NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

MATURITY ASSESSMENT OF SPACE PLUG-AND-PLAY ARCHITECTURE

by

Cheth Ouch

March 2013

Thesis Co-Advisors: Thomas V. Huynh
James C. Lyke

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) WashingtonDC20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** March 2013	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE: Maturity Assessment of Space Plug-and-Play Architecture			**5. FUNDING NUMBERS**
6. AUTHOR(S): Cheth Ouch			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number _______N/A_________.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200words)

Space Plug-and-Play Architecture (SPA), as defined by the SPA subject matter experts, is "a spacecraft development architecture that includes technology and standards developed to facilitate simplified design, assembly, and test of spacecraft systems using modular components to reduce spacecraft development cost and schedule." There is a need to assess the maturity of SPA to determine its benefits and return on investment. SPA, being a system and a combination of technology and standards, poses challenges for the maturity assessment. In this thesis, the author presents the methodologies to assess the maturity of SPA, using the existing Technology Readiness Level (TRL) process for technology and developing new process for the standards. The TRL process is applied to the technology components and the SPA system. The proposed process for assessing the maturity of the product development standards is similar to the TRL process, but tailored for applicability to standards. The methodology for assessing the maturity of SPA standards is based on the premises of "what was done and under what conditions." Applying these methodologies to assess the maturity of SPA gives a complete picture of the status of SPA development, which is used to estimate the cost to reach full maturity with more accuracy.

14. SUBJECT TERMS: Space Plug-and-Play Architecture, SPA, maturity assessment, Technology Readiness Level, System Readiness Level, Standard Maturity Assessment			**15. NUMBER OF PAGES** 73
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

MATURITY ASSESSMENT OF SPACE PLUG-AND-PLAY ARCHITECTURE

Cheth Ouch
Captain, United States Air Force
B.S., University of Washington, 2000

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN
SYSTEMS ENGINEERING MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
March 2013

Author: Cheth Ouch

Approved by: Thomas V. Huynh
Thesis Co-Advisor

James C. Lyke
Thesis Co-Advisor

Clifford Whitcomb
Chair, Department of Systems Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Space Plug-and-Play Architecture (SPA), as defined by the SPA subject matter experts, is "a spacecraft development architecture that includes technology and standards developed to facilitate simplified design, assembly, and test of spacecraft systems using modular components to reduce spacecraft development cost and schedule." There is a need to assess the maturity of SPA to determine its benefits and return on investment. SPA, being a system and a combination of technology and standards, poses challenges for the maturity assessment. In this thesis, the author presents the methodologies to assess the maturity of SPA, using the existing Technology Readiness Level (TRL) process for technology and developing new process for the standards. The TRL process is applied to the technology components and the SPA system. The proposed process for assessing the maturity of the product development standards is similar to the TRL process, but tailored for applicability to standards. The methodology for assessing the maturity of SPA standards is based on the premises of "what was done and under what conditions." Applying these methodologies to assess the maturity of SPA gives a complete picture of the status of SPA development, which is used to estimate the cost to reach full maturity with more accuracy.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

AIAA	American Institute of Aeronautics and Astronautics
ASIC	Application Specific Integrated Circuit
ASIM	Appliqué Sensor Interface Module
ADCS	Attitude Determination and Control System
AFRL	Air Force Research Laboratory
AI&T	Assembly, Integration, and Test
App	Application
APT	Advanced Plug-and-Play Technology
CAS	Central Address Service
Comtech AA	Comtech AeroAstro
COTS	Commercial Off-the-Shelf
CTE	Critical Technology Elements
DoD	Department of Defense
EM	Engineering Model
GAO	Government Accountability Office
GNC	Guidance, Navigation, Control
GOTS	Government Off-the-Shelf
I/F	Interface
IRL	Integration Readiness Level
MOSA	Modular Open Systems Architecture
NATO	North Atlantic Treaty Organization
ORS	Office of Responsive Space
PnP	Plug-and-Play
PnPSat	Plug-and-Play Satellite
RWA	Reaction Wheel Assembly
Sim/Stim	Simulation/Stimulation
SME	Subject Matter Expert
SPA	Space Plug-and-Play Architecture
SPA-S	SPA SpaceWire
SPA-U	SPA USB

SSM	SPA Service Module
SRL	System Readiness Level
TAT	Time-at-Tone
TRA	Technology Readiness Assessment
TRL	Technology Readiness Level
USB	Universal Serial Bus
WBS	Work Breakdown Structure
xTED	Extensible Transducer Electronic Datasheet

EXECUTIVE SUMMARY

Space Plug-and-Play Architecture (SPA) introduces a new paradigm for building spacecraft based on a familiar plug-and-play concept in the computing industry. The purpose of this thesis is to assess the maturity of the current Space Plug-and-Play Architecture development in order to determine its benefits and the future return on investment.

SPA development began in 2004 at the Air Force Research Laboratory, Kirtland Air Force Base, New Mexico. The approach involves representing a complex system as a self-organizing network of composable and discoverable and self-describing components with standard interfaces, rather than with the traditional point-to-point or connections. In a SPA system, the components have build-in software code that describes their functions and characteristics and are fully interchangeable. Once the components are connected, they form the SPA network. The SPA system automatically organizes them by the type of data they provide and/or require from the network. The SPA system mechanical and electrical interface is standardized, thus all the connection points are the same, making it very composable. The SPA network can be formed with as many components as needed. As defined by the SPA developers, SPA is "a spacecraft development architecture that includes technology and standards developed to facilitate simplified design, assembly, and test of spacecraft systems using modular components to reduce spacecraft development cost and schedule."

Three key processes for maturity assessment—the Technology Readiness Level (TRL) process, the Integration Readiness Level (IRL) process, and the System Readiness Level (SRL) process—are reviewed and found to be insufficient for completely assessing SPA maturity, as SPA is not simply a single technology, but a set of concepts (hardware, software, and protocols) forming an architecture that includes both technology and standards. A new maturity assessment approach is thus needed for SPA. This new approach involves assessment of both technology and standards.

For the technology assessment, the TRL process, which is sanctioned by the Department of Defense, was used. The challenge with using the TRL assessment is the fact that it is designed to assess the technology at the component level rather than at the system level. SPA is a network of components, which implies that the network itself is the system or subsystem. The TRL process can be used to assess the maturity of the individual hardware and software components, but not traditionally for a network or system. To overcome this problem, the network had to be thought of as a component, a "super-component" that is made up of components and parameters associate with component interfaces. However, because the network itself is more than the sum of components and their interfaces, it becomes an entity with its own characteristics that differ from the sum of all the characteristics of the components and interfaces. By adding dimensions more specific to the network as factors in the evaluation, the TRL process can be and was applied to assess the SPA network maturity. Unlike the technology assessment, the standards maturity assessment is not guided by or based on any known guidance or, leaving the interpretation of maturity opens to judgment. The standards maturity assessment is the assessment of how mature the standards are—how far along they are in the development cycle and whether they are being accepted and used. In this work, a new standards maturity assessment methodology is developed, which is based on the TRL process's premises of "what was done and under what condition." The two factors used in the standards maturity assessment are the state of the standard development and acceptance of the standard by the community. Rather than using a numerical set, the standards maturity levels are a set of four descriptive levels with supporting information and definitions. The four levels are defined as: (1) immature, (2) sufficient, (3) mature, and (4) fully mature. In some cases such as USB and Wireless adapter specifications, standards are based on the documentation of the agreed-upon specifications, and the numerical values, therefore, have no added benefit. The standards are based on consensus. The maturity assessment is not.

In this new approach to assessing SPA maturity, a SPA rating of "4 (Mature)" means its corresponding TRL rating is "4" and its standards maturity rating is "Mature." It is not necessary to combine the TRL and standards maturity ratings into a single rating, as the main goal of the SPA assessment is to identify future activities needed to estimate the remaining cost to reach a fully mature SPA. As the estimated cost for bringing a system to “fully mature” standards is determined by what else is left to complete the standards based on the current assessment, the cost estimate for the fully mature SPA is determined by what else is left to complete based on the current maturity of the various SPA components and network.

As a final thought, an approach to combine two different sets of maturity assessment is presented for completeness. This approach utilizes a method similar to the risk assessment matrix, where the two dimensions of the matrix are levels of likelihood of occurrence and consequence if it occurs. The traditional risk matrix assessment has 5 levels for likelihood and 5 levels for consequence, and forms a 5 by 5 square matrix. Each square is color-coded for low, medium, and high risk, starting from lower left corner to the upper right corner. This method can be applied to combine the two different sets of rating for the maturity level of SPA and is a subject of future research.

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

First and foremost, I would like to thank Dr. James C. Lyke, for taking time out of his already very busy schedule to advise me on this topic. I also would like to thank Dr. Tom Huynh, my principal advisor at NPS, for being patient and allowing me the flexibility to change the topic at the last minute. Thanks also to Ms. Heather Hahn for all her administrative support.

Also, I would like to thank the SPA Strategic Study team here at the Air Force Research Laboratory, especially Mr. Larry Millikan, for guidance and support throughout the SPA maturity assessment.

Lastly, I would like to thank my friend, Dr. William G. Stevens, who encouraged me to finish the thesis and spent a considerable amount of time proofreading. Thank you.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

"Plug-and-play" is not a new concept. It is best known in the computing industry with the advent of the Universal Serial Bus (USB). The Air Force Research Laboratory (AFRL) has been developing technology to bring the plug-and-play (PnP) concept to building spacecraft, which can result in lower cost and shorter schedules for spacecraft builds. With plug-and-play, a spacecraft manufacturer does not need to develop custom interfaces and software codes to integrate and test spacecraft components and subsystems, saving time and cost for integration. This thesis does not discuss the benefit or debate the merits of the Space Plug-and-Play Architecture (SPA), but, instead, focuses on assessing the maturity of SPA based on a snapshot of the SPA development at the time of this research, September 2011.

