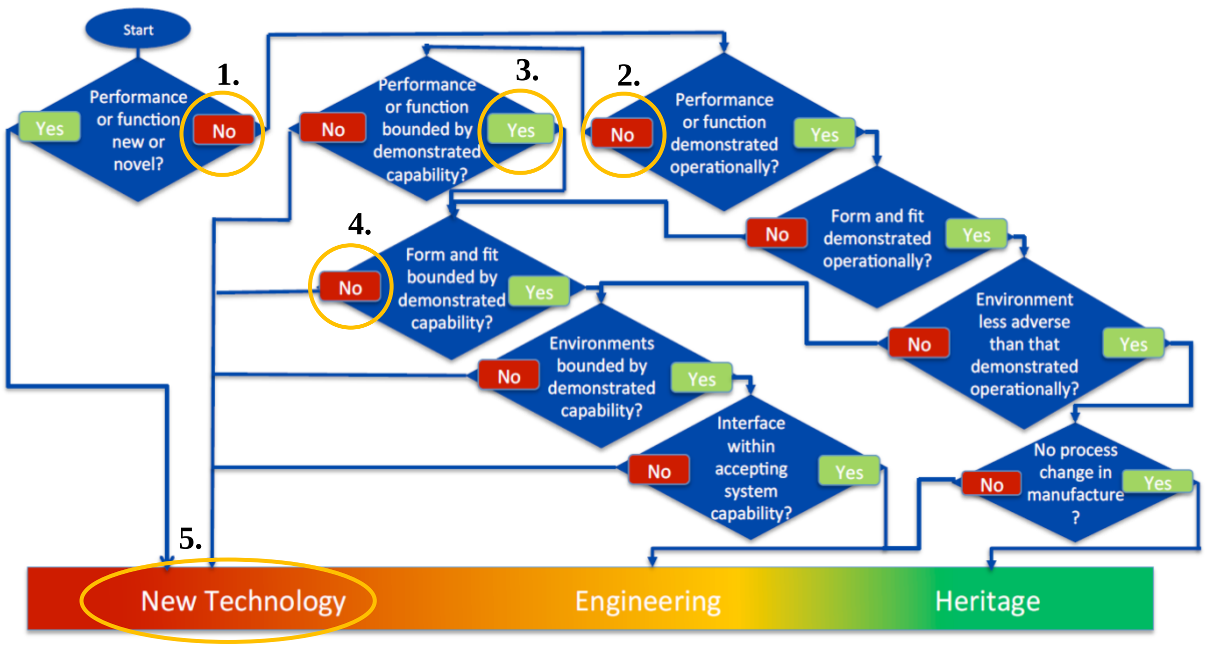

Figure 2.1-2. Example 1: New Detector TRL Assessment Flow

1. The detector is only providing improved capability, so it is not considered new or novel.
2. The detector manufactured with the new process has not flown in space, so it is not demonstrated operationally.
3. The laboratory testing of the smaller detector with similar input to what is expected in flight shows that the requirements for image quality for the mission are met. Therefore, the mission detectors can be assessed to be within the demonstrated capability.
4. The new flight detector is a larger size than the prototype, so the form and fit are not bounded by a demonstrated capability.
5. The above assessment indicates the new flight detector is "New Technology", which is considered < TRL 6.

2.1.3 Assess the System TRL

Since the lowest component/subsystem TRL is less than 6, the telescope system TRL is also less than 6. Since the telescope optical components have no modifications and the detector interface to the ASIC is within the accepting system capability of the ASIC, the incorporation of the new detector will not require any other technology advances and can be considered standard engineering. Therefore, the TRL of the instrument system will not be lower than the TRL of the detector.

2.1.4 Component Path to TRL 6

Using the above TRL chart, the following steps need to be addressed to move the flight detector to TRL 6:

- The form and fit needs to be bounded by the demonstrated capability.
- The environments must be bounded by the demonstrated capability.
- The interface must be within the accepting system capability.

A flight-like detector of similar size to the flight detector needs to be demonstrated in the relevant environment *(e.g.*, vibration, thermal/vacuum, radiation, EMI/EMC) to satisfy the first and second bullets. The ASIC will require modifications to support the higher data rates. Thus, some integrated testing will be needed to verify that the instrument performs as expected.

2.1.5 System Path to TRL 6

Since there are no changes to the optical subsystem and the changes to the detector subsystem do not impact the rest of the instrument system, the maturation of the system can be focused on the detector subsystem as shown in the diagram from the Technology Readiness Assessment Best Practices Guide below:

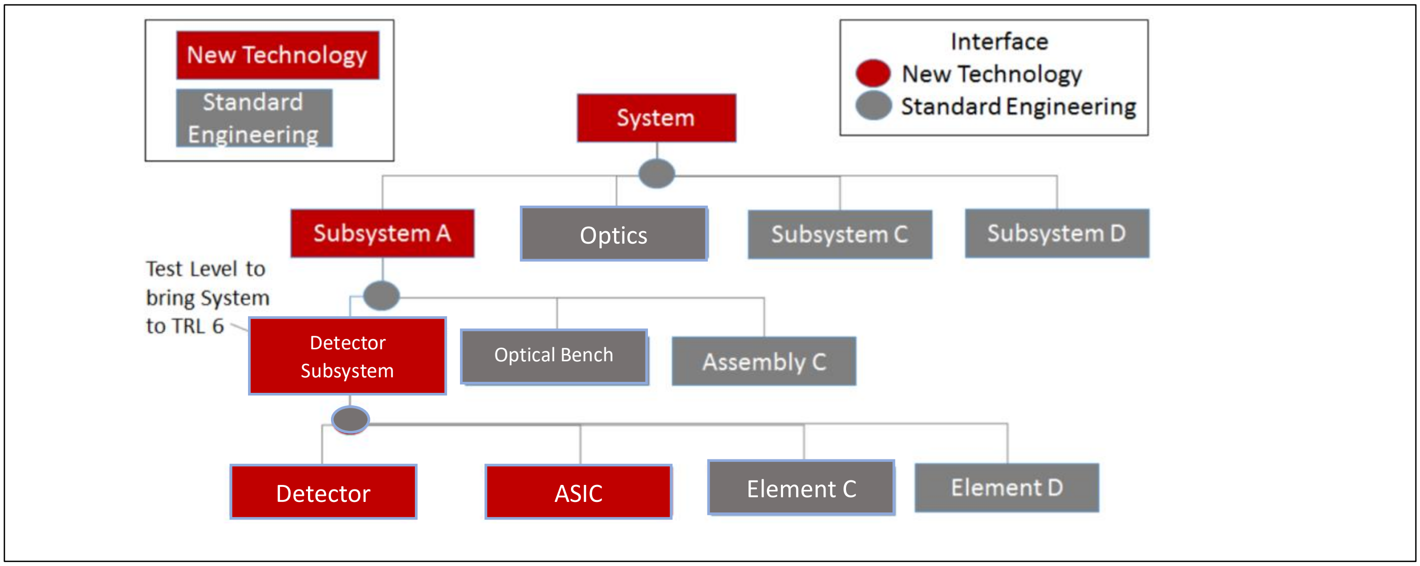

Figure 2.1-3. Example 1: New Detector Integration to Bring System to TRL 6

Note that while the entire system TRL is at a maximum the lowest TRL of a component, there is typically no expectation that the entire system needs to be demonstrated as TRL 6 *if* subsystems can be sufficiently demonstrated to be separable from the other subsystems as shown above. In that case, any demonstrations or discussions of maturing the system can be limited to the subsystem that contains new development work. Example 3: New Instrument Design with all Heritage Components in this document shows a case where the full system should be tested to demonstrate TRL 6.

