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Earth Systematic Missions Program
Technology Readiness Level Assessment Process

Goddard Space Flight Center

Greenbelt, Maryland

Earth Systematic Missions Program
Technology Readiness Level Assessment Process

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CHANGE RECORD PAGE

ISSUE	DATE	PAGES AFFECTED	DESCRIPTION
Baseline	June 2013	All	Approved By CCR 1007
Rev-A	September 2015	All	Approved By CCR TBD

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1. Purpose

This document provides a set of guidelines for the Earth Systematic Mission Program (ESMP) missions/projects to use in assessing the Technology Readiness Level (TRL) of components/instruments that are being considered or have been chosen to be used for flight. At periodic reviews of the mission development status where technology maturity is being reported to ESMP or NASA HQ, the process outlined in this document should be the basis for developing the reported technology levels.

2. Scope

In the past, TRL determination has been performed by missions/projects using an informal process and peer review has not been consistently applied. The TRL Workbook (Appendix D) was developed by the Earth Science Technology Office (ESTO) to evaluate new technologies intended for use in new Earth Science projects. Use of the TRL Workbook using the guidelines in this document, is intended to make TRL reporting more consistent and comparable across the ESMP. Help in completing the Workbook is available upon request from ESTO and the ESMP Systems Engineering Working Group (SEWG). Additionally, peer review of the completed Workbook is available from the ESMP SEWG. Each individual Project is responsible for completing the Workbook and is encouraged to use the resources offered from ESTO and the SEWG. Each NASA Center may also have requirements for management review of TRL reports, and those internal requirements are not affected by this document.

All definitions and exit criteria within the workbook, as included in Appendix A of this document, are in accordance with NPR 7123.1B.

3. Reference Documents

Document No.	Document Title
NPR 7120.5	NASA Program and Project Management Processes and Requirements
NPR 7123.1	NASA Systems Engineering Processes and Requirements
NPR 7120.8	NASA Research and Technology Program and Project Management Requirements
NASA/SP-2007-6105	NASA Systems Engineering Handbook

Document No.	Document Title
420-01-01	ESM Program Plan
N/A	Technology Readiness Level White Paper, April 6, 1995, John C. Mankins, Office of Space Access and Technology

4. Applicability

This guideline applies to all Missions and Projects within the Earth Systematic Missions Program.

5. Authority

NPR 7120.5 – NASA Program and Project Management Processes and Requirements

6. Proprietary Data Protection

The ESM Program Office, ESTO, and NASA HQ recognize that most missions and projects in the pre-formulation and formulation phases are in a competitive environment and project managers may be reluctant to share certain technical information with potential competitors. Project management should indicate which TRL assessment data they consider to be "competition sensitive", and that information will not be shared with other projects without permission.

The ESM Program Office and ESTO will review all TRL assessments and will forward the assessments, with comments, to NASA HQ. NASA HQ will be requested to not disclose "competition sensitive" data to other projects.

7. Process and Procedure

Each Mission or Project within the ESMP is required to provide technology assessments during the Pre-Formulation and Formulation phases of development. Mission/Project management is requested to provide these assessments using the TRL Workbook. The Mission/Project should use the following general process prior to representing a TRL assessment to ESMP or NASA HQ.

- Project management should assign an assessor with appropriate knowledge, experience, and abilities to provide a thorough assessment.
- The assessor should follow the methodology outlined below in Section 7, with subject matter expert advice, to perform the assessment.

- The assessor should work with ESTO and SEWG on a collaborative basis to ensure data is consistent with the workbook and within Appendix A definitions and exit criteria of NPR 7123.1 and that TRL assessments/levels are supported by documented evidence.
- Project management should ensure that any NASA Center level management approvals or peer reviews are obtained if required.

Project management should submit a copy of the completed Workbook to the ESMP SEWG prior to presenting TRL assessments to ESMP or NASA HQ.

8. Assessment Methodology

The TRL Workbook (Appendix D) is used by the technology assessor to record the TRL of the product under evaluation. The workbook provides a template for performing an evaluation in accordance with the Systems Engineering Handbook, Appendix G, Technology Assessment/Insertion. The TRL definitions are established by NPR 7123.1, and are reproduced in Appendix A. If the TRL qualifications are met, and can be substantiated with documented evidence, the technology can be assigned that level in the TRL Workbook. The TRL Assessment Worksheet itemizes the parts of a system and tabulates the rationale for the TRL assigned to the components, subsystems and the overall system. The output of this tool is the TRL for that product at the time of the assessment. The final report consists of the completed workbook and all associated justifications. Note that the justifications are the crucial element in documenting the rationale for any given TRL assessment. Each justification should be of sufficient detail to explain the rationale.

9. Completing the TRL Workbook

Tab 1, Instructions, of the TRL Workbook provides instructions to be followed in completing the TRL assessment for the items being assessed.

10. Summary

Creating a TRL Assessment should not be a difficult process for any Project. The only "tool" required by this process is Microsoft EXCEL®. The Product Breakdown Structure should be the same one used for cost estimates, etc. If the technologies involved have been funded by ESTO, there will already be workbooks for these items which can be adapted. The goal of a TRL assessment is to ensure that all technology areas are being addressed and to highlight those needing further efforts to improve their readiness for use. The goal of a Program-level process is to ensure consistency in these assessments across all Missions and Projects within the ESMP.

Appendix A - Technology Readiness Levels (from NPR 7123.1B)

TRL	Definition	Hardware Description	Software Description	Exit Criteria
1	Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated.	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulations validate analytical prediction.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experimental results validating predictions of key parameters.

TRL	Definition	Hardware Description	Software Description	Exit Criteria
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.	Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant environments defined and performance in this environment predicted.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	End-to-end software elements implemented and interfaced with existing systems/ simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.

TRL	Definition	Hardware Description	Software Description	Exit Criteria
6	System/sub-system model or prototype demonstration in a relevant environment.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.
7	System prototype demonstration in operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test performance demonstrating agreement with analytical predictions.

TRL	Definition	Hardware Description	Software Description	Exit Criteria
8	Actual system completed and “flight qualified” through test and demonstration.	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed.	Documented test performance verifying analytical predictions.
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment.	Documented mission operational results.

Appendix B - Technology Development Terminology

Proof of Concept: Analytical and experimental demonstration of hardware/software concepts that may or may not be incorporated into subsequent development and/or operational units.

Breadboard: A low fidelity unit that demonstrates function only, without respect to form or fit in the case of hardware, or platform in the case of software. It often uses commercial and/or ad hoc components and is not intended to provide definitive information regarding operational performance.

Brassboard: A medium fidelity functional unit that typically tries to make use of as much operational hardware/software as possible and begins to address scaling issues associated with the operational system. It does not have the engineering pedigree in all aspects, but is structured to be able to operate in simulated operational environments in order to assess performance of critical functions.

Proto-type Unit: The proto-type unit demonstrates form, fit, and function at a scale deemed to be representative of the final product operating in its operational environment. A subscale test article provides fidelity sufficient to permit validation of analytical models capable of predicting the behavior of full-scale systems in an operational environment

Engineering Unit: A high fidelity unit that demonstrates critical aspects of the engineering processes involved in the development of the operational unit. Engineering test units are intended to closely resemble the final product (hardware/software) to the maximum extent possible and are built and tested so as to establish confidence that the design will function in the expected environments. In some cases, the engineering unit will become the final product, assuming proper traceability has been exercised over the components and hardware handling.

Mission Configuration: The final architecture/system design of the product that will be used in the operational environment. If the product is a subsystem/component, then it is embedded in the actual system in the actual configuration used in operation.

Laboratory Environment: An environment that does not address in any manner the environment to be encountered by the system, subsystem, or component (hardware or software) during its intended operation. Tests in a laboratory environment are solely for the purpose of demonstrating the underlying principles of technical performance (functions), without respect to the impact of environment.

Relevant Environment: Not all systems, subsystems, and/or components need to be operated in the operational environment in order to satisfactorily address performance margin requirements. Consequently, the relevant environment is the specific subset of the operational environment that is required to demonstrate critical "at risk" aspects of the final product performance in an operational environment. It is an environment that focuses specifically on "stressing" the technology advance in question.

Operational Environment: The environment in which the final product will be operated. In the case of space flight hardware/software, it is space. In the case of ground-based or airborne systems that are not directed toward space flight, it will be the environments defined by the scope of operations. For software, the environment will be defined by the operational platform.

