Technology Readiness Level Assessment Process as Applied to NASA Earth Science Missions

Stephen J. Leete[1]
NASA Goddard Space Flight Center, Greenbelt, MD 20771

Raúl A. Romero[2]
NASA Jet Propulsion Laboratory, Pasadena, CA, 91109

James A. Dempsey[3]
NASA NASA Langley Research Center, Hampton, VA 23681

John P. Carey[4]
Stellar Sollutions, Inc., 250 Cambridge Ave., Suite 204, Palo Alto, CA 94306

Helmut P. Cline[5]
SGT, Inc., 7701 Greenbelt Rd, Suite 400, Greenbelt, MD 20770

and

Carey F. Lively[6]
Risk Management Corp., 597 Moran Ct., Annapolis, MD 21401

Technology assessments of fourteen science instruments were conducted within NASA using the NASA Technology Readiness Level (TRL) Metric. The instruments were part of three NASA Earth Science Decadal Survey missions in pre-formulation. The Earth Systematic Missions Program (ESMP) Systems Engineering Working Group (SEWG), composed of members of three NASA Centers, provided a newly modified electronic workbook to be completed, with instructions. Each instrument development team performed an internal assessment of its technology status, prepared an overview of its instrument, and completed the workbook with the results of its assessment. A team from the ESMP SEWG met with each instrument team and provided feedback. The instrument teams then reported through the Program Scientist for their respective missions to NASA's Earth Science Division (ESD) on technology readiness, taking the SEWG input into account. The instruments were found to have a range of TRL from 4 to 7. Lessons Learned are presented; however, due to the competition-sensitive nature of the assessments, the results for specific missions are not presented. The assessments were generally successful, and produced useful results for the agency. The SEWG team identified a number of potential improvements to the process. Particular focus was on ensuring traceability to guiding NASA documents, including the NASA Systems Engineering Handbook. The TRL Workbook has been substantially modified, and the revised workbook is described.

[1] Program Mission Systems Engineer, Mission Systems Engineering Branch, NASA GSFC, Greenbelt, MD 20771, Mail Code 420, Senior Member.
[2] Deputy Section Manager, Space Experiments Systems, JPL, 4800 Oak Grove Dr, Pasadena, CA, Mail Code 382, Member
[3] Systems Analyst, Systems Mission Analysis Branch, NASA LaRC, Hampton, VA, 23681, Mail Stop 462.
[4] Systems Engineer, NASA GSFC, Greenbelt, MD 20771, Mail Code 420.
[5] Systems Engineer, NASA GSFC, Greenbelt, MD 20771, Mail Code 420.
[6] Systems Engineer, NASA GSFC, Greenbelt, MD 20771, Mail Code 420, Member.

I. Introduction

This paper presents the National Aeronautics and Space Administration (NASA) work performed on an assessment of the Technology Readiness Level (TRL) of planned Earth Science Decadal Survey Missions. It presents the successes and difficulties encountered in applying the TRL assessments to a variety of different instruments with differing levels of complexity and maturity. TRL assessments are among the many factors and processes employed by NASA in evaluating and selecting projects to advance from concept studies to formulation to implementation. The TRL assessment process aids in identifying promising new technologies that can be developed for possible infusion into approved space flight programs. NASA Procedural Requirement (NPR) 7120.5E, NASA Space Flight Program and Project Management Requirements w/Changes 1-13[1], requires conducting technology assessments at various stages throughout a program/project to provide Key Decision Point products necessary for transition between phases. Through the assessment process, technologies are evaluated against the TRL definitions, then assigned a TRL of 1 through 9. According to NPR 7120.5E, it is a good practice that technologies achieve TRL-6 by Preliminary Design Review (PDR). An adjunct to the TRL assessments is a Technology Development Plan that codifies a project's plans for advancing the TRLs of key technologies to the TRL-6 level. For the assessments reported in this paper, the TRL definitions used were those now found in NPR 7123.1B, NASA Systems Engineering Processes and Requirements, Appendix E[2].

Within the NASA Science Mission Directorate, the Earth Science Division (ESD) handles the Earth sciences portfolio. This includes two elements which manage spaceflight missions, the Earth Systematic Mission Program (ESMP), and the Earth System Science Pathfinder Program (ESSP). It also includes the Earth Science Technology Office (ESTO) and sections for Applied Science and Research. ESMP generally handles larger, directed missions, such as Landsat, Ice, Cloud and Elevation Satellite (ICESat), Global Precipitation Measurement (GPM), and Gravity Recovery and Climate Experiment (GRACE). ESSP handles smaller, competed missions, including the Earth Venture series. The ESTO looks to the longer term future, by funding maturation of promising new technologies for future missions. Within the ESMP, a group of systems engineers led by the ESMP Systems Manager is known as the ESMP Systems Engineering Working Group, or ESMP SEWG.

The ESMP formulates and executes missions that were described and prioritized in the 2007 Earth Science Decadal Survey[3]. Some of these are in their implementation phase, including ICESat-2 and Surface Water Ocean Topography (SWOT), while several others are in pre-formulation. This paper concerns work done in 2013 on three of these pre-formulation missions. Each of the three mission teams had been instructed in a yearly letter, in October 2012, from NASA ESD to the program scientist and program executive to do a technology readiness assessment. The three missions are Aerosol-Cloud-Ecosystems (ACE), Active Sensing of CO_2 Emissions Over Nights, Days and Seasons (ASCENDS), and Geostationary Coastal and Air Pollution Events (GEO-CAPE). Each team was directed to provide an assessment of the current TRL for the instrument. ESTO and the ESM SEWG were to assist them in that process and provide and independent review of the instrument assessments. The fourteen instruments are listed in Table 1.

