Advancing the Practice of Systems Engineering at JPL

P. A. "Trisha" Jansma and Ross M. Jones
Systems Engineering Advancement (SEA) Project
Jet Propulsion Laboratory (JPL)
4800 Oak Grove Drive
Pasadena, CA 91109-8099
818-354-0647 and 818-354-7769
Patti.A.Jansma@jpl.nasa.gov
Ross.M.Jones@jpl.nasa.gov

Abstract—In FY 2004, JPL launched an initiative to improve the way it practices systems engineering. The Lab's senior management formed the Systems Engineering Advancement (SEA) Project in order to "significantly advance the practice and organizational capabilities of systems engineering at JPL on flight projects and ground support tasks." The scope of the SEA Project includes the systems engineering work performed in all three dimensions of a program, project, or task:

1. the full life-cycle, i.e., concept through end of operations
2. the full depth, i.e., Program, Project, System, Subsystem, Element (SE Levels 1 to 5)
3. the full technical scope, e.g., the flight, ground and launch systems, avionics, power, propulsion, telecommunications, thermal, etc.

The initial focus of their efforts defined the following basic systems engineering functions at JPL: systems architecture, requirements management, interface definition, technical resource management, system design and analysis, system verification and validation, risk management, technical peer reviews, design process management and systems engineering task management. They also developed a list of highly valued personal behaviors of systems engineers, and are working to inculcate those behaviors into members of their systems engineering community. The SEA Project is developing products, services, and training to support managers and practitioners throughout the entire system life-cycle. As these are developed, each one needs to be systematically deployed. Hence, the SEA Project developed a deployment process that includes four aspects: infrastructure and operations, communication and outreach, education and training, and consulting support. In addition, the SEA Project has taken a proactive approach to organizational change management and customer relationship management – both concepts and approaches not usually invoked in an engineering environment.

This paper[1, 2] describes JPL's approach to advancing the practice of systems engineering at the Lab. It describes the general approach used and how they addressed the three key aspects of change: people, process and technology. It highlights a list of highly valued personal behaviors of systems engineers, discusses the various products, services and training that were developed, describes the deployment approach used, and concludes with several lessons learned.

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1. INTRODUCTION

About JPL

The Jet Propulsion Laboratory (JPL), located in Pasadena, California, is a non-profit federally funded research and development center which is operated by the California Institute of Technology under a contract with the National Aeronautics and Space Administration (NASA). JPL is part of the U.S. aerospace industry, and is NASA's lead center for robotic exploration of the solar system. In addition to its work for NASA, JPL performs tasks for a variety of other federal agencies, such as the U.S. Department of Defense, the Department of Transportation, the Department of Energy, etc. JPL is organized into nine directorates as follows:

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[2] IEEEAC paper #1031, Version 6, January 13, 2006

1. Office of the Director
2. Business Operations Directorate (BOD)
3. Solar System Explorations Directorate
4. Engineering and Science Directorate (ESD)
5. Office of Safety and Mission Success
6. Mars Exploration Directorate
7. Astronomy and Physics Directorate
8. Earth Science and Technology Directorate
9. Interplanetary Network Directorate

The organizational structure within a directorate includes groups, sections, divisions and then directorate. JPL uses the matrix organizational structure such that the technical divisions within the ESD also report to the program and project offices within the programmatic directorates. JPL has approximately 5000 employees: 4000 in the technical divisions of ESD and the programmatic directorates and 1000 in the administrative divisions of BOD. Its annual budget is approximately $1.4 billion.

Background

Motivated by some highly visible failures resulting in mission loss (e.g., Mars '98) and by a NASA-wide systems engineering initiative, JPL undertook an effort to advance the way it practices systems engineering. Another driver was the large increase (almost a factor of ten) in the number of projects being implemented simultaneously, compared to the era in which JPL's traditional practice of systems engineering was developed. The Lab's senior management formed the Systems Engineering Advancement (SEA) Project in order to "significantly advance the practice and organizational capabilities of systems engineering at JPL on flight projects and ground support tasks." The scope of the SEA Project includes the systems engineering work performed in all three dimensions of a program, project, or task:

1. the full <u>life-cycle</u>, e.g., concept through the end of operations
2. the full <u>depth</u>, e.g., Program, Project, System, Subsystem, Element (SE Levels 1 to 5)
3. the full <u>technical scope</u>, e.g., the flight, ground and launch systems, avionics, power, propulsion, telecommunications, thermal, etc.

The SEA Project realizes that major change initiatives must address the three aspects of change – people, process, and technology (see Figure 1) – and that proactively deploying those changes is essential. Hence, the SEA Project is comprised of the following four components.

1. The <u>SEA Project Management</u> manages the SEA Project and all its activities, and communicates with JPL senior management and with other external interfaces.
2. The <u>Process, Product, Tools and Technology (PPTT) Element</u> captures, defines, and refines repeatable systems engineering procedures and practices for project use. It also identifies existing and emerging technology and tools which support systems engineering activities, especially those that provide model-based engineering capabilities.
3. The <u>People Element</u> supports the recruiting, selection and development of systems engineers via strategic hires, career path planning, behavioral competency models, seminars, classroom training, mentoring and on-the-job training (OJT).
4. The <u>Deployment Element</u> promotes communication and infuses practices into project use; measures the project's progress toward its objectives and requirements; and provides the infrastructure for the SEA Project.

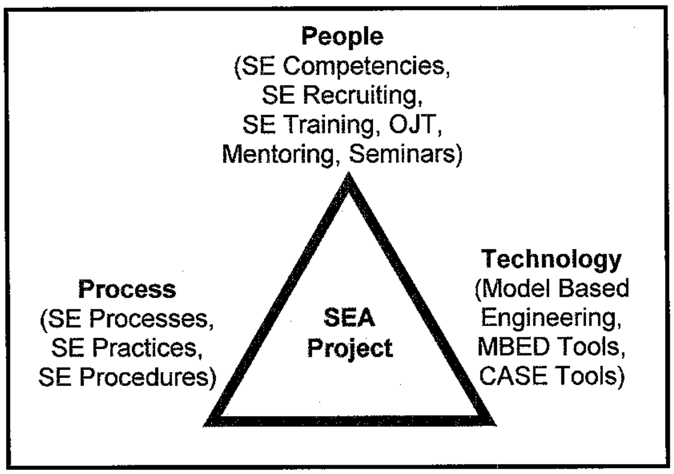

Figure 1 How the SEA Project Addresses the Three Key Aspects of Change

Fortunately, the SEA Project has the four "must haves" necessary for success in creating major change defined by Hutton [8]:

1. Compelling reasons for change – NASA agency-wide systems engineering initiative, Caltech JPL Advisory Council recommendations, JPL Implementation Plan initiatives, recent highly visible failures and corresponding accident reports
2. Suitable sponsors – Associate Director for Flight Projects and Mission Success, Directors for program and technical directorates, Strategic Management Council (SMC), and Project and Engineering Management Council (PEMC)
3. Informed commitment of sponsors – internal funding and active commitment of Directors, senior management, SMC and PEMC
4. A change agent or "champion" – Process Owner for the JPL Systems Engineering process.

The SEA Project was able to build on some previous process improvement activities at JPL in the 1980's and 1990's, including Total Quality Management (TQM), Process-Based Management (PBM), ISO 9000 certification, and the Software Resource Center (SORCE). However, they had to deal with some "baggage" associated with these previous initiatives as well. In addition, significant leverage has been gained from the work of the Software Quality Improvement (SQI) Project initiated in FY 2002. They also conducted several benchmarking trips to aerospace organizations that have achieved high maturity level ratings against SEI's Capability Maturity Model Integration (CMMI) to study and observe their approach to systems engineering and process improvement.