Appendix C – Acronyms

ESMP	Earth Systematic Missions Program
ESPD	Earth Science Projects Division (GSFC)
ESTO	Earth Science Technology Office
GSFC	Goddard Space Flight Center
HQ	NASA Headquarters
NASA	National Aeronautics and Space Administration
NPR	NASA Procedural Requirement
SEWG	Systems Engineering Working Group
SRR	Systems Requirements Review
TRL	Technology Readiness Level

Appendix D – TRL Assessment Workbook

For public access to the current version of the ESMP TRL process document and the TRL Assessment Workbook, see:

http://espd.gsfc.nasa.gov/TRL/

It is included in Portable Document Format (PDF) form in this appendix on the following pages.

Introduction

This spreadsheet is the tool that is to be used during the Technology Maturity Assessment (TMA) of a product. The output of this tool is the Technology Readiness Level (TRL) for that product at the time of the assessment. The TRL scale is defined on the TRL Definitions tab and is the basis for this tool. This approach is hierarchical and develops TRLs for the component, subsystem, system and product levels as described in the Instructions tab. An operational environment (space or airborne) must be specified and all TRLs judged with that environment as the context.

The final report consists of this completed workbook and all associated **justifications.** Note that the justifications are the crucial element in documenting the rationale for any given TRL assessment. Each justification should be of sufficient detail to explain the rationale.

Arrangement of this Workbook

This workbook includes seven worksheets, or tabs. Tab 1 is the Instructions tab. Tab 2 is the TRL Definitions, which includes definitions of the environments and the hardware/software model fidelity levels. Tab 3 is the INFLAME Block Diagram as an illustration/example, and Tab 4 is the INFLAME example. Tab 5 is the Product Block Diagram, which the user is to provide, and Tab 6 is the New TRL Worksheet which the user is to complete. Tab 7 is Background – Guidance, which is information on reference material for NASA TRLs.

Instructions

The following steps should be followed for each product assessment. An example assessment is provided on the INFLAME Example tab. These steps are intended to be an implementation of the process for performing a **Technology Maturity Assessment**, as described in The NASA Systems Engineering Handbook (NSEH), NASA/SP-2007-6105, Rev 1, Appendix G: Technology Assessment/Insertion.

1. Provide a **Functional Block Diagram** of the product that is aligned with and identifies the elements of the Product Breakdown Structure, and place it on the worksheet tab labeled "Product Block Diagram". Note that System, Subsystem and Component is a standard breakdown used in the Goddard Environmental Verification Specification (GEVS) and the TRL definitions, but an evaluator can use their hierarchy nomenclature if it is beneficial.

2. Describe the product being analyzed in a hierarchical Product Breakdown Structure (PBS) format (product / systems / subsystems / components) in the worksheet tab labeled "6. New TRL Worksheet". Further guidance on a PBS is in the NSEH, in App. G and in 4.3.2, Logical Decomposition Guidance. The number of hierarchical levels shall be limited to the minimum necessary to describe the individual technologies being developed. The terminology used to describe the product hierarchy (i.e. product / system / subsystem / component or other) is left to the discretion of the team performing the assessment but terminology other than that provided will require the provision of an index/key. When performing the assessment, refer to these "1. Instructions", the "2. TRL Definitions" and the "4. INFLAME Example" worksheets as necessary. Add pairs of rows for components, and larger blocks of rows for subsystems and systems, as needed to match the PBS.

3. Identify the product operational and relevant environments in accordance with the definitions provided on the worksheet labeled "2. TRL Definitions". The relevant environment may be different for elements of the system, depending on the most stressing environment affecting that element.

4. For mature elements of the system, use the simplified form (in blue). Keep the left-most column, "Component 2.1.2" or similar, but replace the text in the next field with your item name. Fill in the columns to the right with the highest TRL justified ("6", "8", etc.) in terms of model/hardware fidelity, environment, performance/function verification, verification documentation, and form/fit/function. The 'Description' field should briefly describe the element of the product, and summarize the rationale for its TRL. Summarize the flight history (also known as 'heritage') or prior development, and justify the applicability of the prior work to a rating of TRL of 6 or higher to the element. Confirm that performance and demonstrated survival and/or performance in applicable environmental conditions have been evaluated and confirmed.

5. For any Component (or other level of assembly) with New Technology, create a separate group of lines for each New Technology (in pink). Fill in the item name, and TRL levels for hardware fidelity, etc. (as above). Provide a description of the overall item, as above. For each New Technology description, provide the name of the new technology after "Key Technology", and provide a description. Provide the Development Status, addressing development model fidelity, testing and analysis performed, etc. Summarize the justification for the overall TRL based on the considerations of model fidelity, relevant or operational environment, testing completed, etc.

Optional: If NASA’s Earth Science Technology Office (ESTO) has funded development, include the information from the most recent ESTO review for the "Previous Tech Dev. (e.g. ESTO)" Columns.

Model/Hardware Fidelity: Refer to the TRL Definitions tab of this workbook for the Hardware/Software Definitions. Note that there is a tie-in to/between the Model/Hardware Fidelity and the Unit Description.

Environment: Refer to the TRL Definitions tab of this workbook for the Environment Definitions.

Performance/Function Verification: Refer to the TRL Definitions tab of this workbook for the Technology Readiness Level Definitions. For hardware, use the Hardware Description, and for software, use the Software Description. Note that in case of ambiguity between the Definition column and the other two, favor the two description columns over the Definition column. Note that there is a tie-in to/between the Performance/Function Verification and the Unit Description.

Verification Documentation: Refer to the TRL Definitions tab of this workbook for the Technology Readiness Level Definitions, Exit Criteria column.

Unit Description: Check the **Form**, **Fit** and **Function** columns as appropriate relative to the unit configuration. If the unit configuration is full (100%) scale, then that column should also be checked. If the unit is less than full scale, please indicate the unit scaling, either as a percentage (XX%) or as a fractional representation (i.e. 1/4, 1/2, 3/4...). Completing these columns should aid in determining the Model Fidelity. Note that an element that functions but does not meet the final product requirements for form, fit and scaling would be classified as a **Breadboard**. An element that functions and meets the final product requirements for form and fit but not those for scaling would be classified as a **Brassboard**. An element that functions and meets the product requirements for form, fit and scaling would be classified as a **Proto-type Unit** or better.

Implementation / Make/Buy: Note whether the item will be produced by the prime developer, or procured. List the vendor, if available.

TRL: Based on the entries in the other columns, determine the TRL and list it under the System, Subsystem or Component heading. The TRL will be limited by the lowest number assigned in the columns G thru AJ.

6. **Roll-up of TRL:** The TRL at one level of integration must not be higher than the lowest TRL of all constituent items. From the SE Handbook, "The TRL of the system is determined by the lowest TRL present in the system." Integration challenges should be identified, and the SE Handbook calls for consideration of the "TRL state of integration." In practice, the TRL is rarely limited by considerations of integration, except for when development of the integration approach is a major part of the development effort, making integration a New Technology item. If a simple roll-up from lower levels of assembly is used, no further explanation is needed. If TRL state of integration is used, it should be explained.

7. **Header and Footer:** Edit the header and footer of the Product Block Diagram and New TRL Worksheet tabs with information that identifies the name of the product, Date completed, and any other pertinent information.

8. **Competition Sensitive or other restrictions:** If the content of a completed worksheet is competition sensitive or otherwise restricted (ITAR, etc.), this should be clearly designated in the upper-left-hand-corner title block of the New TRL worksheet, as well as in the footer of the Product Block Diagram (if applicable) and New TRL Workbook tabs.

Special Considerations:

Mission Equipment List: The Product Breakdown Structure is generally not a Mission Equipment List. The PBS is generally at less granularity, and does not include details such as part number, mass, power, etc. Note that filling in a column for TRL in a MEL can be a good first step in a Technology Maturity Assessment, followed by focusing in on New Technology using this workbook.

System Cost Estimation: Many parametric cost estimating tools use TRL or a similar measure of maturity in their calculations. For this, every item in the MEL may need a TRL assigned. This workbook is not intended to serve this purpose. However, a team preparing to perform a parametric cost estimate might use this tool to provide further detail and justification for the TRL of key New Technology items.