A. BACKGROUND

USB has brought true plug-and-play to the computing industry, allowing even the unskilled individuals to add peripherals to personal computers without the need to understand all the inner workings of the computer system, its software, hardware, and protocols. In creating a PnP approach for space applications, a similar model was sought. The model sought economies in meeting space mission needs rapidly by allowing spacecraft to be rapidly assembled and tested, reducing cost and shortening the time required to put a spacecraft in orbit. The SPA project began development in 2004 at the Air Force Research Laboratory (AFRL) at Kirtland AFB, NM. Over the years, the Space Vehicles Directorate at Kirtland AFB has invested between $15–$60M[1] to mature the SPA concept and technology (AFRL, 2011). The Directorate considered the project to beat a crossroad in late 2010, following an organizational research portfolio review by the Air Force's Science Advisory Board (SAB). For example, was SPA sufficiently mature for a shift in emphasis, from research to transition? If not mature, would it make sense to invest more to bring the work to a suitable level of maturity? In the traditional model of

[1] Exact estimation is complicated, due to the mixture of concepts in research projects in which a number of ideas are being studied together within particular projects.

laboratories, technologies are germinated, advanced, matured, and transitioned, with the latter state denoting a period in which the laboratories perform a “hand-off” to other groups for insertion into fielded products. As part of the consideration for research into a particular technology, it is typical to stop pursuit of concepts whose maturation requires investments so large as to render the benefits impractical, especially with the risks involved. For SPA, this concern had also been expressed. A SPA Strategic Study team was formed to provide answers to those questions to a SPA Collaboration Review Team. The SPA maturity assessment in this thesis is a critical piece to be used by the SPA Strategic Study team in determining the current state of SPA development.

As SPA is more than just a single point technology, the process to assessing the maturity level of SPA is complex. Such complexity is not conducive to approaches defined in the existing DoD Technology Readiness Assessment (TRA) Deskbook (DODb, 2009). Furthermore, the TRA Deskbook approach provides little guidance for assessing the maturity of standards. In SPA, a set of standards were being developed in parallel with the underlying technologies. These deficiencies suggested a need for a new approach, in which the maturity for more complex technology developments can be estimated, including developments that involve standards. Such an approach, combining the Technology Readiness Level (TRL) assessment with the standards assessment, would provide a needed tool to assess the status of the SPA project at its given stage of development.

B. PURPOSE

The purpose of this thesis is to identify an approach to assessing the maturity of SPA that accommodates the different parts of SPA, to include a body of standards associated with the development.

C. RESEARCH QUESTIONS

The questions to be answered in this thesis are:

1. How might a SPA maturity level be assessed?
2. What is the maturity level of the SPA?

D. BENEFITS OF STUDY

This research is used to support the funding decision for continuation of the Space Plug-and-Play Architecture development at the Air Force Research Laboratory. The AFRL at Kirtland AFB conducted a strategic analysis on SPA and held a SPA Collaboration Review in September 2011. A part of that analysis was the maturity assessment of SPA. In addition, the methodology introduced in this thesis may facilitate future assessment of other systems architecture development.

E. SCOPE AND METHODOLOGY

The thesis focuses on the development of an approach to assessing the maturity of the SPA technology and standards utilizing the following approaches:

1. Review SPA documentation and the SPA standards
2. Review TRA Deskbook and other maturity assessment methodologies
3. Interview SPA subject matter experts (SMEs)
4. Assess the current SPA technology maturity using TRA Deskbook
5. Develop a methodology to assess the maturity of standards
6. Assess the maturity of the current SPA standards
7. Validate assessments with SPA SMEs

THIS PAGE INTENTIONALLY LEFT BLANK

II. LITERATURE REVIEW

A. SPACE PLUG-AND-PLAY ARCHITECTURE DESCRIPTION

Space Plug-and-Play architecture (SPA) is a system architecture that defines a new concept of building spacecraft. The SPA concept involves a variety of technologies (hardware, software, and protocols) and a set of standards designed to permit the scale of implementation sufficient to drive an industry. Unlike assessment of the maturity a single technology, such as a computer memory chip, assessment of the maturity of SPA, which involves many technologies, is difficult and challenging. Appreciating the difficulty in assessing the SPA maturity necessitates an understanding of the concept of SPA, which is described in this chapter.

SPA has been connected with the pursuit of a “six-day spacecraft,” an idea originating from the notion of “responsive space,” to complement previously discussed ideas of responsive spacelift. The requirement for rapid response for space became formalized when the Department of Defense’s Operationally Responsive Space (ORS) was formed to rapidly build and launch spacecraft to meet operational needs (AFRL, 2011). In 2004, AFRL began to explore a range of technology concepts that could dramatically accelerate the pace at which space systems could be created. One of the explored technology concepts was a “plug-and-play” concept, similar to the concept found in a personal computer. The primary focus at the time was on the spacecraft avionics, which include the navigation and attitude determination and control system (ADCS). Thus SPA was originally known as Space Plug-and-Play Avionics. As the SPA program progressed, it became evident that SPA is more than just the spacecraft avionics. The architecture has impact on the whole spacecraft bus (AFRL, 2011). The plug-and-play concept, as it stands, has now been extended to the whole spacecraft.

1. Definition of SPA

One definition of SPA as agreed upon by the SPA subject matter experts is as follows: “Space Plug-and-Play Architecture is a spacecraft development **architecture** that includes **technology** and **standards** developed to facilitate simplified design, assembly, and test of spacecraft systems using modular components to reduce spacecraft development cost and schedule. SPA is composed of standardized interfaces, a standard network, and a common message format that automatically identifies and configures." To better explain it, SPA is the standard network design that includes common message format and data-centric architecture, where focus is on the data and not the physical structure supporting the data generation and movement. It is also a standard modular architecture with standard interface, self-identifying and self-configuring components (Lyke & Peck, 2011). When a component is plugged into the system, it will identify and configure itself to meet the needs of the system.

In brief, a SPA system is a system that meets the guidelines described in the SPA standards. The SPA system can be thought of as a set of building blocks that can be arranged into a seemingly infinite number of configurations. The arrangements are done by connecting each block with a cable. Since the interfaces are standard, there are no ambiguities as to a connection, and many "legal" connections are possible to achieve the same overall function. An overall arrangement of components forms a network, and the network is self-organizing (this notion is captured in USB, as it does not matter which port one plugs the USB device into). Beyond this composability is the notion that components intelligently negotiate their roles within a system. They are self-descriptive, using embedded XML-based electronic datasheets, which can be queried and uploaded into an overall system formed by several of these components. This process, sometimes referred to as "discover and join," is an introspective mechanism in which the pieces are discovered in both hardware and software and linked within an application framework (software). When all the correct pieces are assembled, the system can ostensibly be considered "complete." The plug-and-play concept at this level is abstract, and in principle it could apply to any system, regardless of scale and type. SPA was connected to space systems, owing to its research origins at AFRL in the study of the responsive space problem.

2. The Architecture

Terms such as "architecture" and "system" are overloaded, having many possible meanings that must be made concise by context. While at one level a spacecraft is considered a system, it is but a component of a larger system necessary in the implementation of a space mission. In this context, a complete space system includes the ground control, launch, spacecraft systems, and users. A typical spacecraft life cycle process includes designing, building, launching, operating and sustaining, and disposing of the spacecraft. SPA, as originally conceived, is not intended to affect spacecraft mission operations or end of life. The SPA architecture "sits on top" of an existing space architecture, which means that launch systems and ground systems are not affected by SPA. SPA has impact on the internal spacecraft systems and during the spacecraft design and build phases. The spacecraft external interfaces to launch and ground systems are left unchanged (AIAAa, 2011).

A typical spacecraft is made up of two main subsystems: the bus and the payload. As the name implies, the "bus" is a conveyance (for the payload). It handles all the basic, necessary functions to keep the passenger, its "payload," focused on completing its mission. Some examples of the payload include the camera on a reconnaissance spacecraft or a suite of transmitting and receiving antennas, with its own system processor on a communication spacecraft. The bus is further divided into different subsystems that provide different functions to the spacecraft such as power management, navigation, attitude determination and control system (ACDS), thermal handling and so on. The subsystems are further broken down into different parts and components. The ACDS, for example, consists of the magnetometer, reaction wheel assembly and other parts. In a traditional spacecraft development, the bus and the payload are built separately and then mated together during the space vehicle's assembly, integration, and test (AIT) phase. Since the current SPA development primarily focuses on the bus, this thesis discusses only the topics that are related to the bus.

For a traditional spacecraft build, related bus components connect directly to each other—e.g., a "data source" connects directly to a "data sink." Thus, each connection interface can be different from one another. SPA, however, changes that paradigm with its notion of modular open systems architecture (MOSA). It utilizes a data-centric plug-and-play approach and introduces the concept of running an integrated network for the bus where each subsystem or component has a standard interface that can plug into any available port on the network, similar to a personal computer network running on Ethernet connection. Rather than the point-to-point connections on a traditional spacecraft build, the SPA network employs cascade-able routers and standard protocols for communication between components. This approach promotes the idea of a "composable" system where different pieces can be assembled into a full system, similar to a child's building block system (such as the one popularized by LEGO), where building bricks are stacked together to form an object. The key factor here is that the components utilize standard interfaces and message formats, hidden from the physical layer (i.e., encapsulated), and the components can be arranged into many configurations.

In a basic example, when a component is plugged into the SPA network, it will identify itself and specify to the network what telemetry data it will produce and what it will require. The SPA network will then discover and register the component as a node on the network. The result is a plug-and-play network, comparable to a Universal Serial Bus (USB) plug-and-play device on a computer. The analogy is illustrated in Figure 1. Note that the driver comes with the operating systems in the computer model (or must be supplied by a user, following a system "message box" prompt), while the spacecraft model uses an electronic datasheet embedded on the device itself in lieu of the driver. This difference is insignificant, as Figure 1 shows only a basic concept of how SPA works.

