CURIOSITY: THE MARS SCIENCE LABORATORY PROJECT

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ABSTRACT

The Curiosity rover landed successfully in Gale Crater, Mars on August 5, 2012. This event was a dramatic high point in the decade long effort to design, build, test and fly the most sophisticated scientific vehicle ever sent to Mars. The real achievements of the mission have only just begun, however, as Curiosity is now searching for signs that Mars once possessed habitable environments. The Mars Science Laboratory Project has been one of the most ambitious and challenging planetary projects that NASA has undertaken. It started in the successful aftermath of the 2003 Mars Exploration Rover project and was designed to take significant steps forward in both engineering and scientific capabilities. This included a new landing system capable of emplacing a large mobile vehicle over a wide range of potential landing sites, advanced sample acquisition and handling capabilities that can retrieve samples from both rocks and soil, and a high reliability avionics suite that is designed to permit long duration surface operations. It also includes a set of ten sophisticated scientific instruments that will investigate both the geological context of the landing site plus analyze samples to understand the chemical & organic composition of rocks & soil found there. The Gale Crater site has been specifically selected as a promising location where ancient habitable environments may have existed and for which evidence may be preserved. Curiosity will spend a minimum of one Mars year (about two Earth years) looking for this evidence. This paper will report on the progress of the mission over the first few months of surface operations, plus look retrospectively at lessons learned during both the development and cruise operations phase of the mission.

PROJECT FORMULATION

Preliminary studies on the Mars Science Laboratory Project started in 2001 as part of on-going efforts to restructure the Mars Program after the Mars Climate Orbiter/Mars Polar Lander failures. Early efforts focused on establishing a scientific rationale for a follow-on to the Mars Exploration Rover mission then in development. The objective of the MER mission was to determine whether liquid water had existed on Mars in the past. Although that question had not yet been answered when MSL started, it became evident that the next logical question in understanding the history of Mars was whether a habitable environment could have existed in the past. Answering this question would require both the existence of liquid water in the past and that the right environment be present to allow habitability. In addition, evidence of this habitability would have to have been preserved down through the ~3.5BY interval since Mars was wetter and warmer. The difficulty of establshing a valid approach to answering this fundamental science question was the key reason behind the complexity of MSL.

Addressing the habitability objective required developing and flying the most challenging scientific payload suite every flown to another planet. A total of 10 instruments were selected and flown, including two remote sensing instrument, two contact science, four environmental monitoring and two critical chemical analysis laboratories. These instruments were chosen and will be operated as an integrated payload suite, in which each acquires unique data and helps address critical elements of the habitability question. Successful use of the instruments is only viable, however, because of the engineering capabilities of the Curiosity rover. Unlike previous Mars rovers, Curiosity can acquire samples through a sophisticated drill/scoop and sample processing system that is first of a kind. The intent of this system is to acquire samples from within the interior to Mars rocks, thereby providing access to well preserved samples of ancient Martian environments. Access to a large number of samples is also important, which is a key reason for the long life, large size, and extended mobility capability of the Curiosity vehicle.

The last major enabling element of the Mars Science Laboratory mission is the new Entry, Descent, and Landing system. Because of the size of the Curiosity vehicle (nearly one metric ton), the existing landing systems developed for MER, Phoenix, Viking, etc could not be used. Instead, a new system consisting of a guided entry vehicle and a radical "skycrane" landing approach was developed and successfully landed Curiosity on August 5th. The guided entry vehicle allowed the rover to be placed very near a scientifically interesting landing site in Gale Crater. The skycane system worked exactly as planned, with a touchdown velocity well below the 0.5m/s requirement. Demonstration of this landing approach will hopefully enable future Mars missions of the size and scope of MSL.

A key conclusion that can be drawn from this description of the scientific and engineering challenges facing MSL is that there were a large number of both unique and interconnected developments. This is symptomatic of "flagship" missions in that both the complexity of the scientific endeavor and the engineering required to support that are multi-dimensional. Increasing the number of first-of-a-kind inventions results in a exponential increase in the implementation complexity. Although most of the team responsible for implementing MSL had also worked on previous Mars missions (including MER), there was undoubtedly insufficient recognition of this rapid complexity increase.

