Decision Package #1:

Conjunction Class Missions (Long Surface Stays)
vs.
Opposition Class Missions (Short Surface Stays)

July 23, 2007

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Topic Outline

- **Problem Statement**
  - **Mission Planning Fundamentals**
  - **Trajectory Implications**
  - **Mission Planning Considerations**
- **Typical Short-Stay Mission Overview**
- **Typical Long-Stay Mission Overview**
- **Special Considerations**
  - **Goals and Objectives**
  - **Human Health and Performance**
  - **Flight and Surface Systems**
- **Figures of Merit Assessments**
  - **Performance**
  - **Risk**
  - **Cost**
- **Recommendation**

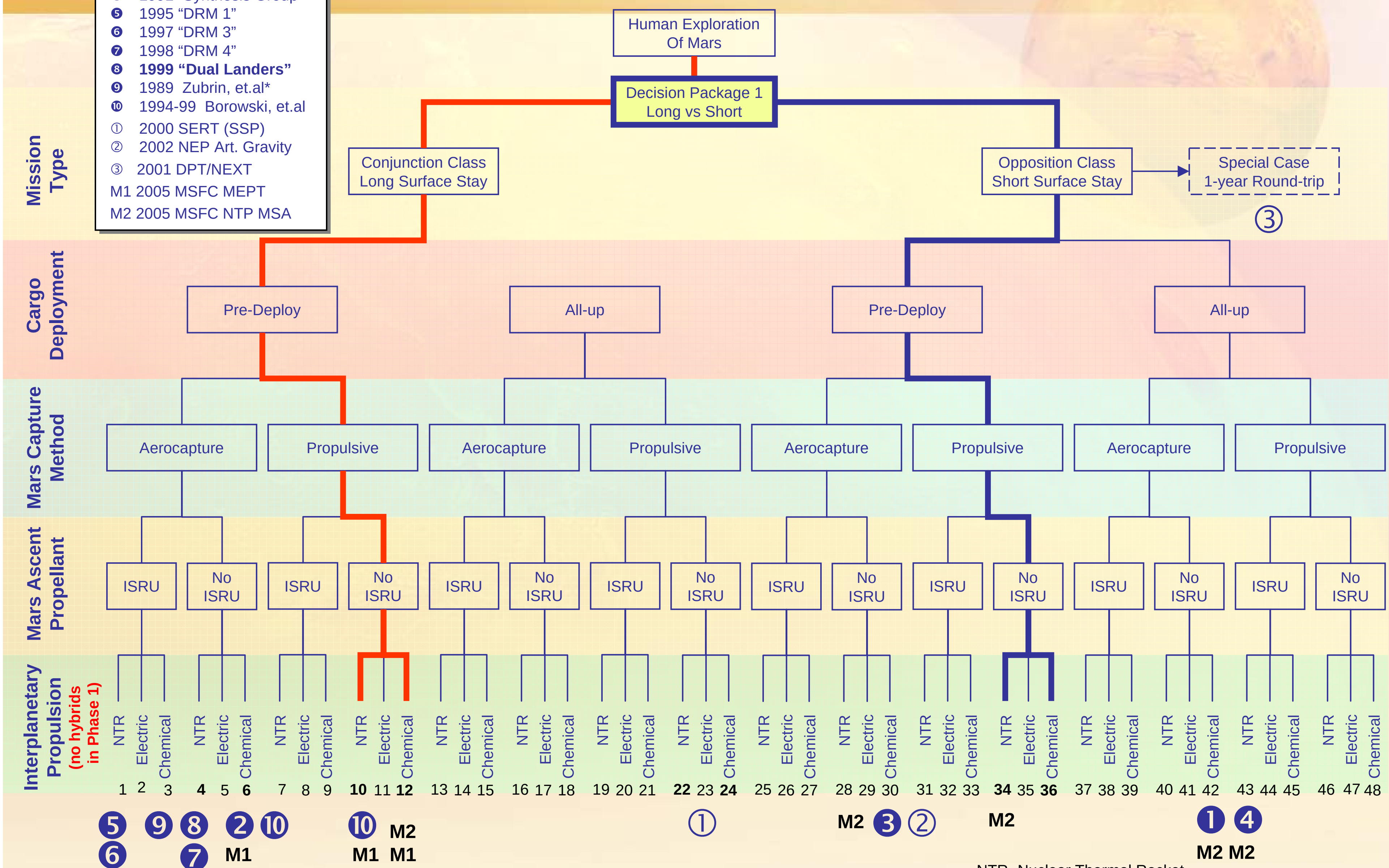
Top-level Trade Tree

- This is the first of three decision packages that addresses the two primary mission types for human exploration of Mars: Long surface stays versus short surface stays. Human missions to Mars are classified into these two primary approaches as governed by orbital mechanics which are described in this package. The attributes of each mission approach, along with the key characteristics and distinguishing features are provided.

- The branches of the trade tree considered in this trade are those numbered 10, 12, 34, and 36 in the trade tree. These branches were chosen because experience has shown that the cases chosen represent typical approaches and the trends will be similar for the other branches of the trade tree.

Top-level Trade Tree

❶ 1988 “Mars Expedition”
❷ 1989 “Mars Evolution”
❸ 1990 “90-Day Study”
❹ 1991 “Synthesis Group”
❺ 1995 “DRM 1”
❻ 1997 “DRM 3”
❼ 1998 “DRM 4”
❽ 1999 “Dual Landers”
❾ 1989 Zubrin, et.al*
❿ 1994-99 Borowski, et.al
① 2000 SERT (SSP)
② 2002 NEP Art. Gravity
③ 2001 DPT/NEXT
M1 2005 MSFC MEPT
M2 2005 MSFC NTP MSA



NTR- Nuclear Thermal Rocket
Electric= Solar or Nuclear Electric Propulsion

Key Findings

- **Recommendation**

  Based on the analysis and deliberations conducted to date, the team has concluded that the best mission approach are the Conjunction Class missions which provide the opportunity for long surface stays on Mars. These factors will be discussed further in this package, but are provided as a summary here.

- **Provides greater mission return**

  Conjunction class missions enable long stays at Mars which provide the opportunity to maximize mission return. Given that the objective is to explore the surface of Mars, providing the crew with the time and tools necessary to explore the surface at Mars at ever greater distances from the landing site is essential. The long-stay missions provide one to two orders of magnitude greater mission return in terms of expected crew-time on the surface. The value of return is also enhanced by the ability to explore at great distances, to greater depth, and with time to collaborate with scientists back on Earth.

- **Provides greater mission flexibility**

  Conjunction class missions enhance mission flexibility by providing for the necessary operational tasks that must be conducted such as vehicle checkout, orbital phasing, plane changes, etc. In addition, the long-stay at Mars provides ample time to account for environmental anomalies such as dust storms. Lastly, providing time for the crew to acclimate to the gravity conditions on Mars after an extended zero-gravity transit is necessary, and thus enhanced by the long stay feature of conjunction missions.

- **Enables transits which are within experience base**

  Transit times to and from Mars are on the order of 180-210 days which is within human mission experience base

- **Requires similar/lower total initial mass**

  Total mission mass for the long stay missions are similar or lower than the short stay missions..

- **Enables equal and consistent transportation vehicles**

- Since the propulsive energy required varies less, it is much easier to design vehicles to operate during each mission opportunity. In addition, the transportation vehicles are very similar for both cargo and crew missions, unlike the short stay variants.

- **Provides better crew safety**

  The overall probability of loss of crew is lower for the long stay missions as compared to the short stay missions even when accounting for the reliability aspects of the longer total mission duration.

Key Findings

- **The Long Stay mission is the preferred approach:**
  - Provides greater mission return (order of magnitude)
  - Provides greater mission flexibility
  - Enables transits which are within experience base
  - Requires similar/lower total initial mass
  - Enables equal and consistent transportation vehicles
  - Provide better crew safety

  While accounting for:
  - Slightly greater cost for additional systems, and
  - Slightly greater mission risk due to longer system operational time

Mars Trajectory Classes

- **Earth-Mars Mission Planning**

  Round-trip missions to Mars and back are, in effect, a double rendezvous problem. The outbound trajectory must be established while considering the position of Earth at the end of the mission. Upon arrival at Mars the Earth is in a relatively unfavorable alignment (phase angle) for an energy efficient return. This unfavorable alignment results in two distinct classes of round-trip Mars missions: Opposition class missions, which are also commonly referred to as short-stay missions, and Conjunction class missions, referred to as long-stay missions. Practical considerations, such as total propulsive requirements, mission duration, surface objectives, and human health considerations must be considered in the mission design process when choosing between these mission classes.. The period of time necessary for the phase angle between Earth and Mars to repeat itself varies. This variation is referred to as the Synodic Cycle. The Synodic Cycle, or mission repetition rate for identical Earth-Mars phasing, and therefore launch opportunities for similar mission classes, is on the order of every 26 months. The mission characteristics such as mission duration, trip times, and propulsive requirements vary to due to the eccentricity of Mars' orbit.

- **Opposition Class: Short-Stay Missions**

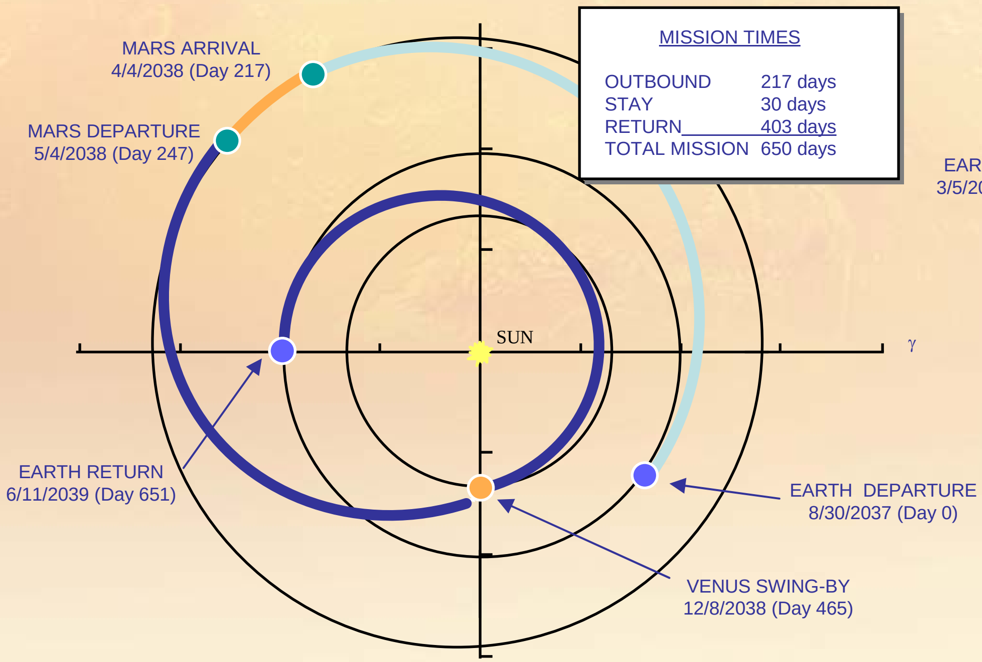
  Short-stay missions consists of short stay-times (typically 30 sols) and round-trip mission times ranging from 550-660 days. This is often referred to as an opposition-class mission, although the exploration community has adopted the more descriptive terminology "short-stay" mission. Trajectory profiles for typical short-stay missions are shown. This class of mission has high propulsive requirements. Short-stay missions always have one short transit leg, either outbound or inbound, and one long transit leg, the latter requiring close passage by the sun (0.7 AU or less). After arrival at Mars, rather than waiting for a near-optimum return alignment, the spacecraft initiates the return after a brief stay and the return leg cuts well inside the orbit of the Earth to make up for the "negative" alignment of the planets that existed at Mars departure. Distinguishing characteristics of the short-stay mission are: 1) short-stay at Mars, 2) medium total mission duration, 3) perihelion passage inside the orbit of Venus on either the outbound or inbound legs, and 4) large total energy (propulsion) requirements.