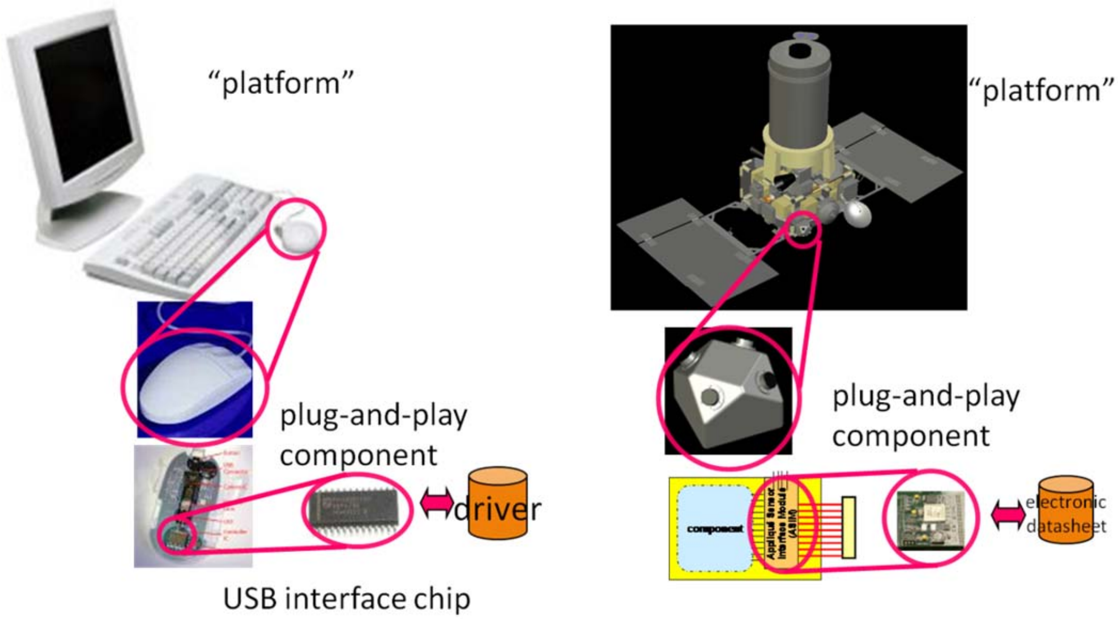

Figure 1. Plug-and-Play Analogy (From Lyke & Peck, 2011)

The real SPA network integration is a bit more complex. Since all the components or subsystems have different functions, the data they provide and receive are different. A computer on the network is still a computer similar to other computers on the network. The computers can talk to each other because they use the same language and data format. On a spacecraft bus, the components and/or subsystems are different from one another. They serve different purposes and thus may use different languages and data formats. A thermal sensor will provide temperature readings to the bus system in degrees Celsius, but a magnetometer will provide the strength and direction of a magnetic field at a particular location. To integrate all the different types of messages and data formats into a single network, a form of middleware is needed. The middleware will act as a go-between for the many different "data sources" and "data sinks" and ensure that each "data source" pairs with the right "data sink." The SPA network architecture showed in Figure 2 illustrates the SPA Network description.

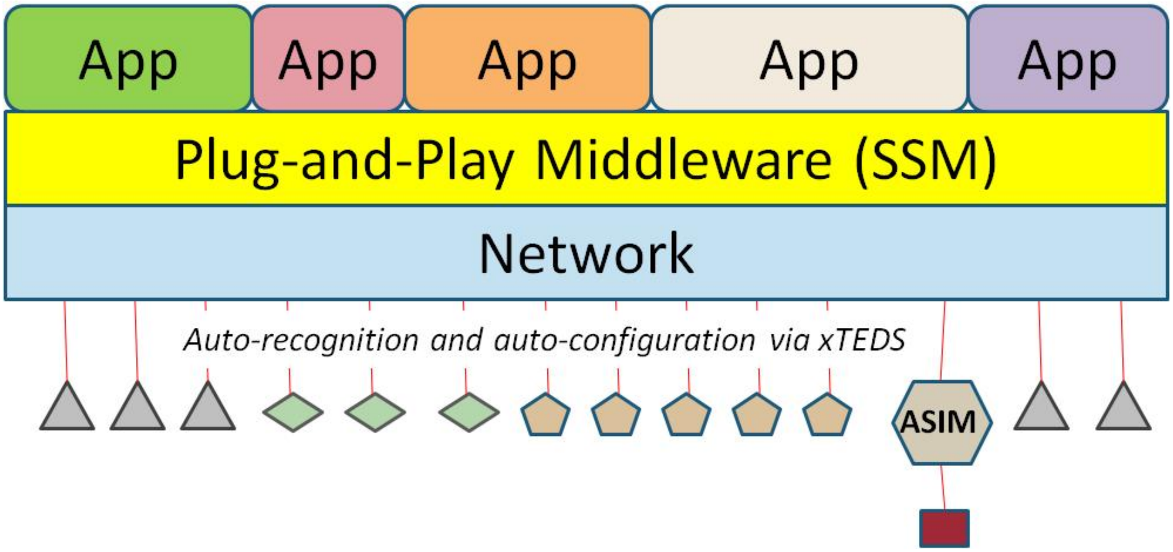

Figure 2. SPA Network Architecture (From Lyke & Peck, 2011)

In Figure 2, the plug-and-play middleware overlays on top of the network and abstracts (or hides) the intricacies of where a component is plugged and the details of its power consumption, etc. A set of applications (apps) is designed for this middleware. The apps are connected through this middleware to components, and sometimes to each other. The middleware is in a sense a unifying broker. The next section, SPA Technology, describes the composition of the SPA network.

3. SPA Technology

SPA is a family of standard interfaces and self-describing and automatically configurable components that create a self-organizing network connecting elementary "data sources" to the "data sinks" that depend on them (Lyke & Peck, 2011). As illustrated in Figure 2, the technologies needed to enable SPA consist of the software, hardware and the network.

a. Software

The software includes the apps and the SPA Service Manager (SSM) that is the middleware. The SSM is a collection of services, network/subnetwork managers and applications within the SPA (AIAAa, 2011). It may be the operating systems or part of the operating systems on a spacecraft. The system developer can decide on the selection of the SPA compliant spacecraft-level software. The services central to the SSM are the Lookup Service, the Routing Table, the Application and Endpoint Subscriber Lists, and the Central Address Service (CAS) (AIAAa, 2011).

The apps are software modules that interface with the SSM. They may be supporting applications such as orbit estimator, subsystem controllers (e.g., power management) or layers, and libraries (e.g., the math library). The apps may be flight heritage codes that have been modified to be SPA-compliant or new modules developed specifically for a mission. The common key feature among these apps is the standard interface to the SSM. In principle, well-designed apps can be re-used and shared through mechanisms like “application stores.”

b. Hardware

SPA defines a new approach for building spacecraft. In order to make possible the SPA architecture, a few key hardware components are needed. These components are the routers, the power hubs, and the Appliqué Sensor Interface Module (ASIM). As previously mentioned, SPA brings the network concept into the spacecraft bus architecture. The point-to-point connections on the traditional spacecraft do not require routers. A network such as SPA, however, requires a router to manage the message traffic. In addition, the various adjunct components utilize different voltages and normally have electronics power controllers (EPC) to convert the standard bus voltage to the necessary component voltages. In light of these voltage requirements, SPA introduced a standard voltage for the various components. The power hubs are required to provide the power management and distribution for the hardware components. With the standard electrical and physical interface, having a power hub reduces the amount of harnesses required for the spacecraft.

The last hardware piece required for the SPA network is the ASIM. The ASIM has been a source of contention among the traditional spacecraft developers. Since different spacecraft components utilize different interfaces and message formats, the ASIM is required to act as a translator for the legacy components to be SPA-compliant. It is a small electronics module, typically containing a programmable microcontroller circuit that provides a logical and physical interface. As a sort of legacy adapter, it allows a non-SPA compliant device to be able to connect directly to a SPA-based network (AIAAa, 2011). Early implementations of the ASIM concept were bulky, requiring implementation as an external box between the legacy component and the router. The bulkiness of these prototype ASIMs are unattractive. They add mass to the spacecraft and consume power; if not otherwise offset, they can drive up costs when launching the spacecraft. However, factoring in the mass savings from reduction in wiring harnesses, and depending on the size of the spacecraft, the additional mass growth is less than a few percent of the overall spacecraft mass, according to Comtech Aero Astro, an aerospace company that demonstrated the SPA network in May of 2010 (Schenk, 2011).

The bulky ASIM prototypes have been perhaps unnecessarily controversial. The ASIM was never meant to be used as a permanent, separate spaceflight component. The SPA developers envisioned the ASIM as a piece of software or an application specific integrated circuit (ASIC) embedded within the component itself that will make the component natively SPA-compliant. This follows the practice for USB circuitry in computer mice and keyboards. Such ASIMs thereby further mitigate any disadvantages of the earlier designs. At any rate, consistent with the MOSA philosophy, developers would be free to implement the ASIM-equivalent functions in any way imaginable, but the early prototypes served as a convenient reference design for experimenters and early adopters.

Figure 3 depicts the role of ASIMs in a system context. "SPA-S" refers to components employing the SpaceWire standard as the native physical/transport layer (other physical layer designs studied, including Ethernet, USB, and I2C). "SPA I/F" is the SPA Interface Board. "Gen 2 ASIM" refers to the second generation of ASIMs. The earlier Gen 1 ASIMs were used in the Plug-and-Play Satellite-One (PnPSat-1) during its development. The layout for PnPSat-2 in Figure 3 depicts the additional components of a test bed for plug-and-play technology development. PnPSat-2 is the current reference design for a SPA-compliant spacecraft (AFRL, 2011).

