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Research Paper

A Concept for NASA's Mars 2016 Astrobiology Field Laboratory

LUTHER W. BEEGLE, MICHAEL G. WILSON, FERNANDO ABILLEIRA, JAMES F. JORDAN, and GREGORY R. WILSON

ABSTRACT

The Mars Program Plan includes an integrated and coordinated set of future candidate missions and investigations that meet fundamental science objectives of NASA and the Mars Exploration Program (MEP). At the time this paper was written, these possible future missions are planned in a manner consistent with a projected budget profile for the Mars Program in the next decade (2007–2016). As with all future missions, the funding profile depends on a number of factors that include the exact cost of each mission as well as potential changes to the overall NASA budget. In the current version of the Mars Program Plan, the Astrobiology Field Laboratory (AFL) exists as a candidate project to determine whether there were (or are) habitable zones and life, and how the development of these zones may be related to the overall evolution of the planet. The AFL concept is a surface exploration mission equipped with a major *in situ* laboratory capable of making significant advancements toward the Mars Program's life-related scientific goals and the overarching Vision for Space Exploration. We have developed several concepts for the AFL that fit within known budget and engineering constraints projected for the 2016 and 2018 Mars mission launch opportunities. The AFL mission architecture proposed here assumes maximum heritage from the 2009 Mars Science Laboratory (MSL). Candidate payload elements for this concept were identified from a set of recommendations put forth by the Astrobiology Field Laboratory Science Steering Group (AFL SSG) in 2004, for the express purpose of identifying overall rover mass and power requirements for such a mission. The conceptual payload includes a Precision Sample Handling and Processing System that would replace and augment the functionality and capabilities provided by the Sample Acquisition Sample Processing and Handling system that is currently part of the 2009 MSL platform. Key Words: Mars—*In situ* science investigations—Astrobiology Field Laboratory. Astrobiology 7, 545–577.

INTRODUCTION

Two questions humanity has striven to answer since it became self-aware are "Are we alone in the universe?" and "How did life on the Earth begin?" Until recently these questions could only be asked in theological discussions, as the technological means to begin to answer them

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

were not available. The recent explosion in technological advances makes it possible for us to begin to address these questions. As such, overriding goals of the National Aeronautics and Space Administration (NASA) include search for evidence of how life started here and determination as to whether we are alone in the universe. Mars is now the focus of these life searches. Discoveries of previous martian epochs with standing surface water, along with tentative observations of atmospheric methane; preliminary evidence of near-surface liquid water; and higher-than-expected cratering rates not only suggest the possibility that habitable zones may have existed on Mars, but also suggest that they may still exist in the near-surface environment, where they could be accessed with currently available technology (Malin and Edgett, 2000, 2003; Formisano *et al.*, 2004; Malin *et al.*, 2006).

NASA's Mars Program is designed to explore Mars by way of a systematic set of missions that will launch at every Earth-to-Mars ballistic transfer opportunity (approximately every 26 months). Each mission will build upon the technology and scientific results of previous missions through a strategic planning process that, in general terms, is characterized by a scientific strategy whereby we will begin by "following the water" and then move on to "finding the carbon." The Astrobiology Field Laboratory (AFL) is the next logical *in situ* search platform that will follow the Mars Reconnaissance Orbiter (MRO) (launched in 2005), Phoenix Scout-class mission (to launch in 2007), Mars Science Laboratory (MSL) (to launch in 2009), and the Mars Science Orbiter (MSO) (to launch in 2013) projects in this strategic effort. (Note: the detailed objectives of the Mars Scout Program's 2011 mission are unknown at this time.)

In a current draft of the Mars exploration strategy, there is the option to send the AFL to Mars in the 2016 launch opportunity (Fig. 1) (Beaty *et al.*, 2006; McCleese, 2006). We have developed an AFL mission concept which can fit within current

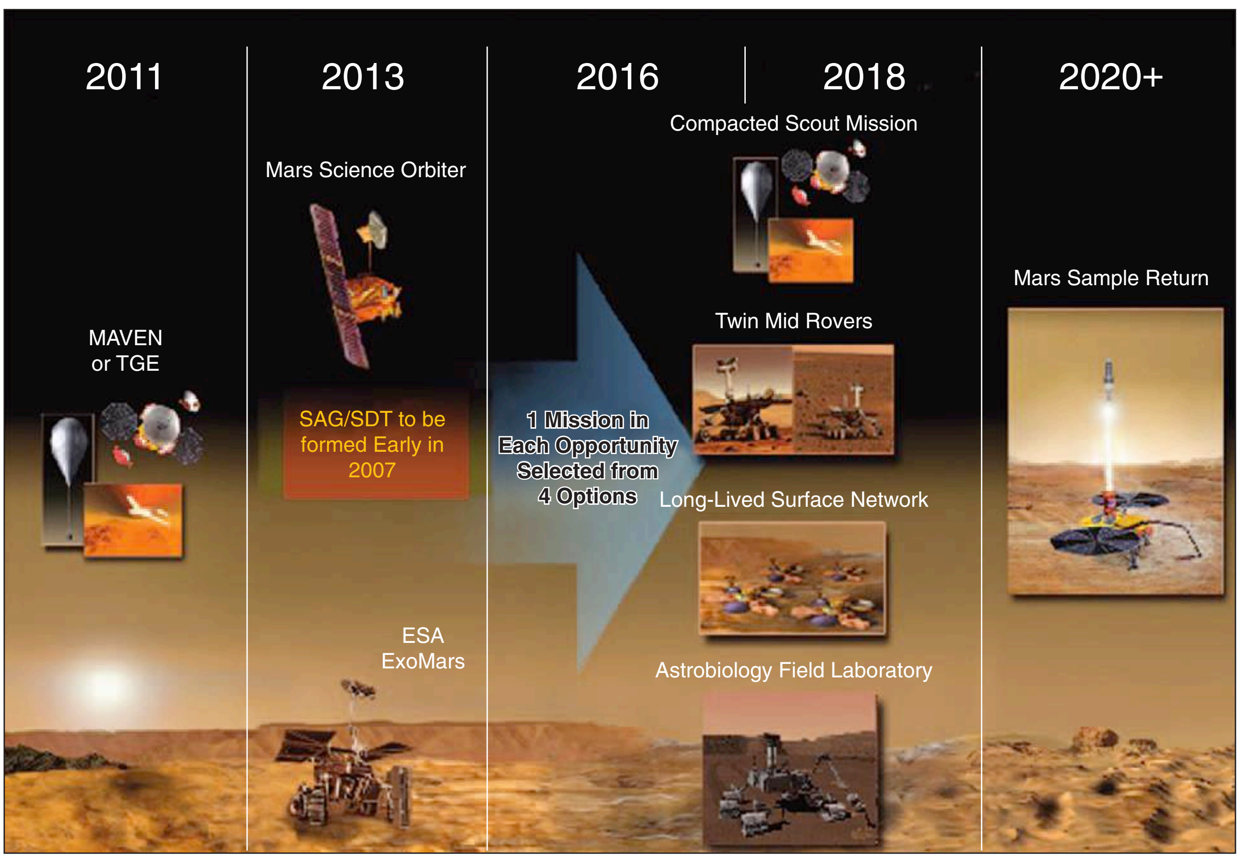

FIG. 1. Mars Exploration Program pathways for potential next-decade missions. The AFL is an option for either the 2016 or 2018 opportunity (Beaty *et al.*, 2006; McCleese, 2006). ESA, European Space Agency; SAG, Science Analysis Group; SDT, Science Definition Team.

and projected Mars Program planning funding constraints. Strawman payload elements were identified from a set of recommendations put forth by the Mars Exploration Program Analysis Group (MEPAG) Astrobiology Field Laboratory Science Steering Group (AFL SSG) in 2004 (Steele *et al.*, 2004), for the express purpose of identifying overall rover mass, power, and other technical requirements for such a mission. Candidate payload suites consistent with the full complement of recommended measurements, and selected subsets and augmentations to those measurement goals, have all been investigated as part of this mission concept. The development of the AFL mission concept allows us to identify technology that needs to be developed to meet identified mission goals. It also gives potential instrument providers a broad mission overview so as to focus instrument development activities that may be capable of contributing to the mission goals.

The AFL SSG developed the goals for the AFL mission based upon the anticipated goals and payload of the MSL rover. However, the findings of the 2004 AFL SSG were submitted prior to the selection of the MSL payload suite, and it is anticipated that a future AFL SSG is expected to begin later in 2007 (Fig. 2) (Arvidson, 2007). The 2007 SSG will revisit the science objectives and measurement strategies for the AFL, taking into account the actual characteristics of the MSL payload that will launch, as well as the wealth of information gathered about Mars by the suite of spacecraft currently in orbit and on the surface of Mars. However, the fundamental rationale and objectives for the AFL are not expected to change significantly.

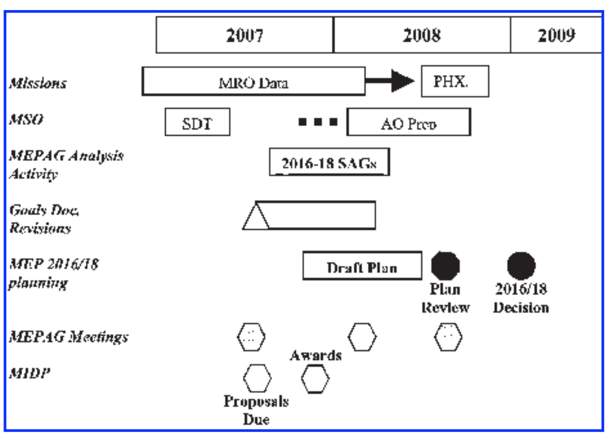

FIG. 2. High-level near-term AFL mission concept schedule and relevant MEP activities. Planning activities and dates are approximate and subject to change by NASA MEP (derived from information presented by D. Beaty at MEPAG meeting, January 2007, Washington, DC). SAG, Science Analysis Group; SDT, Science Definition Team.

The selected payload for the MSL will attempt to determine the habitability potential of a specific site at Mars. That is, could Mars have been habitable in the past, or is it habitable now? The AFL SSG mission goals are

1. To make a major advance in astrobiology by exploring a site with high habitability potential as determined by results from MRO, Phoenix, or MSL missions.
2. To search for evidence of past or present life by identifying the presence of potential biosignatures. If definitive biosignature detections are made, they will be accomplished through mutually confirmed measurements.
3. To test for habitation by investigating whether the environment could have been or currently could be habitable.

In any search for extraterrestrial life, the development of search strategies that give maximum flexibility to find "life as we may not know it" is the real key to formulating a mission concept that will be flexible enough to meet mission goals. Accordingly, the AFL SSG developed the following set of search strategies and assumptions for increasing the likelihood of detecting biosignatures:

1. Life processes produce a range of biosignatures, which leave imprints on geology and chemistry. However, the biosignatures themselves may become progressively destroyed by ongoing environmental processes.
2. Sample acquisition will need to be executed in multiple locations and at depths below that point on the martian surface where oxidation results in chemical alteration.
3. Analytical laboratory biosignature measurements require the pre-selection and identification of high-priority samples. These samples can be subsequently subsampled to maximize detection probability and spatially resolve potential biosignatures for detailed analysis. That is, the AFL must identify the best possible sample for analytical analysis.

The AFL will be an integral part of the strategic exploration of Mars and feed forward technologically and scientifically to the next landed missions, as is evidenced in several aspects of the mission architecture.

2. SCIENCE

Mars is a natural first target in the robotic exploration and search for extraterrestrial life. It is the most Earth-like of all the objects in our solar system, a rocky body with appreciable atmosphere (95% CO_2 at 5 Torr), 25-hour days, and a current obliquity to orbit of 25.19°; and Mars exists within the assumed habitable zone around our Sun (Kasting *et al.*, 1993; Kasting, 1997a). Orbital missions NASA has sent to Mars—the Viking Orbiters, Mars Global Surveyor, Mars Odyssey, and MRO—have all imaged evidence of ample liquid water on the surface. The recent release of Mars Global Surveyor Mars Orbiter Camera images also adds to this evidence and indicates that recent surface water may be possible (Malin *et al.*, 2006).

Geomorphological land forms show evidence of past active gullies, river beds and deltas, lake beds, and even potential seas, which indicates that a warmer and wetter Mars existed in the past (Higgins, 1982; Parker *et al.*, 1989; Gulick and Baker, 1990; Parker *et al.*, 1993; Squyres and Kasting, 1994; Malin and Edgett, 2000, 2003). Recently, both Mars Exploration Rovers (MER) found ample chemical and mineralogical evidence in surface rocks that standing water was present at Meridiani Planum and Gusev Crater (Squyres *et al.*, 2004a; Squyres *et al.*, 2004b; Haskin *et al.*, 2005). The European Space Agency's Mars Express (MEx) orbiter has identified, in the martian atmosphere, trace amounts of methane that could be the result of near-surface volcanism, abiotic processes, or, possibly, life processes taking place in the near surface (Welhan, 1988; Kasting, 1997b; Max and Clifford, 2000; Kotelnikova, 2002; Duxbury *et al.*, 2004; Formisano *et al.*, 2004; Krasnopolsky *et al.*, 2004; Bar-Nun and Dimitrov, 2006). Mars Express orbital investigations indicate that this aqueous period occurred shortly after the planet's formation and may have been present for substantial periods of time on the surface, approaching 500 million years (Bibring *et al.*, 2006). What makes this even more exciting is that this aqueous period is believed to have existed around the time when life began on Earth (Walsh and Lowe, 1985; Schidlowski, 1988; Schopf, 1993; Mojzsis *et al.*, 1996; Rosing, 1999; Westall *et al.*, 2001; Garcia-Ruiz *et al.*, 2003; Tice and Lowe, 2004; Van Kranendonk and Pirajno, 2004; Van Kranendonk, 2006).