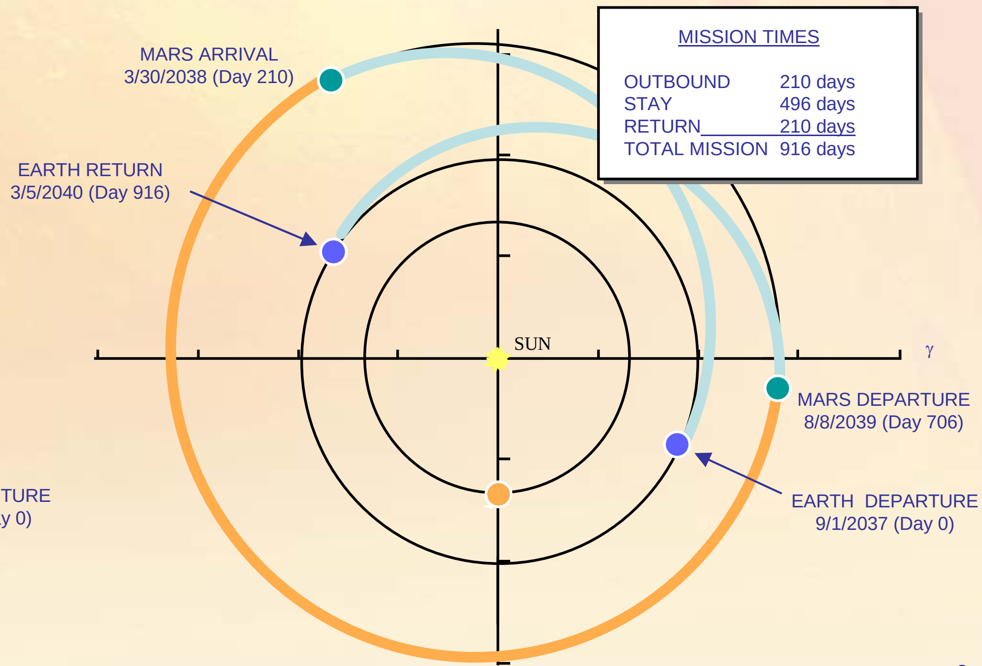
- **Conjunction Class: Long Stay Missions**

  The second Mars mission class is typified by long-duration stay-times (as much as 550 sols) and long total round-trip times (approximately 900 days). This mission type is often referred to as conjunction-class, although the exploration community has adopted the more descriptive terminology "long-stay" mission. These missions represent the global minimum-energy solutions for a given launch opportunity. Unlike the short-stay mission approach, instead of departing Mars on a non-optimal return trajectory, time is spent at Mars waiting for more optimal alignment for lower energy return. Distinguishing characteristics of the long-stay mission include: 1) long total mission durations, 2) long-stays at Mars, 3) relatively little energy change between opportunities, 4) bounding of both transfer arcs by the orbits of Earth and Mars (closest perihelion passage of 1 AU), and 5) relatively short transits to and from Mars (less than 200 days).

Mars Trajectory Classes

- **Short-Stay Missions**
  - Variations of missions with short Mars surface stays and may include Venus swing-by
  - Often referred to as Opposition Class missions
- **Long-Stay Missions**
  - Variations about the minimum energy mission
  - Often referred to as Conjunction Class missions





Close Perihelion Passage

- **Opposition Class Missions (Short-stay):**

  For opposition class missions, mission timing can be generally be set up to utilize Venus, during the outbound transit, inbound transit, and sometimes both, to help shape the trajectory necessary for this class of mission. The Venus swing-by has the same result as a “free” deep-space maneuver and is thus more propulsively efficient. This requires that the mission sequence, timing, and relative phase angles between Earth and Mars be in specific relative geometry.

  As can be seen from the plots the trajectories associated with the opposition class missions, irrespective of the use of a Venus swing-by, require passage within the orbit of Venus. A representative (2037) opposition class mission is shown in the trajectory plot. In addition, as can be in the plots, the closest approach to the sun varies by mission opportunity and surface stay. For example, the 2037 Venus swing-by mission passes within 0.49 AU of the Sun spending 108 days within 0.8 AU.

- **Special Considerations of Close Perihelion Passage**

  Passing within 1 AU of the Sun poses some significant mission, vehicle design and human health issues which must be adequately considered in the overall context of the mission approach.

  Radiation Shielding: Additional shielding mass is required to protect from solar flares during solar maximum. Since the strength of the radiation dose is inversely proportional to the square of the distance, close perihelion passage can have a profound affect on the radiation shielding (solar storm) and radiation dosage to the crew.

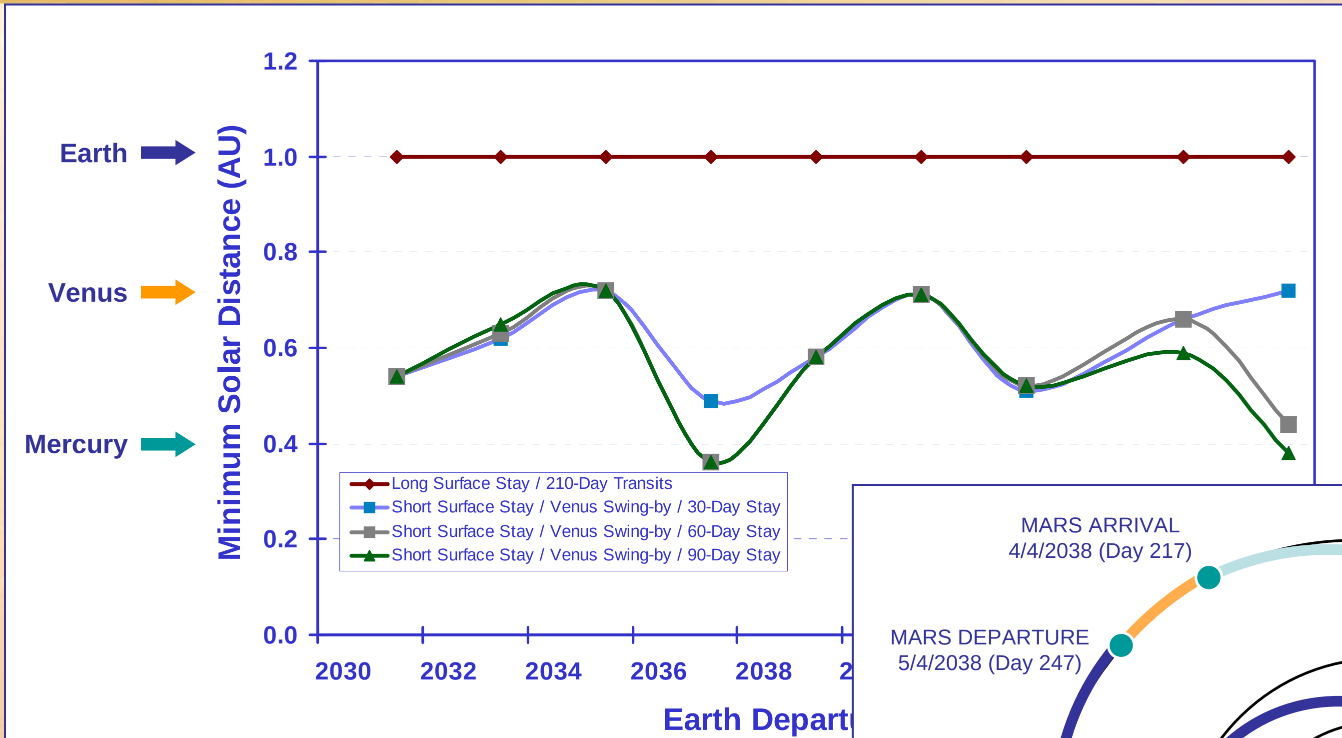
  Thermal Control: Thermal control will be needed for both the long and short stay missions, but the heat load to the vehicle will increase with decreasing perihelion passage. Deployable sun shades are probably required for the short-stay missions to shadow critical vehicle components and areas. In addition, deployable radiators and additional active cooling loops may be required

  Vehicle Orientation: Due to the increased thermal and solar influence, vehicle systems including solar arrays and sunshades must be positioned relative to the sun with tighter control in order to prevent overheating.

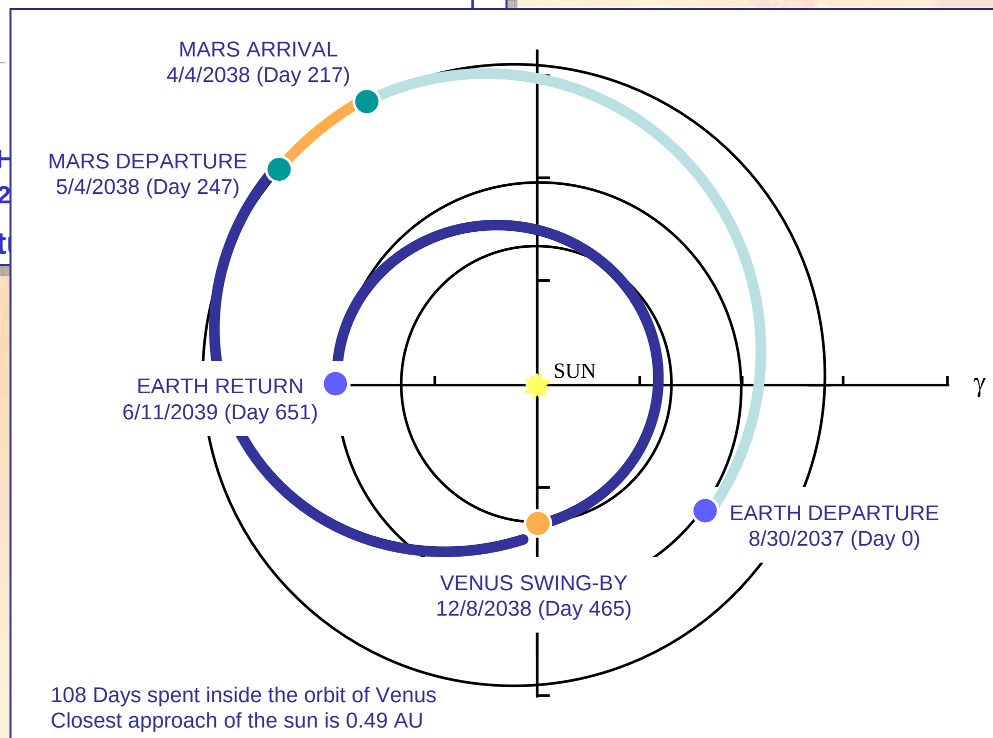
- **Conjunction Class Missions (Long-stay):**

  Since conjunction class missions rely on favorable phasing between Earth and Mars, the trajectory does not require close perihelion passage and thus the vehicles remain at distances greater than 1 AU throughout the mission.