For this example, Figure 2.1-4 shows that the detector and electronics board need to be tested together to demonstrate TRL 6 for the system:

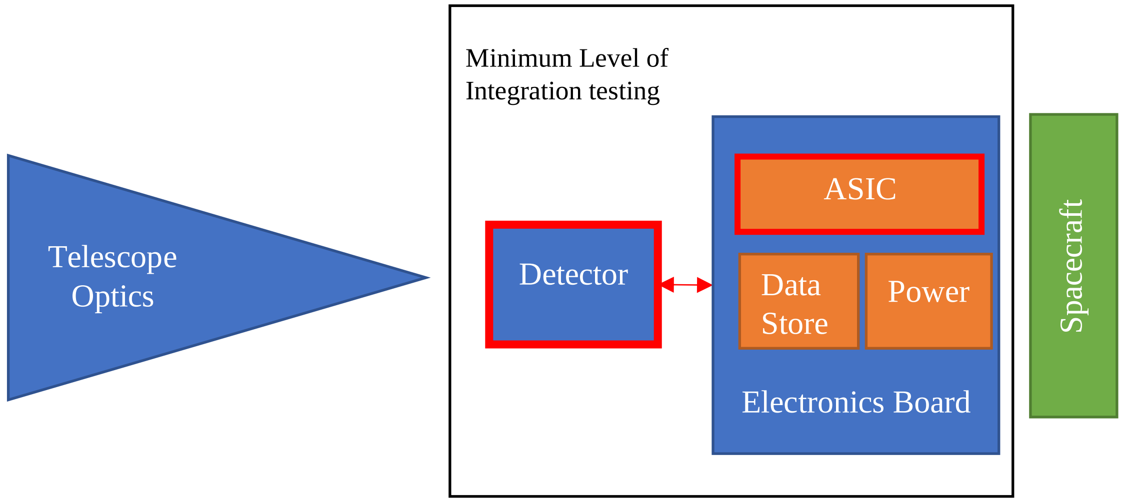

Figure 2.1-4. Example 1: New Detector Minimum Level of Integration Testing

2.2. Example 2: New Mirror Assembly with Critical Alignments in a Heritage Telescope

2.2.1 Define the System

A proposed X-ray telescope consists of two primary subsystems: an X-ray Mirror Subsystem (XMS) and a heritage detector subsystem. The X-ray Detector Subsystem (XDS) (optical bench, detector, and electronics) has flight-proven performance.

The new optical design has a modified optical figure prescription designed to improve the telescope's wide Field of View (FOV) performance and Effective Area (EA) over the prior heritage optical design. This modified optical figure prescription requires changes to the mirrors that make up the concentric shells within the X-ray optics. Each mirror is a single concentric shell with a given diameter. New mounting hardware to the overall mirror assembly is required to support each mirror. The alignment between each mirror is critical to obtain the required performance for the telescope. Interfaces between the XMS and the optical bench (part of the XDS) are expected to have only minimal changes from prior heritage telescopes.

A flight-like mirror of the smallest diameter shell has been fabricated and tested in a relevant environment to validate the new optical fabrication technique and verify the performance of the mirror. The results of this testing have been used to validate the simulation to verify the performance of the larger-diameter mirrors. The flight-like mirror has been mounted to the new assembly and run through environmental test to validate the new mounting technique.

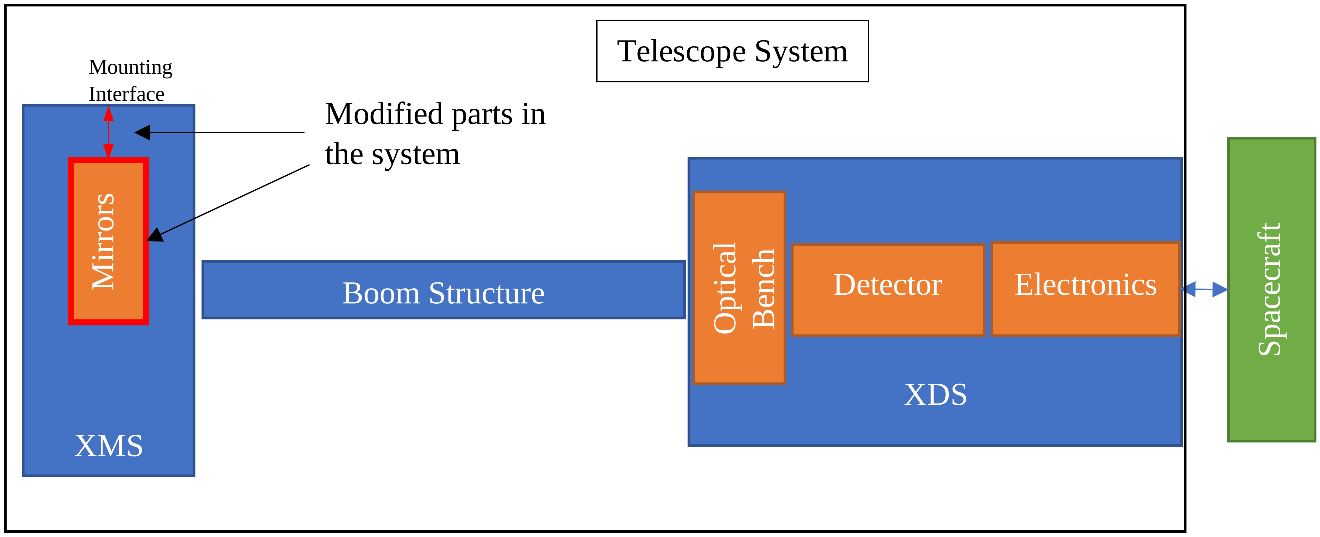

Figure 2.2-1. Example 2: New Mirror Assembly with Critical Alignments in a Heritage Telescope

2.2.2 <u>Assess the Subsystem/Component TRLs</u>

The existing TRLs for the relevant components are assessed as follows:

XDS (TRL > 6) – The optical bench, detector, and associated electronics have not changed from the heritage mission. The optical bench still contains the actuators to make any adjustments to misalignments after boom deployment.

Boom (TRL > 6) – Minor mounting changes need to be made to support the new structure, but no other changes are made to the heritage boom. These modifications do not affect the predicted boom deployment misalignments.

Mirrors (TRL = 6) – A flight-like mirror of the smallest diameter in the XMS has been tested in a relevant environment. All other diameters have been verified via a validated simulation to demonstrate TRL 6.

XMS (TRL < 6) – The following flowchart from Technology Readiness Assessment Best Practices Guide can help assess whether the TRL level of the XMS is below 6:

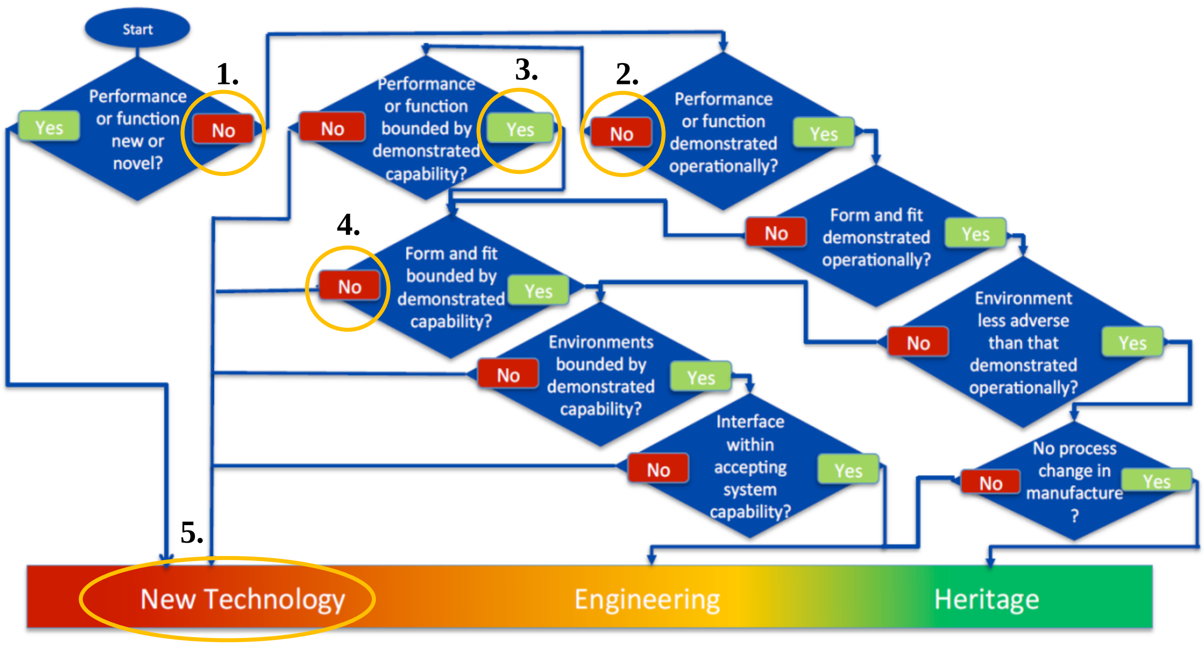

Figure 2.2-2. Example 2: New XMS Subsystem TRL Assessment Flow

1. The XMS is providing improved performance, so it is not considered new or novel.
2. The XMS has not flown in space, so it is not demonstrated operationally.
3. A flight-like mirror has been tested and simulations have been run to show that the performance is better than the requirements for this system.
4. Even though a mounting technique has been demonstrated on a single mirror, the overall XMS performance is reliant upon mirror-to-mirror alignment of all the mirrors. Since the mounting techniques are substantially different from the heritage mission, the mirror-to-mirror alignment is not bounded by any demonstrated capability.
5. The above assessment indicates that the XMS is "New Technology", which is considered < TRL 6.

