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NASA Mars 2020 Landed Mission Development

Michael Wilson,[1)] Jennifer Trosper,[1)] Fernando Abilleira[1)]

[1)] *Jet Propulsion Laboratory, California Institute of Technology, USA*

In January of 2014, NASA received fifty-eight proposals from U.S. and international teams for science and exploration technology investigations, for consideration for inclusion as part of NASA's next mobile landed mission to Mars. The results of the competitive procurement were released in late July of 2014: Seven payloads were selected for the investigations that would contribute to meeting the overall objectives of the mission. The extraordinary scientific and technology development interest in the Mars 2020 mission is a direct result of NASA's sustained and coordinated plan for the exploration of Mars, and ultimately, its search for life elsewhere in the universe. The Mars 2020 Mission will preserve the heritage and directly build upon NASA's Mars Science Laboratory Mission and Curiosity Rover to implement its mission. In this paper, early development history leading to its development announcement, as well as key development status and design features for its implementation, is summarized.

Key Words: Mars 2020, M2020, Mars Sample Return, MSR, Cache

1. Introduction

NASA's Mars Exploration Program (MEP), within the Science Mission Directorate (SMD), has developed and is implementing a long term program of exploration and discovery, with ultimate goals that include understanding Mars' potential for being a habitat for past or present microbial life, and development of technologies in preparation for human exploration of Mars.[1)] The robotic exploration of Mars has been, and continues to be, undertaken by a series of competed and flagship missions that implement scientific investigations following a coordinated strategy guided by the nation's prioritized goals, within the resources set by US Government policy and legislation on an annual basis. Some of these missions are developed in close cooperation with international partners including national space agencies and the European Space Agency (ESA). Fig. 1 summarizes the series of NASA-led and NASA-participation missions conducted within the MEP over the last two decades.

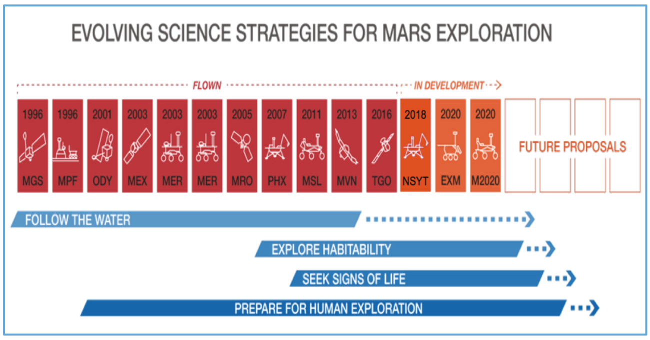

Fig. 1. Mars Exploration Program Missions and Investigation Objectives, Past and Under Development.

Specific and more narrow objectives within the program are addressed by lower budget cost-capped missions with more focused investigations, typically implemented as competed Principal Investigator-led missions within the MEP (e.g. Scout Program's 2007 Phoenix,[2)] (PHX) and 2013 MAVEN,[3)] (MVN) missions) or outside of the MEP (e.g. Discovery Program's 1996 Mars Pathfinder,[4)] (MPF) and 2018 InSight,[5)] (NSYT) missions).

Fundamental objectives within the program are sometimes addressed by larger budget, or NASA-directed (or flagship) missions developed over many years of scientific study, informed by consensus advice coming from the nation's scientific and engineering communities. NASA's Mars 2020,[6)] (M2020) mission is one such mission currently under development; a large budget, flagship mission that is the outcome of such a long development history described in this paper. A short history of the formulation process, as well as a snapshot status of the current development stage and design of the mission is provided in this paper.

2. Mars 2020 Project Development History

Program planning for concepts that have evolved to the current Mars 2020 Project did not happen over a short time period. A long and iterative process guided by NASA Headquarters, factoring evolving budget environments and constraints, informed by the nation's scientific community, and implemented by national engineering capabilities brought to bear by the MEP, eventually led to what is today the Mars 2020 Project. The early part of that process for development of the next flagship mission after Mars Science Laboratory is discussed in Ref. 7). During this early development period, it wasn't until after the deliberations of the Next-Decade SAG (Science Advisory Group),[8)] and during mission concept development efforts associated with the 2007-2008 Mars Strategic Science (MSS) SAG,[9)] that the first caching rover concept for potential Mars Sample Return (MSR) was developed for program planning budget discussions. The Next Decade – Science Analysis Group (or, ND-SAG) final report entitled: '*Science Priorities for Mars Sample Return*',[8)] had identified the desired objectives of a potential MSR campaign and how the greatest value from such a campaign could be attained from carefully selected and documented samples. The 2008 MEP budget development cycle included, for the first time, the first element of a potential three-mission

MSR project that could reasonably begin to address such objectives. This first element of such an MSR campaign that would include both in-situ exploration of a compelling site on Mars (similar to the Mid-Rover concept identified by 2006 Mars Advanced Planning Group (or, MAPG),[10, 11] but with inclusion of a sample collection and caching capability. The beginning of this particular concept development timeline is depicted below in Fig. 2 with the completion of the ND-SAG final report and the early concept development of a MSS-SAG caching rover concept to be launched in 2016.

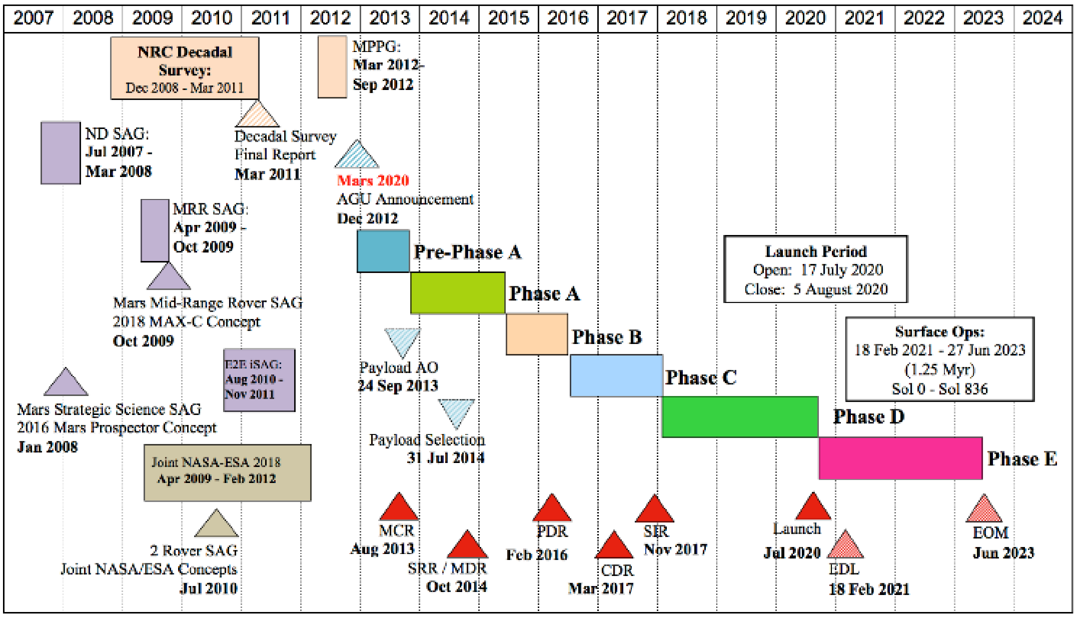

Fig. 2. Caching Rover Concept Development Leading to Mars 2020 Project Planned Lifecycle.

3. Implementation Schedule

The January 2008 MSS-SAG mission concept included a MER-class rover (solar-powered, under 200 kg rover mass) referred to as 2016 Mars Prospector. This MER-class concept development was carried much further by the NASA-chartered 2009 Mid-Range Rover Science Analysis Group (MRR-SAG). The MRR-SAG was asked to formulate a mission concept that would address two general objectives: (1) conduct high-priority in situ science and (2) make concrete steps towards the potential return of samples to Earth. The outcome of this effort was a detailed science and engineering concept referred to as the Mars Astrobiology Explorer-Cacher (or, MAX-C). This effort was focused on a reduced mass rover that is described in the final SAG report,[12] and in Ref. 7). This mission concept was of tremendous importance in the effort to begin what could become a Mars Sample Return campaign.

As illustrated in Fig. 2, in December of 2008, NASA initiated the process of generating its next decadal survey for planetary science. The Committee on the Planetary Science Decadal Survey (Space Studies Board, Division on Engineering and Physical Sciences, National Research Council of the National Academies) implemented the survey. The purpose of the decadal survey was to identify the most important scientific questions in planetary science for the next decade and then prioritize the missions that could address those questions (Squyres, March 2009, Lunar and Planetary Science Conference). As described in the final survey report,[13] (entitled: *Vision and Voyages for Planetary Science in the Decade 2013-2022*) issued in March of 2011, "The highest-priority flagship mission for the decade 2013-2022 is the Mars Astrobiology Explorer-Cacher (MAX-C,[14]), which will begin a three-mission NASA-ESA Mars Sample Return campaign extending into the decade beyond 2022." Additionally, "MAX-C is the critical first element of Mars sample return. It should be viewed primarily in the context of sample return rather than as a separate mission that is independent of the sample return objective." A key factor in the decadal committee decision in selecting MAX-C over other priorities was cost: "The committee recommends that NASA fly MAX-C in the decade 2013-2022, but only if the mission can be conducted for a cost to NASA of no more than approximately \$2.5 billion FY2015." Budget constraint recommendations would be key factors in influencing the subsequent development of the caching rover concept.