Close Perihelion Passage



Perihelion Passage



Typical Opposition Class Mission Profile

Total Interplanetary Propulsion Requirements

- **Opposition Class Missions (Short-stay): Total Interplanetary Propulsive Requirements**

  The variability of total interplanetary propulsive delta-v across the synodic cycle for opposition class missions are provided in the left graph. Opposition class missions require greater total propulsive delta-v in addition to resulting in significant variation of propulsion requirements across synodic cycle. As can be seen from the left graph, the variation of delta-v across the synodic cycle is nearly 100% with an average total delta-v of 10 km/s $\pm$ 3.7 km/s. This variability significantly impacts the space vehicles since they must be designed to provide the propellant capability and design attributes which allow for a wide range of propellant loads or the capability to delivery a wide range of payloads to Mars.

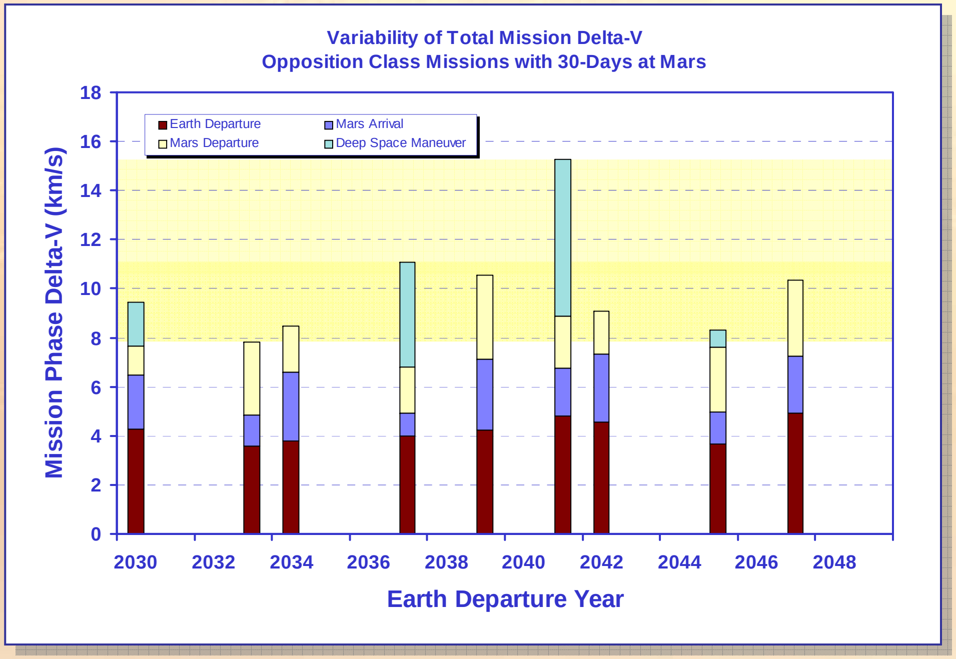
  One can also see that there are some mission cases where the total interplanetary delta-v is so excessive that they are outliers and thus usually eliminated from consideration. This is clearly evident in the 2041 mission opportunity which is twice the magnitude of the best 2033 opportunity. Skipping mission opportunities results in a minimum of 26 month “stand down” before resuming the normal mission sequence.

- **Conjunction Class Missions (Long-stay): Total Interplanetary Propulsive Requirements**

  The variability of total interplanetary propulsive delta-v across the synodic cycle for conjunction class missions are provided in the right graph. As can be seen in this graph the total, as well as the the variation from opportunity to opportunity is fairly small, on the order of 35% while also providing for overall lower delta-v - the average total delta-v was approximately 7 km/s $\pm$ 1 km/s. This small variation of propulsive requirement across the synodic cycle allows the use of a common vehicle and payload design for each opportunity. This common strategy also allows the vehicle systems to be flown in any opportunity reducing the potential of either skipping harder years, as in the case of opposition class missions, or allowing systems to be flown at a later date if necessary due to technical or schedule difficulties.

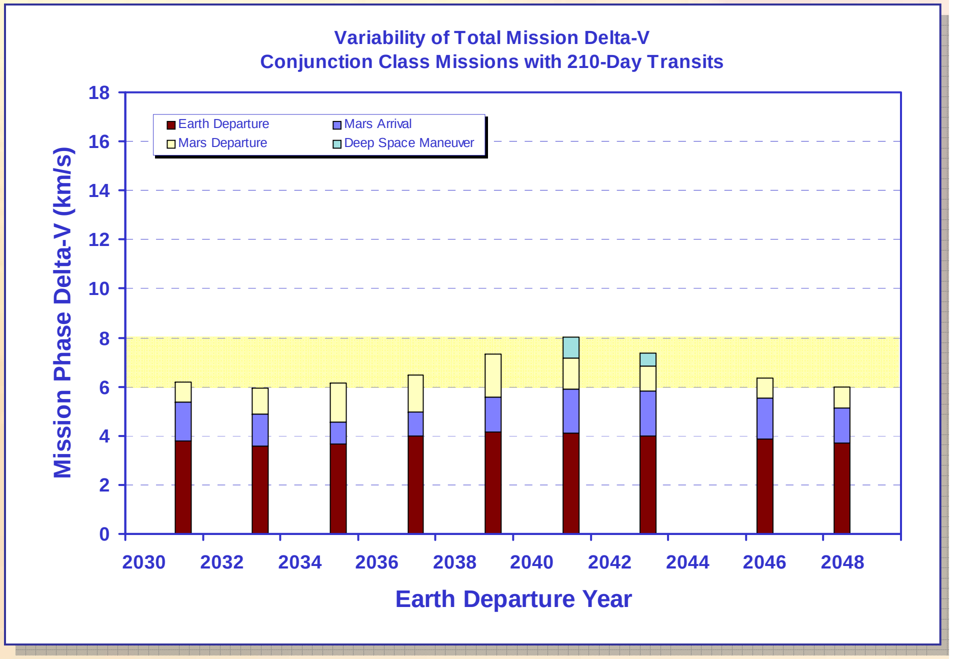
Total Interplanetary Propulsion Requirements

Opposition Class Missions (Short-Stay) Propulsive Delta-V



Note: Optimized trajectories assuming 407 km circular LEO departure orbit, propulsive capture at Mars into a Mars 1-Sol orbit of 250 km x 33,793 km. 30 sols stat at Mars. Direct entry at Earth with an entry speed limit of 13 km/s.

Conjunction Class Mission (Long-Stay) Propulsive Delta-V



Note: Optimized trajectories assuming 407 km circular LEO departure orbit, propulsive capture at Mars into a Mars 1-Sol orbit of 250 km x 33,793 km. 210 day transits to and from Mars. Direct entry at Earth with an entry speed limit of 13 km/s.

Trajectory Sensitivity

- **Opposition Class Missions: Sensitivity to the Length of Stay**

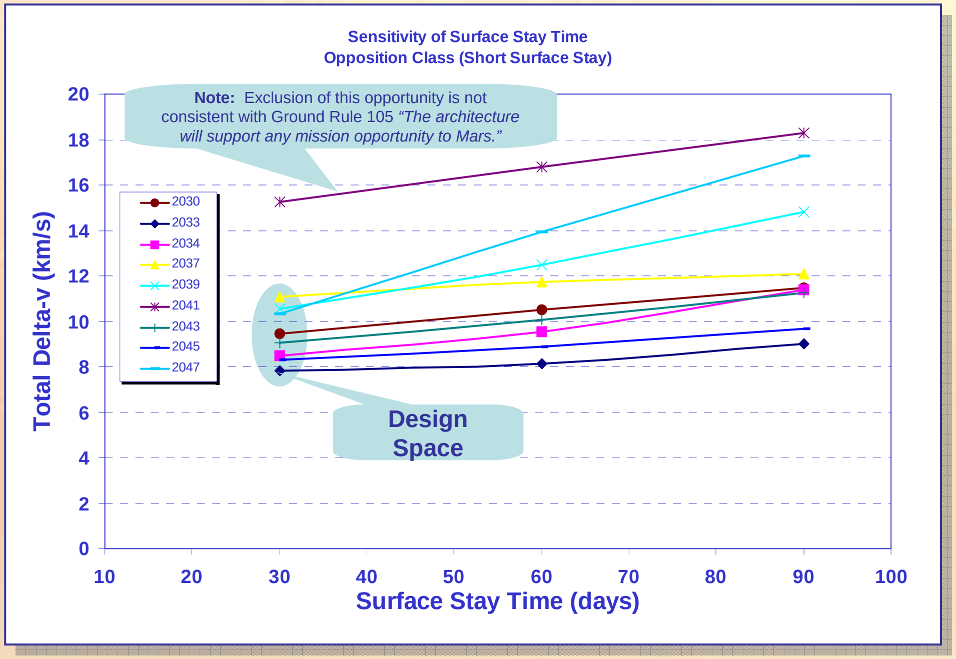
  The sensitivity of the total interplanetary propulsion requirements as a function of time spent in the vicinity of Mars for opposition class missions is shown. As can be seen from this figure, the time spent in the vicinity of Mars has a profound affect on the total inter-planetary delta-v. This increased delta-v translates directly to more initial mass in low-Earth orbit. One can also see that the sensitivity to stay time varies by mission opportunity ranging from a 15% variance in 2033 to 67% in 2047. Thus, in order to minimize the overall mission mass for opposition class missions, emphasis is placed on minimizing the amount of time spent at Mars which is counter productive from a mission strategy point of view – reducing the time at Mars limits the mission objectives and goals that can be achieved. It should be noted that a vehicle designed for a 30 sol stay for a relatively hard opportunity, such as 2037, the same vehicle can extend the surface stay to 90 sols for the easier opportunities, such as 2033. Extending the stay time beyond 90 sols becomes prohibitively expensive from a delta-v and mission mass perspective.

- **Conjunction Class Missions: Sensitivity to Transit Times**

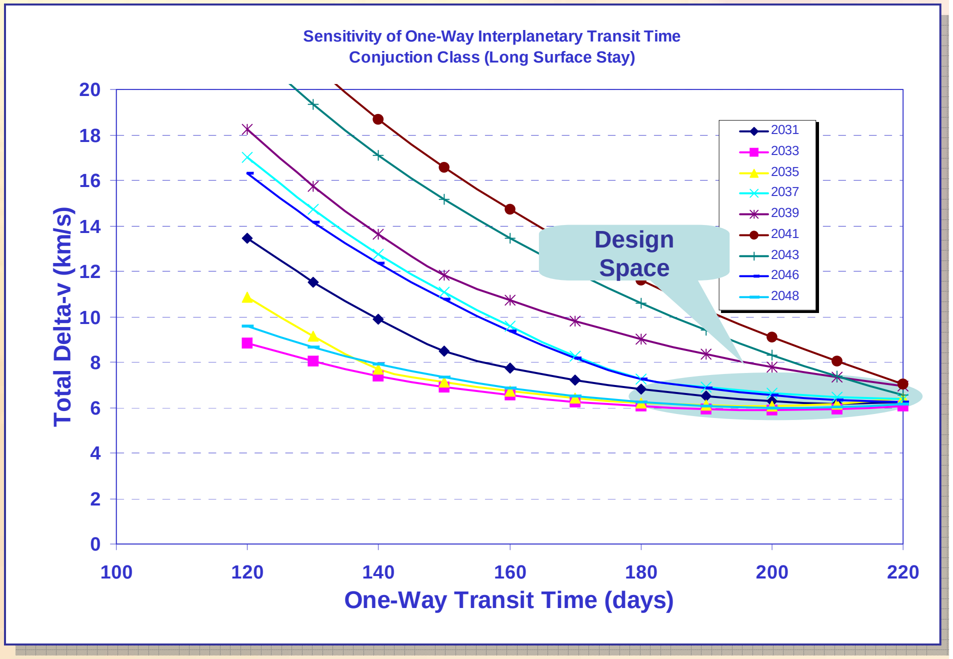
  The sensitivity of total propulsive delta-v to the transit times to and from Mars for conjunction class missions are provided in the right graph. Minimum energy transfers occur with trip times in excess of 200 days where the savings of total delta-v to increased trip times are decreased. Since it is important from a human health and performance perspective to reduce the transit times to the greatest extent possible one can see that reductions in the total trip time begin to be come excessive with times less that 200 days and in some opportunities on the order of 180 days. The design team has chosen to establish the total delta-v capability of the interplanetary transportation system across all opportunities and then use that common system to shorten the trip times to the greatest extent possible.