One overriding question the Mars Exploration Program (MEP) hopes to address is, if life started on Earth, then might it have started on Mars as well? And if so, might life on Mars still survive in protected environments where chemical energy and water exist, such as in the subsurface, in rocks, or under the polar caps? Furthermore, if life never began on Mars, what conditions prevented a second genesis there, and might knowledge of those conditions on early Mars help to constrain the potential geochemical environment at the time of the origin of life on Earth?

Life on Earth inhabits virtually every terrestrial environment where food and energy exist, and destroys chemical and geological evidence of the early Earth. Plate tectonics, the hydrological cycle, and other geological activity further destroy geologic and chemical evidence of early life. As a result, we can only infer what conditions were present at the time of origin of life. Some of these issues, however, do not appear to apply to Mars, where no plate tectonic activity has been identified and a relatively dry environment has persisted for the last ~4 billion years. As we begin to address questions with regard to whether life exists, or has existed, on Mars, we will gain a better understanding of conditions on Earth at the time of the origin of life here.

In 1976, NASA sent two Viking landers to Mars to characterize the surface and determine whether life existed in the unconsolidated surface material that covers the entire planet (Klein, 1977, 1978; Klein *et al.*, 1992). The set of experiments on the two landers were identical and included the Labeled Release, Pyrolytic Release, and Gas Exchange experiments. These experiments acquired unconsolidated surface material (conventionally called martian soil) and tested it for signs of life. In addition, a gas chromatograph/mass spectrometer (GC/MS) was used to analyze the volatiles released from several samples on the surface.

In the Pyrolytic Release experiment, small samples were exposed to CO and CO_2, which were radioactively labeled with C^{14} to determine whether organic matter could be synthesized in the martian soil under ambient martian conditions (Horowitz *et al.*, 1976; Klein *et al.*, 1992). Trace amounts of carbon-containing substances were formed for those samples that were studied under ambient martian conditions as well as those heated to 625 °C, which indicated that life processes were most likely not present in the soil.

In the Labeled Release experiment, soil samples were introduced to a nutrient-rich solution that contained radioactively labeled carbon, and the evolved gases were analyzed by two solid state beta detectors (Horowitz *et al*., 1976; Levin and Straat, 1976, 1977). This process resulted in a rapid release of CO_2 followed by a slow release of CO_2, which is what was expected if organisms were present in the soil. While there are some who feel that the results are indicative of biology, conventional wisdom is that there was no biology in those samples (see Klein, 1978 and Klein *et al*., 1992 for a more thorough discussion on this and on all of the Viking life-detection experiments.)

In the Gas Exchange experiment, soils were exposed to H_2O and, upon humidification, released O2 (Oyama *et al*., 1977; Oyama and Berdahl, 1979).

The GC/MS analyzed two samples on each lander; samples were heated to 200 °C, 350 °C, and 500 °C (Biemann *et al*., 1976; Biemann and Lavoie, 1979). Although there was a detection of the solvent that was used to clean the spacecraft, the GC/MS detected no organic material in any sample. This was unexpected because current estimates of the amount of exogenic organic material delivered to Mars through the infall of meteorites and interplanetary dust particles is 2×10^5 kg yr^{-1}, which almost certainly was higher in the past (Hayatsu and Anders, 1981; Mullie and Reisse, 1987; Flynn, 1996). Furthermore, there should be, by some estimates, almost 500 parts-per-billion of carbon-bearing species in the upper meter of the planet (Benner *et al*., 2000). The results of these three experiments, taken together with the GC/MS results, indicate the presence of one or more surface oxidants, though not necessary life.

The AFL payload will attempt to minimize any conflicting positive detection of life by including a suite of instruments that provide mutually confirming analytical laboratory measurements. Finally, while the results of the Viking GC/MS indicated that no organic material was detected in the surface material sampled, oxidation products from meteoritic in-fall would have been undetectable by that particular instrument (Benner *et al*., 2000; Navarro-Gonzalez *et al*., 2003). Understanding the limits of detection for instrument measurements on complex samples is critically important for the AFL mission so that any possible biosignature measurements made can be interpreted in the proper context.

The Mars Exploration Program Analysis Group (MEPAG) defines science goals and measurements for Mars for consideration by NASA program planners. The current MEPAG document, *Mars Science Goals*, *Objectives*, *Investigations*, and *Priorities: 2006 MEPAG* (MEPAG, 2006) states that the determination of whether life arose on Mars is a key and challenging goal. If life exists or has existed on Mars, scientific measurements to be considered would focus on understanding those systems that support or supported it. Finally, if life never existed while conditions were suitable for life formation, understanding why a martian genesis never occurred would be a future priority.

In 2004, NASA charged MEPAG to convene a Science Steering Group (SSG) that would begin to define the desired measurement characteristics and scientific objectives for an AFL mission (Steele *et al*., 2004). The results and recommendations from this SSG effort have been used to guide the design efforts described in this paper, with the understanding that such recommendations will be revisited as results from MER, MEx, and MRO are factored into the strategic planning process. An example of the process by which an update to the AFL measurement objectives might be incorporated into the Mars Program Plan is illustrated in Fig. 2 (based upon MEPAG planning information), with some key planning milestones highlighted. The outcome of this planning process, in this scenario, would be available in late 2008 and provide supporting rationale for selecting a particular mission and objectives to be met by the mission to be launched 2016.

With the understanding that the Mars Program planning process is not complete, we have taken the 2004 AFL SSG recommendations of the mission scope and goals and formed a mission concept that meets the identified measurement goals. This provides input into the overall advanced planning process for the NASA Mars Program. It should be noted that, as budgetary influences become better known and more focused in the coming budget planning cycles, and the predecessor MSL heritage becomes better understood, the mission design of the AFL would also inevitably change as constraints are better matched with available resources. Though the fundamental mission goals of the AFL are not likely to change, a basic change in the high-level mission design of the AFL could occur during the National Environmental Policy Act (NEPA) compliance stage of mission planning.

It is fundamental to the AFL concept to understand that organisms and their environment constitute a system, within which any one part can affect the other (Steele *et al*., 2004). The overall AFL science investigation will focus on characterization of environments where organisms may be or may have been, and any possible biosignatures of extant and extinct life detected in those environments. Though the current AFL science justification does not include a pre-definition of potential life forms that might be found on Mars, the following assumptions were made:

1. Life utilizes some form of carbon.
2. Life requires an external energy source (that is, electromagnetic, chemical, etc.) to survive.
3. Life is packaged in cellular-type compartments.
4. Life requires liquid water.

The current understanding of Mars is that it was, at one point in its history, warmer and wetter, with ample energy in the form of volcanism and volcanically produced chemical species.

The AFL's objective must balance the need for the project to be a significant extension beyond currently planned missions, yet not an unrealistic extension of current technology. The detailed objectives proposed include (in no order of importance):

- Within the region of martian surface operations, identify and classify martian environments (past or present) with different habitability potential, and characterize their geologic context.
- Quantitatively assess habitability potential by:
  - Measuring isotopic, chemical, mineralogical, and structural characteristics of samples, including the distribution and molecular complexity of carbon compounds.
  - Assessing biologically available sources of energy, including chemical and thermal equilibria/disequilibria.
  - Determining the role of water (past or present) in the geological processes at the landing site.
- Investigate the factors that will affect the preservation of potential signs of life (past or present) on Mars.
- Investigate the possibility of prebiotic chemistry on Mars (including non-carbon chemistry).
- Document any anomalous features that can be hypothesized as *possible* martian biosignatures.

The goal of this AFL concept, as proposed, is to search for the *potential*, rather than definitive, biosignature, and characterize the supporting environment where the signature resides.

The Mars surface environment appears to have been cold and dry from ~4 billion years ago to the present. From a programmatic perspective, understanding the potential for preservation of biosignatures is vital for the development of the next generation of missions. The surface is oxidizing as a consequence of the intense photodissociation by solar UV radiation and the absence of global shielding from harmful space radiation in the form of galactic cosmic rays, which may well render the surface sterile (Hunten, 1979; McDonald *et al*., 1998; Benner *et al*., 2000; Yen *et al*., 2000; Pavlov *et al*., 2002; Kminek and Bada, 2006). Further, understanding the nature of the surface is a goal of the AFL mission concept. This includes the identification and characterization of specific biomolecules (lipids, proteins, amino acids) and potential kerogen-like material.

3. FLIGHT SYSTEMS

The AFL flight system as currently conceived consists of three major components that are modeled after the MSL system currently under development. It is not the purpose of this article to define the MSL heritage system, but rather, to provide a basic description of the system to enable an understanding of why certain constraints (landed mass, landing site latitude, etc.) exist. The fundamental characteristics of the system described here include an Earth-Mars cruise stage; an atmospheric entry, descent, and landing (EDL) system; and a mobile science rover with an integrated instrument package.

Cruise stage

Following launch and during the interplanetary transfer to Mars, the cruise stage provides the necessary functions to deliver the entry system to the atmospheric entry interface at Mars. The spinning cruise stage has minimal capabilities (*e.g.*, power, propulsion, telecommunication) and takes advantage of the rover systems to implement many of its data-handling and commanding functions. The cruise stage propulsion system is separate from the EDL system and is used for spin-rate control, attitude control, and all trajectory correction maneuvers on approach to Mars. The AFL cruise stage as currently conceived is modeled as a direct heritage design from the MSL. As will be discussed later, the mission design for this AFL concept constrained the trajectory option space to minimize any fundamental changes that might be required to the MSL cruise stage. In this example, the trajectory design for this concept precluded the use of sizable deep-space maneuvers to avoid a modification of the cruise stage propellant tank design and accommodation interface.

Entry vehicle and descent

The AFL EDL phase begins when the spacecraft reaches the Mars atmospheric entry interface point. This AFL concept mimics the EDL concept (Fig. 3) that is planned to be used for the 2009 MSL mission (Mitcheltree *et al*., 2006). The design employs an aeroshell/heat shield and a parachute to guide and decelerate the lander through the martian atmosphere. The diameter of the AFL parachute has been scaled up from that of the MSL to approximately 23 m (from ~20 m) to accommodate the possibility of heavier AFL entry and rover masses and a shift in atmospheric modeling conditions from those consistent with a launch in 2009 to those appropriate for launch in 2016.

Like the MSL, the AFL would use an offset center of mass to generate an aerodynamic lift vector during the hypersonic entry phase (Mitcheltree *et al*., 2006). The entry vehicle lift vector is modulated through use of roll-control thrusters to guide the vehicle and compensate for unpredictable vehicle performance, navigation accuracy, and environmental variations that ultimately affect AFL surface targeting accuracy. Lift-vector modulation would be the primary means for meeting the AFL landing accuracy needs, which are currently assumed to be con-

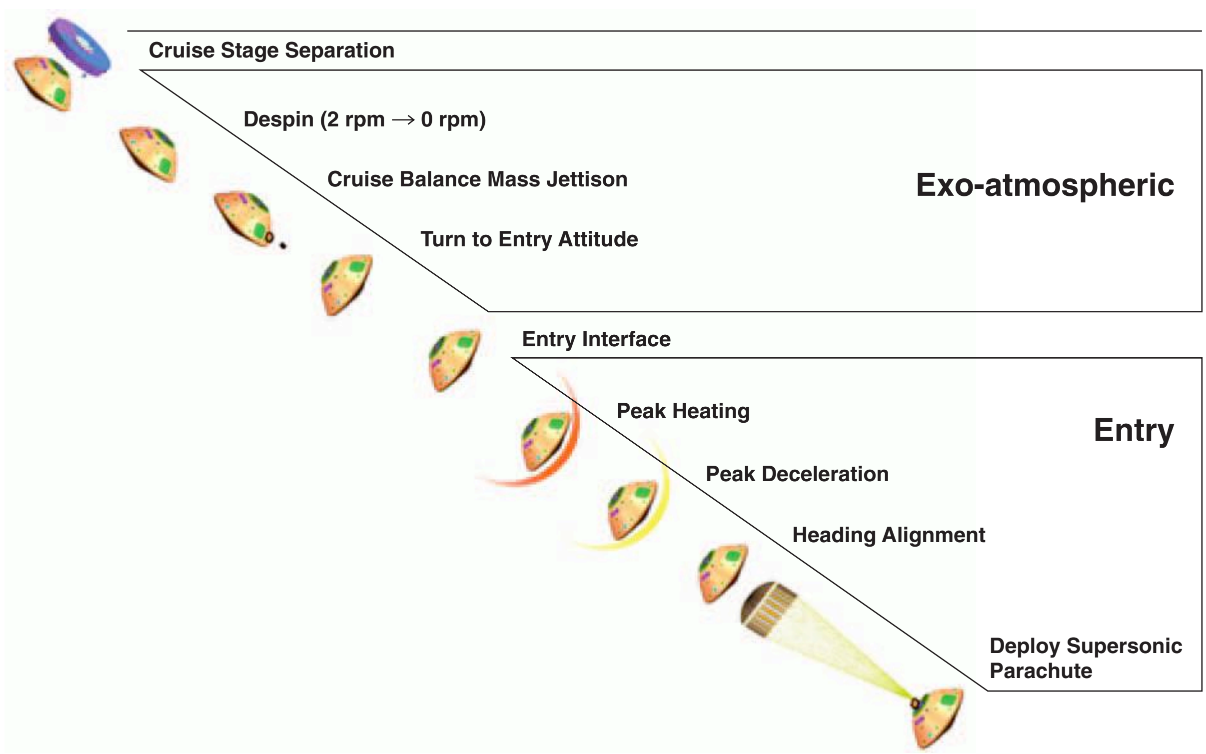

FIG. 3. EDL sequence concept of events for the MSL 2009 mission representing the cruise stage separation to supersonic parachute deploy (Steltzner *et al.*, 2006). This series of events is identical to the EDL sequence for the AFL conception design described here.

sistent with the MSL landing accuracy capability approximated by a 10 km radius footprint on the surface. This AFL concept does not attempt to guide the vehicle following parachute deployment. When investigating a specific site, the necessary landing accuracy requirement is driven by terrain and mobility considerations. If the highest-priority landing sites that support science and mission objectives require increased landing accuracy, this technology would need to be added to the technology development trade space. The vehicle design would also need to be modified to support this capability.

