

# Measuring the Maturity of Robotic Planetary Mission Concepts

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**Robotic space missions are conceived, planned, promoted, and developed through a series of design and resource estimation activities with increasing levels of effort and fidelity, from the cocktail napkin to the Critical Design Review (CDR). As a mission concept increases in maturity, the uncertainties in the estimated performance, cost, and risk of the mission are reduced. For a given concept it is important to measure and describe its level of maturity, and to have a common language for that description, in order to establish reasonable expectations today for a mission in the future and to avoid premature commitments to a highly uncertain value proposition. Furthermore, such a language can be used to define a set of guidelines for the content of a robotic space mission concept as it progresses, so that some dimensions of the concept do not inadvertently lag behind other dimensions in maturity. This paper describes a set of nine Concept Maturity Levels (CML 1 to 9) and the associated concept content at those levels.**

## I. Introduction

NASA has two methods for developing deep space robotic planetary missions. They can assign them to a particular NASA field center (e.g., the Ames Research Center (ARC), the Goddard Space Flight Center (GSFC), the Jet Propulsion Laboratory (JPL)), or they can hold a competition between NASA field centers, university research laboratories (e.g., Johns Hopkins University Applied Physics Laboratory (APL), and potentially, aerospace companies. These competed projects are selected from proposals submitted by numerous interested parties in response to a NASA Announcement of Opportunity (AO). The winning proposal is the one that has the highest science value, the most mature mission concept, and the one that has the greatest likelihood of not exceeding the AO's cost cap.

The proposal's science value comes from a determination by a NASA sponsored science panel about how well the proposed science is aligned to the goals of the National Research Council's (NRC) Decadal Studies. The cost cap is imposed by NASA and reflects the budget that NASA has allocated for implementing a particular class of project. The maturity of a mission concept, in the past, was poorly defined. Mission concepts ranged from ideas that were "just thought-up" to concepts that have been studied for decades. However understanding the details of a mission concept is key to determining, the scope of a mission, the credibility of the proposal team's cost estimate, the concept's technical risk and the validity of the proposed development schedule.

Unfortunately there never has been an objective and quantitative approach for measuring the maturity of mission concepts. As such, some approach was needed to let study teams know what can be known and what must be known as a mission concept matures. It is this problem that drove the need for the development of Concept Maturity Levels (CML).

## II. Concept Maturity Levels

The individual that both recognized the need for an objective and quantitative approach for measuring mission concept maturity and who took the initiative to develop such a scale was the JPL Chief Engineer for Advanced Concepts (Adler). The approach was to model concept maturity after the well-known Technology Readiness Levels (TRL).<sup>2</sup>

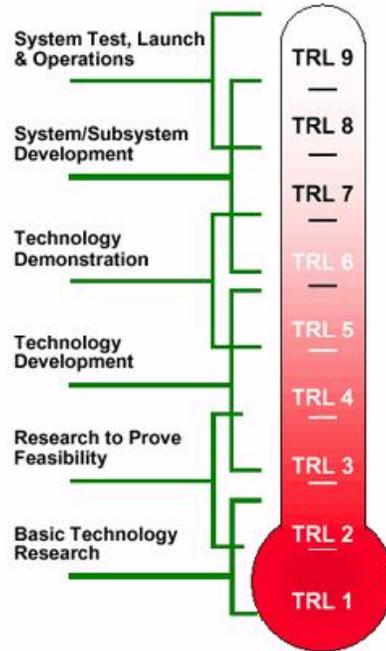


Figure 1. The Technology Readiness Levels provides a common language. As an example, all Project Managers know that any new technology must be at TRL 6 (or higher) by the time of the project's Preliminary Design Review in order to be considered for that particular project.

The TRL scale is used by NASA engineers to describe the level of maturity of a proposed new technology. In this way, a Project Manager can begin to determine how mature a particular technology is and if not as advanced as needed, begin the search for an alternate approach for meeting their project's requirements. The CML scale provides the same common understanding among mission concepts.