Table 1. Instruments Assessed

Mission	Instrument Name	Institution
GEO-CAPE	COEDI	GSFC
GEO-CAPE	CHRONOS	LaRC
ACE	Dual frequency radar	JPL
ACE	ACERAD/C2D2	GSFC & NGES
ACE	ACE Lidar	LaRC
ACE	Pol MPSI	JPL
ACE	APS Polarimeter	GISS
ACE	PACS Polarimeter	UMBC
ACE	Ocean Color Multi-channel spectrometer	GSFC
ASCENDS	LMCT Lidar / CO_2LAS	JPL
ASCENDS	Sounder with CO_2 channel	GSFC
ASCENDS	Broadband CO_2 Lidar	GSFC
ASCENDS	ITT Lidar	LaRC
ASCENDS	2 micron pulsed Lidar	LaRC

Many of the instrument concepts in pre-formulation started out as low-TRL efforts, which advanced under ESTO investment and management. ESTO fosters the development and assessment of innovative remote-sensing concepts in ground, aircraft, or engineering model demonstrations. Under NASA Research Announcements (NRAs), ESTO competitively selects proposals to develop component, instrument, and information technologies. TRL levels typically range from 2 to 4, with the expectation that after 2 to 3 years the

TRL of the proposed development will advance by at least one level. The projects are actively managed by ESTO, and required to have a detailed work plan and budget that is tracked using regular technical and financial reporting and reviews at 6-month intervals from the start date of the project.

The TRL workbook for these ESTO-funded projects was developed to aid the Principal Investigators (PIs) in assessing the technical progression of their projects. The PI is required to have the first iteration of the workbook completed by the first annual review of their project. In preparing for this review the PI iterates inputs to the workbook with their assigned ESTO technology development manager to ensure the TRL rating is both objective and adequately substantiated.

A process for conducting a Technology Assessment is provided in the NASA Systems Engineering (SE) Handbook[4], Appendix G, and the initial part is called a Technology Maturation Assessment (TMA). This is to be performed using the TRL scale, or if another scale is used, to be mapped into the TRL scale. For the purpose of this paper, "TRL assessment" will be considered to be equivalent to a TMA.

Early TRL assessments on NASA projects are typically performed by mission advocates, and then presented to NASA management along with other data to provide a complete picture of a proposed mission. These assessments can vary significantly due to differing interpretations of the TRL definitions and due to advocate and non-advocate perspectives. In 2011, NASA's ESD recognized the difficulties inherent in weighing the TRL assessment of one prospective mission against another. Significant inconsistencies were noted among the TRL assessments made by instrument teams in the pre-formulation stages of the program. The TRL determinations had been performed using informal processes and peer reviews, and the definitions were being inconsistently applied.

II. Evaluation Process

In November 2012, the ESMP SEWG, at the request of ESD, embarked on a process aimed at improving the consistency and uniformity in performing TRL assessments. The ESMP SEWG elected to adapt the TRL Workbook[5] that ESTO had developed. The SEWG and ESTO teams met to review the TRL workbook, and found it to be practical and straightforward to use on pre-formulations mission assessments, with the exception of needing adjustments to fit the need of ESMP missions. It was a Microsoft Excel™ workbook, and is partially illustrated in Figure 1.

The TRL Assessment Worksheet used for these assessments itemized the parts of a system and the rationale for the TRL assigned to the components, assembly and the overall system. The process was used to ensure all parts were accounted for, and highlight those needing further efforts to improve their readiness for use. The TRL Workbook was composed of a set of worksheets, which appear in tabs. Most of these are visible in the bottom of Figure 1. The nine tabs are as follows:

Background and version info - a brief background and top-level instructions for completion of the worksheet as well as a record of workbook version as a form of configuration management.

- *TRL Definitions* - TRL definitions reproduced directly from NPR 7120.8, NASA Space Flight Research and Technology Program and Project Management Requirements[6], App. J, but now found in NPR 7123.1B, Appendix E.
- *Other Definitions* – definitions of common terms used in the TRL definitions. These definitions were reproduced from NPR 7120.8, Appendix J.
- *TRL Worksheet* – the core of the TRL assessment workbook as illustrated in Figure 1; all other tabs support the completion of this worksheet.

Component Questions – questions to be answered for each component in the Product Breakdown Structure identified as a technology item in the affirmative in order for the component to attain the relevant TRL.

- *Assembly Questions* - questions to be answered for each assembly in the Product Breakdown Structure identified as a technology item in the affirmative in order for the assembly to attain the relevant TRL.
- *System-Subsystem Questions* - questions to be answered for each system/subsystem in the Product Breakdown Structure identified as a technology item in the affirmative in order for the system/subsystem to attain the relevant TRL.
- *Mission TRL Assessment* – explicit set of instructions for completing the TRL worksheet.
- *INFLAME Example* – an example of a completed worksheet, see Figure 2.

Product breakdown			*Technology Level Assessment*			*Implementation Approach*	
System / Subsystem	Assembly	Component	Key Technology Items*	TRL	Justification	Implementation Method	Vendors (if applicable)
Your System Name							
Target Environment =	<enter space (LEO, GEO L1, etc) or airborne>						
Your subsystem 1							
	Your assy 1						
		Your component 1					
		Your component 2					
		Your component 3					
		Your component 4					
		Your component 5					
	Your assy 2						
		Your component 1					
		Your component 2					
Your subsystem 2							
	Your assy 1						
	Your assy 2						
	Your assy 3						
	Your assy 4						
	Your assy 5						
	Your assy 6						
Your subsystem 3							
	Your assy 1						
	Your assy 2						
	Your assy 3						
	Your assy 4						
	Your assy 5						
	Your assy 6						
	Your assy 7						
Your subsystem 4							
	Your assy 1						
		Your component 1					
		Your component 2					
		Your component 3					
	Your assy 2						

Background and version info / TRL Definitions / OTher Definitions / TRL Worksheet / Component Questions / Assembly Questions

Figure 1. TRL Worksheet from TRL Workbook. ***This blank worksheet is filled in with the product breakdown, technology level assessment, and implementation approach.***

The following describes the categories of data that are to be documented in the TRL workbook.

