CloudSat System Engineering: Techniques That Point to a Future Success

Ralph R. Basilio, Ronald J. Boain, and Try Lam
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109-8099

Abstract. Numerous books, articles, and technical papers have been written on system engineering's role in successful project management. Components of the project development life cycle such as the definition and analysis of requirements, the design process, configuration control, and risk management are frequently identified as key ingredients to the successful outcome of any endeavor. This is true for deployment of a product or system and also for rollout of an important service. Most of the literature focuses on what the major system engineering steps are without necessarily addressing how to complete each step or how to successfully transition between them. Over the past three years the CloudSat Project, a NASA Earth System Science Pathfinder mission to provide from space the first global survey of cloud profiles and cloud physical properties, has implemented a successful project system engineering approach. Techniques learned through heuristic reasoning of past project events and professional experience were applied along with select methods recently touted to increase effectiveness without compromising efficiency. The use of an online database as the single repository for officially identified requirements and completing a streamlined system-level fault tree analysis and accompanying probabilistic risk assessment are some specific examples. The collective set has allowed the CloudSat Project to be successful through formulation, approval, and at least early implementation phase.

THE CLOUDSAT MISSION

Introduction. CS (CloudSat) is an Earth System Science Pathfinder (ESSP) mission intended to measure clouds around the world for two years (see Figure 1). CS was selected by NASA's Earth Explores Program Office at GSFC in March 1999 in a competition from among proposals submitted in response to a NASA Announcement of Opportunity (Ref. xxx). By their nature, ESSP missions have their costs capped and closely monitored by NASA HQ (Headquarters) and the Earth Explorers Program Office at GSFC (Goddard Space Flight Center) during project execution.

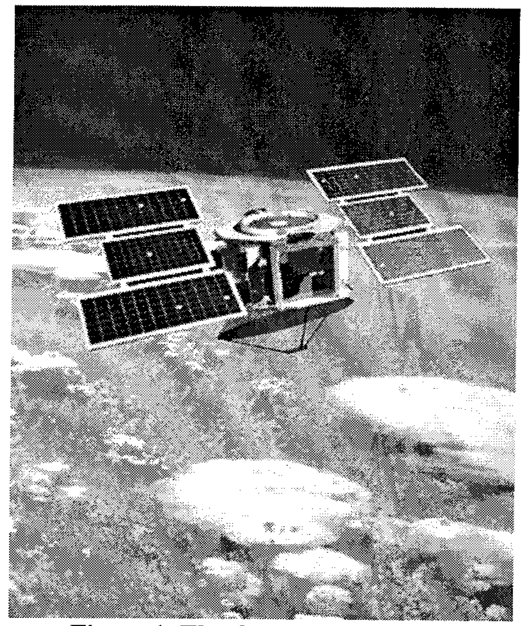

Figure 1. The CloudSat spacecraft

Despite the tight cost constraint and the short development schedule, CS nonetheless has several ambitious aspects that press, perhaps exceed, the current state-of-the-art in terms of the total mission scope and planned achievement. First, the CS spacecraft will be the first space mission to fly and operate a 94 GHz cloud profiling radar (CPR) in earth orbit. This cloud radar is CS's only instrument and is will be used to measure the water/ice contents of clouds. Because CS has only the radar, there are no direct means to measure other key cloud parameters needed to perform a more complete, more accurate interpretation of the cloud properties. So to make up for this, CS has elected to fly in formation with other cloud observing satellites so that their measurements can augment the radar with different, complementary information about the clouds, thereby creating a "virtual platform". CS's two formation flying partners for this endeavor are the Aqua and CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) satellites. In fact, CS relies on coordination, coregistry, and near simultaneous measurements with these other satellites and incorporates these outside data sources in the production of CS's data products. As far as the in-space formation is concerned, Aqua, CS, and CALIPSO all fly in formation together, i.e., measurements on each spacecraft are within 2 minutes of one another; this establishes the leading-part of the so-called PM Constellation of satellites, which also includes the Parasol and Aura spacecraft at the back end.

DPAF. Another aspect of the CS mission which is enabled by a relatively recent development in the realm of launch services is that CS and CALIPSO will be only the third space launch on a Delta rocket as co-manifested payloads using a Dual Payload Attach Fitting (DPAF). The DPAF is a relatively new development, previously used to launch EO-1/SAC-C and Jason-1/TIMED on a single Delta launch vehicle. Unlike the first two DPAF missions, however, this time both spacecraft are to be deployed into the same insertion orbit. Thus, in addition to the formation flying, there are also some relatively new design aspects for the launch and post-injection mission phases.