Trajectory Sensitivity

Opposition Class Missions (Short-Stay) Sensitivity to Stay Time



Conjunction Class Mission (Long-Stay) Sensitivity to Transit Time



Mission Duration

- **Short-Stay Mission: Total Mission Duration Variability**

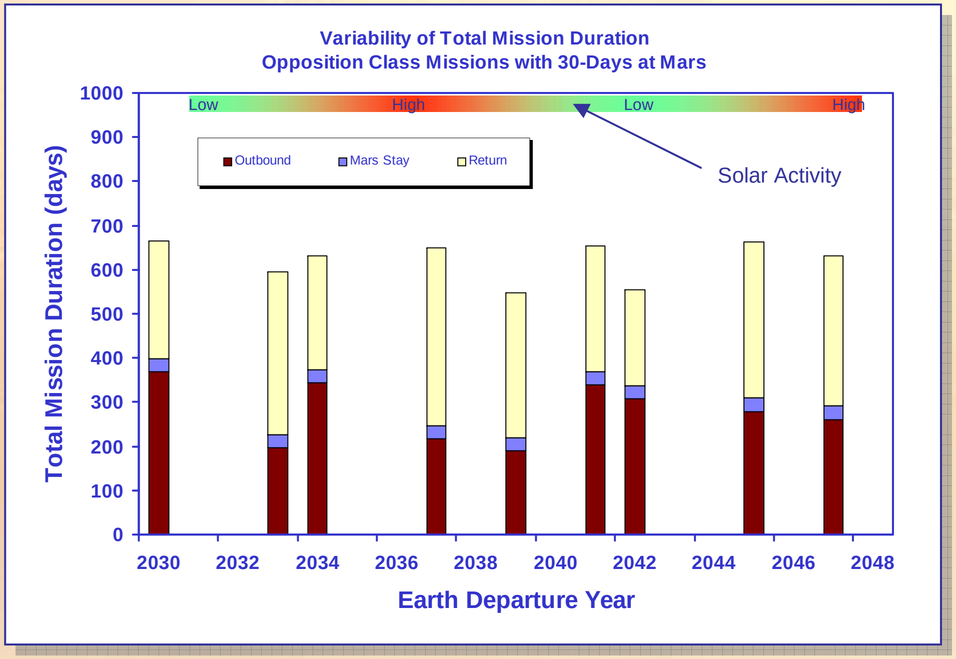
  The breakdown of trip times for the outbound, surface stay, and inbound portions of the short-stay mission are provided on the left graph. Total mission durations for the short-stay missions range from 550-650 days with 30 sols in the vicinity of Mars. For the short-stay missions over 95% of the total mission time is spent in the deep-space interplanetary environment with the balance of 5% spent in the vicinity of Mars. Duration of the transit legs range from a minimum of 190 days and maximum in excess of 400 days.

- **Long-Stay Mission: Total Mission Duration Variability**

  The corresponding trip time breakdown for the long-stay mission is provided in the left graph. The total mission durations range from 890 to 950 days with a range of corresponding surface stay times ranging from 475 to 530 sols in the vicinity of Mars. For the long-stay missions approximately 55% of the total mission duration is in the vicinity of Mars with the balance of 45% spent in transit. The time spent in orbit versus the time spent on the surface of Mars is open to further refinement as the relative tradeoffs between mission return and crew risk are conducted.

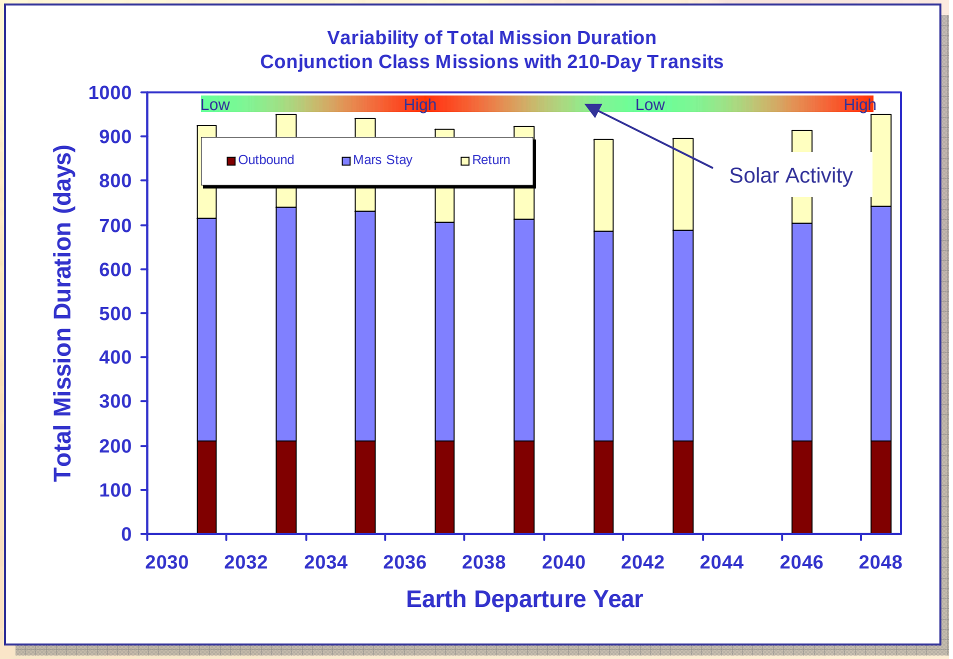
Total Mission Duration

Opposition Class Missions (Short-Stay) Total Mission Duration



% of time at Mars: ~5%

Conjunction Class Mission (Long-Stay) Total Mission Duration



% of time at Mars: ~55%

- **Advantage: Long-Stay – maximizes exploration return**

Mars Vicinity Operations

- **Mars vicinity operations prior to arrival at Mars and before departure include:**

  Capture and Rendezvous: Most mission strategies rely upon the pre-deployment of mission cargo to Mars orbit prior to arrival of the crew to reduce mission mass. Since the cargo elements are pre-deployed many months ahead of the crew, there is sufficient time to adjust their orbits prior to crew arrival to ensure optimal co-planar conditions. The crew vehicle will perform the orbital capture maneuver, capturing into a proper phasing orbit necessary for the subsequent rendezvous maneuver. Assuming that the cargo elements are placed in a 1-Sol (250 km x 33,793 km) parking orbit, the phasing and rendezvous maneuver can take as little as one day, but it could be longer if the relative phase between the target cargo vehicle and the crew vehicle is greatly out of phase after arrival in Mars orbit. Rendezvous and docking might also be delayed in the case of an off-nominal event.

  Landing: After rendezvous with the lander, systems are checked out and verified operational, which is assumed to be at best one day. Additional time must be accounted for additional orbital loiter necessary for proper phasing with the landing site or to wait out Mars environmental factors such as dust storms.

  Crew Acclimation: After arrival, vehicle systems are safed, transitioned to surface operational condition and checked out. The crew will be deconditioned due to the zero-g transit from Earth to Mars. Current estimates for crew acclimation are on the order of 1-2 weeks based on current US and Russian experience.

  Ascent: Ascent and rendezvous with the waiting Transfer vehicle will take 40-50 hours for ascent and rendezvous.

  Departure: During the short surface duration there will be very little apsidal and nodal regression. In order to meet the departure trajectory conditions, a multi-burn departure will be necessary to align with the departure asymptote. This multi-burn departure will require up to a few days including a small departure window to account for contingencies.

- **Short-Stay**

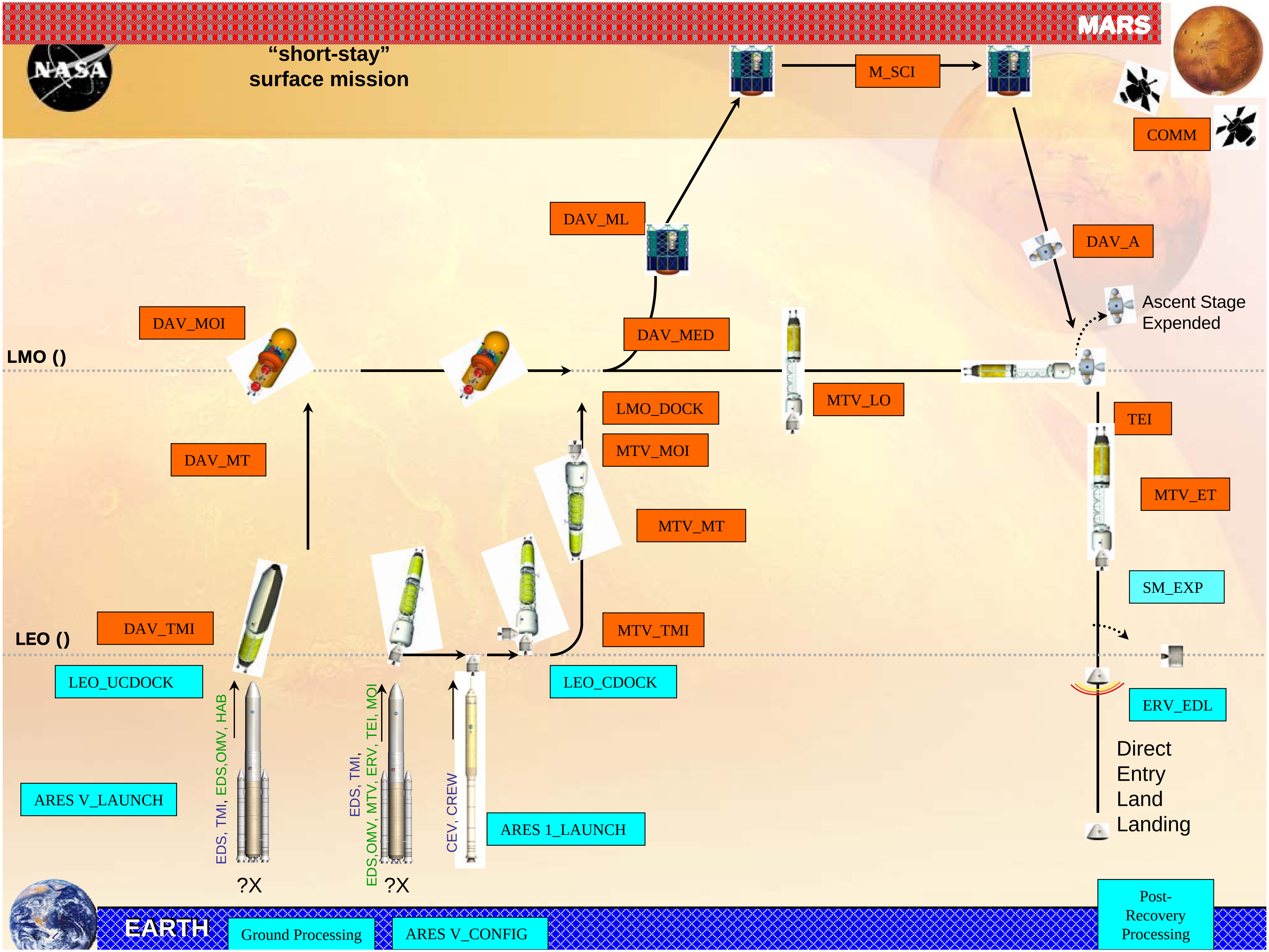
  Due to the short nature of this mission class and number of required operations, the short stay mission will provide on the order of 1-2 weeks of surface exploration with 30 sols in the vicinity of Mars. Easier opportunities can extend the time at Mars up to 90 sols depending on the choice of the propulsion system. Short stay mission will require a scripted operational approach, very similar to the Apollo lunar missions with limited exploration range from the landing site. There is also very little ability to handle any off-nominal events and still conduct a viable surface mission. This mission approach only requires a lander for the surface phase which provides the potential for overall cost reduction and lower risk for the surface phase of the mission.