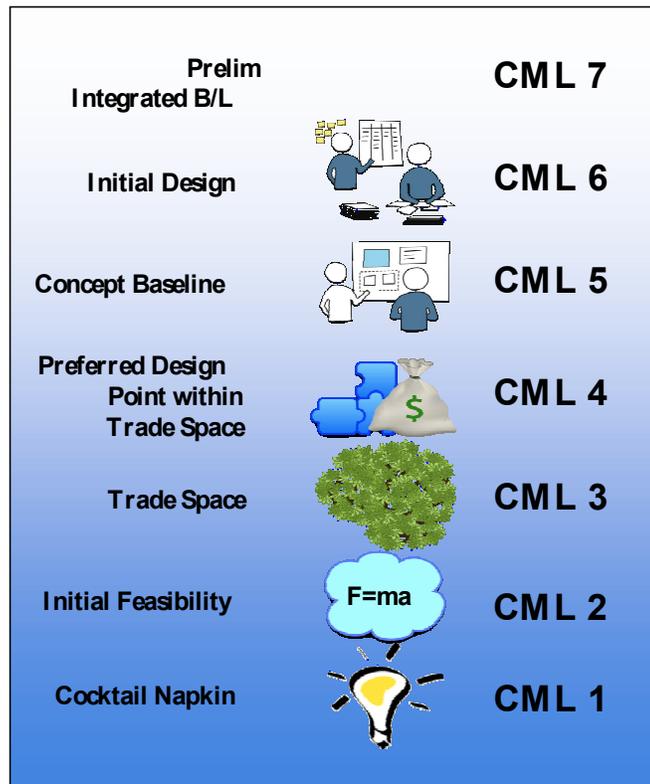


Figure 2. The Concept Maturity Levels (CML) provides a common language for comparisons across various mission concepts. Using this scale, concept maturity measurements are objective, quantitative and repeatable.

The boundary conditions for CMLs are that they do not stifle the desired creativity during the inception of a mission concept (at CML 1), and on the other side (CML 7), they must seamlessly dovetail with the current well-defined procedures for developing planetary missions. Each CML represents a set of completed content elements at that level. Each level can be thought of as a point in time in an idealized development of a concept. For each CML, the incremental completed concept content at that level is summarized here:

- CML 1 *Cocktail Napkin* - The science questions have been well articulated, the type of science observations needed for addressing these questions have been proposed, and a rudimentary sketch of the mission concept and high-level objectives have been created
- CML 2 *Initial Feasibility* - A “notional” design point has been selected, objectives have been specified, key performance parameters quantified and basic calculations have been performed. These calculations, to first-order, determine the viability of the concept
- CML 3 *Trade Space* - Exploration has been done around the notional objectives and architectural trades between the spacecraft, ground system and mission have been performed to explore impacts on performance, cost and risk
- CML 4 *Point Design* – A specific design and cost has been selected within the trade space and defined down to the level of major subsystems with acceptable margins and reserves. Subsystems trades have been performed

- CML 5      *Concept Baseline* - Implementation approach has been defined including partners, contracting mode, integration and test approach, cost and schedule. This maturity level represents the level needed to write a NASA Step 1 proposal (for competed projects) or hold a Mission Concept Review (for assigned projects)
- CML 6      *Initial Design* - Expanded details on the technical and programmatic elements of the concept (e.g., assembled project team, implementation plan, driving subsystem requirements, etc.) have been defined and documented. A NASA Step 2 Concept Study Report (CSR) is at this level of maturity. There is no corresponding milestone for assigned projects
- CML 7      *Integrated Baseline* - Preliminary system and subsystem level requirements & analyses, demonstrated (& acceptable) margins and reserves, prototyping & technology demonstrations, risk assessments and mitigation plans have been completed. This is the maturity level needed for competed missions to hold their Preliminary Mission System Review (PMSR) and for assigned projects to hold their Mission Definition Review (MDR)
- CML 8      *PDR* — Design and planning commensurate for a Preliminary Design Review
- CML 9      *CDR* — Design and planning commensurate for a Critical Design Review

Each CML requires progressively more resources than the previous CMLs combined. There may be many concepts at low CMLs, with fewer and fewer in development at higher CMLs. Only a small number of concepts proceed past CML 8 and eventual launch as confirmed projects. The concept content at each level is used to promote the concept for continued funding to the next level.