2.2.3 Assess the System TRL

Since the lowest component/subsystem TRL is less than 6, the telescope system TRL is also less than 6. The XMS does not need any modifications and the interface to the boom only needs minor modifications to accommodate changes to the XMS structure. Since there are only minor accommodations to the boom and misalignments of the XMS to the XDS are adjusted via an actuator, these modifications to attach the new XMS to the boom are considered within the accepting capability of the instrument system and are thus deemed to be standard engineering. Therefore, the TRL of the instrument system will not be lower than the TRL of the XMS.

2.2.4 Subsystem Path to TRL 6

Using Figure 2.2-2, the following steps need to be addressed to move the XMS to TRL 6:

- The form and fit needs to be bounded by the demonstrated capability.
- The environments need to be bounded by the demonstrated capability.
- The interface needs to be within the accepting system capability.

The form and fit needs to be demonstrated by performance testing with an appropriate X-ray source and multiple mirrors integrated into the mounting structure. This configuration also needs environmental testing to show that all the critical mirror alignments are maintained to sufficient tolerances. Since the electrical interfaces to the electronics in the XMS are not expected to change from the heritage XMS, the interfaces can already be considered within the accepting system capability.

2.2.5 System Path to TRL 6

Since there are no changes to the XDS and only minor changes to the boom, the changes to the XMS do not impact the rest of the instrument system. The maturation of the system can be focused on the XMS as shown in the diagram from the Technology Readiness Assessment Best Practices Guide below:

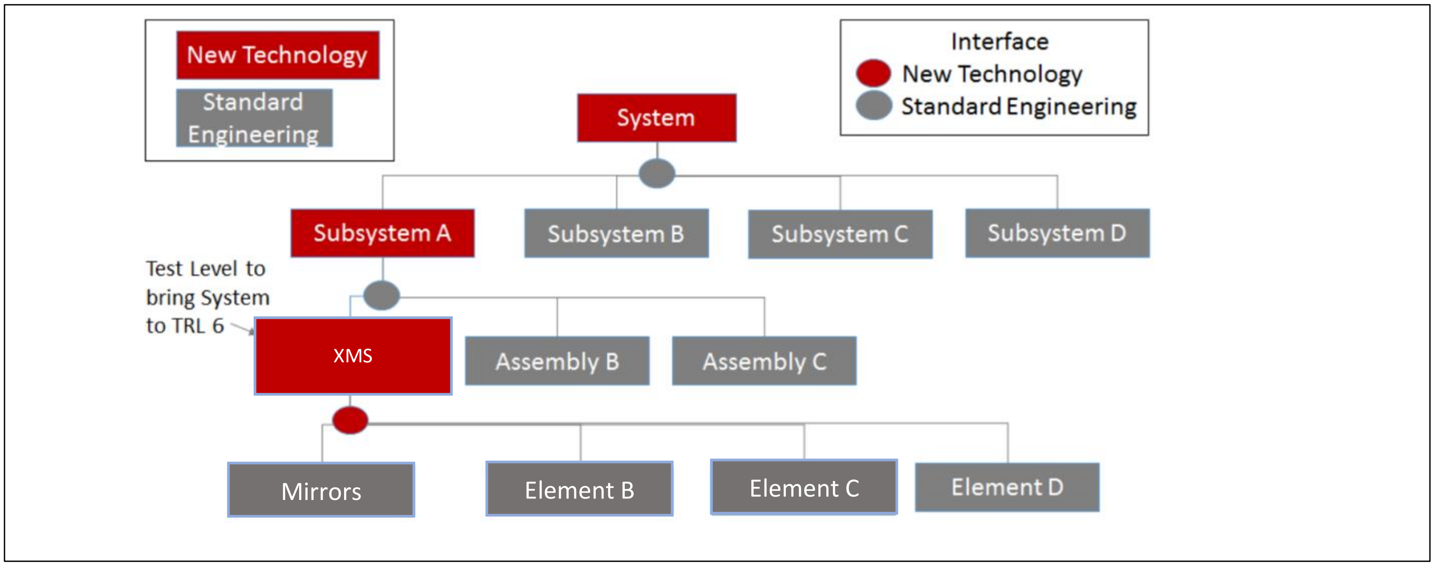

Figure 2.2-3. Example 2: New XMS Integration to Bring System to TRL 6

This system can be considered matured to TRL 6 by performing the above XMS testing because there are no upstream interdependencies that impact the operation of the subsystem.

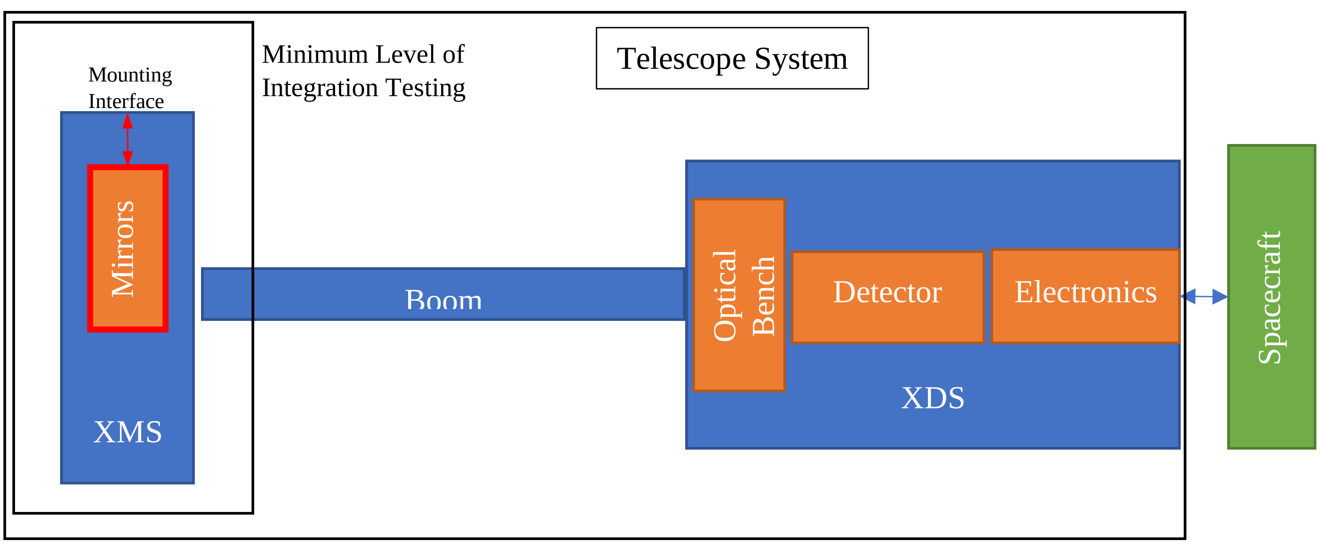

Figure 2.2-4. Example 2: New XMS Minimum Level of Integration Testing

2.3. Example 3: New Instrument Design with all Heritage Components

2.3.1 Define the System

A new instrument is being developed that uses heritage parts from previous missions that have either flown in space or have completed ground qualification. The new instrument operates in an environment that is within the environments that all the parts have either been tested to or operated in. All of these parts have all been analyzed to verify that the lifetime of the mission is within the lifetime capability of the parts. The parts that make up this instrument have been used by different instruments in the past but have not been used in a configuration that enables the measurements this instrument is designed to capture. Parts A, B, and C have been connected and tested together at room temperature to demonstrate that the desired measurement can be taken in this configuration.