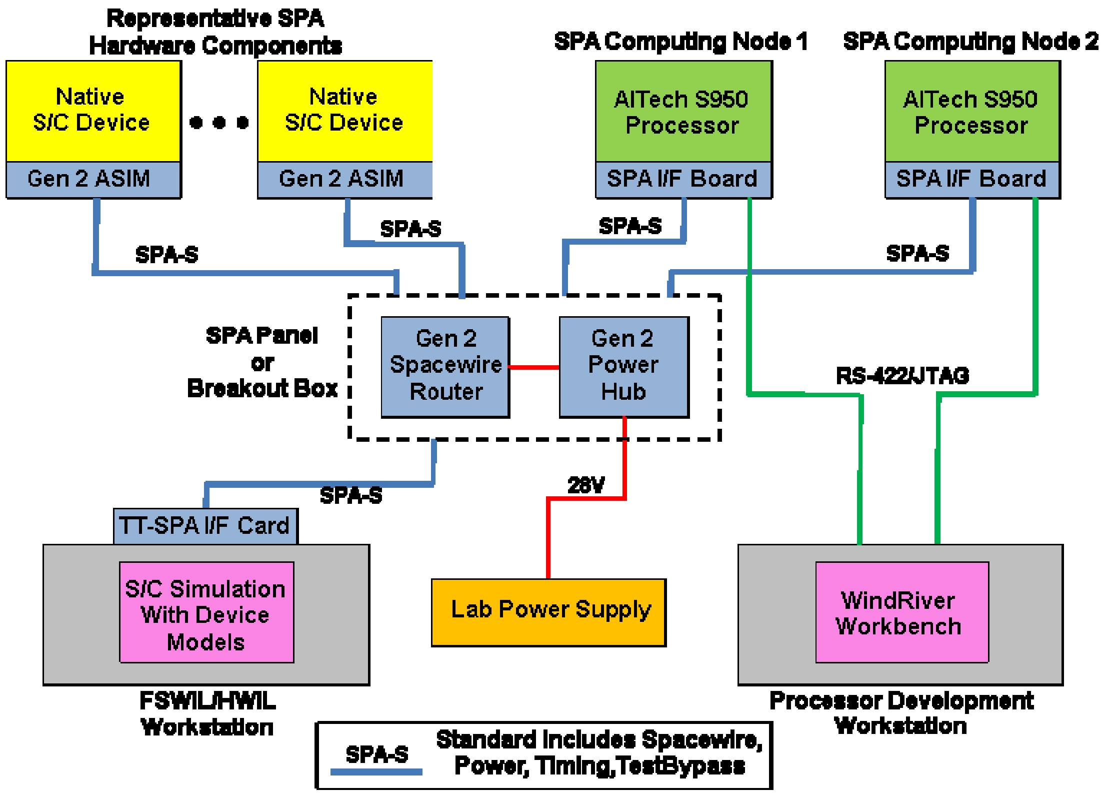

Figure 3. PnPSat-2 Layout (From AFRL, 2011)

c. Network

Defined as "an addressable and routable physically connected infrastructure composed of standard SPA transports for the purpose of transporting SPA messages between SPA endpoints and SPA gateways," the SPA network is a byproduct of the integration of the software and hardware (AAIAa, 2011). The network is an entity of its own, but it is dependent on both the software and hardware. However, it is more than just the sum of both the hardware and software. By turning the bus into a robust network of integrated components, which is different from a customized *ad hoc* network of a typical spacecraft bus, the network of integrated components becomes the bus system. The use of modular networks is an important hallmark of the SPA concept, and makes possible the composability and scalability of system designs that employ it.

4. SPA Standards

SPA’s success hinges on having standard interfaces for all the components and subsystems. Thus, a set of standards was generated by the SPA developers to provide references for constructing hardware and software capable of interfacing with a SPA satellite system. The current set of SPA standards is grouped under two categories—general standards that apply to all SPA systems, and components and application-specific standards that allow for varied applications of SPA to support a wide variety of needs (AIAAa, 2011). Table 1 lists the current SPA standards. Standards will change as further testing and development uncover issues that may not be apparent at the current stage of SPA development.

Table 1. List of SPA Standards (From AIAAa, 2011)

SPA Standards	Description
General SPA standards	
SPA System Capability Standard	Correlates SPA core concepts, SPA system services, and the basic capabilities that are required of a SPA system to specific requirements derived directly from SPA core concepts.
SPA Ontology Standard	Revolves around the extensible Transducer Electronic Data Sheet (xTEDs). Every hardware device or software application used within a SPA system must have an associated self-describing electronic data sheet that fully explains the component to other components in the system.
SPA Logical Interface Standard	Describes the high level capabilities provided by components within a SPA network. Defines the messages, protocols, and interactions a standard SPA component will use to participate in the SPA network.
SPA Networking Standard	Defines normative requirements for networking topology discovery, routing, component registration, and subscription processing.
SPA Timing Standard	Establishes a common method of synchronizing time across all SPA devices, processors, and applications through the distribution of a time-at-tone (TAT) message and synchronization pulses.
SPA Physical Interface Standard	Details the mechanical, thermal and electrical connector interface requirements for SPA hardware components on a SPA-compliant spacecraft.

SPA Standards	Description
SPA Power Standard	Explains the means by which power service will be supplied to SPA system components.
SPA Test Bypass Extension	Establishes how to implement optional test bypass functionality in SPA components to support component-level and integrated system test activities.
SPA Application-Specific Standards	
SPA-S Subnetwork Adaptation Standard	Specifies the required physical interface, with signal characteristics, for a SPA-S device based on the SpaceWire data transport standard.
SPA-U Subnetwork Standard	Specifies the required physical interface, with signal characteristics, for a SPA-U device and the ASIM data transfer protocol developed for low-data-rate devices based on the USB data transport standard.

5. SPA Summary

SPA introduces a new approach to building spacecraft. In contrast to the traditional approach of point-to-point connections between related components on a traditional spacecraft with customized interfaces and protocols, this new approach requires defining a new network-based architecture that standardizes interfaces and message formats among spacecraft components and subsystems. To enable network-based architecture and standard interfaces and message formats, new hardware and software technologies and standards were developed. The hardware and software technologies are required to standardize and adapt legacy spacecraft components to meet the requirement of the new architecture. The set of standards ensures compliance and interoperability of the components within the SPA network.

B. TECHNOLOGY READINESS LEVELS AND OTHER MATURITY ASSESSMENT METHODOLOGIES

Technology maturity is related to program risk, which affects performance, cost, and schedule. According to the review of 54 Department of Defense (DoD) programs by the U. S. Government Accountability Office (GAO) in 1999, programs with mature technologies averaged 9% cost growth and a 7-month schedule delay, while programs without mature technologies averaged 41% cost growth and a 13-month schedule delay.

Currently, major U. S. government acquisition programs are required to certify that all Critical Technology Elements have been demonstrated in a relevant environment at program initiation (GAO, 1999). Thus, maturity assessment has become a critical part of system acquisition. Technology Readiness Levels (TRL) are now discussed.

1. Technology Readiness Levels

In an environment of restricted resources, cost overruns and schedule slips, the TRL concept emerged to help system developers and program managers gain control over the schedule and cost (JBCI, n.d.). In 1989, in a paper titled "The NASA Technology Push towards Future Space Mission Systems," Saden et al. were the first to ascribe the levels of maturity to technology (Moore, 2008). A TRL describes the maturity of a technology relative to its development cycle. Simply, a TRL is defined at a given point in time by what has been done and under what conditions (Moore, 2008). According to Mankins (1995), TRLs constitute "a systematic metric/measurement system that supports assessment of the maturity of a particular technology and the consistent comparison of maturity between different types of technology."

The first set of TRLs defines seven levels of technology maturity that represent the evolution in technology from initial concept to validation in space. Mankins (1995) then expanded the TRLs to nine levels with a more complete set of definitions for all levels. Until 2002, the use TRLs was required by DoD for contract initiation, but readiness level assignment was typically left to the technology developer. There was no underlying guidance or rigor for TRL assignment; thus evaluations of technology maturity varied widely.

In 2002, the Department of Defense (DoD) was directed to use NASA's TRLs as the foundation for maturity assessment and began to develop a myriad of processes. DoD published the first Technology Readiness Assessment (TRA) Deskbook in 2003, which provides the user a methodological approach to assessing the maturity of a technology. It lists two different sets of definitions for the TRLs, one for software and one for hardware. The user has to identify the Critical Technology Elements (CTEs) for a system. These CTEs are the critical elements the system needs to meet operational requirements yet still fall within acceptable production and operation costs and schedule. The CTEs can be new or modified and may be software, hardware, manufacturing, or life cycle related at the subsystem or component level. The program risk ties directly to the development of the CTEs. Immature CTEs increase risk to the program cost and schedule. Thus the maturity of the CTEs is critical in controlling cost and schedule, and can be determined by the TRL process (DoDb, 2009).

In another initiative, Congressional requirements added to the Fiscal Year 2006 authorization a set of bills for NASA and DoD stipulating that technologies required for any program be demonstrated in a relevant laboratory or test environment. William Nolte, a researcher at the Air Force Research Laboratory (AFRL), went a step further and developed the TRL calculator to automate the process. The calculator was developed for AFRL internal use and is only available upon request. The calculator had been modified to incorporate other features such as tracking by project and by Work Breakdown Structure (WBS) product, incorporating ten TRL levels as defined by the NATO TRL scale, and incorporating the AD2 (Advancement Degree of Difficulty) process (JBCI, n.d.).

In addition, the concept of TRL began to proliferate to other countries and agencies including NATO, European Space Agency, Canada, the United Kingdom, and Japan. There is even an international working group attempting to develop a set of international TRLs. Furthermore, TRL offshoots have emerged, including “Design Readiness Levels,” “Material Readiness Levels,” “Manufacturing Readiness Levels,” “Integration Readiness Levels,” and so on (JBCI, n.d.).

SPA defines a system of integrated network for spacecraft. For this thesis, the DoD Technology Readiness Levels and Integration Readiness Levels (IRL) and System Readiness Levels (SRL) developed by the research team at Stevens Institute of Technology were reviewed (Sausera, 2006). The shortfalls of these current maturity assessment methodologies are now discussed.

2. Shortfalls of Current Maturity Assessment Methodologies

SPA includes both the technology and standards, complicating the simpler assessment approaches the TRL process provides. The Stevens Institute of Technology published a list of shortfalls found within the TRL process (Sauserb, 2006). Some of those shortfalls were also identified by the review of the TRL performed in this thesis. They include (Sausera, 2006):

- TRL is only a measure of an individual technology, and does not assess its maturity at the system level.
- TRL distorts many aspects of technology readiness into one metric.
- TRL cannot assess uncertainty involved in maturing and integrating a technology into a system.

The fact that the TRL process only measures an individual technology can be construed from how the TRA is performed. As described in the TRA Deskbook, the first step in performing the assessment is identifying the CTEs. The CTEs are elements of the system and not the system itself. The TRL assessment is made for each individual CTE. The definitions for the levels describe where each CTE is in the development cycle, whether it is still a breadboard or has been integrated into the system. The TRL process thus measures only the readiness level for individual technology.