### **III. Concept Maturity Level Detail**

The concept content for the Preliminary Design Review and the Critical Design Review have been well established and documented, and so CMLs 8 and 9 will not be discussed further in this paper. As such the focus will be on CMLs 1 through 7 as they relate to the life cycle of robotic space missions developed by NASA.

There are two main paths that NASA mission concepts follow as they increase in maturity and progress to implementation. Those are AO-Driven (competed) Projects and Assigned Projects. They have somewhat different milestones through CML 7, and so the Concept Maturity Levels are mapped to both life cycles in Figure 3.

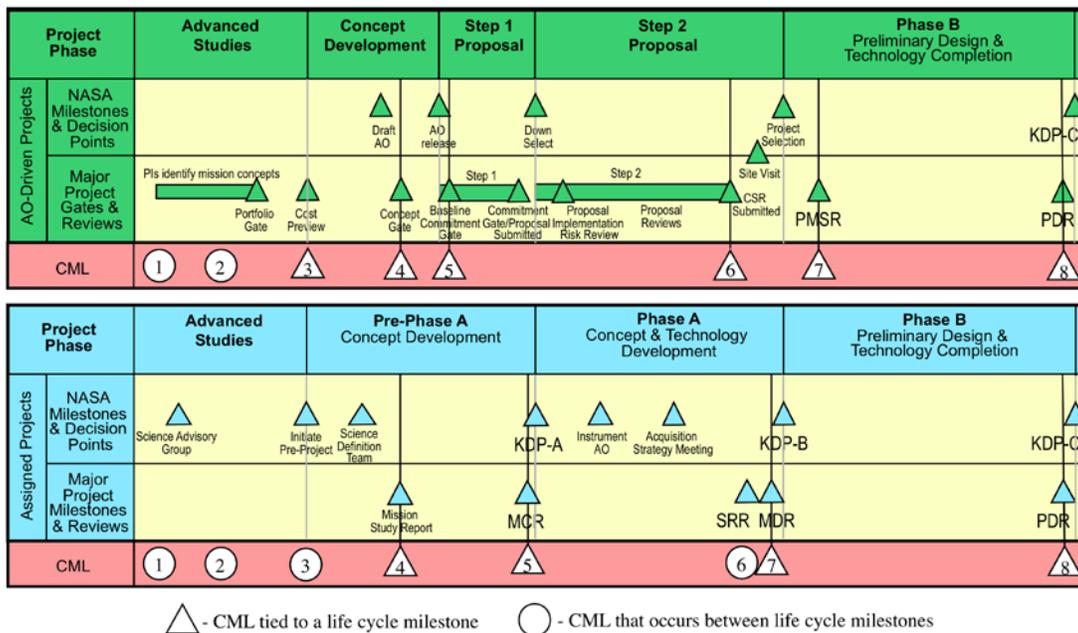


Figure 3. The Pre-Phase A Formulation Phase life cycle for both AO-driven projects (green) and assigned projects (blue). The CML scale actually goes to CML 9 but CML 7 – 9 correspond to the already defined Development Phase reviews, gates and gate products.

Proceeding from left to right, CMLs 1, 2, and 3 are completed before an institution completes the down-select to a portfolio of missions for development in response to an anticipated draft AO (competed) or before NASA initiates a pre-project (assigned).

CML 4 provides a design and cost estimate complete enough and accurate enough at the system level to assess margins and reserve. At JPL, this is the level reached by a Team X mission study. The content at CML 4 is used at the Concept Gate (competed) to decide to commit the resources to complete the development of a concept baseline against a recently released draft AO. CML 4 is also the content required for a Mission Study Report (assigned).