- **Long-Stay**

  The long-stay mission architecture lends itself to a flexible surface exploration strategy. The crew has approximately eighteen months to perform the necessary surface exploration activities and thus the strategy follows a less rigorous, less scheduled approach. Ample time is provided to plan and re-plan the surface activities, respond to problems, and readdress the scientific questions posed early in the mission. In addition, the long surface mission duration maximizes mission and scientific return enabling a robust exploration strategy with the ability to reach ranges at greater distance from the landing site, explore a greater number of sites, as well as conduct more complex exploration such as deep drilling. The extended surface operations does pose additional risk to the crew depending on the specific tasks and frequency. In addition, the long surface stay imposes additional system reliability and maintainability requirements.

Mars Vicinity Operations

- **Short-stay Missions**
  - **Mars stay time is limited and thus operations will be highly scripted, with limited time for re-planning and contingencies**
    - Hard opportunities limited to 30 sols in the vicinity of Mars
    - Easier opportunities can extend time at Mars up to 90 sols (depending on propulsion choice)
  - **Operations must include time for**
    - Phasing and rendezvous with orbital assets upon arrival (days)
    - Systems checkout, entry, descent, and landing (days)
    - Crew acclimation to Mars gravity (7-14 sols)
    - Ascent & rendezvous with transit vehicle at end of surface mission (days)
    - Trans-Earth Injection including window (days)
  - **Additional risk of Mars environmental factors (e.g. dust storms) or ability to select backup landing sites.**
  - **Exploration range limited to 10's of km from landing sites**
- **Long-stay Missions**
  - **Provide 475-530 sols in the vicinity of Mars**
  - **Ample of time for nominal operations as well as contingencies**
  - **Time to conduct more complex exploration such as increased mobility range from the landing site, trenching, drilling, collaboration with scientists on Earth, etc.**
- **Advantage: Long-Stay provides ample time for Mars vicinity operations, contingencies and replanning.**


MARS
"short-stay"
surface mission
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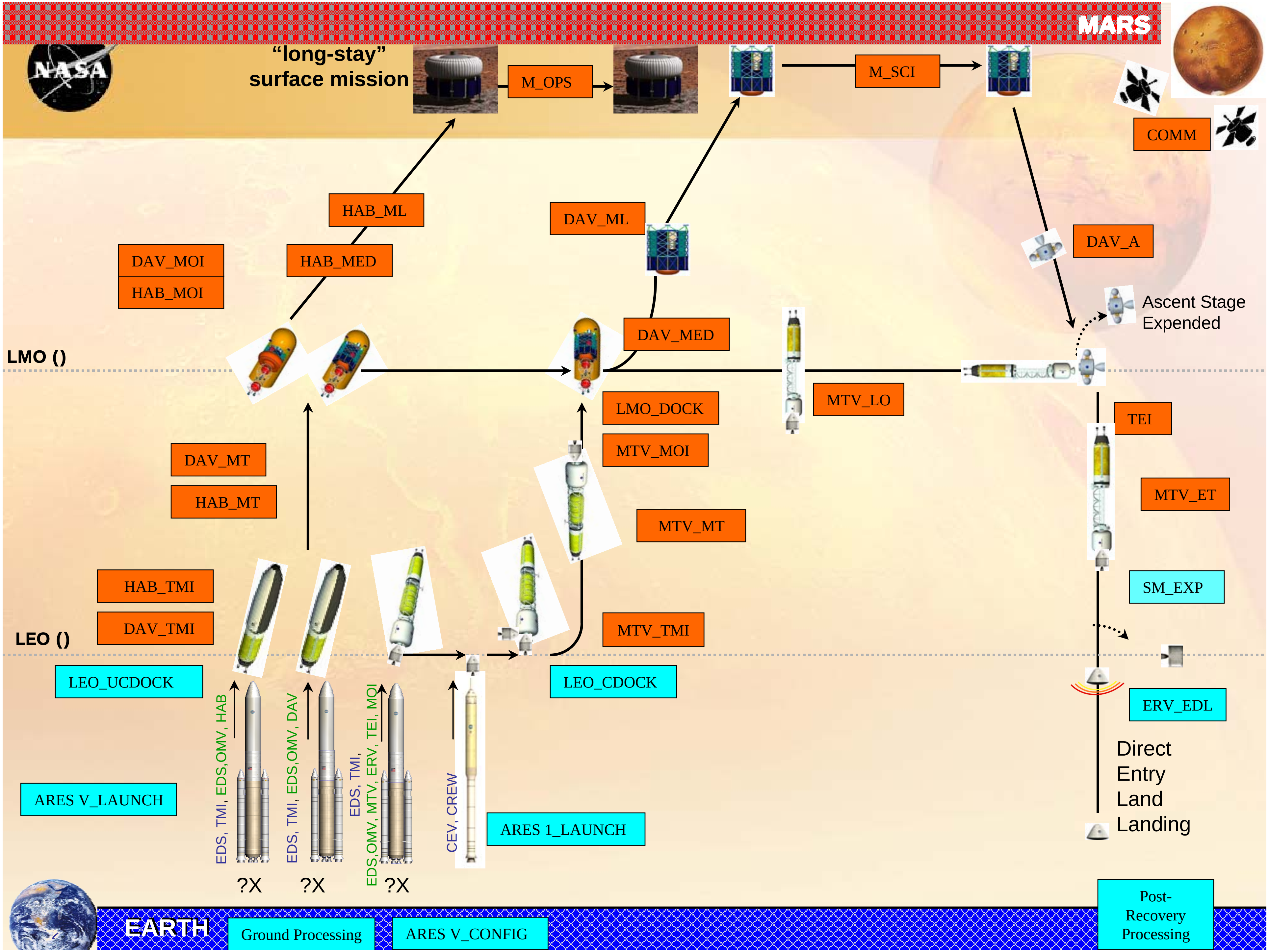
MARS
"long-stay"
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Surface Architecture

- **Mars Lander (Descent / Ascent Vehicle)**

  The Descent / Ascent Vehicle serves as the primary transportation and crew support element for the initial planetary exploration phase of the mission. The vehicle is designed to transport the mission crew from a high Mars orbit to the surface of Mars, support the crew for up to 30 sols while on the surface, and return the crew from the surface to the high Mars orbit whereby it performs a rendezvous with the Mars Transfer Vehicle. The functional capabilities of the Descent / Ascent Vehicle must accommodate the ability to operate in a fully automated mode since it is anticipated that the crew will not be capable of performing complicated tasks due to the long exposure to micro-gravity while in transit. Vehicle terminal phase targeting/control, post-landing safing, initial flight-to-surface transition, and appendage deployments must occur without crew exertion. Thus, the vehicle must provide adequate time for the crew to re-adapt to 0.38 G on Mars. During this period, no strenuous activities (e.g., EVA) will be scheduled for any crewmembers and the focus of the operations will be on developing adequate crew mobility and maintaining systems operability

- **Surface Habitat**

  The Surface Habitat (SHAB) provides the capabilities necessary to support the crew during a long stay on the surface of Mars. The SHAB is designed to meet the basic needs of maintaining crew health and performance. The SHAB supports both physical and psychological needs with the inclusion of a galley, wardroom, personal stowage, housekeeping supplies, crew health systems, medical accommodations, sleep accommodations as well as operational capabilities such as scientific laboratory capabilities, EVA and system maintenance. . The system includes technology challenges such as closed-loop life support, composite materials, ISRU for gas makeup and EVA consumables, wireless avionics, etc.

- **Short Stay Strategy**

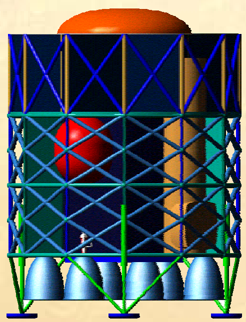
  The focus of the surface exploration phase is to conduct scientific investigations of the local landing vicinity. This strategy provides time for the crew to acclimate to the martian environment as well as perform the closeout and vehicle checks necessary at the end of the surface mission prior to ascending back to orbit. During the science investigations, a rover is provided for local exploration near the landing site.

- **Long Stay Strategy**

  The crew has approximately eighteen months to perform the necessary surface exploration activities and thus the strategy follows a less rigorous, less scheduled approach. Ample time is provided to plan and re-plan the surface activities, respond to problems, and readdress the scientific questions posed early in the mission. The focus during this phase of the mission will be on the primary science and exploration activities that will change over time to accommodate early discoveries. A general outline of crew activities for this time period will be provided before launch and updated during the interplanetary cruise phase. This outline will contain detailed activities to ensure initial crew safety, make basic assumptions as to initial science activities, schedule periodic vehicle and system checkouts, and plan for a certain number of sorties. Much of the detailed activity planning while on the surface will be based on initial findings and therefore cannot be accomplished before landing on Mars. The crew will play a vital role in planning specific activities as derived from more general objectives defined by colleagues on Earth.