Presentations or Reports: The completed workbook must be accompanied by a presentation explaining the instrument and the development accomplished so far. A presentation should include background material, with key information such as the objectives and requirements for the instrument, a product breakdown functional diagram, prior work, current status, future plans, in addition to filling out the workbook per the instructions. The workbook is a place to pull the relevant details together to allow a succinct snapshot of the current state of development. The presentation also helps a reviewer understand the system and its state of development.

Treatment of previously flown items. If it is not immediately clear that a previously flown item will be used in a way that allows it to be considered TRL 9 for the new system, its assessed maturity is initially reduced to TRL 5. The TRL can be raised by conducting further analysis or testing. The worksheet should record what is needed to bring the heritage hardware up to TRL 6 for the new system.

Special Instructions: A request for a technology maturation assessment may be made with specific instructions. These should supersede the instructions in this workbook in case of a conflict. For example, if preparing a proposal in response to an Announcement of Opportunity, instructions in the AO take precedence.

Software TRL: For software, the code is usually going to be produced using conventional high-level languages, using well-known compilers and programming techniques, and should not then be considered new technology. While software TRL definitions were added recently, there is not general agreement on their use. Issues in using the current TRL definitions is explored in Seablom 2012, who finds that because of the growing complexity of software systems, the existing software TRL assessment process will be increasingly inadequate going forward and an enhancement to the existing software TRL definitions is in order.

Electronics. There are certain special cases which are worthy of specific guidance. One of these is electronics. For electronics, a convention has been adopted at the GSFC which the SEWG team finds very useful. If an electronics box has been determined to be able to be produced with existing parts that are flight-qualified for the relevant environment (including radiation), using conventional assembly methods, then it can be assigned a TRL of 6 for the application in question, and use the simplified form (in blue). There is still development risk, but it is not technology risk.

Engineering Development versus New Technology: For guidance on how to distinguish between technology development and engineering development, refer to NPR 7120.5E, Appendix F.3, Formulation Agreement Template, Section 8.0, Technology Readiness Assessment and Development, and Section 9.0, Engineering Development Assessment, Prototyping, and Software Models.

Formatting Note: For legibility, feel free to change the page layout setting for the New TRL Worksheet for Size to [Tabloid, 11" x 17"]. Alternately, this can be done at the time of printing.

This workbook, in Excel ™ format, plus the Earth Systematic Missions Program Technology Readiness Assessment Process document, can be obtained at:
http://espd.gsfc.nasa.gov/TRL

Technology Readiness Level Definitions [Taken from NPR 7123.1B, NASA Systems Engineering Processes and Requirements, Appendix		
Technology Readiness Level (TRL)	**Definition**	**Hardware Description**
1	Basic principles observed and reported	Scientific knowledge generated underpinning hardware technology concepts/applications.
2	Technology concept and/or application formulated	Invention begins, practical applications is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.
3	Analytical and experimental critical function and/or characteristic proof-of-concept	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to final operating environment.
5	Component and/or breadboard validation in relevant environment. Component and/or breadboard validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrate overall performance in critical areas. Performance predictions are made for subsequent development phases.
6	System/sub-system model or prototype demonstration in a relevant environment.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.

7	System prototype demonstration in an operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne or space).
8	Actual system completed and "flight qualified" through test and demonstration.	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.
Hardware/Software Definitions [Taken from NPR 7120.8, Appendix J, Technology Development Terminology inclusive of all changes thru		
Proof of Concept: Analytical and experimental demonstration of hardware/software concepts that may or may not be incorporated into subsequent development and/or operational units.	**Breadboard**: A low fidelity unit that demonstrates function only, without respect to form or fit in the case of hardware, or platform in the case of software. It often uses commercial and/or ad hoc components and is not intended to provide definitive information regarding operational performance.	**Brassboard**: A medium fidelity functional unit that typically tries to make use of as much operational hardware/software as possible and begins to address scaling issues associated with the operational system. It does not have the engineering pedigree in all aspects, but is structured to be able to operate in simulated operational environments in order to assess performance of critical functions.
Environment Definitions [Taken from NPR 7120.8, Appendix J, Technology Development Terminology inclusive of all changes thru #3 dat		

Laboratory Environment: An environment that does not address in any manner the environment to be encountered by the system, subsystem, or component (hardware or software) during its intended operation tests in a laboratory environment are solely for the purpose of demonstrating the underlying principles of technical performance (functions) without respect to the impact of environment.	**Relevant Environment**: Not all systems, subsystems, and/or components need to be operated in the operational environment in order to satisfactorily address performance margin requirements. Consequently, the relevant environment is the specific subset of the operational environment that is required to demonstrate critical "at risk" aspects of the final product performance in an operational environment. It is an environment that focuses specifically on "stressing" the technology advance in question.*	**Operational Environment**: The environment in which the final product will be operated. In the case of space flight hardware/software, it is space*. In the case of ground-based or airborne systems that are not directed toward space flight, it will be the environments defined by the scope of operations. For software, the environment will be defined by the operational platform.

* By convention, if the operational environment is 'Space', the operational environment, and often the relevant environment, includes launch.

E, Technology Readiness Levels inclusive of all changes thru #3 dated April 13, 2015]

Software Description	Exit Criteria
Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
Practical application is identified but is speculative; no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations, and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experimental results validating predictions of key parameters.
Key, functionality critical software components are integrated and functionally validated to establish interoperability and begin architecture development. Relevant environments defined and performance in the environment predicted.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.
Prototype implementations of the software demonstrated on full-scale, realistic problems. Partially integrated with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.

Cell Color Key
Red (TRL $\leq$ 2)
Orange (TRL 3)
Tan (TRL 4)
Yellow (TRL 5)
Green (TRL $\geq$ 6)

Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test performance demonstrating agreement with analytical predictions.
All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and validation completed.	Documented test performance verifying analytical predictions.
All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All documentation has been completed. Sustaining software support is in place. System has been successfully operated in the operational environment.	Documented mission operational results.

#3 dated April 18, 2013]

Proto-type Unit: The proto-type unit demonstrates form, fit, and function at a scale deemed to be representative of the final product operating in its operational environment. A subscale test article provides fidelity sufficient to permit validation of analytical models capable of predicting the behavior of full-scale systems in an operational environment.	**Engineering Unit**: A high fidelity unit that demonstrates critical aspects of the engineering processes involved in the development of the operational unit. Engineering test units are intended to closely resemble the final product (hardware/software) to the maximum extent possible and are built and tested so as to establish confidence that the design will function in the expected environments. In some cases, the engineering unit will become the final product, assuming proper traceability has been exercised over the components and hardware handling.	**Mission Configuration**: The final architecture/system design of the product that will be used in the operational environment. If the product is a subsystem/component, then it is embedded in the actual system in the actual configuration used in operation.