2. TARGET AUDIENCE

JPL's employees are classified into 13 job families, and each family has several disciplines and sub-disciplines. While the majority of the JPL Systems Engineering Community consists of practitioners in the Engineering job family and Systems Engineering discipline, systems engineering managers are categorized as either Line Management or Program/Project Management. Also, personnel who are categorized as Information Systems and Computer Science (IS&CS) and Technical would still be considered part of the Systems Engineering Community provided that at least 50% of their work involves systems engineering. Given this range of categories, the systems engineering community at JPL consists of approximately 900 people – about 700 practitioners and 200 managers. In order to limit the scope of the effort to highest priority sectors, the SEA Project initially narrowed their definition of their target audience to exclude those who are performing systems engineering related to basic research and development, and advanced technology development.

Use of Customer Relationship Management (CRM)

The SEA Project has taken a proactive approach to customer relationship management (CRM), an approach not usually invoked in an engineering environment. CRM is "a strategy used to learn more about customer's needs and behaviors in order to develop stronger relationships with them." [5] It helps ensure that all products and services truly provide value to the customer, and that the "real" customers are being targeted and reached. CRM defines a customer acquisition life-cycle with six stages labeled unaware, aware, interest, action, user, and evangelist. CRM involves identifying and prioritizing customer target segments, creating customer profiles, and tailoring the communication messages and approach to their specific needs [4], [7], 15].

The SEA Project identified five customer segments as shown in Table 1. Systems engineering line management customers (Segment 1) include Level II and III line managers (section managers and division managers) of system-intensive organizations. Project management customers (Segment 2) include managers in JPL program and project offices whose purview encompasses the entire system and its entire life-cycle. Systems engineering management customers (Segment 3) include Level I line managers (supervisors) of system-intensive organizations, Project Element Managers (PEMs), and Mission Assurance Managers (MAMs). Systems engineering practitioner customers (Segment 4) include Program SEs, Project SEs, Flight System SEs, Instrument SEs, MOS SEs, GDS SEs and the other 15 systems engineering disciplines. Process improvement customers (Segment 5) include SE process engineers and other members of the SEA Project itself.

The SEA Project prioritized their outreach based on classes of systems. Their primary customers are those working on flight and ground projects such as spacecraft, instruments, and associated ground systems. Their secondary customers are those working on enterprise, business or administrative systems. Using these definitions, they characterized all sections within the Engineering and Science Directorate, Mission Assurance Office, and Institutional Business Systems Division as either system-intensive (S), partial system focus (P), or no or very limited system focus (N), and then identified whether they were part of their primary (1) or secondary (2) audience. After they had characterized their target audience and established their priorities, they tailored their training and presentations to the unique needs of each segment, and worked to focus their initial efforts on their primary audience.

3. GENERAL APPROACH

The SEA Project began by completing an extensive effort to understand the views of senior management with respect to the current state and needed improvements for systems engineering at JPL. They conducted face to face interviews with all the JPL senior managers (i.e., Directors for Program Directorates, Division Managers of the Engineering and Science Directorate (ESD), the JPL Chief Technologist, the JPL Chief Engineer, the JPL Project Support Office, the JPL Associate Director for Flight Projects and Mission Success) and with all the middle (section) managers of the Systems and Software Division. These interviews used the following four questions as a basis for conversation.

- What are your systems engineering "care abouts"?
- What is your vision for systems engineering at JPL circa 2008, 2013?
- How would you measure the change in systems engineering?
- Who are the top systems engineers you've known, or know of?

A summary of the significant "findings" was used as the business case for the SEA Project and for establishing improvement goals and change objectives.

The mission of the SEA Project is to measurably improve the practice of systems engineering at JPL, contribute to increasing the efficiency and decreasing the risk associated with the development and operation of JPL's missions, and to ensure there is a pipeline of qualified systems engineers with the critical skills needed for current and future missions

[41]. The objectives the SEA Project wants to achieve by FY 2008 are as follows.

- JPL routinely meets the demand for high quality **systems engineers** at all level
- Standard, mature, high quality systems engineering **practices** span the entire project life-cycle.
- Complexity is managed via incremental refinement of **models** to improve their fidelity.

In addition, the SEA Project identified several factors that are critical for the systems engineering of successful systems. The initial focus of their efforts included basic systems engineering functions: systems architecture, requirements management, interface definition, technical resource management, system design and analysis, system verification and validation, risk management, technical peer reviews, design process management and systems engineering task management.

The SEA Project created a management oversight group called the SEA-MOG that serves as a liaison between the SEA Project and divisions, sections, and groups in the Engineering and Science Directorate (ESD). The purpose of the SEA-MOG is to ensure that SEA Project activities and products respond to ESD needs and that these ESD elements are committed to the people, process and technology elements sponsored by the SEA Project. Specifically, the SEA-MOG members:

1. Provide two-way communication between the SEA Project and ESD elements.
2. Represent the position of their respective ESD elements on SEA topics, e.g., SEA formulation and content.
3. Implement SEA processes and products within their respective ESD elements.
4. Provide oversight of the SEA activities by participating in SEA reviews.

Systems Engineering Products

In the past two years, the SEA Project developed a range of products, services, and training to support managers and systems engineering practitioners throughout the entire system life-cycle. These products fall into the following categories:

1. Institutional systems engineering requirements and procedures
2. Compliance matrices
3. Checklists and Templates
4. Sample documents
5. Studies and Reports

Each of these products is designed to assist managers and SE practitioners in generating the required deliverable products that are part of the JPL flight project life-cycle, and to ensure that those products comply with the JPL SE requirements. Of course, as products, services and training are developed, each one needs to be systematically deployed.

Use of Organizational Change Management (OCM)

Aware of the danger that these products could become "shelfware," SEA's management was willing to commit the resources to ensure that these changes were deployed into the systems engineering community, and that they impacted the way that systems engineering is implemented at JPL. As a result, the SEA Project took a very proactive approach to both organizational change management and customer relationship management. This approach is the antithesis of the typical one affectionately known as "If we build it, they will come." Instead, it involves proactively reaching out to customers, and doing whatever it takes to facilitate their understanding and usage of processes, products and services.

Organizational change management (OCM) is "the methodology that integrates change and the ability to adapt into the organization." [16] It helps an organization accept and adopt new ways of doing business. OCM involves working with a target community to systematically introduce them to desired changes in such a way that those changes are eventually adopted and become commonplace [10], [27]. It is based largely on Rogers' seminal work on diffusion of innovation [14] which is summarized in Table 3. The SEA Project has employed several of Rogers' strategies for diffusing innovations including relevance, customer focus, user friendliness, education, likelihood, measurement and testimony [1].