> Key Lesson: Assess the potential for high implementation complexity driven by multiple interconnected development challenges

IMPLEMENTATION CHALLENGES

The implementation chronologies of the MSL Project is shown in Figure 1. During the early implementation phase, the project team focused on establishing a baseline technical design and validating the key enabling technologies. The Project conducted a focused technology program that did advanced the key technologies while also identifying some of the elements that wouldn't be complete in time for the 2009/2011 opportunities. Unfortunately, a few key technology elements did not progress as much as desired early on. These elements (low temperature/high life motor actuators and integrated sample acquisition/processing systems) eventually experienced significant development

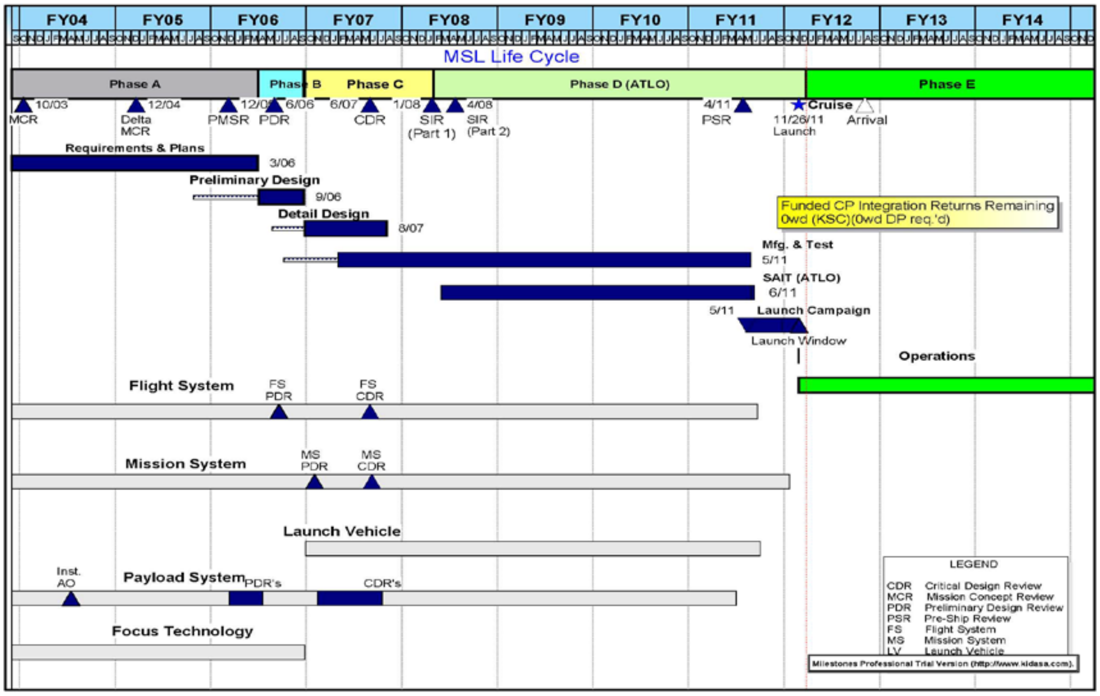

Figure 1 MSL Implementation Chronology

problems that were key contributors to the launch slip and implementation difficulties.

Key Lesson: Rigorously complete required technology developments prior to start of full scale development.

The project team also conducted a number of design architecture studies early on, including crucial ones focused on avionics architecture, instrument interfaces, power system design, redundancy approach, and motor control/sensing design. The project ended up implementing a new, largely redudant avionics architecture in which a number of high density, low mass/power designs were required. The complexity of this system architecture and the relatively late point at which it matured into a preliminary design also led to key schedule challenges during the implementation phase. These problems were compounded by our underestimating the difficulty in verifying such a complex architecture. Insufficient time and effort were placed early on in developing a design which could be easily verified.

Key Lesson: Do not underestimate the complexity of developing a new avionics system even if the underlying technology is mature.

The impact of the actuator/sampling system technology immaturity and the complexity of the avionics development was not evident when the Project was approved for full scale development in mid-

2006. In fact, it wasn't until after the Project Critical Design Review in mid-2007 that the schedule impact (and associated budget increase) was recognized. Failures in development life tests on the actuators forced the project to return to the more well understood wet lube actuator approach and a very late redesign cycle was required. A significant redesign of the sampling system was also conducted between the Preliminary Design Review and CDR to minimize dependency on immature technology elements. Finally, the pace of development of the custom high density Field Programmable Gate Array logic chips in the avionics hardware was not keeping up with the original plans. The Project's response to these changes was to accelerate efforts by adding additional personnel and to juggle the integration and test plan to accommodate the likely late deliveries. Unfortunately, continued schedule erosion threatened the adequacy of the system test campaign by late 2008. As a result, the Project was forced to delay the launch from the 2009 to 2011 launch opporunity. The additional two year development interval was sufficient to resolve the remaining challenges.

SUMMARY

Despite the initial, high visibility success of the Mars Science Laboratory project, there were a number of challenges that made the project exceptionally difficult to implement. These problems include issues with the basic mission concept, a highly aggressive schedule, and a significantly modified Entry, Descent, and Landing system. Fortunately, these problems were successfully resolved and the mission was executed. Nevertheless, a number of useful lessons were learned that should prove to be useful for both future Mars rover missions and general space exploration efforts.

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