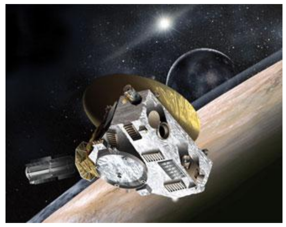
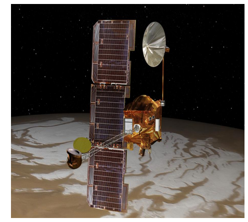
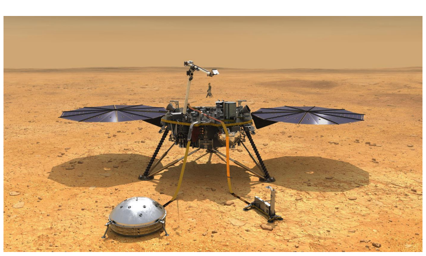
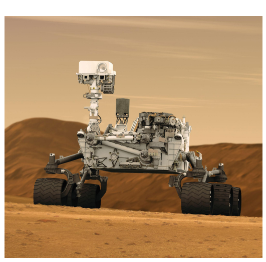





Final Report Package

2022 NASA Planetary Mission Senior Review (PMSR22)

April 25, 2022

PMSR22 Final Report Package

- Final Report
- Individual Mission Evaluations
  - InSight
  - LRO
  - MAVEN
  - MRO
  - MSL
  - Mars Odyssey
  - OSIRIS-APEX
- List of Panelists

2022 Planetary Mission Senior Review (PMSR-22) Final Report

30 March 2022

1 Executive Summary

The 2022 Planetary Mission Senior Review (PMSR) was conducted by two separate groups of reviewers assembled as (1) an independent Panel for each of eight missions led by a Group Chief and (2) two senior Review Chairs covering the overall process and generating the final report. All meetings and caucuses were conducted on Google Meet. The Panels conducted the in-depth review and analysis of each mission proposal and produced a detailed report. Mission proposals were available to Panels two weeks prior to the initial discussions. Questions were generated by each Panel for their assigned mission and advanced to the mission proposers three weeks prior to their presentation to the Panel. Each extended-mission team was allotted 2 hours for their presentation consisting of updates since proposal submission and responses to the Panel questions. Six and one-half hours of caucus time were set aside for each Panel in which they carefully established and refined strengths and weaknesses and then crafted the core of the Panel's report. The Review Chairs participated in every presentation and Panel caucus, primarily as observers with occasional input as relevant to their expertise but remained neutral during Panel scoring. Once the Panel reports were complete the Review Chairs independently deliberated and scored all missions while providing a top-level synthesis and leveling function across the eight missions and Panels. This independent scoring resulted in the Review Chairs' scores being different than the final Panel score for Insight, MAVEN, and MSL. Table 1 shows the Panel and Review Chair scores and a brief description of the 3 differences.

Table 1. Summary of Top-Level Mission Scores (Ordered Alphabetically)

Mission	PMSR Panel's Score	PMSR Review Chairs' Score	Difference Rationale (details in mission evals)
InSight	E/VG	N/A	Probable loss of lander before EM2 makes scoring misleading.
Lunar Reconnaissance Orbiter (LRO)	E/VG	E/VG	
Mars Atmosphere and Volatile EvolutioN (MAVEN)	E/VG	E	Excellent is consistent with numerous major and minor strengths plus no major and few minor weaknesses.
Mars Reconnaissance Orbiter (MRO)	E	E	
Mars Science Laboratory (MSL)	E/VG	VG	Very Good better reflects leadership and operational challenges to achieve impactful study of sulfate-bearing unit given declining power and limited consumables.
Mars Odyssey (ODY)	VG	VG	
New Horizons (K2) --Planetary	VG/G	VG/G	
--Incl Astro/Helio	E/VG	E/VG	
OSIRIS-APEX	E/VG	E/VG	

The Review Chairs identified nine top findings and actionable recommendations as the most important outcomes of the 2022 PMSR. The following summary includes review process (1-2), specific missions (3-5), and overarching coordination of spacecraft operations (6-9):

(1) Setting reasonable, achievable review schedules are critical to perceptive reviews, especially when reviews are done virtually.

(2) Clearer budgets in a defined format, and eliminating descope proposals, will improve budget assessment and Panel efficiency.

(3) The Planetary Science Division should consider forming a formal lessons-learned activity over the loss of InSight.

(4) LRO operations need guidance on adjusting to NASA's growing programmatic needs across multiple NASA and commercial activities.

(5) MSL leadership should seriously consider the possibility that EM5 is its final period of Mars exploration, and plan operations accordingly.

(6) Consider a dedicated Program Scientist (PS) and/or Program Executive (PE) to enhance scientific and programmatic coordination among all PSD (and SMD) missions.

(7) Develop principles to enhance top-leadership opportunities.

(8) Consider casting a broader net to cover infrastructure upgrade costs for MMOLMWEB, utilized by all JPL/Lockheed Martin (LMA) missions.

(9) Immediate planning is needed for cross-NASA and inter-Agency coordination of Solar Energetic Particle (SEP) observations during the coming solar maximum.

2 Review Process

2.1 Background and Panel Construct

The Planetary Mission Senior Review was conducted over a six-week period in February through March 2022 comprising several distinct processes. Two separate groups of reviewers were convened. The first group consisted of an independent Panel for each of eight missions with Subject Matter Experts (SMEs) and a Group Chief, and the second group consisted of two senior Review Chairs for the overall process and final report. The Review Chairs participated in all sessions held by the Group Chiefs, serving primarily as observers to assess fairness and balance in scoring across mission Panels. The overall review process was divided into four segments: (1) detailed review and analysis of mission proposals conducted by each Panel member, (2) eight independent Panels convened to develop questions, followed by direct interchanges with each project, (3) Panels then caucused to develop their report summarizing results and articulating major and minor strengths and weaknesses followed by voting on a single mission score, and lastly (4) Panel results were synthesized by Review Chairs, summarized, scored, and key mission observations and recommendations were generated. Mission Program Executives and Program Scientists were invited to attend these proceedings, and some participated. These activities were all incorporated into this final report to NASA's Director, Planetary Systems Division (PSD) of the Science Mission Directorate (SMD). Missions were evaluated by the Panels on their own merit and not ranked against each other. The Review Chairs considered group dynamics within each of eight separate Panels to ensure PSD had an equitable view of results and concluded that final grades were balanced across the missions without need to level any differences across panels. Once the Review Chair's writeups and findings of Section 3 were completed, we voted on each mission and assigned a final score. The reviews were conducted following the guidelines and requirements of the Applicable Documents cited in Section 2.6.

Logistics and scheduling for PMSR-22 were an essential aspect of this review considering there were eight extended-mission proposals and Panels involved 55 Panelists and three External Reviewers (ERs). All meetings were conducted virtually spanning 3 time zones, as well as a Panel member in Europe and a PSD representative in Asia. ERs were brought in as needed for specific topics, and heliophysics and astrophysics experts were voting Panel members for New Horizons.

2.2 Preparatory Meetings—Written Question Videocons (WQV) and Plenary

Mission proposals were available to Panels the week of January 17th and Written Question Videocons (WQV's) were conducted the week of January 31st using Google Meet. The format of the eight WQV's was analogous to those in the 2020 senior review. Consolidation of eight WQV's into three sequential days was necessary to manage logistics which still resulted in conflicts for some Panelists, but they provided written questions in advance which were incorporated into Panel discussions. The Review Chairs participated in all WQV sessions, generally as observers but actively contributing to the discussion when relevant to their expertise or to balance topics across missions. PSD's PMSR leads also participated in all WQV sessions to provide context, encourage reasonable complexity of questions, and emphasize the importance of the Panel questions as the focal points for mission presentations. Panel questions were given to mission proposers three weeks prior to their Panel presentation. Following the 8 WQV sessions, a plenary session was held to prepare Panelists for upcoming questions-and-answer sessions with mission proposers, clarify Panel-voting processes, reiterate schedules for Panel caucuses, and confirm timing for submission of final Panel reports.

2.3 Mission Presentations Overview

Extended-mission proposers were allotted 2 hours for presentations covering updates since the proposal submission and responding to the Panel questions which were provided about 2 weeks prior to the scheduled presentation. Panelists asked follow-on and new questions during mission presentations and, in some cases, submitted additional questions for later written response from missions. Presentations and impromptu mission responses were essential to the Panel's deliberations and allowed Panelists to refine their views from what they initially submitted as individual NSPIRES proposal evaluations. Six and one-half hours of caucus time was set aside for each Panel in which they carefully established and refined strengths and weaknesses and crafted the core of the Panel's report. In nearly all cases, the Panels needed the entire time allotted to craft high-quality reports with definitive major and minor strengths and weaknesses. The only exception was one Panel required some of their allotted backup caucus time to fully conclude deliberations.

Perception and balance across the 8 Panel reports was directly due to the excellence of the Group Chiefs. Without their leadership and organizational skills these caucuses, in a virtual environment, would not have resulted in effective and thorough evaluation. Two Executive Secretaries were a key element in facilitation of the caucuses Panel, allowing simultaneous discussion and record keeping on complex issues. Specific aspects of leadership and record keeping are discussed below in Lessons Learned.

