Exploring Mission Concepts with the JPL Innovation Foundry A-Team

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The JPL Innovation Foundry has established a new approach for exploring, developing, and evaluating early concepts called the A-Team. The A-Team combines innovative collaborative methods with subject matter expertise and analysis tools to help mature mission concepts. Science, implementation, and programmatic elements are all considered during an A-Team study. Methods are grouped by Concept Maturity Level (CML), from 1 through 3, including idea generation and capture (CML 1), initial feasibility assessment (CML 2), and trade space exploration (CML 3). Methods used for each CML are presented, and the key team roles are described from two points of view: innovative methods and technical expertise. A-Team roles for providing innovative methods include the facilitator, study lead, and assistant study lead. A-Team roles for providing technical expertise include the architect, lead systems engineer, and integration engineer. In addition to these key roles, each A-Team study is uniquely staffed to match the study topic and scope including subject matter experts, scientists, technologists, flight and instrument systems engineers, and program managers as needed. Advanced analysis and collaborative engineering tools (e.g. cost, science traceability, mission design, knowledge capture, study and analysis support infrastructure) are also under development for use in A-Team studies and will be discussed briefly. The A-Team facilities provide a constructive environment for innovative ideas from all aspects of mission formulation to eliminate isolated studies and come together early in the development cycle when they can provide the biggest impact. This paper provides and overview of the A-Team, its study processes, roles, methods, tools and facilities.

Acronyms

ASL	=	Assistant Study Lead	*PI*	=	Principal Investigator
CML	=	Concept Maturity Level	*PO*	=	Program Office
LSE	=	Lead Systems Engineer	*SL*	=	Study Lead
IE	=	Integration Engineer	*SME*	=	Subject Matter Expert
PDC	=	Project Design Center			

I. Introduction

IN June of 2011 a new collaborative engineering approach for early concept formulation began in the JPL Innovation Foundry[1] called the A-Team. Responding to a need for exploring mission architecture-level trades[2], the A-Team precedes Team X[3,4] in a sequence of concurrent engineering teams at JPL that can be used to mature a concept from a "cocktail napkin" level idea to a complete mission point design. The A-Team efficiently explores the science, implementation, and programmatic trade space in early concept formulation. Small, facilitated groups of experts generate innovative ideas, quantitatively assess feasibility, and discover key sensitivities in the trade space through collaborative analysis and use of advanced methods and tools. The A-Team process builds off the experience within JPL and other recent approaches to early concept formulation[5] including best practices of the JPL Innovation Foundry, Mission Systems Concept Section, Team Eureka and the Rapid Mission Architecture Team[6].

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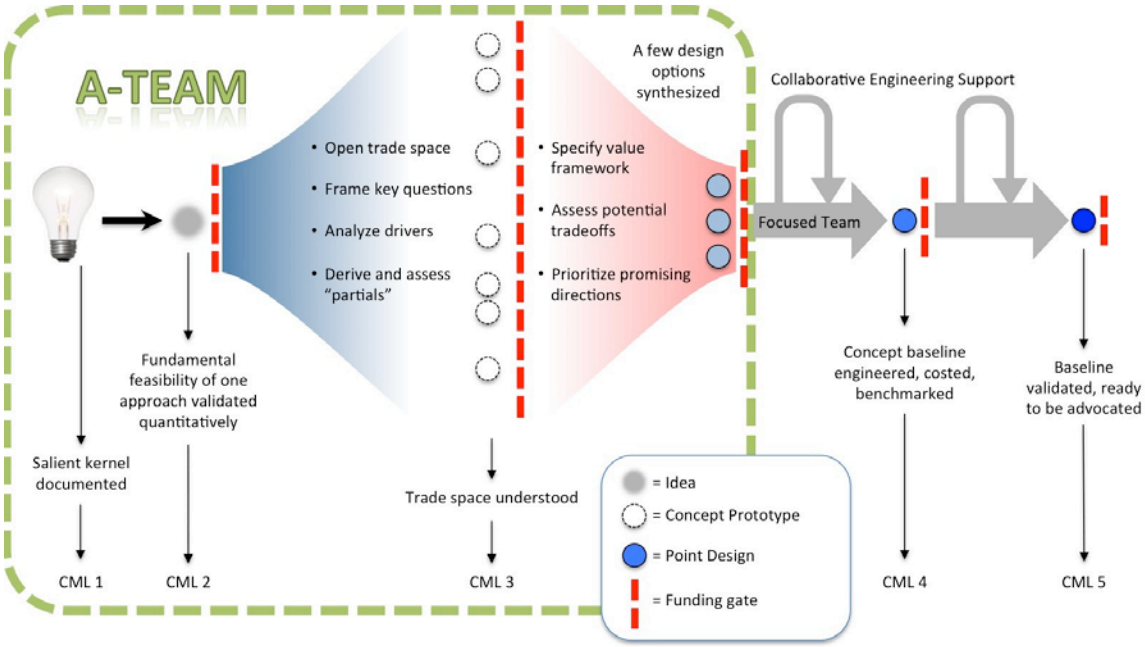

Figure 1. The A-Team develops concepts through Concept Maturity Levels 1-3.

The A-Team is a focal point for innovative formulation approaches and people within JPL. It relies on a large background of study resources, creative thinkers and "grey beard" scrutinizers, advanced tools, and subject matter experts with both breadth and depth in experience and expertise that are all available at JPL. The A-Team is designed to be a rapid and efficient process taking approximately 6 weeks (the entire process can be as short as just a few days or as long as up to three months) and costing the equivalent of one-and-a half work-months of a full-time employee or less. Studies begin with detailed planning and client review followed by study sessions, analysis work, and reporting. The staffing on each study is customized to the study goals and objectives, and it is addressed early in the A-Team process. Sessions are generally half-day or whole-day events and conducted over a series of days with focused agendas that are moderated by a trained facilitator. Preliminary results and knowledge capture are available within hours of each sessions, and a final report is generally available two weeks later.