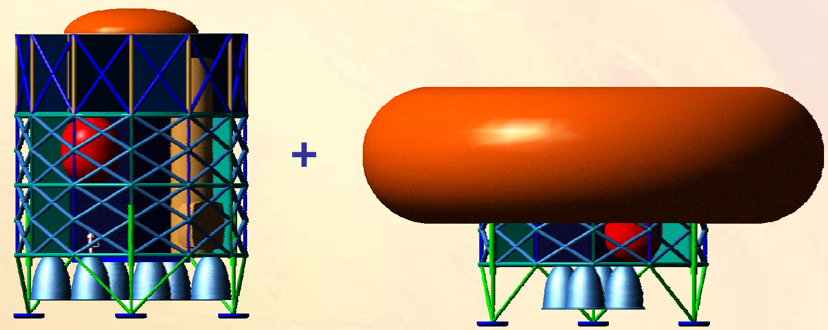
Surface Architecture

Short-Stay Missions
(Lander Only)



- **Short-stay capability (30 sols)**
  - Ascent vehicle and propellant (abort-to-orbit)
  - Contingency science
  - Common lander design

Long-Stay Missions
(Lander & Surface Habitat)



- **Full surface mission support systems (550 sols)**
  - Power
  - Life Support
  - Maintenance
  - Thermal
  - Crew accommodations
  - Science
  - Common lander design

Flight Sequence for Successive Missions

- **Strategy Overview**

  For this comparison, the surface exploration capability is implemented through a split mission concept in which cargo is transported in manageable units to the surface of Mars or orbit and checked out in advance before committing the crews to their mission. The first phase of this approach begins with the pre-deployment of the elements of the mission that the crew will use upon arrival at Mars. These vehicle sets are launched, assembled, and checked out in low-Earth orbit. After all systems have been verified and are operational, the vehicles are injected into minimum energy transfers from Earth orbit to Mars. Upon arrival at Mars the vehicles are captured into a high-Mars orbit. The Descent / Ascent Vehicle (DAV) remains in Mars orbit in a semi-dormant mode, waiting for arrival of the crew two years later. The Surface Habitat (SHAB) used for the long-stay mission is captured into a temporary Mars orbit, and then performs the entry, descent, and landing on the surface of Mars at the desired landing site. After landing the vehicle is remotely deployed, checked out, and all systems verified to be operational. Periodic vehicle checks and remote maintenance are performed in order to place the vehicles in proper orientation prior to crew arrival.

- **Short-Stay Flight Sequence**

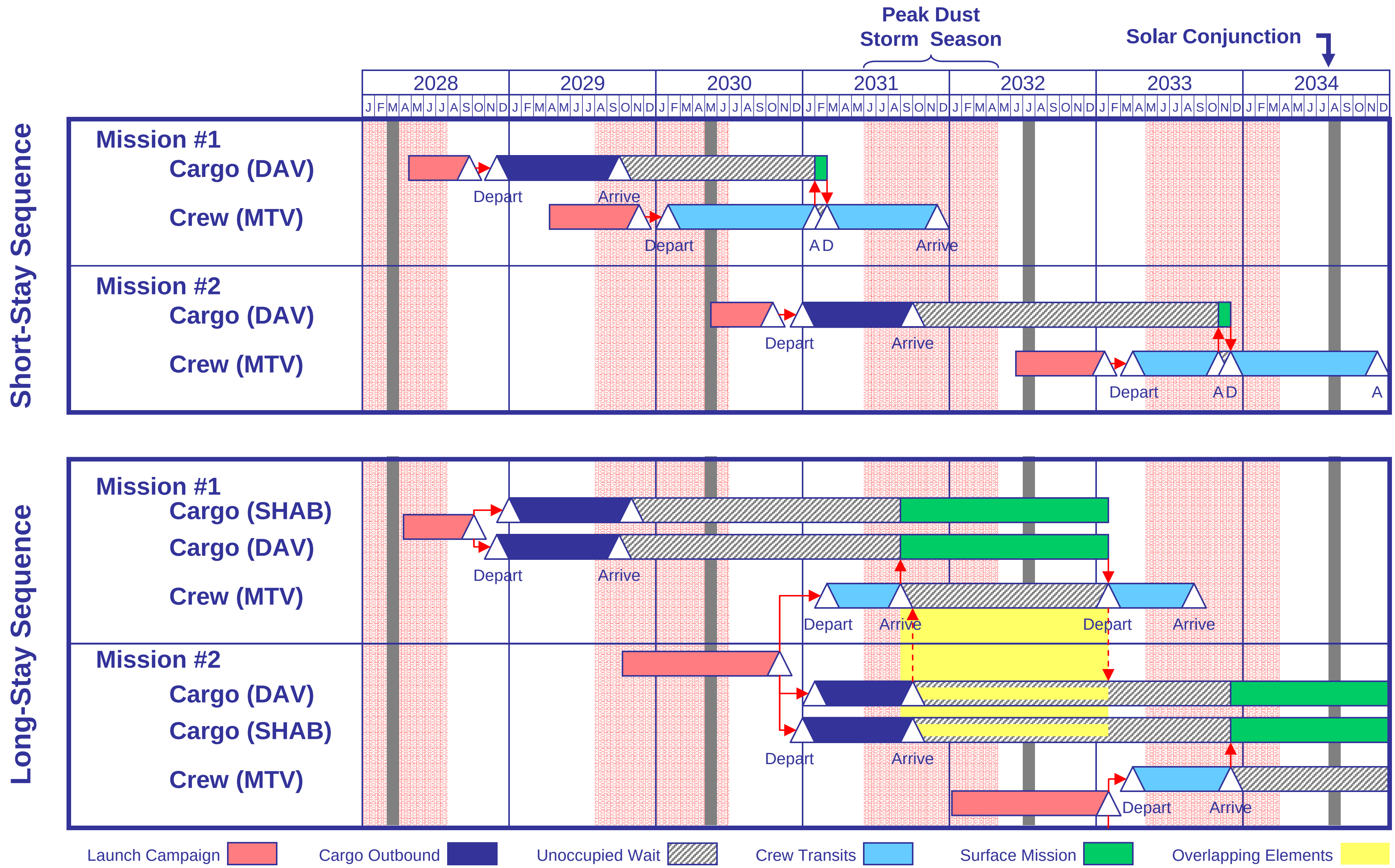
  Due to the short duration of the opposition class missions only one crew lander is required for each mission. This cargo element is sent ahead of the crew on the previous minimum energy trajectory and arrives before the crew departs LEO in the next mission opportunity. Since the time at Mars is, by definition short, the mission sequence will be very scripted with little time for replanning for unanticipated situations. In addition, the short stay missions sometimes occur during high dust storm season as is shown in the 2032 mission opportunity.

- **Long-Stay Flight Sequence**

  Due to the extended duration of the surface mission, this mission approach requires the deployment of the long-duration surface exploration equipment including the surface habitat (SHAB) as well as the research and exploration gear necessary for the robust surface exploration phase (rovers, laboratories, etc). As with the short stay missions, the crew portion of the mission is initiated only after it is known that the cargo vehicles have arrived at Mars and are operating as expected.

  Unlike the short stay missions, the long-stay mission provides a very unique risk reduction characteristic: the ability for complete functional redundancy of overlapping mission resources. As can be seen from the graph, the first two cargo elements are sent ahead of the crew one opportunity. These elements are checked out and functional prior to committing the crew. During the next mission opportunity 26 months later, the next two cargo elements are sent out to Mars just prior to the crew. These elements are intended for the next crew, but can be used by the current crew if necessary.

Flight Sequence for Successive Missions



Scientific Requirements for Surface Mission Duration (HEM-SAG consensus)

- **Opposition Class Missions (Short-stay): Scientific position**

  Short-surface duration missions, while offering potential for breakthrough, human-enabled science are **NOT** favored for science-driven exploration for several reasons:

  (1) Short stay human surface missions cannot make best use of mobility to optimally explore a REGION due to time available for EVA (and for sub-surface access system operation, such as a deep drill)

  (2) Short stay human surface missions do NOT optimize the "iteration cycle time" associated with in situ field investigations on the basis of time available (too few cycles for adapting to the unexpected scientific context that is likely to emerge)

  (3) Short stay human surface missions do NOT allow time for sample high-grading to ensure a best subset of materials for detailed analysis on Earth. This limits the *serendipity potential* intrinsic to field sampling.

- **Conjunction Class Missions (Long-stay): Scientific position**

  <u>MOST FAVORED TO OPTIMIZE SCIENTIFIC YIELD</u>:

  Long surface stay allows maximal use of human "on site" observational and intuitive scientific capabilities, even if EVA is restricted to ~25% of available time. By maximizing opportunities for adapting scientific investigations to a given region, the probability of paradigm-busting discoveries increases exponentially over focused, robotic surface investigations such as those presently in operation with the Mars Exploration Rovers (MER).

  Long surface stay also maximizes human opportunities for using mobility (horizontal and vertical) to more completely explore a compelling REGION at scales commensurate with processes that preserve evidence of past life on Earth. In addition, the long surface stay scenario provides the humans "on site" to make best use of their non-EVA time to employ general analysis "tools" to investigate sampled materials and hence to best select the optimized subset (so-called *splits*) for return to Earth.

NOTE : **Long surface stays at 3 independent and different human exploration sites is the most favored option**

HEM-SAG Preliminary Capabilities Summary

	Short Stay (30-90 sols)	Long-Stay (500 sol)	COMMENTS
One Site (same each mission)	• LEAST FAVORED • Below the "science floor" (but there is science that could be done, especially via samples back to Earth)	• 3rd Most favored (of 4) • <u>CAPABILITIES</u> • 100's km mobility • Ideally 1000 km mobility (pressurized) • May require unique landing site (with extreme local diversity)	• *Long stay may require 1000's km surface mobility if to same site each time (otherwise not scientifically favored)*
Multiple Separate Sites	• 2nd Most Favored • <u>CAPABILITIES</u>: •10's km mobility •100 kg samples to Earth (total Apollo-class) •MER-class analytical? •Robotic "fetch" rovers? •Leave-behind robotic systems (auton. drill?) •Favors sample collection over in situ analysis	• MOST FAVORED • <u>CAPABILITIES</u> •100's km surface mobility •100 m vertical (drilling) •TBD analytical capability (in situ, possibly MSL class) •100's kg to Earth (Apollo-class) •Extensive lab for sample high-grading key for many science issues (astrobio.)	• *Highest Science yield requires Diversity (time, space) for optimization* • *Requires ~ 100's km horiz. mobility (all cases)* • *ISSUE: Drilling? (100m desire, 1 m pits req'd)* • *Mass to Earth? (likely to be 100kg minimum)*

***<u>RESULT:</u> Long-stay with multiple independent sites maximizes science potential across all relevant variables (i.e., to the HEM-SAG charter)**

Special Considerations: Human Health & Performance

- **Human Health & Performance considerations do not predominantly favor either Short Stay or Long Stay option**
  - **Both scenarios pose significant risks for HHP**
    - Shorter is better, but short-stay option is not that much shorter
      - still has ~73% exposure risk (due to time away from Earth) of long-stay option
    - Many—but not all—HHP risks increase most rapidly early in flight
  - **These are DRAFT positions—not yet vetted by NASA Human Research Program or JSC Space Life Sciences Directorate**

- **HHP and parent organizations are committed to enabling either strategy, if Program and Agency accept residual risks**

Special Considerations: Human Health & Performance

- Both options pose significant risks
  - Differences between options are often a matter of degree only

HHP Component	Short Stay (Opposition-class; 22 months total)	Long Stay (Conjunction-class, 30 months total)
Physiological Countermeasures	▪ Extended 0-g transits at limits of human spaceflight experience base ▪ Preferred option only if AG available	▪ 0-g transit phases well within experience base ▪ 3/8-g surface phase outside experience base, will be partially mitigated by Lunar Outpost experience
Human Factors & Habitability	▪ Not preferred option without access to Surface Habitat	▪ Preferred option with access to Surface Habitat
Radiation	▪ Higher risk of carcinogenesis, acute syndromes, CNS effects and degenerative effects due to longer transits (SPE & GCR) and close perihelion passage (SPE effects) ▪ Option is well outside current permissible exposure limits	▪ Prolonged exposure to poorly-understood surface mixed-field (neutrons and charged particles) environment ▪ Option is well outside current permissible exposure limits
Behavioral Health & Performance	▪ Preferred option due to shorter overall duration ▪ Possible risk due to higher acute radiation exposure within 0.7 AU	▪ Increased risk due to longer overall duration
Medical Capabilities	▪ Slightly preferred option due to less risk exposure of shorter duration	▪ Slightly increased risk due to longer overall duration