2.4 Review Chairs' Synthesis Process and Observations

While the Review Chairs were participants in every mission presentation and Panel caucus, we intentionally remained neutral in identification of strengths and weaknesses and for scoring. Since each Panel had its own leadership style, Panel dynamic, and the mission characteristics, the Review Chairs felt that neutrality was critical to perform a balancing/leveling function across Panel scores to provide PSD an evenhanded view of mission evaluations without ranking missions against each other. This resulted in the Co-Chairs' scores being different than the final Panel score for three missions, as explained in Section 3 below for Insight, MAVEN, and MSL.

2.5 Lessons Learned from the Review Process

This section details several lessons learned from the overall process. Key findings and recommendations for PSD attention are in Section 4 below.

2.5.1 Mission-related

2.5.1.1 While detailed budget reviews are not called for in PMSRs, better budget details would be extremely informative in evaluating an aging mission's balance of science and operations, and their ability to deal with risk. Panels spent unnecessary time discussing budget tables due to varying formats, lack of conformity to WBS Level 2 requirement, and masking of reserves, carry-over, and science reductions. Consistently formatted budget information in proposals will provide more effective risk assessments for aging spacecraft and instrument systems. Managing risk, whether electronics and instrument deterioration or consumables, to maximize mission life and recover from unexpected failures is tightly tied to budgets and budget flexibility. ***PSD should consider requiring more specific details for budget table submission in extended mission proposals.***

2.5.1.2 Although the Call for Proposals stated that missions were "encouraged to propose meaningful descopes," six out of eight missions offered no descopes, implying that New Obligation Authority (NOA) typically declines over time and descopes become infeasible. Most of the proposed descopes were of minimal value or were drastic and unlikely to be implemented, therefore providing little or no value to the review process. When budget reductions are determined necessary by a program office or Division, program/project leadership are better suited to evaluate descope options against resultant mission impacts in real-time. In more than one instance the descopes created confusion within the Panel, including how to vote on them. ***PSD should consider discontinuing requesting descopes for extended missions.***

2.5.1.3 Some of the reviewed extended missions have no reserve, some bury reserve in WBS elements (and with poor budget tables the overall budget is obfuscated), some carry it in risk pools at contractors, and some have sizable reserves. Differences may be appropriate based on mission age, remaining resources, and surface vs orbital operations but most Panels were unable to meaningfully assess budget risk for these aging spacecrafts. ***PSD should consider a mission reserve policy (or guidelines), and ensure reserves are identified in proposals.***

2.5.2 Review Process-related

2.5.2.1 ***The WQV's are a critical element in the senior review process***, especially without face-to-face meetings. Panels have their first opportunity in WQV to meet one another and know the Group Chief's leadership style. Panelists are immediately immersed in technical aspects of science goals and spacecraft capability allowing rapid recognition of coverage or gaps in Panel expertise during dialogue. PMSR leads can quickly add Panel members and/or ERs. For the 2022

PMSR two Panelists and two ERs were added after the WQV meetings. In addition, some issues were resolved in the WQVs, reducing the number of questions forwarded to the missions.

2.5.2.2 ***An Executive Secretary is a particularly important position*** in a virtual meeting environment, allowing the Group Chief to concentrate on guiding and managing the conversation. Both positions are needed to monitor “hands up,” follow chat messaging, and ensure caucus input is balanced among Panel members. The Executive Secretary focuses on taking notes, tracking strengths/weaknesses, tallying votes, and crafting text for the Chief. In a 2-week compressed schedule, two executive secretaries with 4 proposals each was a nearly overwhelming workload.

2.5.2.3 Schedule is an important aspect of successful review and reporting processes, especially in a virtual environment cutting across multiple time zones. Overly compressed schedules put pressure on reviewers and can result in late reports and delayed review completion. Inadvertent stress is placed on review team members if work-day length, session breaks, and due dates for report completion are not carefully considered. The PMSR scheduled 76 hours of meeting time over eight days. Compressing three weeks’ work into two weeks is still three weeks of work. In a virtual environment, compression can be unforgiving as attention spans are reduced and meeting burn-out leads to reduced engagement. ***We encourage minimizing large virtual reviews, but when necessary, it is important to set reasonable schedules so review quality is sustained start to finish***. Setting realistic report generation/completion timelines is also essential *with margin* for complex or contentious caucus activity factored into initial schedules.

2.5.2.4 A single engineering/project management/mission operations individual was assigned to cover all eight missions but was unable to participate in the WQVs due to scheduling conflicts. He did an admirable job of attending all presentations and caucuses, but the heavy workload and compressed schedule was unrealistic for one person. This is an important position considering the technical nature of risks for spacecraft operation and instrument function in older systems. For example, the power situation on InSight is mission-ending, and OSIRIS-APEX orbital/thermal issues, would both have benefitted from broader engineering/ops insight. ***PSD should consider assigning both a mission operation and an engineering/management representative for each Panel, with a limited number of proposals per reviewer.*** These discipline fields were consistently under-represented areas in the past several extended mission reviews (the 2020 out-of-cycle review being the exception) and the problem warrants attention.

2.6 Applicable Documents

- Terms of Reference, NASA Planetary Mission Senior Review—2022, Dr. Lori Glaze, Director, Planetary Science Division; 16 December 2021
- Call for Proposals, 2022 Planetary Mission Senior Review; 9 July 2021 revised 16 December 2021

- Evaluation Criteria, 2022 Planetary Mission Senior Review; 18 January 2022

3 Summary and Assessment of Mission Proposals

Each of the Mission Panels produced a final mission assessment report, which are included as attachments to this report. The Panels voted on an overall mission score in accordance with NASA standard definitions (see Appendix 2) and the Review Chairs agreed on their independent adjectival scores for this Final Report. With careful considerations, there were three differences in scoring between the Co-Chairs' final scores and the Panels' scores, each described below.

3.1 InSight — N/A (Panel score E/VG)

The InSight Extended Mission 2 (EM2) refines the science goals and objectives of the prime mission and EM1, investigating Martian interior and surface/impact science and meteorology. Considering the nature of the intrinsic science of InSight, these refinements could comprise significant advancements in our knowledge of Mars' interior and expand our understanding of the overall meteorology of the planet. Recent discoveries substantiate the importance on continued, long-term observational records which can be used to provide knowledge of the layered structure of the crust and mantle. Longer baselines of seismic data coupled with new impacts can help confirm and refine the morphology of the Martian core, along with additional geodetic measurements of core oscillations. Nearly all seismic events used to probe the Martian interior have been observed in the Martian summer, seismically the "quiet season." The next "quiet season" begins a few months into EM2, with another later in EM2, therefore doubling the number of "quiet seasons" monitored by InSight, significantly increasing the likelihood of recording events at or below magnitude 4, which are the majority of events.

InSight appears to be in an unusual meteorological environment as well, largely devoid of "dust devils" that could clean the solar panels. Therefore, continued observations and modelling will further the understanding of local and global atmospheric dynamics when coupled with measurements from other surface assets around the globe. Differentiating between unusual characteristics of InSight's location and "micro-climate", and the properties of InSight's solar Panels, is important to understand power loss from dust accumulation and to develop mitigation strategies on future Mars missions. The timing of EM2 is also important for InSight to develop longer-term baseline observations.

The power condition of InSight is currently at a critical juncture for mission termination. Solar array cleaning attempts have continued but have been essentially unsuccessful—possibly due to very low wind states. Unless something changes the mission is expected to reach a critical energy state (possibly safe mode entry) in June 2022, and degrade to inoperability, Dead Bus Recovery (DBR) mode, in December 2022. The team will manage instrument data gathering as power allows, but there is no fully manageable "graceful degradation" capability. Once InSight enters DBR the team has no control over recovery but needs to set up a monitoring process in the unlikely event power levels return. At this point the team will disperse. Recovery largely depends on minimum exposed temperatures and the resultant damage to avionics in the Martian winter.

Evaluation of the InSight proposal was challenging considering its unusual situation of potential mission failure before EM2 even begins. After much deliberation on relevance of reviewing EM2 considering its situation, the Panel decided to review it as if there was not a pending mission-ending event. Additionally, the Panel provided perceptive recommendations for the remainder of EM1 in the Additional Comments section of their report.

While the Review Chairs agree with the Panel's score of Excellent/Very Good for EM2 itself, the score is misleading. The likelihood of InSight surviving EM1 appears minimal (~5% according to the project). If the spacecraft can "resurrect" itself from DBR after depth of winter, about 6 months into the EM2 time frame, system operability would need to be determined at the time to construct a feasible EM2. Therefore, the Review Chairs felt unable to assign a meaningful overall score to InSight and recommend an out-of-cycle review of InSight's EM2 based on the lander's condition following shut down and a successful exit from DBR. If a power-restoring event occurs and the lander continues operations through EM1 then the EM2 score is appropriate.

The mission presented no overguides or descopes.

KEY FINDING/RECOMMENDATION: ***With the likely loss of InSight power there needs to be a communications strategy and plan for DBR in case InSight "phones home" in 2023***. The Jet Propulsion Laboratory (JPL) is well versed in these techniques after experiencing the losses of Spirit and Opportunity in similar power-deprived modes.