The high-level objectives for the A-Team are to provide:

- A facilitated process for building, analyzing, exploring, understanding, synthesizing, and communicating concepts quickly at a low-cost
- A specialized and custom group of JPL-leaders in innovative methods and technical expertise
- A center for intellectual honesty that can act as a trusted agent without an agenda
- A safe and productive environment to disassemble assumptions, mature ideas, and solve hard problems
- A way to bring concepts "into the box" or push them "out of the box" by design and managing the conversation
- An infusion path for strategic science and technology into early formulation
- A focus point in a growing history and network of people, ideas, and concepts in early formulation at JPL

A-Team methods and tools are align with the Concept Maturity Level (CML) scale[7,8,9] including idea generation and capture (CML 1), initial feasibility assessment (CML 2), and trade space exploration (CML 3), as shown in Figure 1. This convenient alignment allows the tools and methods to correspond to the work that needs to be conducted to mature a concept at each CML. For example, a discussion on a CML 1 idea might include brainstorming, while a CML 3 discussion might focus on generating concept "seeds" or "prototypes" for exploring the trade space. The A-Team costing tools have a gradually increasing number of input parameters for each CML as more information becomes known about the concept. Outputs have gradually decreasing uncertainty corresponding to the CML: showing statistics of analogous mission at CML 1, notional cost "bins" at CML 2, and cost broken down by the highest level WBS elements in CML 3. More discussion of A-Team methods and tools can be found in later sections of this paper.

Along with unique methods and tools, A-Team studies are conducted in a new facility at JPL, "Left Field". Left Field is designed to be configurable for each study, i.e. as a meeting room for presentations and discussions, an active open space for brainstorming, many small separated collaborative areas, as a fabrication shop for concept "prototyping", or customized for individual study needs. The A-Team infrastructure also includes the Foundry Furnace, a repository for building and deploying analytical tools, a storehouse for study method and result documentation, and an analogous concept search capability with configuration and access control built-in.

This paper is organized by section with descriptions of the A-Team study process, roles, methods, tools, and facilities.

II. A-Team Study Processes

An A-Team study starts with a question or idea that can come from almost anywhere including a Principal Investigator (PI), Program Office (PO), Directorate, Chief Scientist, Chief Technologist, or Task / Project / Program Manager within JPL or NASA and, in some case, externally with JPL or NASA sponsorship (see Figure 2). Example topics include the following:

"I am a Principle Investigator for an upcoming competitive mission proposal and I would like to explore alternative mission concepts that achieve my science goals."

- What innovative mission concepts can investigate the science I am interested in examining, how do my science objectives trace to the various implementation ideas, and how can we do it all inexpensively?
- What should be the baseline vs. threshold science requirements, and what is the impact of descoping?
- What new technologies are available to enable my science objectives?
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"I am developing a new piece of technology, and I would like to identify system-level applications, mission concepts, and potential sponsors to justify additional development."

- What mission concepts does my technology enable?
- What are some system-level requirements I need to apply to make my technology more attractive?
- Who should I talk to about future development opportunities?

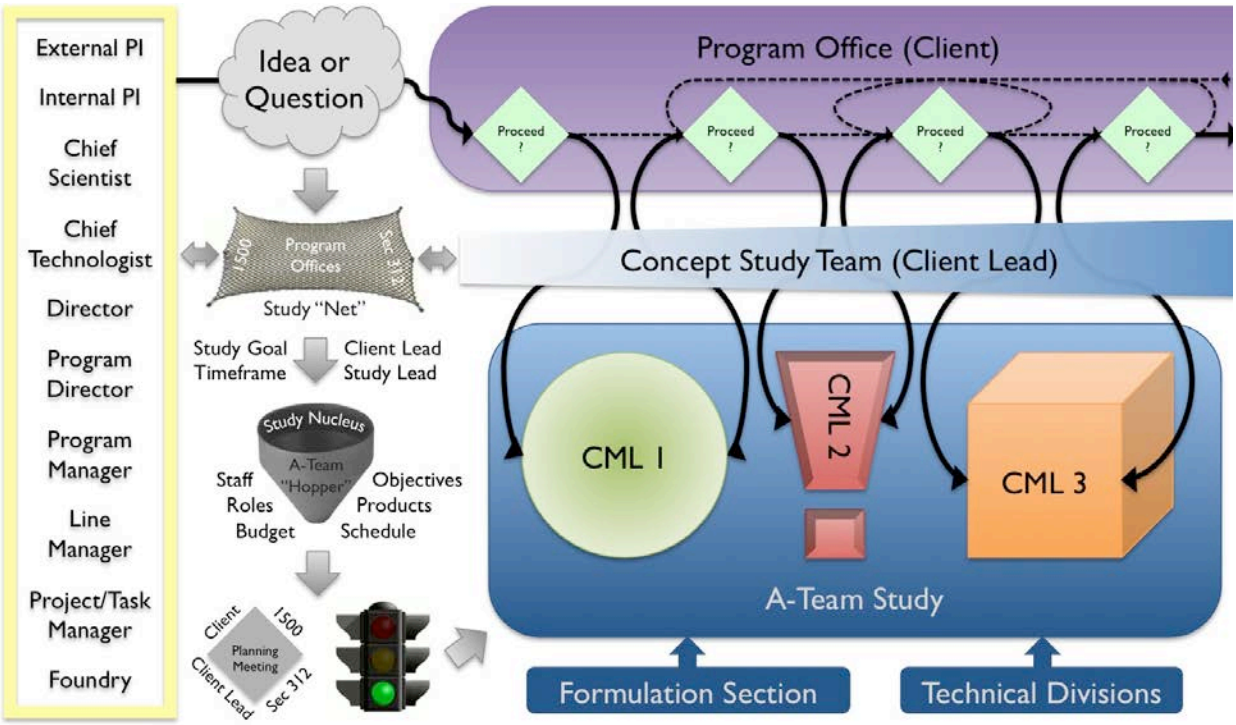

Figure 2. The A-Team process starts with an idea and develops a concept through Concept Maturity Levels (CMLs) 1- 3 with Program Office support and feedback.