During the multi-year process of generating the Decadal Survey, NASA and the MEP were considering multiple options as possibilities for implementing its next landed mission. Caching rover concepts and development cost estimates were generated for configurations that spanned MER-class solar-powered rover concepts (<200 kg rover) to MSL-class MMRTG-powered rover concepts (or, multi-mission radioisotope thermoelectric generator, ~1000 kg rover). In the 2009 – 2011 timeframe, extensive efforts were devoted to solar-powered rover concepts between those mass extremes. In April of 2009 NASA and ESA initiated a joint effort to develop an international collaborative mission that would satisfy both agencies objectives,[16]. Joint Science and Engineering Working Groups (JSWG & JEWG) explored joint rover / surface missions with the goal of eventual return of samples from Mars (MAX-C objectives,[14]) and in-situ remote sensing and sub-surface analytical sample analyses (ExoMars objectives,[15]). Initial efforts focused on delivering both MAX-C and ExoMars Rovers to the surface of Mars using an MSL-derived entry, descent and landing system. A pallet designed to restrain and deliver both rovers to the surface was studied. Individual objectives of each rover would be independently met following egress of each mobile system from the delivery pallet. Later efforts integrated elements of the ESA ExoMars Rover mission and the NASA 2018 Mars caching rover concept, into a single multi-objective rover concept. These implementations proved extremely difficult to develop in an overly constrained environment. Technical constraints (including volume and mass), an inability to descope key / fundamental agency science objectives, and programmatic issues all contributed to a difficult path to reach workable technical solutions. Such challenges contributed to NASA independent cost estimates,[13)] that would exceed available resources. In late 2011 / early 2012 it became apparent that NASA budget issues, exacerbated by a 20% budget cut in the FY13 budget plan, would not sustain the direction the collaboration was headed, so in February 2012 NASA announced it was scaling back dramatically the possible contributions to 2016 ExoMars Orbiter and 2018 ExoMars / MAX-C,[17, 18)]. As a result, ESA would restructure their program and continue ExoMars 2016 / 2018 in a major collaboration with Russia, with smaller contributions from NASA to each mission. 2016 ExoMars Trace Gas Orbiter successfully entered Mars orbit in October of 2016, and the ESA ExoMars rover and the associated Russian stationary surface science platform are continuing development and are planning for a launch in July 2020, with a planned arrival at Mars in March 2021,[19)].

Following withdrawal from collaboration with ESA on the 2018 landed mission, the NASA Administrator, in February 2012, asked SMD Associate Administrator Grunsfeld to lead a team with Human Exploration and Operations Mission Directorate (HEOMD) Associate Administrator Gerstenmaier, Chief Scientist Abdalati, and Chief Technologist Peck to reformulate an agency-wide Mars Exploration Strategy. This new exploration strategy development effort was supported by a newly formed group, referred to as the Mars Program Planning Group (MPPG), led by Orlando Figueroa (former NASA Headquarters Mars Program Director),[20)]. MPPG members were drawn from SMD, HEOMD, and Space Technology (STP) mission directorates, as well as MEP and recognized community experts. Their task was to propose pathways for the next two (or more) decades and be guided by the 2011 Decadal Survey, related MEPAG studies, HEOMD studies and other recent sources of knowledge about Mars. The NASA HQ press release,[20)] from that time indicated that "MPPG was to develop foundations for a program level architecture for robotic exploration of Mars that is consistent with the President's challenge of sending humans to Mars in the decade of the 2030s, yet remain responsive to the primary scientific goals of the 2011 National Research Council (NRC) Decadal Survey for Planetary Science". The plan would be consistent with the NASA FY13 budget submittal through FY17.

The MPPG results were briefed to NASA SMD at the end of August 2012, and a final report was delivered in September 2012,[21)]. The MPPG found that Mars sample return architectures provided a 'promising intersection of objectives and integrated strategy for long term SMD/HEOMD/STP collaboration'. The report provided program architectures that could be assembled by varying the scope, sequence, and risk posture assumed for the building blocks provided and analyzed by MPPG; NASA would be able to choose from these to build a program strategy consistent with its long-term objectives. The options included landed missions of various scope and complexity that could be launched in 2018 – 2022 Mars opportunities. These options are discussed in significantly more detail in Ref. 28).

In December 2012, at the San Francisco gathering of the American Geophysical Union (AGU), NASA Associate Administrator Grunsfeld announced the NASA decision that the next mission to be developed would be an MSL-heritage sample caching rover to be launched in the 2020 opportunity,[22)]. With this announcement, many scenarios and options (including launch year) under study were eliminated; the fundamental architecture of the mission and the launch year were specified and focused development could begin. Also announced at that time, NASA would be establishing a Science Definition Team (SDT) that would be "… tasked to formulate a detailed mission concept that is traceable to highest priority, community-vetted scientific goals and objectives (i.e., Vision and Voyages NRC Planetary Decadal Survey,[13)] and related MEPAG Goals/Objectives) that will be formally presented to the Mars Exploration Program and SMD leaders". NASA would then openly compete the science payload to be flown on Mars 2020, with the competition following the established processes of SMD.

4. Payload Selection and Description

An open call from NASA for membership in the Mars 2020 Science Definition Team (SDT) was released in late December 2012,[23)], very soon after the initial announcement of the mission in early December. The SDT was formed by late January 2013 and then spent the next five months developing the detailed mission concept. The report of the Mars 2020 SDT,[24)] was released in July 2013 and provided key inputs to NASA Headquarters that would enable the open and competitive call for the science investigations and instrumentation that would support the overall Mars 2020 mission objectives (including sample collection) of the mission.

The Mars 2020 Announcement of Opportunity (AO) was released in September of 2013,[25)], beginning the competitive and open opportunity for payload proposals to be developed for selection consideration for flight on the Mars 2020 mission. Responses to the AO were due and were submitted by mid-January 2014. On July 31st, 2014, from the 58 proposals submitted, NASA selected 7 for flight on Mars 2020. The selected investigations and their principal investigators are summarized below,[26)] and are depicted in Fig. 3:

1. Mastcam-Z, an advanced camera system with panoramic and stereoscopic imaging capability with the ability to zoom. The instrument also will determine mineralogy of the Martian surface and assist with rover operations. The principal investigator is James Bell, Arizona State University in Phoenix.

2. SuperCam, an instrument that can provide imaging, chemical composition analysis, and mineralogy. The instrument will also be able to detect the presence of organic compounds in rocks and regolith from a distance. The principal investigator is Roger Wiens, Los Alamos National Laboratory, Los Alamos, New Mexico. This instrument also has a significant contribution from the

Centre National d'Études Spatiales, Institut de Recherche en Astrophysique et Planétologie (CNES/IRAP), France.

3. Planetary Instrument for X-ray Lithochemistry (PIXL), an X-ray fluorescence spectrometer that will also contain an imager with high resolution to determine the fine scale elemental composition of Martian surface materials. PIXL will provide capabilities that permit more detailed detection and analysis of chemical elements than ever before. The principal investigator is Abigail Allwood, NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California.

4. Scanning Habitable Environments with Raman & Luminescence for Organics and Chemicals (SHERLOC), a spectrometer that will provide fine-scale imaging and uses an ultraviolet (UV) laser to determine fine-scale mineralogy and detect organic compounds. SHERLOC will be the first UV Raman spectrometer to fly to the surface of Mars and will provide complementary measurements with other instruments in the payload. The principal investigator is Luther Beegle, JPL.

   Following the Project SRR / MDR (October 2014), NASA Headquarters augmented the capability of the SHERLOC investigation by including a Wide Angle Topographic Sensor for Operations and eNgineering (WATSON) that: a) Augments turret fine-scale imaging capability by adding MSL MAHLI (Mars Hand Lens Imager) heritage optics, along with a multiplexer device, to the SHERLOC instrument, and b) provides contextual science and engineering data to the operations teams.

5. The Mars Oxygen ISRU (in-situ resource utilization) Experiment (MOXIE), an exploration technology investigation that will produce oxygen from Martian atmospheric carbon dioxide. The principal investigator is Michael Hecht, Massachusetts Institute of Technology, Cambridge, Massachusetts.

6. Mars Environmental Dynamics Analyzer (MEDA), a set of sensors that will provide measurements of temperature, wind speed and direction, pressure, relative humidity and dust size and shape. The principal investigator is Jose Antonio Rodriguez-Manfredi, Centro de Astrobiologia (CAB), Instituto Nacional de Tecnica Aeroespacial (INTA), Spain.

7. The Radar Imager for Mars' subsurFAce eXperiment (RIMFAX), a ground- penetrating radar that will provide centimeter-scale resolution of the geologic structure of the subsurface. The principal investigator is Svein-Erik Hamran, Forsvarets Forskning Institute (FFI), Norway.

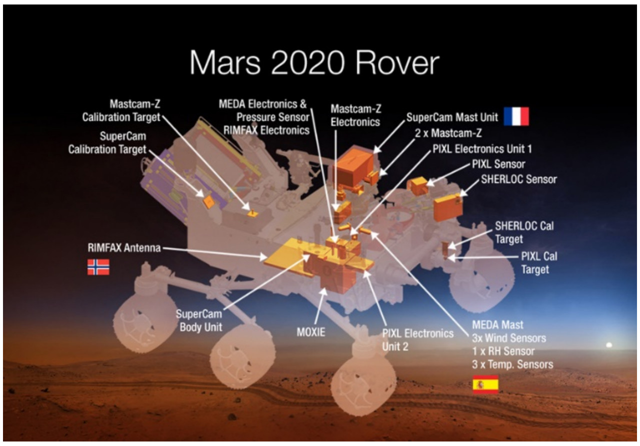

Fig. 3. Competed Payload Selection: Mars 2020.

5. Key Science Requirements

As described in the project's planning and requirements documentation, the Mars 2020 mission will deliver a rover to the surface of Mars; the rover will be designed to take scientific *in situ* measurements on Mars. The mission will also acquire, encapsulate, and cache individual scientifically selected samples of martian material for possible return to Earth by a future mission. The Mars 2020 Project primary science goals are to:

A. Characterize the processes that formed and modified the geologic record within a field exploration area on Mars selected for evidence of an astrobiologically-relevant ancient environment and geologic diversity.

B. Perform the following astrobiologically relevant investigations on the geologic materials at the landing site:

   1. Determine the habitability of an ancient environment.

   2. For ancient environments interpreted to have been habitable, search for materials with high biosignature preservation potential.

   3. Search for potential evidence of past life using the observations regarding habitability and preservation as a guide.

C. Assemble rigorously documented and returnable cached samples for possible future return to Earth.

   1. Obtain samples that are scientifically selected, for which the field context is documented, that contain the most promising samples identified in Objective B and that represent the geologic diversity of the field site.

   2. Ensure compliance with future needs in the areas of planetary protection and engineering so that the cached samples could be returned in the future if NASA chooses to do so.