KEY FINDING/RECOMMENDATION: ***The Planetary Science Division should consider instituting a formal lessons-learned activity over the loss of InSight***. There are many elements at play, including atmospheric dynamics, solar array surface properties, physical properties of Martian dust/sand, and power system design and distribution (e.g., actively managed shutdown/degradation), which could provide new considerations in technology development and future landing site selection.

KEY FINDING/RECOMMENDATION: ***The Project plans a data users workshop this fall at AGU, which will help expand awareness of InSight data and grow the user community.*** Seismology data is complex, and the planetary seismology community is small, shown by a somewhat thin collection of research papers to-date. The PSD should consider furthering these efforts to expand familiarity, increase usability, and develop open-source tools and products.

3.2 Lunar Reconnaissance Orbiter (LRO) — EXCELLENT/VERY GOOD

The Lunar Reconnaissance Orbiter (LRO) entered lunar orbit and began exploration in 2009, focusing on assessment of resources and safety for future robotic and human missions. The exploration mission was completed in 2010 and LRO was transferred to the Science Mission Directorate for a two-year science mission which continues to the present day with a proposed 5th Extended Mission (EM5). The spacecraft is healthy and the only mission risks, an aging battery and degraded Miniature Inertial Measurement Unit, are being addressed and compensated for by the team and appear to represent low risk to the mission completing EM5. LRO's exploration and science discoveries reinvigorated lunar research, demonstrated by more than 600 peer-reviewed publications to-date. EM5 continues LRO's focus on lunar processes including lunar volatiles, volcanism, tectonics, impact cratering, and regolith development through coordinated multi-instrument, nadir/off-nadir, and multi-wavelength investigations, however the proposal merited a major weakness since they provided minimal rational for numbers and locations of new observations needed to address major scientific objectives. Theme lead investigators will oversee the goals of both discovery and extension of baseline scientific observations. The EM5 campaign will also put significant effort into improving understanding of volatile sequestration in cold traps associated with Permanently Shadowed Regions (PSR's) in the lunar polar regions. Differences in the inferred distribution of water ice between the northern and southern PSR's remain enigmatic despite more than a decade of study since LCROSS, where LRO's higher resolution observations are necessary to advance scientific understanding.

LRO's importance as an Agency-wide resource in NASA's Moon to Mars theme cannot be overstated. Studies such as the distribution of water ice in PSRs is an excellent example of essential investigations for upcoming landed robotic and human resource exploration. Exquisite topographic images derived from LRO laser altimetric data points are now available and essential to Artemis and Commercial Lunar Payload Services (CLPS) while concurrently providing science with evidence of recent changes in the lunar surface. It is an essential multi-Directorate asset for planning, monitoring, and supporting the upcoming CubeSats deployed by Artemis I, the crewed missions of Artemis II and III, and likely the pre-arrival research for CLPS missions. It remains to be seen however, how LRO operations and schedule will be impacted by CLPS due to uncertainty in project maturity and demand for LRO services from the 14 eligible vendors. The Agency needs to plan for a replacement asset considering the risk of LRO being out of fuel in 2026/27 to support these highly important NASA missions in the return to the Moon.

The Review Chairs agree with the grade of Excellent/Very Good assigned by the Panel, yet we believe the programmatic component of LRO requires greater attention from the Agency. Close coordination by the Planetary Science Division with the two human exploration directorates and CLPS will become more critical as commercial activities and Artemis missions accelerate. LRO recognizes this pending increased workload and reliance on them, reflected in the decision not to provide a descope option due to overall mission impact, and the Review Chairs agree with this decision. Increased emphasis and support for LRO from these other NASA organizations will be needed for orchestration of schedules, observations, and communications. Depending on actual demand from Artemis and CLPS, augmenting budgets should be planned and be responsive to rapidly evolving lunar missions, as addressed in the Panel's evaluation of the Overguides.

While the overguides all could add value to NASA programmatic objectives, their scientific value was not convincing. Overguide 2 is actually an outreach product associated with a crewed mission called "Return to the Moon with LRO" and is considered out-of-scope according to the Call for Proposals.

KEY FINDING/RECOMMENDATION: ***There appears to be little motivation for LRO leadership to prioritize their investigations.*** This is likely due to exceptionally high levels of science data collected by LRO over a decade of almost continuous operation. With LRO's increasing importance to the Agency there needs to be greater oversight and assistance in accommodating NASA's growing programmatic needs in returning to the Moon. The complexity of melding scientific and programmatic drivers cannot be overstated, and SMD/PSD should actively facilitate orchestration across the Agency to maximize science while supporting programmatic needs.

KEY FINDING/RECOMMENDATION: ***Review Chairs agree with the Panel that uncertainty in spacecraft pointing is degrading resolution of LRO's high-resolution digital elevation models.*** Assessing the magnitude of this issue and developing technical strategies for compensation should be a mission priority. Coordination across the Agency is needed to effectively estimate the number and quality of digital elevation models needed over EM5 to support landing site selections and operations during upcoming scientific and resource exploration.

KEY FINDING/RECOMMENDATION: ***The Review Chairs agree with the Panel that each of the EM5 overguides has potential programmatic value to NASA but direct application to advancing planetary science goals is not well demonstrated***. If funding is provided it should be from non-PSD sources. In particular, delays for Artemis and uncertainties for the CLPS missions suggest that LRO could continue to support these needs within the guideline budget as was done for EM4.

3.3 Mars Atmosphere and Volatile EvolutioN (MAVEN) — EXCELLENT (Panel score E/VG)

The MAVEN mission is currently executing its fourth extended mission (EM4), having initiated science observations at Mars in September 2014 and being incorporated into the Mars Relay Network in 2019. Recent appointments of a new PI, two new deputy PIs, and identification of deputy leads for nearly all instruments has proceeded smoothly and demonstrates commitment to leadership development. The proposed fifth extended mission (EM5) anticipates continuation of MAVEN's aeronomy science and relay activities through FY25, spanning the predicted rise and peak of Solar Cycle 25. Despite uncertainty in modeling future solar cycles, it is likely that EM5 will provide multiple opportunities to observe dust storms coincident with intense solar activity as well as atmospheric behavior during high solar Extreme

Ultraviolet irradiance at aphelion. MAVEN's EM5 proposal targets three science themes of direct relevance to goals in the 2011 Planetary Science Decadal Survey and 2020 Mars Exploration Program Analysis Group:

- How does solar maximum affect the Martian atmosphere and climate?
- How does the upper atmosphere system respond to Mars' seasons and dust?
- How does the Hybrid magnetosphere control basic physical processes in the Mars-solar wind interaction?

Successful EM5 science observations would continue to advance knowledge of atmospheric chemistry and gas escape as well as the coupling between dust storms and upper atmosphere processes. Fundamental discoveries are expected in understanding how Mars' hybrid magnetosphere influences atmospheric response to high solar activity. The proposed EM5 observations address high-level Mars science questions integrating across atmosphere, surface, and subsurface systems.

At the time of the PMSR Panel, the MAVEN spacecraft and instruments were largely healthy with many potential years of lifetime remaining for major components and expendables. Planning is underway for normal instrument degradation and new instrument capabilities and modes are being implemented. Risk related to failure of both Inertial Measurement Units (IMUs) will be mitigated by the development of an "all stellar mode" (ASM) of operations. Implementation testing of MAVENS's has a readiness target of March 2022.

The MAVEN team has a strong publication record extending from primary operations through EM4 and non-team led publications and community access to MAVEN data have steadily increased. Additionally, MAVEN leadership opportunities and succession planning is a benchmark approach, where even the former MAVEN Principal Investigator Dr. Bruce Jakosky (2003-2021) has turned over leadership to Dr. Shannon Curry who was initially hired as a MAVEN post-doctoral scientist.

With 8 major strengths, 12 minor strengths, 0 major weakness, and 3 minor weakness, the Review Chairs believe the minority Panel ranking of Excellent is more reflective of the strength of the primary plus secondary ranking criteria than Excellent/Very Good.

<u>KEY FINDING/RECOMMENDATION</u>: ***Impactful outcomes for NASA, other space agencies, and commercial ventures result from multi-vantage-point observations and cross-mission calibration.*** MAVEN's EM4 proposal includes ongoing radiation collaborations with other NASA spacecraft at Earth and Mars, the Emirates Mars Mission, ESA's Trace Gas Orbiter, and ESA's Mars Express. The MAVEN team creates and disseminates space weather alerts for missions at Mars, which alert spacecraft of enhanced solar activity that can affect spacecraft operations, an excellent example of a developing capability that is cross-Directorate and cross-Agency in applicability and importance as we head towards solar maximum Gaining experience in issuing warnings for potentially damaging radiation is also a critical safety endeavor for future human exploration of Mars.

KEY FINDING/RECOMMENDATION: ***Knowledgeable energetic leadership can be achieved through career advancement within an extended-mission team.*** The recently appointed MAVEN PI (October 2021) was initially hired as a post-doctoral scientist and then acquired technical, scientific, and administrative expertise with the MAVEN spacecraft by immersive operational participation and increasing levels of responsibility. This change in leadership included a change in institutional affiliation from University of Colorado to UC Berkeley. MAVEN is a laudable example of professional development and diversity which should be highlighted by NASA and used as a model best-practice for other extended missions.