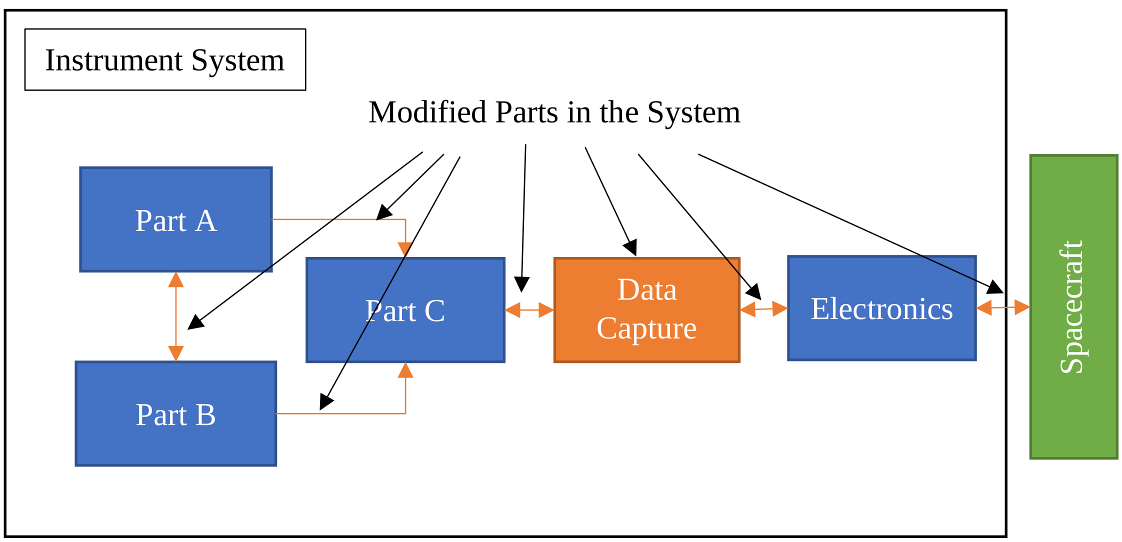

Figure 2.3-1. Example 3: New Instrument Design with all Heritage Components

2.3.2 Assess the Subsystem/Component TRLs

The existing TRLs for the relevant components are assessed as follows:

Part A (TRL >= 6) – This component has gone through ground qualification testing for a mission in a similar environment. There are no changes to any of the electronics within the components. The electrical interfaces have been modified to support interfacing with Part B and Part C.

Part B (TRL >= 6) – This component has previously flown on a balloon mission and has since gone through environmental testing in an environment similar to this mission. There are no changes within this part, but the mounting and electrical interfaces have been changed to integrate with Part C. The electrical interfaces have been modified to support interfacing with Part A.

Part C (TRL >= 6) – This component has gone through ground qualification testing for a mission in a similar environment. There are no changes to any of the electronics within the components. The electrical interfaces have been modified to support interfacing with Part A and Part B.

Data Capture (TRL >= 6) – This component has flown in space on a mission in a similar environment but interfaced to a different component with a different number of outputs. This component will need to be modified to access the data from Part C. These modifications are typical modifications for the data capture component for new missions.

Electronics (TRL >= 6) – This component has flown in space on a mission in a similar environment in a different instrument system. The previous interface to the spacecraft will need to be modified to support a new spacecraft interface. The changes are within standard modifications for these electronics.

2.3.3 Assess the System TRL

Even though all of the elements are at TRL >= 6, this does not automatically make the instrument system TRL 6. The same flowchart used to assess components and subsystems can also be used to assess the system TRL. The following flowchart from Technology Readiness Assessment Best Practices Guide was used to assess the TRL of the instrument:

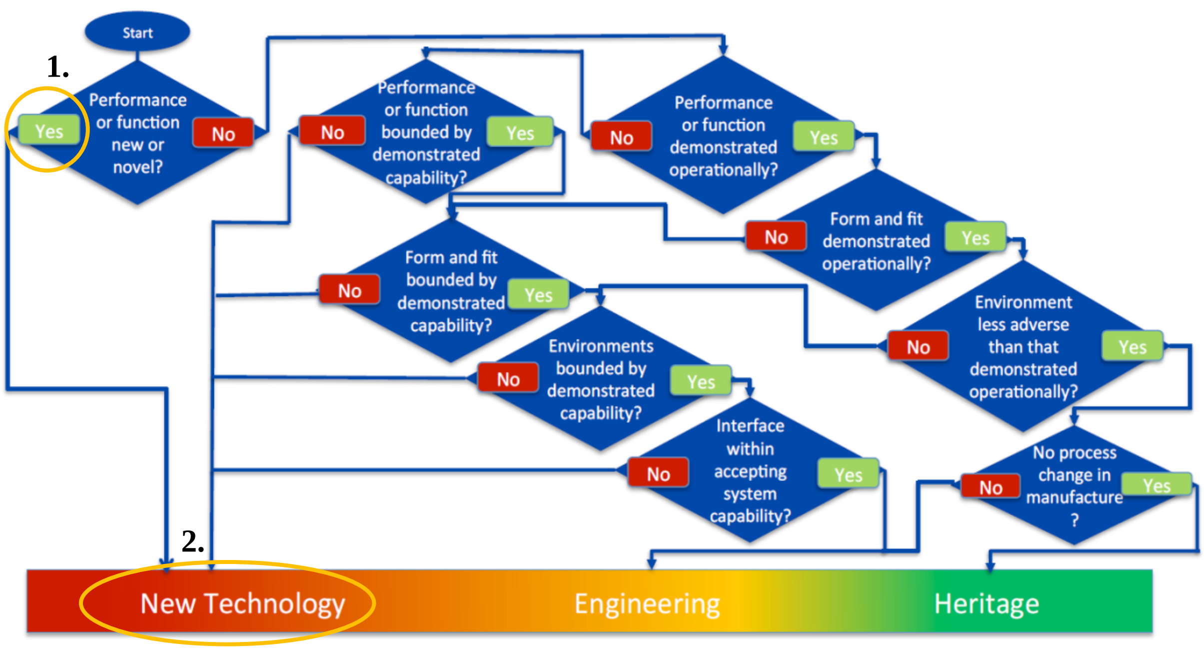

Figure 2.3-2. Example 3: New Instrument with Heritage Parts TRL Assessment Flow

1. If a system consists of multiple heritage components that have not been previously put together in an instrument to perform the same functions or collectively the multiple heritage components perform a different function in than used in heritage applications, the function is considered new.

2. This sets the instrument at "New Technology", which is considered < TRL 6.

Note that in general, heritage parts with different interfaces are not necessarily considered standard engineering. If the parts have the same function as in previous applications, the assessment flow still must be considered to determine if the form, fit, and interfaces are within the accepting system capability. For example, modifications to support a different interface may require new coding schemes and different electronics that would need to be tested to ensure that commands and telemetry are received and decoded appropriately.

2.3.4 Component Path to TRL 6

In this case, no components are below TRL 6.

2.3.5 System Path to TRL 6

Using the above TRL chart, the following steps need to be addressed to move the instrument system to TRL 6:

- The overall system function needs to be bounded by the demonstrated capability.
- The form and fit needs to be bounded by the demonstrated capability.
- The environments need to be bounded by the demonstrated capability.
- The interface must be within the accepting system capability.

This system is highly dependent on all the components successfully interfacing with each other in this new design and configuration to demonstrate that the desired measurement at the required accuracy can be achieved. Therefore, a sufficiently representative prototype of the entire system needs to be integrated and tested to demonstrate TRL 6. Although the components have been tested in a relative environment, the design changes for the new interfaces have not been demonstrated in a relevant environment. Therefore, the system should be tested in a relevant environment to demonstrate TRL 6. A relevant environment would be the aspects of the operational environment that would impact the functioning of the new design. For example, electronics in the new interfaces may be susceptible to radiation and have the potential for unexpected operation at extremely cold temperatures. In this case, testing in a relevant environment would include radiation testing and thermal testing.