In accordance with the objectives described above, the in-situ instruments in the selected payload suite will provide scientific measurements of martian surface materials that support surface geological and astrobiological investigations and provide contextual information for sample selection, including searching for potential biosignatures.

In addition to its scientific objectives, the M2020 project will conduct the following mission operations and technology validation experiments in order to support feed-forward to future Mars exploration missions:

D. Contribute to the preparation for human exploration of Mars by making significant progress towards filling at least one major Strategic Knowledge Gap (SKG). The highest priority SKG measurements that are synergistic with Mars 2020 science objectives and compatible with the mission concept are:

1. Demonstration of *In-Situ* Resource Utilization (ISRU) technologies to enable propellant and consumable oxygen production from the Martian atmosphere for future exploration missions.

2. Characterization of atmospheric dust size and morphology to understand its effects on the operation of surface systems and human health.

3. Surface weather measurements to validate global atmospheric models.

4. A set of engineering sensors embedded in the M2020 heatshield and backshell to gather data on the aerothermal conditions, thermal protection system, and aerodynamic performance characteristics of the M2020 entry vehicle during its entry and descent to the Mars surface.

6. Landing Site Selection

One of the most important open science questions at this stage in the development of M2020 is the upcoming NASA Headquarters decision finalizing the choice of landing site. Landing site selection for Mars 2020 is an open process informed by inputs from the international scientific community through a series of dedicated workshops and meetings, and guided by NASA Headquarters. The third workshop was completed in February 2017, narrowing the scientific recommendation for landing site to a final set of three primary landing sites (Jezero Crater, Northeast Syrtis, and Columbia Hills), and two backup sites (Mawrth Vallis and Nili Fossae) as summarized Table 1 and depicted below in Fig. 4.

Table 1. Post-Landing Site Selection Workshop #3: Top 3 Finalists,[27] & 2 Backup Sites.

Landing Site	Latitude (deg, N)	Longitude (deg, E)	Approximate Elevation (km)	Approximate Buffered Ellipse Axes (km)
Jezero Crater	18.4386	77.5031	-2.64	10.7 x 8.3
NE Syrtis	17.8899	77.1599	-2.04	11.1 x 8.2
Columbia Hills	-14.551	175.4527	-1.95	9.6 x 8.7
Mawrth Vallis	23.9685	-19.0609	-2.24	11.9 x 9.8
Nili Fossae	21.0297	74.3494	-0.65	9.7 x 7.7

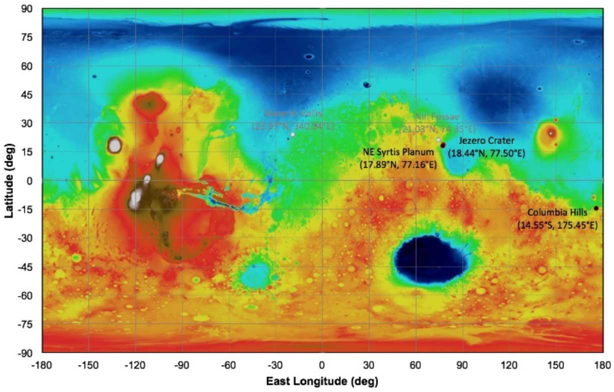

Fig. 4. Mars 2020 Landing Site Recommendations; top 3 sites.

The plan and expectation is that the final landing site would be selected two years before launch, in Summer 2018, following a fourth workshop earlier that summer.

A full discussion and status of the site selection process can be found in Ref. 27).

7. Flight System Description

The M2020 project will accomplish the above science and technology objectives by landing a single mobile science laboratory (i.e., a "rover") on the surface of Mars. Within the project development organization, the Mars 2020 Project Flight System (FS) is responsible for development of all of the flight hardware for launch, including the rover. The FS will use the proven design and technology developed for the 2011 Mars Science Laboratory (MSL) mission and rover (Curiosity) that arrived at Mars in August 2012 and is still in operation on the surface. The mission will fly a near-duplicate of the MSL rover outfitted with new payload elements to meet the above described science objectives and human exploration measurement goals. The project is highly dependent on heritage residual hardware, hardware designs and flight software proven by MSL. The flight system is overwhelmingly composed of MSL heritage components and assemblies and presents unique challenges during development when merged with the necessary new capabilities of the Mars 2020 mission,[28]. A key rover subsystem that deviates significantly from MSL heritage includes the Sampling and Caching Subsystem (SCS); the system designed to acquire rock cores in individually sealable tubes for later caching. The project is also integrating a new suite of instruments, as described above, that will necessitate redesign of the rover chassis for their accommodation. Highlights of the MSL-heritage design, and deviations, for the M2020 flight system are summarized below in Fig. 5.

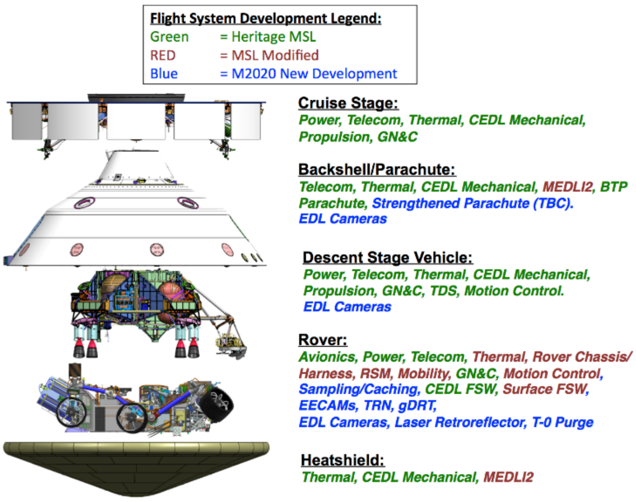

Figure 5. Mars 2020 Flight System, MSL Heritage and Deviations

The flight system, as configured for launch and cruise is shown below in Fig. 6.

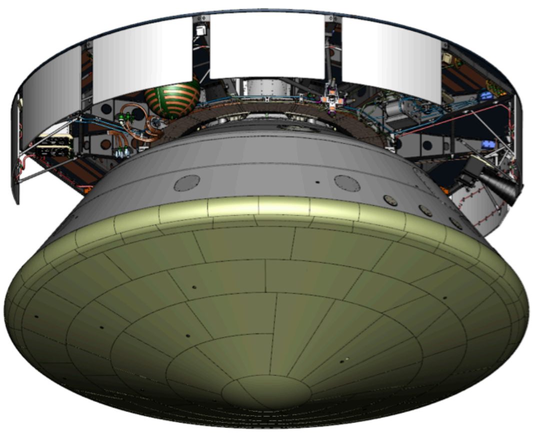

Figure 6. Flight System in the Launch / Cruise Configuration.

Fig. 7 shows a depiction of the aeroshell encapsulated flight system; the rover in its pre-deployed state enabling its accommodation within the Entry, Descent and Landing (EDL) descent stage propulsion system (the later shown in Fig. 8 below).

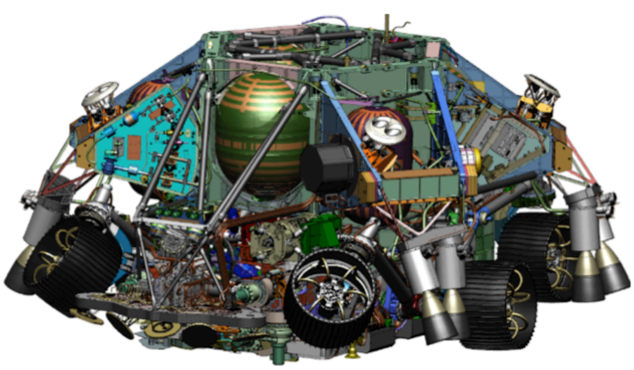

Figure 7. Descent Stage with Rover in Stowed Configuration

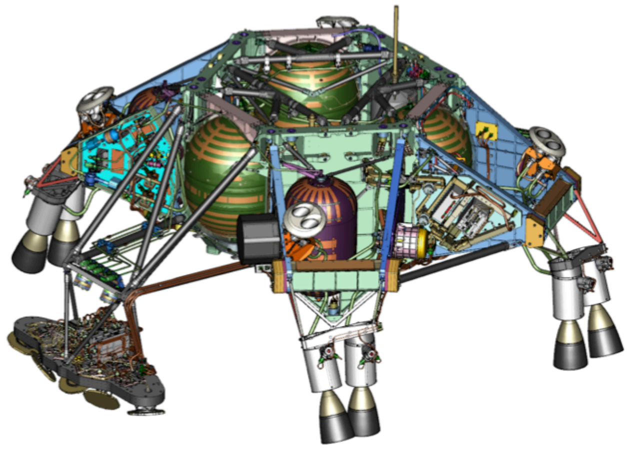

Figure 8. Mars 2020 Descent Stage (without Rover in Stowed Configuration)

The EDL timeline for landing is discussed below in a Section 8.3, showing the primary functions of each of these stages, enabling deployment of the rover to the surface of Mars.

The Mars 2020 rover (fully deployed from its descent stage configuration) is illustrated below in Fig. 9.

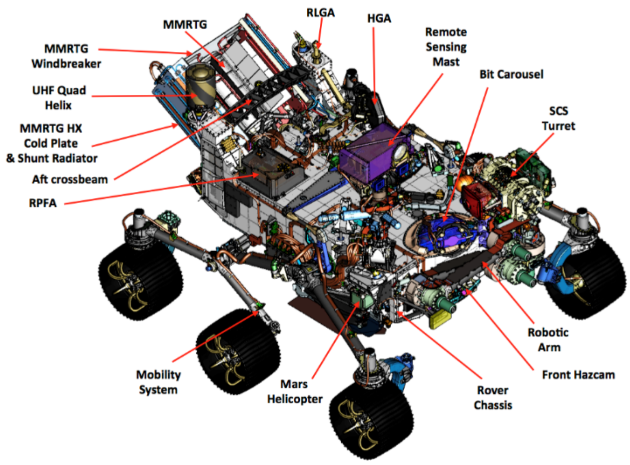

Figure 9. Mars 2020 Rover: Labeled Depiction

The sampling and caching system includes the robotic arm, the turret and all equipment necessary to interact with the surface of Mars and collect / store / release samples (located on the front of the rover). The functions of the SCS, as depicted below in Fig. 10, include the following:

- Accommodate PIXL & SHERLOC instruments.
- Prepare surfaces for further scientific examination or for coring through:
    - Abrasion (coring tool abrading bit).
    - Removal of dust (robotic arm accommodates a high pressure gas-driven dust removal tool, or, gDRT).
- Position instruments precisely on targets located in the workspace of the robotic arm.