Following the parachute phase, the vehicle would employ the skycrane architecture for shedding the remaining velocity of the system and deploying the rover on the surface. No modifications to the MSL skycrane phase depicted in Fig. 4 are anticipated for this concept. For other AFL concepts with stricter landing accuracy requirements, such as those that require pinpoint landing techniques for highly constrained hazardous locations (*i.e.*, landing accuracies on the order of 100 m), a departure from strict MSL heritage design may need to be considered. Further elaboration of pinpoint landing technology is summarized in the technology development discussion to follow. For the AFL concept to be described here, a summary of Key Design Assumptions and Results is given in Table 1.

A key difference between the MSL flight system and the flight system concept for the AFL has to do with the anticipated need for the AFL to perform a vehicle-level sterilization activity prior to launch. This key difference is discussed in the technology development section.

Rover

The AFL rover for this mission concept is a direct descendant of the MSL rover system currently under development for launch in 2009. Although no analysis has been performed to examine the power options for the AFL, we are considering the MSL Radioisotope Power System (RPS) as a concept to enable the same landing site flexibility and surface operations performance capability that was selected for the MSL. As this

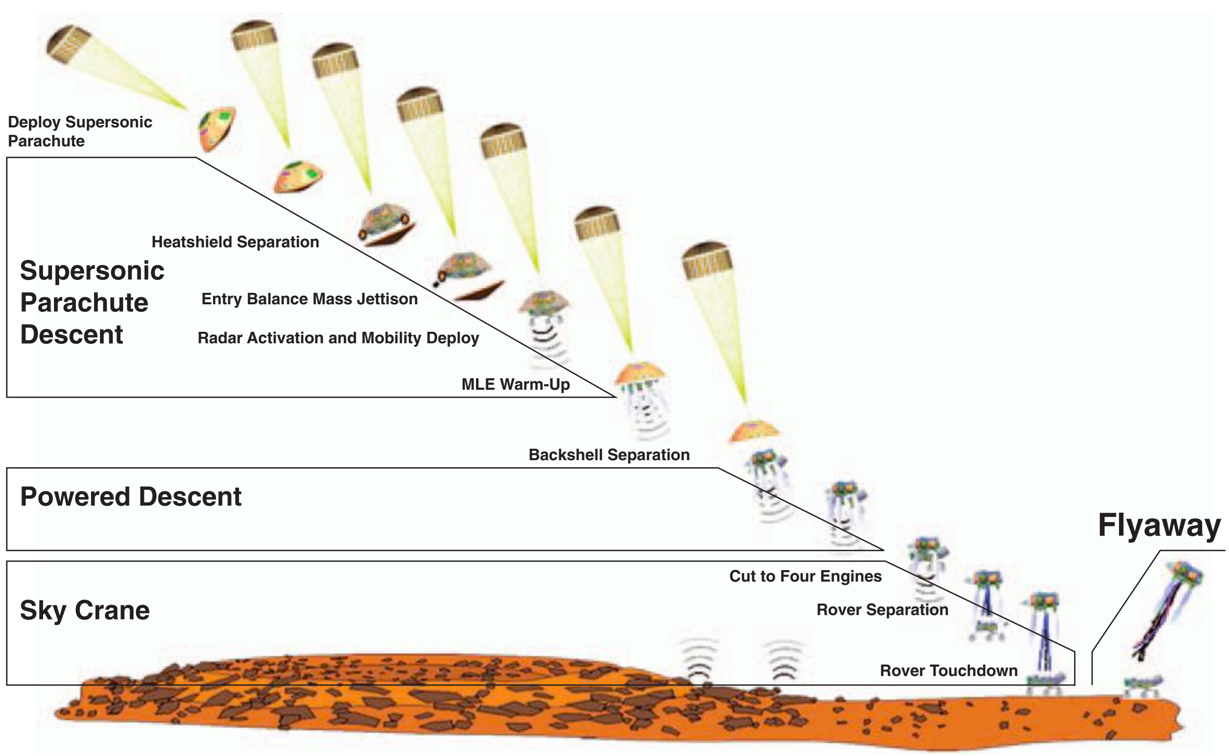

FIG. 4. EDL Sequence concept of events for the MSL 2009 mission representing the supersonic parachute deploy to touchdown (Steltzner *et al.*, 2006). This series of events is identical to the EDL sequence for the AFL conception design described here. MLE, Mars Lander Engines.

TABLE 1. APPROXIMATE DESIGN PARAMETERS FOR THE 2016 AFL MISSION CONCEPT DESCRIBED HERE

Design parameter	*Design value*	*Comment*
Launch mass (wet)	4400 kg	Enable C3 = 14.2 km^2/sec^2, max. DLA = 15.6°
Entry mass (wet)	3800 kg	Limit Mars atmosphere relative entry speed to <6.2 km/sec.
Rover landed mass	1000 kg (for sizing EDL system)	Assume 150 kg rover mass increase beyond current MSL rover allocation (placeholder).
Approximate parachute diameter	23 meters	Stretch MSL capability beyond 19.7 meters. No flight test re-qualification.
Inertial entry flight path angle	−14.5°	

mission concept is further developed, the power-generation options will be investigated thoroughly for suitability to the specific objectives of the AFL.

As currently conceived, the AFL rover would be expected to conduct its mission over a period of one martian year (669 Mars sols or 687 Earth days). The fundamental rover design features of the MSL are expected to carry forward to this AFL concept. These include the basic size of the rover (Table 2).

The mass of the rover is expected to be greater than that of the MSL, as the payload and the sample acquisition and processing systems are augmented to meet the challenging science objectives discussed earlier. At the time of the detailed design for this concept, the AFL was approximately 10% more massive than the MSL heritage concept. For an MSL rover in the 850 kg class, this would correspond to an AFL rover in the 935 kg class. For EDL and flight system design considerations, the rover for this concept was assumed to be constrained to less than 1,000 kg.

Strawman instrument payload

Part of the mass increase is due to the possible inclusion of the full desired science payload and the associated precision sample acquisition and processing system. The AFL SSG 2004 reached consensus on a suite of core AFL instruments that met a set of key measurement objectives of the nominal AFL mission (Steele *et al.*, 2004). As discussed earlier, these were defined for planning purposes only and are not meant to pre-judge future budget considerations, science analysis group activity, or the instrument selection process. For this concept discussion, the strawman instrument payload measurement objectives are defined below:

Remote Sensing Suite (site characterization)

- color and stereographic images
- reconnaissance scale mineralogy

Contact Suite (sample selection, context)

- obtain mid-scale imaging and spectroscopy of samples
- identify geochemistry and mineralogy of samples

Biosignature Analytical Laboratory (detailed sample analysis)

- meso-scale structure of samples
- definitive mineralogy

TABLE 2. AFL MISSION CONCEPT APPROXIMATE ROVER SYSTEM DIMENSIONS

Characteristic	*Size (meters)*
Height to top of deck	1.1
Height of mast	2.1
Wheel diameter	0.5
Clearance	0.7
Approximate deck dimensions (L, W, H)	2.0, 1.2, 0.5
Approximate wheel base (L, W)	2.3, 2.5

- oxidation/reduction potential, advanced carbon chemistry
- abundance/molecular structure of carbon
- isotopic composition of carbon

The AFL concept described here has looked at accommodating all measurements, as well as selected subsets of these measurements. In addition, the SSG called for the analysis of 100 samples, with analysis of over 10 samples in the full analytical laboratory, and a rover with greater than 10 km linear traverse distance.

While the exact instrument package would be selected through Announcements of Opportunity (AO), we have sized several potential instrument packages to ensure that they meet the above measurement objectives. When a well-characterized instrument with high technology readiness levels (TRL) met one of the measurement objectives listed above, we carried that instrument and its accommodation characteristics (*i.e.*, mass, volume, power) as a placeholder. For a more complete discussion of TRL concepts with respect to instrument development and future flight readiness, please see Mankins, 1995. For example, the physical parameters of the panoramic camera aboard MER were used to size the AFL remote sensing suite (color and stereographic imaging measurement). This gave us the most confidence in sizing the payload, while allowing us to acknowledge that further improvements on the performance characteristics of instruments (which would be over a decade old at the time of launch) would occur. In those instances when comparable instruments have not yet flown, we combined physical characteristics of instruments that will fly aboard the MSL, or obtained best estimates from current instrument developers and merged them into a single instrument. This was done primarily for analytical instruments that could analyze over 50 samples and wet chemistry instruments that have not flown or are yet to be developed to a high TRL. Again, this is for the purpose of discerning a reasonable estimate on which to base our mass estimates. Instrument costs were estimated in a similar manner, with current best estimates for instruments taken from various MSL-proposed instruments and flight heritage for the MER and Phoenix mission spacecraft. The total payload cost estimates for the strawman suite, which meet every measurement objective, only fit within the scope of the most optimistic Mars Program budget. Reduced capability payloads were also costed, and most fit within our presumed Mars budget. Table 3 includes the payload mass, power, and volume summary for the complete instrument suite. The volume of rover subsystems is an important design concern for rover missions due to the severe engineering packaging constraints associated with hypersonic entry vehicles. While we have not identified any volume concerns for the instruments identified in this concept, there have been significant packaging issues on past missions, and volume can be expected to be an ongoing concern as this development continues and changes are introduced. The expected instrument volume envelope for this concept is included in Table 3 as a reference.

Of importance here is the need to improve our understanding of the accommodation needs for all potential instruments aboard the AFL. Several instruments we were aware of had "special

Table 3. Predicted Best Estimates (PBE) for Several Payload Elements

	PBE mass budget (kg)	*PBE average power budget (W)*	*PBE volume budget (m^3)*
PSHPS, mast, IDD, and sample acquisition	125	TBD	TBD
Remote instruments	10	12	0.018
Contact instruments	7	18	0.028
Analytical instruments	98	60	0.43

This includes the Current Best Estimates (CBE) with a 30% contingency on all values. The power budget is the average power consumption during daily operations and is dependent on the length of operations. (Here assumed to be no more than 6 hours.) For the PSHPS system we only provide the estimated mass due to the low TRL of that concept.

needs," which included increased radiation shielding from a potential radioisotope power system, extreme tolerances on the particle size for analysis, and radius of curvature for the storage of arm-mounted instruments. The need to understand potential thermal tolerances for astrobiology themed instruments is of special interest, particularly with regard to how they may relate to potential Planetary Protection (PP) requirements. In the event that an instrument is intolerant to heat sterilization, it is conceivable that the instrument could be sterilized on the component level, aseptically assembled, and accommodated into the flight systems in a thermally isolated manner. Early understanding of these issues can lead to design modifications of the flight systems, but it is conceivable that certain instruments may be disqualified from consideration because of PP requirements on the system and subsystems that cannot be met.

Since this is an ongoing study, any instrument data that we receive from instrument developers only makes for a more realistic platform and, hence, more realistic costing data. Finally, it is intended that the physical parameters listed in this work inform instrument developers of this particular concept and its constraints and provide a discussion data point for further instrument development activities.

4. MISSION DESIGN AND DESCRIPTION

Launch/Arrival strategy

This AFL concept has a primary objective of placing an advanced mobile science laboratory on the surface of Mars. Current planning efforts include the use of the 2016 launch opportunity (which includes late December 2015 launch opportunities) to launch and deliver the rover to a selected site on Mars. As noted previously, the planning for the AFL assumes that surface operations would be conducted over a primary mission duration of at least one martian year (687 Earth days).

The design of the launch strategy for the AFL must consider many of the same issues that face any of the surface missions going to Mars. There are numerous engineering and science constraints that are placed upon the mission design, which manifest themselves in the design of the launch period and launch vehicle. Engineering constraints and considerations can include

- Entry, Descent, and Landing (EDL) telecommunications visibility during the entry and landing phases of the mission (both relayed and Direct-To-Earth communications).
- Entry speed at the vehicle interface to the Mars atmosphere.
- Entry flight path angle.
- Landing target conditions (*e.g.*, altitude).
- Time of day of landing (*e.g.*, landing aid sensors such as passive optical cameras must have adequate lighting conditions).
- Atmospheric dust loading (typically manifesting itself through a Mars atmospheric dust model such as MarsGRAM (Justus and Johnson, 2001)) results in environmental considerations associated with the arrival season for a particular landing site.
- Landing site Mars season at the arrival time (*e.g.*, a potential landing during the predicted Mars dust storm season is an important event that the AFL may need to be designed to withstand).

The Earth-relative departure conditions that must be achieved by the upper stage of the launch vehicle are specified by defining the launch energy (or C3, which is the departure trajectory hyperbolic excess velocity, or V-infinity, squared) and the direction of the hyperbolic departure trajectory (typically characterized by the declination of the launch asymptote (DLA), and the right ascension of the launch asymptote (RLA), at a specific time).

The AFL launch period for this concept is summarized and described in Table 4 and depicted graphically in Fig. 5. The figure also shows relevant geometric events that affect the orbital trajectories between Earth and Mars.