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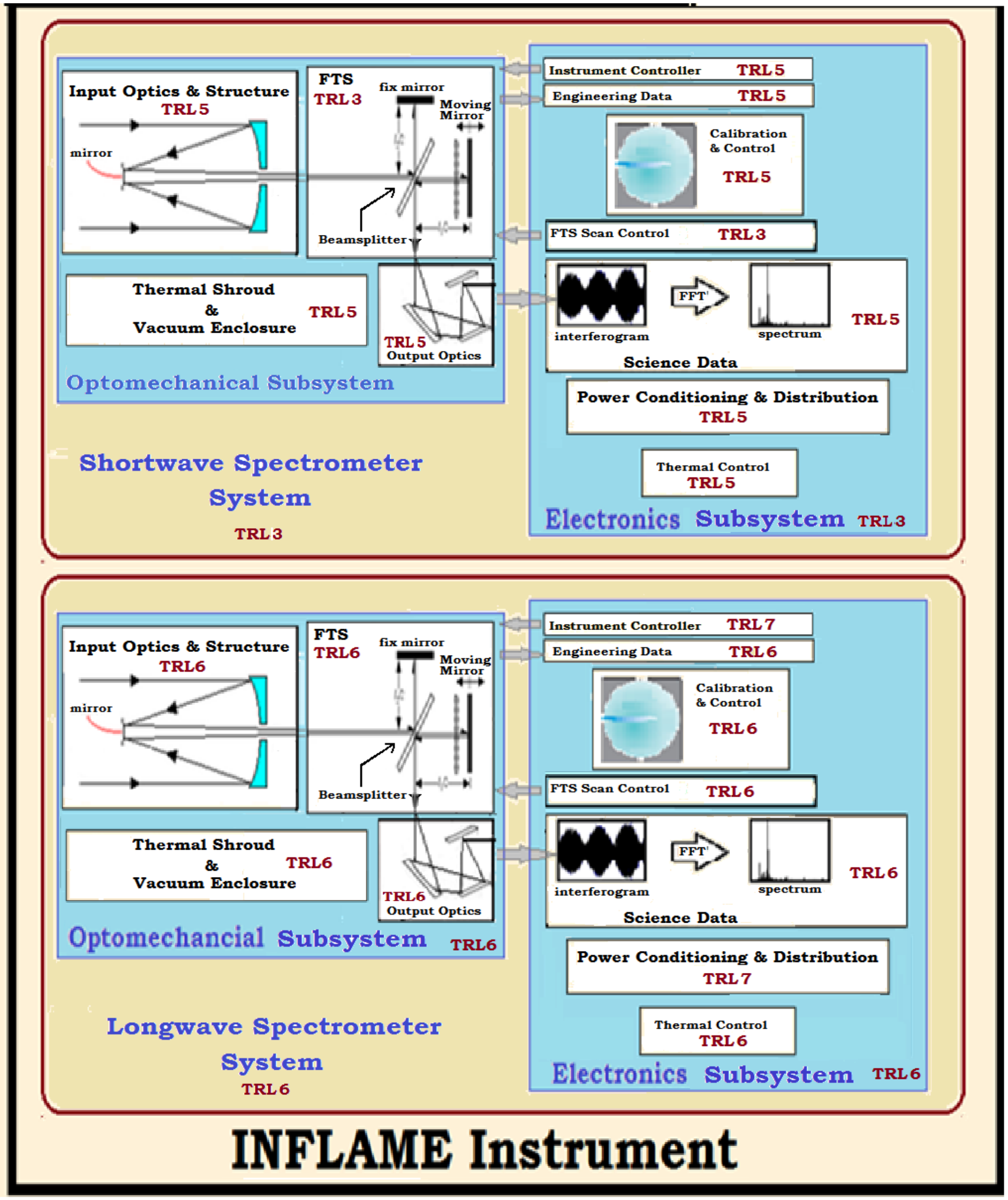
Input Optics & Structure
TRL 5
mirror
FTS
TRL 3
fix mirror
Moving Mirror
Beamsplitter
Thermal Shroud & Vacuum Enclosure
TRL 5
TRL 5
Output Optics
Optomechanical Subsystem
Shortwave Spectrometer System
TRL 3
Instrument Controller TRL 5
Engineering Data TRL 5
Calibration & Control
TRL 5
FTS Scan Control TRL 3
FFT
interferogram
spectrum
TRL 5
Science Data
Power Conditioning & Distribution
TRL 5
Thermal Control
TRL 5
Electronics Subsystem TRL 3
Input Optics & Structure
TRL6
mirror
FTS
TRL6
fix mirror
Moving Mirror
Beamsplitter
Thermal Shroud & Vacuum Enclosure
TRL6
TRL6
Output Optics
Optomechancial Subsystem TRL6
Longwave Spectrometer System
TRL6
Instrument Controller TRL 7
Engineering Data TRL 6
Calibration & Control
TRL 6
FTS Scan Control TRL 6
FFT
interferogram
spectrum
TRL 6
Science Data
Power Conditioning & Distribution
TRL 7
Thermal Control
TRL 6
Electronics Subsystem TRL6
INFLAME Instrument

Hierarchical Levels & New Technologies (Note: provide TRL justification for each new technology & for heritage rollups)		Previous Tech Dev. (e.g. ESTO)			Model/Hardware Fidelity	Environment	Performance/Function Verification	Verification Documentation (A, T, D)	Unit Description				Implementation	TRL		
					1 2 3 4 5 6 7 ≥8	≤3 4 5 6 ≥7	1 2 3 4 5 6 7 8 9	1 2 3 4 5 6/7 8 9					Make/Buy			
		TRL (in)	TRL (current)	Date	Scientific Basis Established; Application Identified; Proof of Concept; Breadboard; Brassboard; Prototype; Engineering Unit; Mission Configuration	N/A; Laboratory; Relevant; Relevant; Operational	Basic Principles Observed; Technology Concept Formulated; Concept Demonstrated; Basic functionality demonstrated; Overall performance demonstrated; Operation in critical environments demonstrated; Performance in critical environments demonstrated; Flight qualification; Mission operation	Peer reviewed publication of concept; Concept feasibility and benefit; Analytical/experimental results of critical functions; Test performance and relevant environment; Definition of scaling requirements; Test performance matches analytical prediction; Flight qualification; Mission operation	Form	Fit	Function	Scale	Red (TRL ≤ 2); Orange (TRL 3); Tan (TRL 4); Yellow (TRL 5); Green (TRL ≥ 6)	System	Subsystem	Component
Product	**Product Name: INFLAME Instrument**															
Product Description	Longwave measurements below 1100 cm-1 are at TRL 7 as a result of the flight demonstration, but improvements to the LW and SW instruments are required to achieve the full wavelength coverage of 100-0.3 µm.															
Operational Environment Description		705 km, sun-synchronous orbit, 3 year mission duration,														
Relevant Environment Description		Vibration testing of shortwave optomechanical assemblies. Thermal vacuum testing of Electronics subsystem assemblies. Demonstrate control of shear with FTS followed by thermal vacuum testing of shear control														
System 1	***Longwave Spectrometer***												Both	6		
System 1 Description	This system consists of an optomechanical subsystem and an electronic subsystem which performs the power conditioning, instrument, thermal and calibration control and data acquisition functions. The system consists of subsystems with components supplied from both in house sources and procured from vendors. The system was designed, assembled and tested in house. During airborne and environmental testing, this system met all specified requirements.															
Subsystem 1.1	Optomechanical												Both		6	
Subsystem 1.1 Description	This subsystem is comprised of four components; a Fourier Transfer Spectrometer, input optics and associated structure, output optics and associated structure and a combination thermal shroud and vacuum enclosure. The subsystem components are supplied from both in house sources and procured from vendors. The subsystem was designed, assembled and tested in house. During airborne and environmental testing, the subsystem met all specified requirements.															
Component 1.1.1	Fourier Transform Spectrometer (FTS)				6	6	6	6	✓	✓	✓	✓	Both			6
Component 1.1.1 Description	This component consists of a bilayer pellicle beamsplitter, a fixed corner cube mirror and mount and a Lead Zirconate Titantate (PZT) peizo-electric actuated translation stage. This component was designed and assembled in house using in house fabricated parts and parts procured from vendors built to supplied specifications. The beamsplitter was supplied by Smithsonian Astrophysical Observatory, the cornercube was supplied by Newport Optics and the translation stage was supplied by Physik Instrumente. During airborne and environmental testing, this component met all specified requirements.															
Component 1.1.2	Input optics & structure				6	6	6	6	✓	✓	✓	✓	Both			6
Component 1.1.2 Description	This component consists of a compound parabolic concentrator (CPC), a flip mirror and associated actuators and two temperature-controlled miniature blackbody calibration sources. This component was designed and assembled in house using in house fabricated parts and parts procured from vendors built to supplied specifications. The optics were supplied by ProSystems, Inc., the CPC was supplied by IR Laboratories, the actuators were supplied by Firgelli and the lamps for the calibration sources were supplied by Carley Lamps, Inc. During airborne and environmental testing, this component met all specified requirements.															
Component 1.1.3	Output optics & structure				6	6	6	6	✓	✓	✓	✓	Both			6
Component 1.1.3 Description	This component consists of a compound parabolic concentrator (CPC), a pyroelectric detector assembly and associated optics. This component was designed and assembled in house using in house fabricated parts and parts procured from vendors built to supplied specifications. The CPC was supplied by IR Laboratories, the detector was supplied by Goodrich and the optics were supplied by ProSystems, Inc. During airborne and environmental testing, this component met all specified requirements.															
Component 1.1.4	Thermal shroud & vacuum enclosure				6	6	6	6	✓	✓	✓	✓	Make			6
Component 1.1.4 Description	The thermal shroud and vacuum enclosure provides control of the thermal environment and maintains a vacuum environment for FTS and input and output optics. This component was designed, fabricated and assembled in house. During airborne and environmental testing, this component met all specified requirements. This component employs no new technology.															
Subsystem 1.2	Electronics												Both		6	
Subsystem 1.2 Description	This subsystem is comprised of seven components; the scan control electronics (card) for the Fourier Transfer Spectrometer (FTS) PZT translation stage, the electronics for science data acquisition (card), the electronics for engineering data acquisition (card) the control electronics (card) for the calibration source, the control electronics (card) for thermal control, the control electronics (card) for the instrument and the power conditioning electronics (card). The subsystem components are supplied from both in house sources and procured from vendors. The subsystem was designed, assembled and tested in house. During airborne and environmental testing, the subsystem met all specified requirements.															
Component 1.2.1	FTS scan control				6	6	6	6	✓	✓	✓	✓	Buy			6
Component 1.2.1 Description	This component controls the actuation (position, velocity and acceleration) of the FTS PZT translation stage. This component was procured from FTS PZT translation stage provider, Physik Instrumente. During airborne and environmental testing, this component met all specified requirements. This component employs no new technology.															
Component 1.2.2	Science data acquisition				6	6	6	6	✓	✓	✓	✓	Both			6
Component 1.2.2 Description	This component provides signal conditioning and analog-to-digital conversion (3 channels) of science data. This component was designed in house and fabricated by RTD Embedded Technologies. During airborne and environmental testing, this component met all specified requirements.															