Special Considerations: Physiological Countermeasures

- Long-stay (shorter transits)
  - Total duration—30 months is well outside current human total mission experience envelope (n = 1 @ 14 months)
  - Transit
    - 6-month transits are well within current human 0-g experience base (n ≈ 60 @ 6-14 months)
    - Effects of back-to-back transits possibly cumulative, due to unknown mitigation from 18-month hypogravity surface stay
    - Without artificial gravity, physiological risk may be less than short stay due to reduced 0-g exposure
      - Even with artificial-g (assume 1-g), possible increased physiological risk over whole mission due to longer (18 months vs. 1 month) surface hypo-gravity exposure, as partial gravity effects are not understood (lunar outpost missions may reduce uncertainty).
    - Surface—18-month surface period is well outside Apollo lunar experience base (by 180x)
    - Risks partially mitigated by 6-month Lunar Outpost missions

- Short-stay (longer transits)
  - Total duration—22 months is outside current human 0-g experience envelope (n = 1 @ 14 months)
  - Transit
    - 13-month transit is near limit of current human 0-g experience base (n = 6 @ 10-14 months)
    - Effects of back-to-back transits probably cumulative, due to unknown mitigation from 1-month hypogravity surface stay
    - Without artificial gravity, physiological risk is greater due to longer 0-g exposure.
      - If artificial-g (assume 1-g), then less physiological risk over whole mission due to less deconditioning during shorter (1 month vs. 18 months) surface hypo-gravity exposure;
    - Surface—1-month surface period is outside Apollo lunar experience base (by 10x)
    - Risks partially mitigated by extended Lunar Sorties and Lunar Outpost missions

Special Considerations: Human Factors & Habitability

- **Scenario-independent considerations**
  - **Food, microbiology, water quality and toxicology issues relatively independent of mission scenario**
- **Long-stay (shorter transits)**
  - **More risk from exposure to dust, potential toxins due to longer stay, more EVAs**
  - **Surface Habitat provides lower risk due to larger volume, less constrained habitability**
- **Short-stay (longer transits)**
  - **Less risk from exposure to dust, potential toxins due to shorter stay, fewer EVAs**
  - **If Surface Habitat is baselined out, then higher risk due to constrained volume issues**

Special Considerations: Radiation issues

- Scenario-independent considerations
  - Current knowledge base does not support discrimination between options
    - Both options are well above (≥5x) current permissible exposure limits due to large uncertainties
    - No first-order discriminator in mission-threatening SPE risk during transit or surface phases if assumed capabilities (*in situ* radiation monitoring and alarms, and established preventative actions) are provided
    - Similar risks of cancer mortality due to comparable GCR exposures in both options
  - Assume properly-designed non-parasitic shielding against SPE effects by 20 g/cm^2 shelter area
  - Poorly-understood non-targeted ("by-stander cells") effects of GCR for cancer induction
  - Individual-based risk assessments for crew selection

- Long-stay (shorter transits)
  - Transit—long (2 @ 6-7 months) unimpeded exposure to GCR and SPE
  - Surface—extended (18 months; 60% of total mission) shielding by Mars mass and atmosphere
    - Possibly offset by exposure to poorly-understood surface mixed-field (neutrons and charged particles) environment—both median value and uncertainties

- Short-stay (longer transits)
  - More challenging option due to longer time in interplanetary space and to closer perihelion passage
  - Transit—longer (up to 13 months) continuous exposure to GCR & higher probability of SPE
    - Greater exposure to heavy-ion GCR (due to longer transits) increases risk of non-cancer fatalities
    - Probability of single large SPE event ≤1.7x long-stay mission
    - Close perihelion passage
      - $1/R^{2.5}$ effect: of SPE event (compared to 1 AU) ≈ 2.5x @ 0.7 AU, 5.6x @ 0.5 AU
      - Effects are non-mission threatening: increased life-time cancer risk; some acute radiation syndromes
  - Surface—brief (1 month; 5% of total mission) shielding by Mars mass, atmosphere
    - Effects of poorly-understood surface mixed-field (neutrons and charged particles) environment less dependent on uncertainties than long-stay option

Special Considerations: Behavioral Health & Performance issues and Medical

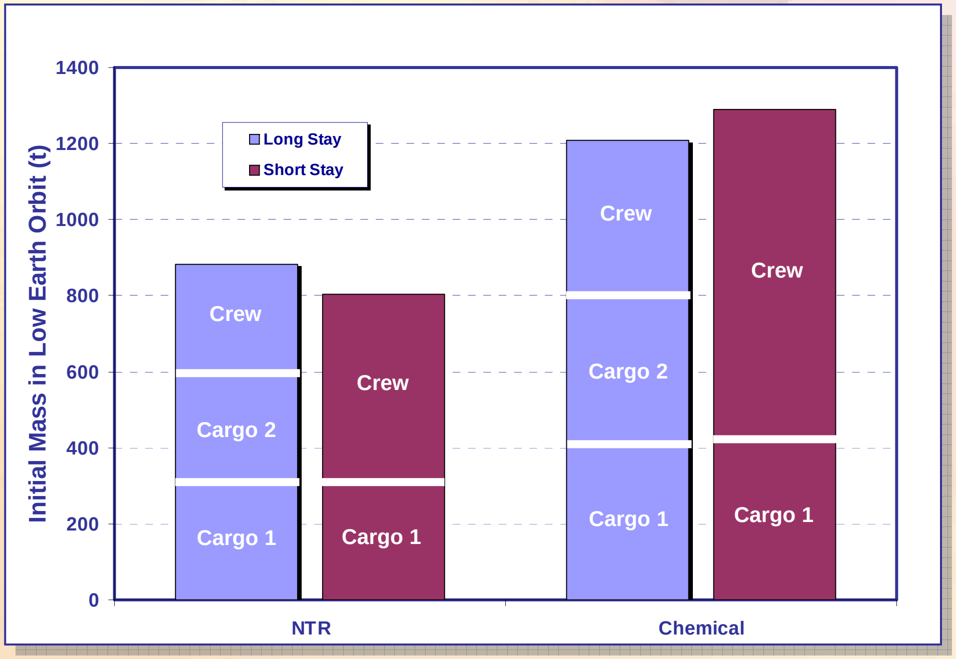
- **Behavioral Health & Performance**
  - **Long-stay (longer mission)**
    - Higher risk of behavioral problems than Short Stay mission due to ~35% longer duration
  - **Short-stay (shorter mission)**
    - Lower risk of behavioral problems than Long Stay mission due to ~30% shorter duration
    - Increased (TBD) risk of neurobehavioral effects of higher GCR exposure during longer transits and higher SPE exposure during close perihelion passage
- **Medical**
  - **Long-stay (shorter transits)**
    - Longer overall mission duration, more exposure to mission risks, including surface trauma; less total radiation exposure due to less time in interplanetary space and to perihelion = 1 AU
  - **Short-stay (longer transits)**
    - Shorter overall mission duration, less exposure to overall mission risks, including surface trauma; however more acute radiation exposure due to more time in interplanetary space and to perihelion $\leq$ 0.7 AU

Total Mission Mass Comparison

- **Short-Stay**
  - Note: The hardest, 2041, opportunity has been eliminated from consideration due to the excessive propulsive requirements. Elimination of this mission opportunity violates the ground rule for successive opportunities, but is only one missed opportunity across the synodic cycle. Inclusion of this opportunity would change the results drastically
  - Short stays which on the order of 30 sols do not require long-duration surface infrastructure, thus requiring one less cargo flight. If the surface duration is extended beyond 30 sols, up to 90 sols, an additional cargo flight may be required, but that strategy has not been address thus far.
  - The mass savings of fewer cargo flights is offset by more difficult trajectories
  - Size of crew vehicle becomes an issue – approximately twice the size of the cargo vehicles. Increases LEO on-orbit assembly, checkout, and verification issues.
- **Long-Stay**
  - All opportunities covered by similar vehicle design
  - Faster trajectories flown for better opportunities
  - Common vehicle design between crew and cargo versions
  - Long-duration surface mission requires additional cargo flight and surface exploration gear

Total Mission Mass Comparison

- Total mission mass essentially the same when "hardest" short-stay opportunity not considered.
- Short-stay missions require fewer elements (no surface habitat), but require more interplanetary propulsion (3-7 km/s extra)
- Long-stay mission utilizes more energy efficient trajectories, but requires more mission elements:
  - Surface Habitat Lander
  - Surface exploration systems



- Advantage: Long-Stay - enables common vehicle design for both crew and cargo missions

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Architecture Sensitivity (aka “Gear Ratios”)

- The use of “gear ratios” is a measure of the sensitivity of an architecture to change in mass growth and is measured change in total mass for a unit change in system mass
- Short-stay missions much more sensitive to architectural change.
  - For Example: e.g., adding 1 mt for a 0.5 AU deployable sun shade adds ~14 mt to launch mass for the chemical architecture

Architecture Gear Ratio (kg/kg)

	Short-Stay		Long-Stay	
	NTR	Chemical	NTR	Chemical
Cargo: $\Delta M_{IMLEO} / \Delta M_{MO}$	2.24	3.29	2.24	3.49
Crew: $\Delta M_{IMLEO} / \Delta M_{MO}$	2.90	5.67	2.14	3.80
Crew: $\Delta M_{IMLEO} / \Delta M_{TE}$	4.36	13.89	2.58	6.12

ΔM_{IMLEO} = Initial Mass in LEO ΔM_{MO} = Mass in Mars Orbit ΔM_{TE} = Round-Trip Mass LEO/MO/Trans-Earth

- **Advantage: Long-Stay – less sensitive to architecture change**

Risk Findings

- **Key notes to consider**
  - First order risk assessments conducted thus far.
  - Utilized “best” known data to date including STS and ISS history
  - **No credits taken for flight demonstrations (e.g. large scale EDL) or other architectural activities (e.g. lunar) yet.**
- **Mission Success**
  - Although the short stay missions appear to provide better overall loss of mission, there is no clear advantage given the maturity of the understanding of the systems to date
  - Overall system reliability is a driver for the long stay missions. Gaining better understanding of the system performance for long periods is necessary. Technology and system demonstrations on the ISS and lunar programs provide a vital link to reducing this risk. Risk mitigation will be addressed further in Phase 2 of the study.
- **Crew Safety**
  - No credits taken for flight demonstrations (e.g. large scale EDL) or other architectural activities (e.g. lunar) yet.
  - EDL is first use and overall system reliability are key contributors.
  - Close Perihelion passage becomes a crew risk driver for short stay missions
- **Mission Comparisons**
  - Short Stay Missions decrease the duration of equipment reliability, but increase the number of AresV launches.
  - Certain elements are reduced with no Surface Habitat, but cause a lack in maturity leading to greater risk for crewed missions (i.e. EDL).
  - Venus fly-by causes radiation risk in Short Stay Missions.
- **Driving Assumptions and Uncertainties**
  - Launch availability is modeled with 120 day contingency and may require new infrastructure.
  - Nuclear propulsion has potential to mature.
  - Chemical propulsion missions are already credited with maturity.
  - Equipment reliability can be enhanced by scavenging techniques when crew is present. These techniques can be learned during lunar missions.