The selected launch period falls within the launch/arrival space as indicated in Fig. 6. An important characteristic of past landed missions is the ability to freeze the arrival date across the full 20-day launch period. This in turn enables the supporting infrastructure (*e.g.*, orbiter overflights, specific Deep Space Network antenna coverage) for the critical EDL phase to be planned independent of the actual launch date within the launch period. For a constant arrival date, and other design constraints, the launch/arrival date

Table 4. 2016 Astronomical Field laboratory Concept: 20-Day Launch Period Characteristics (Case 2 of Table 5)

Launch date	*Arrival date*	*C3 (km^2/sec^2)*	*DLA (deg)*	*VHP (km/sec)*	*DAP (deg)*	*VEntry (km/sec)*
29-Dec-2015	13-Oct-2016	14.25	0.05	3.72	−27.25	6.18
30-Dec-2015	13-Oct-2016	14.00	0.56	3.71	−27.48	6.17
31-Dec-2015	13-Oct-2016	13.75	1.09	3.71	−27.72	6.17
01-Jan-2016	13-Oct-2016	13.52	1.65	3.70	−27.97	6.17
02-Jan-2016	13-Oct-2016	13.30	2.24	3.69	−28.23	6.16
03-Jan-2016	13-Oct-2016	13.09	2.87	3.69	−28.51	6.16
04-Jan-2016	13-Oct-2016	12.89	3.52	3.69	−28.80	6.16
05-Jan-2016	13-Oct-2016	12.71	4.21	3.68	−29.11	6.15
06-Jan-2016	13-Oct-2016	12.54	4.93	3.68	−29.43	6.15
07-Jan-2016	13-Oct-2016	13.38	5.69	3.68	−29.77	6.15
08-Jan-2016	13-Oct-2016	12.24	6.49	3.68	−30.13	6.15
09-Jan-2016	13-Oct-2016	12.12	7.32	3.68	−30.50	6.15
10-Jan-2016	13-Oct-2016	12.01	8.20	3.68	−30.90	6.16
11-Jan-2016	13-Oct-2016	11.92	9.12	3.69	−31.32	6.16
12-Jan-2016	13-Oct-2016	11.85	10.09	3.69	−31.76	6.16
13-Jan-2016	13-Oct-2016	11.79	11.10	3.70	−32.22	6.17
14-Jan-2016	13-Oct-2016	11.77	12.16	3.71	−32.71	6.17
15-Jan-2016	13-Oct-2016	11.76	13.27	3.72	−33.23	6.18
16-Jan-2016	13-Oct-2016	11.78	14.42	3.73	−33.78	6.19
17-Jan-2016	13-Oct-2016	11.83	15.64	3.75	−34.36	6.20
	Max C3	**14.25**	**Max VHP**	**3.75**		

for the AFL was designed to maximize the spacecraft injected mass.

Trajectory design

The 2016 AFL concept follows a Type II interplanetary transfer trajectory to Mars (*i.e.*, the heliocentric transfer angle is between 180° and 360°). This selection was made to keep the flight time to Mars at a reasonable duration (interplanetary trajectories that arrive later or at comparable times to a 2018 Type I or II trajectory were excluded) while satisfying the other key engineering constraints. Table 5 summarizes the trajectory trades that were considered for this AFL 2016 concept.

All cases analyzed were optimized for maximum entry mass and constrained the arrival V-infinity to 3.75 km/sec (entry speed of approximately 6.2 km/sec). The arrival V-infinity constraint will be revisited for this concept as the design of the MSL heritage system progresses and the heat shield thermal constraints for the AFL are better defined. The option selected for this concept (corresponding to Case 2 in Table 5) is a Type II transfer, with a maximum C3 of approximately 14.2 km^2/sec^2 and a fixed arrival date. The Mars landing site latitude is allowed to vary from 36°N to 75°S for this option. The absence of specific high-priority sites that would have required potential AFL landing site latitudes to be as far north as those under consideration for the MSL (*i.e.*, 45°N) allowed us to avoid a significant launch mass penalty (*e.g.*, compare with Case 4 of Table 5 where the landing site included a higher northern latitude constraint for the trajectory design). For this preliminary concept definition, the adopted latitude band encompassed most MSL sites under consideration, as well as possible AFL-specific sites associated with the recently discovered gully regions (*e.g.*, see Dietrich *et al.*, 2006). The interplanetary trajectory for the cruise to Mars for the opening of the launch period is illustrated in Fig. 7. Figures 8, 9, 10, and 11 show some key parameters for this trajectory during transit to Mars.

Entry, descent, and landing design

A high-level illustration of the MSL-developed EDL sequence is shown in Figs. 3 and 4, which highlight the key phases of the EDL timeline. Approximately 9 months after launch, the spacecraft will enter the martian atmosphere directly from the interplanetary trajectory. Like the MSL, the AFL would be expected to follow a guided entry

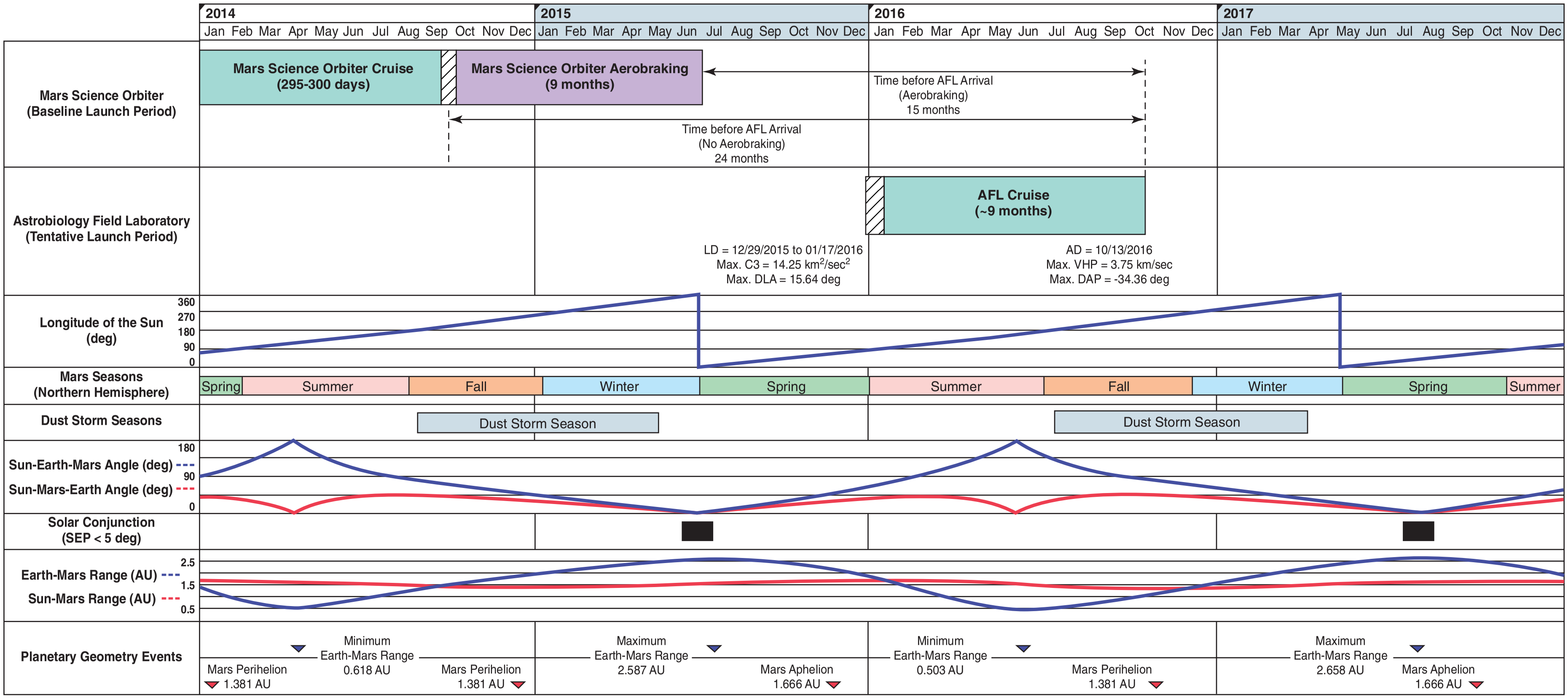

FIG. 5. AFL 2016 mission design and trajectory characteristics summary including the expected AFL launch period, cruise phase, and arrival times. AD, Arrival Date; AU, Astronomical Unit; DAP, Declination Arrival Asymptote; DLA, Declination of the Launch Asymptote; LD, Launch Date; VHP, Arrival V-Infinity (hyperbolic excess velocity).

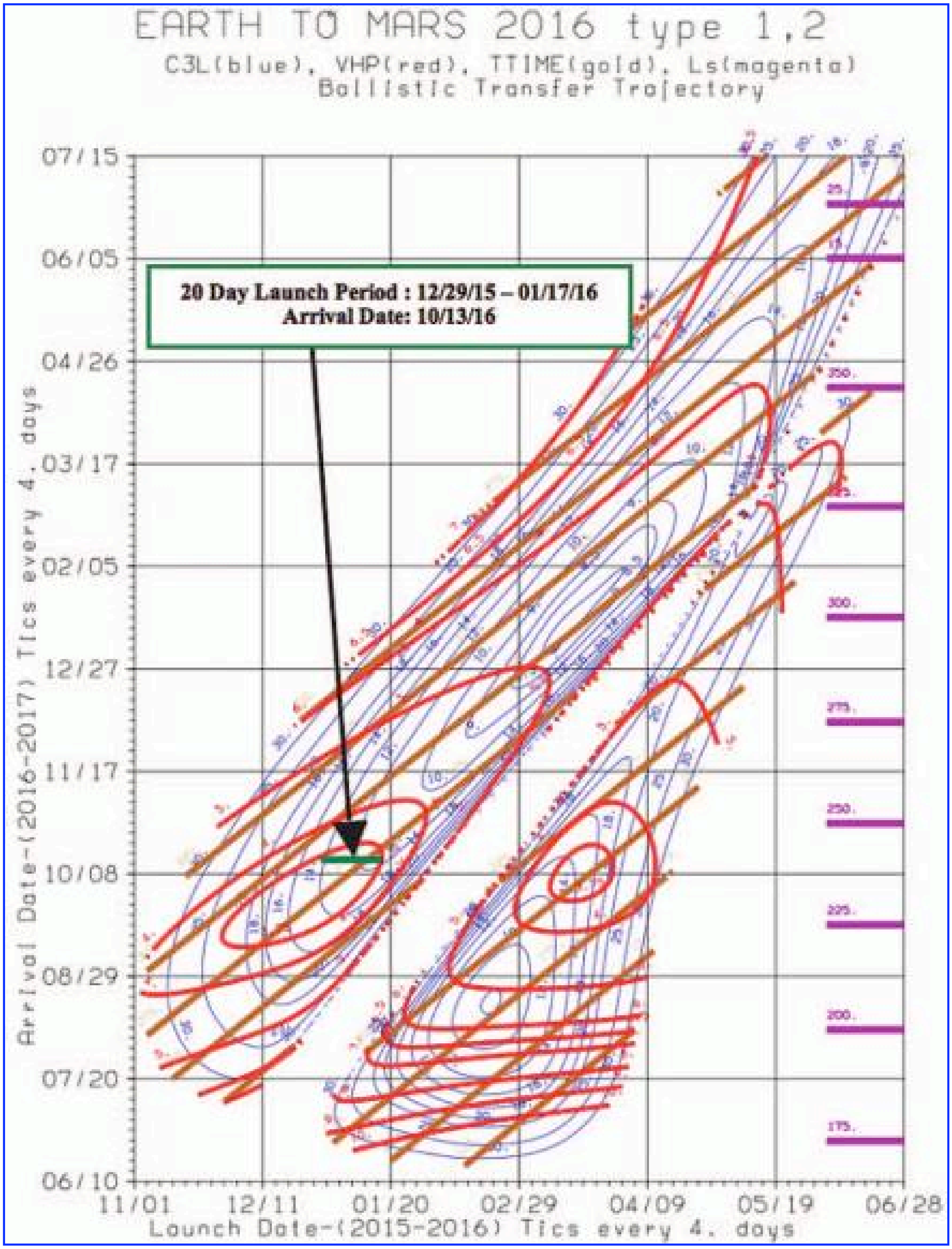

FIG. 6. AFL 2016 Earth-to-Mars ballistic transfer launch/arrival trajectory data. C3, Launch Energy; Ls, Areocentric Longitude of the Sun (Global Dust Storm Season occurs between Ls = 185° and Ls = 345°); TTIME, Flight Time to Mars; VHP, Arrival V-Infinity (hyperbolic excess velocity).

TABLE 5. TRAJECTORY DESIGN OPTIONS CONSIDERED FOR THE ASTROBIOLOGY FIELD LABORATORY MISSION CONCEPT

Case	*Departure dates*	*Arrival dates*	*Traj type*	*Max. C3 (km^2/sec^2)*	*Max. VHP (km/sec)*	*Min. inj. Mass (kg)*	*Max. Lats (deg)*
1	29-Dec-2015 to 17-Jan-2016	02-Oct-2016 to 17-Oct-2016	II	13.9	3.75	4539	36 to −75
2	29-Dec-2015 to 17-Jan-2016	13-Oct-2016	II	14.2	3.75	4510	36 to −75
3	10-Mar-2016 to 29-Mar-2016	1-Oct-2016 to 13-Oct-2016	I	18.2	3.75	4197	67 to −63
4	6-Dec-2015 to 25-Dec-2015	16-Sep-2016	II	20	3.74	4063	45 to −85

Case 1: Floating arrival date, no bounds on achievable latitudes.
Case 2: Fixed arrival date, no bounds on achievable latitudes.
Case 3: Floating arrival date, minimum achievable latitudes ± 45 degrees.
Case 4: Fixed arrival date, minimum achievable latitudes ± 45 degrees.
Case 2 selected; fixed arrival date, unconstrained landing site latitude, Type II trajectory.
Type III and Type IV trajectories rejected and excluded due to excessive Earth-Mars cruise duration.

trajectory (pre-parachute deploy) through the atmosphere. The spacecraft would rely on a heat shield and parachute to slow its descent through the martian atmosphere and would fire retrorockets to reduce its landing speed while deploying the MSL-developed skycrane system (Mitcheltree *et al*., 2006) to place the rover on the surface of Mars. Following a soft landing, the AFL rover would be poised to commence its surface mission.