3.4 Mars Odyssey (ODY) — VERY GOOD

Twenty years after Mars Orbit Insertion, Odyssey continues to produce important science and provide critical programmatic relay support for surface assets and landing events. The Review Chairs concur with the Panel's grade of VERY GOOD for Extended Mission (EM) 9. The spacecraft can support a successful EM9, and the proposed science was viable and generally well developed. Extended coverage in their "new" orbit (which they've been in since EM7) is valuable to continue imaging at local early morning and post-sunset. ODY will be able to conduct new surveys of thermophysical properties of the surface including rock abundance and subsurface ice, extend the already comprehensive record of climate monitoring, add new limb observations while continuing High Energy Neutron Detectors (HEND) and Neutron Spectrometer data collection for seasonal CO_2 ice, hydrogen abundance mapping and measuring of the radiation environment. HEND is also a significant contributor to the Mars Space Weather Network and the Inter-Planetary Network (IPN), both important resources as we move towards solar maximum. ODY is also coordinating THEMIS observations with the Emirates/Hope mission's EMIRS instrument with some overlap in science team membership. This type of collaboration can result in discoveries otherwise unavailable with single-platform measurements.

The ODY spacecraft is remarkably healthy for its age and risks are well understood by the team. The greatest current risk is uncertainty in remaining fuel predictions but there is a study underway to resolve recent discrepancies. ODY fulfills a critical programmatic function as well, providing relay functions with pseudo-real time "bent pipe" capability unique among Mars orbiting assets. The 6:30 LMST orbit also provides added contact opportunities for surface asset relay, including Curiosity, Perseverance, and InSight. Depending on fuel state there is some chance ODY could even support Mars Sample Return arrivals. The budget is considered adequate, and no descopes or overguides were proposed. The team is well experienced but upward mobility paths to senior science leadership positions have not been exercised adequately.

KEY FINDING/RECOMMENDATION: ***While EM9 is likely not in jeopardy, the fuel uncertainty could significantly affect remaining mission life*** and impact the surface asset communications network at Mars. The Review Chairs recommend close oversight of the study by PSD to ensure timeliness and an unambiguous result to build confidence in programmatic planning.

3.5 Mars Reconnaissance Orbiter (MRO) — EXCELLENT

The Mars Reconnaissance Orbiter (MRO) is truly a workhorse orbiting asset, providing critical programmatic support for NASA, ESA and other agencies with missions at Mars since its orbital insertion in 2006. MRO proposes to continue in a 6th Extended Mission (EM6) with a focus on examination of change processes on Mars, from ancient habitable environments to the inhospitable cold desert of today. EM6 proposes 17 investigations within 4 major science goals directly traceable to Decadal Survey priorities. MRO's EM6 goals are (A) Mars Surface and Climate Through Time, (B) Evolution of Martian Ices, (C) Active Geological Processes, and (D) Modern Mars Atmosphere and Climate. While a significant portion of the investigations builds on key successes of EM5, there are important discovery investigation such as crater-filling ice mounds, stratigraphy and structure of polar layered deposits, dynamic changes in Recurring Slope Lineae changes, and potential identification of lava tubes/caves. MRO's programmatic mission objectives include (1) relay communications with landed assets; (2) landing site characterization for science and safety; (3) environmental data acquisition for future mission design; and (4) coverage of other missions' critical events such as Entry, Descent, and Landing (EDL).

Individual and time-paired images from MRO are heavily utilized by the community and provide compelling evidence of active processes on the surface of Mars under current climate and weather conditions, leading to scientific discoveries and supporting surface operations. It is also remarkable that MRO accepts imaging requests from the community (e.g. HiWISH), and accommodates a significant portion of them in observation planning—it may be the only mission with this type of open collaboration. As budgets are reduced in extended missions, it appears that the MRO team itself has limited resources to do their own research and publishing.

The MRO team continues to adeptly handle technical issues with an aging spacecraft, and while there are several potential mission-ending risks, the overall robustness of operations is exceptional and none of these risks are currently of pending concern. The failure of the last CRISM cryocooler is a significant science loss, yet the team is to be commended for willingness to discontinue operations if their submitted overguide is not accepted (see below).

The Review Chairs agree with the Panel's grade of EXCELLENT for continuing science and support activities of this remarkably impactful mission.

The Review Chairs agree with the Panel that the science case for Overguide #1, CRISM VNIR investigation of Martian ices was poorly justified in how the investigation would make major advances in understanding CO2 and H2O ice distribution in the polar latitudes. Considering this rational and the low Panel score the Review Chairs do not recommend funding Overguide #1. However, we strongly recommend fully funding Overguide #2 for conversion of previous mission data to PDS4 format, especially in light of our recommendation on Overguide #1 since the CRISM team will likely disperse.

Neither the Review Chairs nor the Panel support recent requests from roving missions concerning changes in MRO's orbit, an impact that the MRO team is highly concerned about. A negative scientific impact resulting from improvement of Perseverance's operational efficiency will reach far across planetary science disciplines with only minor improvements in surface mission efficiency. A change in orbit will end MRO collection of time-paired images used for surface-change detection. Image comparison has yielded numerous discoveries at Mars with more likely to come in critical areas of ice and water resources for NASA's human exploration goals.

<u>KEY FINDING/RECOMMENDATION</u>: ***Don't change the orbit*.** The overall science impact for MRO coupled with the minimal 2020 improvements and reduced ExoMars Entry, Decent and Landing coverage do not justify such a drastic degradation in MRO science. A significant change in MRO's orbit could be revisited at such time as significant changes in MRO instrument state-of-health (i.e. science capability) occur or in response to the timing of MSR arrival.

<u>KEY FINDING/RECOMMENDATION</u>: ***The Review Chairs and Panel are concerned about the high cost-risk impact to MRO for upgrading institutional elements***, in particular the MMOLMWEB. The impacts presented were significant, and the high cost (nearly $1M) is apparently specific to MRO. PSD should ensure the scope of the MMOLMWEB upgrades are justified and the costs are borne by either institutional funding or spread across all users rather than impacting such a critical and productive asset.

3.6 Mars Science Laboratory (MSL) — VERY GOOD (Panel score E/VG)

NASA's Mars Science Laboratory (MSL) rover landed on Mars in August 2012. During the primary and first three extended missions, images of pebbly conglomerates combined with chemical signatures of mudstones have been interpreted by team and non-team scientists as indicative of ancient habitable environments for microbial life on Mars. After a decade of exploration in these siliciclastic deposits, the MSL rover is now located close to or at the clay-sulfate transition. Orbital evidence of a sulfate-bearing unit on Mount Sharp was a crucial factor in selection of Gale Crater as the landing site and was a key milestone in multi-year planning for rover routes. For the proposed EM4, it is now imperative for the team to improve operational strategies and provide assurance of success in acquisition of ground-truth images and geochemical measurements needed to understand the time period when surface water on Mars is inferred to have transitioned from widespread and dilute (mudstones and pebbly sandstones) to restricted and highly saline (hydrous and anhydrous sulfates). The MSL instruments, power systems, and mechanical devices remain capable of collecting information relevant to understanding formation and alteration of chemically diverse sulfates (primary evaporative and diagenetic), provided multiple sites are reached without time-consuming distractions.

Large-scale 'boxwork' structures, visible from orbit, are described in the proposal for two areas along the EM4 transect. These impressive landscape features are inferred to form by mineral infill of groundwater-flow pathways. In addition to boxwork, the EM4 team anticipates encounters with diverse sulfate- and/or salt-mineralized strata indicative of surface precipitation from closed-basin brines. CheMin and ChemCam are prime instruments for characterization of evaporative phases with both crystalline and amorphous phases and the EM3 team is working on operational strategies to preserve these declining resources for use during EM4 investigation of these important sulfate-bearing units.

In situ measurements of atmospheric methane by MSL are reported at a persistent, but seasonally variable, background abundance of about 0.4 part per billion by volume (ppbv) with transient spikes up to about 20 ppbv. Non-detection (less than 0.05 ppbv) of methane by ESA's Trace Gas Orbiter (Korablev et al., 2019) raises questions about the reliability of measurements from one or both spacecraft and drives conjecture about active, near-surface processes removing methane from the lower atmosphere or rover contamination. Spikes followed by rapid disappearance of atmospheric methane are inconsistent with conventional understanding of atmospheric methane chemistry. Due to high scientific and public interest in methane as an indicator or past or present biological activity on Mars, EM4 needs to bolster efforts to understand the apparent incompatibility of landed and orbiting methane measurements.

The Review Chairs disagree with the overall Panel score, but agree with the minority Panel score of Very Good, considering 3 major weaknesses and 8 minor weaknesses plus the challenges in operational strategies when approaching key scientific targets from the primary mission phase. Immediate changes are need in operational strategies and traverse benchmarks to assure successful acquisition of ground-truth data on a wide range of sedimentary and diagenetic textures in the sulfate-bearing unit rather than a narrow focus on boxwork structures, the first of which was not well supported and considered more of a distraction by the Panel.