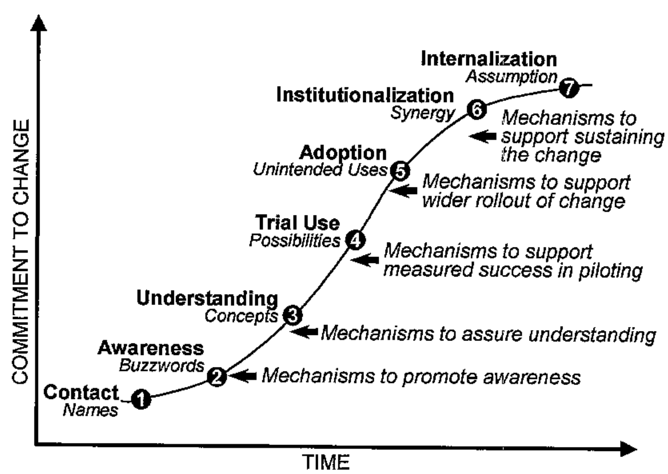

Figure 2 OCM Curve and Stages [6]

A premise of OCM is that people tend to fall into one of five change adoption categories and respond accordingly, as shown in Table 3. Another premise is that individuals tend to commit to change in predictable, sequential stages, beginning with contact and moving through awareness, understanding, installation or "trial use", adoption, institutionalization, and finally, internalization [6]. These stages are shown along the OCM curve in Figure 2 above. The SEA Project developed specific descriptions for what each of the OCM stages means at JPL and utilizes them in their OCM approach. See Table 4 for their OCM stage definitions and activities. They chose a couple of system-intensive sections to be "early adopters" and worked closely with them to implement various aspects of the JPL systems engineering requirements. In addition, they proactively reached out to projects in the early stages of development, e.g., Phase A – Mission and System Definition and Phase B – Preliminary Design. Also, they developed several venues for reaching out to the systems engineering community as a whole. These are described in more detail in Section 7.

4. Processes and Products

The purpose of the SEA Process, Product, Tools and Technology (PPTT) Element is to improve the quality of systems engineering at JPL by infusing local systems development procedures with "best practices" and tools. The PPTT Element captures, defines, and refines repeatable systems engineering procedures for project use. The SEA PPTT Element began by reviewing systems engineering handbooks and standards from a number of respected organizations such as INCOSE, IEEE, ISO, EIA, DoD, NASA, etc. as shown in Table 6. This served as a "review of the literature" and established the state of the SE practice for the team. It helped ensure that they didn't leave anything out of their new JPL SE requirements. Their goal was to cover all systems engineering levels and to span the full system life-cycle.

The five levels of a flight project hierarchy and the systems engineering levels at JPL are:

- Level 1 – Program
- Level 2 – Project
- Level 3 – System (Flight, Ground and Launch)
- Level 4 – Subsystem (Avionics, Electrical Power, Instrument, Mechanical, Propulsion, Telecommunications, Thermal, Software, etc.)
- Level 5 – Element or Assembly

The full system life-cycle includes:

- Pre-Phase A – Advanced Studies
- Phase A – Mission and System Definition
- Phase B – Preliminary Design
- Phase C – Design and Build
- Phase D – Assembly, Test and Launch Operations
- Phase E – Operations

They identified the following ten systems engineering functions, wrote summary statements for each and offered them as seed material for the teams writing the new SE requirements and practices:

1. Develop the system architecture
2. Develop and maintain requirements
3. Develop and maintain interfaces
4. Manage and allocate technical resources
5. Analyze and characterize the system design
6. Verify and validate the system requirements and designs
7. Identify, manage and mitigate risks
8. Organized technical peer reviews
9. Manage the design process
10. Manage the systems engineering task

The ten SE requirements and practices were generated by "Blue Teams" comprised of Function Masters from the engineering line organizations. Then they were reviewed by "Red Teams" comprised of representatives from the JPL Chief Engineer's Office, the Joint Engineering Board (JEB), and the JPL Project Offices. The SE practices will be instantiated in discipline or application domain specific local procedures owned by the line organizations. In addition, they integrated these practices into the overall process architecture at JPL for the Develop New Products (DNP) process and with the software development requirements (process). They also generated a generic system development template that can be tailored locally. See Figure 3 for the SEA Process and Tools task flow.

5. Tools and Technology

The SEA PPTT Element also identifies existing and emerging tools and technologies that support systems engineering activities, especially those that provide model-based systems engineering capabilities. Model-based systems engineering (MBSE) is the application of scientific and engineering efforts to transform an operational need into a description of system performance parameters and a system configuration by creating executable, explicit representations (model) of a system in order to predict, simulate and explain the resultant behavior of the system from the structure [37], [38].

The SEA Project evaluated a number of systems engineering tools against a specified set of criteria and attempted to evaluate each tool using a real-world scenario. They compared the tools using the following four categories and criteria:

1. Architecture and Design Modeling
   - System Modeling Language (SysML)
   - Unified Modeling Language (UML)
   - Enhanced Functional Flow Block Diagram (eFFBD)
   - Generic
2. Executable Modeling and Simulation
   - Interoperability
   - Trade space modeling

- Performance modeling
- Time-based simulation
- State-based simulation
- Resource simulation

3. Information Management
   - User-definable schema
   - Metadata query
   - Data query
   - Document linking
   - Document storage
   - Change management
   - Consistency checking
   - Consistency checking external sources
   - Data retrieval format
   - Application Program Interfaces (APIs)

4. Administration and Usage
   - Usability
   - Stability
   - System requirements
   - Links to external tools

They evaluated Functional Modeling tools such as CORE® from Vitech Corp. and CRADLE® from 3SL, visual modeling tools for UML/SysML such as Rhapsody® from I-Logix, TAU/Architect™ from Telelogic, and Real-Time Studio from Artisan Software. They also evaluated requirements management tools such as TeamCenter Requirements from UGS. They rated each tool as poor, fair or good against the four criteria and generated a report of their findings. The general strengths they observed were:

- The diagramming options available are generally mature and do a good job of capturing/defining the information relationships.
- The information models are generally extensible and tailorable to any application.
- The UML heritage tools have good APIs for external tools to access.
- Most tools provide data in XML format.
- The tools are typically easy for end-users to learn.

The general weaknesses they observed were:

- Creating new diagrams (e.g., DoDAF views) in the UML heritage tools is not straightforward and would require a "power user."
- Adding custom modeling and simulation capability to any of these tools is a non-trivial task.
- None of these tools deal well with maintaining links to external information sources, e.g., documents, spreadsheets, etc.
- Setting up licensing seems to be overly cumbersome for many of these tools.

They also utilized a metrics tool to evaluate the effectiveness of their use of DOORS® from Telelogic for requirements management. It is their hope that these tool evaluations will facilitate their use in supporting the systems engineering functions and in promoting a model-based systems engineering culture at the lab.

6. People Element

The purpose of the SEA People Element is to improve the quality of systems engineering at JPL by enhancing the capabilities of personnel who perform systems engineering functions. It supports the recruiting, selection and development of systems engineers via strategic hires, career path planning, competency models, seminars, classroom training, mentoring and on-the-job training (OJT). This is highly consistent with aspects of SEI's People Capability Maturity Model (P-CMM) [34].

Systems Engineering Competency Model

The SEA Project developed a systems engineering competency model along three axes that includes Processes, Personal Behaviors and Technical Knowledge (see Figure 4). The Processes axis encompasses the ten systems engineering functions described in Section 4. The Personal Behaviors axis encompasses the five clusters and 17 behaviors discussed below. The Technical Knowledge axis encompasses the 21 systems engineering disciplines shown previously in Segment 4 of Table 1 [29], [30]. This model will be used to screen candidates for external hire, to conduct internal assessments of systems engineers, and to drive training content and active career management.

Highly-Valued Behaviors of Systems Engineers

The SEA Project utilized a rigorous process to identify a list of highly valued personal behaviors of systems engineers [40]. The process was performed by a person from the Leadership and Organizational Development Group in the Human Resources Professional Development Section who is trained in psychology. She interviewed and shadowed nine highly regarded systems engineers and administered the Myers Briggs Type Indicator (MBTI®) to them to identify their personality or psychological type. Then she analyzed common themes and grouped information into clusters of competencies with associated behaviors. Finally, she reviewed and sought concurrence with the interviewees on the overall competencies. The behaviors identified fall into the five clusters shown below.