A number of EDL engineering constraints are dependent upon the mass of the entry and landed systems, and it is not a straightforward process to capture all of those constraints in a list of fixed design values. As any part of the mission design changes, there can result a waterfall of changes throughout the EDL system. For example, the entry speed constraint is influenced by the allowable thickness and materials used for the design of the entry heat shield. Across their respective launch periods (and their corresponding arrival conditions at Mars), the Mars atmosphere-relative entry speeds for AFL in 2016 are higher than those for the MSL in 2009. The heat shield must be designed within manufacturing constraints and account for expected heat flux and rate. This in turn constrains the amount of mass that can strike the atmosphere and be delivered to the surface. Retrograde entry conditions tend to exacerbate these constraints and can limit the launch/arrival space or landing sites that can be considered. Increasing the landing accuracy requirements to a level such that pinpoint accuracy is a necessity (*i.e*., 100-meter accuracy range) may require additional landing propellant and tank mass to counter expected local near-surface wind environments. Such considerations can manifest, ultimately, in larger elements for the EDL system (*i.e*., parachute), a larger launch vehicle class, or interplanetary trajectory design changes. Science constraints and considerations also influence the launch/arrival design strategy and include landing site altitude and landing site latitude.

A much more complete discussion of the EDL problem for an MSL-type entry system can be found in Mitcheltree *et al*. (2006) and Steltzner *et*

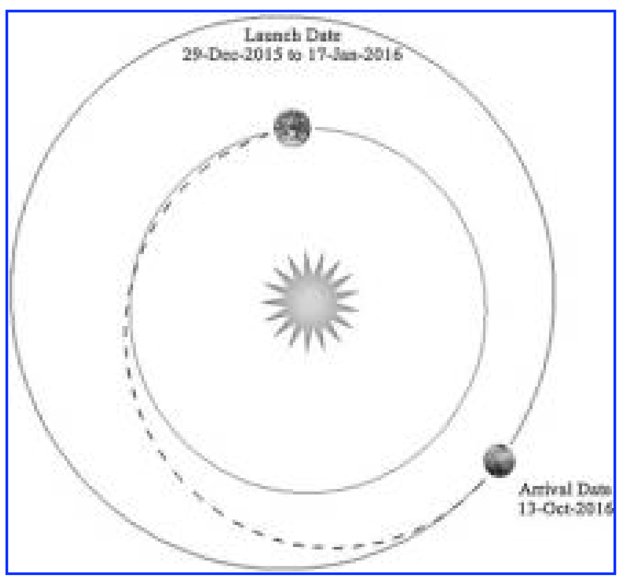

FIG. 7. Graphical representation of AFL concept interplanetary cruise trajectory for the opening of the proposed launch period.

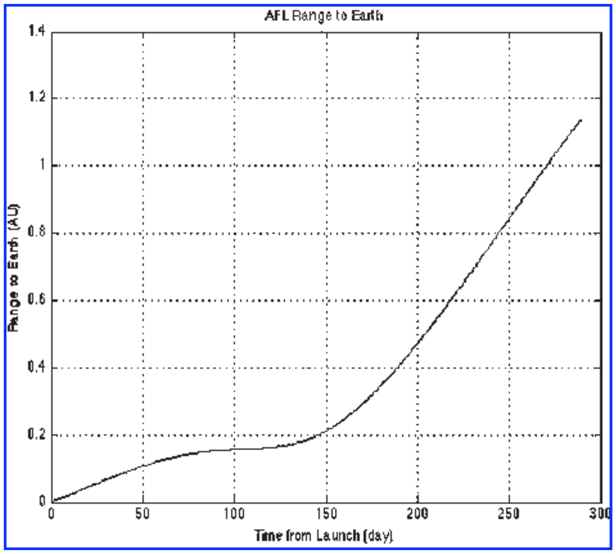

FIG. 8. AFL range to Earth during the cruise phase from Earth to Mars. AU, Astronomical Units.

al. (2006). For this AFL concept, a snapshot of some key parameters and results are summarized in Tables 1 and 2. This set of assumptions shows a point design for this AFL concept that is consistent with the MSL heritage system, with identified departures, and with the 2016 Mars opportunity. As the precise limitations of the MSL heritage system evolve during the development of that mission, so too will the design evolve for this AFL concept.

Telecom during EDL

Similar to previous Mars landed missions, there is an expectation that the mission design will plan for Earth to be in view during EDL, which will allow for the transmission of direct-to-Earth signals during all phases of EDL, as well as during a post-landing time period. It may be possible to rely on relay systems during this phase, but for this conceptual design it is an assumed requirement for both communication paths. A preliminary trajectory design shows that a relay orbiter in an MRO science orbit offers the possibility for meeting these telecommunications constraints, consistent with the rest of the design for this concept. Figure 12 shows how, for many AFL landing scenarios under consideration here, the possibility for an orbiter in an MRO, Odyssey, or a candidate MSO orbit can meet these AFL critical event relay requirements. Key coverage gaps exist for landings at mid-latitudes with this example, but may be addressed by other assets in orbit at that time (e.g., 2011 Scout or 2013 Mars Science Orbiter).

This is a proof-of-concept design that takes into consideration this telecom requirement during the design phase of the interplanetary trajectory for this option, which highlights a key criterion in the final selection of the AFL landing site and the necessity for coordination among other elements of the Mars Program.

Landing site selection

The final landing site selection for most NASA Mars missions takes place close to launch and after a thorough site selection process that includes input from the full science community and consultation with the flight system engineering development team (Grant and Golombek, 2006). It is expected that a 2016 AFL landing site would be chosen by way of data returned from MEx, MRO, and perhaps 2013 MSO orbital observations, with input from MSL surface chemistry results. However, since MRO will have nominally completed its primary science and initial two-year relay mission by the end of 2010, it may be beneficial to select a landing site early in AFL Phase A/B (see Fig. 13) while MRO high-resolution imaging is still capable of performing at the required imaging resolution levels. This would enable the characteristics of potential landing sites to be thoroughly vetted, with contributions

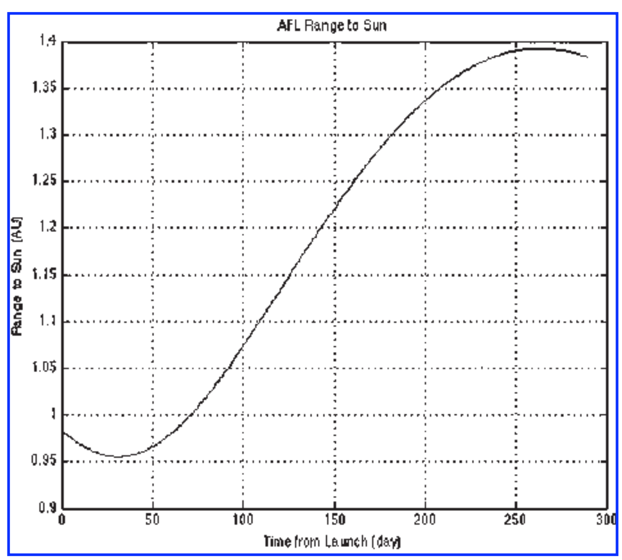

FIG. 9. AFL range to Sun during the cruise phase from Earth to Mars. AU, Astronomical Units.

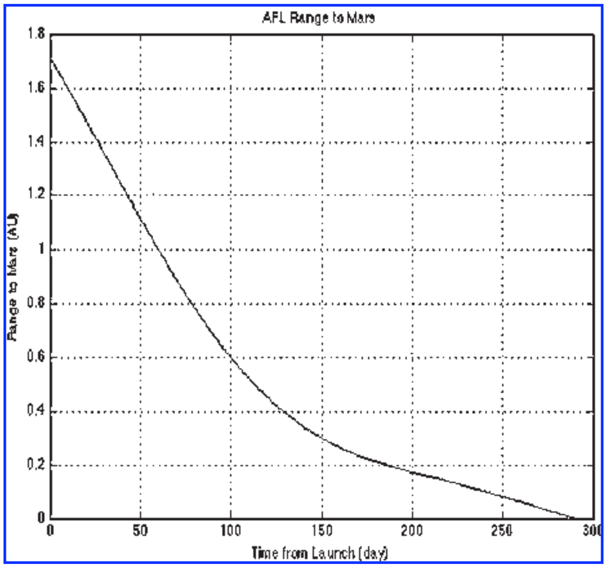

FIG. 10. AFL range to Mars during the cruise phase from Earth to Mars. AU, Astronomical Units.

from maximum resolution data sets. Here, we discuss some advantages to an early site selection, as well as potential site characteristics that a 2016 AFL would be able to reach.

The advantages of making an early site selection first become apparent in the selection of a specific and highly focused science payload optimized for site-specific measurements. Different types of sites require different types of instruments to maximize scientific investigations. The AFL SSG strawman payload that was selected to size this mission concept was formulated for an "average" non-specific martian environment, while there were four specific site types individually discussed. For each of these individual sites (stratigraphic, ancient hydrothermal, ice, and current water/current hydrothermal), different types of measurements had higher priority, which required different instrumentation for measurement objectives. For example, in the event that a near-surface, volcanically active special region is the target landing site, it would be important to include a thermal emission spectrometer to determine the exact location of hot spots. However, that instrument concept may not be as vital in a gully region, where a long focal length imager that can identify processes occurring in geological regions that are out of reach may be more appropriate (Malin *et al.*, 2006). Finally, in an ice-dominated region, special sample acquisition and handling strategies will have to be developed to ensure ice sample interrogation in a 5 Torr CO_2 environment (Taylor *et al.*, 2006; Peters *et al.*, 2007).

Also, early site selection carries a benefit to the engineering of the rover systems. The engineering development team necessarily constrains parameters of all potential landing sites so that they are consistent with the technical capabilities of any system that affects the ultimate success of the EDL phase, as well as the ultimate use of the rover system on the surface. These engineering constraints span many flight subsystems and include such diverse elements as interplanetary navigation, heat shield design, parachute design, available propellant, telecommunications visibility, as well as local environment concerns such as slopes, rock abundance, rock size, and winds. If the landing site options are focused and highly constrained, the engineering of the rover does not overdesign a system that takes into account all potential EDL characteristics (including atmospheric pressure, wind speed, and hazard avoidance) but rather opts for a highly focused design. This design scenario would reduce developmental cost and, potentially, mission risks. Programmatic and technical considerations related to planetary protection may also argue for earlier site selection than has been customary for past MEP missions especially if a special region is the targeted landing site. (For a more thorough discussion on this, please see the section titled *For-*

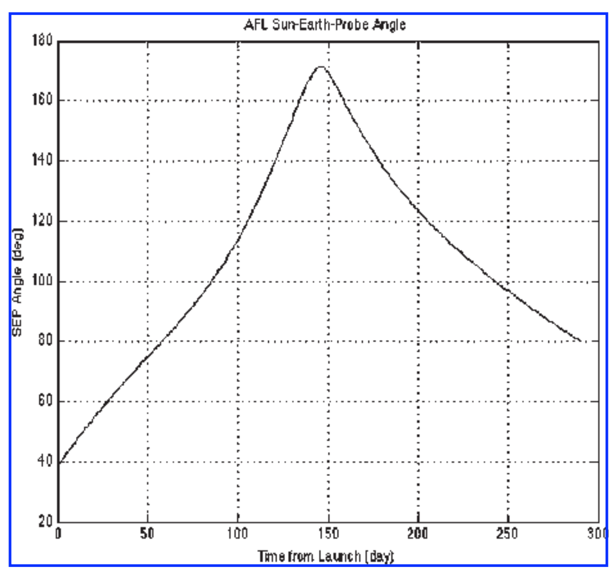

FIG. 11. AFL Sun-Earth-Probe (SEP) angle during the cruise phase from Earth to Mars.

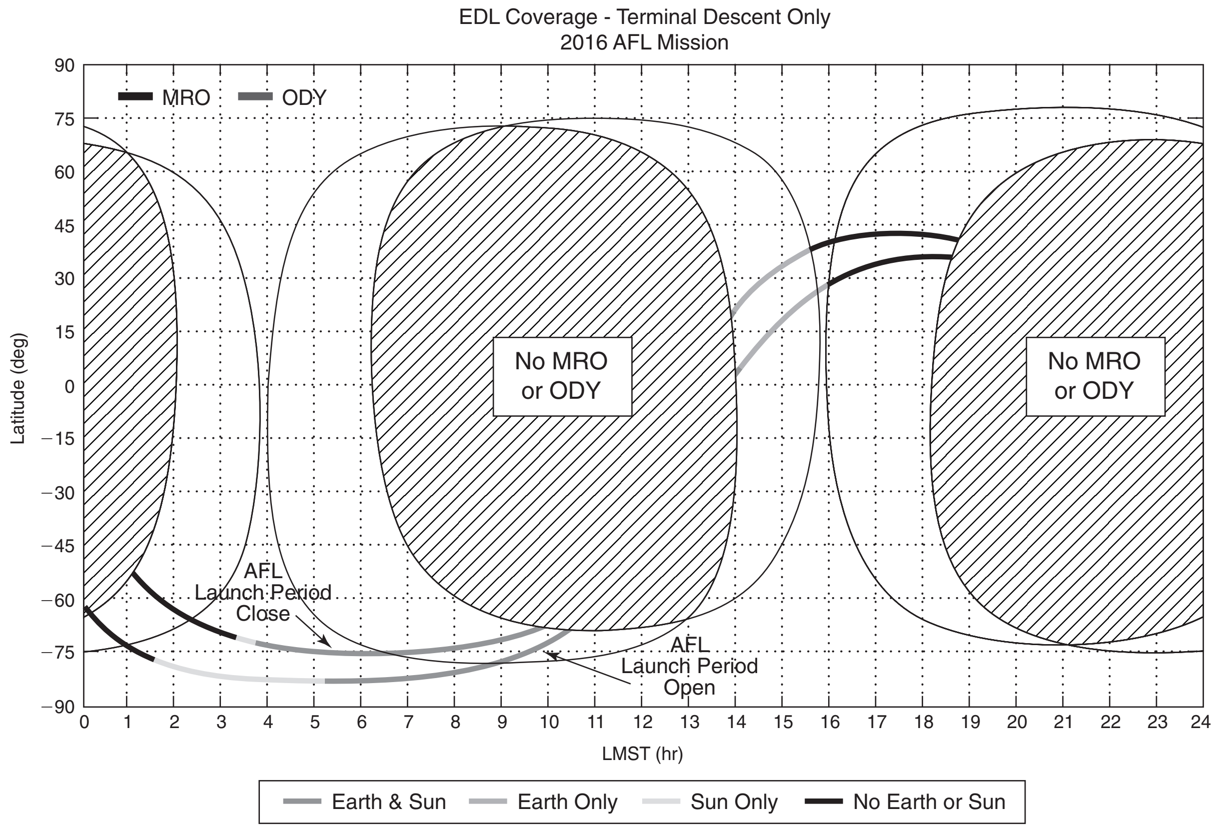

FIG. 12. EDL relay orbiter telecommunications coverage during AFL concept terminal descent with MRO and Odyssey represented as examples. While key coverage gaps exist for landings at mid-latitudes, it is expected that these gaps may be addressed by other assets in orbit at that time (*e.g.*, 2011 Scout or 2013 Mars Science Orbiter). LMST, Local Mean Solar Time; ODY, Mars Odyssey.

ward planetary protection for life-detection mission to a special region). From a program risk standpoint, the Mars Program may consider an early site-selection campaign, or the program can consider including MRO-class imaging resolution as a payload element on the proposed 2013 MSO mission.