The **Product Breakdown Structure** is similar to a Master Equipment List (MEL). If a MEL exists, it can serve as the starting point for the Product Breakdown. The instrument is decomposed into its subsystems, the assemblies within each subsystem, and the components within those assemblies. Each instrument subsystem, assembly, and component is entered into a separate row. Some examples of instrument subsystems would include the optics, the structure, the main electronics, thermal control, command and data handling, and power. An assembly is defined as a distinct box. For example on an instrument, it might be a separate optics module, electronics module, or a pointing platform. A simple instrument might not have any assemblies if it is a single box. A component is defined as any separate element within an assembly. For an instrument, a component could be a detector, cryo-cooler, aluminum mirror, etc. This is done for the hardware, but the workbook does not call for a similar treatment of software.

The **Target Environment** is the expected operational environment. For satellites it is the orbital parameters, such as altitude and inclination, but could be something else for suborbital, airborne or balloon systems. The **Relevant Environment** is the critical environment identified for the operational environment, that an element or the entire system must be tested against to gain TRL 5 or 6 level of maturity.

For the components, assemblies or subsystems, any **Key Technology** items are identified by writing a short phrase defining the new technology, i.e., developments that have not been accomplished before. This should include any items that are beyond the limits of routine engineering and that might require some form of verification that the item designed performs in the manner consistent with the intended purpose. Technology items are most often identified at the component level. However, if the new effort is to integrate the components in a new way, or to new requirements, then the **Technology Item** is the novel integration effort at the assembly or higher level.

The Workbook contains separate tabs with a series of **Questions** that, when answered, will guide the assessor to the appropriate TRL level for that item. For each item (component, assembly, or subsystem) all questions must be answered in the affirmative in order to claim the corresponding TRL level. For items that are truly NOT new technology (i.e., are routine, proven engineering) the TRL assessment entry is simply “No new technology.” This should not be used if the component is used in a way that differs significantly from past, proven applications. Note that while there is a version of the workbook that has a second TRL column for software, the one used in this study does not. Software could be included by making one or more lines for it.

A	B	C	D	E	F	G	H
Product breakdown			***Technology Level Assessment***			***Implementation Approach***	
System / Subsystem	**Assembly**	**Component**	**Key Technology Items***	**TRL**	**Justification**	**Implementation Method**	**Vendors (if applicable)**
INFLAME Instrument				**3**	**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.**	**Designed, assembled, and tested in house.**	
Target Environment =	**Airborne Instrument for use on a Lear Jet at 45,000 ft.**						
Longwave spectrometer				**6**	**Flight spectra meeting requirements over part of the desired wavelength range have been obtained.**	Designed, assembled, and tested in house.	
	Optomechanical			6	Flight spectra meeting requirements over part of the desired wavelength range have been obtained.	Designed, assembled, and tested in house.	
		Fourier transform spectrometer (FTS)		6	Demonstrated direct measurements of net flux during test flight.	Designed, assembled, and tested in house.	
			Bilayer pellicle beamsplitter	6	Full wavelength coverage demonstrated in lab calibration	Designed in house; fabricated externally.	Smithsonian Astrophysical Observatory.
						Designed in	

Assembly Questions | System-Subsystem Questions | Mission TRL Assessment | **INFLAME Example**

Figure 2. INFLAME Example Worksheet from TRL Workbook. *This worksheet illustrates how to follow the instructions and complete a TRL evaluation using the workbook.*

The **TRL of a System** cannot be higher than the lowest TRL of its constituents. At higher levels of assembly, the questions in the tabs for Subsystem/System ask if the prototype has been tested, and if these questions could not be answered in the affirmative, then a higher level of assembly may have a lower TRL than its constituents.

Justifications are to be provided to substantiate the TRL selected in each case. The justifications should be in the form of analysis and test reports, whitepapers, log entries, etc. Note that in practice, most instrument developers in this study provided background information and details of their overall test program, descriptions of the various developmental models (brassboard, engineering model, etc.), their strawman space-flight instrument design, and the outcomes of the various tests in a presentation format, in parallel with the spreadsheet. The spreadsheets did not typically include formal references to test reports, as one might find in formal flight test verification documentation. The "Justifications" were informal descriptions of the basis for the TRL rating.

The **Implementation Approach** section aids in the overall assessment process and to determine that a maturation plan exists for the lower TRL components. The assessor is expected to enter information that will enable a reviewer to determine the relative maturity of the implementation approach. The assessor should enter the implementation method including technology maturation plans. Questions to be addressed include the following:

- "Who is expected to implement the technology?"
- "Has a vendor been selected and are they under contract?"
- "What is the plan for advancing the technology?" and "Is there a documented plan for the advancement?"

In addition to producing the updated TRL Workbook described above, the SEWG also released the TRL workbook instructions as a configuration control board controlled document, GSFC 420-01-05, ESMP TRL Assessment Process[7]. Note that significant work on the TRL assessments was already underway before this document was signed off.

Several of the instrument teams were already engaged with the ESTO, and had applied for and won technology development funds from ESTO. They had previously used the ESTO TRL workbook to perform a self-evaluation, and simply had to update it to reflect their current status. Other teams had never used this assessment method, so the SEWG and ESTO teams provided the necessary guidance. The original direction had been issued to the Program Scientist and Program Executive of the three Decadal Survey Missions, ACE/ASCENDS/GEO-CAPE, to perform the assessments with the SEWG. The SEWG/ESTO team began their 2013 TRL assessment process by holding a kick-off meeting in February 2013 with the teams and the Program Scientist or Executive. The teams were then provided a copy of the current version of the TRL Assessment workbook with advice that this was to be used to complete the work requested in the NASA ESD annual letters. Consultation was provided by assigning a SEWG team member familiar with the instrument and the newly modified TRL assessment workbook and process to work with the instrument team to assist in completing the workbook, answering questions, and checking it at intermediate points.