In addition, the TRL process ascribes a level to the technology based on where it is in the development cycle. For example, the definition of TRL 6 is “system and/or subsystem model or prototyping demonstration in a relevant environment.” Note that the “system and/or subsystem” in this case does not indicate the whole system being assessed. It refers to the CTEs being integrated in a system or subsystem. The readiness level ascribed by the TRL process is for the whole CTE—one single readiness measurement. It does not take into account the different facets of the technology elements such as how well the technology is integrated with the system (Sausera, 2006). If integration of a mature technology into an existing system is difficult or challenging, then it may not be as readied as what the TRL implies.

The technology readiness level also cannot be used to determine the uncertainty involved in maturing or integrating the technology into the system. By definition, a TRL is assigned based on a snapshot in the system development cycle. There is no indication of the difficulty in reaching that level or going to the next level. This quandary arises because the TRL process was purposely developed to help program managers gain control over program cost and schedule (JBCI, n.d.). Without knowing the uncertainty involved, it is difficult to determine the risk to the program.

To overcome these drawbacks, the concept of System Readiness Level (SRL), introduced by the Stevens Institute, is suggested. The SRL is defined as a function of the individual TRL in a system and its subsequent integration points with other technologies, where the measure of readiness for integration is the IRL (Sausera, 2006). The IRL has seven levels and is modeled after the TRL. But the IRL is different from the TRL in that it defines the different level of readiness of the integration of components into the system. The IRL is defined as "a systematic measurement of the interfacing of compatible interactions for various technologies and the consistent comparison of the maturity between integration points" (Sausera, 2006). Basically, the IRL only assesses the integration readiness and not the technology as a whole. Thus, the IRL cannot itself assess the maturity of the technology.

In brief, the SRL is a function of the individual TRLs in a system and their subsequent integration readiness with other technologies as defined by the IRL. The resulting interaction of the TRL and IRL is correlated to a five-level SRL index, which is defined by the state of development corresponding to the DoD's Phases of Development described in the Life Cycle Management Framework (Sauserb, 2006). Starting from level 1, the SRL indexes are: Concept Refinement, Technology Development, System Development & Demonstration, Production & Development, and Operations and Support. A system can be assigned an SRL based on the resulting outcome of the TRL and IRL integration. As such, using the SRL to assess the maturity of SPA seems to make sense because SPA is basically an integrated network of plug-and-play software and hardware components. But, by making SRL a function of TRL and IRL, the SRL model fails to provide an overall SPA system maturity assessment for these reasons:

1. A system is greater than the sum of its parts. It is more than just the sum of the components and their interfaces. SRL does not treat the system as a different, independent entity. For example, in the case of SPA, all the components may have gone through individual testing in a relevant environment and achieve a certain TRL and IRL. But when they are integrated into a single system, the system itself will have to undergo testing in its own "relevant environment." There are also other dimensions that have to be considered, such as, in the case of SPA, the reliability of the network and the network performance, which cannot be concluded from the test results of each individual component. Even if all the components are at TRL 6 and at the highest IRL, it does not necessarily mean that the system also attains a high SRL.

2. SPA is an architecture with lots of moving parts, and is not just a single point technology. The SPA standards are included as part of this architecture. The SPA standards are neither technologies nor processes. They are documents that provide guidance for the developers. The maturity of the SPA standards is also critical to the success of SPA. A separate assessment of the maturity of the standards is thus also required.

3. A key reason for performing maturity assessment of SPA is to determine the cost to reach a maturity level that can be transitioned to industry. In order to estimate the cost, "what else needs to be done" must be identified. There are different activities that need to be performed for each individual component and for the system. Using the SRL would limit the scope of the assessment to the whole system. A breakdown of what is needed to be done at the component level would be difficult giving just the SRL level. Assessing both the individual components and the network as a system allows a breakdown of the cost estimation that would provide a more accurate overall estimation.

Given the analyses above, a new approach to assessing the SPA maturity is needed. This new approach and the actual maturity assessment are detailed in Chapter III.

C. CHAPTER SUMMARY

This chapter describes the Space Plug-and-Play Architecture and provides the results of a review of the different maturity assessment methodologies that may be relevant to SPA. Information from SPA documentation supports the fact that SPA is not just a technology. It is an integration of self-register and self-configure hardware components and software modules that make up the SPA network. The SPA components, which include the SPA hardware and software, are also discussed along with the SPA standards. In addition, different maturity assessment methodologies reviewed discussed with a primary focus on the Technology Readiness Level.

THIS PAGE INTENTIONALLY LEFT BLANK

III. SPA MATURITY ASSESSMENT

A. APPROACH

Based on the review of the assessment methodologies and their alignment with the SPA description, an assessment of SPA technology maturity using the Technology Readiness Level (TRL) model is determined to be the best approach. As such, the DoD Technology Readiness Assessment (TRA) Deskbook is heavily utilized to guide the process. The key point in assessing the technology is to understand "what has been done and under what condition."

Assessing the different software modules and hardware components is a straightforward process when one follows the guidelines in the TRA Deskbook. The Spa network consists of all the components networked together via software and hardware interfaces. The term "SPA network" is synonymous with the "SPA system," since the SPA system is the combination of software and hardware components connect together. For the SPA network, assessing its maturity is a challenge, since one of the key shortfalls of the TRL model is its inability to assess the maturity of a whole system. To get around the problem, the SPA network is assumed to be as just another SPA technology component, instead of the integration of all the components. By that assumption, the TRL process can be used to assess the maturity of the network.

However, one key difference with the SPA network is the fact that it is not a software module, nor is it a hardware component. There are different sets of TRL definitions for hardware and software (DoDb, 2009). But the two definition sets are similar, and thus can be consolidated to use for the network. There is no variation in the TRL levels for the network using either set of definition because the activities and environment for the levels are the same in both sets. However, different factors must be considered when doing an assessment on the network. The network maturity assessment section describes in detail the approach to assessing the network..

As for the SPA standards, there is no formal published guidance on how to assess them. A new methodology for assessing the maturity of the standards is needed and developed and is described in the standards assessment section.

B. ASSUMPTIONS AND ASSERTIONS

Multiple government organizations and industry partners help to develop SPA. There are varying approaches, focuses, and degrees of success. Thus, the maturity assessment process requires certain assumptions and assertions to be made to limit the scope of the assessment to what the government's program office considers as the main effort. These assumptions/assertions are as follows:

1. SPA is currently being developed for the satellite bus. Thus only the elements associated with the bus will be assessed. The SPA reference design (PnPSat-2) provides the basis for the maturity assessment. There may be different implementations of the SPA concept such as the different levels of modularity. The modularity of PnPSat-2 is at the component level. Other developers have also attempted to implement the SPA concept at the subsystem level. A subsystem usually consists of one or more components. To limit the scope, only the technology being used in the reference design, which is at the component level of modularity, will be assessed.

2. SPA may evolve with different transport layer protocols. This maturity assessment is for the current SPA implementation, which is SPA-S using the SpaceWire transport protocol.

3. Certain software functions are not called out in the SPA standards. It is left to the developers to decide how to implement those functions. Assessing software maturity for contractor-developed software will be difficult at best and therefore will not be assessed in this thesis. The SPA program manager lists those functions in the development efforts because they are necessary for further development and testing of the SPA system. Some of those functions are (AFRL, 2011):

a. Mission Information Service

b. File Management

c. Buffer Management

d. Orbit Estimator

e. Attitude Estimator

f. Momentum Management

g. Reaction Wheel Torque Distribution

h. Sun Solution

i. Target Manager

j. Telemetry Manager

k. Uplink Manager

l. Downlink Manager

4. The Plug-n-Play Satellite 1 (PnPSat-1) is an Engineering Model (EM) to have incorporated SPA concept and technology. Although it has not been flown, it is still a complete system with integrated payload. It has gone through rigorous testing for flight, such as a vibration test and 100+ hours of thermal vacuum test (AFRL, 2011).

5. Comtech AeroAstro (Comtech AA) and Seakr are two of the Advanced Plug-and-Play Technology (APT) contractors. Comtech AA demonstrated a full system utilizing SPA architecture with integrated payload. The demonstration utilized minimal numbers of real hardware, but mainly used heritage flight simulators with real data. The Comtech AA's demo environment is considered a "relevant environment" for the software (DoDb, 2009).

C. IDENTIFYING CRITICAL TECHNOLOGY ELEMENTS

The first step in assessing the maturity of a system is to identify the critical components of that system. The TRA Deskbook was used as a guide to help identify the Critical Technology Elements (CTEs) for SPA system (DoDb, 2009). The government SPA program manager already had a list of hardware and software that are in development. The list was scrubbed with the SPA subject matter experts (SMEs) and narrowed down to what is critical to implement SPA. The SPA SMEs include government and contractor personnel who were involved with developing SPA technologies and standards from the beginning of the program. Table 2 lists the CTEs and provides the reason for their selection. Note that some of the listed CTEs may not be called out in the SPA standards and may be common to the normal satellite build process. But they still can be considered critical elements of SPA because either they are significantly modified to meet SPA standards or they are assumed to be high risk with the implementation of SPA.