"There is an opportunity on the horizon for my program office, and I need new ideas that can actually work. I would like the A-Team to:"

- Explore the science priorities & technological capabilities trade-space,
- Identify key enabling technologies for further investment, and
- Evaluate the feasibility of various mission concepts.

A study can begin at any time with an idea or a question coming into the JPL Innovation Foundry or Mission Systems Concept Section. Locating sponsorship from one of the JPL Program Offices or a NASA Directorate is key to initiating the planning process. The study then goes into the "hopper" and planning begins with a client meeting between the sponsor or client, client lead, and the JPL Innovation Foundry Office. During the client meeting, study background, goals, objectives, initial staffing, timeframe, reporting, and funding level requirements are discussed at length and recorded as notes for future reference. The JPL Innovation Foundry Office then assigns an A-Team study lead to work on a study plan template with the client lead. Notes from the various planning meetings and the study plan document itself are available to the study lead, Concept Innovation Methods Chief in the Foundry, and the A-Team administrator through an on-line wiki-based resource (each study receives its own wiki "space"). The plan documents the scope of the study including all the areas covered during the client meeting along with a complete staffing list, study methodology description, schedule, budget, and details on how the results will be handled, what facilities and tools will be used, and the format and requirements for the final report. The study plan is reviewed at an official Planning or "Green Light" Meeting where the client, client lead, study lead, A-Team manager, and A-Team administrator are present to agree on the study scope. This part of the process generally takes 1-2 weeks but can be condensed to just a few days if an immediate need arises.

Once the study plan is approved, study pre-work begins and sessions occur over the next few days to 4 weeks, depending on the study scope (typical duration is two weeks). Often times research on previous studies or papers and some basic analysis tasks are required before it is useful to bring the study team together for the first time. The study lead forms a small team (described later as the study "nucleus") to assign and manage the tasks and design all the sessions in the study. Each session can have one or more of the following objectives:

- Describing background research
- Reviewing and refining science objectives including traceability
- Brainstorming new ideas
- Organizing and prioritizing ideas
- Defining the feasibility and trade space boundaries / axis with figures of merit
- Creating science cases or "seeds" and implementation cases or "prototypes" to explore the trade space
- Real-time analysis to answer targeted questions or trades
- Assigning tasks that will occur between sessions
- Reviewing results from off-line tasks
- Synthesizing a small number of concepts that should go forward for more in-depth analysis
- Developing a "strategic map" based on recommendations for the concept's development path

During each session, the conversation is directed by a facilitator and captured by one or more team members for future use by the entire study team (including the client team) on the study's wiki space. Between sessions the study lead discusses the progress with the client lead, makes adjustments to the session plans as necessary, and continues to initiate and monitor analysis tasks between full sessions. Smaller meetings between sessions may also be necessary to maintain forward progress, meet with subject matter experts who are not available during full session times, and present intermediate results to the client. Any changes in study scope during the in-session phase are negotiated with the client and client lead and reviewed by the A-Team manager for potential impacts to budget and schedule.

Once the sessions are complete, the study nucleus team generates the final report within 1-3 weeks, again depending on the scope of the study and report format. The final report and wiki space are archived, and the study lead briefs the results to the client team to close-out the study. The entire study process can take just days to as long as two or three months depending on the nature and scope of the study. As a follow-up to the process, the A-Team manager follows up with the client a few weeks after the final report briefing to gather feedback on the process, results, and how the study products were used.

III. A-Team Roles

For each A-Team study there is a "nucleus" of 3-6 members that lead the methods design, study implementation, architectural guidance, and technical work. The client and any existing members of the concept study team are also considered members of the A-Team study team along with any additional subject matter experts that are needed based on the study topic, goals, and objectives. While the study nucleus attends every session, other team members may or may not be required for each session according to the specific objectives covered during that session.

In general, any member of the A-Team must have many of the following qualities:

- Creative and open to new ideas
- Inquisitive with an at-will "skeptical switch"
- Comfortable in new situations and tolerant of ambiguity
- Proven problem solver with ability to take multiple rejections
- Self-motivated with an entrepreneurial spirit
- Deep knowledge of certain areas, broad base of experiences
- As good at being a leader, a teacher, and a listener
- Belief in a team of peers: staff positions and egos are left at the door

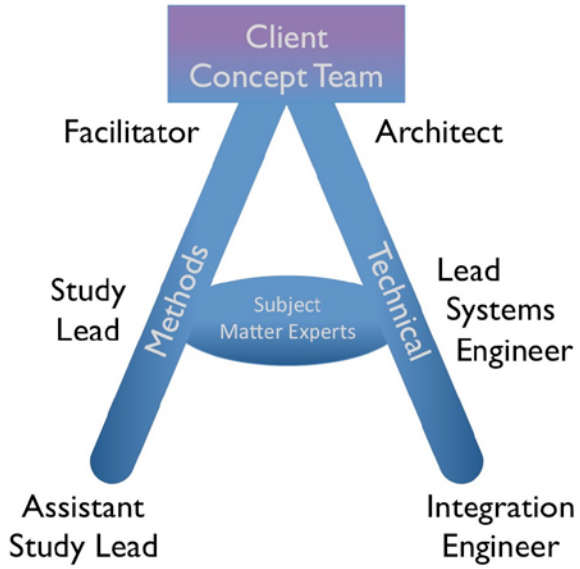

Figure 3. The "A-Frame" shows both the methods and technical expertise of the study nucleus along with the client team and subject matter experts.