One key difference between potential AFL landing sites and MSL landing sites is that, while the MSL must avoid special regions, the AFL may specifically target a "special region." From a PP standpoint, a special region is defined as a region within which terrestrial organisms are likely to propagate or a region that is interpreted to have a high potential for the existence of extant martian life forms (COSPAR 2005; MEPAG special regions-science, 2006). Given our current understanding of Mars, this definition is applied to regions where liquid water is present or where liquid water may result if potential long-lived radioisotope heat sources are put in contact with the local environment. Special regions may include ancient hydrothermal systems, areas where near-surface ground water may reside, volcanically active regions, or methane hot spots (Beaty *et al.*, 2006). Because of the PP restrictions, the MSL will not land within a special region's landing site that requires horizontal traverse by the unsterilized rover. In these regions, vertical mobility through the martian regolith may be possible through the use of sterilized sampling hardware.

If the landing site selection process is consistent with that which the MSL project (Grant and Golombek, 2006) is currently exercising, the AFL flight systems will be consistent with engineering design constraints applicable to the MSL flight system. (Mitcheltree *et al.*, 2006). The engineering constraints are derived from the natural environment conditions at all potential landing sites and from the capabilities and characteristics of the spacecraft and EDL system. Some key, high-level landing site constraints for this conceptual study mirror those of the current MSL design. Whether these capture the regions of interest for the AFL

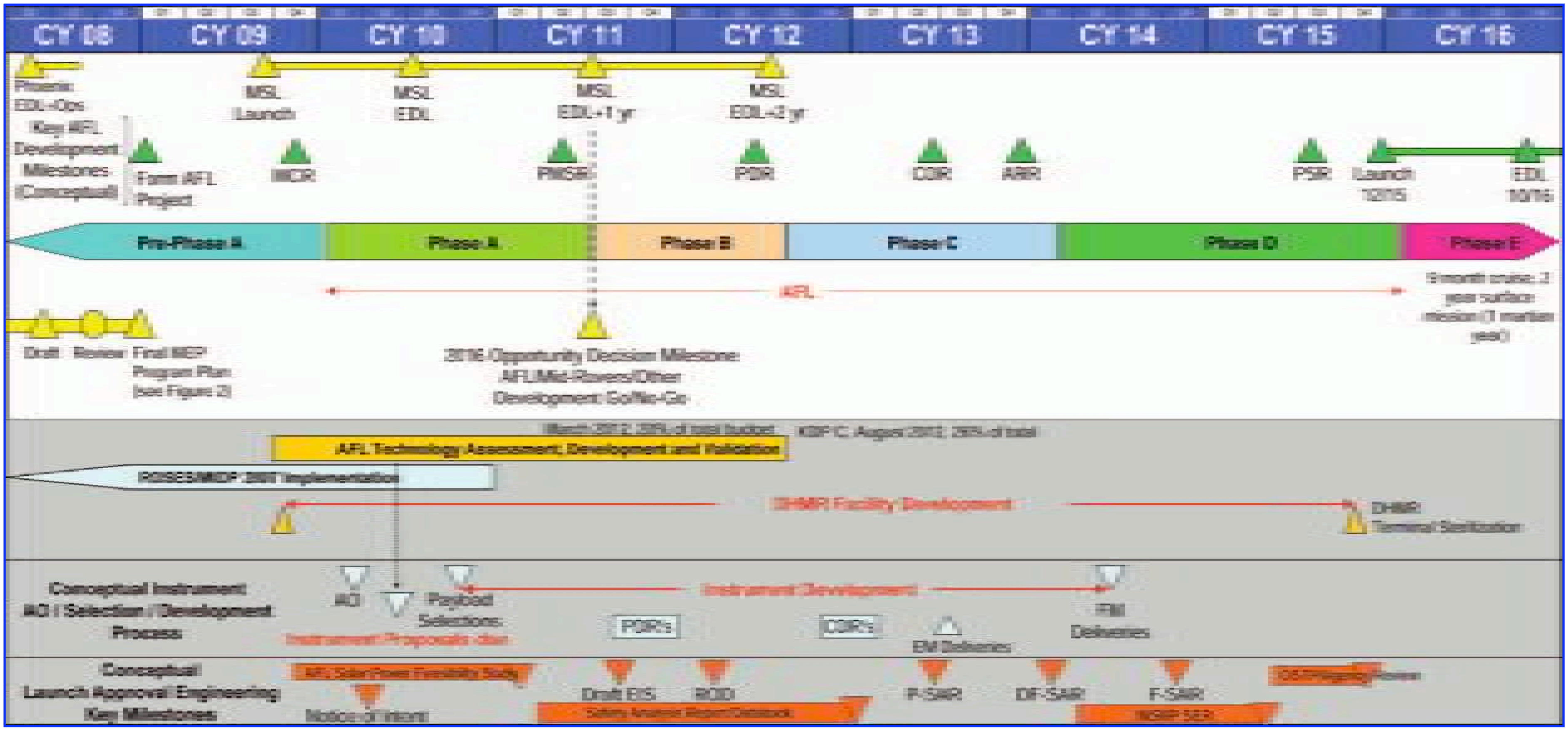

FIG. 13. AFL conceptual development schedule showing key decision points. ARR, Assembly, Test, Launch, Operations (ATLO) Readiness Review; CDR, Critical Design Review; CY, Calendar Year; EIS, Environmental Impact Statement; EM, Engineering Model; FM, Flight Model; INSRP, Interagency Nuclear Safety Review Panel; MCR, Mission Concept Review; OSTP, U.S. Office of Science and Technology Policy; PMSR, Preliminary Mission and System Review; PSR, Pre-Ship Review; ROD, Record of Decision; SAR, Safety Analysis Report; SER, Safety Evaluation Report.

FIG. 14. Artist's conception of a core being analyzed by the PSHPS on the AFL rover. Since this system is not yet undergoing development, the actual system may hold no actual resemblance to this conception. The core representation here is from an endolithic colony collected from the Dry Valleys in Antarctica and was provided by H. Sun at the Desert Research Institute.

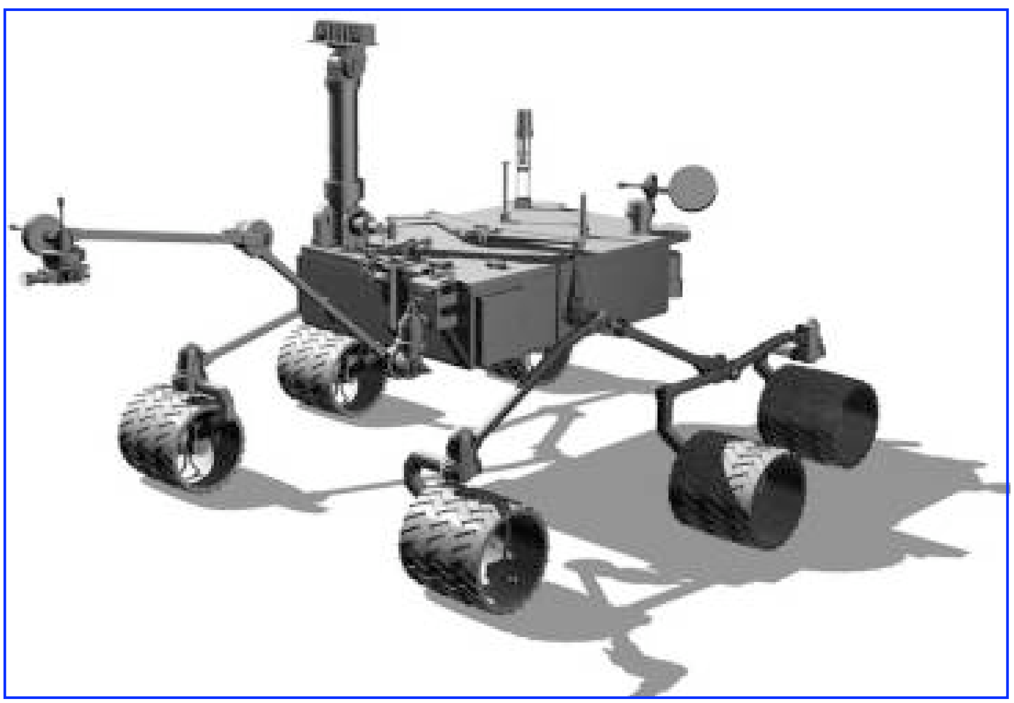

FIG. 15. Artist's conception of the AFL mission concept. The rover systems are based upon 2009 MSL heritage systems.

will be a subject of discussion for the key mission development science analysis groups. For current planning purposes, the desired landing sites are constrained to ±45° latitude, elevation with respect to the Mars Global Surveyor Mars Orbiter Laser Altimeter (MOLA) ≤1.0 km, 10-km landing ellipse radius. It is important to note that the current launch period is not able to reach 45° in latitude in the northern hemisphere without a dramatic change in launch capability. The ability of the AFL to land within a 10-km landing ellipse radius is consistent with the rover engineering capability to traverse a total of 20 km. This ensures that the AFL has the ability to drive to any desired target within the landing ellipse.

Daily operations on Mars

Once EDL is complete, the day-to-day surface operations of the AFL are constrained mainly by the power available to the rover and the data volume generated by the instruments. Data uploading to Earth would primarily be achieved using an orbiter such as MSO, which would act as a relay link (analogous to the way the MER mission currently uses the Odyssey orbiter). It is expected that, once in its telecom orbit, an orbiter such as MSO would be able to relay as much as 1–2 gigabits of daily science data. Any direct-to-Earth communications would be done via X-Band and would primarily be used for EDL and as a backup communication system. The largest single daily data volume generation is expected to occur when the full-resolution color panorama imaging is obtained, at an estimated volume of 500–750 megabits. If an instrument exceeds this value, options for data storage would have to be explored that are either instrument specific or occur at the system level.

Several daily operational power scenarios were studied to determine the power-generation requirements. We compared the power requirements with several potential instrument concepts to the power required for traverse, and found them to be roughly similar. Like all previous Mars rovers, the AFL drive train was assumed to be a 6-wheel rocker-bogie design. All wheels have two motors: one for driving the wheel and one for turning the wheel. All motors are expected to be brushless with 2, 4, or 6 wheels operational at any time, depending on the terrain. Power profiles assume that, in a worst-case scenario, each wheel will consume 18–25 W or 100–150 W·Hrs for all wheels during traverse, depending on the surface characteristics of the site (i.e., slop, rock distribution, surface material, etc.). In addition to individual wheel power draws, NavCam, HazCam, and other image processing occur during these traverses, which increases the total power draw during traverse. The MSL is currently assuming slopes as great as 30° and a total traverse length approaching 90 m during a fully autonomous drive (please see the mission website http://marsprogram.jpl.nasa.gov/msl/index.html for updates to these values). During the assumed one-martian-year lifetime of the mission, it is expected that >10 km of total linear distance will be achieved. The AFL would expect to match any of the final characteristics of the MSL rover for traverse, if not improve on the capability when operations are developed and refined in the course of that mission.

2018 opportunity

The current Mars Program Plan shows an opportunity for AFL launch in either 2016 or 2018 (Fig. 1), thus, as part of this effort, there has been high-level mission design for the later opportunity as well. The performance results across the two launch opportunities are similar. While the preliminary analysis showed that the 2018 opportunity is more energetically favorable (lower launch C3 and lower arrival V-infinity), it occurs during a season of increased dust storm activity and changed lower atmospheric parameters of importance to the EDL problem. The net effect on the ability to land the desired payload, within the same engineering constraints, is minimal.

5. SCHEDULE AND PROGRAMMATIC CONSIDERATIONS

Schedule

A strawman 2016 AFL schedule of major milestones has been developed to support long-range planning efforts that may be considered by the Mars Program for this concept (Fig. 13). It is important to identify those long lead items that would enable a launch in the late 2015 / early 2016 time frame and ensure that the necessary resources are in place to support those efforts in a timely manner. An early allocation of resources must be consistent with the scope of the mission objectives as well as the projected budget profile available for the development of this mission, which will ultimately lead up to the launch and subsequent operations. Budget assumptions for the Mars Program would dictate whether the full complement of proposed AFL core measurements discussed above would be feasible.