Partners. From an organizational point of view, CS has participating partners that span a wide breadth. With the Jet Propulsion Laboratory (JPL) as the Project Office, reporting to GSFC's Earth Explorers Program Office, the CS Project is counting on contributions from the United Sates Air Force, the Canadian Space Agency, the Cooperative Institute for Research in the Atmosphere (located at Colorado State University), and the Ball Aerospace and Technologies Corporation. Each of these partners makes its own unique contribution to the CloudSat Project.

System Engineering. With this picture of the CloudSat system and its various elements, one might ask how does the Project coordinate actions, decide priorities, make decisions, and make sure that the system produced yields the "desired" output? The answer is "system engineering".

For CloudSat, system engineering is the interdisciplinary activity of defining the user needs, defining the required functionality of the system responsive to those needs, and then overseeing/directing the technical design and development effort to assure that the resulting system can be operated to deliver those needs. Moreover, system engineering directs and oversees the project's activities during those transitions from one phase of development to the next.

CS is presently in the middle of its hardware and software development phase with major system elements entering into test and integration over the next six months. Project conceptualization, i.e., the defining of various roles and responsibilities, requirements, and preliminary designs, was done during the proposal and project formulation phases, which immediately followed the proposal effort. This conceptualization and formulation effort will not be addressed in this paper. Rather the emphasis here will be on system engineering activities during the development phase and the start-up of integration and test. These are the project phases where the system design is finalized, detailed design is completed, and hardware and software components are manufactured. These are also the phases that lead to the launch and operations activities. With the completion of the formulation phase, CS's overall architecture was defined along with a set of requirements which flowed from the mission objective to the lower tiers of the system's requirements hierarchy have also been developed and placed under configuration control. So the emphasis in this paper with focus on those actions and activities that follow.

System engineering is an activity that involves the ability of performing design synthesis, the ability to make decisions that give consideration to technical, schedule, and cost matters in a timely manner, the ability of assessing that the system design is compliant with requirements at all levels, and lastly the ability to conceptualize how all elements of the system will interact.

CONFIGURATION MANAGAMENT

Management and control of project items, such as documents, hardware, software, and other key items are essential for managing an efficient project. Identifying these controllable items - which are project documents, items, records - and baselining the items at appropriate milestones throughout the mission are only some of the aspects in configuration management. Configuration management also serves as the system to evaluate and manage changes to the items. Although many projects lack a configuration management, CloudSat has adopted it fully.

For the CloudSat mission, configuration management has played a more vital role in managing and controlling the projects items then for trace-ability purposes. Items are not only easy identified and their repository known, but owner of the documents and status of documents are also identified in the Configuration Management Plan. The configuration management system also insures a complete and accurate description of the approved configurations, and assures systematic evaluation of proposed changes and their implementation. This comprehensive "controllable objects" listing acts as an index to all identified items, including complete and accurate identification of all control materials, parts, hardware and software codes. Access to these items and access to change items are accessible through a small number of standardize tools and repository.

Tools. Utilizing a minimum number of resources for the configuration management process reduces the amount of confusion and necessary personnel training. Efficiency of the process, with the usage of selected tools, is achieved by converting to a paperless repository system. CloudSat has four major repositories associated with the different type of control items:

1. CloudSat Docu-Share Electronic Library serves as the projects main repository for most of the documentations and records for the project.

2. DOORS (Dynamic Object-Oriented Requirement Systems) serves as the repository for all requirements documents.

3. The JPL PDMS (Project Data Management System) serves as the repository for a majority of the change records and items, such as waivers and change requests.

4. The JPL UPRS (Unified Problem Reporting System) is the official repository for problem/failure and ISAs (Incident, Surprise, Anomaly) reports.

These tools have made project items readily accessible and can be retrieve electronically to all personals that have permission.

Baselining. Configuration baselines should be established throughout the projects life cycle, ensuring continuous trace-ability and control over items. All items that are a part of the baseline, including hardware, software, and documentation, are archived and placed under configuration control. The appropriate establishment of the baselines are crucial to the success to the trace-ability and control of the items. Early establishment of baselines results in immature products and impairs the configuration management process and its usefulness. Items that are late in baselining will results in the lost of trace-ability and control of the item, which can lead to unexpected surprises. Avoidance can be assure by synchronizing baselines with key milestones, such as formal deliveries, project reviews, or the completion of specific testing.