The number of people in each session is intentionally kept small, generally 8-12 team members except in sessions where the purpose is to provide background information to the entire, larger team. While such a small team promotes active discussion and productivity, each member must also be chosen for their expected role and impact, and the session must be designed to tackle a series of specific study objectives. Often times expert generalists are used over many studies in place of multiple engineers representing various disciplines (e.g. propulsion, mission design, attitude control, telecom, etc.). Session planning and pre-work may also dictate where a subject matter expert with deep knowledge on a particular topic is required. In other smaller meetings, only one or two of the nucleus attend along with 2-3 other team members to achieve a single, very focused objective. The roster and agenda for any session does not support the distraction of a member simply attending to observe. With detailed session capture and wide availability to shared data, other team members can keep track of the study details and progress via the wiki space. The A-Team follows a simple rule: if you are in the room, you participate.

The remainder of this section provides more detail on specific roles within the study and the Foundry including the nucleus, subject matter experts, and the Core A-Team. As shown in Figure 3, the study nucleus includes six roles filled by 3-6 people along an "A-Frame" with two legs based on methods and technical expertise. Team members can move up or across the legs of the A-Frame with training and experience gained during A-Team and other concept studies. In some smaller studies, nucleus members can take on multiple roles; for example, the Assistant Study Lead and Integration Engineer can be the same person. The Study Lead and Facilitator are often the same person, and similarly the Lead Systems Engineer and Architect can also be the same person. The minimum three-member study nucleus includes all three of these combinations along with Study Lead / Lead Systems Engineer and Facilitator / Architect combinations. The Foundry also sustains a "Core" of A-Team experts who establish performance standards for the roles, adapt them for unusual studies, participate in studies as needed, and oversee the development of analytical tools optimized for the A-Team environment.

A. Methods Roles

The A-Team process relies on innovative methods to conduct study sessions that fall on three important roles: the Facilitator, Study Lead (SL), and Assistant Study Lead (ASL). These team members hold the control of study process and method and represent the A-Team best practices and experience.

1. Facilitator

The Facilitator deeply understands the client's objectives and designs and orchestrates individual sessions to achieve the study objectives. He or she sets the final, detailed session agenda, the methods that will be used during the session, and guides the "in session" conversation. The Facilitator is trained in facilitation and team building techniques to keep the sessions on track and productive. While the facilitator helps decipher ideas, information and data produced during the session, he or she is not specifically responsible for any part of the final report except potentially as a review function. This senior member must have a wide breadth of expertise and should feel comfortable leading the conversation on complex topics with experts in their respective fields. The facilitator implements innovative methods and assists in high-level planning for the study working with the study lead to determine the number and type of sessions that will be required for the study to meet the client's objectives.

2. Study Lead

The Study Lead (SL) organizes and manages the study, in a role very analogous to a project, task, or proposal manager. The SL is the main point of contact with the Client Team and works with them to set study goals, objectives, staffing, roles, analysis tasks, products, budget and schedule. Working with the A-Team administrator, he or she is ultimately responsible for holding the sessions, managing analysis tasks, and delivering the final product within the agreed upon schedule and budget. This skill set demands a pro-active approach, at least mid-career level experience, and a high degree of communication and management skills and experience. The SL leads the planning of the study and produces the final study products, which may include coordinating various team members to provide any necessary inputs.

3. Assistant Study Lead

The Assistant Study Lead (ASL) manages the day-to-day information flow and organization for the study. The ASL captures and organizes ideas and work from each session and analysis task and distributes all information to the full study team. He or she maintains the wiki space for each study and helps implement any methods-based tools used throughout the study. Often times the ASL produces intermediate products, including research and session reports within hours or days of each session's completion. This junior-level position requires a strong initiative and good organizational skills. The ASL helps the Facilitator develop conversation maps and agendas for each session, as well as assisting in the final report generation with the Study Lead.

B. Technical Roles

The A-Team employs three main roles to manage the technical content of the study: the Architect, Lead Systems Engineer, and the Integration Engineer. Each role is responsible for a different layer of assessing feasibility and exploring the trade space during study execution with a varying degree of technical aptitude and experience.

1. Architect

The Architect deeply understands the client's objectives and is responsible for the architectural level decisions that are made throughout the course of the A-Team study. The Architect defines the scope, boundaries, and branches of the trade space. He or she determines the concept seeds or prototypes that will receive the most attention and determines when the trade space is fully explored. The Architect has access to an extensive network of subject matter experts to assist in the study and knows when to bring them in as needed. The skill set for this role is very similar to the capture lead role on a proposal effort. This senior level engineer utilizes their extensive experience to determine how the study will progress, steering the conversation and guiding the study toward a mission architecture that meets the client's needs. The Architect can "drop-in" on sessions to help guide them, is part of the session planning process, and often provides a review function for the final report.

2. Lead Systems Engineer

The Lead System Engineer (LSE) is responsible for the technical validity of the spacecraft and instrumentation approaches used throughout the study. The LSE is required to make engineering level decisions that drive the mission, spacecraft, and payload design, ensuring that certain subsystems are examined in sufficient detail to inform the Architect in his or her decision making process. The LSE also keeps track of the various science seeds and concept prototypes to explore feasibility and the full trade-space. This mid-level engineer utilizes their experience and contacts to determine which tools and analysis should be used to better understand the major spacecraft and instrument drivers throughout the course of the study. The LSE assists the study lead in planning all aspects of the study and is responsible for the technical content of the final report.