CML 5 is the concept content required for a Step 1 proposal (competed), as well as for the Mission Concept Review (assigned). The concept content at CML 5 is used at the Baseline Commitment Gate to decide to commit the resources to write the Step 1 proposal (competed). Ideally, the concept development for Step 1 is complete at the time of the Baseline Commitment Gate, scheduled shortly after the final AO is released. Generally the concept maturity does not change through the writing of the proposal (shown as Step 1 in the life cycle), its evaluation, and its possible selection to Step 2. Phase A (assigned) and Step 2 (competed) begin with the concept at CML 5.

CML 6 is useful mainly for the AO-driven, competed life cycle, and represents the concept content required for a Step 2 Concept Study Report. There is no corresponding milestone for CML 6 in the assigned life cycle, and there is no need to synchronize the maturity of the various components of the concept to CML 6 at some point in the middle of Phase A, so long as they all reach CML 7 by the end of Phase A.

CML 7 is the concept content required for KDP-B (assigned) and the Project Mission and System Review (competed). For assigned missions, CML 7 represents the completion of the expected Phase A concept products. For competed missions, CML 7 represents the completion of those concept products not required for the Step 2 Concept Study Report, but that would be required in an assigned project for Phase A.

#### IV. Tools for Measuring a Concept’s Maturity

CMLs provide the terminology for describing maturity but in order to use it to make quantitative measurements, the contents of a mission concept must be defined. In essence a vocabulary had to be developed to go with the terminology. With this vocabulary, CMLs can be used as a means of communications to allow members of different study teams to describe, compare and contrast one mission concept with another.

To develop this vocabulary, the main components of a mission concept had to be described. Fundamentally, mission concepts can be divided into 14 technical elements (e.g., mission objectives, requirements, spacecraft design, ground system design, risk, technology, etc.) and 11 programmatic elements (e.g., cost, schedule, inheritance, organization, etc.). Important attributes of each of these elements and how they mature throughout the Pre-Phase A life cycle were then determined. The results were captured in a tabular format, known as the “CML Matrix.”

The CML Matrix was organized with CMLs at the top of the columns and one technical or programmatic element at the start of each row. With this framework, the contents of individual cells could be generated. (See Figure 4) The approach was to ask a series of questions, and then to fill each cell with the answer. As an example, the questions for the mission objectives row were, what should a concept be expected to have for mission objectives at the Cocktail Napkin stage (CML 1)? What about at the Initial Feasibility (CML 2) stage?

Life Cycle Phase	Pre-Phase A						
	Advanced Studies			Concept Development		Phase A	
	1	2	3	4	5	Early Formulation	
CML	1	2	3	4	5	6	7
Name	Cocktail Napkin	Initial Feasibility	Trade Space	Point Design w/ Trade Space	Concept Baseline	Initial Design	Preliminary Cost-Schedule-Design Integrated Baseline
Mission Objectives & System Requirements	Document prime science, exploration & technology objectives	Quantify objectives to levels that allow comparison with previous investigations; Document draft Level 1 requirements	Broaden objectives to include acceptable alternatives; Identify driving Level 2 & 3 requirements to cost & risk; Quantify cost & risk sensitivities to varying levels of science return	Document end-to-end approach for achieving science; Document possible Level 1 requirements; Document distinction between baseline & threshold (floor) success criteria; Quantify Key Performance Parameters (KPP); Document mission success boundaries (subset of mission obj sponsors feels must be met)	Produce Science Traceability Matrix	Document Level 2 & 3 driving requirements	Submit final PLRA; Document preliminary Level 2 & 3 requirements

Figure 4. One row (Mission Objectives & System Requirements) of the CML Matrix. This tabular format allows study team members to determine how mature a particular technical or programmatic element has to be as a function of time. In this example, a science traceability matrix has to be produced by the time of the Baseline Commitment Review (CML 5) in order to have a complete concept baseline.