CloudSat has five configuration baselines each associated in approximation with a major project review.

Baseline 1	REQUIREMENTS baseline
Baseline 2	PRELIMINNARY DESIGN baseline
Baseline 3	DETAILED DESIGN baseline
Baseline 4	SYSTEM/ELEMENT baseline
Baseline 5	FINAL PRODUCT baseline

During baselining items are systematically evaluated and changes to items are then apporved or disapproved. Items are then place in configuration control.

REQUIREMENTS GENERATION, ANALYSIS, AND MANAGEMENT

Requirements. For the CloudSat Project, requirements were formally developed and documented during the Project's so-called Formulation Phase. The Formulation Phase came after the writing and acceptance of the proposal submitted to the Program Office as a part of the competition, so a preliminary system concept and architecture existed but no real details about how to make this system concept work in an integrated manner. Thus, the Formulation Phase is an early development phase in the Project's overall lifecycle but not so early that the Project's engineers were without a rough sense of purpose or of the system performance that would ultimately be expected of their individual Project elements. The Project's engineers had only conceptual ideas about the overall designs and how their project element fit into the "big picture". But most importantly as an overarching operative principle on CloudSat, the Project's system and subsystems designs flowed from and were responsive to the requirements, and did not flow directly from the early concept alone.

Ideally the requirements generation process begins with the development of a Mission Objective statement and the definition of level-1 requirements as provided by the Principle Investigator and the Program Office. These items are needed early since they give the Project a sense of purpose and direction. They are intended to capture in writing the essential character of the Project and the key things that the Project must accomplish. As an example for CloudSat, the Mission Objective clearly captures the notion that it is a space mission intended to observe clouds on a global basis. The Mission Objective also alludes to the intent of deriving fundamental science principles from CloudSat's measurements. And the level-1 requirements (among other things) capture the type of measurements to be made, the accuracy with which these measurements must be made, and the amount of data to ultimately be collected.

In practice, the requirements generation process rarely starts at the top with the Mission Objective, but rather usually starts in the middle with some key requirements being clearly understood from the Project's inception, while others are not nearly so well defined. Moreover, this process is complicated by the fact that rarely does the Program Office have sufficient understanding of its role to provide definitive statements about what it requires of the Project. One reason for this reluctance by the Program Office's to rigorously participate in the requirements process is that the Program Office is too often afraid of sacrificing flexibility in redirecting the Project's efforts at some future time as the result of changes in the political and/or programmatic climate. Similarly, the Project's Principal Investigator is not eager to write down precisely what it is that the Project absolutely must do to achieve the tenuous list of science objectives or for that matter, what precisely is the Project's desire outcome. As a consequence, when the requirements definition process begins on a Project, there are frequently only unspecified notions about what should and should not be written down as a hard requirement. CloudSat was no exception, despite the fact that CloudSat had written a winning proposal, which was selected by the Program Office for implementation.

At this point, it becomes necessary for the Project's System Engineer, along with the cooperation and participation of the Project's other lead engineers, to take charge and start writing requirements statements with clear knowledge that many of these statements will be challenged, rejected, and/or significantly modified before they are finally accepted. The important thing here is to get started and get candidate requirements statements down on paper so that the stakeholders can begin to think about, exchange ideas about, and react to what they believe the Project can and must do within the overall cost limitation.

The writing of candidate requirements statements is the start of the long and laborious requirements development process and the negotiations that ultimately involve everyone on the Project. From it evolves a requirements hierarchy that flows down requirements from the Mission Objective to the first level, then to the second level, and so on. This results in the formation of a requirements pyramid that captures all requirements within one level of the pyramid and allows requirements at the next level below to be developed in a traceable manner. In this way, all requirements in the pyramid should be derived from and traceable to another requirement at a level above and/or traceable directly to the Mission Objective, which sits at the top of the pyramid.

Along with this process of writing and discussing candidate requirements comes the need to analyze these statements and their content as to their implications to the system design, their technical feasibility and achievability, their affordability, and their ability to be verified. And as the requirements pyramid is populated with more and more entries, it is important to verify that they are compatible and logically consistent.