Once each instrument team had completed their assessment, members of the team met with the SEWG to review the results. These meetings were held between May – July 2013. The meetings were conducted in-person at the NASA centers closest to the home institutions of the instrument teams, in Greenbelt, MD, Hampton, VA, and Pasadena, CA. The SEWG/ESTO reviewers provided informal feedback at each of the meetings to the instrument teams. Feedback letters made recommendations as to specific changes that should be made, and recommended that a revision to the assessment be made. In September 2013, the Program Scientists and Program Executives reported to the NASA Earth Science Division on progress on their Decadal Survey missions. These reports included the results of the TRL assessments performed with the SEWG. After completing these assessments, the SEWG/ESTO team met to discuss the outcome of the activity, and compiled a set of findings and recommendations. These are listed in the following section.

III. Findings and Recommendations

A. Finding 1. Utility of the Workbook.

Properly used, the workbook provides a good way of carrying out the NASA instructions on performing a TRL assessment. If the instructions are carefully followed, including answering all the questions in the tabs for the various levels of assembly, including the availability and testing of analytical, sub-scale, and full-scale prototypes, an assessment that is compatible with NPRs and the NASA SE Handbook will result.

B. Finding 2. Evaluation Team Membership

The evaluation team members should match the needs of the assessment. For the purpose of these assessments, a team of a SEWG representative from each center plus an ESTO representative was sufficient. For a more in-depth evaluation, technical experts on the relevant technologies should be added. Similarly, the level of independence needed depends on the potential impact of the assessments. For the pre-formulation stage, a self-assessment followed by an evaluation by a small panel is adequate. For a higher stakes situation, such as a TRL 6 determination in a high budget space mission, an independent assessment is called for.

C. Finding 3. Presentation with Background Material

The completed workbook must be accompanied by a presentation explaining the instrument and the development accomplished so far. The TRL workbook alone proved to be insufficient with the early reviews, and it became apparent that additional information was needed to aid in the understanding not only of the technology items, but of the system architecture the technology would eventually be infused into. Teams who were reviewed later in the year were asked to prepare a presentation of 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 additional supplemental material served to increase the review team's understanding of an unfamiliar instrument concept and helped greatly with the technology assessments and technology infusion.

D. Finding 4. Not a Design Review

A Technology Readiness Assessment is not a Design Review. In a couple of cases the SEWG reviewers became overly interested in the novel instrument design concepts being presented as background information, resulting in questions more often concerning the design and aimed at solving the engineering problems of the concept design. This diluted the proper focus on the technology maturity aspects of TRL assessment. Future reviews will still require the instrument teams to provide and present the supplementary material along with the results in the workbook. However, the review team will have to be diligent at focusing on the maturation questions contained within the workbook. The review team must ensure that the TRL evaluation process has been completed properly, and the team must guarantee each of the technology items and their roll-ups have sufficiently met their maturation criteria.

E. Finding 5. No New Technology

The instruction to identify portions of the system that are mature as "No new technology" can save time and focus attention. The detail and level of completeness at filling out the TRL worksheet varied greatly. In one case, great effort was given to filling out the TRL workbook. Each and every level of the instrument product breakdown had detailed maturity assessments. Even for the parts of the instrument design that contain no new technology items, assessments were performed. The end result was a very thorough and detailed instrument TRL assessment with a completely filled in workbook. While a complete or comprehensive assessment may be necessary for a proposal or cost estimate, it is not necessary for a technology readiness assessment. In another example, one instrument team filled in only sections of the TRL workbook that contained new technology items. The other sections of the instrument architecture that contained no new technologies items were either left out or were filled with a "NT" (not technology). In this particular case, it was extremely difficult to gain a complete understanding of the instrument maturity and left a feeling of large uncertainty with the review team. Both cases represent extreme examples of the amount of effort at filling out the worksheet. The solution lies between the extremes. In cases where there are subsystems and assemblies with no new technologies, it is still beneficial to the stakeholders and decision makers to know the maturity levels of those subsystems and assemblies. If a strong justification can be provided for assigning a high TRL at a high level of assembly, then details at lower levels of assembly need not be provided. An efficient approach is to start with a complete Mission Equipment List (MEL), identify a TRL for each (with minimal explanation), then focus on the new technology in the TRL workbook. This allows the reviewer to see that adequate consideration was given to the mature items, without needing to see it in the format of the TRL workbook.

F. Finding 6. Software TRL

The SEWG/ESTO team found that the instrument developers did not generally accept the software TRL definitions as valid or useful. Those that did attempt to rate their software made various errors. One team rated very standard, commonplace, and relatively simple flight software as the lowest TRL of the entire system because that part of the flight software had not yet been started. Another team rated ground data processing software for higher level data products as being at a low TRL. Since this software does not need to be ready early on, and may even be done by a separate group under a separate agreement, and will not likely be very expensive or hold up the flight system development, the SEWG/ESTO team advised that this not limit the system's TRL. While the SEWG/ESTO team considered several possible cases, none were found for which a software TRL rating distinct from that of the flight hardware seemed to be meaningful.

G. Finding 7. Need for Improvement of the Workbook

The Questions in the tabs of the workbook seemed to be difficult for developers to follow consistently. While some of the instrument development teams used the questions, during the review it was somewhat awkward to turn back to the tabs and check on whether all questions were answered. The tendency was for the reviewers to rely on their recollection of the questions. It would be beneficial for the reviewers to select a portion of the workbook, and verbally ask for confirmation that the answers to the questions were 'yes' or 'no' for a selected set of TRL ratings. In preparation for this, the questions must be confirmed to be self-consistent, logical, aligned with the TRL definitions, and value-added. The SEWG team considered adding columns to the workbook for reviewers to affirm each question, but it was not clear how to implement this in a simple spreadsheet. Discusions of how to resolve this issue led the SEWG to look back at the source documents, and consider more substantial modifications to the workbook.