Component 1.2.3	Engineering data acquisition			6	6	6	6	✓ ✓ ✓ ✓	Both			**6**
Component 1.2.3 Description	This component provides signal conditioning and analog-to-digital conversion of engineering data. This component was designed and fabricated in house using electronic parts procured from multiple vendors. During airborne and environmental testing, this component met all specified requirements. This component employs no new technology.											
Component 1.2.4	Calibration source control			6	6	6	6	✓ ✓ ✓ ✓	Both			**6**
Component 1.2.4 Description	This component provides measurement and control of the of the blackbody cavity temperature used for instrument calibration. This component was designed and fabricated in house using electronic parts procured from multiple vendors. During airborne and environmental testing, the component met all requirements and was able to go from ambient temperature to +/- 20 °C about ambient and stabilize at the commanded temperature within 60s while meeting a commanded temperature accuracy of 0.1 °C.											
Component 1.2.5	Thermal control system			6	6	6	6	✓ ✓ ✓ ✓	Both			**6**
Component 1.2.5 Description	This component provides control of the optical bench temperature uniformity and drift. This component was designed and fabricated in house using parts procured from multiple vendors. During airborne and environmental testing, the optical bench temperature gradients and drift were controlled within specification and useful data was collected.											
Component 1.2.6	Instrument controller			7	7	7	7	✓ ✓ ✓ ✓	Buy			**7**
Component 1.2.6 Description	This component is a single board computer Commercial Off The Shelf (COTS) procurement from WinSystems which provides real time instrument control and data logging. The unit has space flight heritage but has not previously flown in the specified mission orbit. During airborne and environmental testing, the component executed the preprogrammed command sequence autonomously and flight data was logged flawlessly.											
Component 1.2.7	Power conditioning			7	7	7	7	✓ ✓ ✓ ✓	Buy			**7**
Component 1.2.7 Description	This component is a Commercial Off The Shelf (COTS) procurement from RTD Embedded Technologies. The unit has space flight heritage on multiple DOD classified missions but has not previously flown in the specified mission orbit and due to the nature of the heritage, the missions cannot be disclosed. This component is also heritage to the airborne test campaigns for the LW Spectrometer demonstration instrument.											
System 2	***Shortwave Spectrometer***								Both	**3**		
System 2 Description	This system is similar to/based upon the Longwave Spectrometer and consists of an optomechanical subsystem and an electronics subsystem which performs the power conditioning, instrument, thermal and calibration control and data acquisition functions. The system consists of subsystems with components supplied from both in house sources and procured from vendors. The system was designed, assembled and tested in house. Testing of this system has been limited due to problems with shear in the FTS and with temperature-dependent drift in the SW PZT controller.											
Subsystem 2.1	Optomechanical								Both		**3**	
Subsystem 2.1 Description	This subsystem is similar to/based upon the Optomechanical subsystem for the Longwave Spectrometer and is comprised of four components; a Fourier Transfer Spectrometer, input optics and associated structure, output optics and associated structure and a combination thermal shroud and vacuum enclosure. The subsystem components are supplied from both in house sources and procured from vendors. The subsystem was designed, assembled and tested in house. During airborne and environmental testing this subsystem was unable to demonstrate overall performance.											
Component 2.1.1	Fourier transform spectrometer (FTS)			5	4	4	3	✓ ✓ ✓	Both			**3**
Component 2.1.1 Description	This component is similar to/based upon the FTS for the Longwave Spectrometer and consists of a bilayer pellicle beamsplitter, a fixed corner cube mirror and mount and a Lead Zirconate Titantate (PZT) peizo-electric actuated translation stage. This component was designed and assembled in house using in house fabricated parts and parts procured from vendors built to supplied specifications. The beamsplitter was supplied by Rocky Mountain Instruments, Inc., the cornercube was supplied by Newport Optics and the translation stage was supplied by Physik Instrumente. During airborne and environmental testing this component failed to demonstrate overall performance. Component performance was limited by the ability to control shear, probably due to poor performance of corner cube adjustments.											
New Technology 2.1.1a	Low-OH fused silica beamsplitter and compensator pair	3 5	Jul-15	5	5	5	5	✓ ✓ ✓ ✓	Buy			**5**
New Technology 2.1.1a Description	Key Technology: Custom optical coatings											
Development Status	Currently as noted by assigned TRL while working toward TRL 6											
TRL Justifications	Test data for beamsplitter/compensator indicate requirements for efficiency were met over the desired range of wavelengths from 0.3 µm to 3 µm.											
New Technology 2.1.1b	Fixed corner cube mount			5	4	4	3	✓ ✓ ✓	Both			**3**
New Technology 2.1.1b Description	Key Technology: Corner cube with commercial adjustment stages.											
Development Status	Currently as noted by assigned TRL while working toward TRL 6											
TRL Justifications	The corner cube adjustment provides inadequate control, not meeting requirements or advertised performance.											
New Technology 2.1.1c	Translation stage (PZT)			5	4	5	5	✓ ✓ ✓ ✓	Buy			**4**
New Technology 2.1.1c Description	Key Technology: Enhanced performance/resolution piezo-electric actuator											
Development Status	Currently as noted by assigned TRL while working toward TRL 6											
TRL Justifications	Stage performed well during laboratory calibration but experienced a failure during flight (airborne) testing due to a known issue with the PZT controller.											
Component 2.1.2	Input optics & structure			5	4	4	5	✓ ✓ ✓ ✓	Both			**4**
Component 2.1.2 Description	This component is similar to/based upon the input optics and structure for the Longwave Spectrometer and consists of a compound parabolic concentrator (CPC), a flip mirror and associated actuators and two temperature-controlled miniature blackbody calibration sources. This component was designed and assembled in house using in house fabricated parts and parts procured from vendors built to supplied specifications. The optics were supplied by ProSystems, Inc., the CPC was supplied by IR Laboratories, the actuators were supplied by Firgelli and the lamps for the calibration sources were supplied by Carley Lamps, Inc. During airborne and environmental testing this component demonstrated overall performance with the exception of the Compound Parabolic Concentrator (CPC).											
New Technology 2.1.2a	Input compound parabolic concentrator			5	4	4	5	✓ ✓ ✓ ✓	Buy			**4**
New Technology 2.1.2a Description	Key Technology: Design modifications to observe the SW spectrum											
Development Status	Currently as noted by assigned TRL while working toward TRL 6											
TRL Justifications	CPC provided desired collimation of input flux; angular acceptance was fully verified only during laboratory testing.											
New Technology 2.1.2b	Input flip mirror actuators			5	5	5	5	✓ ✓ ✓ ✓	Both			**5**
New Technology 2.1.2b Description	Key Technology: Design modifications to observe the SW spectrum											
Development Status	Currently as noted by assigned TRL while working toward TRL 6											
TRL Justifications	Performed well during lab calibration and flight.											
New Technology 2.1.2c	Long-life tungsten lamp calibration sources			5	5	5	5	✓ ✓ ✓ ✓	Both			**5**
New Technology 2.1.2c Description	Key Technology: Design modifications for calibration in the SW spectrum inclusive of new/different lamps											
Development Status	Currently as noted by assigned TRL while working toward TRL 6											
TRL Justifications	Performed well during lab calibration and flight.											