Once the rows were complete (horizontal integration), an assessment was made down each column (vertical integration) to ensure that all elements in that column made technical sense (i.e., had all elements at the same expected level of maturity). As one would expect, the technical elements of a concept mature at a slightly faster rate than the programmatic elements. Obviously, one must have some understanding of the spacecraft configuration and the supporting ground system design before its cost or the amount of time needed for its development can be determined.

To get an appreciation for this matrix, a summary table has been constructed for this paper. (See Figure 5) The 25 rows of the CML Matrix have been summarized into 13 high-level areas, and only CML 3 (Trade Space) and CML 5 (Concept Baseline) columns are included. This summary table provides a comparison for how a concept matures between trade space exploration and the level of detail needed to begin writing a NASA Step 1 proposal.

Sample Attributes	CML 3 (Exploration Across Trade Space)	CML 5 (Concept Baseline)
Requirements	Draft mission objectives & Level 1 Requirements	Science objectives traced to measurement requirements; and B/L & threshold success criteria established
Mission Design	Alternative mission architectures	High-level scenarios, timelines and critical events; and delta-V budgets
S/C System Design	Alternative S/C architectures assessed for sensitivities to cost, risk & performance	Documented subsystem & instrument designs to enable external evaluations & costing
Ground System Design	Mission ops drivers	Ground system block diagrams
Risk	Development risks and mitigations across trade space	Allocated technical and programmatic margins based on risk
Technology	New technologies required across trade space	Baseline technology selected and development approach established
Master Equipment Lists	Selected assemblies as required for trades	Document to assembly level
Project Organization	Identify PI	Project Manager and roles/responsibilities of key partners
Technical Margins	None	Technical margins defined
Proposed Inheritance (value)	Options characterized across trade space	Value and appropriateness of selected options validated to subsystem level
Schedules	Schedule sensitivities across trade space	One page Gantt chart to 4-month resolution with critical path, long lead procurements and funded schedule reserves
Cost	Parametric cost sensitivities	B/L cost estimate validated using at least 2 cost estimation models
Test Beds & Models	None	Number and type of spacecraft models, simulators and test beds

Figure 5. This summary table is used to show how the CML Matrix provides guidance without having to “wade” through all of the information contained in its 13-pages. It also only has columns CML 3 and CML 5 to show how the particular elements mature.

To illustrate how a particular element matures, notice the third row “S/C System Design” of Figure 5. At CML 3, the spacecraft system is still being evaluated across multiple architectures (i.e., “Alternative S/C architectures assessed for sensitivities to cost, risk and performance”). During this point, study teams are widening the performance-cost trade space by at least 25%. That is, if the notional architecture used for initial feasibility had a spacecraft system that provided 400 w-hrs of power, then the power subsystem would be evaluated between 300 and 500 w-hrs to identify how power output impacts the overall mission performance. By explicitly exploring the trade space, study teams can find “performance cliffs and opportunities.” In this way an architecture can be found that captures the desired science with a specific spacecraft and ground system which can be designed, built and operated for the proposed cost and schedule.

At CML 5, the S/C System Design row states that the spacecraft system should have “Documented subsystems & instrument designs to enable external evaluations and costing.” This is consistent with the JPL approach that mission concepts, both technical and programmatic, be complete, viable and documented prior to the release of NASA’s Final Announcement of Opportunity (AO). In this way, the proposal teams can focus on responding to the AO and writing the proposal rather than being distracted with trade studies or the evaluation of new technologies.

## V. Evaluating the Usefulness of CMLs

Once the CML Matrix was completed and thoroughly reviewed by the program offices at JPL, the matrix was evaluated against several relatively mature mission concepts to assess its usefulness. These concepts included the Outer Planet Flagship Mission’s (OPFM) Mission Study Reports (MSR) and the proposals being considered for the New Frontiers opportunity. New Frontiers is a competed NASA program for deep space robotic projects.