H. Finding 8. Reporting on Evaluations

It is desirable for the group that is evaluating the assessments performed by the development team to report back directly to the official who made the request. The development team may not respond to the recommendations, and the official needs to know the result of the group's evaluation. Without this, there may be little or no value to the evaluation because it is ignored.

I. Finding 9. Roll-Up

Roll up using the weakest link approach, but allow exceptions. When to assign a higher level of assembly a lower TRL than the lowest of its constituents is a difficult and contentious matter, and the tendency is to take the simple 'weakest link' approach, which produces the highest possible TRL for a system. However, examples can be found, such as the co-alignment of otherwise mature hardware items under extreme environments, such that the feasibility of the system to achieve the required performance is in doubt.

J. Recommendation 1. Continue to use the TRL Workbook.

Continue to perform the Technology Maturity Assessments using the TRL Workbook directly. The SEWG's workbook is similar to other approaches for determining technology maturity. The SEWG's approach uses a Microsoft Excel™ workbook and implements the approach recommended in the NASA SE Handbook. It is consistent with NASA's TRL definitions in NPR 7123.1B.

K. Recommendation 2. Research Alternative Approaches

Do additional background research on other methodologies and approaches, especially on the NASA guiding documents, to guide the updates to the TRL Workbook. This research was performed, and is summarized in Section IV.

L. Recommendation 3. Update the Workbook.

Review differences between the NASA SE Handbook and the TRL Workbook. Evaluate what modifications should be made to the workbook to improve it. Improve the clarity of instructions to avoid confusion. The outcome of this work, informed by the review of methodologis and approaches in Section IV, is described in Section V.

M. Recommendation 4. Special Case – 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 designated "No New Technology". There is still development risk, but it is not technology risk.

N. Recommendation 5. Clarify New Technology vs Advanced Engineering vs Heritage.

During the TRL evaluations that were performed in 2013 by the SEWG, some confusion regarding what was considered "new technology" vs "no new technology" arose in several of the reviews. To address those concerns, changes within the workbook are now required identifying each assembly, subsystem, and system as new technology, advanced engineering, standard engineering, or heritage along with a justification for each of those assignments. The current process of identify "new technology" vs "no new technology" does not adequately capture the issue for those engineering developments that push the envelope of engineering bordering on the edge of technology development. This is future work for the SEWG, and has not yet been addressed in the TRL Workbook.

IV. Review of Methodologies and Approaches

The SEWG conducted a literature search to review other approaches to technology readiness level evaluation and other supplemental readiness evaluations to provide additional information to enhance the understanding of TRL. Those other supplemental assessment approaches included: technology readiness level, system readiness level, the difficulty associated with advancing a technology to higher levels, and the determination of programmatic risk related to the technology development.

A. Technology Readiness Levels and Assessment Methodology

A NASA researcher, Stan Sadin, conceived the technology readiness methodology in 1974 and later formally defined technology maturities in seven distinct readiness levels. Later in the 1990s, the readiness levels would increase to nine levels to include technology development through operations and support. J. Mankins, the former Director of the Advanced Concepts Office at NASA Headquarters, expanded the TRL descriptions in Ref. 8, later becoming a NASA Standard in NASA Policy Documents. These definitions were widely accepted and have since been adopted by many agencies of the US government including the Department of Defense (DOD) and Department of Energy (DOE) as well as the European Space Agency (ESA). It was concluded that the NASA TRL metric has become a standard across other US Agencies and ESA and therefore has a high degree of acceptance.

NASA, DOD, and others have used various tools for determining technology maturity. Each of the tools surveyed calculate a single value TRL based on allowing the user to answer a series of question about the technology. Many of the tools are Microsoft Excel™ spreadsheet application based having the questions embedded within the spreadsheet. Once the questions have been answered, the tool guides the user to the achieved TRL. The advantage of the tool is that several technologies can be evaluated with the same standard questions and the tool provides a repeatable process for each TRL assessment.

Other suggestions have been put forward to supplement the TRL definition for purposes of assessing the level of technology readiness of the system into which the technology will be incorporated. These suggestions take into account the difficulty of technology integration with the different elements of the system architecture called integration readiness level. The integration readiness level thus becomes a factor along with the technology maturity level for determining the system maturity level. There are various such meta-scales, combining TRL with other readiness factors to create a new, more comprehensive scale. The NASA SEWG is evaluating these metrics for inclusion in the process.

For the TRL evaluation performed by SEWG these metrics were not included. The SEWG evaluation depended on the experience of the team members to take these factors into account.

The normal development of flight hardware for NASA is challenging. Many of the elements of a spaceflight mission have such stringent requirements that there is always some development risk, even if every part of the system has direct flight heritage. There can be supply chain problems, loss of key personnel, and a company may stop production or move facilities or sell part of a company. Some components are so difficult to make that almost anything could result in failure of a previously reliable component. A high TRL is therefore not a guarantee of success, but it is a way to reduce Technology Development Risk.

As a result, NASA tends to separate engineering development risks from technology development risks. Experience shows that large development problems mostly arise when flight system development is dependent on a technology development schedule and budget compliance. The notion is that if you can reduce the technology readiness risk early, a competent team can handle the rest of the development risks with a reasonably high level of assurance, and with a quantifiable chance of modestly higher costs and delayed schedules. So, for NASA, it seems inappropriate to try to re-combine development risk with technology risk into a single metric, since they have such distinctly different effects on flight projects.

The difficulty in applying the TRL scale to software is explored by Seablom in Ref. 9. He describes the general value of using the TRL scale, and how it has been used to evaluate Earth science missions and technology developments. He notes that the software definitions are only recently added, and there is a limited body of experience relating them to outcomes on NASA missions. He notes specific difficulties with the current software TRL definitions, regarding how they differ from criteria used by the Carnegie-Mellon Software Engineering Institute.