Table 2. SPA Critical Technology Elements

CTE	Reason for Selection
Software	
SPA Service Manager (SSM)	SSM is the backbone of SPA software. It is to SPA as Microsoft Windows to a personal computer. SSM is the updated version of the Satellite Data Model or SDM. PnPSat1 utilized SDM.
SPA API	The SPA API provides a standard means of accessing the functionality provided by the SPA messaging layer. It facilitates all of the common functions supported by the SPA data functions.
Layers/Libraries	Layers and libraries are a collection of utilities and functions that provide the interfaces among different elements within the SPA system. Most layers/libraries are not new, but require modification for implementation within SPA system.
Subsystem Controller	The Subsystem Controllers are not unique to SPA. But the SPA implementations of these subsystems differ from the normal spacecraft. They are critical to the SPA

CTE	Reason for Selection
	approach.
o GNC	The GNC Subsystem Controller is the master of all applications and device involved in GNC/ADCS subsystem functionality.
o Power	The Power Subsystem Controller provides a system-level view of the satellite's power. It is responsible for managing SPA endpoint power and also shedding of loads.
o Comm (Contact Manager)	The Communications Controller or Contact Manager provides the ground user interface to configure the "channels" that are used by multiple users to interact with the satellite.
Hardware	
SpaceWire Router	SPA requires a network for implementation. A network requires a router or switch for robustness and flexibility. The router is the center piece of the network and is critical to SPA.
Power Hub	The Power Hub is unique to SPA in that it helps to reduce the wiring harness that provides power to components. It is necessary for full SPA implementation.
Gen2 ASIM (include analog Interface Board)	The ASIM is the middleware interface between the SPA network and the spacecraft components such as Reaction Wheel Assembly (RWA), Magnetometer and Star Tracker. Normal spacecraft components have different input/output data. The ASIM enables the components to communicate with the SPA network. Gen2 ASIM is the second generation of ASIM. PnPSat1 used the Gen1 ASIM.
Network	Network operation is the byproduct of the integration of the SPA software and hardware and deserved to be recognized independently because it is the SPA system itself. The network has to be assessed to ensure it is meeting the performance and that it does not degrade the functionality of the whole system or any individual component.

CTE	Reason for Selection
SPA standards	SPA standards will not be assigned a TRL. It is a standard. But it is critical to SPA since the plug-and-play approach implies a common set of standards for components. The Standard’s assessment will be based on industry or community acceptance.

D. CURRENT SPA TECHNOLOGY ASSESSMENT

As stated previously, assessing the maturity of the hardware components is straightforward. Tests and activities and the conditions that the components have gone through were noted. A TRL is then assigned to a component by comparing the noted information with the different TRL definitions and supporting information. The maturity assessment of SPA technology is broken down into three separate categories: the hardware, the software, and the network.

1. Hardware

Table 3 lists the relevant TRL definitions for hardware, excerpted from the TRA Deskbook (DoDb, 2009).   A technology component is assigned a certain technology readiness level based on what development and tests it has gone through and in what environment. The definition of each level gives details on the activities and environment. The complete list of the definitions from TRL 1 to TRL 9 can be found in the TRA Deskbook.

Table 3. Hardware TRL Definitions Excerpt (After DoDb, 2009)

TRL	Definition	Description	Supporting Information
4	**Component and/or breadboard validation in laboratory environment**	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.	System concepts that have been considered and results from testing laboratory-scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals.
5	**Component and/or breadboard validation in relevant environment**	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.	Results from testing a laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the "relevant environment" differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals?
6	**System and/or subsystem model or prototyping demonstration in a relevant environment (ground or space)**	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.	Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve

TRL	Definition	Description	Supporting Information
			problems before moving to the next level?
7	**System prototype demonstration in an operational environment.**	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space).	Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
8	**Actual system completed and qualified through test and demonstration.**	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design?

The TRL definitions for hardware involve several characteristics. One characteristic is the scale of the application, where the component is being utilized/integrated, which ranges from device to component, subsystem, and system. Another characteristic is the environment, which is perhaps the most difficult characteristic to interpret because it is subjected to different types of technology and where it is being used. Both TRL 5 and TRL 6 depend on demonstration in a “relevant environment.” The criterion for a “relevant environment” is as follows: “A relevant environment is a set of stressing conditions, representative of the full spectrum of intended operational employments, which are applied to a CTE as part of a component or system/subsystem to identify whether any design changes to support the required functionality are needed" (DoDb, 2009). Table 4 displays the assessment of the SPA hardware with supporting information.

Table 4. Hardware TRLs

Hardware CTE	TRL	Supporting Information
SpaceWire Router	5	The SpaceWire Router in PnPSat-1 went through thermal and vibe test for over 100 hours. The router used in Comtech AA has gone through performance testing, but not environmental testing. Although the router used in the Comtech AA demo met and exceeded the performance requirement, the router was not radiation-hardened, which is required for operation in space. Another point to note also is that there are different flavor of routers being used by the contractors. Seakr used a switch that has not been flown and was considered an EM at best, while Northrop Grumman utilized a space flight heritage router. The TRL assigned here is for the router used in the PnPSat reference design and in Comtech AA demo.
Power Hub	5	The Power Hub is in similar situation to the SpaceWire Router. Not all APT contractors use the Power Hub in their design. The assigned TRL is for the Power Hub developed and built by Goodrich and used in the reference PnPSat design as well as the one demoed by Comtech AA.
Gen2 ASIM (include analog Interface Board)	5	The first generation ASIMs were used in PnPSat-1. The Gen2 ASIMs were used in the Comtech AA demo. Similar to the power hub and router, the Gen2 ASIM hardware was not radiation-hardened.

Hardware CTE	TRL	Supporting Information
Overall	**5**	The overall score for the hardware is based on the lowest score for the hardware. The hardware assessed here was used in the demos, but they did not have the required environmental protection for used in space. The demo environment for the hardware was not representative of the actual operational environment. Developers are currently building these component using radiation-hardened parts. The SPA hardware should be assessed in term of their functionality rather than the hardware themselves. For example, the current ASIM added additional weight and power requirement to the system. Depending on industry acceptance, the ASIM's functionality may be embedded within the component itself.

2. Software

Table 5 lists the excerpt of the software TRL definitions from the TRA Deskbook. The complete list of the definitions from TRL 1 to TRL 9 can be found in the TRA Deskbook (DoDb, 2009).

Table 5. Software TRL Definitions Excerpt (After DoDb, 2009)

TRL	Definition	Description	Supporting Information
4	**Module and/or subsystem validation in laboratory environment**	Basic software components are integrated to establish that they will work together. They are relatively primitive with regard to efficiency and robustness compared with the eventual system. Architecture development initiated to include interoperability, reliability, maintainability, extensibility, scalability, and security issues. Emulation with current/	Advanced technology development, stand-alone prototype solving a synthetic full-scale problem, or standalone prototype processing fully representative data sets.

TRL	Definition	Description	Supporting Information
		legacy elements as appropriate. Prototypes developed to demonstrate different aspects of eventual system.	
5	**Module and/or subsystem validation in relevant environment**	Level at which software technology is ready to start integration with existing systems. The prototype implementations conform to target environment/interfaces. Experiments with realistic problems; simulated interfaces to existing systems. System software architecture established. Algorithms run on a processor(s) with characteristics expected in the operational environment.	System architecture diagram around technology element with critical performance requirements defined. Processor selection analysis, Simulation/Stimulation (Sim/Stim) Laboratory buildup plan. Software placed under configuration management. Commercial Off-the-Shelf/Government Off-the-Shelf (COTS/GOTS) components in the system software architecture are identified.
6	**Module and/or subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space)**	Level at which the engineering feasibility of a software technology is demonstrated. This level extends to laboratory prototype implementations on full-scale realistic problems in which the software technology is partially integrated with existing hardware/software systems.	Results from laboratory testing of a prototype package that is near the desired configuration in terms of performance, including physical, logical, data, and security interfaces. Comparisons between tested environment and operational environment analytically understood. Analysis and test measurements quantifying contribution to system-wide requirements such as throughput, scalability,

TRL	Definition	Description	Supporting Information
			and reliability. Analysis of human-computer (user environment) begun.
7	**System prototype demonstration in an operational, high-fidelity environment.**	Level at which the program feasibility of a software technology is demonstrated. This level extends to operational environment prototype implementations, where critical technical risk functionality is available for demonstration and a test in which the software technology is well integrated with operational hardware/software systems.	Critical technological properties are measured against requirements in an operational environment.
8	**Actual system completed and "mission qualified" through test and demonstration in an operational environment (ground or space)**	Level at which a software technology is fully integrated with operational hardware and software systems. Software development documentation is complete. All functionality tested in simulated and operational scenarios.	Published documentation and product technology refresh build schedule. Software resource reserve measured and tracked.

Similar to the hardware definitions, the definitions of the software TRLs involve several factors. At the application level are values of the software module to the system. Other factors pertaining to the environment or application can include integration issues, laboratory user environment issues, logical relationship issues, data environment issues, security environment issues, and possible interface issues. All these factors must be considered when assigning a TRL to each software module. Table 6 depicts the assessment of the SPA software technology.

Table 6. Software TRLs

Software CTE	TRL	Supporting Information
SPA Service Manager (SSM)	5	Comtech AA and Seakr demonstrated the working SSM during the Critical Design Review. Although there were slightly different opinions on the outcome, all agreed that the core functionalities are there. Comtech AA demo used heritage flight end-point simulators that use actual data in the complete systems to include the payload. It is rated a 5 instead of a 6 due to the fact that there were inconsistent results from the different contractors conducting the demo and SSM is still being refined and troubleshoot. One thing to note also is that the previous version of SSM, which was called Satellite Data Model was used on PnPSat-1.
SPA API	5	SPA API was in the same demo as the SSM. API is still being developed and tested.
Layers/Libraries	6	The layers and libraries were also involved in the demos by Comtech AA and Seakr. These modules utilized heritage code with SPA modification.
Subsystem Controller		
GNC	6	The GNC module was demonstrated with PnPSat-1 and by the APT contractors.
Power	6	The Power module was demonstrated with PnPSat-1 and by the APT contractors.
Comm (Contact Manager)	6	Comtech AA has this module interacting with heritage ground systems. It was demonstrated with PnPSat-1 and by the APT contractors during the CDR.
Overall	**5**	Although the system was demonstrated in a “relevant environment,” the software modules are still being refined. There are inconsistencies with the testing results from the different contractors. Minor issues still crop up that required resolution. The fault tolerance and security of the software, in general, have not been fully implemented.