The findings were that the OPFM MSRs were indeed at CML 4 (Point Design) but, as expected, were weak in the area of programmatic. As a result, the OPFM teams were requested to place a little more emphasis on the programmatic portions of their concepts and the other areas that the CML Matrix identified as weak. As a result, the MSRs submitted to NASA were much stronger than they might have been without the CML Matrix assessment.

Next the matrix was used with the New Frontiers mission concepts. Prior to our evaluation, the proposal teams were working to “complete” their concepts in preparation for their respective Baseline Commitment Reviews

(CML 5). According to the CML scale, CML 5 is the level of maturity a concept should attain in order to be able to write a strong Step 1 proposal. As such, only the CML 5 column of the CML Matrix was used for this evaluation. The basic approach was to query the Capture Lead, Proposal Manager and the System Engineer for each team prior to their Baseline Commitment Review. The intent was to determine if the matrix would indeed tell us that their individual concepts were at the desired level of maturity.

Each interview lasted approximately 30 minutes. At the interviews the proposal teams were asked about each element of their concept. Elements were evaluated as either green - that element was indeed included in their concept; yellow - that element was partially addressed, or red - that element had been omitted. The assessment showed that the CML Matrix was able to accurately assess the maturity of the concepts. From Figure 6 we see that all concepts were measured as basically green. This indicated that, based on the CML Matrix, all of the proposal teams had most of the information needed, at the required level of maturity to begin writing their Step 1 proposals.



Figure 6. This evaluation proved that the CML Matrix was able to show that 1) the mission concepts were basically green (i.e., at the required level of maturity), 2) there were portions of the concepts that required additional work, and 3) the programmatic portion of the concepts (bottom half of each column) were generally weaker (less green) than the technical portions of the concepts (top half of each column).

In addition, each proposal team was provided with the results of their interview. This allowed each team to see which areas of their concept were at the expected level of maturity and which were not. Proposal teams then decided if additional action was necessary to address the identified weaknesses. As a result of this assessment, all New Frontiers proposal teams were able to have a much stronger Baseline Commitment Review.

The matrix was also able to provide other information. As an example, if all concepts were yellow or red for a particular element, it could be interpreted as either 1) all concepts were deficient in that area and more laboratory resources should be placed in that area to improve the maturity of that particular element or 2) the CML Matrix was asking for material that really should be required later on in the development process. As such “adjustments” could be, and indeed were made to the matrix to provide better assessments of future mission concepts.

## VI. Conclusions

The Concept Maturity Levels are themselves just reaching a level of maturity making them ready for broader use outside of JPL. In their use at JPL over the past two years, we have shown the value of the terminology in discussing concept development, funding, review, and down-selection, and we have shown the value of the preliminary CML Matrix in evaluating concept maturity and recommending action to improve lagging elements of the concept.

JPL is currently utilizing CMLs to help the National Research Council's Solar System Decadal Survey teams assess the maturity of the concepts being considered for inclusion in their study report. It is also envisioned that CMLs will be used to mature the concepts for the next Discovery Program Announcement of Opportunity. In the future, the CML Matrix could be used to evaluate the Announcement of Opportunity itself. An assessment of the contents of an AO could produce some thought-provoking questions like, why does the AO request information that should not be known to the requested level of maturity during a Step 1 proposal? Or how come the AO does not request some technical and programmatic elements that indeed should be known?

CMLs can also be used to frame questions like:

- How are CMLs related to funds expended?
- Is it meaningful to prioritize mission concepts that have a CML of less than 3?
- Should the acceptable margins and reserves be higher for concepts below CML 5, and if so, by how much?

The detailed definition and applications of CMLs and the CML Matrix will continue to evolve as they gain wider use outside of JPL. We can provide the current CML Matrix on request, and welcome comments and suggestions. We expect that the use of CMLs will facilitate discussions of concept maturity, will provide a basis for consistent concept development practices, and will help establish reasonable expectations based on the maturity of the concepts in consideration.

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