B. NASA Requirements

NASA has two primary documents that concern requirements for technology development. The first is NPR 7120.8, which guides technology development (TD) projects. This document says that a technology assessment and development plan is central to the TD project. For NASA's Earth science portfolio, this early technology development is handled in a number of ways. Some is being done by industry or other agencies using their own resources, and NASA is a by-stander. Some is funded and managed by ESTO, generally guided by the priorities of the ESD. Some is funded by NASA center-level chief technologists, or by the NASA Office of Chief Technologist via the Space Technology Mission Directorate. In at least two other NASA programs in the area of Astrophysics, technology money is prioritized by the program office and dispersed by the Astrophysics Science Division of SMD. For nearly all of these cases, however, the general approach is to assess the current TRL, and then assess the scope of the work that remains to be done to achieve higher levels of maturity.

NPR 7120.5E calls for a document to be released at the end of Pre-Phase A, at the time of the Mission Concept Review, known as the Formulation Agreement (FA). It calls for the FA to include an appendix that describes the necessary technology development, and the NPR calls for a Technology Development Plan (TDP) to be baselined at this time either as a stand-alone document or in the form of the FA appendix. It requires the following:

> 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.

A TDP describes the technology advancement needed, with the steps necessary to bring the technology to a level of maturity for successful integration into a program/project. The plan provides the roadmap and the amount of resources and effort needed for technology development and infusion. The TDP includes the results of a risk assessment. The NPR requires that the status against this plan be reviewed at subsequent gate reviews up through

PDR. This approach achieves the objectives of the other analysis approaches found in the literature, and is compatible with the TRL evaluation discussed in this paper.

The NASA approach, which is addressed in the NASA SE Handbook, enables the assessment of technology maturity at all levels of assembly. It addresses how to incorporate a new technology at the component level into an otherwise mature system configuration. It also allows consideration of challenges in combining existing elements under more stringent requirements for performance, or use of resources (e.g., mass), or environments (thermal, radiation) by assessing each sub element for technology readiness and building up the system by evaluating the TRL for sub-systems and the TRL of combinations of sub-systems at the system level. The integration is inherent in the process and has usually been achieved by an integrated test of the sub-systems at a lower level conducted in an equivalent environment. An example of this is the aircraft flight of an instrument under evaluation. The aircraft flight has been accomplished with the sub-systems of the instrument system; however, the results must be scaled for the intended environment and configuration of the instrument.

The SEWG/ESTO team concluded from this research, as well as the prior findings and recommendations, that re-working the workbook to align closely with the NASA SE Handbook was needed.

V.   Modifications to the Workbook

After conducting literature searches, investigating numerous other approaches to TRL evalutions, and the lessons learned from the 2013 SEWG TRL assessesment, the SEWG decided to continue to use Microsoft Excel™ spreadsheet application, however with major modifications to the workbook. The SEWG decided to migrate away from having the technologist answer a series of questions about the new technology(s) to assess readiness level to a different approach based on the notional example described in NASA SP-6105 Rev 1. This approach reqires the technologist to fill in a TRL assessment table very similar to the TRL assessment matrix in Figure G-6, Appendix G, of the NASA SE Handbook. The modified TRL Workbook is as Ref. 10. The modifciations to the TRL Workbook are summarized below.

A. Single Set of Instructions

The TRL workbook contained instructions for completing the workbook, but these instructions were located in two different tabs. The ‘Background and version info’ tab provided some top-level guidelines while the ‘Mission TRL Assessment’ tab provided a more explicit set of instructions. In practice, it was found that the information given in the two tabs was inconsistent and not easily located, due to neither of the tab labels saying anything about ‘Instructions.’ The workbook has been modified to contain one tab clearly labeled as “Instructions”. In addition, the instructions have been made more explicit by describing exactly what information is needed in each cell of the spreadsheet.

B. Background – Guidance

The TRL workbook contains a “Background – Guidance” tab which provides an overview of NASA’s best business practices related to technology readiness assessment and development. The “Background – Guidance” tab has excerpts of best practices from NPR 7120.5E, NPR 7120.8, and SP-2007-6105 Rev 1 contained within the tab.

C. Reformatted to Follow Guidance in the NASA SE Handbook

The overall format of the TRL Worksheet was modified to include columns which can be filled in to indicate the TRL earned by various categories for an element. The TRL for that element can be determined by the lowest number on that row. A wide text box is provided for a full justification of the numbers entered. An image of the blank new workbook is shown in Figure 3.