- Position turret instruments on respective calibration targets located on Rover chassis.
- Acquire, document, prepare, and place on the surface Martian sampled materials (encapsulated drilled cores) and blanks (also know of as science witness materials). These particular SCS functions include:
  - Acquire rock cores (to a depth of ~10 cm) and regolith.
  - Accommodate and manipulate witness plate assemblies.
  - Assess samples (vision and volume).
  - Seal samples.
  - Store samples.
  - Drop prepared samples on Mars.

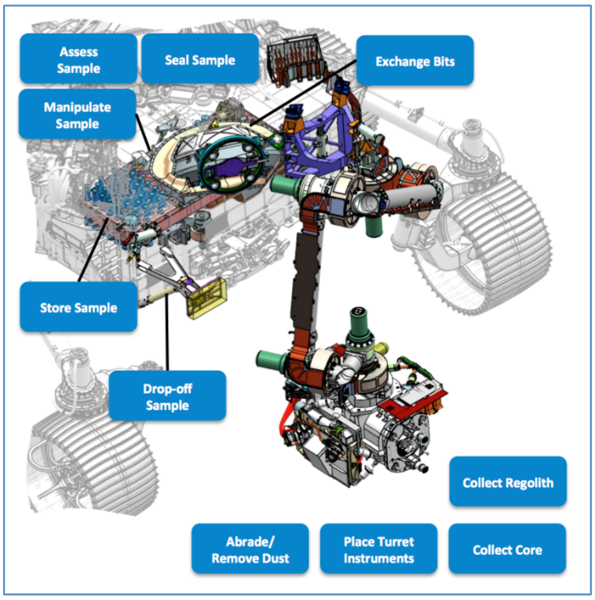

Figure 10. Mars 2020 Rover (front): Functionally labeled depiction of the Sampling and Caching System.

The SCS, along with the competitively selected payload described earlier, implements the investigation and mission objectives of NASA's Mars 2020 mission.

8. Mission System Description

Within the Mars 2020 project development organization, the Mission System (MS) comprises Mission Design (including launch vehicle targeting and Earth-Mars trajectory development) and Navigation (MDNAV) development, Mission Operations System (MOS) development, and Ground Data System (GDS) development as depicted below in Fig. 11. The MS is the ground-based system required to conduct project mission operations and consists of the following key components:

a) Human resources: Trained and certified personnel to operate and navigate the vehicle following separation from the launch vehicle, through cruise, EDL and all subsequent surface operations.

b) Procedures & Training: Documented, tested procedures and training to ensure that operations are conducted in a reliable, consistent and controlled manner, sustainable for the duration of mission operations. During development, this includes all mission design, trajectory design, mission planning and navigation analyses that would ensure proper targeting of the launch vehicle and a successful Earth-Mars transit in preparation for EDL. Also included are all surface operations plans and procedures that would ensure the daily and timely uplink of sequences and plans that would implement all rover-based science and technology development investigations, leading to the deposition of sample cache(s) on the surface of Mars.

c) Facilities: Offices, conference rooms, operations areas, training facilities, testbeds and other space to house the personnel, train the personnel, and perform the operations (with appropriate consideration for international partners / participation).

d) Hardware: Ground-based communications and computing hardware and associated documentation required to perform and sustain mission operations.

e) Software: Ground-based software and associated documentation required to perform mission operations and includes deep space navigation as well as all ground-based surface operations software (does not include payload-specific science analysis and operations software).

f) Tracking stations of the Deep Space Network (DSN); Tracking stations of the Earth network for on-orbit contingency operations; Tracking stations for specialized EDL UHF communications monitoring.

g) Relay network assets for EDL and Surface Operations (NASA and ESA network assets; coordinated through the Mars Exploration Program Relay Operations office).

The key MS systems engineering and subsystem development organizations are depicted below in Fig. 11. M2020 MS development seeks a significant improvement in performance and in the integration of GDS and MOS (tools and teams) than in past traditional JPL project developments. M2020 mission requirements necessitate a highly efficient and fast operations cadence, above and well beyond that employed by the heritage MSL Mission System. These key developments will be briefly discussed below in the MOS and GDS sections.

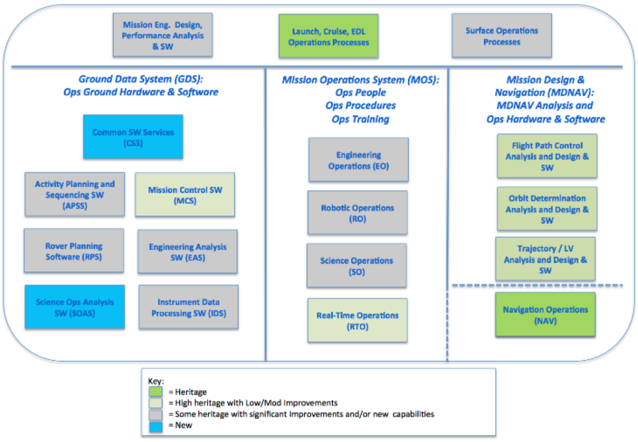

Figure 11. Mars 2020 Mission System Functions and MSL Heritage Summary (GDS, MOS and MDNAV)

8.1 Launch and Mission Design Description

A key tailored M2020 mission design activity is the development of the Launch Vehicle target specifications (launch vehicle aimpoints in 5-min increments for each 30-120 minute launch window, on each day of the currently planned twenty days of the launch period), the subsequent mission design and navigation analyses of the response to these specifications that is provided by the launch services contractor (LSC), and the selection of the landing site to be targeted by the M2020 mission.

The Mars 2020 mission will launch from the Eastern Test Range (ETR) at Cape Canaveral Air Force Station (CCAFS) in Florida during the 2020 Earth-to-Mars opportunity on an Atlas-V 541 launch vehicle using a Type 1 interplanetary trajectory (i.e. heliocentric transfer angle on the interplanetary trajectory is less than 180 degrees). The launch/arrival strategy consists of a launch period of 20 consecutive launch days extending from July 17th through August 5th, 2020 and a constant arrival day of February 18th, 2021. The launch period has a maximum launch energy, or C3, of 16.0 km^2/s^2 and a maximum declination of the launch asymptote of 35.3 deg. The daily launch windows are expected to be of at least 30 minutes in duration. The key characteristics of the launch period are shown in Table 2.

Table 2. Mars 2020 Reference Launch Period Characteristics

Launch Day	Launch Date (2020)	Arrival Date (2021)	Time of Flight (Days)	Earth Mean Equator of J2000 (EME2000)		
				C3 (km^2/s2)	DLA (deg)	RLA (deg)
1	07/17	02/18	216	14.4747	35.2561	13.9781
2	07/18	02/18	215	14.2705	34.2100	13.7234
3	07/19	02/18	214	14.1142	33.2317	13.4270
4	07/20	02/18	213	13.9870	32.2342	13.0942
5	07/21	02/18	212	13.8973	31.2597	12.7339
6	07/22	02/18	211	13.8435	30.3065	12.3541
7	07/23	02/18	210	13.8243	29.3743	11.9615
8	07/24	02/18	209	13.8381	28.4640	11.5621
9	07/25	02/18	208	13.8860	27.7060	11.1908
10	07/26	02/18	207	13.9569	26.8314	10.7891
11	07/27	02/18	206	14.0557	25.9844	10.3913
12	07/28	02/18	205	14.1805	25.1645	9.9983
13	07/29	02/18	204	14.3296	24.3714	9.6106
14	07/30	02/18	203	14.5016	23.6044	9.2279
15	07/31	02/18	202	14.6958	22.8629	8.8497
16	08/01	02/18	201	14.9118	22.1463	8.4755
17	08/02	02/18	200	15.1495	21.4542	8.1048
18	08/03	02/18	199	15.4096	20.7876	7.7369
19	08/04	02/18	198	15.6929	20.1497	7.3700
20	08/05	02/18	197	15.9999	19.5476	6.9952

The launch/arrival strategy is designed to inject a total launch mass of at least 4050 kg and deliver the flight system to the martian atmosphere with entry velocities between 5.2 km/s and 5.6 km/s, while allowing for EDL communication paths via orbiter relay or Direct-To-Earth (DTE) during Entry, Descent, and Landing (EDL), from atmospheric entry through landing plus one minute. The launch period for this particular design has a maximum atmosphere-relative entry speed of 5.4 km/s, occurring on a launch on day 1 of the launch period, for a scenario with Jezero (JEZ) crater as the landing site target.

It is highly desired to have at least two EDL communication paths should an anomaly occur during this critical event. The Mars Reconnaissance Orbiter (MRO), which successfully recorded open loop data during the Mars Science Laboratory (MSL) EDL event, will again be planned to be pre-positioned in an optimal geometry prior to the arrival of the vehicle to capture the M2020 Ultra-High Frequency (UHF) signal. The MRO sun-synchronous orbit is currently at a Local Mean Solar Time (LMST) of 3:00 PM. EDL coverage via MRO will be provided from an LMST as close as possible to that value to minimize impacts to the ongoing MRO Science mission. The range of required LMST values for the remaining candidate landing sites is between 3:00 PM and 3:30 PM. The X-band DTE link adds robustness to the EDL communication strategy; however, X-band semaphores do not contain telemetry data and are likely to be insufficient to fully reconstruct most EDL fault scenarios. In the 2020 Earth-to-Mars opportunity, later arrival dates favor DTE communications; hence, the launch/arrival strategy has the latest arrival date possible to extend DTE communications while preserving the required launch vehicle performance for a minimum of 20 continuous launch days. Even though, the launch/arrival strategy maximizes DTE communications, only the Columbia Hills (CHL) site has coverage from entry to landing plus one minute. The other two candidate landing sites, Jezero (JEZ) and Northeast Syrtis (NES), have DTE coverage from entry through some time after heatshield separation making EDL communications via MRO critical, since that path would be the only means to obtain EDL data should the M2020 mission target one of those locations. Currently, the Project is actively working with the Mars Program Office (MPO) to include the MAVEN orbiter as part of the EDL communications baseline. This would add a second UHF link to capture M2020 EDL telemetry. Key launch / arrival characteristics are illustrated in Fig. 12.