Once written this way, the next key step is to have them reviewed by an independent set of reviewers who will then confirm that the requirements pyramid so constructed still makes sense and actually captures the long list of what the Project must do to meet its Mission Objective. For CloudSat, this was done in the formal Systems Requirements Review held roughly midway through the Formulation Phase.

After this important test and after working off any inconsistencies and/or other issues derived from the Systems Requirements Review, the Project then to systematically place requirements modules in the various levels of the requirements pyramid under configuration control from the top of the pyramid down to successively lower levels, always monitoring the traceability. In this way, CloudSat's various requirements modules were each brought before a Configuration Management Control Board, summarily reviewed by the board members and approved. Once this was done, the only way to further add new requirements and/or modify old ones was to again convene the Configuration Management Control Board to further deliberate on the proposed change and to accept or reject it.

RESPONDING TO CHANGE

Many project managers can atest to the fact that requirements, designs, and expectations seldom remain stagnant during a project's development life cycle. Changes are usually driven by a better understanding of what is required, the results of analyses or tests, or changing customer needs. However, what is not usually factored are changes in processes or procedures stemming from a changing 'climate/environment'. In 1999, the NASA community was adversely affected by the loss of MCO (Mars Climate Orbiter), MPL (Mars Polar Lander), and the DS2 (Deep Space 2) microprobes. After detailed investigations, NASA instituted a series of requirements/guidelines that would minimize the probability of failure for future space missions, including CloudSat. The project could have attemped to to disregard any recommendations; after requesting additional funding and/or schedule resources, chose to implement the recommendation merely for compliance; or to understand the intent, analyze the benefit to the project, and tailor the specific implementation - all the while being sensitive to cost and schedule constraints and needs. For the mostpart, the CloudSat Project chose to go with the third of these three options. For example, a directive was received requiring the use of risk management processes and risk management techniques, including fault tree analysis and probabilistic risk assessment. Rather than waiting for a standard to be dictated, the project chose to complete a streamlined, system-level, relative rather than absolute-based analysis and assessment (Basilio, et al, 2001). This implementation took into consideration the flight heritage of the spacecraft bus and the new, mostly single-string design of the payload instrument. In addition, this minimized both cost and schedule impacts while adding value to the spacecraft design and analysis process. In the end, the analysis and assessment confirmed the robust design of the spacecraft bus, but also lead to two (2) design changes/enhancements to the payload instrument to increase reliability. However, there have been times where the project has challenged a 'new' requirement/directive - only after having performed a cost and benefits analysis supporting this. The benefits of standardizing processes and procedures is obvious, but this also needs to be balanced by the specific needs of the projects, especially those that are severely cost and schedule constrained. As long as projects provide clear, compelling technical rationale/justification supporting a decision counter to the requirement/directive, they should retain some flexibility in being able to do so. Under no circumstances should any requirement/directive be disregarded without any thought being given to it.

PROJECT REVIEWS

Some of the most important milestones in the project schedule are the major reviews, since they are key decision points in the development life cycle. A significant amount of planning and preparation is needed in order to ensure success. These include, but are not limited to:

1. Defined success criteria
2. A knowledgeable review board
3. A process for the disposition of action items

However, one of the most important steps that a project can take is to conduct a series of more informal peer reviews. These not only allow review board personnel an opportunity to be exposed to the details, but also allows the project to respond to action items and incorporate necessary modifications or revisions to the material that will be presented at the major reviews. Underlying the peer reviews and the major reviews is a process for reviewing the proposed material/charts in a storyboard manner and opportunity to conduct a dry run with project personnel present.

TEAM RELATIONSHIPS

The Team. In any team, various types of information must be communicated between project members. This is especially true of projects or teams with partnership arrangements. Information to be communicated ranges from the extremely complex, e.g. design drawings, to the relatively simple, e.g. schedule status (Kerzner, 1998). Example types of information are listed in order of least complex to most complex.

1. General Status / Issues should be communicated throughout the project and relate to any design, scheduling, or cost issues already defined.

2. Schedule Planning should be communicated at the beginning of the project and is typically laid-out in a straightforward timeline. Schedule status is communicated throughout the project and relates to and modifies the planned schedule communicated early in the project.

3. Cost Planning should be communicated at the beginning of the project and, as with the schedule, is relatively straightforward. Cost status is communicated throughout the project and relates back to the original cost planning.

4. Priorities and Goals should be put forth at the beginning of the project and are reinforced or modified throughout the project. Priorities may be relatively simple to complex depending on the project.