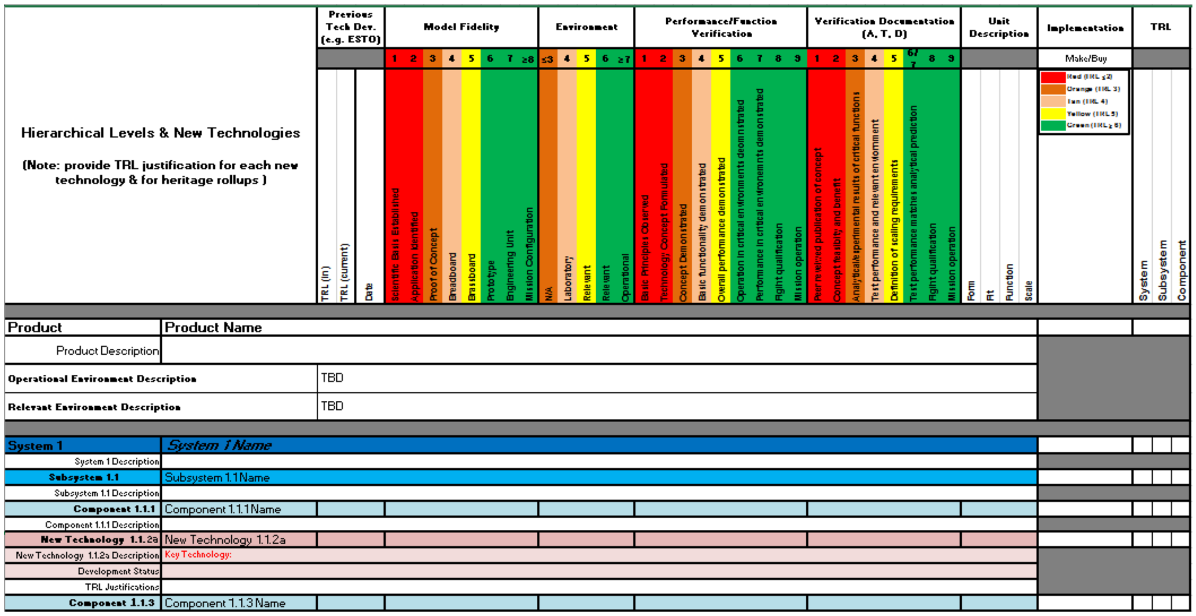

Figure 3. Overview of Modified TRL Worksheet. *Reformatted to follow guidance in the NASA Systems Engineering Handbook.*

D. Product Breakdown Functional Diagram

The completed workbook must now be accompanied by an hierarchical breakdown of the hardware products. The TRL workbook proved to be insufficient with the early reviews and it became apparent that additional information was needed to aid in the understanding not only of the technology item, but of the system architecture the technology would eventually be infused into. The additional supplemental material served to increase the review team's overall understanding at the system, subsystem, and component levels.

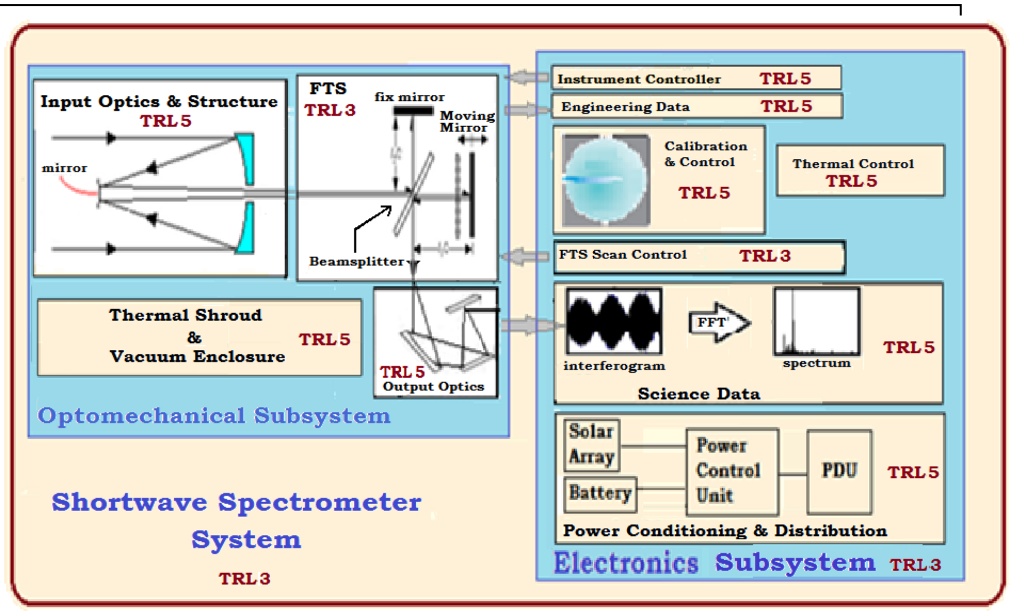

Figure 3. Product Functional Diagram. *Include a figure that illustrates the breakdown of the system into subsystems and components, corresponds to how the data is organized in the TRL Worksheet tab.*

Contained within the workbook is an example, using the INFLAME instrument, of an hierarchical breakdown. This breakdown is consistent with the product breakdown contained within the TRL worksheet. As shown, the INFLAME instrument has two systems composed of two spectrometers (LW, SW). Contained within the shortwave spectrometer are two subsystems each with a different number of assemblies and components. Additionally for clarity, the TRLs shown and denoted for each level of the product breakdown. This includes using the weakest link methodology and the rolling up the TRL to the highest level of the hierarchy.

Note: the system hierarchical structure can be broken down into many various substructures. No matter how the system archetictureis subdivided, it is important to ensure that there is a consistent mapping from the diagram to the product breakdown structure used in the TRL worksheet.

E. TRL Color Coding

The TRL worksheet has color codes which serves the purpose of providing an indication of the technology risk for the new technology and its rollup. Lowest level TRLs are denoted with red symbolizing technologies carrying the highest risk. Highest level TRLs, TRLs six or higher, are denoted with green symbolizing technologies carrying the lowest risk and yellow symbolizing medium risk. The five-level risk color codes are shown in Figure 4.

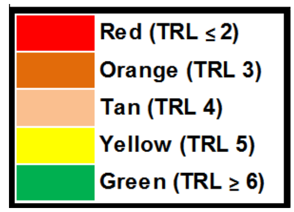

Figure 4. TRL Color Code.

F. Modifications to TRL Worksheet

As described earlier in Section II, the old workbook contains separate tabs with a series of questions that, when answered, will guide the assessor to the appropriate TRL level for that item. In practice, it was found that the questions, although helpful, were not structured in a way that would provide confidence in the TRL level thus derived. The new workbook still uses the rows of the assessment matrix to provide the framework for the hierarchical breakdown of the hardware and software products within the arrangement of the program/project product breakdown structure. The columns of the matrix have been enhanced to include more classifiers used to determine the maturity of a particular technology. –i.e., one category or set of classifiers would assess the environment in which testing of the new technology has occurred.

There are five categories used to characterize a maturity level for each of the key technologies contained within the system. The five categories are: Previous Technology Development, Model Fidelity and Unit Description, Environment, Performance/Function Verification, and Verification Documentation. An illustration of the column categories are shown below in Figure 5.