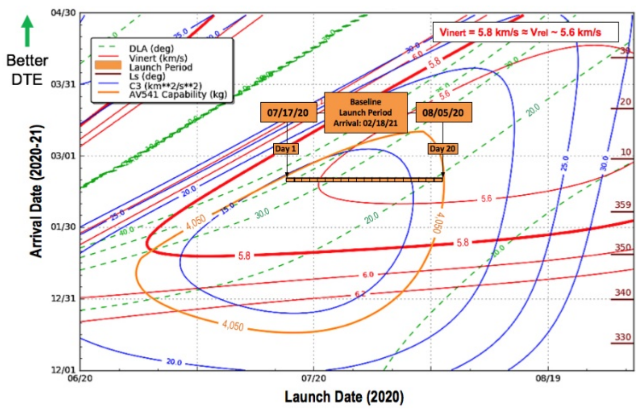

Figure 12. Launch/Arrival Performance Space: Hyperbolic Excess Energy & Launch Vehicle Injected Mass Performance

The cruise phase begins after the spacecraft has separated from the launch vehicle and it has reached a thermally stable, positive energy balance and a commandable configuration, and it ends when the vehicle reaches an altitude of 125 km with respect to Mars. During this phase, there is a series of events designed to characterize the flight system and perform checkouts of spacecraft and payload functions. Delivery accuracy at Mars will be achieved by executing as many as six Trajectory Correction Maneuvers (TCMs) during the cruise phase, which also encompasses the approach phase beginning 45 days prior to atmospheric entry. The cruise trajectory and TCM timing is shown in Fig. 13.

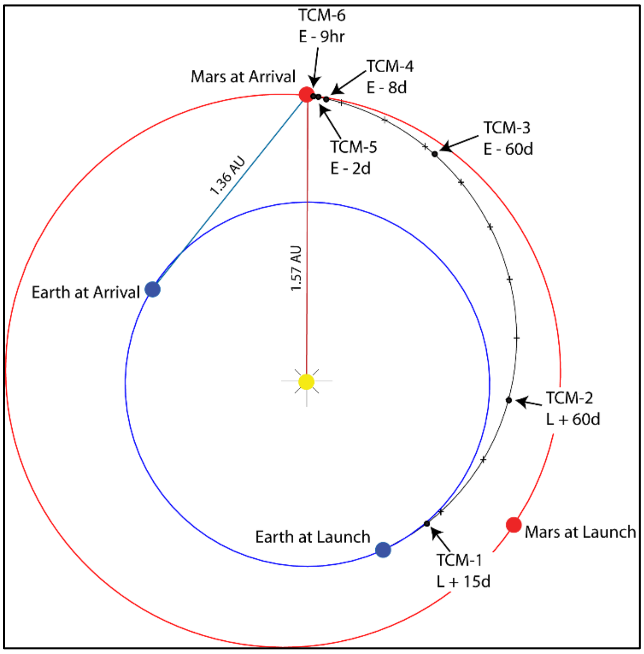

Figure 13. Earth-Mars Heliocentric Trajectory View

8.2 Navigation

The navigation system is the set of processes, procedures, software and hardware tools, and interfaces that are used to accomplish navigation functions during flight operations. As depicted in Fig. 14, the navigation system consists of three general functional elements: spacecraft trajectory propagation and analysis (s/c orbital dynamics), spacecraft trajectory determination (flight path estimation / orbit determination), and propulsive maneuver design and analysis (flight path control). The primary navigation functions during Mars 2020 flight operations are the following:

- Process radiometric tracking data (Doppler, range, and Delta-Differential One-way Range (or, ΔDOR; a very-long baseline interferometry, or VLBI, measurement)) to estimate and propagate the spacecraft trajectory with associated uncertainties.
- Perform EDL trajectory analysis to determine desired atmospheric entry aimpoints for Trajectory Correction Maneuvers (TCMs) and to evaluate landing site coordinates and landing footprints.
- Determine the ΔV vector for TCMs (flight path control) to achieve the specified atmospheric entry aimpoint and verify the TCM implementation & commands provided by the spacecraft team (for subsequent uplink to the spacecraft).
- Generate the spacecraft ephemeris and ancillary trajectory data products used by other operations and science teams.
- Provide real-time monitoring during TCMs and reconstruct the TCM ΔV using pre- and post-TCM tracking data.
- Perform EDL trajectory analysis to provide inputs for uplink of EDL parameter updates, including an estimate of the atmospheric entry state vector for initializing the hypersonic entry guidance algorithm.
- Provide design and analysis support for the UHF communications links between the entry vehicle and the Mars Odyssey, MRO, MAVEN, TGO, and Mars Express orbiters (as appropriate).

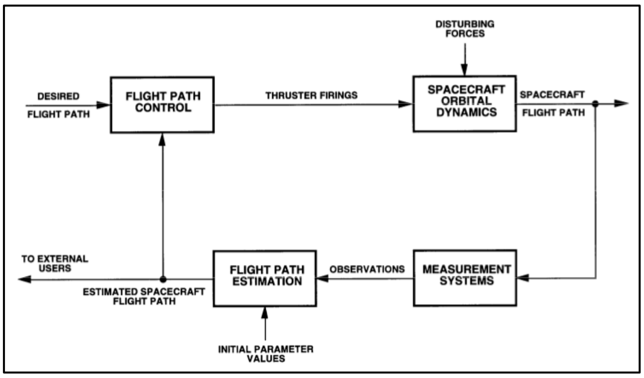

Figure 14. Mars 2020 High-level Depiction of Navigation Functions

Monte-Carlo and analytical methods are used by the Navigation Team to gain insight into the uncertainties in the navigation performance during all phases of the mission, and are used to V&V navigation requirements. M2020 will use the heritage Navigation S/W capabilities of MSL and key implementation strategies (e.g. Trajectory Correction Maneuver (TCM) modes and timelines during Earth-Mars cruise). TCM nominal timeline, and purpose of each TCM is summarized below in Fig 15.

TCM	Date	Purpose
TCM-1	L + 15 days	Correct injection errors; remove all or part of injection bias for planetary protection; aimpoint biased for planetary protection.
TCM-2	L + 60 days	Correct TCM-1 errors; remove all or part of injection bias for planetary protection (if needed); first opportunity to target to desired atmospheric entry aimpoint; vector-mode maneuver.
TCM-3	E - 60 days	Correct TCM-2 errors; target to desired atmospheric entry aimpoint; vector-mode maneuver.
TCM-4	E – 8 days	Correct TCM-3 errors; vector-mode maneuver.
TCM-5	E – 2 days	Correct TCM-4 errors; final entry targeting maneuver required to achieve EFPA delivery accuracy requirement; vector-mode maneuver.
TCM-5X	E – 1 day	Contingency maneuver for failure to execute TCM-5; vector-mode maneuver.
TCM-6	E – 9 hours	Contingency maneuver; final opportunity for entry targeting; vector-mode maneuver.

Figure 15. Mars 2020 Earth-Mars TCM Timeline / Plan

Navigation tracking coverage (Doppler, range, and ΔDOR) by the DSN for Mars 2020 is baselined using the 34-meter High Efficiency (HEF) subnet, with critical support augmented by the DSN 70-meter subnet. The M2020 flight system uses its X-band telecommunications system, with an X-band Uplink / X-band Downlink to communicate with the DSN. Several different X-band antennas are used on the FS to establish these links with the DSN:

- The Parachute Low Gain Antenna (PLGA) on the backshell and a Medium Gain Antenna (MGA) on the cruise stage provide communications during interplanetary cruise. A backshell-mounted Tilted Low Gain Antenna (TLGA) provides spacecraft-to-Earth downlink during EDL.

- A High Gain Antenna (HGA) and Rover Low Gain Antenna (RLGA) pair on the rover for surface operations.

Two redundant UHF transceivers in the rover are used with the following antenna configurations for entry and surface operations purposes:

- Antennas mounted on the parachute cone (PUHF) and on the descent stage (DUHF) in support of EDL Mars 2020-to-orbiter downlink.
- Rover-mounted UHF antenna (RUHF) to support surface communications and 2-way coherent Doppler collection by the orbiters.

For about the first 70 days of flight, the spacecraft will utilize the PLGA on the cruise stage. After that time, the spacecraft will utilize the cruise MGA. The baseline coverage includes ΔVLBI measurements (ΔDOR) during the Cruise and Approach phases. The ΔDOR data type has been incorporated into the navigation baseline in order to satisfy the entry delivery accuracy requirement (providing key plane-of-sky direction information that complements line-of-sight range and range rate information from the flight system's X-band radios). As illustrated in Figs. 16 - 19, navigation statistical analyses completed across all Landing Site Selection Workshop (LSSW) #2 landing sites under consideration (8 sites = 8 curves per figure), at that time, span all possible latitude bands and encompass the final 3 sites described earlier) provide assurance that the MS will meet all key navigation performance requirements including those targeting and uncertainty requirements depicted below. These key performance metrics include B-Plane targeting (Fig. 16), as well as entry flight path angle (EFPA) targeting and uncertainties (Fig. 17) and, position (Fig. 18) and velocity (Fig. 19) uncertainties at arrival. In summary, the EFPA Entry Requirement is expected to be met for all landing sites at the time of the design of TCM-5, and the EDL Update Requirements (position and velocity) are met for all landing sites at Entry-6 hours (E-6h).