1. Leadership Skills
   - Has the ability to influence
   - Has the ability to work with a team
   - Has the ability to trust others
   - Communicates vision and technical steps needed to reach implementation

- Mentors and coaches less experienced systems engineers

2. Attitudes and Attributes
   - Has intellectual self-confidence
   - Has intellectual curiosity
   - Has ability to manage change
   - Remains objective and maintains a healthy skepticism

3. Communication
   - Advances ideas and fosters open two-way discussions
   - Communicates through storytelling and analogies
   - Listens and translates information

4. Problem Solving and Systems Thinking
   - Manages risk
   - Thinks critically and penetrates a topic in a methodical manner

5. Technical Acumen
   - Successfully expresses a technical grasp of system engineering at all levels
   - Is a generalist in nature, with proven technical depth in one or two disciplines
   - Has proven knowledge of systems engineering practices

These findings are consistent with the literature on highly successful and effective people [2], [3], [12], [13]. Now the SEA Project is working with line managers to inculcate these valued behaviors into members of their systems engineering community and to utilize this list in their interviewing process.

SEA On-the-Job Training (OJT) Program

The SEA On-the-Job Training (OJT) Program responds to a strategic initiative at JPL the objective of which is to increase the number of highly trained systems engineers at the Lab. The goal is to establish a systems engineering development program and to identify 10 engineers currently at JPL to go through training, mentoring, shadowing, and internship. The selection criteria for SEA OJT candidates includes:

1. **Career Phase:** Is in early or mid-career phase
2. **Potential:** Has the potential of being among the best SEs in their organization
3. **SE Ability:** Is able to implement the SE functions
4. **SE Behaviors:** Has many of the preferred SE behaviors
5. **Experience:** Has had flight project delivery experience (software or hardware) and SE work experience
6. **SE Disciplines:** Is representative of a cross section of the 21 systems engineering disciplines at JPL

The SEA OJT program funds each protégé about eight hours per week to be allocated, on average, as follows:

- 1 hour spent with project ***mentor***
- 2 hours spent ***shadowing*** mentor or others
- 2 hours spent attending **project events** not directly related to their project assignment
  - Events within their assigned project
  - Events on other projects
- 3 hours spent attending **training events**
  - JPL Systems Engineering course
  - JPL Case Studies in SE course
  - Section and discipline specific training
  - Planning with SEA Training Coordinator
  - 1 hour spent with a SE Function Master or SE function training
  - 1 hour spent with technical discipline training
  - Monthly protégé meeting with SEA Training Coordinator and management
  - Problem solving: concentrated doses of value-added systems engineering.

The SEA Project also funds mentors to work with each protégé and to share their expertise.

SEA Seminar Series

The SEA Project sponsors two seminar series and one users group in order to reach out to the systems engineering community as a whole.

1. SEA Seminar Series – Shares processes, practices and tools for advancing systems engineering. This series consists of one-hour noon-time presentations usually by internal JPL speakers on various topics ranging from model-based engineering design tools, methodologies, and project experiences to valued SE behaviors.

2. SEA "Lunch and Learn" Series – Provides general overviews of specific engineering disciplines for personnel not familiar with that discipline. This series consists of one-hour noon-time presentations usually by internal JPL speakers on various topics ranging from flight system to software, mechanical and thermal systems engineering, etc.

3. SEA UML/SysML Users Group -- Provides the JPL community with information to help advance the use of visual modeling techniques on JPL projects through use of industry standards and best practices; specifically, use of the Unified Modeling Language (UML) and the Systems Modeling Language (SysML) visual modeling standards. This users group provides a forum to discuss UML/SysML modeling issues, provides educational talks on various issues related to visual modeling of systems and software, and hosts presentations by commercial vendors of UML/SysML modeling tools.

Education and Training

The SEA Project is working with JPL Professional Development to develop and provide educational materials and classroom and computer-based training in the desired functions, products and tools. It includes a Systems Engineering Training approach that defines the target customers, required discipline knowledge, and training goals, and describes the training process to be utilized. The following courses are being offered or are under development (*):

- Systems Engineering Principles
- Systems Engineering at JPL*
- System Requirements Definition and Management
- How to Document and Trace Requirements Using DOORS
- State Analysis
- MOS Systems Engineering
- Case Studies in Systems Engineering*
- Using Model-Based Systems Engineering Tools*

In addition, they are developing detailed discipline or application domain specific training for each of the systems engineering disciplines.