KEY FINDING/RECOMMENDATION: ***There is uncertainty about the commitment of the EM4 team to prioritize key science goals and to adjust operations*** in response to the likely failures of instruments and hardware on an aging rover traversing rugged terrain, discussed in depth during Panel deliberations. Investigating the clay-sulfate transition is a long-standing mission priority and previous MSL extended mission have repeatedly fallen short of end-traverse targets. The EM4 proposal does not identify specific operational strategies or leadership principles that will result in successful scientific exploration of the sulfate-bearing unit during the EM4 mission, and Q&A did not reveal persuasive strategies either. Mars and MSL managers are urged to be proactive in assessing short- and long-term traverse planning and to facilitate articulation of incremental benchmarks for completion of EM4 goals. Review Chairs agree with Panel that the EM4 Team should revise their goals to be clearly attainable, targeted scientific studies as opposed to the EM3 goals which tend to be open ended and difficult to convincingly close (e.g. determine the mineralogy and chemical composition of surface and near-surface materials).

KEY FINDING/RECOMMENDATION: ***Given widespread interest and importance of the detection of methane on Mars, addressing the significant mismatch between MSL and TGO methane measurements is a scientific imperative.*** It is incumbent on NASA to make a more substantial effort to unravel this enigma and to improve understanding of methane generation and destruction processes on Mars.

Reference: *Korablev et al., 2019, No detection of methane on Mars from early ExoMars Trace Gas Orbiter observations. Nature, 568, 517-520.*

3.7 New Horizons KEM2 — Planetary Portion — VERY GOOD/GOOD
Complete Proposal — EXCELLENT/VERY GOOD

New Horizons launched in 2006 and performed a Jupiter gravity assist in 2007. Six months of reconnaissance studies were conducted during a fly-by of Pluto in 2015, followed by their first extended mission exploring the Kuiper Belt. The spacecraft is now in an unexplored, distant region of the Kuiper Belt, currently located at 52 AU and traveling at about 3 AU/year. The proposed second extended mission for New Horizons in the Kuiper Belt Extended Mission 2 (K2) continues exploration of solar system objects ranging in size from nm particles to dwarf planets and incorporates heliophysics and astrophysics investigations at mid-latitudes in the outer heliosphere as New Horizons heads towards the heliopause. Planetary Science opportunities include high-phase observations of dwarf planets, large-phase angle studies of Uranus and Neptune as analogues for ice giant exoplanets, and direct detection of dust particles at increasing heliocentric distance including efforts to distinguish between interstellar and interplanetary sources. Astrophysics opportunities include studies of the cosmic optical and UV backgrounds with unprecedented sensitivity, UV observations of the local interstellar medium (LISM), and searches for microlensing events potentially leading to detection of free-floating black holes. Heliophysics opportunities include measurements of particle populations and processes across distant heliospheric boundaries, observations of dust and hydrogen gas in the outer solar system, and collaboration as part of the Heliophysics System Observatory.

The Panel identified one major plus one minor strength and one major plus one minor weakness in the scientific merit of the K2 planetary science investigations. In contrast, the Panel identified five major strengths and no weaknesses in the scientific merit of heliophysics and astrophysics investigations. A notable primary conclusion of the Panel was that the proposed studies of Kuiper Belt Objects are unlikely to markedly improve knowledge because the spacecraft lacks resources for long term, high cadence observations for light curves, which are necessary for their proposed planetary science goals/objectives. As a result, the Review Chairs agree with the Panel's scores for both constructs of the K2 proposal. Although not addressed in the Panel report, the Review Chairs note that there is a considerable amount of data from the Arrokoth encounter still on board that requires decisions for downlinking versus other K2 activities.

All of the instruments on New Horizons are still functioning and the spacecraft has sufficient propellant and power resources (RTG) to perform the K2 proposed science goals. RTG output predictions, however, show available power dropping below what is necessary for instruments to be active in 2027-2028 (beyond K2). From data in the proposal, it also appears that spacecraft hibernation is necessary for about 50% of each year in order for cruise science (SWAP, PEPSSI, SDC) to be carried out continuously and to have other instrument turned on. Thus, hibernation would be used when no active pointing for science operations or data downlink are required.

KEY FINDING/RECOMMENDATION: ***Major advances in knowledge and discoveries are far more likely for heliophysics and astrophysics than for planetary science*** during K2. With the New Horizons spacecraft traveling from 54-63 AU in the ecliptic plane during K2, priorities for data collecting and downlinking should focus on heliophysics and astrophysics. Thinking outside the box will be needed to successfully change ordering of science goals and development of operational strategies. NASA is encouraged to seek external community input on measurement objectives during the final months of the current extended mission to ensure the most successful K2.

KEY FINDING/RECOMMENDATION: ***K2 can be a model for long-lived probes with funding from multiple SMD divisions, if successful.*** The New Horizons spacecraft and instruments are healthy and located at a never-before-explored sector of the outer solar system which presents an extraordinary opportunity to observe, measure, and collect data. Meritorious science can be achieved in heliophysics, astrophysics and planetary science but science optimization will require creative problem solving and cross-divisional leadership.

3.8 OSIRIS-APEX— EXCELLENT/VERY GOOD

OSIRIS-APEX (APophis EXplorer) is arguably the most imaginative extended mission proposal of recent PMSRs, and the Review Chairs agree with the Panel scores. After the OREx Sample Return Capsule is released to Earth's surface in 2023, the spacecraft will divert into an orbit around the Sun with remaining potential to observe other Near-Earth Objects (NEOs). This EM proposal is unusual in requesting approval for the full extended mission through FY31 without another significant review. A complete re-alignment of this New Frontiers-class mission to target and rendezvous with a high-value S-class, potentially hazardous NEO makes use of a spacecraft that has been specifically optimized for small body investigations. The plan also capitalizes on the seasoned team that has already "rehearsed" proximity ops at Bennu and demonstrated their flexibility in reacting to unknowns such as the significant adaptations to sample collection and navigation required when the Bennu encounter showed unanticipated surface characteristics. The proposed target is a ~340-m-diameter asteroid named Apophis which will fly by Earth's surface in April 2029 at <10% the lunar distance and will be the largest object to pass Earth this closely in recorded history. This highly visible celestial event will be broadly publicized by NASA and other global space agencies. After chasing Apophis during close encounter, APEX will enter a 1.4km orbit of Apophis in August 2029. Science plans will enable close analysis of an S-class asteroid for the first time, allowing space-truthing of ground observation, close observation and analysis of surface change from tidal forces *during* encounters, rotational effects (Apophis is tumbling), mass wasting and particle ejection, cm and mm scale topological imagery, and meter-scale spectral mapping. Surface excavation using the OSIRIS thruster technique will provide unparalleled information and understanding of a rubble-pile asteroid. APEX also proposes to capitalize on several synergistic opportunities, including coordination with ground-based observations and the small bodies Special Action Team, and the Planetary Defense Coordination Office to expand their understanding of the characteristics and risks of S-class asteroids, which are a very common NEO. This mission even directly addresses mission goals in the PDCO National NEO Preparedness Strategy and Action Plan. Earth observations may even provide an opportunity for the Exoplanet community to collect data to improve their habitable world search models, however critical details of imaging “Earth-as-an-analog” requires greater engagement with the exoplanet community to confirm viability. APEX’s inability to conduct any significant imaging of Apophis prior to encounter means that coordinated space and ground-based pre-encounter imagery will be of very high importance.

APEX has a strong professional development plan, with this new APEX mission being staffed by many new leaders that have moved up in the organization, including the new Principal Investigator (PI). Their approach, including a solid professional development plan, team building activities, etc., could be a model for other extended missions.

The spacecraft and instruments are healthy, and consumables will support this long-extended mission. The only real known spacecraft risk is spacecraft effects with perihelion at 0.506AU, which is ~35% closer to the sun than the original OSIRIS-REx mission. This results in many systems/subsystems at, near or above their qualification temperatures before the Apophis encounter, and with 6 perihelion passes represents and unknown cumulative-effect risk as well. Initial thermal modelling indicates the risk is low, however prudent understanding (which may require limited testing) of select subsystems margin over qualification limits would be advantageous for risk mitigation to improve spacecraft survival likelihood especially for cumulative effects of multiple perihelion passes.

While the budget table provided did not identify reserves, the APEX team stated they have virtually no reserves, which is problematic in truly understanding the thermal risks prior to the first perihelion pass. The proposal also requests adjusting their budget profile to provide higher funding levels nearer the Apophis encounter, which both the Panel and Review Chairs support. Overguides 1 and 2 are operational and engineering related options addressed in a finding below; overguide 3 is related to PDS-4 conversion and is supported by the Panel and Review Chairs but is small enough to be funded out of reserve if the budget information was of higher fidelity. The descopes are inappropriate to consider at this time and therefore not supported by the Review Chairs.

Overall, the potential science return of the OSIRIS-APEX mission far outweighs the risks to the spacecraft with the potential for a tremendous Return-On-Investment, from this high-value New Frontier spacecraft.

<u>KEY FINDING/RECOMMENDATION</u>: ***Perihelion survival testing for <u>targeted</u> systems at/near/above for margin above thermal qualification limits should be conducted***, especially to understand cumulative effects. The first perihelion pass is late 2022 and the Review Chairs are concerned that a “wait and see” approach to harmful effects could result in unnecessary degradation of a healthy high-value asset. Thus, a small investment in testing is strongly recommended as safety assurance for an inspirational science and public outreach mission a decade from now.

<u>KEY FINDING/RECOMMENDATION</u>: ***PSD should assist APEX in coordination/facilitation of pre-arrival ground- and space-based observations of Apophis*** to maximize APEX’s close encounter data, as well as coordination with exoplanet community.