5. Requirements should be communicated at the beginning of the project, and are clarified or modified throughout the project. Requirements are often modified due to their relevance to multiple teams and are therefore quite complex.

6. Design Details should be communicated throughout the team almost continuously from the beginning of the project through delivery.

Each method of communication can be effective if used consistently, and in the appropriate context. The efficacy of a communication method is strongly tied to the formal team structure as well as the informal team organization. Informal communication within a team can either work with the formal team organization or against it (Thorton and Luczak, 1998).

THE CHALLENGES AHEAD

Challenges Ahead. The CloudSat Project has successfully completed the formulation and approval phases, and the initial portion of implementation phase. Currently, detailed designs have been developed, engineering and flight model hardware is being fabricated, assembled, and tested, and software is being coded. This represents a significant change from the previous tasks such as requirements definition, preliminary design and analysis. With this change in 'complexion', there is a change in the type of challenges presented to CloudSat Project personnel. Did we procure all of the correct parts? Does the flight model hardware pass the functional and performance test requirements? If not, do we have the necessary expertise to diagnose the problems? Have we allocated enough margin in the schedule to resolve these problems? In addition, these challenges in a sense 'test' the foundation developed during the early project phases. As with the early project phases, project personnel need to be keenly aware of not just "what" is needed, but also "how" it is to be achieved.

CONCLUSION

Conclusion. Components of the project development life cycle such as the definition and analysis of requirements, the design process, configuration control, and risk management are frequently identified as key ingredients to the successful outcome of any endeavor. This is true for deployment of a product or system and also for rollout of an important service. However, most of the available literature focuses on what the major system engineering steps are without necessarily addressing how to complete each step or how to successfully transition between them in a collective manner. Over the past three years the CloudSat Project has implemented a successful project system engineering approach. Techniques learned through heuristic reasoning of past project events and professional experience were applied along with select methods recently touted to increase effectiveness without compromising efficiency. The use of an online database as the single repository for officially identified requirements and completing a streamlined system-level fault tree analysis and accompanying probabilistic risk assessment are some specific examples. The collective set has allowed the CloudSat Project to be successful through formulation, approval, and at least early implementation phase.

ACKNOWLEDGEMENTS

This work described in this publication was performed at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California under contract with the National Aeronautics and Space Administration.

REFERENCES

Basilio, Ralph R., Plourde, Kim S. and Lam, Try, "Systematic Risk Management Approach Employed on the CloudSat Project." *Proceeding of the 2001 IEEE Aerospace Conference* (Big Sky, Montana, March 10-17, 2001), 2001.

Kerzner, Harold, Ph.D, *Project Management: A Systems Approach to Planning, Schedule, and Controlling*, 6th ed. John Wiley & Sons, Inc., New York, 1998.

Thorton, John A. and Luczak, Michael A., "An Approach to Successful Integrated Product and Process Development (IPPD)." *Proceeding of the 1998 International Council on System Engineering Symposium,* 1998.

BIOGRAPHIES

Ralph R. Basilio is the CloudSat Spacecraft Manager and serves as the contract technical manager for the Ball Aerospace & Technologies Corporation spacecraft system contract. He has thirteen years of engineering and management experience working on space flight projects such as the Space Shuttle, and Galileo, Cassini, Mars Pathfinder, and Deep Space 1 Projects. He is a recipient of the NASA Exceptional Achievement Medal, over twelve NASA Group Achievement Awards, a JPL Group Award for Technical Excellence, and a JPL Level A Bonus Award for Outstanding Accomplishments. He is a graduate of the California Institute of Technology's Executive Engineering Management Program, and holds MS and BS Degrees in Aerospace Engineering from the University of Southern California (USC) and the California State Polytechnic University, respectively. He is pursuing further graduate studies in the USC Aerospace and Mechanical Engineering Department leading up to the Engineer and PhD degrees. He has authored/co-authored thirteen technical papers, and served as the general co-chairman for a technology validation symposium.

Ronald J. Boain is theCloudSat Project Engineer. He has thirty plus years of aerospace engineering and management experience, with twenty-five of these years at the Jet Propulsion Laboratory. His expertise lies in mission design and analysis, systems engineering, and project planning and management.

Try Lam is an academic part-time employee pursuing a BS Degree in Aerospace Engineering at the California State Polytechnic University, Pomona. His areas of interest are in space exploration, structures, and propulsion. He recently co-authored a IEEE technical paper on risk management techniques.