Component 2.1.3	Output optics & structure			5	5	5	5	✓	✓	✓	✓	Both			**5**
Component 2.1.3 Description	This component is similar to/based upon the output optics and structure for the Longwave Spectrometer and consists of a compound parabolic concentrator (CPC), a pyroelectric detector assembly and associated optics. This component was designed and assembled in house using in house fabricated parts and parts procured from vendors built to supplied specifications. The CPC was supplied by IR Laboratories, the detector was supplied by Electro-Optical Systems and the optics were supplied by ProSystems, Inc. During airborne and environmental testing this component demonstrated overall performance.														
New Technology 2.1.3	Output CPC/multicolor detector assembly			5	5	5	5	✓	✓	✓	✓	Both			**5**
New Technology 2.1.3 Description	Key Technology: Design modifications to observe the SW spectrum inclusive of a redesigned optical path, new optics and a new detector														
Development Status	Currently as noted by assigned TRL while working toward TRL 6														
TRL Justifications	Performed well during lab calibration and flight.														
Component 2.1.4	Thermal shroud & vacuum enclosure			5	5	5	5	✓	✓	✓	✓	Both			**5**
Component 2.1.4 Description	This component is similar to/based upon the thermal shroud and vacuum enclosure for the Longwave Spectrometer. The thermal shroud and vacuum enclosure provides control of the thermal environment and maintains a vacuum environment for FTS and input and output optics. This component was designed, fabricated and assembled in house. During airborne and environmental testing this component demonstrated overall performance.														
New Technology 2.1.4	Thermal control using radiative shroud			5	5	5	5	✓	✓	✓	✓	Both			**5**
New Technology 2.1.4 Description	Key Technology: Design modifications to observe the SW spectrum inclusive of different component thermal fluxes and operational/non-operational temperature requirements and thermal control hardware														
Development Status	Currently as noted by assigned TRL while working toward TRL 6														
TRL Justifications	Performed well during lab calibration and flight.														
Subsystem 2.2	Electronics											Both		**3**	
Subsystem 2.2 Description	This subsystem is similar to/based upon the Electronics subsystem for the Longwave Spectrometer and is comprised of seven components; the scan control electronics (card) for the Fourier Transfer Spectrometer (FTS) PZT translation stage, the electronics for science data acquisition (card), the electronics for engineering data acquisition (card) the control electronics (card) for the calibration source, the control electronics (card) for thermal control, the control electronics (card) for the instrument and the power conditioning electronics (card). The subsystem components are supplied from both in house sources and procured from vendors. The subsystem was designed, assembled and tested in house. During airborne and environmental testing this subsystem was unable to demonstrate overall performance.														
Component 2.2.1	FTS scan control			5	4	3	3	✓	✓		✓	Buy			**3**
Component 2.2.1 Description	This component controls the actuation (position, velocity and acceleration) of the FTS PZT translation stage and is similar to/based upon the FTS scan controller for the Longwave Spectrometer but required modifications for position, velocity and acceleration range differences. This component was procured from FTS PZT translation stage provider, Physik Instrumente. During airborne and environmental testing, this component failed to meet all specified requirements. Component performance was limited by the ability to control shear due to temperature-dependent drift in the FTS														
New Technology 2.2.1	FTS scan control			5	4	3	3	✓	✓		✓	Buy			**3**
New Technology 2.2.1 Description	Key Technology: Replacement/enhancement of electronic components for a different position, velocity and acceleration range/envelope														
Development Status	Currently as noted by assigned TRL while working toward TRL 6														
TRL Justifications	The controller exhibited temperature-dependent drift ~10x greater than that of the LW controller.														
Component 2.2.2	Science data acquisition			5	5	5	5	✓	✓	✓	✓	Both			**5**
Component 2.2.2 Description	This component provides signal conditioning and analog-to-digital conversion of science data and is similar to/based upon the science data acquisition electronics for the Longwave Spectrometer but required modifications for 5 channels of data. During airborne and environmental testing this component demonstrated overall performance.														
New Technology 2.2.2	Signal conditioning & A/D convertor (5 channels)			5	5	5	5	✓	✓	✓	✓	Both			**5**
New Technology 2.2.2 Description	Key Technology: Redesign and replacement/enhancement of electronic components to accommodate more (5 versus the previous 3 for the LW spectrometer) data channels														
Development Status	Currently as noted by assigned TRL while working toward TRL 6														
TRL Justifications	Performed well during lab calibration and flight.														
Component 2.2.3	Engineering data acquisition			5	5	5	5	✓	✓	✓	✓	Both			**5**
Component 2.2.3 Description	This component provides signal conditioning and analog-to-digital conversion of engineering data and is similar to/based upon the engineering data acquisition electronics for the Longwave Spectrometer but required modifications to accommodate different data ranges required for the Shortwave Spectrometer. During airborne and environmental testing this component demonstrated overall performance.														
New Technology 2.2.3	Conditioning & A/D conversion			5	5	5	5	✓	✓	✓	✓	Both			**5**
New Technology 2.2.3 Description	Key Technology: Replacement/enhancement of electronic components for a different operational/non-operational data ranges/envelopes														
Development Status	Currently as noted by assigned TRL while working toward TRL 6														
TRL Justifications	Performed well during lab calibration and flight.														
Component 2.2.4	Calibration source control			5	5	5	5	✓	✓	✓	✓	Both			**5**
Component 2.2.4 Description	This component provides measurement and control of the of the blackbody cavity temperature used for instrument calibration and is similar to/based upon the Calibration Source Controller for the Longwave Spectrometer but required modifications to meet the both the thermal environment and calibration control specifications for the SW Spectrometer. During airborne and environmental testing, the component demonstrated overall performance and was able to go from ambient temperature to +/- 20 °C about ambient and stabilize at the commanded temperature within 60s while meeting a commanded temperature accuracy of 0.1 °C.														
New Technology 2.2.4	Conditioning & A/D conversion			5	5	5	5	✓	✓	✓	✓	Both			**5**
New Technology 2.2.4 Description	Key Technology: Replacement/enhancement of electronic components for a different operational/non-operational temperature environment range/envelope and different source lamp voltage input/thermal and spectral output characteristics														
Development Status	Currently as noted by assigned TRL while working toward TRL 6														
TRL Justifications	Performed well during lab calibration and flight.														
Component 2.2.5	Thermal control system			5	5	5	5	✓	✓	✓	✓	Both			**5**
Component 2.2.5 Description	This component provides control of optical bench temperature uniformity and drift and is similar to/based upon the Thermal Controller for the Longwave Spectrometer but required modifications to meet the both the thermal environment and thermal control specifications for the SW Spectrometer. During airborne and environmental testing this component demonstrated overall performance.														
New Technology 2.2.5	Control of optical bench temperature uniformity			5	5	5	5	✓	✓	✓	✓	Both			**5**
New Technology 2.2.5 Description	Key Technology: Replacement/enhancement of electronic components for a different operational/non-operational temperature environment range/envelope and thermal control requirements														
Development Status	Currently as noted by assigned TRL while working toward TRL 6														
TRL Justifications	Performed well on the ground over a range of environment temperatures as demonstrated by repeatability of visible interferogram peaks once TCS had brought the optical bench back up to operating temperature.														
Component 2.2.6	Instrument Controller			5	5	5	5	✓	✓	✓	✓	Buy			**5**

Component 2.2.6 Description	This component is single board computer Commercial Off The Shelf (COTS) procurement from WinSystems and is similar to/based upon the Instrument Controller for the Longwave Spectrometer but required modifications to meet the thermal environment specifications for the SW Spectrometer. The component is heritage to the airborne test campaigns for the SW Spectrometer demonstration instrument. During airborne and environmental testing this component demonstrated overall performance.														
New Technology 2.2.6	Real time instrument control and data logging			5	5	5	5	✓	✓	✓	✓	Buy			5
New Technology 2.2.6 Description	Key Technology: Replacement/enhancement of electronic components for a different operational/non-operational temperature environment range/envelope														
Development Status	Currently as noted by assigned TRL while working toward TRL 6														
TRL Justifications	Commercial single-board computer. Performed well during lab calibration and flight (airborne) testing.														
Component 2.2.7	Power Conditioning			5	5	5	5	✓	✓	✓	✓	Buy			5
Component 2.2.7 Description	This component is a Commercial Off The Shelf (COTS) procurement from RTD Embedded Technologies and is similar to/based upon the Power Conditioning for the Longwave Spectrometer but required modifications to meet the thermal environment specifications for the SW Spectrometer and to produce the specified output voltages and tolerances. This component is heritage to the airborne test campaigns for the SW Spectrometer demonstration instrument. During airborne and environmental testing this component demonstrated overall performance.														
New Technology 2.2.7	Control of voltage stability and drift			5	5	5	5	✓	✓	✓	✓	Buy			5
New Technology 2.2.7 Description	Key Technology: Replacement/enhancement of electronic components for a different operational/non-operational temperature range/envelope and different operational/non-operational voltage outputs and tolerances														
Development Status	Currently as noted by assigned TRL while working toward TRL 6														
TRL Justifications	Commercial avionics power supply. Performed well during lab calibration and flight (airborne) testing.														