3. Network

The SPA network is the byproduct of the integration of software and hardware components. The network in this sense is an entity of its own, but is dependent on both the software and hardware. However, it is more than just the sum of both the hardware and software. Turning the spacecraft bus into a network of components, a non-traditional interpretation of a spacecraft, implies that the network is the bus system itself. The success of SPA depends on how well this network of component performs.

a. Approach to Assessing Maturity of the Network

Since the network depends on both the hardware and the software, and the definitions for the software and hardware TRLs are similar, the merged set of definitions for TRL for hardware and software is utilized with focus on two factors to assess the maturity of the network. These two factors, performance and mission assurance/fault tolerance, are pertinent to any network. For performance, the network bandwidth must meet or exceed the total required for the bus and should not be a hindrance to the overall working of the system—insignificant or no delay in messaging traffic. For the mission assurance/fault tolerance, the network must be able to handle minor glitches and has means to correct itself. For example, if the system fails, a command will be sent to reboot the system?

The motivation for this approach is very simple. The network is also part of the SPA technology. Since the TRL model exists to assess the maturity of the technology, it would not make sense to develop a new method. When using the TRL process, the factors can vary from one component to the next. The key is to identify the right factors and the environment for the SPA system.

b. SPA Network Assessment

The SPA network performance was successfully shown during the demonstrations by the Advanced Plug-and-Play Technology (APT) contractors (Schenk, 2011). "APT" refers to a body of contract activities within the larger SPA technology research programs at AFRL. A SPA network was demonstrated on real and simulated hardware and software in a "relevant environment." Thus, based on the TRL definitions, the SPA network should be at TRL 5 or 6. However, the network depends greatly on the software and hardware. Misbehavior of one component has a big impact on the whole network. Such concern has never been fully analyzed or evaluated. In addition, even though the software components are functioning, there are missing pieces. The software has not gone through an Independent Verification and Validation process. The security and mission assurance parts of the network have not been thought through. As such, the SPA network is rated at a TRL 4 for the following reasons:

1. Performance of the network exceeds the requirement. On average, the bus subsystem only requires about 1 megabit/second (Mb/s). The SPA network was demonstrated at 10 Mb/s at Comtech AA (Schenk, 2011). Spacewire, which is the basis of SPA networks on PnPSat-2, is actually capable of several hundred Mb/s.

2. The demonstration lacks the mission assurance/fault tolerance piece. It is critical for network stability. Comtech AA acknowledged that their mission assurance module, even if it is working, is rudimentary at best (Schenk, 2011). PnPSat-2 developers have just recently begun thinking of mission assurance. No methods for rigorous assessment of network margins in terms of quality of service have been done in the SPA program at the time of this work. Based on the TRL definitions, the successful demonstration of the SPA network in a "relevant environment" would rate the network at TRL 5. However, the lack of long-term reliability data for mission assurance reduces the rating to TRL 4.

E. SPA STANDARDS ASSESSMENT

There is no published guidance on how to assess the maturity of SPA standards. The TRA Deskbook is a guideline specifically created for assessing technology maturity. A standard is not technology; it is a description of the effects or implementation of technology. It is a controlled reference model that, especially for composable architectures, permits a number of independent groups to make interchangeable elements. A good example of a standard is the guideline for manufacturing the Universal Serial Bus (USB) connector. The standard calls out the number of pins and electrical currents and voltages required. The dimensions for the connector are also specified. A USB standard is set so that all components utilizing the USB port will be physically and electrically compatible. Other parts of the USB standard detail the protocols necessary to recognize particular component classes, speed grades, and treat the nuances of power distribution in a USB network.

1. Approach for the Development of Standard Maturity Assessment

Since there is no existing guide on how to assess the maturity level for standards under development, a new methodology is defined in this thesis. This methodology in essence follows the same principle as the TRL process, which identifies the key characteristics or dimensions of each technology component and assesses maturity based on the notion of "what was done and under what condition."

The main difference between this methodology and the TRL process is the interpretation of maturity level. The TRL process uses a set of numbers to rate the maturity of technology, whereas this methodology uses a set of descriptive words. The reason for doing this starts with the fact that the SPA standards complement the SPA technology. While the technology is the right arm of SPA, the set of standards is the left arm of SPA. Both arms are needed to have a successful SPA. Additionally, the standards would have to be fully developed to be effective. The phase between start development and end development is insignificant; one cannot have an incomplete standard and expect the community to accept it. So, whether the standard maturity level is a set of numbers or a set of descriptive words is not as important as having a hierarchy for completeness. Thus, for the standards, the maturity assessment is defined as follows:

1. There will be four maturity levels for a standard: Immature, Sufficient, Mature, and Fully Mature.
2. Maturity level will be assessed based in where it is in the development cycle, and acceptance by the community. These are the only two factors or dimensions considered.
3. The four maturity levels are defined in Table 7. A standard will be assessed by comparing the development progress to the definitions.

Standard Maturity Level Descriptions

Standards do evolve. This is true even with solid legacy standards such as Ethernet and USB. Parameters can change, but they will require user community involvement and feedback. With that in mind, Table 7 depicts the description of each level.

Table 7. Standard Maturity Level Description

Maturity Level	Description	Supporting Information
Immature	Standard is starting to develop. Established standard configuration management team.	SMEs and various entities working on the technology meet to discuss commonalities and standard parameters.
Sufficient	Standard is developed but not refined. It is being implemented in the laboratory environment on engineering model. Standard configuration management team meets regularly to resolve issue.	Team establishes regular meeting to resolve issues. Draft copy of standard available and in review.
Mature	Standard documentation completed, and standard is implemented by a limited number of players. Standard is submitted to a recognized entity such as IEEE or AIAA for approval.	The standard is being reviewed by the recognized standard entity. The contractors/developers working on the technology produces product based on the agreed standard.
Fully Mature	Standard is approved by the recognized entity such as IEEE or AIAA. Standard is being widely used in the industry.	Industry picked up on the standard. The recognized standard entity published the approved standard.

2. SPA Standards Assessment

The SPA standards provide the guidelines for building plug-and-play spacecraft. At the time of this writing, the SPA standards consist of nine different documents detailing the electrical and interface standards. The SPA standards are rated "Mature" for the following reasons:

1. The SPA standards were submitted to the American Institute of Aeronautics and Astronautics (AIAA) for approval.
   a. AIAA reviewed the SPA standards and gave feedback to be addressed by the standard configuration management.
   b. Issues were expected to be resolved within a few months after the SPA collaboration review board convened. The standards were expected to be finalized and approved by the end of the calendar year 2011. However, this did not happen. According to information from the government SPA program office, the SPA standards are still in review at AIAA.
2. The three APT contractors were using the standards during the 3rd phase of SPA development, where an actual SPA system with real hardware and software is demonstrated. Northrop-Grumman is also using the standards to build ORS satellite. Sierra Nevada Corporation and Miltec are both on board to use the standards (AFRL, 2011).

F. ASSESSMENT VALIDATION

The readiness assessment of both the technology and standards was briefed to the SMEs and the government SPA program manager before it was presented to the SPA Collaboration Review Board. At a meeting in August, 2011, the SMEs and the SPA program manager reviewed the methodology and concurred with the maturity assessment. Some contractors have rated the maturity of some pieces of the technology at higher TRLs, an understandable point (Schenk, 2011). Those particular contractors might not have any major problem during integration, and only had insight into a portion of the overall program. The government program office had the overall oversight and had knowledge of problems encountered by other contractors, which were factored into the assessment.

As reconciliation for the difference between the government's and the contractors' TRL rating, it is important to note that the early focus of plug-and-play technology was for small satellites. Big satellites that have a mission life of 10 to 15 years would have additional requirements that the smaller spacecraft do not. The Advanced Plug-and-Play Technology contractors were focusing on developing the technology for the smaller spacecraft. The smaller satellites have shorter mission life and long-term reliability factor is less critical when doing the maturity assessment. Thus, from the contractors' perspective, the maturity rating of the SPA technology was higher. In contrast, this assessment took into account the needs of the big satellite, where long-term reliability is a major factor. From the government program office's perspective, a lower rating on the maturity level of SPA is logical because the early development of SPA focused on meeting the need of the smaller spacecraft and not the bigger spacecraft.

G. COMBINING THE STANDARDS AND TECHNOLOGY MATURITY

For the overall assessment of SPA maturity, the question remains on how the maturity level of the standards can be combined with the maturity level of the technology to give a one maturity assessment for SPA. In this thesis, a method to combine the maturity level of the technology and the standard is provided. This method is taken from a method defined in the Risk Assessment process (DoDa, 2006). Needless to say, the reason for the maturity assessment is to determine the risk with going ahead with the program. So using the Risk Assessment process as an analogy helps to facilitate the explanation.

In the Risk Assessment process (DoDa, 2006), the risk levels (low, medium, and high) are assessed using two dimensions—the likelihood of occurrence and the consequence if it occurred. Each of these dimensions has five levels. So, based on the combination of the two, a corresponding risk level can be assigned. For SPA, a similar approach can be used to combine the standards and the technology maturity. The two dimensions of the matrix will be the standards maturity and the technology maturity. Figure 4 illustrates the concept.

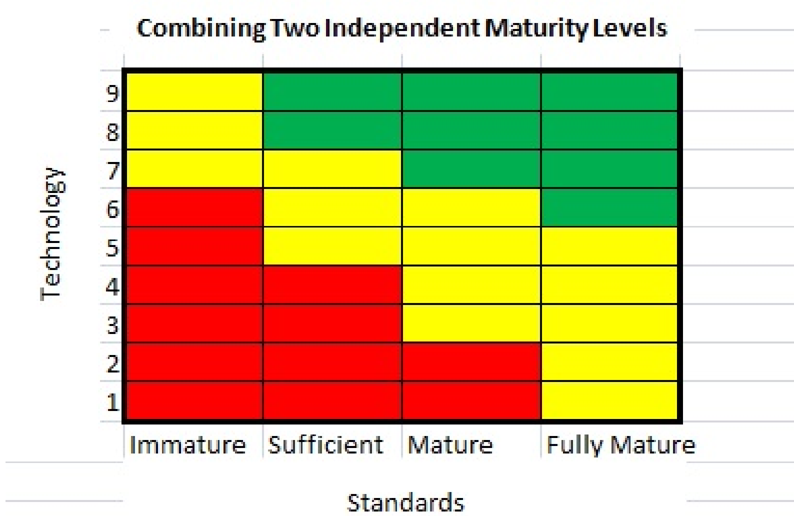

Figure 4. Combining Two Independent Maturity Levels Example

Similar to the Risk Reporting Matrix, the color coding here would represent the overall maturity levels. But the assigned colors are only notional and not meant to represent the overall SPA maturity assessment. In addition, the number of overall levels is not limited to three. The assigned levels based on the combination of the two are also open for interpretation. For example, having "Mature" standards and a TRL 5 may not represent a medium level of maturity in this case.