3. Integration Engineer

The Integration Engineer (IE) is responsible for the day-to-day technical aspects of the A-Team study and is primarily responsible for implementation of the A-Team technical-based tools for each study. The IE collects the analysis provided by the study team members and works closely with the LSE to determine the major drivers of the study. Often times the IE also helps generate configurations for the concept prototypes and organize technical data

(mass, power, data rate, etc.) for information and comparisons. This junior-level engineer provides the necessary support for the LSE and Architect to make fundamental decisions that allow for close examination of feasibility and the trade space. The IE keeps the assumptions and data consistent throughout the study and helps in all phases of the planning and product development.

C. Subject Matter Experts

Subject matter experts (SMEs) on science, instruments, mission design, operations, spacecraft subsystems, technology, and programmatics are used uniquely on every A-Team study. While many SMEs are often used for more than one A-Team study, the majority have only been to a handful of sessions during one study. SMEs do not require specific training to be part of or participate in A-Team studies, which opens up the possible candidate list to almost anyone that is affiliated with JPL or even external experts from academia and industry. Very often one properly chosen SME can greatly impact the study, eliminating lengthy analysis tasks with background knowledge, flight project and technology development experience, and specialized analysis tools. SMEs can provide PIs and other clients deep expertise when a wide array of options are present and feasibility is being assessed, yet participate in a managed environment and process that helps foster new ideas. SMEs also bring their own network of engineers and best practices for their respective disciplines, dramatically improving the quality of early formulation work and frequently educating other study participants from around the Laboratory.

D. A-Team Core Group

The Foundry supports 12 members of a "Core Team" that help develop the A-Team process, methods, tools, and products. Since mainly *people and methods* differentiate the "A-Team" from other study teams, these core members are specially selected for 1-2 year rotational positions based on discipline expertise on both sides of the A-Frame. A Core A-Team member is expected to have both deep knowledge in one area and multiple skills over a wide-range of formulation activities, a "T" personality, and get to experience a wide range of study types and topics to hone their formulation craft. They are recognized experts in their field, already networked to JPL expertise base, that are dedicated to moving formulation and innovation forward on lab. The core group has a wide distribution of age, experience, background and personality types.

Individual A-Team studies draw members from this group, but not everyone on the Core A-Team will be used for every study. In some cases when core team members are not available for a study that requires their expertise, they will assist in staffing and finding a suitable replacement. Currently the following disciplines are represented on the Core A-Team: facilitation, study leadership, tools and infrastructure, flight system and mission architecture, configuration, mission design, remote sensing instruments, in situ instruments, radar systems, technology infusion, and cost and risk.

Core A-Team members have access to the plans and products for every A-Team study that passes through the Foundry, improving study design and becoming a knowledge base of formulation work. The Core A-Team is the repository for best study practices and review the feedback from clients on study performance. Each core team member is expected to lead a number of A-Team studies throughout their tenure. An annual set of pilot studies using mostly the Core A-Team are used to develop skills, methods, and build experience in formulation studies. Core team members often lead tool development activities and participate in other formulation work. They can be used, as a group, to provide basic feedback, expansion, and strategic direction ideas for any idea that comes into the Foundry.

IV. A-Team Methods

A-Team study methods are grouped along the CML scale with specific environments, conversation management techniques, staffing strategies, analysis and knowledge capture tools designed to provide the most efficient and useful results. At CML 1, studies are focused on idea generation and organization. CML 1 sessions often produce 100's of ideas from a single question or topic, which are then organized and potentially ranked based on figures of merit. At CML 2 studies are focused on initial feasibility assessment with only the bare basics of concept information to work with: science objectives, a basic payload description, destination, mission type and class, and flight system type (i.e. orbiter, lander, etc.) along with high level subsystem specifications (e.g. telecom band, propulsion system type, etc.). CML 2 sessions often quantitatively examine an idea or set of ideas for both technical and programmatic feasibility using advanced analysis tools. At CML 3 studies are focused on exploring the trade space of options including evaluation of science return, cost, and risk. CML 3 sessions focus on developing concept analysis "seeds" based on subsets of science objectives and implementation "prototypes" for each seed that efficiently explore the value, cost, and risk architectural trade space. Table 1 describes the environment and methodology for each of the CML focused studies.

Table 1. Study environment and methodology for each Concept Maturity Level.

CML	Environment	Methodology
1	• In session, group (8-12 people) activity • No fear, no intimidation, everyone participates • All ideas are fertile - no stone is left unturned • Fun – good ideas are recognized by the group	• Facilitated, objective oriented discussion • Find ideas and associated ideas (including analogies) with research and experts • Use and create related images and objects • Work at appropriate high level - do not get bogged down in details • Focus on opening up the options first; apply the feasibility filter later • Connect and group ideas together – organize, link, capture and "tag" them for future use
2	• Ideas are "owned" and championed • Uncertainty and risk is accepted and managed, not feared • Small break-out teams work independently, but in the same room to analyze ideas with a shared set of tools • Feasibility discussion focuses on honesty – pointing out what we know and don't know without calling out individuals • Challenging assumptions, building, and incorporating good parts of various ideas is encouraged	• Key Figures of Merit (FOMs) and thresholds are specified by the group in a facilitated conversation • Architect assigns multiple ideas to individuals who have some natural relationship to the concept • Small teams (2-3 people) build case for or against the feasibility of each set of ideas • Groups report out to the full team on results, and ideas are place in FOM "bins" based on analysis • Analysis work is not complete at this stage, and focused analysis tasks are recommended where needed
3	• Safe place for discussion of alternatives • Collaborative space and tools, both for information sharing and personal interaction • A mixture of large group work to distribute and review ideas and small team or individual analysis efforts • Focused and intense "burst" of analysis work with tools providing basis for concurrent engineering in group setting	• Facilitated, objective oriented discussion to determine the best way to explore the trade space • Architect designs concept analysis "seeds" and analysis tasks that will be studied by rest of team • The Lead Systems Engineer guides the selection of implementation "prototypes" that can carry out the various science seeds • Seeds and prototypes are built to explore the trade space, not specifically as options that could be "the concept" • Experts are brought in and out as needed to provide backing on analysis efforts • New ideas and analysis tasks are still encouraged, often at the individual level, but study goal and objectives are kept as priority – client is continually in the loop • Architect determines when the trade space has been explored enough to synthesize concepts