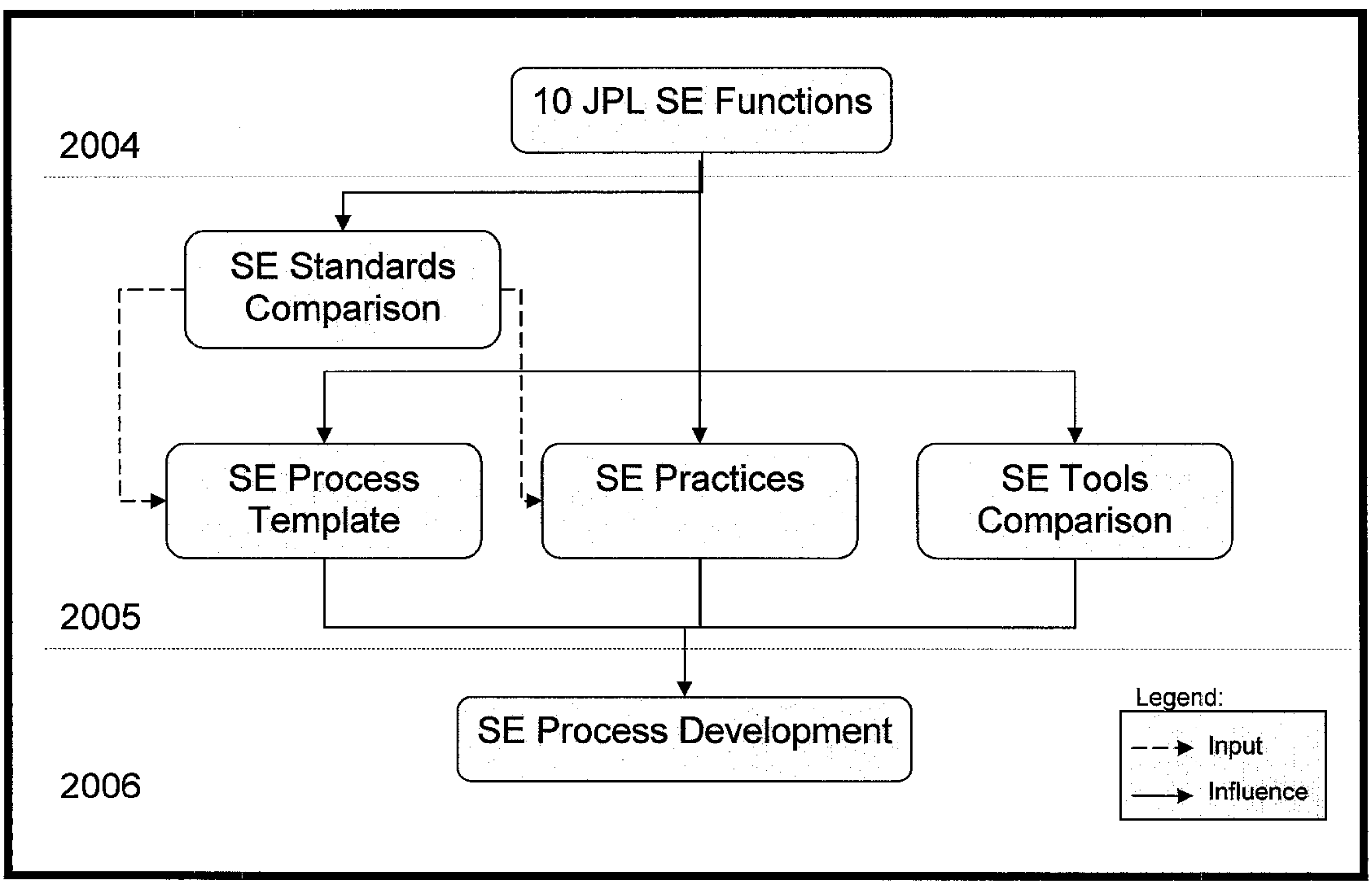

Figure 3 SEA Process and Tools Task Flow

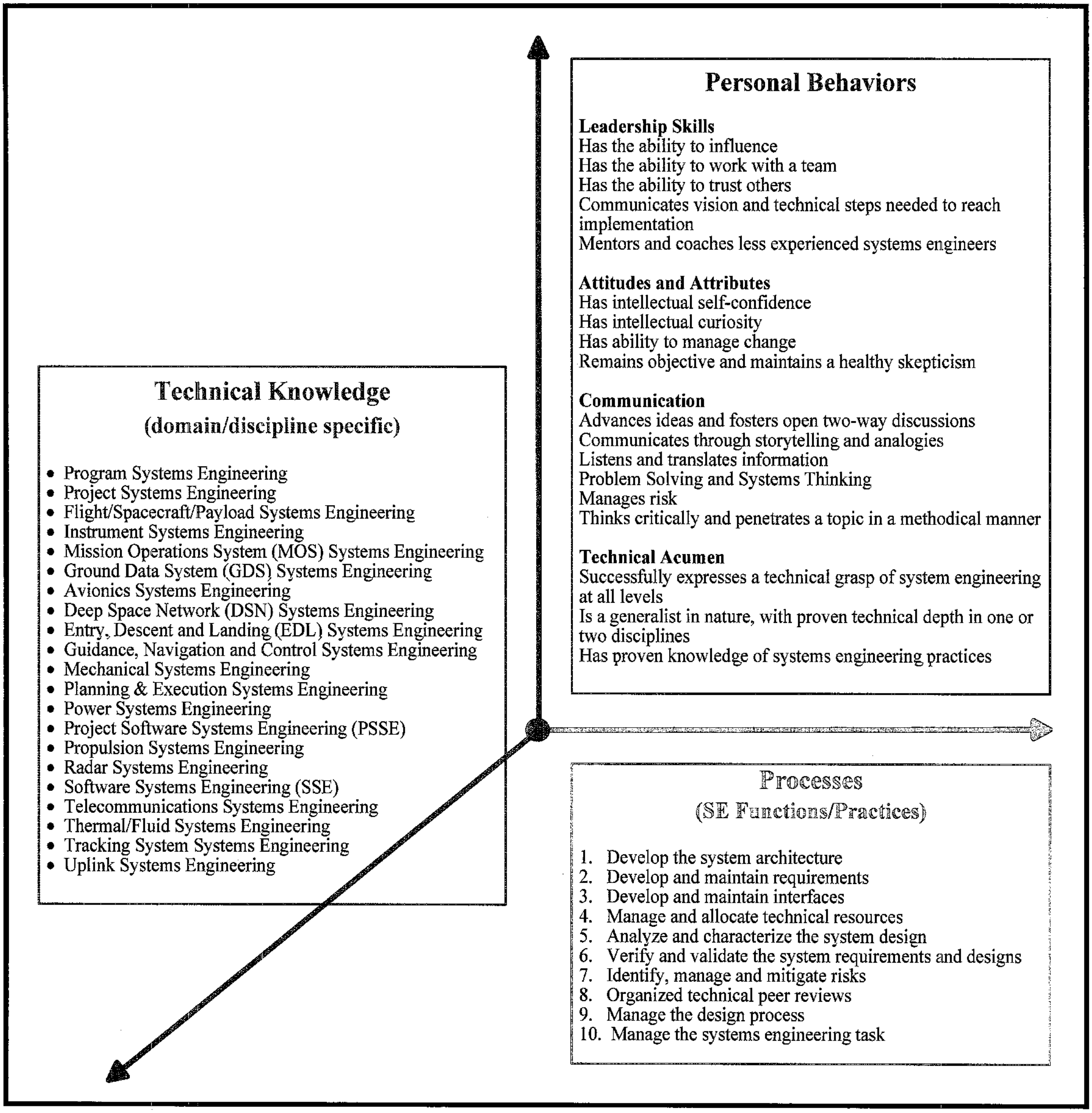

Figure 4 Three Axes of the JPL Systems Engineering Competency Model

7. Deployment Process

The SEA Project developed a process for creating and deploying an asset. The entire process includes:

1. Define and analyze user requirements and/or sponsor needs.
2. Generate the process, product or artifact.

Core Deployment Process

3. Develop Infrastructure and Operations approach and tools to support it.
4. Develop Communications and Outreach materials to support it.
5. Develop Education and Training materials to support it.
6. Perform Customer Support to promulgate it.

7. Collect process and customer metrics to track it.
8. Capture and document Lessons Learned.
9. Update the process, product or artifact based on feedback.
10. Institutionalize the artifact and transfer responsibility to the appropriate line organization.

Hence, the core of the deployment process includes four parts (steps 3-6 above) which occur sequentially whenever a product is deployed, as shown in Figure 5 below.

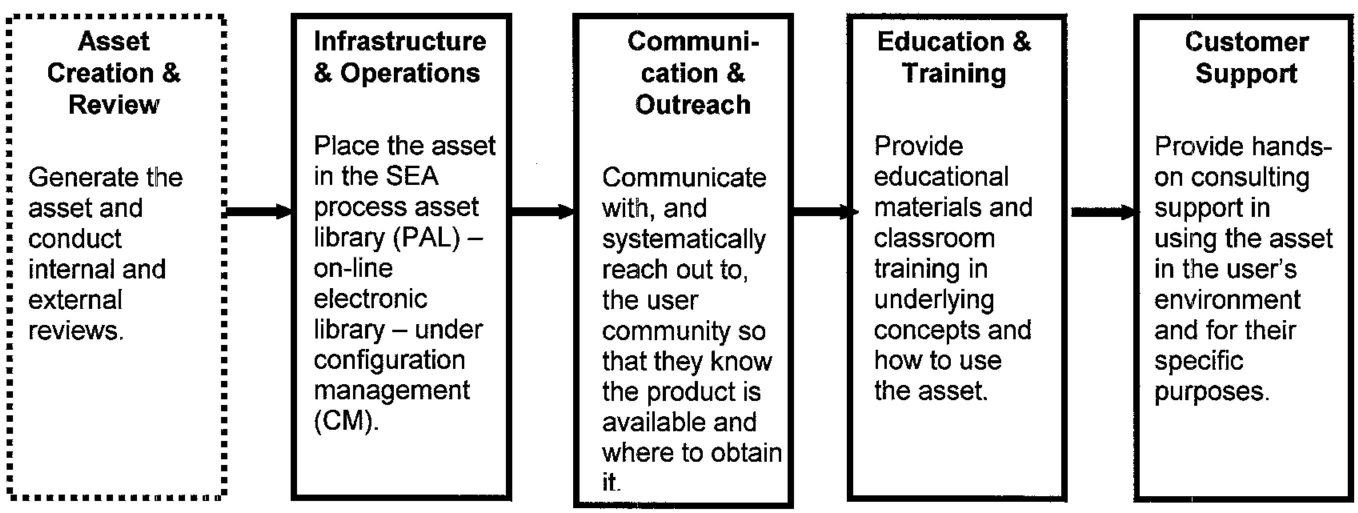

Figure 5 SEA Deployment Process

1. Infrastructure and Operations -- develop the necessary infrastructure and operations approach for each area
2. Communication and Outreach – communicate with, and systematically reach out to, the user community so that they know what is available and understand where to obtain it.
3. Education and Training – provide classroom and computer-based training in the desired processes, products and tools
4. Customer Support – provide consulting support to projects across a broad range of relevant topics.