<u>KEY FINDING/RECOMMENDATION</u>: ***A formal review by subject matter experts across key disciplines, balancing engineering and science, should be conducted a year or two prior to the Apophis encounter.*** This should not be a PMSR-like review, but more targeted to spacecraft health and encounter readiness. Review of the overguides (and possibly descopes) would be most appropriate at such a review as well, when overguides 1 and 2 will be much better constructed with then-current science and spacecraft status being well understood.

4 Top-Level Findings and Actionable Recommendations

This section contains the Co-Chairs’ key findings and recommendations, focusing on the most important outcomes of the PMSR in the areas of review process, specific missions, and overarching coordination of spacecraft operations.

4.1 Recommendations for the Review Process

4.1.1 ***Setting reasonable, achievable review schedules are critical to perceptive reviews, especially when reviews are done virtually.*** Realistic schedules create an environment where member burn-out is minimized thus focus is maximized, quality participation is consistent, and members are willing and interested in participating in future reviews. Please refer to details in Section 2.5.2.

4.1.2 ***Clearer budgets in a defined format, and eliminating descope proposals, will improve budget assessment and Panel efficiency.*** Several missions’ budget tables were not compliant with the Call for Proposals. Asking missions to propose descopes when already “stretched” through years of gradually declining budgets (typical profile for extended missions) result in trivial options at best, or un-executable options at worst. Please refer to details in Sections 2.5.1 and 3.

4.2 Recommendations for Specific Missions

4.2.1 *The Planetary Science Division should consider forming a formal lessons-learned activity over the loss of InSight.* There are many elements at play, including atmospheric dynamics at its landing site, solar array surface properties, and power system design and distribution (e.g. actively managed shutdown/degradation), which may also provide new considerations in technology development for solar array cleaning and even future landing site selection. Please refer to details in Section 3.1 and the Panel report.

4.2.2 *LRO operations need guidance on adjusting to NASA's growing programmatic needs across multiple NASA and commercial activities.* SMD/PSD should coordinate closely with LRO leadership on evolving schedules for Artemis and CLPS on LRO programmatic support, and on reduced capacity for science investigations. Science goals in the LRO EM5 proposal were similar to the previous extended mission, not being well justified in terms of significant advances in knowledge. Please refer to details in Section 3.2 and the Panel report.

4.2.3 *MSL leadership should seriously consider the possibility that EM5 is its final period of Mars exploration, and plan operations accordingly.* Relatively healthy operation of the Curiosity rover should not be assumed past EM5 due to declining energy and consumable resources in addition to wheel wear. Under this scenario, planning for traverse navigation and instrument usage would prioritize up-section progress and exploration of as many types of sulfate-bearing strata as possible. Please refer to details in Section 3.6 and the Panel report.

4.3 Overarching Coordination Recommendations

4.3.1 *Consider a dedicated Program Scientist (PS) and/or Program Executive (PE) to enhance scientific and programmatic coordination among all PSD (and SMD) missions.* The number and complexity of PSD operational and extended missions, coupled with opportunities for collaboration across numerous international missions, requires significant awareness of these mission's science and engineering activities. An individual with relevant mission operations experience could assess prospects for collaboration, track mission status, and advise PSD management in cross-cutting technical, budget, and operational issues. The 2022 PMSR revealed numerous missed opportunities for coordination of mission-to-mission investigations and for effective interfaces with infrastructure elements such as networks and Mission Operations/Ground Data Systems.

4.3.2 *Develop principles to enhance top-leadership opportunities.* Extended missions provide a clear pathway for early and mid-career professionals to gain leadership experience in both science and engineering/management disciplines. The implementation and commitment to providing these opportunities varied markedly from mission to mission in the 2022 Senior Review. The PSD would be well served to develop policy for routinely utilizing operating missions for training of future leaders including goals for turnover of extended mission leadership at all levels including PI. See also details in Section 3.3.

4.3.3 ***Consider casting a broader net to cover infrastructure upgrade costs for MMOLMWEB, utilized by all JPL/Lockheed Martin (LMA) missions.*** While MRO made the Panel aware of serious budget and science impacts (nearly $1M in FY22-24) to fund improvements to the MMOLMWEB communications system between JPL and LMA, other missions acknowledged that they were aware of possible impacts but did not anticipate a major impact. While infrastructure systems must be maintained for security and functionality, PSD should ensure that costs are allocated appropriately across all users and the institutions themselves. See also details in the MRO presentation and Panel report.

4.3.4 ***Immediate planning is needed for cross-NASA and inter-Agency coordination of Solar Energetic Particle (SEP) observations during the coming solar maximum.*** Although many missions in the 2022 Senior Review had science goals related to predicted increase in SEP activity, there were few plans for specific collaboration of instruments on spacecraft across the solar system. As NASA plans for crewed mission at the Moon and then Mars, heliosphere data collected and synthesized as a network could significantly advance knowledge of radiation exposure for crew during interplanetary travel and exploration.

5 Conclusion

It has been a pleasure to be Review Chairs of the 2022 extended mission's review. The structure of individual mission Panels with an independent Co-Chair team to construct final opinions for the Division, worked well. The PSD PMSR Leads were essential to orchestration of this review and did an excellent job of constructing the Panels and supporting the Review Chairs. The Panels were strong in terms of technical knowledge and teamwork, creating lively and unencumbered deliberations for every mission, many of which were challenging due to unusual circumstances and remarkable possibilities for scientific discoveries. The Group Chiefs were focused, well organized, and receptive leaders, with proactive support from their Executive Secretaries, together resulting in smooth-running caucuses and generation of lucid Panel reports. We thank you for the opportunity to participate in this important, recurring process to ensure PSD missions produce the best science throughout their operational lifetime. We are at your disposal to discuss this final PMSR report or supporting Panel reports.

Appendix 1: Review and Panel Leadership

PMSR Review Chairs

Doug McCuistion—McQTech, LLC
Lisa Pratt—Emeritus, Provost Professor, Indiana University

Mission Panel Group Chiefs

InSight—Lara Wagner/Carnegie
LRO—Bob Craddock/Smithsonian
MAVEN—Melissa McGrath/SETI
ODY—Wendy Calvin/UNR
MRO—David Williams/ASU
MSL—Tim Lyons/UCR
New Horizons—Faith Vilas/PSI
OSIRIS-APEX—Hap McSween/UTK

Appendix 2: NASA Ranking Definitions

Standard NASA usage for evaluating/ranking proposals consists of five qualitative descriptions, which, in turn, are linked to numerical scores. While there were primary and secondary evaluation criteria the Panels only held one vote overall for the mission, plus votes for each overguide or descope if submitted. The Review Chairs participated in the Panels but did not vote with the Panels, and instead determined their own adjectival ratings at the end of the review process.

The following adjectival scoring levels were applied uniformly by the Panels and the Review Chairs in arriving at their final, overall mission scores. Since the Review Chairs attended all Panel meetings and votes, they also provided an informal levelling function to ensure consistency in **how** scores were applied in voting, but did not influence the actual votes.

Excellent

A comprehensive, thorough, and compelling proposal of exceptional science/technical merit as documented by numerous or significant strengths and having no [or minimal] major weaknesses.

Very Good

A fully competent proposal of very high science/technical merit whose strengths fully outbalance any weaknesses.

Good

A competent proposal having neither significant science/technical strengths nor weaknesses, or whose science/technical strengths and weaknesses essentially balance.

Fair

A proposal whose science/technical weaknesses outweigh any perceived strengths.

Poor

A seriously flawed proposal having one or more major science/technical weaknesses and no offsetting strengths.

Appendix 3: PMSR 2022 Evaluation Criteria

Evaluation Criteria
2022 Planetary Mission Senior Review
18-Jan-2022

Proposals will be evaluated based on factors related to both the proposed EM, and the performance of the mission and team in the previous cycle. These criteria are classified as Primary and Secondary; the Primary criteria each carry a greater weight in the overall evaluation than the Secondary criteria. The evaluation criteria to be used are as follows.

Primary Criteria

- Scientific merit of the proposed investigations to be undertaken during the EM.
- Responsiveness of the proposal to goals described in the Decadal Survey Vision and Voyages for Planetary Science in the Decade 2013-2022 (2011).
    - Missions originally proposed before the 2011 Decadal Survey may optionally also refer to goals in New Frontiers in the Solar System: An Integrated Exploration Strategy (2003).
    - Missions which include substantial cross-divisional content, and identify goals from those divisions, may also be evaluated relative to those respective goals.
- Capability of the spacecraft to achieve proposed science.
- Merit of programmatic objectives.
    - The PMSR will evaluate separately the objectives of relevance to PSD, and those of relevance to other divisions or directorates at NASA, and may assign different weights to each.
- Scientific productivity of the mission team in the previous cycle.
- Performance in archiving data to the PDS in the previous cycle.

Secondary Criteria

- Extent to which the science community beyond the mission science team utilizes data and conducts published research
- Scientific merit of observations to be taken and archived to the PDS, for future use by the scientific community.
- Science value.
    - The PMSR will not perform a detailed cost analysis of each proposal. However, the Panels may assess in broad terms the science return of the mission relative to its overall cost. The Panels may also assess the relative science return of descope and/or overguide options presented.
- Demonstrated capabilities, experience, and expertise of key personnel.
- Expected effectiveness of the proposed PDP in training future leaders.
- Thoroughness and appropriateness of the PDMP.