In addition to the three study methods, a majority of studies can also fall into one of three study types, depending on their focus: science traceability, technology impact, and strategic investments and opportunities. Studies focused on science traceability trace science questions to goals, objectives, investigations, measurements, and instruments including assessing relative science value and ranking. Studies focused on technology impact generate lists of ideas and potential applications and assess feasibility of using the technology in various missions as well as quantitatively examining the science and architectural impacts. Studies focused on strategic investments and opportunities investigate the programmatic aspects of a concept and its future development including portfolio building, strategic directions, decision support, and proposal strategy. These study types are broken down along with a more detailed description of efficient trade space exploration in the remainder of this section.

A. Trade Space Exploration

Trade space exploration and decision making takes place during all phases of concept development. CML 3 is designated as "Trade Space Exploration" to insure this process is not over simplified or skipped by directly going to a point design (CML 4) from a single idea (CML 1), as commonly occurs. The relative position of CML 3 activities between examining the basic feasibility of an idea and developing a point design for a mission concept requires a certain amount of expansion, contraction, and prioritization to efficiently and fully explore the trade space.

In almost every situation, the client would like to see a higher value returned using less resources, which indicates an optimization problem. The key differential at each CML level is the amount of information available and the depth to which trades can be made. At CML 1 almost no trades are actually made except to examine previous studies to determine where and why trades where made on related efforts. At CML 2, trades are conducted at the architectural level based on science requirements (e.g. do we need to land, orbit, fly-by, or send in a probe?) with minimal payload specification by analogy to other missions. At CML 3, subsystem level trades should be considered and rolled up to differentiate similar architectures vs. the quality of science return, cost, and risk. At CML 4 trades are conducted at even a finer component level, which may then feedback to larger subsystem-level or even architectural level trades as more detail is uncovered. In fact, often concepts cycle through CMLs 2-4 multiple times before being ready to advance onto CML 5 (full proposal or detailed mission concept study).

The main goal of the A-Team trade space exploration methods and activities is to reduce the number of iterations through the lower CMLs. Science objectives are broken down into concept analysis "seeds" that drive various implementation (mainly payload) approaches. Implementation approaches start as "prototypes", where it is well understood that the first iteration in design will not be optimal or final. Later prototype iterations allow new combinations of solutions and refinement of the science seeds. In the end, science seeds are evaluated for relative quality and science return while their respective implementation prototypes are evaluated for cost and risk. If done correctly, client and study teams will have an *understanding* of the trade space. They will know and be able to communicate 1) what ideas that were considered, what was rejected, and why, 2) the key sensitivities – what happened when the key parameters were varied, 3) where to fall back to if high-risk ideas do not mature as expected, and 4) other applications that were identified for the ideas considered by the study. This includes documenting the "soft spots" unique to the concept (worthy of priority penetration), the "threshold" for an acceptable idea to move onto the next step of concept development, and the technology, science, and programmatic advancements that could change the trade space and merit further investigation.

B. Study Types

As mentioned above, there are three distinct study types that can be used to categorize a majority of A-Team studies: science traceability, technology impact, and strategic investments and opportunities. These three study types will now be described in more detail and statistics from the first 50 A-Team studies are shown in Figure 4.

1. Science Traceability

Science traceability focused A-Team studies advance the understanding of science linkages to implementation options. They reveal areas of the science trade space that need more attention and focus, directing next steps forward for mission and instrument requirement development. These studies range from mapping higher levels of the science traceability space to a more detailed look at lower levels of traceability, depending on the level of maturity of the question or problem and depth of previous examination of the science topic.

These type of studies first focus on a range of potential science questions or objectives. Using various methods and prioritization techniques based on potential science return, a small number of well-defined objectives become the focus. Each science question/objective is traced into quantities of observables, measurement requirements, and mission requirements broken into four categories: current state of the art, enhancing science, enabling science, and breakthrough science. This breakdown helps the science and study team understand where the quality thresholds lie that also impact concept complexity, cost, and implementation risk.

Science traceability studies often function like science workshops with a great deal of interactive discussion. The final output product of these studies is aimed at informing fruitful science paths forward including developing new colleague relationships, suggesting detailed analysis or modeling tasks and journal article topics, and recommending technology investments to improve science quality and return.