The strawman schedule developed for the AFL ties into the long-range planning efforts of the program outlined in Fig. 1. This AFL schedule is consistent with a plan to provide an update to the Mars Program Plan by the end of calendar year 2008. At that time, it can be expected that sufficient data from MER, MEx, MRO, and Phoenix will be in hand to provide more specific guidance to the mission selection or goals for the 2016 launch opportunity. The developmental stages for a typical NASA mission proceed sequentially from Pre-Phase A through Phase E, where Pre-Phase A is the advanced study or conceptual study phase; Phase A is the mission and systems definition phase; Phase B is the preliminary design phase; Phase C is the detailed design phase; Phase D is the assembly, test, and launch phase; and Phase E is the operations phase of the mission. In the scenario discussed here, the AFL is designated as a compelling mission opportunity based on the data from MER, MEx, MRO, and Phoenix, and begins a Pre-Phase A effort in early 2009. As discussed in the current update to the Mars Program Plan, this is consistent with a school of thought that the selection of AFL investigations need not be dependent on MSL results (Beaty *et al.*, 2006; McCleese, 2006). A redirection of the program away from the current AFL concept would be expected to occur no later than mid-2011, one year after MSL EDL and sufficiently early to redirect development efforts toward a newly defined 2016 objective (*i.e.*, one of the other missions under consideration for 2016/18, such as the Mid-Rover concept). The AFL Pre-Phase A effort would support flight system advanced technology development activities, instrument technology efforts, and project development in support of the Mission Concept Review (a key project review supporting entry into Phase A). These activities would be complete by the end of 2009 and would enable instrument procurement activity to begin during the first part of 2010 (*e.g.*, an AFL Instrument Announcement of Opportunity). This would also kick off a 72-month development cycle (*i.e.*, Phase A–Phase D) for the AFL project. The AFL development schedule for this concept is approximately 1–2 months longer than the MSL development currently underway. The phase durations within this time period are expected to be different than those of the MSL in order to reflect some of the key advantages of having the MSL development as a heritage system and to reflect some of the key differences with respect to the MSL. For example, the candidate instrument selection process defined for this concept would be completed by late 2010. This enables a slightly longer (10%) instrument development activity of 44 months for the potentially more complicated AFL instrumentation (as compared with the MSL), by which time the flight instruments would have to be delivered for the final assembly, test, and sterilization process. To support such a schedule, a mid-level TRL development effort for instrument technologies should be initiated in early to mid-2007, with a technology development effort nearly complete by the time of the kickoff of the instrument selection activity in early 2010.

Spacecraft subsystem and system cleaning and sterilization will be a key challenge for the AFL and its payload. The cleaning and recontamination avoidance procedures for AFL introduce schedule pressure relative to MSL development timelines, as these are new and necessary steps in the assembly, test, and acceptance processes for both instruments and flight systems. As a result, our conceptual design anticipates a relative increase in the duration of Phases C/D (as compared with the MSL) leading up to launch. As the technology efforts for PP and organic contamination control proceed, this will need to be revisited. As part of long-range planning for AFL development, the major milestones for sterilization facility construction must also be considered. A Viking-like sterilization facility would need to be constructed at the launch facility (NASA, 1990). A candidate schedule for the steps leading up to the construction and initial operations capability of such a facility (in this case a dry-heat microbial reduction, or DHMR facility) has been developed as shown in Fig. 13. The initial steps for facility requirements development and early budget planning would begin before 2009.

In this concept, technology development for the AFL would begin in earnest at the beginning of 2010, which would be early enough to achieve TRL-6 maturity at the time of an AFL Preliminary Design Review (or PDR, a key project review supporting entry into Phase C) in late 2012. It may be desirable to consider initiation of some AFL advanced developments even earlier than 2010 to ensure that critical/low TRL/high risk technologies are brought to the required readiness level well before the system PDR. The precision sample handling and processing system (PSHPS) would be an example of technology that fits into that category.

Another key long-lead development effort was discussed earlier. One of the key trades to be conducted for the AFL mission concept will be the evaluation of the power source alternatives for surface operations. This trade is slated to begin early in Phase A and will be completed in time to support System Definition Review (a key project review supporting entry into Phase B) in mid-2011. This plan is also consistent with the development schedule for Nuclear Launch Approval, should the studies show that RPS or other radioactive sources are required in this mission. A candidate Launch Approval Schedule (which considers data and products in support of NEPA and Presidential Directive NSC/25 launch approval processes) has been developed for this concept in consideration of the possibility that such systems may be proposed for the baseline design of the rover.

Science feed-forward

As with any mission that is part of the coordinated MEP, there is a plan for AFL science measurements and results which the Mars Program can build upon and develop follow-up investigations consistent with overall agency objectives. The AFL would impact future missions by:

1. Improving the understanding of Mars biosignature preservation potential by providing:
   a. A thorough understanding of the nature, structure, and concentration of near-surface carbon.
   b. An assessment of the amount of chemical alteration a site has experienced since its formation.
   c. Identification of sites with high preservation potential such as those that contain aqueously deposited chemical sediments.
2. Identifying specific sample types for possible return. The potential for caching high-value samples for targeted sample return is in the mission architecture trade space. This would be an added consideration for a Mars Sample Return (MSR) landing site selection or mission architecture definition.
3. Detecting potential biosignatures. If the AFL identifies potential biosignatures, the development of a mission to characterize extant or extinct life would be the next logical development.
4. Further exploring the martian surface for chemical and mineralogical diversity, including environmental characterization for future human missions.
5. Spurring development of robotic tools for the exploration of life on other bodies (*e.g.*, a Europa or Enceladus Lander). This includes developing sample acquisition, handling, and processing hardware and infrastructure that will lead to better scientific measurements of future missions and sample contamination control and cleaning processes.

6. TECHNOLOGY AND TECHNOLOGY DEVELOPMENT

The required technologies for Mars missions are developed by the Mars Technology Program (MTP), which is an element of the MEP. MTP develops technologies via two subprograms: Base and Focused Technology Programs. The Base Technology Program is an on-going program that funds low-TRL technologies to mature technology concepts to breadboard or early brassboard levels. These technologies are acquired via NASA Research Announcements (NRAs) such as Research Opportunities in Space and Earth Sciences (ROSES). The Focused Technology Program funds and develops technologies for specific missions. This advanced technology development program is designed to raise the TRL of enabling and strongly enhancing technologies to level 6 at the PDR stage of the mission development. For a brief review of all technologies currently in development, see http://marstech.jpl.nasa.gov.

The AFL mission will benefit from many technologies that have been developed and successfully infused into MER and the upcoming MSL missions. In the area of EDL, these include more accurate landing (20 km landing ellipse for the MSL) via guided entry technology and soft landing of ~850 kg rovers on the surface of Mars. Soft-landing technologies include sensor, parachute, and propulsion advanced development efforts. In the area of rover technology, these include autonomous navigation, instrument placement, ground control tools, and power storage devices. The AFL can also benefit from technologies being developed outside of the Mars Program (*e.g.*, the Crew Exploration Vehicle heat shield and materials development).

To meet the challenging AFL-SSG-derived science objectives and remain consistent with the necessary engineering constraints of the observation platform, a number of key technology development activities must take place. At this stage of development, the following items must be considered preliminary and are summarized here to provide insight into some of those challenges. Early identification of potential technology development needs helps to support the next decade MEP planning efforts (*i.e.*, budget and schedule planning). The technology funding profile to support these activities will need to be synchronized with the AFL development and funding schedule if this concept is to be implemented. Also, it should be noted that advanced development plans for certain technologies (*e.g.*, the need for pinpoint landing with a 100-m landing accuracy level, subsurface access to 2 m, or extreme terrain access) may shift in priority as appropriate and as the needs of the mission are better defined and understood. Some of these technologies are included in the discussion below. For this AFL concept, the technology development effort includes

1. Precision Sample Handling and Processing System (mission-enabling technology).
2. Forward Planetary Protection for Life-Detection Mission to a Special Region (mission-enabling technology).
3. Life Detection-Contamination Avoidance (mission-enabling technology).
4. Astrobiology Instrument Development (mission-enabling technology).
5. MSL Parachute Enhancement (possibly mission-enabling technology).
6. Autonomous safe long-distance travel (mission-enhancing technology).
7. Autonomous single-cycle instrument placement (mission-enhancing technology).
8. Pinpoint landing (100–1000 m) (mission-enabling technology if necessary to reach specific science targets in hazardous regions).
9. Mobility for highly sloped terrain $>30°$ (mission-enabling technology if required to reach science targets).

Here we focus our discussion on mission-enabling technologies, while only briefly touching upon those technologies currently considered to fall within the mission-enhancing category for this concept.

Precision sample handling and processing system (PSHPS)

To date, only simple sample acquisition, handling, and processing have been attempted on Mars. Viking had a robotic arm and a simple scoop, MER had an Instrument Deployment Device (IDD) with a Rock Abrasion Tool (RAT) for cleaning off the outer few mm of weathering on surface rocks, Phoenix has a robotic arm with a scoop and a simple Icy Soils Acquisition Device for obtaining samples with tensor strength above $\sim$10 MPa, and the current design for the MSL is configured with an IDD, RAT corer, and a jaw rock-crusher (Peters *et al.*, 2007). The centerpiece of the AFL design would be the most ambitious sample acquisition, handling, and processing hardware flown to date.

MSL's rock corer was designed to acquire a core from rocks, bedrock, and sediments with a 1-cm diameter and a length of up to 5 cm. This core would then be fed into a simple jawrock-crusher that creates fines for analysis by MSL's CheMin XRD/XRF and SAM GC/MS instruments (Hansen *et al.*, 2007). However, it is reasonable to assume that the MSL will have a design that is much different than what was originally baselined in order to maintain overall system mass limitations and cost. This may result in the use of a powdering drill bit on the MSL instead of a corer or crusher. This would not be an option for the AFL. For the AFL to reach its science goals as defined by the 2004 AFL SSG, it is imperative that the AFL have the capability to acquire and analyze a core (Steele *et al.*, 2004). Furthermore, the ability to subsample that core is a priority measurement goal of the mission. The PSHPS on the AFL would allow us to make spatially resolved measurements that were simply not possible on previous missions.

The AFL would acquire an intact core of 5–30 cm in length. Since small-diameter cores tend to fracture rather than be collected intact, we have relaxed the 1-cm diameter requirement on the core and left that as a manufacturer design parameter that would likely be defined only with power and mass as the driving requirements.

Once collected, and after any surface obscuration is removed (*e.g.*, coring dust layer), the core would be analyzed to determine its meso-scale structure by identifying stratigraphy and mineralogical variations along the core axis. This core would then be subsampled within an area of roughly 4 mm^2. That powderized subsample would then be transferred to the analytical instruments for analysis. Depending on this analysis, further samples may be acquired and a chemical/mineralogical map of the core constructed. Once completed, this core is to be ejected and a new one obtained. As of yet, we know of no system that can accomplish these tasks. It is planned that a specific Mars advanced development task will be requested as part of the long lead-time technology necessary to implement the AFL, which could augment any Planetary Instrument Definition and Development Program (PIDDP) or Mars Instrument Development Program (MIDP) tasks that may be funded in the meantime. Other sample processing technologies, such as the acquisition and processing of petrographically important thin sections, have not been considered for this particular concept, though they may be included as the need develops. For an artist's rendition of the PSHPS please see Fig. 14.

Forward planetary protection for life-detection mission to a special region

A fundamental difference between the 2009 MSL mission and the 2016 AFL mission is that the AFL mission would be designed to preserve the option to explore special regions on Mars and make measurements that may search for extant life. To preserve the option to implement a mission of this type, it will be necessary to develop the capability to implement the required PP controls (COSPAR 2005; MEPAG special regions-science, 2006). Should a choice be made to target a special region, implementation of the necessary controls would almost certainly involve sterilization of the landed system and encapsulation of the system in a bioshield until after launch to avoid recontamination by live organisms. To prepare for this scientific option, it would be necessary to conduct any required long lead-time planning and capability development in advance of the pertinent 2016 mission-planning decisions. The long lead-time items include technologies associated with pre-launch system cleaning and sterilization; flight qualification of parts, materials, and processes; and design of facilities to accomplish the required planetary protection controls prior to launch.

To achieve maximum mission flexibility (*i.e.*, to target a special region and perform extant life-detection measurements), AFL mission engineering is currently planned assuming both Planetary Protection Category IVb and IVc requirements. Because the mission may target a special region, the entire spacecraft (rover, payload, descent stage, aeroshell, and probably the cruise stage) would need to satisfy requirements for total bioburden reduction comparable to those of the Viking lander missions. This implies that spacecraft design would include a biobarrier that would envelope the aeroshell and permit system-level terminal sterilization using heat (*i.e.*, >110°C). Full PP implementation planning for the AFL would include many of the following:

- development and qualification of a system-level DHMR facility at Kennedy Space Center.
- development and qualification of bioshield.
- system design changes to accommodate bioshield (*i.e.*, thermal, propulsion, separations).
- identification of hardware elements incompatible with or sensitive to DHMR.
- definition and qualification of DHMR-compatible parts, materials, and practices.
- qualification of sensitive, high-risk instruments at card/assembly level.
- qualification of sensitive, high-risk engineering subsystems and sensors at card/assembly level.
- design, development, and qualification of a sterile fueling and de-fueling operation.

This latter process must consider the possibility that the AFL will require an RPS with the associated handling and safety considerations. All of these tasks inherently imply a possible departure of the AFL system from MSL heritage.

Contamination avoidance in support of organics or life detection

For AFL contamination control, it will be crucial that potential sources of prelaunch contamination on the landed spacecraft be identified and excluded. This includes organic material that remains on the spacecraft after sterilization, as the measurements to be made by the AFL can be corrupted if those remnants of the sterilization process (*e.g.*, spores, terrestrial organics) produce false positives. This would entail that the critical path of contamination (*i.e.*, the path the sample takes to the instrument) be cleaned of organic material to a level below the detection limit of all instruments before mission launch.

Measurements that the AFL would make must include appropriate methods to identify and exclude contamination as a source of any potentially positive detection. To identify potential contaminants, instruments may be required to produce procedural blanks that allow potential contaminates to be identified and characterized. This blank analysis would be undertaken upon the beginning of AFL surface operations and follow the sample acquisition, handling, and processing path to the instruments themselves. In the event of a positive detection, the procedural blanks may be used before a confirming second analysis to ensure a blank measurement. Additionally, cross-sample contamination caused as multiple samples are acquired and processed by the system must be held at a level consistent with the sensitivity of the selected instruments. It is anticipated that organic contamination issues for the AFL will exceed those addressed by the current 2009 MSL mission development effort (Mahaffy *et al.*, 2004).