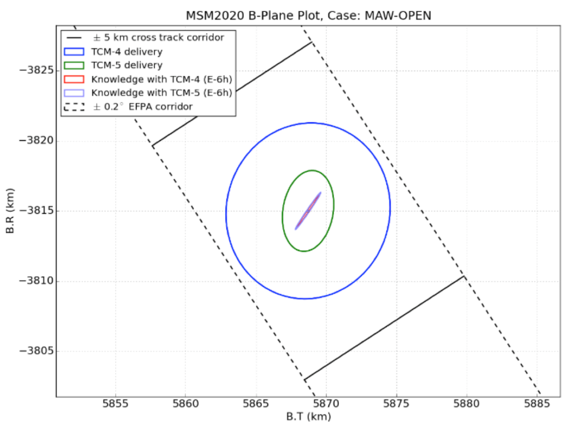

Figure 16. Mars 2020 Approach: B-Plane delivery

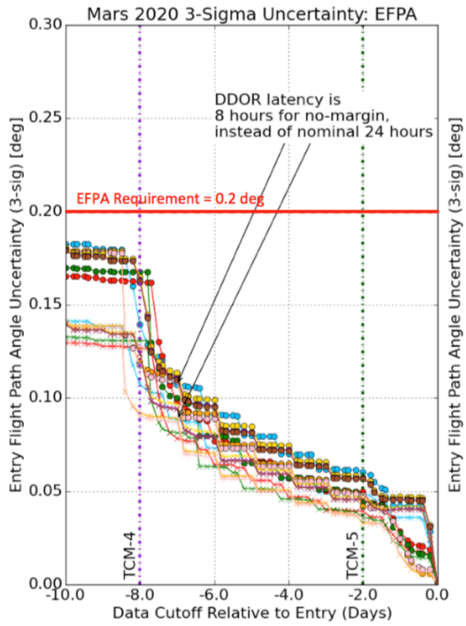

Figure 17. Mars 2020 Approach Navigation Accuracy (Delivery), Entry Flight Path Angle

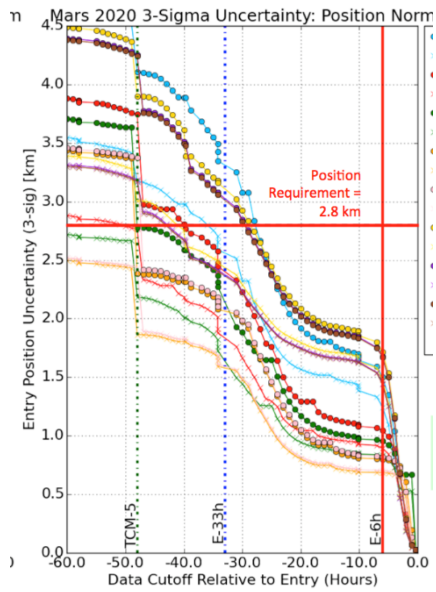

Figure 18. Mars 2020 Approach Navigation Accuracy (Knowledge), Position Uncertainty vs Requirement

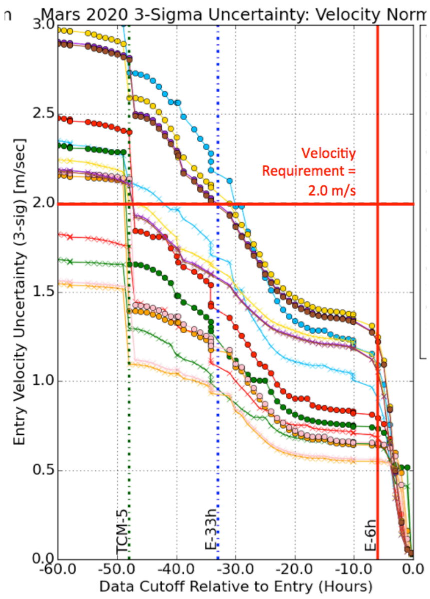

Figure 19. Mars 2020 Approach Navigation Accuracy (Knowledge), Velocity Uncertainty vs Requirement

8.3 Entry, Descent and Landing Description

The Mars 2020 EDL system is part of the flight system (Section 7), and is based heavily on the as-flown 2011 MSL EDL architecture. Just as with MSL, the EDL phase will begin at entry vehicle separation from the cruise stage and end with the soft touchdown of the rover on the surface and the subsequent separation and descent stage flyaway (see Fig. 20).

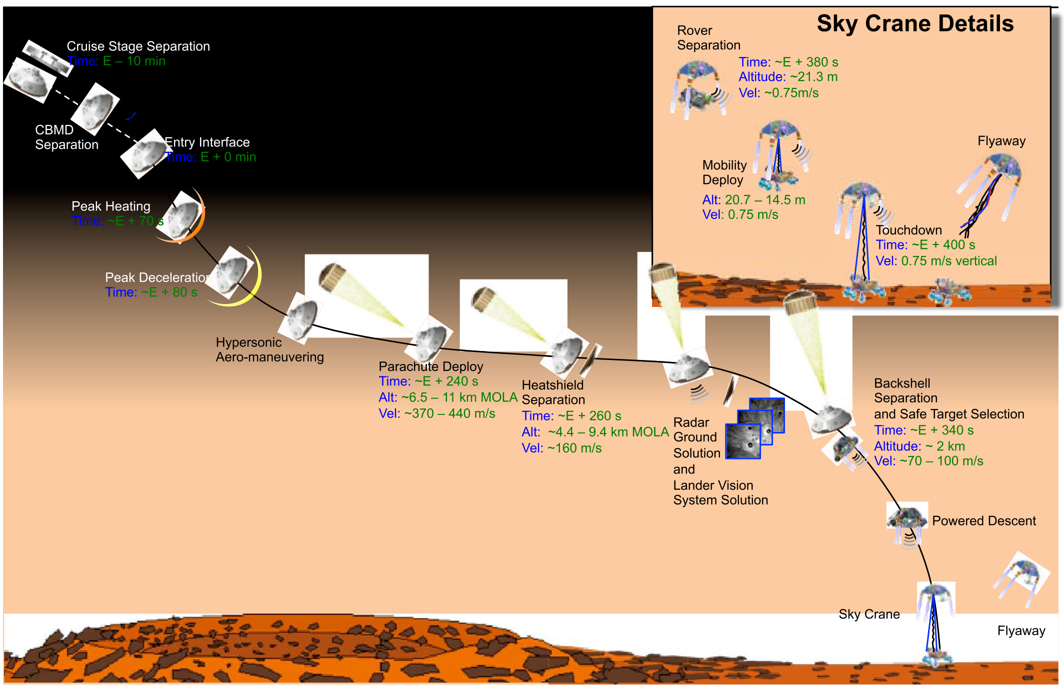

Figure 20. Entry, Descent and Landing high-level timeline.

Like MSL, the spacecraft will enter the Mars atmosphere directly from its interplanetary trajectory, without first entering orbit about Mars. Aero-maneuvering will be performed during the hypersonic and supersonic portions of atmospheric flight in order to reduce the landing site errors that result from atmospheric variations and aerodynamic uncertainties. For M2020, the deployment of the parachute will be based upon "range to the target" rather than "navigated velocity" as was the case for MSL parachute deployment. This is referred to as "range trigger" for supersonic parachute deployment. "Range Trigger" enables a more accurate landing capability and is described more completely in M2020 EDL Refs. 29) – 35). Additionally, a new capability will be included in M2020 to enable a hazard avoidance capability that would steer the vehicle relative to an on-board map. This capability is referred to as Terrain Relative Navigation (TRN).

TRN, during the actual descent to the surface, gives Mars 2020 "eyes" to enable avoidance of previously identified landing hazards (i.e. hazards identified pre-launch based upon high resolution orbital imagery). TRN is a critical capability for the mission as it enables landing at sites that would otherwise have been rejected as having too many landing hazards within the predicted landing ellipse (two of the three final landing sites require TRN to enable their selection consideration). When combined with range trigger, the TRN system (see below) gives the system a significant improvement in landing site accessibility.

As depicted below in Fig. 21, the Terrain Relative Navigation system (TRN) takes images during parachute descent and matches them to an onboard map using a dedicated computer (vision compute element, or VCE) and a rover-mounted down-looking camera. These sensors are used to provide a landing position prediction solution during EDL, while the spacecraft is priming the descent engines. The system uses the position solution and an onboard map to select a nearby safe landing point (within an adjustment radius of approximately 650 meters). This solution is used to augment an original MSL-heritage backshell avoidance divert maneuver to avoid the selected hazard. This capability is implemented within the heritage descent propellant constraints of MSL and within the heritage EDL timeline described below and illustrated earlier.

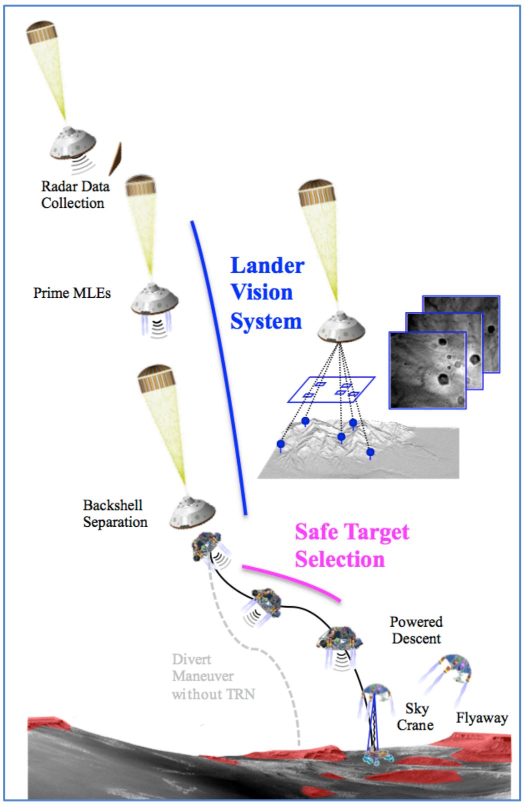

Figure 21. Terrain Relative Navigation (TRN) during Entry, Descent and Landing Phase

Before entry, the cruise stage is jettisoned, and the thermal fluid loop vented. The entry vehicle, consisting of the backshell, heat shield, descent stage and rover, performs a series of guided maneuvers to reduce the effects of atmospheric and aerodynamic uncertainties, thereby reducing the size of the landing ellipse as compared to prior missions. This is followed by parachute deployment, heat shield separation, and initiation of the landing radar. Powered descent guidance will trigger backshell separation at about 1,600 m above the surface and the Mars Lander Engines (MLE) will be ready to slow down the descending vehicle. One second after the vehicle free falls out of the backshell (timed to avoid recontact) the main engines will be throttled up from their 1% near shutdown condition set just prior to triggering backshell separation. The descent stage will approach the surface, and at approximately 19 m above the surface, it will begin to lower the rover, whose wheels have been deployed during the descent, to the surface. Upon successful touchdown, the descent stage will fly away, eventually impacting the surface at a safe distance from the rover. The rover will be delivered to the surface on its mobility system, ready for implementation of key final rover deployments prior to the beginning of surface operations.