These four parts of deployment are described in more detail in the next four subsections of this paper.

Infrastructure and Operations

Infrastructure and Operations involves developing the necessary infrastructure and operations approach for the SEA Project as a whole, and also for each item to be deployed. It includes an integrated tracking system (for tracking action items, problem/failure reports, customer contacts, etc.), configuration management system, electronic library, metrics collection, customer e-mail lists, CRM database, project calendar, target audience definition and strategy, intellectual property approach, and SEA Deployment and Operations Plan. This infrastructure is the foundation upon which all other aspects of deployment are built. Of course, the products and services themselves must first be generated, and this infrastructure greatly assists that process.

Communication and Outreach

Communication and Outreach involves communicating with, and systematically reaching out to, the user community so that they know and understand what is available. It includes a website, presentations, seminars, brochure, OCM and CRM approaches, surveys, forums, interest groups, etc.

The SEA Project generated a SEA OCM approach that defined the following:

- Organizational change management strategy
- Infusion goals and change acceptance time lines
- Themes and thrusts
- Key stakeholders and segments
- Communications vehicles
- SEA logo, brochure, fliers, and tag lines
- Roles and responsibilities, and interactions amongst the elements to achieve the changes.

This OCM approach informs all aspects of their communication and outreach activities and provides a well-integrated approach to their customers.

Similarly, the SEA Project generated a SEA CRM approach that defined the primary and secondary customer target segments and corresponding customer profiles. The project is using this as a basis to tailor specific communication messages and approaches to the needs of each customer segment.

The SEA Project developed a website to support their user community, and gave the site a URL that is very easy to remember. The site includes information about training, seminars, contacts, standards, etc. The SEA Project also generated a tailorable presentation describing the products, services and training available, and is in the process of giving the presentation to all organizations involved in systems engineering at the Lab. In addition, the Project developed a 3-fold brochure to help promote their website and services. They use multiple communication channels to communicate their message, ranging from community e-mail lists, to websites, posters, fliers, cafeteria monitors, newsletters, etc.

The SEA Project conducted a survey of about 500 members of the systems engineering community in order to determine their needs and to aid in setting priorities and allocating funds. The survey asked participants to: 1) rate their ability to perform the JPL systems engineering functions compared to their peers, 2) rate their ability to perform the SE functions compared to the needs of their job, 3) rank the SE functions in order of their need for self-improvement, 4) rank the SE functions in order of need for improvement in terms of institutional support, and 5) recommend how to allocate funds for SE improvement in the areas of tools, products, and training. The survey also included a comment area where participants could suggest improvements they would like to see at JPL. Over 45% of those who responded to the survey took the time to provide comments. The respondents indicated that training was their first priority, followed by tools, and lastly products. Also, this survey will serve as a baseline against which to compare progress in the future.

Customer Support

Customer Support involves providing consulting support to practicing systems engineers supporting flight projects across a broad range of relevant topics so that they can use the processes, products and tools in their own environment and for their specific purposes. It includes consulting in the ten functions of systems engineering and on the use of model-based engineering tools, etc.

All customer contacts made by SEA are tracked via the SEA contact management system and categorized as follows: Information, Outreach, Training, and Consulting.

8. Lessons Learned

The JPL SEA Project has collected a number of observations or "lessons learned" from its efforts to improve the practice of systems engineering at the lab. These observations or lessons fall into three basic categories: process improvement, creating assets, and deploying assets.

Process Improvement

1. <u>Build on previous efforts.</u> – The SEA Project was able to build on previous reengineering efforts, especially the major reengineering activities associated with Process-Based Management (PBM) and ISO 9000 in the late 1990's. Significant leverage from the Software Quality Improvement (SQI) Project in the mid 2000s was achieved by sharing deployment personnel.

2. <u>Take the time to survey your stakeholders and identify their "care abouts."</u> – Understanding what your stakeholders care about gives legitimacy to your effort and ensures that you focus on the things that are "wildly important" to them [3].

3. <u>Address all three aspects of change management: people, process and technology</u>. It's tempting to just focus on generating processes or on exploring fascinating technology and ignore or minimize the people component. But systems engineering is a people intensive activity, and the behaviors and training needs of systems engineers must be addressed to truly have an impact on the culture.

4. <u>Reach the "front line" and middle managers too.</u> – The SEA Project is very fortunate to have the "must haves" necessary for success in creating major change (as described in Section 1). Senior management support is important, however, so is the support of "front line" managers (Group Supervisors) and middle managers (Section Managers). That support needs to be painstakingly earned, one meeting or presentation at a time.

5. <u>Other concurrent major changes can be a mixed blessing</u>, i.e., sources of distraction or opportunity [8]. – Recently the entire Engineering and Science Directorate (ESD) at JPL underwent a major reorganization and

downsizing. The effects on the SEA Project still need to be fully understood. It means many new players in key roles, but also provides many additional opportunities.

Creating Assets

6. Start by defining the basic systems engineering processes. – Defining these processes is a necessary step to ensure that a robust process is available and ready to be utilized.

7. Evaluate and select tools to support the design process. – When you do the ground work of evaluating model-based systems engineering tools and setting up a framework for their use, then users are much more likely to try them and view them as "user friendly."

8. Utilize many reviewers to promote ownership. – When many reviewers who are representative of different domains and perspectives provide comments on new or revised products, it promotes ownership or "buy-in" of the final result.

9. Allocate sufficient time for curriculum development. – Curriculum development and defining course content is very time consuming. On average, it takes approximately four months to develop a new course.

Deploying Assets

10. Use OCM and CRM to facilitate change. – There are several advantages to proactively using OCM and CRM. It helps to maintain a customer focus and to create motivation for reaching out to customers. Also, when setting priorities, it helps to know who your primary target audience is vs. your secondary audience. For example, some "eager beavers" or early adopters may not be part of your primary customer group.

11. Address "culture issues" head on. – The SEA Project needed to address some culture issues it encountered when deploying assets.
    a. The major paradigm shift involved in using model-based engineering design (MBED) tools.
    b. Factors that engendered resistance to change, such as the perception of insufficient time and resources to try something new, program and project constraints, and the difficulty of change itself.
    c. "Baggage" from previous process improvement efforts and the false perception of "just another unfunded mandate."

12. Conduct surveys and measure regularly. – Conduct regular surveys and user forums to determine the level of infusion into the organization and to uncover any barriers to acceptance. Measure infusion, effectiveness, customer satisfaction, progress, etc. Remember that "without measurement, you're just guessing!"

13. Communicate via multiple avenues and promote shamelessly. It never helps a change effort if it remains a "well kept secret." No matter how many times a message is communicated, there still may be some who haven't gotten the message. Some people prefer e-mail, while others prefer fliers, posters, presentations or seminars. It helps to think of novel ways to attract attention such as bookmarks, cubicle pins, brochures, websites, etc.