Astrobiology instrument development

The 2004 AFL SSG (Steele *et al.*, 2004) highlighted examples of development shortcomings in critical areas of science instrument development. To meet the objectives as described in the 2004 AFL SSG report, there must be a focused effort to fund science instruments for the AFL mission concept. New instrumentation techniques as well as methods to integrate techniques are desired and encouraged to meet the objectives of the AFL as currently conceived. This necessitates a well-funded, well-advanced instrument development and integration program. It is expected that, in addition to MIDP (which is an element of the Mars technology program), other programs such as the Astrobiology Science and Technology Instrument Development (ASTID) and the Astrobiology Science and Technology for Exploring Planets (ASTEP) programs will step in to meet these long-term needs. Funding for this AFL instrument development effort, regardless of the form, must be sufficiently early to enable a timely attainment of TRL-6 (*i.e.*, in time to support system PDR) that is consistent with the AFL development schedule. To meet a late 2015 / early 2016 launch date, as discussed earlier, the proposed AFL instrument PDRs must be in the 2012 time frame. In addition, these instruments must be at a TRL sufficient to enable a competitive risk management assessment by the NASA selection authority during the instrument selection process (this date is unknown, but it could be justified planning for this to occur as early as fall 2010).

MSL parachute enhancement

As discussed above, the increased mass of the AFL concept payload and flight systems would require additional landed mass capabilities beyond those provided by the MSL heritage system. Our current understanding of the science measurement objectives and technologies drives this augmentation in capability. This parachute-enhancement technology item is an enabling capability with the objective to increase the landed payload mass by increasing the parachute diameter and parachute deployment Mach number above that necessary for the MSL. The current expectation is that parachute performance increases for the AFL are developed and validated through analysis and actual MSL performance results only (*i.e.*, only a limited parachute re-qualification program is assumed necessary).

AFL technology parking lot

As indicated above, the AFL concept is subject to modification as the science objectives, high-level requirements, and budget for the mission are defined in the coming years. As the character of the mission changes, the expectation is that new technology thrusts will be identified to meet the changed mission objectives. Some enhancing technologies that fit into this category have been identified for the AFL and are relegated to the technology parking lot (*i.e.*, are not being integrated into this particular concept or are not funded in our concept cost estimates) until a specific need and direction are identified. For the current AFL concept, the technology parking lot includes these technologies:

- Larger-diameter (*e.g.*, >23 m) Supersonic Parachute: This is a high-leverage option that will significantly improve payload mass beyond that of the MSL (currently baselining a 19.7 m diameter chute) and counter the adverse effects of dust loading in the atmosphere associated with the 2016/2018 launch opportunities. Other technologies, such as inflatable aerodynamic braking devices, can also be considered for this application. Based on internal analyses and trades, as well as a current understanding of MSL parachute development and extensibility, this full development and qualification effort for a large-diameter parachute has been put on a lower priority at this time. It is expected that a modest diameter and capability enhancement beyond that of the MSL can be implemented, following a successful MSL landing, through analysis and simulation. As MSL development proceeds and information is updated, this technology prioritization assessment will be revisited.

- We could not identify technology currently available at (or near) TRL-6 to support acquisition of >10 cm cores on the robotic arm. The AFL SSG called for acquiring 10–30 cm cores. While it currently is unlikely that the MSL is going to acquire a core, this AFL concept requires a core delivered to the PSHPS. Development of a corer would be a high priority in future technology developments. The MTP Base Technology Program has been, and will continue, funding technologies to access the subsurface, including coring required for the AFL.
- The Mars 2007 Phoenix mission is flying a tool that could be developed into a simple rock-, permafrost-, or ice-sampling system, referred to as a RASP or Rapid Active Sampling Package (Peters *et al.*, 2007). Our concept has not yet identified the RASP as an enabling technology that is required to support the measurement objectives. However, since a properly developed RASP could do precision sampling for the AFL PSHPS, RASP, or similar technology development for the AFL should continue to help reduce overall mission risk. This technology enhancement can be developed by the MTP Base Technology Program.
- The recently discovered gully regions on Mars may be key areas of interest for AFL exploration. As an example, MSL landing site discussions indicate that gullies are located at middle and polar latitudes and may be key sites for water and habitability science and exploration (Dietrich *et al.*, 2006; Grant and Golombek, 2006). The MSL will not visit these sites because of planetary protection and terrain access issues. Future AFL science analysis groups, or science steering groups, may recommend that these new features be key targets for AFL exploration. Although no specific terrain models have been identified for many of these specific areas of possible AFL interest, it is expected that an MSL heritage system will have difficulty accessing either the source or the deposits identified from orbit (landing accuracy issues and post-landing accessibility issues). Terrain characterization and extreme terrain access technologies may need to be pursued to enable this specific mission option (see also pinpoint landing discussion below). The technologies to access extreme terrain are planned to be addressed by the MTP Base Technology program.
- The Mars Program is nurturing a capability to enable a pinpoint landing technology development with the objective of achieving 100 m landing accuracy error (99% probability). This capability provides for landing at scientifically interesting targets unreachable with MSL-heritage landing accuracy or through rover mobility systems (Wolf *et al.*, 2006). Assuring a hazard-free landing area as determined through pre-arrival site reconnaissance and landing accuracy analyses will determine the need for this technology for AFL applications. The development of this capability also provides feed-forward technology for a static AFL lander option that must land near specified targets, such as deep-drill lander sites, or for missions retrieving samples previously cached by an earlier mission. The SSG-derived concept and mission objectives for the AFL have not identified a driving requirement for pinpoint landing. Pinpoint landing requirements also introduce flight system design and mass changes that include the addition of an optical navigation sensor for precision Mars approach navigation (and a consequent design change from a spinning to a 3-axis stabilized cruise stage) and larger EDL propellant tanks for removing and countering residual and environmental landing accuracy error sources, following the jettison of the descent parachute.
- Site certification and science objectives will dictate whether an investment in budget and, ultimately, of spacecraft resources to enable Hazard Detection and Avoidance for the AFL is necessary. There are ongoing efforts within other NASA programs that are pursuing this technology (see for example Epp and Smith, 2007) for earlier missions. There is a strong con-

nection between pinpoint landing and landing safety.

- As more and more is learned as to how to operate rover systems on Mars, more types of autonomy are possible. The MER have been driving autonomously using GESTALT, (Maimone *et al.*, 2006) a stereo hazard avoidance program that allows for the evasion of steep slopes and rocks. As MSL operation software is developed, it is hoped that recent developments in single-cycle arm placement and potential autonomous science investigations will be at a heritage level so as to increase the scientific output of the AFL (Pedersen *et al.*, 2006; Castano *et al.*, 2007; Estlin *et al.*, 2007).

7. TRADES

As with any mission in Pre-Phase-A development, there are multiple trade options that are continually being studied and can change the mission concept. These options, while originally outside the base mission concept, augment the mission's return and allow for greater return on investment. Some of the trades we have planned or studied include the utilization of a 2 m drill that would reduce the instrument payload, solar versus nuclear power generation, and the possibility of caching samples for future analysis or sample return. The augmentation that these concepts provide increases mission potential if more resources become available.

Drilling

The need for subsurface access is apparent given current martian surface conditions. These conditions may result in a sterile layer that exists down to a depth greater than 1 m (Kanavarioti and Mancinelli, 1990). To get under that potential sterile layer, a 2 meter drill design is currently being studied. An advantage to this drill is its ability to collect samples at 25 cm intervals, which will provide an opportunity to produce a map of the subsurface chemistry, measure the depth of the oxidizing layer, and determine the extent of destruction due to galactic cosmic rays (Kanavarioti and Mancinelli, 1990; Kminek and Bada, 2006; Dartnell *et al.*, 2007). As with any trade, the inclusion of the drill would come at the monetary and mass expense available for other payload elements. While the payload monetary costs are something that can be estimated, the cost to other payload elements is something that needs future discussion. The inclusion of a drill presents a packaging problem with the current rocker-bogie type rover system. The only attachment point for a drill may be where the fully instrumented IDD with corer is currently located, away from the current mast location (Fig. 15). Hence, the payload cost of the drill may be the exclusion of an instrumented robotic arm (IDD) that can thoroughly investigate surface features. Therefore, before a drill can be included in the payload, a scientific debate will have to take place to decide which acquisition apparatus maximizes the science return for the AFL. Other locations where the drill could be included are near the "back" of the rover, near a potential RPS. In this scenario, it is unclear how sample transfer would take place and if there would be any sample alteration due to the location of a potential RPS.

Sample caching

The possibility that the AFL will make a major discovery related to Mars habitability and potential biosignatures may require a follow-on mission to confirm or validate results from the AFL mission. One way to accomplish this would be to cache samples that have been analyzed by the AFL payload, retrieve them in a future MSR mission, and bring them back to Earth for analysis in state-of-the-art laboratories. This scenario greatly reduces the potential cost of MSR because the MSR rover would be less complex than a rover that would be required to perform complex sample acquisition and initial analysis to maximize the probability of returning the highest-priority sample (Mattingly *et al.*, 2004). Individual sample containers would have to be sealed to prevent cross-sample contamination and degradation of samples as a result of exposure to the martian surface environment. These containers could either be dropped on the martian surface or stored on the rover for later retrieval. Designs for the caching concept have been developed, but a working system needs to be developed and demonstrated (Backes and Collins, 2007). MSL is currently considering a design for a sample caching system for inclusion in the 2009 mission.

Solar power versus nuclear power

Our preliminary designs made the assumption that the conditions that resulted in the MSL being designed as a RPS-powered rover may also exist for the AFL. As a proof of concept, instrument power profiles for AFL were determined to fit with the MSL RPS capability envelope. As the science and technology objectives and engineering constraints for the AFL concept are further defined, there will necessarily be a rigorous trade analysis for the power system.

8. COSTS

The MEP encompasses all NASA Mars robotic mission activities and data analyses with regard to understanding Mars and its evolution, and directly supports NASA's Vision for Space Exploration. As described in the Mars Exploration Program Plan (Beaty *et al*., 2006; McCleese, 2006), it is a science-driven, technology-enabled effort to characterize and understand Mars. The AFL mission is a concept that meets strategic objectives of NASA and MEP, and a key part of an integrated set of missions that are mutually supporting and working toward the program's scientific goals. The AFL concept described here is a facility-class mission and is not merely a re-flight of the MSL. At a minimum, this mission concept as defined here carries a more sophisticated and astrobiology-focused science payload, a more complex sample acquisition and processing payload, a more challenging EDL environment, and a much more challenging organic contamination and PP protocol than that of the MSL (one that is currently assumed to include full system DHMR, similar to that performed by Viking). However, this AFL concept is also leveraging a tremendous amount of flight system development heritage from the MSL that offers significant development savings over a non-heritage system concept. The net effect is that this facility-class mission tends toward a cost expectation consistent with an MSL-class development effort ($1–2 billion range). This is a key consideration in planning the relative timing of missions in the 2016/2018 timeframe, as illustrated in Fig. 1.

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ABBREVIATIONS

AFL	Astrobiology Field Laboratory
AO	Announcement of Opportunity
ARR	ATLO Readiness Review
ASTEP	Astrobiology Science and Technology for Exploring Planets
ASTID	Astrobiology Science and Technology Instrument Development
ATLO	Assembly, Test, Launch, Operations
C3	Launch Energy (Earth departure V-infinity, squared)
CBE	Current Best Estimate
CDR	Critical Design Review
CheMin	Chemistry and Mineralogy (MSL Instrument)
COSPAR	Committee on Space Research
CY	Calendar Year
DAP	Declination Arrival Asymptote
DHMR	Dry Heat Microbial Reduction (system level sterilization technique)
DLA	Declination of the Launch Asymptote (Earth departure hyperbola)
EDL	Entry, Descent and Landing
EIS	Environmental Impact Statement
EM	Engineering Model

FM	Flight Model
GC/MS	Gas Chromatograph/Mass Spectrometer
GESTALT	Grid-based Estimation of Surface Traversability Applied to Local Terrain (rover navigation software)
IDD	Instrument Deployment Device
JPL	Jet Propulsion Laboratory
Ls	Areocentric Longitude of the Sun
MCR	Mission Concept Review
MEP	Mars Exploration Program (NASA)
MEPAG	Mars Exploration Program Analysis Group
MER	Mars Exploration Rovers (Spirit and Opportunity)
MEx	Mars Express (European Space Agency)
MGS	Mars Global Surveyor (non-operational)
MIDP	Mars Instrument Development Program (NASA, MTP)
MOLA	Mars Orbiter Laser Altimeter (MGS instrument)
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
MSO	Mars Science Orbiter (2013 Launch)
MSR	Mars Sample Return
MTP	Mars Technology Program (NASA)
NASA	National Aeronautics and Space Administration
NEPA	National Environmental Policy Act
NRA	NASA Research Announcement
ODY	Mars Odyssey
PBE	Predicted Best Estimate (includes growth uncertainty)
PIDDP	Planetary Instrument Definition and Development Program
PDR	Preliminary Design Review
PMSR	Preliminary Mission And System Review
PP	Planetary Protection
PSHPS	Precision Sample Handling and Processing System
PSR	Pre-Ship Review
RASP	Rapid Active Sampling Package
RAT	Rock Abrasion Tool
RLA	Right Ascension Launch Asymptote (Earth departure hyperbola)
ROD	Record of Decision (NEPA process)
ROSES	Research Opportunities in Space and Earth Sciences (NASA)
RPS	Radioisotope Power System
SAM	Sample Analysis at Mars (MSL instrument)
SAR	Safety Analysis Report
SSG	Science Steering Group
TRL	Technology Readiness Level (Levels 1–9 represent a qualitative assessment of technology readiness for spaceflight. For example, TRL-6 indicates that the system validation model has been successfully demonstrated in a relevant environment)
VHP	Arrival V-Infinity (hyperbolic excess velocity)
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

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Address reprint requests to:
Luther Beegle
Jet Propulsion Laboratory
4800 Oak Grove Drive
MS 183-601
Pasadena, CA 91109

E-mail: Luther.Beegle@jpl.nasa.gov