2. Technology Infusion

Technology Infusion focused A-Team studies identify areas of applicability for the technology in question and a path forward for infusion. These studies examine potential applications for the technology considering scientific applications (e.g. NASA SMD), exploration applications (e.g. NASA HEOMD), and technology applications (e.g. NASA OCT). For the applications identified, each are ranked based on various figures of merit such as direct applicability, stakeholder interest, funding available etc. The highest ranked applications are carried forward and

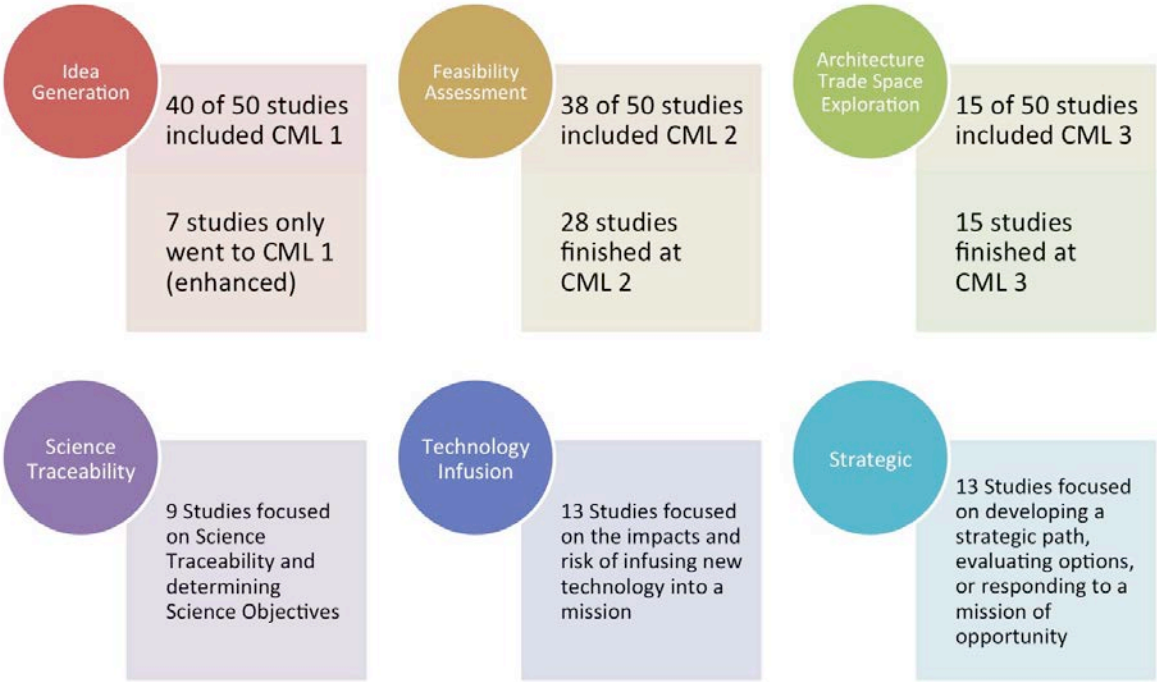

Figure 4. Statistics of study types from the first 50 A-Team studies.

potential infusion paths are created. These studies make the connection between the technologists and their potential customers who may be able or desire to push the technology to flight readiness.

Technology focused studies can also come from more mature mission concept studies where a demanding problem has prevented an architectural option from closing or meeting science requirements. In these technology "pull" cases, a wide range of new technologies are examined for the greatest impact or best solution to a problem.

3. Strategic Investments and Opportunities

Strategic A-Team studies identify a strategic path forward for addressing a concern, problem, or question. The strategic aspect of these studies can be translated as considering "all" perspectives, opportunities, barriers, and solutions that bound the solution space. These aspects considered in snapshots of time (past, present, future), help the study participants to understand and create a series of strategic paths forward. The final product of this type of study is a "strategic map" showing multiple paths to a desired destination with task precedence, expected outcomes, decision points, off-ramps, and milestones clearly indicated.

V. A-Team Tools and Facilities

The A-Team is developing new tools and has dedicated facilities for early concept studies. The tool set is currently focused in four areas: 1) knowledge capture and management, 2) science traceability, thresholds, and value, 3) mission, flight system, and payload design, and 4) cost, complexity, and risk assessment. Each tool development is based on a set of stakeholder requirements and designed to be used in session as much as possible to enhance the conversation. The analysis tools are validated against more mature Team X studies, proposals, and actual missions where appropriate. While most of the A-Team tools are still under development, the following sections describe the tools and facilities available for all studies.

A. A-Team Tools

1. Knowledge Capture and Management

Knowledge Capture and Management is a major part of each A-Team session. Since most studies utilize an idea generation phase of the study, capturing the information and surrounding discussion as it is produced is critical to ensure the intent and meaning behind the ideas are also captured. Once captured, the information can then be sorted and visually organized allowing for important connections and relationships between ideas to be made. These tools enable to organization and distribution of information necessary to the success of a study.

The A-Team employs a variety of techniques to achieve capture and manage the information within a study. During the idea generation phase, mind mapping tools, electronic whiteboards, and extensive whiteboards with cameras provide ideal platforms to quickly capture the information while allowing the recreation of the study in the event the information is taken down or erased. Once captured, the A-Team leverages a host of visual aid tools that allow the team to quickly and easily define the trade space and analyze potential relationships between concepts. All information from each session is shared in a wiki-based IT environment with a single access controlled space for each study containing child pages for each session. Basic study parameters and final products are also maintained in the Team X Fredrick database for archival purposes and later easy retrieval.

2. Science Traceability, Thresholds, and Value

Science traceability is an important part of early formulation studies, allowing for early examination of the driving mission requirements and identifying new potentially revolutionary science mission concepts. In order to facilitate this process, the A-Team has developed a study approach that allows the team to define, examine, and categorize the "goodness" of a science concept and how it will drive the mission concept. The process utilizes a idea generation phase that provides access to a wide range of potential science objectives. Once the objectives have been identified, the team works together to define a potential investigation and hypothesis including identifying observables, time and special scales. From there, the team works together to identify a variety of measurements, instrument requirements, and mission requirements that fall into the "state of the art", "enhancing", "enabling", and "breakthrough" science categories. Using this method to examine a range of science investigations, the A-Team is able to identify potential investigation that leverage similar instrumentation or to determine which investigation is driving the mission architecture. Additional tools related to science traceability are under development.