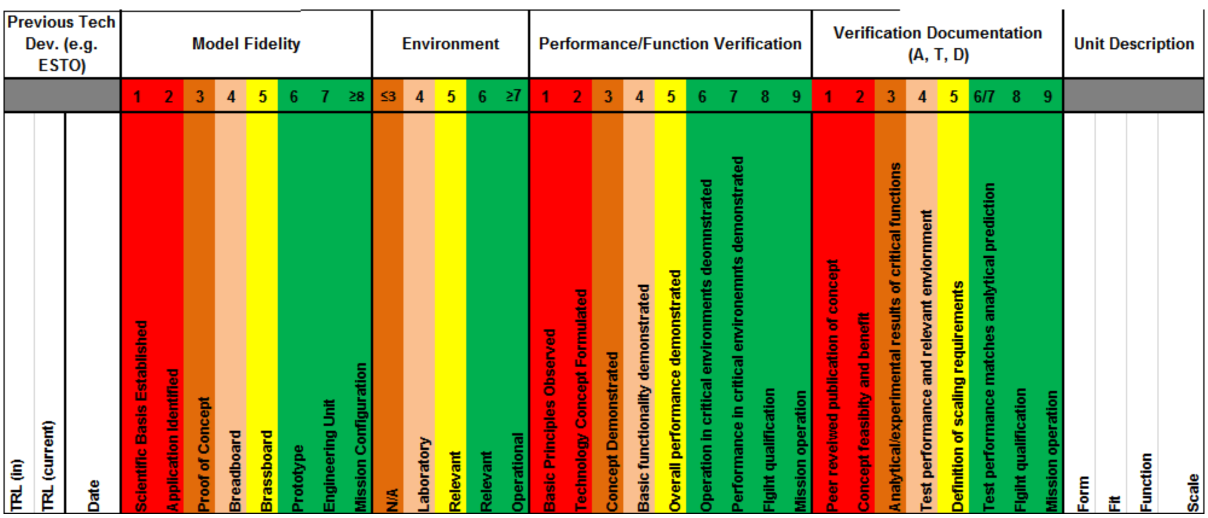

Figure 5. TRL Worksheet Column Categories. *The columns indicate what information goes into determining a TRL. A TRL number in each group of columns leads to an overall TRL.*

1. *Previous Technology Development*

Since many early technology developments within NASA Earth science are managed by ESTO, the TRL worksheet captures previous ESTO readiness level assessments. The past ESTO project documentation includes the technology maturity at the beginning of the funded project and the exit TRL and at project completion along with the project completion date.

2. *Model Fidelity and Unit Description*

Both the model fidelity and unit description (form, fit, and function) provides a means of quantifying the hardware or software fidelity based on its final configuration both in terms of final design intent and performance. The fidelity of the hardware/software can often take on different meaning depending on the assessors past experience[4]. The TRL workbook contains a tab with hardware/software definitions, from NPR 7120.8, Appendix J, for the different levels of product fidelity to be used for the workbook.

3. Environment

The technology readiness assessment depends on the specifics of the intended system application. Identification of the operation environment is required to be documented at the beginning of the worksheet thus the intended operational environment must be known. Additionally, along with the operation environment, a description of the relevant environment of the system must be specified. For example, in the INFLAME example, the operational environment is specified as a 705 km, sun-synchronous orbit with a three year mission duration. For the relevant environment, the critical subset of final product performance, is specified as vibration testing of the shortwave optomechanical assemblies and thermal vacuum testing of the electronic subsystem assemblies. Knowledge of both the operational and relevant environment is needed to conduct an effective TRL assessment.

The environment in which the new technology was tested is expected to be filled out for each of the new technology items. This will aid in determining the degree of similarity between the new technology environmental testing and to the environment in which the technology will be used in operation. It is this degree of similarity that is one factor that helps determine the readiness level of the new technology.

4. Performance/Function Verification

New technologies have performance and functional requirements that they must meet to ensure full system capability. The degree to which the required level of performance is achieved aids in determining the readiness level of the new technology.

5. Verification Documentation

Verification documentation generated by technology development activities must be identified to support TRL determination. Documentation provides evidence that the new technology meets specified requirements for intended use. Documentation serves as an exit criteria for each of the TRL levels in NASA's TRL definitions and must be completed before entering the next higher TRL level.

G. Modifications to the Example

The workbook contained a tab labeled 'INFLAME Example' as shown in Figure 2. This example was intended to aid in completing the workbook by giving examples of the information to be entered into each row and column. In practice, it was determined that a more comprehensive example will provide significantly better guidance to the assessor by addressing the many nuances that can be encountered in performing a TRL assessment. For future use, the workbook example has undergone substantial enhancement to make it more illustrative of all of the instructions, and updated to match the reformatted TRL Worksheet.

H. Modifications to the Training

Since the SEWG determined that the 'ad hoc' training provided was considered inadequate, improvements have been developed. First, the improvements to the instructions discussed above will make user training much easier. Secondly, a PowerPoint™ tutorial was developed to help guide the user in completing the TRL worksheet. These improvements should make completion of the worksheet less confusing for the user. Future training sessions for those unfamiliar with the TRL workbook will be conducted with sufficient time allowed for effective exchange of information.

VI. Summary

The NASA TRL assessment process has been carried out on several Earth science instrument concepts using an assessment workbook. The workbook used for those assessments was found to be adequate and compatible with the NASA TRL assessment methodology, but in need of improvement. The SEWG has incorporated the findings and recommendations into a revised TRL review process and workbook, with the goal of having a much improved process that can be used for the next set of future TRL reviews. A copy can be obtained via the web site given in the references, or by contacting an author.

Acknowledgments

We would like to thank Pamela Millar for her participation as the ESTO representative in the SEWG/ESTO review team.

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