Insert the Product Functional Block Diagram on this worksheet

Hierarchical Levels & New Technologies (Note: provide TRL justification for each new technology & for heritage rollups)	Previous Tech Dev. (e.g. ESTO)	Model/Hardware Fidelity	Environment	Performance/Function Verification	Verification Documentation (A, T, D)	Unit Description	Implementation	TRL
		1 2 3 4 5 6 7 ≥8	≤3 4 5 6 ≥7	1 2 3 4 5 6 7 8 9	1 2 3 4 5 6/7 8 9		Make/Buy	
	TRL (in); TRL (current); Date	Scientific Basis Established; Application Identified; Proof of Concept; Breadboard; Brassboard; Prototype; Engineering Unit; Mission Configuration	N/A; Laboratory; Relevant; Relevant; Operational	Basic Principles Observed; Technology Concept Formulated; Concept Demonstrated; Basic functionality demonstrated; Overall performance demonstrated; Operation in critical environments demonstrated; Performance in critical environments demonstrated; Flight qualification; Mission operation	Peer reviewed publication of concept; Concept feasibility and benefit; Analytical/experimental results of critical functions; Test performance and relevant environment; Definition of scaling requirements; Test performance matches analytical prediction; Flight qualification; Mission operation	Form; Fit; Function; Scale	Red (TRL ≤ 2); Orange (TRL 3); Tan (TRL 4); Yellow (TRL 5); Green (TRL ≥ 6)	System; Subsystem; Component

Product	**Product Name**		
Product Description			
Operational Environment Description	TBD		
Relevant Environment Description	TBD		
System 1	***System 1 Name***		
System 1 Description			
Subsystem 1.1	Subsystem 1.1 Name		
Subsystem 1.1 Description			
Component 1.1.1	Component 1.1.1 Name		
Component 1.1.1 Description			
Component 1.1.2	Component 1.1.2 Name		
Component 1.1.2 Description			
New Technology 1.1.2a	New Technology 1.1.2a Name		
New Technology 1.1.2a Description	Key Technology:		
Development Status			
TRL Justifications			
Component 1.1.3	Component 1.1.3 Name		
Component 1.1.3 Description			
Component 1.1.4	Component 1.1.4 Name		
Component 1.1.4 Description			
Subsystem 1.2	Subsystem 1.2 Name		
Subsystem 1.2 Description			
Component 1.2.1	Component 1.2.1 Name		
Component 1.2.1 Description			
Component 1.2.2	Component 1.2.2 Name		
Component 1.2.2 Description			
New Technology 1.2.2a	New Technology 1.2.2a Name		
New Technology 1.2.2a Description	Key Technology:		
Development Status			
TRL Justifications			
Component 1.2.3	Component 1.2.3 Name		
Component 1.2.3 Description			
Component 1.2.4	Component 1.2.4 Name		
Component 1.2.4 Description			
System 2	***System 2 Name***		
System 2 Description			
Subsystem 2.1	Subsystem 2.1 Name		
Subsystem 2.1 Description			
Component 2.1.1	Component 2.1.1 Name		
Component 2.1.1 Description			

Component 2.1.2	Component 2.1.2 Name
Component 2.1.2 Description	
New Technology 2.1.2a	New Technology 2.1.2a Name
New Technology 2.1.2a Description	Key Technology:
Development Status	
TRL Justifications	
Component 2.1.3	Component 2.1.3 Name
Component 2.1.3 Description	
New Technology 2.1.3a	New Technology 2.1.3a Name
New Technology 2.1.3a Description	Key Technology:
Development Status	
TRL Justifications	
Component 2.1.4	Component 2.1.4 Name
Component 2.1.4 Description	
Component 2.1.5	Component 2.1.5 Name
Component 2.1.5 Description	
New Technology 2.1.5a	New Technology 2.1.5a Name
New Technology 2.1.5a Description	Key Technology:
Development Status	
TRL Justifications	
System 3 Description	***System 3 Name***
System 3 Description	
Subsystem 3.1	Subsystem 3.1 Name
Subsystem 3.1 Description	
Component 3.1.1	Component 3.1.1 Name
Component 3.1.1 Description	
Component 3.1.2	Component 3.1.2 Name
Component 3.1.2 Description	
Component 3.1.3	Component 3.1.3 Name
Component 3.1.3 Description	
New Technology 3.1.3a	New Technology 3.1.3a Name
New Technology 3.1.3a Description	Key Technology:
Development Status	
TRL Justifications	
New Technology 3.1.3b	New Technology 3.1.3b Name
New Technology 3.1.3b Description	Key Technology:
Development Status	
TRL Justifications	
Component 3.1.4	Component 3.1.4 Name
Component 3.1.4 Description	
New Technology 3.1.4a	New Technology 3.1.4a Name
New Technology 3.1.4a Description	Key Technology:
Development Status	
TRL Justifications	
Component 3.1.5	Component 3.1.5 Name
Component 3.1.5 Description	

Background / Guidance

A TMA is required at the time of KDP-B. The following guidance comes from NPR 7120.5E, in the Project Formulation Agreement Template, on the role of a TMA in a Technology Development Plan.

NPR 7120.5E Guidance (Appendix F.3, Formulation Agreement Template, Section 8.0 Technology Readiness Assessment and Development)

Identify the specific new technologies (Technology Readiness Levels (TRL) less than 6) that are part of this project or single-project program; their criticality to the project's or single-project program's objectives, goals, and success criteria; and the current status of each planned technology development, including TRL and associated risks. Describe the specific activities and risk mitigation plans, the responsible organizations, models, and key tests to ensure that the technology maturity reaches TRL 6 by PDR. (Refer to NPR 7120.8 for TRL definitions.) Identify off-ramp decision gates and strategies for ensuring there are alternative development paths available if technologies do not mature as expected. Identify potential cost, schedule, or performance impacts if the technology developments do not reach the required maturity levels. Provide technology development schedules, including intermediate milestones and funding requirements, during Phases A and B for each identified technology development to achieve TRL 6 by PDR. Describe expected status of each technology development at SRR, MDR/SDR, and PDR. Reference the preliminary or final Technology Development Plan for details as applicable. Describe how the program will transition technologies from the development stage to manufacturing, production, and insertion into the end system. Identify any potential costs and risks associated with the transition to manufacturing, production, and insertion. Develop and document appropriate mitigation plans for the identified risks.

A TMA is defined to be "***critical to technology advancement and subsequent integration into operational products*** " per NPR 7120.8 and the project leads for Technology Development (TD) are required to ensure that TMAs are used in conjunction with KDPs throughout a project life cycle.

Guidance from NPR 7120.8, NASA Research and Technology Program and Project Management Requirements (w/change 3 dated 04/18/13), Section 4.7, Evaluation

4.7.1 Technology Maturity Assessment

4.7.1.1 Accurate assessment of technology maturity is critical to technology advancement and its subsequent incorporation into operational products.

4.7.1.2 The TD project lead shall ensure TRLs and/or other measures of technology maturity that are important to the customer/beneficiary are used in conjunction with KDPs to assess maturity throughout the project life cycle. When a TD Project uses a measure of maturity other than TRLs, the measurement system should map back to TRLs. TRLs are defined in NPR 7123.1.