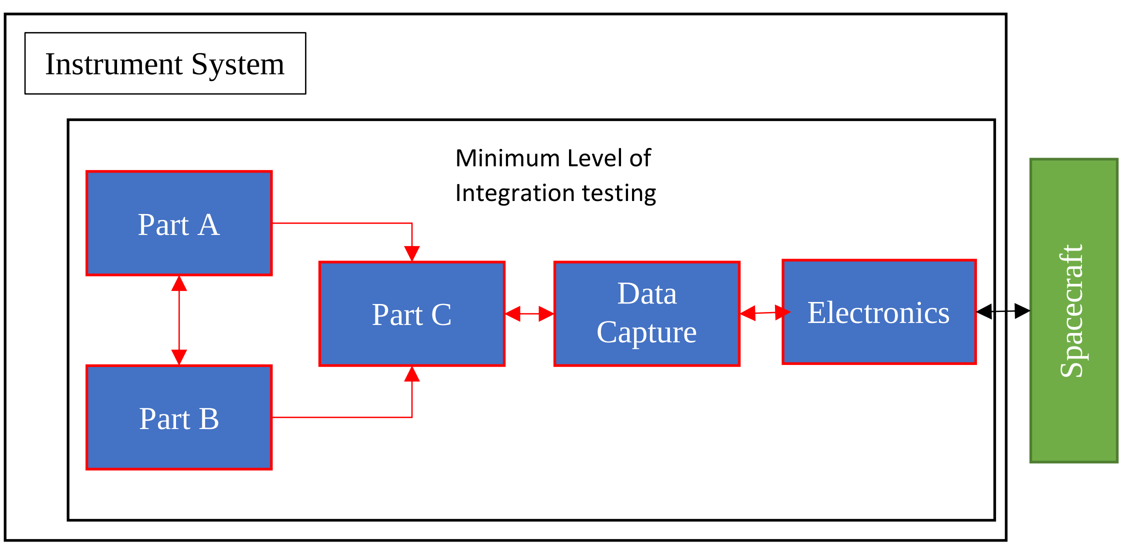

Figure 2.3-3. Example 3: New Instrument with Heritage Components Minimum Level of Integration Testing

2.4. Example 4: New Telecom System with a New Operational Mode

2.4.1 Define the System

The spacecraft design for proposed mission A is based on a previous spacecraft bus design, flown on various missions including mission B. Mission B operated in a harsher environment with a longer lifetime than mission A. Mission A includes a new telecommunications system where the transceiver is replaced with a Software Defined Radio (SDR) to support dynamic ranging. The dynamic ranging will be a software-only function within the spacecraft. This dynamic ranging function will adjust the parameters of the SDR during the mission and is currently estimated to require minimal software memory and CPU utilization. The telecommunications amplifier is a heritage product that has been flown on another previous mission, mission C, that used a larger spacecraft bus. Mission C also used an SDR, but from a different vendor. The mission C amplifier has a higher input power than the previous amplifier on the spacecraft bus for mission B. The proposed SDR has not flown but has gone through ground qualification for another mission, mission D, that is going through final verification. Mission D has the same environment and operational lifetime as the proposed mission A. The SDR has not interfaced with the proposed amplifier, but there are no interface modifications required to support the proposed amplifier. No other hardware, functional, or operational changes from mission B's heritage spacecraft bus are required.

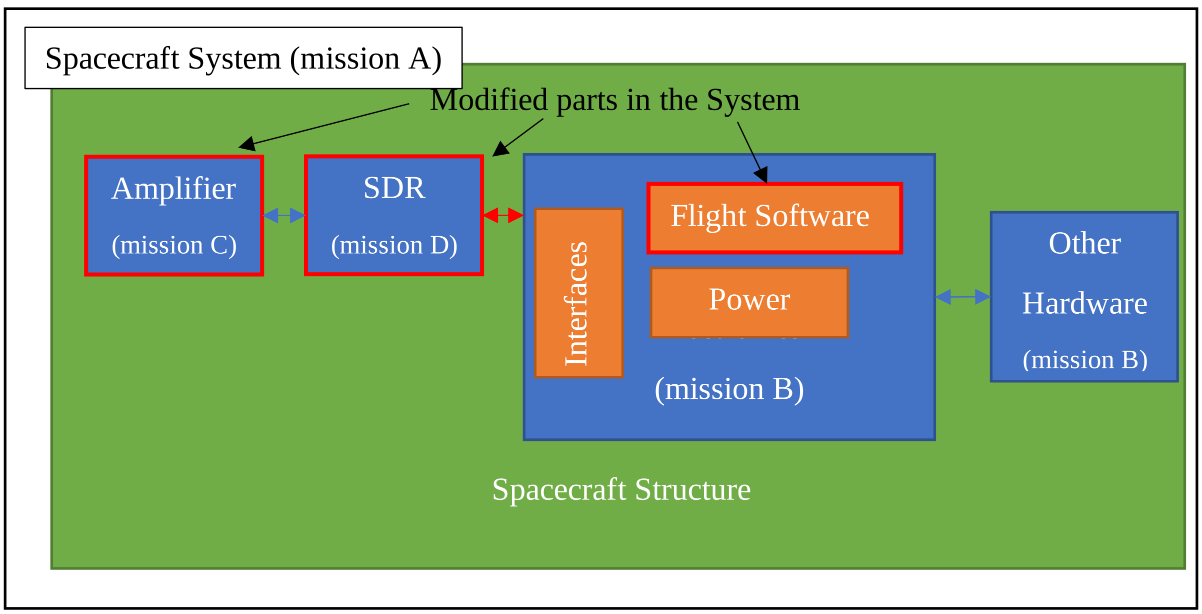

Figure 2.4-1. Example 4: New Telecom System with a New Operational Mode

2.4.2 Assess the Component TRL

The existing TRLs for the relevant components are assessed as follows. The assessment of a subsystem is not limited to hardware and must include the flight software as well. For ease of assessment, the flight software will be considered its own component independent of the hosting electronics.

Spacecraft (TRL >= 6) – The spacecraft has minimal changes to the previous mission and the electronic interfaces to the SDR are similar. The power supplied to the amplifier is bounded by the available power capability of the spacecraft. New mounting brackets need to be developed to attach the amplifier and the SDR to the bus structure.

Amplifier (TRL >= 6) – The amplifier and its interfaces to the electronics for the proposed mission are the same as the previous mission C. There are no changes to the interface with the proposed SDR. The power supplied to the amplifier is bounded by the available power capability of the proposed spacecraft.

SDR (TRL >= 6) – The SDR has been qualified for flight on mission D that has a similar environment and operational lifetime.

Electronics (TRL >= 6) – The hardware electronics and boards associated with interfacing to the telecommunications system are the same as on the previous mission B. In this instance, the interfaces only refer to the electrical and hardware interfaces, not the software interfaces.

Flight Software (TRL < 6) – The following flowchart from Technology Readiness Assessment Best Practices Guide was used to assess the TRL level of flight software:

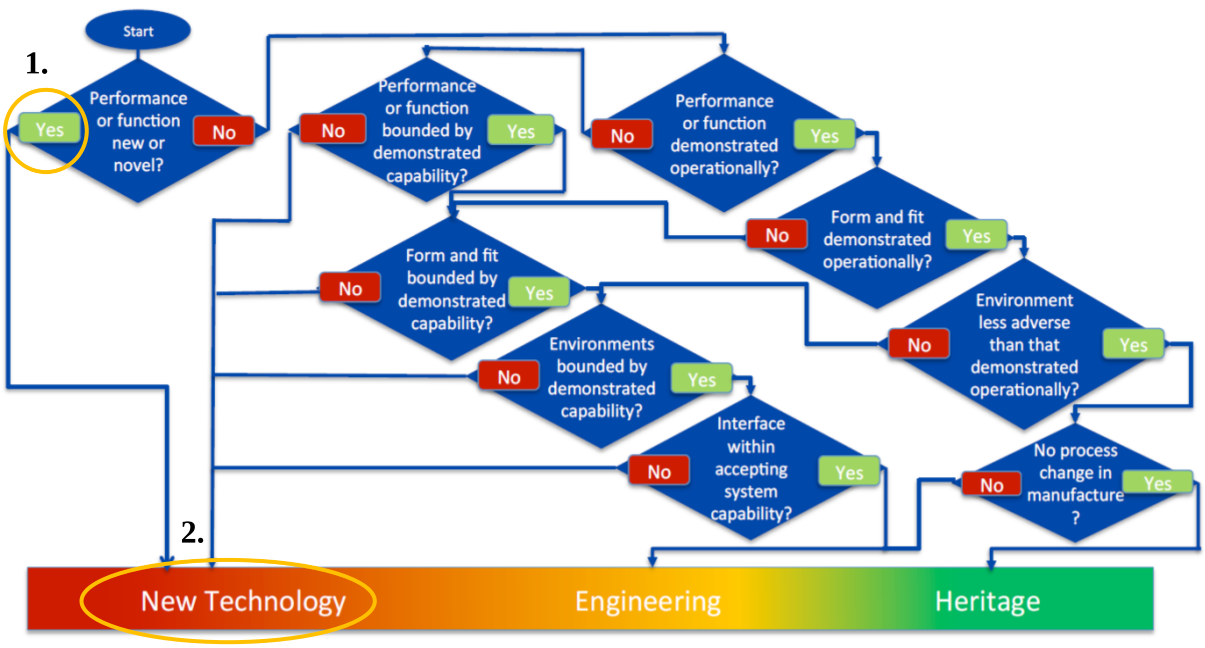

Figure 2.4-2. Example 4: Telecommunications Flight Software TRL Assessment Flow

1. A new function is being developed within the flight software to support dynamic ranging, so the flight software is considered new technology.
2. This sets the flight software at “New Technology”, which is considered < TRL 6.