Risk Findings

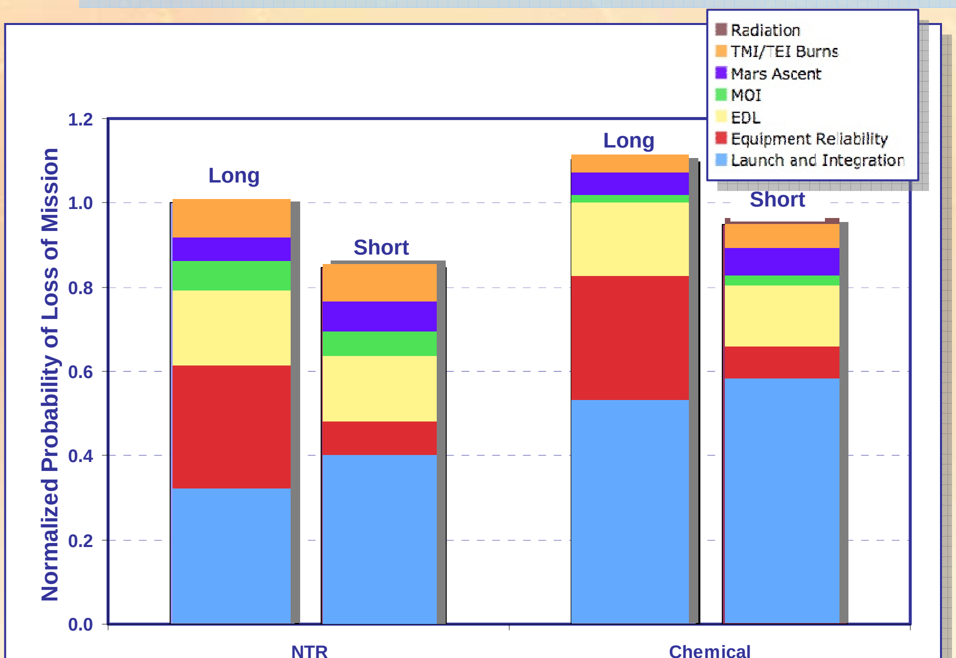
Mission Success

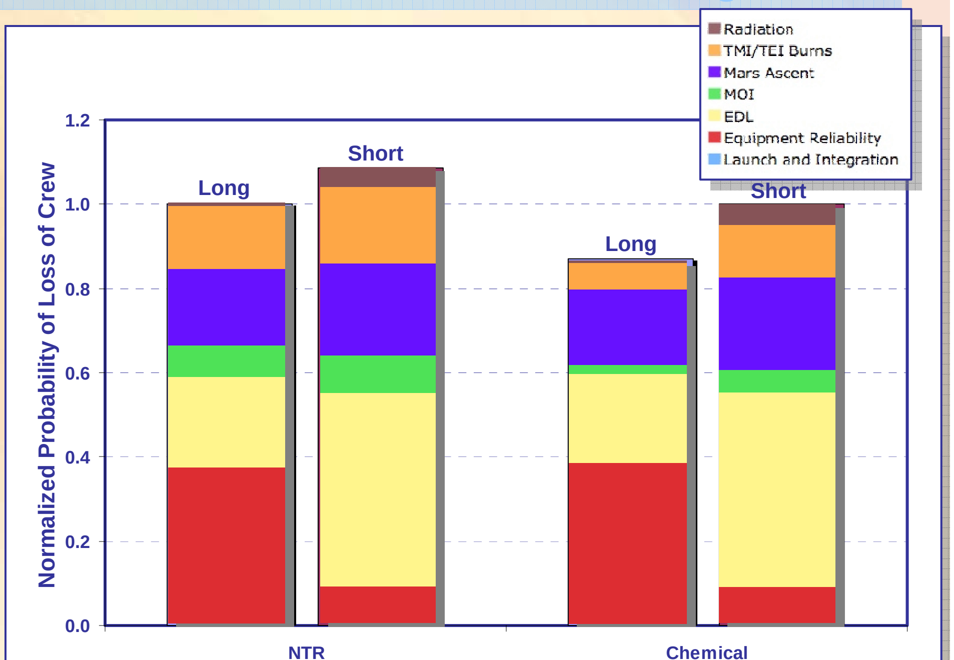
- No clear advantage to short stay
- Order of magnitude more content for slight increase in Plom
- Key driver is system reliability

Crew Safety

- No clear advantage to long stay
- Key driver is EDL

- No risk reduction strategies (e.g. Earth, ISS, lunar, robotic) incorporated yet
- Earth, ISS, lunar program, and flight demonstrations are vital to reducing risk





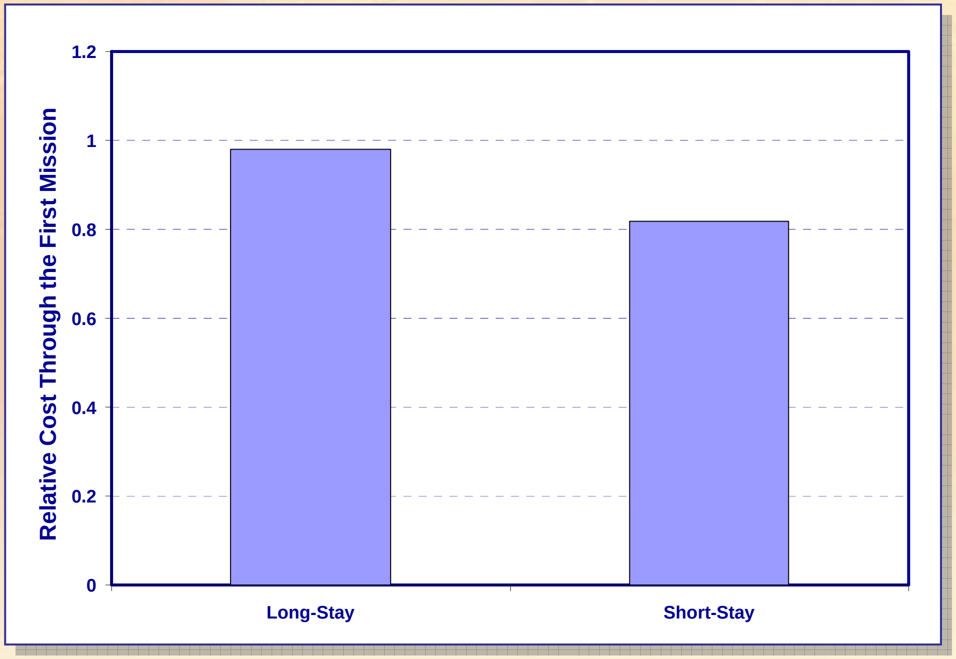
Cost Findings

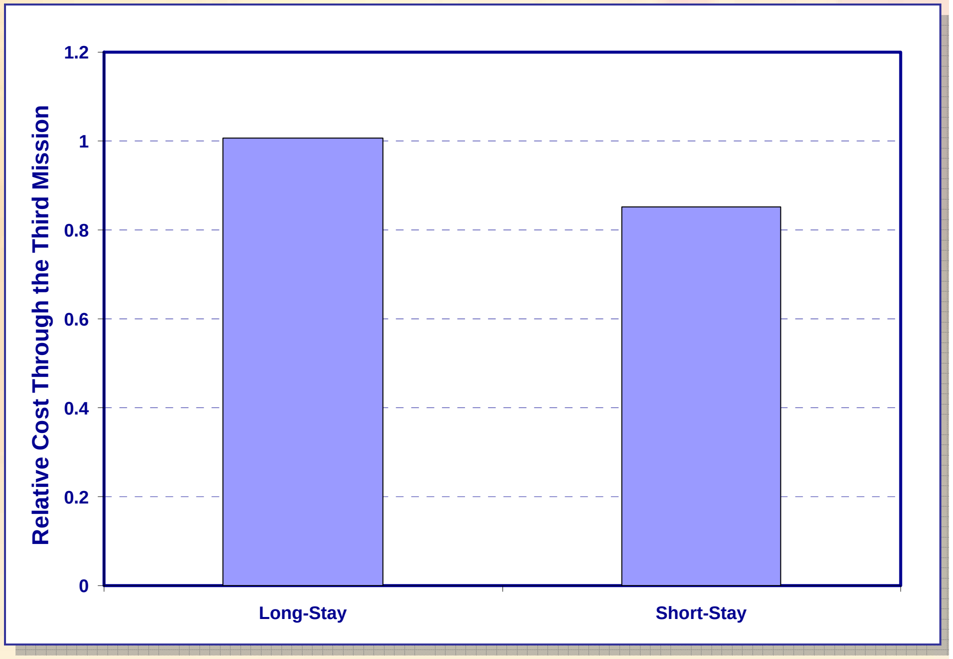
For the short versus long stay, the difference in cost is due predominately to the surface systems including the development and recurring cost of the extra surface habitat, the recurring cost of an extra descent stage, the long duration rover, the additional scientific equipment, etc. There is some uncertainty in the magnitude of the difference as some of these systems are not well defined yet.

The cost differences in the flight systems is swamped by the cost differences in the surface systems. This is due to the modular nature of the Mars Transfer Vehicles and the similar number of total launches and flight elements. Even so, there is a slight cost savings for the Short Stay flight systems and launch costs. Cost of the surface systems for the long-stay missions may be further reduced depending on the commonality with lunar systems and lunar technology development activities. These potential cost savings will be addressed further during the architecture refinement phase of the study.

Cost Findings

- Short-Stay provides some cost advantage
- Primary difference is the development and recurring cost of the additional systems for the long-stay mission
  - Surface habitat
  - Additional EDL system
  - Additional surface exploration systems
- Note: Credit for lunar systems heritage not included yet





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Figures of Merit Summary

Human Exploration Of Mars

Long Surface Stay (Conjunction Class)	Figure of Merit	Short Surface Stay * (Opposition Class)
Similar	Total mass in Low-Earth Orbit (mt)	Similar *
45% Smaller	LEO Complexity / Size of Crew Vehicle	Larger
~3100 crew-sols	Expected Useful Crew Sols on Surface (mission return)	~80-500 crew-sols
Best	Exploration Goal Satisfaction (range, depth, frequency)	Lower
3 / 6 kg/kg	Architecture Sensitivity (gear ratios: NTR/Chem)	4 / 13 kg/kg
No Clear Advantage	Probability of Loss of Crew	Somewhat Less
Somewhat Less	Probability of Loss of Mission	No Clear Advantage
950	Total Mission Duration	**650 days**
500 sols	Mission Flexibility (contingency replanning)	Few sols
Less	Crew Exposure to Radiation	More
200 / 500 / **200**	Crew Exposure to Zero-G (days out / surface / back)	180 / 30 / 360
Available	Backup Lander and Surface Habitat	None
Somewhat More	Cost Through First Mission	Slight Advantage
Somewhat More	Cost Through Third Mission	Slight Advantage

* Excluding very hard opportunities

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Long-Short Recommendation

- **Based on the Figures of Merit and other considerations, the study team recommends that the Long-Stay mission be used as the reference approach**
  - **Provides greater mission return (order of magnitude)**
  - **Provides greater mission flexibility**
  - **Enables transits which are within experience base**
  - **Requires similar/lower total initial mass**
  - **Enables equal and consistent transportation vehicles**
  - **Provide better crew safety**

While accounting for:

- **Slightly greater cost for additional systems, and**
- **Slightly greater mission risk due to longer system operational time**

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