4.7.1.3 An independent group should validate the current state of maturity. The maturity assessment should involve or be reviewed by the customer(s)/beneficiary(ies) or their representatives. The initial maturity assessment is done in the Formulation phase and updated at the project status reviews. At the conclusion of the TD Project, an independent assessment of the final TRL is performed. The program lead shall assign the independent group responsible for the Technology Maturity Assessment.

4.7.1.4 TRLs establish the baseline maturity of a technology at a given time. Moving to a higher-level of maturity (higher TRL) requires the assessment of an entire range of capabilities for design, analysis, manufacture, and test. These additional assessments may be embodied in other measures of technology maturity such as a Technology Maturity Index (TMI) or an Advancement Degree of Difficulty (AD2), which are described in the NASA Systems Engineering Handbook (SEHB).

4.7.2 Assessment Process

4.7.2.1 The following steps outline the process for assessing technology maturity and identify activities that should be accomplished on the part of the project.

a. Clearly define all terminology used in the TRL descriptions to be used throughout the life of the project.

b. Provide a formal Gap Analysis (see section 4.3.4.2) of technology needs supporting project content and identify the process for periodic project assessment, including the termination or transition of technologies out of the project and introduction of new technologies into the project.

c. Provide a formal assessment of the TRL for each new technology incorporated into the TD Project, and annually assess progress toward defined TRL goals. The assessment should occur at the system, subsystem, and component levels, as described by the TD Project's WBS.

d. The "weakest link" concept will be used in determining overall technology maturity wherein the TRL of the system is determined by the subsystem having the lowest TRL in the system, which in turn is determined by the component having the lowest TRL in the subsystem.

e. The depth of this assessment varies greatly according to the state of the project, e.g., at the concept level, only the basic building blocks are known and the major challenges identifiable. However, as the technology matures, the WBS becomes more defined and the assessment is required to go into
greater detail.

f. On the basis of the assessment, prepare a list of Critical Technology Elements that are absolutely essential in meeting overall technology requirements and that have substantial risk, cost, and/or schedule associated with their development.

g. The assessment of heritage elements should consider the intended application and operational environment compared to how they were previously used.

h. Following the maturity assessment and the identification of critical technology elements, perform an Advancement Degree of Difficulty assessment of what is required to advance the technology to the desired TRL. This is done in conjunction with the WBS and is used as the basis for the technology roadmap and cost.

i. Prepare a roadmap for each TD Project that addresses the cost, schedule, and risk associated with advancing each element to the point necessary to meet requirements in a timely manner. Identify alternate paths, decision gates, off-ramps, fallback positions, and quantifiable milestones with appropriate schedules. The roadmap outlines the overall strategy for progressing toward the KPPs, and shows how interim performance milestones will be verified through test.

j. The TD Project will be assessed on an annual basis through the aggregate assessment of the individual technologies and their progress toward the stated TRL goal.

Typically, a TRL of 6 is required for technology to be integrated into a flight system. The following guidance comes from NPR 7120.5E, Appendix A, Definitions.

NPR 7120.5E Guidance (Appendix A. Definitions, Technology Readiness Level)

Provides a scale against which to measure the maturity of a technology. TRLs range from 1, Basic Technology Research, to 9, Systems Test, Launch, and Operations. Typically, a TRL of 6 (i.e., technology demonstrated in a relevant environment) is required for a technology to be integrated into a flight system. (See Systems Engineering Handbook NASA/SP-2007-6105 Rev 1, p. 296 for more information on TRL levels and technology assessment.)

The following guidance is provided in the NASA/SP-2007-6105 regarding the development/construction of a Product Breakdown Structure (PBS)

Guidance from NASA/SP-2007-6105 Rev1, NASA Systems Engineering Handbook (December 2007), Section 4.3.2, Logical Decomposition Guidance

4.3.2.1 Product Breakdown Structure

The decompositions represented by the PBS and the Work Breakdown Structure (WBS) form important perspectives on the desired product system. The WBS is a hierarchical breakdown of the work necessary to complete the project. See Subsection 6.1.2.1 for further information on WBS development. The WBS contains the PBS, which is the hierarchical breakdown of the products such as hardware items, software items, and information items (documents, databases, etc.). The PBS is used during the Logical Decomposition and functional analysis processes. The PBS should be carried down to the lowest level for which there is a cognizant engineer or manager. Figure 4.3-2 is an example of a PBS.

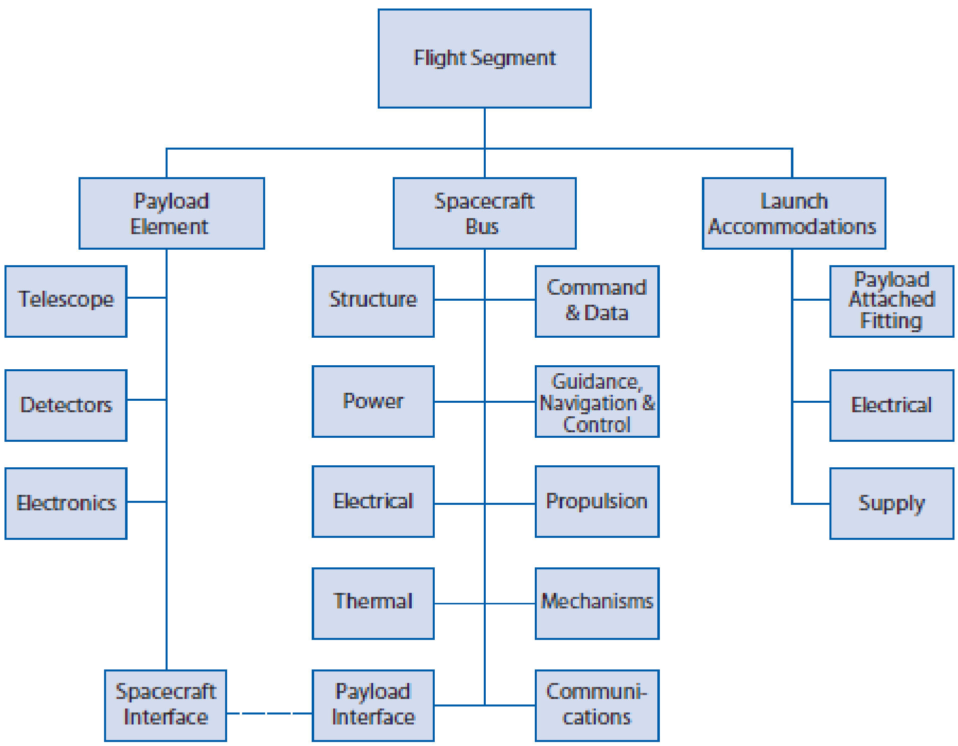

Figure 4.3-2 Example of a PBS

The following guidance is provided in the NASA/SP-2007-6105 regarding the performance of an Technology Maturity Assessment (TMA) via the NAS Technology Readiness Level (TRL) scale

Guidance from NASA/SP-2007-6105 Rev1, NASA Systems Engineering Handbook (December 2007), Appendix G, Technology Assessment/Insertion

A number of processes can be used to develop the appropriate level of understanding required for successful technology insertion. The intent of this appendix is to describe a systematic process that can be used as an example of how to apply standard systems engineering practices to perform a comprehensive Technology Assessment (TA). The TA comprises two parts, a Technology Maturity Assessment (TMA) and an Advancement Degree of Difficulty Assessment (AD2). The process begins with the TMA which is used to determine technological maturity via NASA's Technology Readiness Level (TRL) scale. It then proceeds to develop an understanding of what is required to advance the level of maturity through AD2. It is necessary to conduct TAs at various stages throughout a program/project to provide the Key Decision Point (KDP) products required for transition between phases. (See Table G-1.)

Table G-1 Products Provided by the TA as a Function of Program/Project Phase

Gate	Product
KDP A—Transition from Pre-Phase A to Phase A	Requires an assessment of potential technology needs versus current and planned technology readiness levels, as well as potential opportunities to use commercial, academic, and other government agency sources of technology. Included as part of the draft integrated baseline.
KDP B—Transition from Phase A to Phase B	Requires a technology development plan identifying technologies to be developed, heritage systems to be modified, alternative paths to be pursued, fall-back positions and corresponding performance descopes, milestones, metrics, and key decision points. Incorporated in the preliminary project plan.
KDP C—Transition from Phase B to Phase C/D	Requires a TRAR demonstrating that all systems, subsystems, and components have achieved a level of technological maturity with demonstrated evidence of qualification in a relevant environment.