3. Mission, Flight System, and Payload Design

There are multiple A-Team tools that can fall under the general description of a "design tool". The tools can be broken down by CML applicability. For example, mass equipment lists from previously flown missions are a CML 1 research tool that can be used to help design an early flight system. Rules of thumb and analogy-based models are often used at CML 2 to provide basic architectural comparisons and payload options. At CML 3, parametric design relationship and specific subsystem requirements and selection drive the tools to maintain the flight system and payload configuration.

For mission design specifically, the A-Team is leveraging JPL's expertise in trajectory optimization, navigation, and operations. A new tool is being developed to rapidly search through multiple mission design options and optimize based on inherent value functions such as trip time, delta-V, or maximum delivered mass. What normally has taken days of analysis work will be able to be conducted *in session* based on a massively parallel computation scheme. While these tools will still require expert users, at least initially, the potential for dramatically enhancing early feasibility and trade study discussions is high.

4. Cost, Complexity, and Risk

The A-Team is currently developing and using a variety of cost tools designed to the appropriate level of detail for each CML. At CML 1, cost statistics are generated for similar missions based on a small set of filter criteria: destination, mission type, and basic flight system architecture. At CML 2 rules of thumb and a simple cost estimating relationship are used to "bin" the potential cost of the mission with a large range of uncertainty. The payload is specified by analogy using a built-in NICM (NASA Instrument Cost Model) look-up function. At CML 3, parametric and quasi-grass root cost models are applied at each sub-system and instrument type to determine cost and cost uncertainty.

The Foundry has also invested in complexity assessment tools that can first be applied at CML 3. These tools help PIs and client teams understand how their mission concept complexity compares to similar class missions. In the cases of higher relative complexity, there can often be savings and risk reduction techniques identified by the tool. The A-Team continues to evaluate these kind of cost and complexity tools in sessions and pilot studies.

B. A-Team and Foundry Infrastructure: The Furnace

The Foundry is developing an infrastructure to house its tools, study processes, and results for the A-Team. More than a tool repository, the Furnace is designed to reproduce study results based on configuration controlled input files and models. Individual access is controlled for each model; however, other users may "branch" off existing models to modify and customize them for an individual study purpose. A web-browser based interface and various APIs ensure compatibility with multiple platforms and analysis tools (i.e. Matlab, Mathematica, Maple, Excel, etc.). Analytic based modules are used to build more complex relationships between subsystem design models, including parameter storage and forwarding capability.

The Furnace is currently under development with the first year of a three-year program nearly complete. The first year focused on architectural design and component requirement definition along with a few prototype

Figure 5. Pictures of Left Field, Out There, and the PI Lounge (from left to right).

demonstrations. The second year will focus on infusing new tools into the furnace, and the third year will focus on expanding the usability to a larger audience.

C. Left Field, Out There, and the PI Lounge Facilities

The A-Team uses three main, dedicated spaces for its studies: Left Field, Out There, and the PI Lounge, as shown in Figure 5.

Left Field is a newly designed open, reconfigurable room with floor-to-ceiling wall-to-wall white boards on one wall and multiple rollaway white boards, tables, and desks. The room also contains building and prototyping materials, a large format printer, and a high-speed color printer for use during and in preparation for studies. The room is configured for each study depending on the type, session focus, and the people expected to attend the session. Half of the white boards are equipped with electronic sensors that monitor the position of various markers and stylus to capture images and even text through handwriting recognition software. The room also contains multiple projectors and a new set of cameras designed to periodically take images of the white boards and room to provide a "time-lapse" movie of the study progress.

Out There is a patio area adjacent to Left Field that takes advantage of Pasadena's Mediterranean climate to provide a comfortable outdoor location for side meetings and larger team functions. The PI lounge is also adjacent to Left Field and equipped with a large seating area and three basic offices that can be used temporarily for visiting PIs or external study participants.

VI. Conclusion

The A-Team is a recent addition to the JPL Innovation Foundry capabilities for early concept formulation. A-Team studies provide one proven and accessible way for Program Directorates to establish early concept feasibility and to explore and understand the critical elements of the trade space. The A-Team has become a reliable and configurable process where people, ideas, and concepts come together in new ways that help foster innovation.

Since it's inception in mid-2011, there has been over 50 A-Team studies conducted with an ever-growing rate, up to approximately 1 study per week near the end of FY13. To date, PI and client response has been strong and affirming. The Foundry has and will continue to invest in developing the A-Team process, methods, tools, and facilities to improve the quality of study results, decrease study time, and improve the awareness and communication of study results.

Acknowledgments

The authors would like to acknowledge Kelley Case, Lynne Cooper, Tony Freeman, Johnny Kwok, Steve Matousek, Dan McCleese, Brent Sherwood, Randii Wessen, and Melissa Vick of the Jet Propulsion Laboratory for their assistance and guidance in developing the A-Team process, roles, methods, and tools. The authors would also like to thank the other members of the Core A-Team: Jordana Blacksberg, Bjorn Cole, John Elliott, Douglas Hofmann, Kelli McCoy, Al Nash, Dragana Perkovic, Raul Polit-Casillas, and Nathan Strange for their assistance in building the A-Team process, developing core products, and leading new tool creation. Finally, the authors would like to acknowledge other members of the Mission Systems Concept Section: Richard Bennett, Chester Borden, Keith Grogan, Peter Kahn, Robert Moeller, Hoppy Price, and James Smith for their support and assistance in making the A-Team successful.

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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