Similar to hardware, flight software also needs to be considered for TRL assessment. If a function within the flight software is considered less than TRL 6, any demonstrations or discussions of maturing flight software can be limited to the new function and any interfacing functions and/or hardware that require updates.

2.4.3 Assess the System TRL

Since the lowest component/subsystem TRL is less than 6, the system is also less than 6. Since there are minimal changes to the electrical and software interfaces for the new SDR and amplifier, these changes do not impact the rest of the spacecraft system. However, all of the telecommunication components are within the closed structure of the spacecraft, which can affect the environment of the subsystems. It is necessary to demonstrate that the changes to the spacecraft environment do not adversely impact the other subsystems.

2.4.4 Subsystem Path to TRL 6

Using the above TRL chart, the following steps need to be addressed to move the flight software to TRL 6:

- The function needs to be bounded by the demonstrated capability.
- The form and fit needs to be bounded by the demonstrated capability.
- The environments need to be bounded by the demonstrated capability.
- The interface must be within the accepting system capability.

In the case of form and fit for the flight software, this would represent the physical limitations of the CPU. The memory size and processing throughput of the CPU would be considered the physical limitations. The function for the dynamic ranging is a small percentage of the overall software memory and CPU utilization. Since there is still plenty of margin on the memory and CPU utilization, the addition of this function can be considered bounded by the demonstrated capability.

The dynamic ranging software function is new and thus has currently not been demonstrated to meet the needs of the mission. The software also has different interfaces to the SDR, so a subsystem test needs to be performed to show that the ranging software in concert with the SDR measures and corrects the frequency to maintain sufficient signal-to-noise ratio based on the expected signals during mission A. The ability of the flight software to detect the appropriate signals and operate correctly in the specified mission environment with realistic signal errors will also need to be demonstrated. The above testing does not need to be done with a single test to demonstrate TRL 6. A combination of hardware testing to verify interfaces can be performed in conjunction with a closed-loop simulation that emulates expected signal noise and errors.

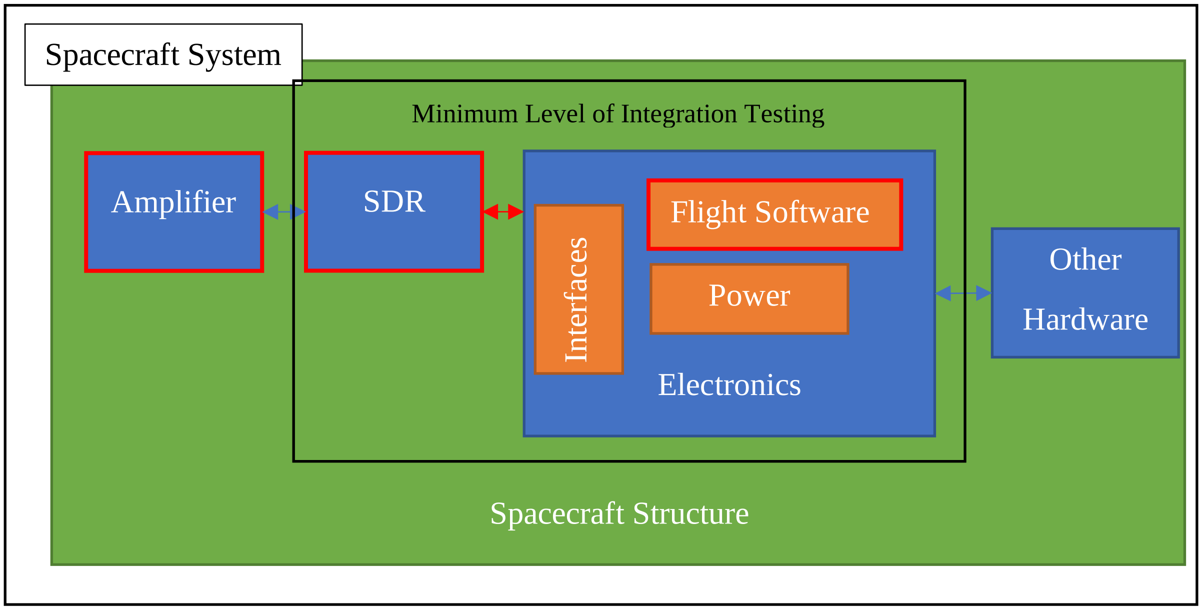

Figure 2.4-3. Example 4: Telecommunications Software Minimum Level of Integration Testing

2.4.5 System Path to TRL 6

Since the amplifier is being used on a smaller spacecraft, the amplifier and the rest of the electronics need to be verified in this smaller enclosed space. This means a complete verification of the spacecraft needs to be performed to demonstrate the system is at TRL 6. Physical testing is not required – a validated simulation can be used to demonstrate that the spacecraft can maintain all its subsystems within their operational temperatures (bounded by existing capability). The validated simulation from the previous mission can be used, but the heat modeling for the amplifier and the SDR is new. The simulation must be validated against heat dissipation measured on the physical amplifier and SDR.

2.5. Example 5: A Real-Life Example: CubeSat Attitude Control Subsystem

2.5.1 Define the Subsystem

An Attitude Determination and Control System (ADCS) for a 6U CubeSat is being proposed. Two control modes are identified: initial de-tumbling and operations. For the science operations, the ADCS Subsystem will provide control of the nadir vector to 1° with a knowledge of 0.5°. The CubeSat will operate in LEO for 24 months. The ADCS is based on a similar system used on a 3U CubeSat.

The control modes are the same as the previous mission, but the previous mission requirements were to control the attitude to within 5° and provide an attitude knowledge to within 2°. The estimate of the spacecraft position, required to support determination of attitude knowledge, is provided by the spacecraft for both missions. The previous CubeSat operated for 90 days in LEO. The following hardware-related updates were identified for the proposed mission to support the new requirements: a new Reaction Wheel Assembly (RWA) is needed to implement the tighter pointing control; larger magnetic torque rods are required to handle the larger inertia of the 6U CubeSat; and an increase in the expected radiation dose due to the increased lifetime. Updates to the

ADCS control algorithms are also required to support the tighter pointing requirements and attitude knowledge requirements.

The ADCS simulation/software model from the 3U CubeSat has been augmented to reflect the proposed configuration with best estimates of the component performance and new algorithms.

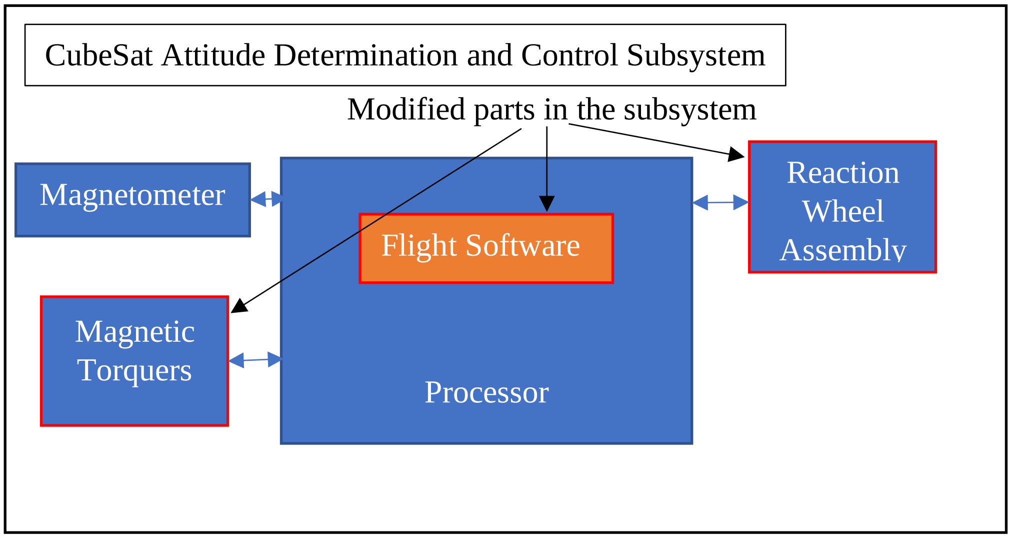

Figure 2.5-1. Example 5: CubeSat Attitude Control Subsystem

2.5.2 Assess the Component TRL

Magnetometer (TRL >= 6) - Although the previous mission was only 90 days, the unit is COTS with demonstrated LEO heritage of sufficient duration and radiation exposure on other missions. Demonstrated flight performance meets the required accuracy.