Again, Figure 4 is only used to illustrate a concept to combine two dimensions of maturity assessment. In prior part of this thesis, the author provided the methodologies to assess the maturity of the SPA technology using existing DoD TRL process and the maturity of the SPA standards using a methodology the author developed. The author then assessed the maturity of the SPA technology and SPA standards independently. However, the primary reason for the maturity assessment of SPA was to determine the status and cost to reach a transition phase. It was not necessary to combine the SPA technology readiness level with the SPA standard readiness level into a single readiness level. But the author did present a method to combine the two independent readiness level into a single one based on the Risk Matrix process. More research should be done to produce a set of standards for combining independent readiness levels into a single level.

H. CHAPTER SUMMARY

This chapter describes the approach and assumptions made in order to assess the maturity of SPA and the result of the assessments. Table 8 summarizes the maturity assessment of SPA. Each TRL assigned is based on what had been done for each element and under what condition. The activity and the environment each element underwent in the development process were matched up with the TRL definitions to come up with the TRL level.

Table 8. Overall SPA Maturity

CTEs	TRL
Software	
SPA Service Manager (SSM)	5
SPA API	5
Layers/Libraries	6
Subsystem Controller	
o GNC	6
o Power	6
o Comm (Contact Manager)	6
Hardware	
SpaceWire Router	5
Power Hub	5
Gen2 ASIM (include analog Interface Board)	5
Network	4
Standard	Mature
Overall	**4 (Mature)**

The overall maturity assessment of SPA technology is level 4. It is based on the CTE having the lowest maturity level. The standard approach in the industry is to use the lowest level, as the system is only as strong as its weakest component. In this case, the Standard is at a level that does not impact the overall SPA maturity. It is mature enough to be used and adopted by some of the spacecraft developers. The overall rating is dragged down by the network rating, which lacks the mission assurance piece necessary to reduce risk on the overall system. The breakdown of the elements allows the SPA program office to identify different activities requiring action to further mature them. Consequently, it will help with the cost estimation to reach an acceptably mature SPA by combining the estimated cost for each activity.

IV. CONCLUSIONS

The Space Plug-and-Play Architecture (SPA) introduces a new concept in building spacecraft. By turning the traditional spacecraft bus into a network of plug-and-play components, it allows more flexibility and modularity at the component level. SPA is unique in that, to achieve full functionality, it requires mature components and systems with a fully mature set of standards for industry to follow. This uniqueness of SPA creates a challenge for assessing its maturity. For this reason, to answer the main question of how to assess the maturity of SPA, the SPA maturity assessment was performed on two different critical elements, the technology and the standards.

The TRA Deskbook makes the maturity assessment of the SPA hardware and software components a straightforward process. The TRL process, however, was not designed to assess the maturity level of a system, and in this case the SPA network is a system. But with the system being considered as another technology component, the TRL process still can be used to assess the network. This approach comes with a caveat: additional dimensions that are critical to the network had to be taken into consideration as well. There are sets of TRL definitions for hardware and software. But the two sets are very similar and focus on "what was done and under what condition." Any one set can be used for the network; even consolidating the two sets would not change the outcome. The two sets of definitions use the same key factors for the same level, which are "event" and "environment." Thus, the conclusion is to use the TRL process to assess the maturity of the network.

For the SPA standards, a different approach has to be taken to assess their maturity. There is no published guidance for standards assessment. A standard is neither a technology nor a system. It is guidance on how to do things to meet certain specifications, a reference implementation that nails down a specific set of instances of a broader technology. The traditional notions of TRL are not adequately suited for assessing maturity. But a new methodology based on the same principle can be developed to assess its maturity. The TRL process calls for dimensions that need to be considered in the evaluation, and the same assertion of "what was done and under what condition" still applies. The process to assess the maturity of standards is based on these same guidelines, just with a different implementation. Unlike the TRL process, which uses nine numerical levels, this process uses only four “descriptive” levels for the standards. The reason for this is because the standard is not a technology.

The answer to the second and final question of this thesis is the SPA maturity level is 4(Mature). The outcome of the assessment is a set of two results, “4” and “mature,” which need to be combined if the true purpose of the assessment is to determine the maturity level of the architecture. However, the goals of assessing the maturity of SPA are to determine the status of each element and, based on that status, to provide a cost estimate to further mature the element. The goals are successfully achieved by assessing each technology component separately and then determining what else needs to be done to reach the next level. The overall system is also assessed to determine what else need to be done for the system to reach the next level. Once the required additional activities are identified, the cost for each activity is estimated using costs from past or similar efforts.

V. RECOMMENDATIONS

- The TRL process provides the methodology for assessing the maturity of a component, but lacks the details on how to assess the maturity of a system. It is recommended that DoD update the TRA Deskbook (given its current popularity) to include maturity assessment of technology at the system level.
- The approach for combining the two dimensions as described previously can be useful for future assessment of other architectures and frameworks involving a mixture of technologies and standards bound to that mixture. Future research should define a standard set of levels of maturity for the system and develop an approach to combine other sets of maturity levels.
- Finally, it is recommended that the SPA standards assessment process be refined and applied in future architectures of plug-and-play spacecraft.

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

Air Force Research Laboratory [AFRL]. (2011). *SPA Technology Program* [Draft]. Kirtland Air Force Base, NM.

American Institute of Aeronautics and Astronautics [AIAAa], (2011). *Standards development guidebook for Space Plug and Play Architecture* [Draft]. Reston, VA.

American Institute of Aeronautics and Astronautics [AIAAb]. (2011). *Space Plug-and-Play Architecture (SPA) Standard: System Capabilities* [Draft]. Reston, VA.

American Institute of Aeronautics and Astronautics [AIAAc]. (2011). *Space Plug-and-Play Architecture (SPA) Standard: Networking* [Draft]. Reston, VA.

American Institute of Aeronautics and Astronautics [AIAAd]. (2011). *Space Plug-and-Play Architecture (SPA) Standard: Physical Interface* [Draft]. Reston, VA.

American Institute of Aeronautics and Astronautics [AIAAe]. (2011). *Space Plug-and-Play Architecture (SPA) Standard: Ontology* [Draft]. Reston, VA.

American Institute of Aeronautics and Astronautics [AIAAf]. (2011). *Space Plug-and-Play Architecture (SPA) Standard: Logical Interface* [Draft]. Reston, VA.

American Institute of Aeronautics and Astronautics [AIAAg]. (2011). *Space Plug-and-Play Architecture (SPA) Standard: SpaceWire Subnet Adaptation* [Draft]. Reston, VA.

American Institute of Aeronautics and Astronautics [AIAAh]. (2011). *Space Plug-and-Play Architecture (SPA) Standard: 28V Power Service*[Draft]. Reston, VA.

American Institute of Aeronautics and Astronautics [AIAAi]. (2011). *Space Plug-and-Play Architecture (SPA) Standard: Test Bypass Extension* [Draft]. Reston, VA.

Department of Defense [DoDa]. (2006, August). *Risk management guide for DOD acquisition*, Sixth Edition, Version 1.0. Retrieved from http://www.dau.mil/pubs/gdbks/risk_management.asp

Department of Defense [DoDb]. (2009, July). *Technology Readiness Assessment (TRA) Deskbook*. Retrieved from http://www.DoD.mil/ddre/doc/DoD_TRA_July_2009_Read_Version.pdf

Government Accountability Office [GAO]. (1999, July). *Best practices: Better management of technology development can improve weapon system outcomes*. GAO/NSIAD-99-162.

Homeland Security Institute [HSI]. (2009, September 30). *Department of Homeland Security science and technology readiness level calculator (ver 1.1), Final report and user's manual*. Retrieved fromhttp://www.homelandsecurity.org/hsireports/DHS_ST_RL_Calculator_report20091020.pdf

JB Consulting International [JBCI], (n.d.).*Technology readiness level*. Retrieved 7 July 2011 from http://jbconsultinginternational.com/TechnologyReadinessLevel.aspx.

Kujawski, E. (2010, October 25–28). *The trouble with System Readiness Level (SRL) index for managing the acquisition of defense systems* [PowerPoint]. National Defense Industrial Association 13th Annual Systems Engineering Conference. San Diego, CA. Retrieved from http://www.dtic.mil/ndia/2010systemengr/ThursdayTrack7_10745Kujawski.pdf

Lyke, J. C., & Peck, N. (2011). *Introduction to Space Plug-and-Play Architecture (SPA)* [Draft PowerPoint]. Air Force Research Laboratory. Kirtland Air Force Base, NM.

Mankins, J. (1995, April 6). *Technology readiness levels: A white paper*. Advanced Concepts Office, Office of Space Access and Technology, NASA.

Moore, C. (2008, February 20). *TRL usage at NASA* [PDF document]. DoD Cost Analysis Symposium. NASA Headquarters.

Sauser, B., Ramirez-Marquez, J., Magnaye, R., & Tan, W. (2008). A systems approach to expanding the technology readiness level within defense acquisition. *International Journal of Defense Acquisition Management*, *1*, 39–58.

Sauser, B., Ramirez-Marquez, J., Verma, D., & Gove, R. [Sausera].(2006). *Determining system interoperability using an integration readiness level* [PDF document]. Retrieved from http://www-ferp.ucsd.edu/ARIES/MEETINGS/0712/Waganer/ILR%20Description%20(sauser).pdf

Sauser, B., Ramirez-Marquez, J., Verma, D., & Gove, R. [Sauserb]. (2006). *From TRL to SRL: The concept of systems readiness levels* [PDF document]. Retrieved from http://sse.stevens.edu/fileadmin/cser/2006/papers/126-Sauser-TRL%20SRL.pdf

Schenk, S. W. (2011, May). *CAA APT business case summary* [PowerPoint]. SPA Strategic Analysis Kick-off Meeting. Kirtland Air Force Base, NM

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California