9. CONCLUSIONS

Changes in the practice of systems engineering do not come quickly or easily. The improvement process needs to be approached with many of the same deliberate methods and practices that are used in actual system development. Proactively reaching out to customers instead of merely waiting for them to come to you is essential. It is important to maintain the proper balance between defining processes or generating assets and actually deploying them and supporting customers. If this balance is not achieved, all the products generated just become "shelfware." Lastly, all three aspects of change management must be addressed – people, process and technology – and the people component is where the maximum leverage is gained. Knowing how successful systems engineers behave and sharing that information with the SE community establishes a standard for hiring, evaluation and personnel development.

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11. Acronyms and Abbreviations

API	Application Program Interface
BOD	Business Operations Directorate
Caltech	California Institute of Technology
CM	Configuration Management
CMMI	Capability Maturity Model Integration
CORE®	Model-based Systems Engineering tool from Vitech
CRADLE®	Model-based Systems Engineering tool from 3SL
CRM	Customer Relationship Management
DNP	Develop New Products (process)
DoD	Department of Defense
DoDAF	DOD Architecture Framework
DOORS®	Dynamic Object-Oriented Requirements System (requirements management tool from Telelogic)
DSMS	Deep Space Mission System
DSN	Deep Space Network
ECAP	Employee Contribution Assessment and Planning (JPL annual employee performance evaluation)
EDL	Entry, Descent and Landing
EIA	Electronic Industries Alliance
ESA	European Space Agency
ESD	Engineering and Science Directorate
FPP	Flight Project Practices
FY	Fiscal Year
GDS	Ground Data System
GSFC	Goddard Space Flight Center (NASA Center)
IEEE	Institute of Electrical and Electronics Engineers
INCOSE	International Council on Systems Engineering
ISO	International Standards Organization
IS&CS	Information Systems & Computer Science
JEB	Joint Engineering Board
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center (NASA Center)
MAM	Mission Assurance Manager
MBED	Model-Based Engineering Design
MBSE	Model-Based Systems Engineering
MBTI®	Myers-Briggs Temperament Indicator
MED	Mars Exploration Directorate
MOS	Mission Operations System
MSFC	Marshall Space Flight Center (NASA Center)
NASA	National Aeronautics & Space Administration
OCM	Organizational Change Management
OJT	On-the-Job Training
PAL	Process Asset Library
PBM	Process Based Management
P-CMM	People Capability Maturity Model
PEM	Project Element Manager
PEMC	Project and Engineering Management Council
PPTT	Process, Product, Tools and Technology
PSSE	Project Software Systems Engineer
QA	Quality Assurance
R&D	Research and Development
SE	Systems Engineer(ing)
SEA	Systems Engineering Advancement
SEA-MOG	SEA Management Oversight Group
SEI	Software Engineering Institute
SMC	Strategic Management Council
SQI	Software Quality Improvement
SSE	Software Systems Engineer
SysML	System Modeling Language
TAU®	Model-based Systems Engineering tool from Telelogic
TQM	Total Quality Management
UML	Unified Modeling Language
USN	U.S. Navy
V&V	Verification and Validation
XML	Extensible Markup Language

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BIOGRAPHY

P. A. "Trisha" Jansma *is the Project Element Manager (PEM) for the Deployment Element of the Systems Engineering Advancement (SEA) Project and for the Software Quality Improvement (SQI) Project at the Jet Propulsion Laboratory (JPL) in Pasadena, California. With over 30 years at JPL in both line and project management positions, she has a broad background in systems and software engineering in both engineering and scientific environments. Jansma has extensive experience in the management, design, development and delivery of cost-effective, software-intensive systems. She has experience in all facets of project life-cycle development, from initial feasibility analysis, proposal development and conceptual design through documentation, implementation, user training, enhancement and operations. Jansma has a B.A. in Mathematics from Point Loma Nazarene University, an M.S. in Computer Science from the University of Southern California, and an Executive M.B.A. from the Peter F. Drucker Graduate School of Management at Claremont Graduate University. Also, she has taught Systems and Software Engineering courses at the graduate level.*

Ross M. Jones *is the Project Manager for the SEA (Systems Engineering Advancement) Project at the Jet Propulsion Laboratory (JPL) in Pasadena, California. He is also the Systems Engineering Lateral Process Owner for the Engineering and Science Directorate, and the Assistant Division Manager for Systems Engineering in the Systems and Software Division at JPL. He began working at JPL 25 years ago, starting in the Electric Propulsion Group and then moved to the Advanced Mission Concepts Group in the early 1980s. He was the spacecraft bus system engineer on the Mars Observer Mission before becoming the Supervisor of the Advanced Spacecraft Systems Group in the Systems Engineering Section. Jones formulated and led the effort to develop and use micro-spacecraft for JPL missions, and was the Project Manager of the MUSES CN Nano-Rover Project. More recently he was the Project System Engineer on the Mars Reconnaissance Orbiter Project and the Supervisor of the Project System Engineering Group. Jones has a B.S. from Purdue University, and a M.S. in Aeronautical and Astronautical Engineering from the Massachusetts Institute of Technology. He is married, has two daughters both in college, and runs in competitive track and field events in his age group.*

TABLES

Table 1 Customer Segments in the SEA Target Audience

#	Customer Segment Name	Target Audience	Job Family/ Career Level
1	Mid-level Line Management Customers	• Division Managers & Deputy Managers and Section Managers & Deputy Managers of SE-intensive divisions and sections.	Line Management / Manager II, III
2	Project Management Customers	• Project Managers and Deputy Managers of major flight and ground projects, systems and subsystems	Project Mgmt. / Manager II or III
3	Systems Engineering Management Customers	• Technical Group Supervisors (TGSs) of SEs • Project Element Manager (PEMs) • Deep Space Mission System (DSMS) Task Managers • DSMS Operations & Engineering Managers (formerly Service System Managers) • Mission Assurance Managers (MAMs) • Other SE Managers	Project Mgmt. / Manager I, or Line Management / Manager I, or Engineering , IS&CS or Technical/ Principal, Senior A, or Senior
4	Systems Engineering Practitioner Customers (Systems Engineering Disciplines)	• Program Systems Engineer • Project Systems Engineer • Flight/Spacecraft/Payload Systems Engineer • Instrument Systems Engineer • Mission Operations System (MOS) Systems Engineer • Ground Data System (GDS) Systems Engineer • Avionics Systems Engineer • Deep Space Network (DSN) System Engineer • Entry, Descent and Landing (EDL) Systems Engineer • Guidance, Navigation and Control (GN&C) Systems Engineer • Mechanical Systems Engineer • Planning & Execution Systems Engineer • Power Systems Engineer • Project Software Systems Engineer (PSSE) • Propulsion Systems Engineer • Radar Systems Engineer • Software System Engineer (SSE) • Telecommunications Systems Engineer • Thermal/Fluid Systems Engineer • Tracking System Systems Engineer • Uplink Systems Engineer • Other SE practitioners	Engineering, IS&CS or Technical/ Principal, Senior A, Senior, Staff or Associate)
5	Process Improvement Customers	• SEA Project personnel • Systems Engineering Process Engineers • "Blue" Team and "Red" Team members	Varies

Table 2 Rogers Diffusion of Innovation Model

Attributes of Innovation	Strategies for Optimizing Attributes
Relative Advantage – degree to which the innovation is perceived to improve upon existing solutions	**Technology Improvement** – Introduce a new technology that is more powerful than the existing technology.
Compatibility – the difficulty associated with mastering the new innovation	**Relevance** – Make sure the problem solved by the innovation is important to adopters. **Realism** – Do not try to change too much at once or to please too many different types of users. **Customer Focus** – Seek input from current and future adopters and design a solution that they want.
Complexity – the difficulty associated with mastering the new innovation	**Developer Friendliness** – Reduce the learning curve for developers of the innovation. **User Friendliness** – Reduce the learning curve for adopters by making the innovation easy to learn and use. **Reuse** – Reuse as much of the old process and technology as possible. **Education** – Provide tutorials and demonstrations to potential users and managers. Publish useful information on Web pages and offer pointers to Early Adopters.
Trialability – the ability to experiment with the innovation before adopting it in normal operations	**Cost** – Reduce the cost of trial use. **Likelihood** – Increase the likelihood that trial use will succeed.
Observability – the ease with which improvement is noticed after adoption of the innovation	**Measurement** – Collect data about the old and new technologies for comparison. **Testimony** – Provide forums for adopters to describe their experiences. **Shadowing** – Provide a side by side comparison by running two projects with the same goals, but with one using the old technology and the other using the new.