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2022 NASA Planetary Mission Senior Review
Panel Evaluation

Proposal	**22-PMSR22-0007**
Title	**InSight Proposal for the 2022 Planetary Mission Senior Review**
Principal Investigator	**William Banerdt / California Institute of Technology**

Summary of Proposal

This proposal describes a potential second Extended Mission (EM2) for NASA's Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport (InSight) mission. The Prime Mission (PM) for InSight comprised one full martian year of operation (slightly less than two Earth years) ending in December 2020. EM1 extended these efforts for another two Earth years, and will expire at the end of 2022. The proposed EM2 would extend the operation of the InSight mission for almost three additional Earth years, until the end of FY2025.

The EM2 proposal has six primary science goals and twelve associated science objectives that seek to improve upon many of the achieved objectives from the PM and EM1. During EM2, the InSight team would acquire an additional three years of continuous seismic data from the InSight seismometers, including two additional "quiet seasons" that allow for the detection of the larger "long period" Marsquakes used to probe the martian interior. This additional recording time would double the number of quiet seasons experienced by the InSight lander. The additional Marsquakes recorded during this time would help to improve the understanding of the statistics of martian seismicity as a function of magnitude and location, which could in turn help us to understand the relationship between seismicity and martian tectonics. The InSight team would also use EM2 seismic data to help discriminate between the two end-member crustal-structure models that are currently both consistent with the available data. The recording of diverse larger events would help the InSight team to better constrain the structure, composition, and thermal state of the martian mantle. Looking deeper, the InSight team would be able to confirm and refine the size and state of the martian core by providing additional measurements of core seismic phase arrival times and amplitudes, as well as by providing additional geodetic measurements of martian core nutations using the Rotation and Interior Structure Experiment (RISE).

In addition to collecting seismic and geodetic data, the InSight team would collect continuous data from the InSight atmospheric package along with additional data from the InSight magnetometer. The atmospheric data would not only help to identify and ameliorate noise on the seismometers, but it would also allow the InSight team to further study apparently unique atmospheric patterns present at the InSight lander's location. Additional data from the magnetometer would allow the mission team to investigate the causes of short- and long-term observed magnetic variations which could illuminate dynamics of the martian interior.

This proposal was unusual because the mission team does not expect the InSight lander to be operational at the beginning of EM2 due to the projected loss of power caused by the accumulation of dust on the solar arrays. The proposal was written in the hopes that a vortex-induced cleaning event will clear the solar panels of dust as has occurred for other Mars missions in the past. The InSight team currently estimates that the likelihood of such an event positively benefitting the InSight mission before the end of EM1 is approximately 5%. This review is for the proposal for EM2, and as such is based on the assumption that such a vortex-induced cleaning event occurs before the start of EM2. The Additional Comments section addresses the more likely eventuality that there will be no cleaning events before the end of the EM1.

Overall Proposal Score: Excellent / Very Good

This reflects the Primary and Secondary criteria for the guideline proposed mission.

Primary Evaluation Criteria

Each section may have multiple findings, Please mark each finding as Major or Minor.

1. **Scientific merit of the proposed investigations to be undertaken during the Extended Mission.**

Strengths

MAJOR: During the second Extended Mission (EM2), the InSight broadband seismometer (SEIS) would be likely to collect data that would help to refine the internal structure of Mars beyond the resolution defined by the Prime Mission (PM) and first Extended Mission (EM1) objectives. Two of the critical structural targets are the internal structure and thickness of the martian crust, and the structure of the martian core-mantle boundary. For the crust, there is still uncertainty between a two-layered and three-layered model. The recording of additional Marsquakes of magnitude > 3.5, especially those from unique distances and backazimuths, would provide significant additional constraints that could allow for a discrimination between these models. For the core-mantle boundary, the current constraints depend heavily on low amplitude signals in relatively high noise level data from a very small number of events. Additional events of magnitude ~4, similar to the strongest events thus far recorded, would help to refine these estimates by allowing for the stacking and comparison of signals. Furthermore, a fortuitous recording of an event with magnitude >5 could prove revolutionary in the ability to constrain the deep interior of Mars. While there is no guarantee that any of these events will occur during the period of time covered by EM2, they will not be recorded if InSight is not operating.

MAJOR: The additional data collected during EM2 would provide important additional constraints on the spatial and temporal distribution of both Marsquakes and impactors. The temporal and spatial variability of Marsquakes is a poorly resolved phenomenon, especially because many of these patterns appear to be seasonal, and with the completion of EM1 there will only be data from two martian years. The recording of another martian year and a half would provide significantly more certainty in the identification of these patterns and therefore also their genesis. In particular, these seismicity patterns will provide insight into martian tectonics. A longer baseline of measurements would also provide more opportunity for the identification of martian impacts, which seem to be less numerous than predicted by models.

MAJOR: The second Extended Mission is fortuitously timed so that, if completed, it would double the number of quiet seasons recorded by the InSight mission while increasing total recording time by only 75%. To date, virtually all of the large seismic events that have been used to investigate Mars' internal structure have been recorded during the two 'quiet seasons' (martian summers, during which reduced winds allow for more sensitive seismic detections) that InSight has recorded thus far. The current quiet season is about to end, and the next one is expected to begin in January, 2023 shortly after the end of EM1. While an as-of-yet unseen event of magnitude > 5 would likely be visible even during the "noisy season," the more common events of magnitude 4 or higher are almost exclusively recorded during the quiet seasons. During EM2, over 2/3rds of the recording time would be during these optimal recording conditions, making the proposed recording extension particularly valuable.

MAJOR: The additional data from the atmospheric package on the InSight lander would provide insight into the apparently unique, dust-devil free microclimate present at the landing site. A longer baseline for these data would be critical for a full assessment of atmospheric patterns on Mars, as it has been shown that dust accumulation is somewhat higher than other landed Mars missions and the number of cleaning events if vastly lower at InSight's location (Lorenz et al. 2021). These data could also be coupled with the atmospheric data collected by other Mars Landers, allowing for additional cross-comparison analyses of the martian atmosphere.

Minor: The data collected during EM2 would provide new data on the martian regolith. A variety of measurement techniques will characterize the gas exchange between the regolith and the atmosphere, shrink the uncertainty of seismic velocities in the upper 10's of meters of the regolith, image the structure of the regolith, and allow for greatly improved characterization of the physical properties of the local regolith.

Minor: Additional measurements from the RISE data would provide additional constraints on the size, density, and state (*i.e.* liquid vs. solid) of the martian core. These refinements would be necessary steps to assess hypotheses about the evolution and dynamics of the deep martian interior.

Weaknesses

Minor: Some of the objectives described in EM2 would be extremely difficult to achieve even on Earth where data fidelity and coverage are significantly better, and are therefore unlikely to be fulfilled on Mars. For a seismological example, the science team proposes to use measurements of seismic attenuation to achieve objective D, "Constrain the volatile content of the crust and mantle." This has proven exceedingly difficult on Earth where seismic data are of vastly greater number and quality. This is because attenuation measurements, while important and plausible, are fundamentally difficult to attribute to any particular source, whether that be through inherent attenuation of the material, scattering, or source characteristics. Similarly, related to objective C, it is not likely on Earth or Mars to determine liquid core flows with current nor near future data. Nonetheless, the mission's potential for mapping attenuation and refining core radius are of fundamental importance.

2. **Responsiveness of the proposal to goals described in the Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013-2022" (2011).**

   Missions originally proposed before the 2011 Decadal Survey may optionally also refer to goals in "New Frontiers in the Solar System: An Integrated Exploration Strategy" (2003). Missions which include substantial cross-divisional content, and identify goals from those divisions, may also be evaluated relative to those respective goals.

Strengths

MAJOR: The link between Decadal Survey Goals and InSight Science Objectives were well described in the science traceability matrix and thoroughly linked the objectives of this Extended Mission to the Decadal Survey Goals/Objectives. Given that all of the current objectives are refinements on the objectives of EM1 and the PM, the link to the Decadal Surveys remains the same.

Weaknesses

None noted.

3. **Capability of the spacecraft to achieve the proposed science.**

Strengths

MAJOR: **All the instruments proposed for use continue to operate to the high standards seen during the PM and EM1, including the SEIS, RISE, PS, and TWINS instruments**. Notably, the very broad band seismometer (VBB SEIS), the first and only seismometer of its kind deployed extraterrestrially and the instrument responsible for recording Marsquakes that can probe Mars' deep internal structure, has consistently provided excellent data and continues to do so. The avionics also continue to function nominally. Commanding during the extended mission has allowed many science observations under challenging energy conditions.

Weaknesses

Minor: The mission did not provide specifics on the low-temperature instrumentation shut–down sequence. The proposal did not describe a plan for which instruments would be performing measurements and which would be shut down for the sake of a longer time-series in the event of an EM2 low power situation. This plan would also be relevant to the current situation which is projected to involve a low power situation before the start of EM2.

Minor: The InSight team has not found a solution to the problem of reduced solar energy collection due to the accumulation of dust on the solar arrays. This proposal for EM2 operates under the assumption that the array will experience a cleaning event (*i.e.,* dust storm), unlike any encountered by InSight thus far, that will allow it to continue/resume activity into EM2. However, even if a sufficient dust cleaning event occurs, dust will almost certainly re-accumulate during EM2. Given the apparent paucity of these cleaning events at this location on Mars, the lander is likely to experience at least periodic power shortages during EM2, even if an ideal cleaning event happens in the last 9 months of EM1.