8.4 Surface Operations

Following landing of the rover on the surface of Mars, and following a period in which key post-landing engineering deployments and software updates are completed, the rover will be ready for implementation of daily tactical surface activities that would conduct desired engineering and science investigation activities.

The M2020 MS uses MSL-heritage mission planning scenario tools and sophisticated image processing and path planning capabilities to model surface mobility and traversability, to guide design choices in the MOS and GDS systems and to simulate the value of various design trades and capabilities. The M2020 scenario modeling tool brings these capabilities together and links together many of the important conditions and constraints for rover engineering and payload operations, as well as science investigation goals and strategies, to simulate 'days-in-the-life' surface mission investigation scenarios. These scenarios are linked together to simulate end-to-end mission performance over the surface mission lifetime. Monte-Carlo techniques can statistically vary key parameters of the scenario model to provide insight into the uncertainties in mission performance.

A key part of the simulation effort is an understanding of how the duration of the tactical timeline (combined with other factors) can change what is referred to as the 'operations efficiency' for surface operations. For Mars surface missions, a given operations configuration—including ground operations team staffing schedules and relay communications patterns of an assumed relay orbiter configuration—has an associated "ops efficiency"; a ratio indicating how often the ground operations team can interact with the spacecraft effectively (as defined and described in Ref. 36). This ratio is that of an unconstrained activity plan (s/c state data is available such that any activity can be planned) to a constrained activity plan (where not all activities can be planned due to downlink state information unavailability). This ratio can then be used in the surface mission model to ensure that the interaction of ground teams with the spacecraft is taken into account when determining the prime mission duration and science productivity during that mission. Mars 2020 has developed an ops efficiency tool to quickly analyze various staffing patterns, workday durations and relay overflight scenarios to provide input into the scenario simulation tool.

M2020 scenario and mission modeling include rover execution of specific sol template activities within the sol-by-sol resource constraints and factor the following:

- Rover activities to acquire next sol's decision data (and other science and engineering data).
- Time based constraints (duration available, daytime, Communication Periods, etc.).
- Power consumption and constraints (Watt-Hrs (e.g. actuator and instrument heating), Battery State-of-Charge, SOC).
- Data Production and Storage
- Data Volume

The model must also factor how much and how quickly data can be transferred to the ground operations teams on Earth. Mars 2020 assumes a relay and deep-space telecommunications configuration as illustrated in Fig. 22 below.

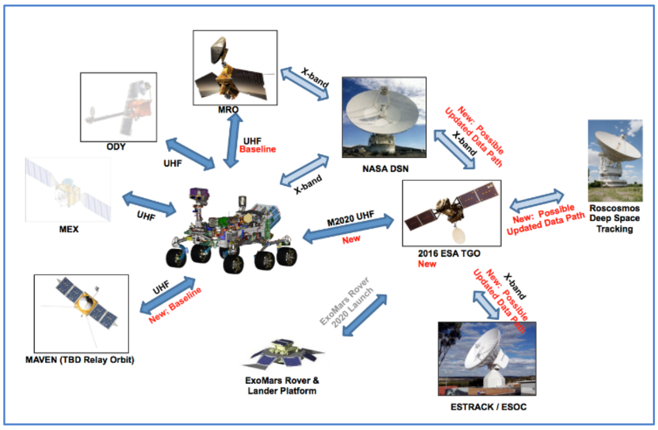

Figure 22. Deep Space and Mars Relay Network Configuration Illustration

Modeling of the relay and direct-from-Earth (DFE) communication patterns enable capture of sol-by-sol Uplink and Downlink opportunities and bandwidth performance:

- Relay Orbiter(s) and link performance (pass-by-pass simulations factoring antenna performances, elevation views and slant ranges):
  - Assume various permutations of Odyssey, MRO, MAVEN and ESA TGO relay overflights, cadences and data return latencies that would span possible configurations (and orbit geometries) that could be in place when the M2020 surface mission begins in February of 2021.
- DSN passes for Uplink of daily tactical sequences.

Ground-based flight team activities necessary to analyze downlinked data and produce uplink command products include:

- Data preparation & Distribution,
- Data Analysis,
- Activity Generation & Planning (science and engineering operations),
- Sequence Generation & Verification,
- Command Approval and Release to DSN for uplink and radiation to the vehicle.

All of the above factors are modeled as illustrated below in Fig. 23 to produce mission performance data to compare against the requirements necessary to meet overall mission objectives.

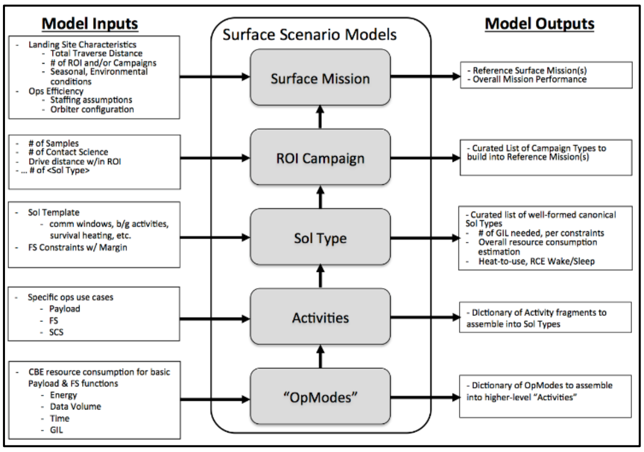

Figure 23. Mars 2020 Surface Operations Model Illustration

The M2020 simulation tool provides many mission cumulative reports. The MS uses these reports and analyses to inform the project of status and to inform key engineering trades. The MS scenario-based tools have been used in the project development period to evaluate various flight and ground system options, and individual landing site considerations.

Productivity modeling results (e.g. number of samples collected over time) lead to MS requirements that significantly challenge MSL-heritage surface operations capabilities. Fig. 24 below summarizes a few key highlights of the challenges posed by M2020 when compared against actual MSL surface operations performance. Detailed performance model results from the above capabilities provide specific improvement targets for meeting the M2020 requirements.

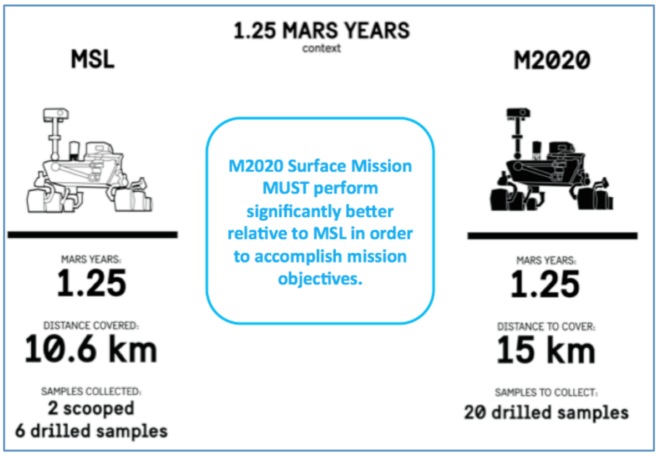

Figure 24. Mars 2020 Operations Challenge with respect to MSL Performance

8.5 Mission Operations System Description

Mars 2020 requirements specify that 20 samples for a cache must be collected within 1.25 Mars years. To meet this science and mission objective significant operations productivity improvements are necessary. There are five basic guiding principles that the project is following to improve productivity and meet the science objectives:

1. Remove ground in the loop (GITL) cycles as much as reasonable
   - Trades must be made on productivity impact versus effort to remove GITL cycles
2. Remove restricted planning sols as much as possible
   - Process and timeline trades can potentially minimize tactical planning such that Earth-Mars phasing cycle has much less impact on operations
3. Perform functions (flight and ground) more quickly between GITL cycles
   - Speeding up the ground ops process as well as key activities on the vehicle (e.g. auto-navigation) will enable better productivity
4. Increase the time the vehicle is actively pursuing science per sol
   - Utilize available time and resources onboard the rover to the greatest extent practical
5. Design things that are regularly done on the vehicle to be simple for operations to implement
   - Focus design of nominal and regular activities on operational ease to execute.

These guiding principles would increase the amount of surface science that can be accomplished over a given period of time, maximizing the number of individually tailored sequences that can be uploaded to the rover on a daily basis (i.e. increase the number of ground-in-the-loop, or GITL, sequence development cycles over a given time period of surface operations time).

A key method for increasing the number of GITL cycles is to decrease the amount of time it takes for the ground operations team to develop the daily sequence of commands to send to the rover, and yet still have those commands accomplish the necessary number of tailored science measurements on a given day (item 2 in the list above). The MS performance analyses, simulations and predictions (relying upon the tools described earlier) have led to a requirement to develop daily tactical uplink products within a five hour tactical timeline (i.e. from the time of receipt on the ground of the key information pertaining to the previous sol's activities, there is only five hours of ground development time available before the next sol's sequence of activities needs to be available for timely uplink to the rover via the DSN and the rover's HGA). This is a key and driving operations performance challenge.

Mars 2020 expects to meet this challenge of a five-hour development timeline, through the development and implementation of capabilities within the MOS processes and within the ground software capabilities to be delivered by the GDS that would include:

- Auto-expansion, simulation and validation to enable the development of higher-level surface operations plans into verified and uplinkable sequences, without resorting to command line review and / or manipulation.
- Proximity science and coring target planning utilizing common target viability assessment tools for science and engineering and automation of many rover planner tasks.
- Data transformed to information quickly such that key information and spacecraft status are available as soon as possible after receipt of the previous sol's data, for commencement of uplink planning.
- Science decision-making with strategically thought out and documented criteria such that newly downlinked information can be quickly and easily formulated into an appropriate sol plan tactically.

Implementation and modeling of this new MS capability shows, over a 1.25 Mars Year surface mission (beginning in February of 2021), that all engineering, science and technology activities can be implemented, achieving the overall M2020 mission objectives.

To meet the daily 5-hour development timeline objective, the uplink process is started months in advance with strategic and campaign planning to establish clear science intent and gross resource estimation such that downstream plans are likely to succeed with the exception of unforeseen circumstances (see steps 1 & 2 in Fig. 25).