Processor (TRL >= 6) - Similar to the magnetometer, the COTS unit has excess capability relative to the previous mission requirements and can accommodate the new algorithms needed to support the updated attitude control logic and magnetic field models. The processor has demonstrated LEO heritage of sufficient duration and radiation exposure on other missions.

RWA (TRL < 6) - After examining available COTS RWAs, a suitable COTS unit is found that is under development but has not flown yet. Successful performance testing of an engineering model has been performed in the laboratory. Life testing and radiation analysis has been performed on the engineering model for a 6-month mission. The following flowchart from the Technology Readiness Assessment Best Practices Guide was used to assess the TRL level of the RWA:

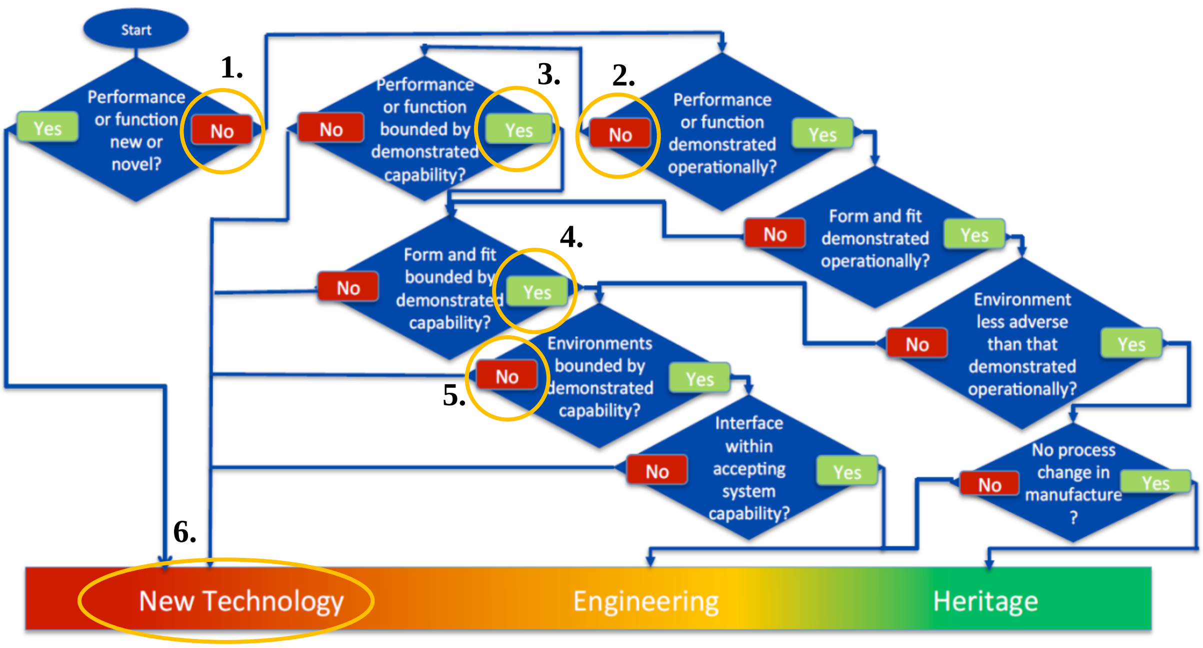

Figure 2.5-2. Example 5: RWA TRL Assessment Flow

1. The RWA is not fundamentally different from the design and operation of other flight-qualified RWAs. The RWA is not considered new or novel.
2. The RWA under development has not flown in space and has not been demonstrated operationally.
3. The performance testing on the RWA engineering model shows that the control authority will support the larger CubeSat and tighter pointing control.
4. Initial CAD modeling of the proposed CubeSat demonstrates that the current RWA with fit within the constraints of the CubeSat volume.
5. The 6-month life and radiation testing that has been performed does not demonstrate that the RWA will perform for a 24-month mission. The demonstrated capability does not bound the environment for the needed lifetime.
6. This sets the RWA at "New Technology", which is considered < TRL 6.

Magnetic Torquers (TRL < 6) - The units used on the previous 3U CubeSat are too small to handle the increased mass and the lifetime was too short. The proposed units need to be scaled up from the previous mission. The parts comprising the torquers have been evaluated for radiation exposure and mechanical environments (vibe/shock). The following flowchart from Technology Readiness Assessment Best Practices Guide was used to assess the TRL level of the Magnetic Torquers:

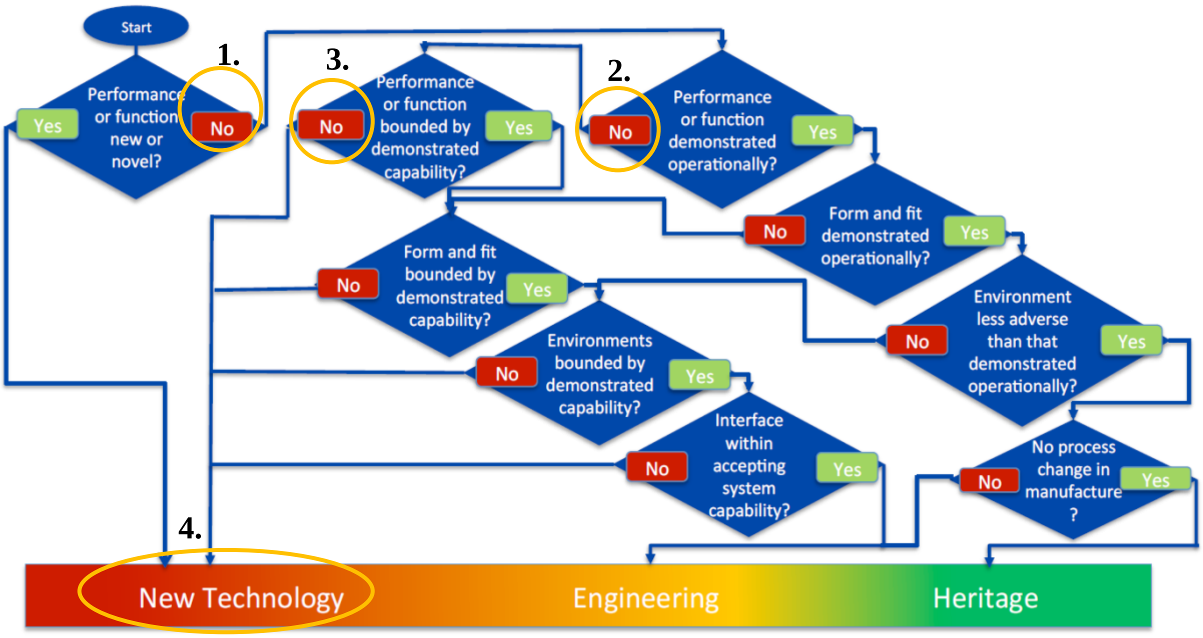

Figure 2.5-3. Example 5: Magnetic Torquers TRL Assessment Flow

1. The magnetic torquer is increased in size to provide more capability but it is not fundamentally different from the initial design and operation. The magnetic torquer is not considered new or novel.
2. Only the smaller magnetic torquers have been demonstrated operationally on the previous 3U CubeSat mission.
3. Since the smaller magnetic torquers do not provide enough torque for the 6U CubeSat, the performance is not bounded by the demonstrated capability.
4. This sets the magnetic torquers at “New Technology”, which is considered < TRL 6.

Flight Software (TRL < 6) - New algorithms are required to integrate the RWA control and desaturation logic. The magnetic field model needs to be upgraded to utilize the accuracy of the magnetometer to meet the tighter knowledge requirements. Processor loading with the new capabilities needs to be evaluated. The following flowchart from Technology Readiness Assessment Best Practices Guide was used to assess the TRL level of Flight Software:

2.