Table 3 Roger's Categories of People and Their Responses to Innovation

Categories	Characteristics	Responses to Innovation
Innovators or "Techies" – those who create new technologies	Gatekeepers for any new technology; appreciate technology for its own sake; appreciate architecture of technology; will spend hours trying to get technology to work; very forgiving of poor documentation, slow performance, incomplete functionality, etc.; helpful critics	Will settle for buggy or difficult-to-use solution components; are accustomed to finding their way around the glitches.
Early Adopters or "Visionaries" – those who are the first to try innovations	Dominated by a dream or vision; focus on business goals; usually have close ties with "techie" innovators; match emerging technologies to strategic opportunities; look for breakthrough; thrive on high visibility, high risk projects; have charisma to generate buy-in for projects; do not have credibility with early majority	Can see the strategic advantage of the improvement or change and are willing to help the organization get there.
	"The Chasm" in the Adopter Continuum	
Early Majority or "Pragmatists" – those who establish an innovation's success by adopting it for regular use	Do not want to be pioneers (prudent souls); control majority of budget; want percentage improvement (incremental, measurable, predictable progress); not risk averse, but want to manage it carefully; hard to win over, but are loyal once won.	Can see the advantage of the improvement or change and are willing to carefully adopt it.
Late Majority or "Conservatives" – those who adopt an innovation after its success has been demonstrated	Avoid discontinuous improvement (revolution); adopt only to stay on par with the rest of the world; somewhat fearful of new technologies; like pre-assembled packages with everything bundled.	Need a lot of support to adopt the solution component.
Laggards or "Skeptics" – those who never adopt or who do so reluctantly after it becomes necessary	"Nay sayers"; adopt only after technology is not recognizable as separate entity; constantly point at discrepancies between what was promised and what is	Are very resistant to changing the status quo, despite the effectiveness of the solution component.

Table 4 SEA OCM Stages and Activities

OCM Stages	OCM Stage Name	OCM Definition at JPL	Associated OCM Activities
0	None	Never heard of SEA Project	None
1	**Contact**	Have heard of SEA Project	SEA publicity and outreach activities -- SEA brochure, bookmark, announcements, e-mail, fliers, posters, etc.
2	**Awareness**	Aware of SE standards, practices and procedures, and existence of SEA Seminar Series, SEA website, SEA Road Show, and model-based design concepts	SEA Target Audience list and SE disciplines, SEA website, SEA Seminar Series, SEA "Road Show", BEACON SE Online Guide, user forums, surveys, SE procedures and FPPs in JPL Rules!, MBED Overview/Tutorial
3	**Understanding**	Understand SE practices and procedures, model-based design concepts, basic SEA products (templates,), SE competencies	Systems Engineering at JPL course, SEA training courses, SE Discipline training, SEA Seminar Series, SEA "Lunch and Learn" Series, SEA function masters
4	**Installation (Trial Use)**	Utilize SE practices and procedures, model-based design tools, and some SEA products and services	SEA consulting – planning, SE practices and procedures, , tools, etc.; benefits & rationale, case studies, SEA impact metrics, SEA OJT internships, model-based design tools
5	**Adoption**	Some orgs/projects comply with institutional policies and practices (SE practices and procedures); use model-based design tools; apply SE competencies to hiring, annual evaluations (ECAPs) and SE career management	SE target sections, SEA consulting support, more training/coaching, lessons learned; address barriers to change; SE career paths & development plans, SE Competencies List, Fellow-level SE recruiting, ESD model-based design framework
6	**Institutionalization**	All orgs and projects performing SE comply with institutional policies and practices (SE practices and procedures); use model-based design tools; apply SE competencies to hiring, annual evaluations (ECAPs) and SE career management	SEA Element activities in concert with ESD line orgs, SEA OCM activities and metrics; SE career paths & development plans, SE competency model and valued behaviors, ESD model-based design Center and consulting support
7	**Internalization**	Institutional policies and practices (SE practices and procedures) inculcated into ESD line organizations	Appraisals or assessments, continuous process improvement, comprehensive training program, annual institutional performance appraisal of line managers that appropriately rewards and reinforces desired behavior

Table 5 Systems Engineering Handbooks and Standards Evaluated by the SEA Project

Document Category	Document Sponsor	Document Title
Handbooks	Department of Defense (DoD)	*Defense Acquisition Guidebook,* Version 1.0 (http://asks.dau.mil/dag/) October 10, 2004, Chapters 4 and 9. [17]
	International Council on Systems Engineering (INCOSE)	*Systems Engineering Handbook,* Version 2a (INCOSE-TP-2003-016-02) June 1, 2004. [24]
	National Aeronautics and Space Administration (NASA)	*Systems Engineering Handbook* (SP 610S) June 1995. [32]
Standards	Department of Defense (DoD)	*Systems Engineering Management* (Mil. Std. 499B) July 17, 1969. [18]
	Electronic Industries Alliance (EIA)	*Processes for Engineering a System* (ANSI/EIA 632-1999) January 1999. [19]
	European Space Agency (ESA)	*System Engineering — Part 1: Requirements and Process* (ECSS-E-10 Part 1B) November 18, 2004. [20]
	NASA Goddard Space Flight Center (GSFC)	*Systems Engineering* (GPG 7120.5) June 29, 2004. [21]
	Institute of Electrical and Electronics Engineers (IEEE)	*Recommended Practice for Architectural Description of Software-Intensive Systems* (IEEE 1471-2001) September 21, 2000. [22]
	Institute of Electrical and Electronics Engineers (IEEE)	*Standard for Application and Management of the Systems Engineering Process* (IEEE 1220-1998) January 22, 1999. [23]
	International Standards Organization (ISO)	*Systems Engineering — System Life Cycle Processes* (ISO/IEC 15288:2002(E)) November 1, 2002. [25]
	Lockheed Martin Corp.	Integrated Engineering Process Standard (LM-IEP), EPI 280-01, Rev 2.0, January 3, 2003 [39]
	National Aeronautics and Space Administration (NASA)	NASA Procedures and Guidelines, *Systems Engineering Processes and Requirements* (Draft NPG 71xx.x) December 2, 2002. [33]
Tailored Standards	NASA Johnson Space Center (JSC)	*Project Management: Systems Engineering and Project Control Processes and* Requirements (JPR 7120.3) March 2004. [26]
	NASA Marshall Space Flight Center (MSFC)	*Project Management and System Engineering Handbook,* Revision A (MSFC-HDBK-3173) October 27, 2003. [28]
	United States Navy (USN)	*Naval Systems Engineering Guide* (https://www.kmsonline.net/41G/KMS/Library/SE%20Guide.pdf) October 2004. [35]