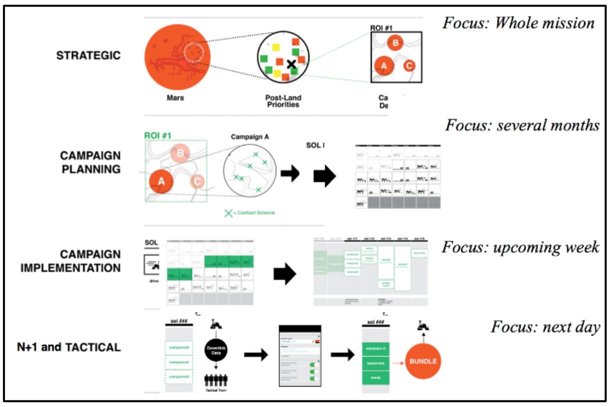

Figure 25. M2020 Surface Operations Uplink Process: Illustration of Strategic, Campaign Planning, Campaign Implementation and Tactical Processes.

During campaign implementation (step 3 in Fig. 25), the details of resource estimation and science intent are codified. Detailed plans developed during campaign implementation are fed to the daily tactical process (the last step depicted in Fig. 25). In order to meet the 5 hour tactical timeline, only the minimal set of activities required to be informed by the downlink (e.g. targeting) are allowed to be completed during the final tactical process. All other functions will have been completed prior to tactical, in one of the previous three stages of planning.

8.6 Ground Data System Description

The GDS is the computing information technology (IT) infrastructure and facilities required to operate the mission operations system (MOS) during development, training, test and flight operations. It is the integrated set of ground software, hardware, facilities, and networks that support M2020 mission operations during all phases of the M2020 mission. The GDS supports spacecraft and instrument testbeds; flight software development environments; spacecraft simulators; Mission Support Areas (MSA) for cruise, EDL, surface and training; ATLO Flight System integration and test; Launch; and on-orbit contingency operations. Operations teams and processes, and the flight system including the payload system, and associated ground support equipment, are not considered part of the GDS.

The GDS includes the generation of all instrument (science and camera) Level-0 products (Experiment Data Records, or EDRs). Production of all camera (cameras on all instruments except MOXIE) Level-1 products (Image and Terrain Reduced Data Records, or RDRs) is also under the purview of the GDS. The bulk of science RDRs will be produced using GDS generated relevant EDRs, by the respective science teams and their GDSs.

Some of the key drivers for M2020 GDS design are dictated by the need to revamp the MSL GDS infrastructure and tool suite to respond to the 5 surface productivity guiding principles (see MOS section above) needed to meet M2020 mission objectives to acquire 20 drilled samples in 1.25 Mars years while traversing a total distance of 15 km. The key GDS design drivers (or key requirements) are as follows:

1) Reduced 5-hour tactical timeline for surface operations: Tools need to be simpler, more integrated, and of higher performance.
2) Sub-processes requirements within the 5-hour tactical timeline include: 5-minute deadline on downlink processing, and 20-minute deadline on downlink assessment for planning "Go/No-Go" during the 5 hr tactical timeline for surface operations: Downlink processing, including science data processing, needs to be very fast and streamlined.
3) Provide the ability for local and remote users of mission data to access it from one central repository: Faster access to data from a unified repository.
4) Automate tasks wherever possible: Automation will be needed during the 5 hr and 5 minute downlink processing timelines.

5) Smaller, more focused tools with higher usability and ease of operations.

6) 'Push' data immediately upon creation, to tools and users that need it, contrary to 'pull' data when needed.

7) Optimize for system-wide performance and throughput.

8) Sustainable GDS infrastructure that leverages modern technologies such as the Cloud.

9) Ability to maintain minimum operations capabilities of uplink and downlink processing without reliance on external services such as the Cloud.

10) Secure data access compliant with government and NASA policies that include International Traffic in Arms (ITAR), Export Administration Regulations (EAR), and Space Asset Protection policies.

11) Employ flight like GDS configurations in Assembly, Test and Launch Operations (or, ALTO) and System Testbeds to gain experience and to avoid test as you fly exceptions.

The approach for the ground architecture is to adapt the baseline MSL software to the Mars 2020 GDS requirements, building upon prior mission design, development, and operations legacies to the largest extent possible. Mars 2020 GDS continues to make use of the standard multi-mission services / capabilities where possible and affordable. These include the following components:

- Deep Space Network (DSN); for commanding (CMD) and telemetry (TLM)
- Advanced Multi-Mission Operations System (AMMOS) for:
  - Tracking, Telemetry, Command & Data Management (TTC&DM)
  - Sequencing Software & Tools (SEQ)
  - Navigation Software & Tools (NAV)

In addition to these key design drivers, the Mars 2020 GDS architecture also incorporates the lessons learned from MSL and MER. GDS will incorporate modern design, development, test, and deployment practices and tools, as are commonly found in the software industry. This will significantly improve software integration and the efficiency of development, test, and deployment across the GDS. The use of shared infrastructure across the GDS, by leveraging 3rd party tools and services wherever possible, will enable the GDS to focus on work specific to the M2020 mission.

The M2020 GDS is broken down into seven different subsystems, namely, Mission Control Subsystem (MCS), Engineering Analysis Subsystem (EAS), Instrument Data Subsystem (IDS), Rover Planning Subsystem (RPS), Activity Planning and Sequencing Subsystem (APSS), Common Software Services Subsystem (CS3), and Science Operations and Analysis Subsystem (SOAS). Fig. 26 depicts the operations functionality of each subsystem in the daily MOS flow / process of generating uplink products and acquiring downlink products.

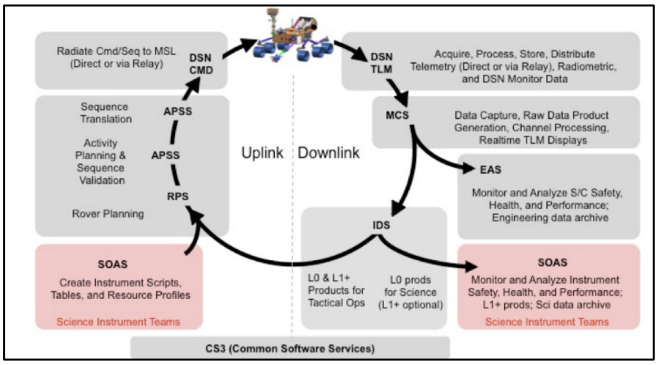

Figure 26. MOS & GDS Subsystem Functions and Flow in Tactical Surface Operations

The Common Support Services Subsystem (CS3) ties together GDS development with a unified team of s/w development personnel providing common libraries, scripting, development processes and controls under uniform management. The interfaces and key products of each of the seven GDS subsystems are further defined in Fig. 27 and provide an indication of their function within the MOS processes.

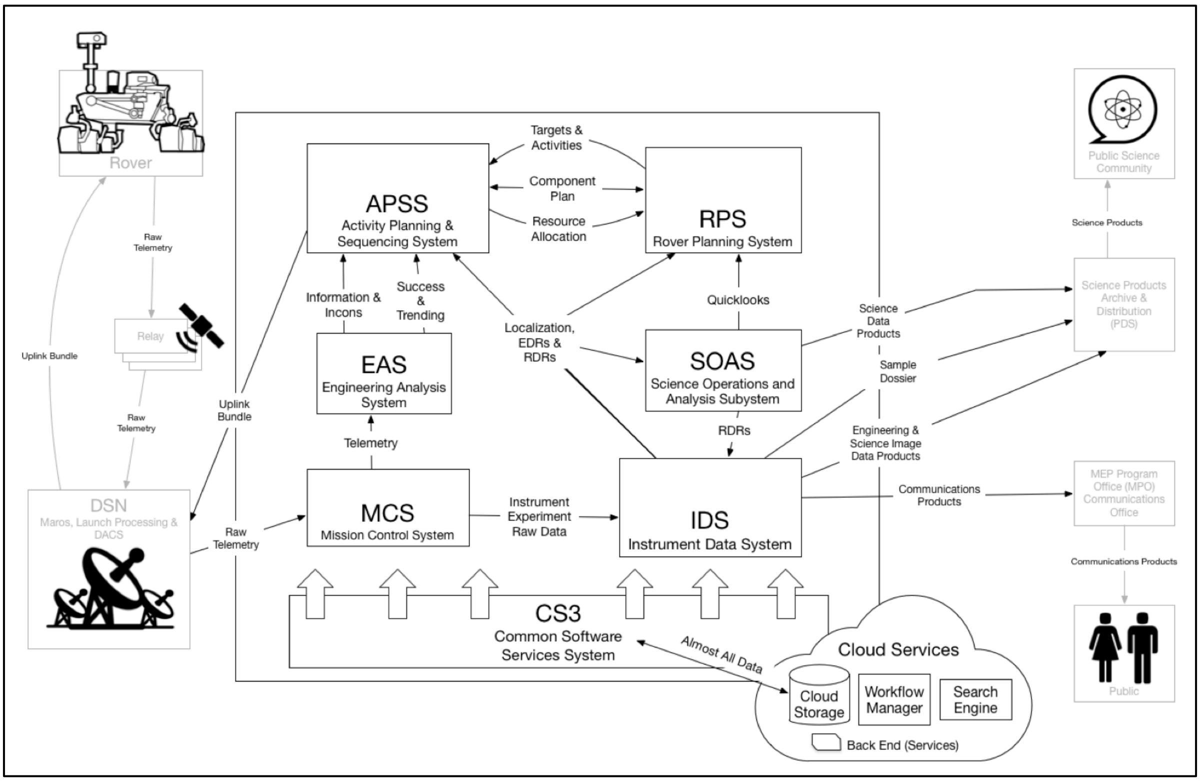

Figure 27. M2020 GDS Subystems

M2020 GDS architecture will expand the use of cloud-based storage and compute resources, beyond MER and MSL usage levels. Cloud computing is the on-demand delivery of compute power, database storage, applications, and other IT resources through a cloud services platform via the internet. M2020 GDS is expanding the use of cloud computing as it allows for an easily scalable, highly available, and cost effective architecture.

9. Acknowledgements

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