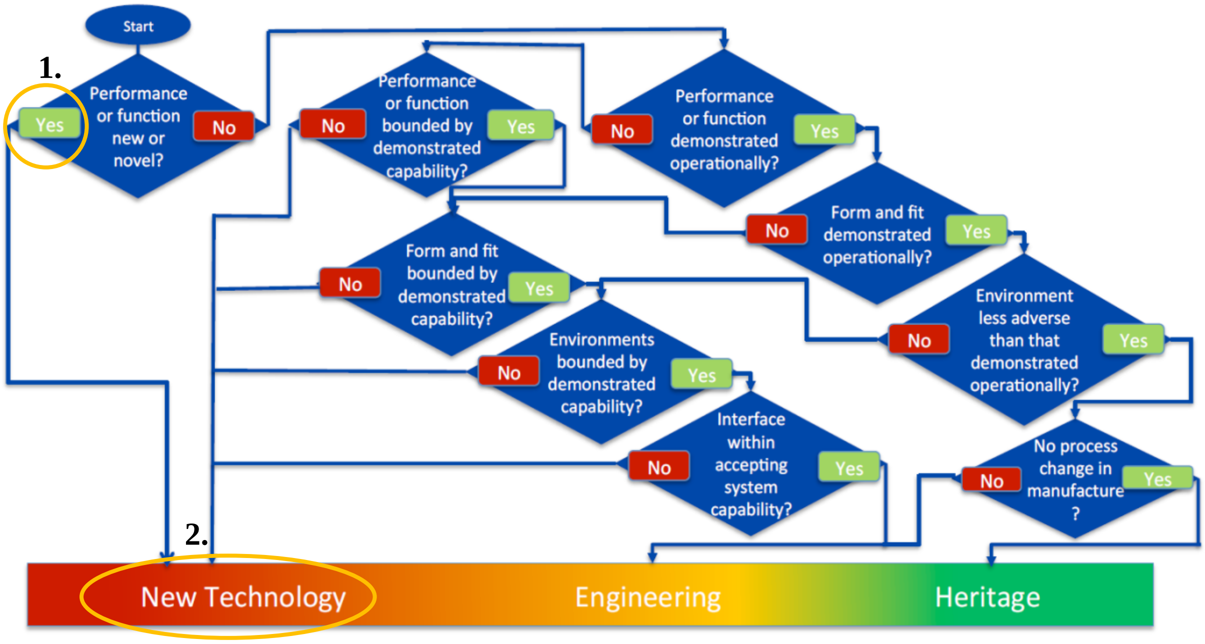

Figure 2.5-3. Example 5: ADCS Flight Software TRL Assessment Flow

1. The flight software is providing an entirely new function to integrate the bias RWA control and desaturation logic. Although similar algorithms of this nature have been developed, this is the first time this function is available in this flight software and coded by the company developing the spacecraft. This software is effectively a new function for this application.
2. This sets the flight software at “New Technology”, which is considered < TRL 6.

2.5.3 Component Path to TRL 6

2.5.3.1 RWA

Using the above TRL chart, the following steps need to be addressed to move the RWA to TRL 6:

- The environments need to be bounded by the demonstrated capability.
- The interface must be within the accepting system capability.

The life testing and radiation testing and analysis needs to be performed for a 24-month mission to demonstrate a relevant environment. Equivalent accelerated life testing and analysis need to show that the limited-life components such as the ball bearings and lubrication can survive the wear and tear of 24 months of use. Radiation testing and analysis needs to be performed such that radiation-sensitive components such as the microcontroller can survive the higher dosage from operating in orbit for 24 months. This RWA was chosen during initial selection because the signal and power lines were already supported.

2.5.3.2 Magnetic Torquer

Using the above TRL chart, the following steps need to be addressed to move the magnetic torquer to TRL 6:

- The function needs to be bounded by the demonstrated capability.
- The form and fit needs to be bounded by the demonstrated capability.
- The environments need to be bounded by the demonstrated capability.

- The interface must be within the accepting system capability.

A high-fidelity prototype of the scaled-up magnetic torquers needs to be built and tested in a relevant environment to demonstrate capability. The testing should include measurement of performance parameters (e.g., torque output, power consumption, magnetic emissions) to validate the software simulations used to demonstrate TRL 6. The relevant environment needs to be defined and the prototype functionally demonstrated in this environment. Since magnetic torquers are susceptible to mechanical environments, vibration and shock testing are needed. Loads for the magnetic torquers can be verified by similarity and analysis. Vacuum is not typically a driver for these components (i.e., they behave similarly in vacuum) so the environmental considerations for vacuum can be considered bounded by the demonstrated capability of the previous torque rods. Parts need to be evaluated for radiation tolerance and shown to meet 24 months in LEO.

2.5.3.3 Flight Software

Using the above TRL chart, the following steps need to be addressed to move the flight software to TRL 6:

- The function needs to be bounded by the demonstrated capability.
- The form and fit needs to be bounded by the demonstrated capability.
- The environments need to be bounded by the demonstrated capability.
- The interface must be within the accepting system capability.

The software needs to be prototyped and executed on the target processor. Measurements from the physical interfacing components (magnetic torquer, magnetometer, RWA) are needed to validate the simulation. Processor utilization needs to be measured to show the flight software is bounded by the capability of the processor. The relevant environment is already bounded by the heritage processor and evaluation of radiation effects by analysis.

2.5.4 <u>Subsystem Path to TRL 6</u>

Accounting for the interactions of the various components is critical to the performance of the ADCS subsystem. Consequently, component TRL is insufficient to establish the ADCS subsystem TRL. To demonstrate subsystem TRL 6, a prototype CubeSat with parameters relevant to ADCS testing (e.g., mass, moments-of-inertia), with prototype components appropriately mounted, and running the prototype software in the processor is needed. Testing is needed to demonstrate performance in a relevant environment. Simulation results used to demonstrate system-level performance should be anchored by documented test performance and include interactions of the various components. A combination of testing may be required since all aspects of the relevant environment may not be achievable simultaneously. For example: immersion into a Helmholtz cage may be required to emulate a realistic on-orbit, time-varying geomagnetic field to verify the magnetometer and magnetic torquer interactions. Simulations with an air bearing table may be used to verify the control interactions. These results may be combined analytically. The need for any of these tests to be conducted in vacuum should be assessed, with vacuum testing conducted as needed. TRL 6 is achieved with documented test results demonstrating agreement with the simulations and that all critical performance requirements are met.

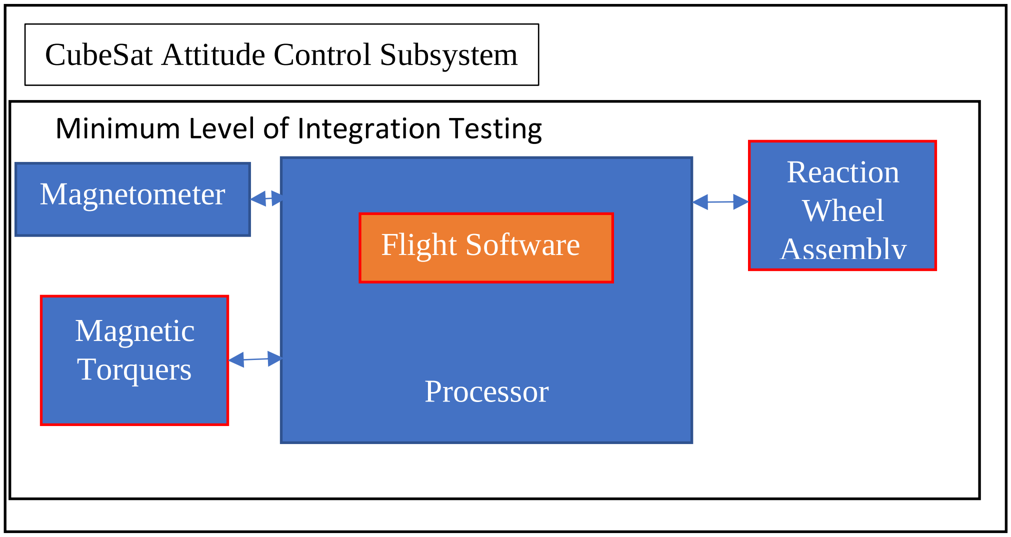

Figure 2.5-4. Example 5: ADCS Subsystem Minimum Level of Integration Testing