4. **Merit of programmatic objectives.**

Programmatic objectives may include goals such as data relay, preparation for future missions, or goals of relevance to other divisions or directorates at NASA. The PMSR will evaluate separately the objectives of relevance to PSD, and those of relevance to other divisions or directorates at NASA, and may assign different weights to each.

Strengths

MAJOR: InSight provides significant meteorological data and observations that can be used to refine global climate models, as ground truth for orbital observations, and for EDL projections for future landers.

Minor: Quantification of modern impact rates and rates of significant magnitude seismicity could meaningfully inform future mission considerations on peak ground motion and hazards.

Weaknesses

None noted.

5. **Demonstrated scientific productivity of the mission team during the previous phase.**

Strengths

MAJOR: The science team has clearly maintained and even improved their scientific productivity in the previous cycle, EM1. In 2021, they published almost as many papers (57) as they did in the previous two years combined (58). The papers in 2021 cover essentially all of InSight's areas of scientific investigation, including seismology, magnetism, atmospheric physics, and even spacecraft engineering (e.g., characterizing the landing of other Mars missions).

Minor: The extensive research already performed on this unique dataset by the science team has laid the groundwork for future analyses from this and other possible future seismic missions to Mars and other planets. This is much in the same way that scientists on Earth had to develop new methodologies and routines to account for the unique types of noise they encountered with ocean bottom seismometers at different ocean depths. These routines eventually become routine, enabling a broader swath of the seismological community to use these data in an efficient manner.

Weaknesses

None noted.

6. **Performance in archiving data to the PDS in the previous phase.**

Strengths

MAJOR: In addition to consistently archiving data to the PDS on schedule, the team has gone above and beyond by making the seismic and geodetic data simultaneously available at the Institut de Physique du Globe de Paris (IPGP) Data Center, and the Incorporated Research Institutions for Seismology (IRIS) Data Management Center (DMC). Both of these are common data archiving locations for the large terrestrial seismology community.

Weaknesses

None noted.

Secondary Evaluation Criteria

7. **Extent to which the science community beyond the mission science team utilizes data and conducts published research**

Strengths

Minor: The seismic data collected by the InSight mission is currently used by a relatively small community of non-mission scientists due to the overall comparatively small community of planetary seismologists relative to the number of terrestrial seismologists. The EM2 would allow the science team to build the community of planetary seismologists by providing a data user workshop at the Fall AGU meeting that would help terrestrial seismologists navigate some of the challenges involved in using martian seismic data.

Weaknesses

None noted.

8. **Scientific merit of observations to be taken and archived to the PDS, for future use by the scientific community.**

Strengths

MAJOR: This is an incredibly unique and valuable dataset that would certainly continue to bear fruit, especially once a broader scientific community becomes comfortable/familiar with its use. The analyses performed thus far by the mission team will benefit from re-assessment and refinement from the scientific community, and additional types of analyses are almost certain to be performed. InSight data also stand to serve as a baseline for future potential seismological missions on Mars.

Weaknesses

None.

9. **Science value**

    The PMSR will not perform a detailed cost analysis of each proposal. However, the panels may assess in broad terms the science return of the mission relative to its overall cost.

Strengths

MAJOR: The low cost of EM2 relative to the cost of the overall mission, combined with the uniqueness of this fundamentally important data set, results in outstanding scientific return for NASA's Discovery Program. Observation of additional seismic data has the potential to render visible many first-order attributes of the poorly-understood martian interior. Features in the crust, mantle, and core may be glimpsed. Exotic seismic sources of shaking and details of tectonics may be indicated for the first time. The very unpredictability of what might be seen is part of the power of the proposed investigation.

Weaknesses

None noted.

10. **Demonstrated capabilities, experience, and expertise of key personnel.**

Strengths

MAJOR: The team leadership is very capable and experienced. The leadership of the InSight mission has successfully navigated this program through numerous challenges which required difficult decisions and significant out-of-the-box thinking (*e.g.,* attempts to understand and remedy the challenges faced by the mole; various efforts to remove dust from the solar panels, etc). In spite of these challenges, the leadership team has managed to collect all of the data necessary to answer most of the primary science objectives. They have also displayed flexibility in their willingness to utilize data from ancillary systems (atmospheric instruments, magnetometer) to do science beyond that envisioned in the PM.

Weaknesses

None noted.

11. **Expected effectiveness of the proposed PDP in training future leaders.**

Strengths

Minor: The InSight mission routinely rotates leadership within their science working groups to provide younger scientists with leadership opportunities. The mission has also developed a program (InSightSeers) to invite early career (graduate student & postdoctoral) scientists to science team meetings to observe the inner workings of planetary missions.

Weaknesses

Minor: The InSight proposal discussed providing leadership training, experience, and mentorship to mid-career scientists, but these were actually targeted for early-career scientists (<10 year post terminal degree).

12. **Thoroughness and appropriateness of the PDMP.**

Strengths

MAJOR: In addition to having solid plans to archive data to the PDS, the team proposes to continue to make the seismic and geodetic data simultaneously available at the IPGP Data Center and IRIS DMC, both of which are common data archiving locations for the larger terrestrial seismology community.

Minor: The Science Team is making available not just the original complete data stream, but also de-glitched and glitch-only versions to make the dataset more user-friendly for non-mission scientists.

Weaknesses

None noted.

Comments on Overguides and Descopes

Please list and comment explicitly on each Overgude and Descope

The proposal included no overguides or descopes.

Additional Comments

Comments here may include suggestions, or feedback about portions of the proposal which were not covered by the Evaluation Criteria. None of these comments affect the score.

InSight lander operations for the remainder of EM1, assuming no cleaning event occurs: The panel spent significant time discussing the likely end of the InSight mission during EM1. Overall, the panel recognizes the superb accomplishments of the InSight power system and the mission team to maintain sufficient power throughout the entire Prime Mission and much of the first Extended Mission. We recommend that the science team work to promote the longevity of the SEIS instruments, in particular the VBB instrument, for as long as possible while maintaining as close to a continuous data stream as possible.

Assuming the lander does not experience a cleaning event and loses power as currently anticipated, it will enter “Safe Mode” in Fall 2022. By the end of EM1 or the first few months of the proposed EM2, the lander would likely enter the “Dead Bus Recovery” (DBR) stage. During DBR, Command and Data Handling (C&DH) is powered off as is the Power Delivery and Drive Unit (PDDU) and the Consolidated Power System - High Efficiency (CPS-HE). All mission phase knowledge would be lost. However, the lander would remain sufficiently operational to revive itself should a cleaning event clear the solar panels and allow the batteries to recharge. Theoretically, DBR could last indefinitely. However, the low temperatures of the electronics will likely result in the loss of resurrection capability by approximately June 2023 (six months into EM2).

While DBR mode has no staffing requirements for the mission, the panel strongly encourages NASA to ensure a continued communications strategy with the DBR system to ensure that any attempts from the lander to reestablish communications be received. This strategy should extend at least as long as thermal considerations make it possible for the lander to resurrect itself. Should the InSight lander resume battery charging, either during Safe Mode or during the DBR period, NASA should resume scientific operations as described in the EM2 proposal.

Finally, should power be restored to significant levels, either during the remainder of EM1 or during EM2, we encourage the mission team to consider resuming their efforts to bury the seismic tether, which was halted in EM1. Data presented by the team indicates that this has reduced the number of glitches in the seismic data set.

Lessons learned from InSight power issues during the Extended Mission(s): Based on the experience of the Mars InSight team and recent research, solar-powered NASA missions to the surface of Mars can no longer assume that dust accumulation on solar panels will be mitigated by periodic, serendipitous winds that remove the dust. Since future robotic and human missions to Mars will likely continue to use solar arrays to power instruments, rovers, and more, the Panel recommends that the Mars Program Office A) conduct a 'lessons learned' exercise and B) explore in depth the issues related to this important technical challenge.

The Mars Program Office in collaboration with the InSight project, and possibly relevant team members from the Mars Exploration Rovers and Mars Phoenix projects, should conduct a lessons learned exercise to document the observed problems with dust accumulation on the solar arrays. This exercise should include a careful examination of martian meteorologic conditions that affect dust transport and adhesion to spacecraft surfaces, the atmospheric boundary layer conditions and solar panel materials that are conducive to wind-driven dust clearing events, and an assessment of technology solutions that could mitigate the risk of dust collection, especially for the possibility that wind-driven dust clearing does not occur (i.e., what InSight has experienced).

Following this exercise, and the public release of its findings, the Panel recommends that the Mars Program Office develop a research program to explore both the physics of dust accumulation (including dust lifting, dust adhesion, martian atmospheric boundary layer physics, and electrostatic conditions) and the technologies for dust removal (e.g., physical removal, induced saltation, vibrations, acoustic levitation, etc.) and/or dust accumulation prevention (e.g., electrostatics, acoustic levitation, etc.).

Usage of planetary seismic data by non-mission scientists: Given the paucity of extra-terrestrial seismic data prior to the InSight mission, it is perhaps unsurprising that the community of seismologists working on planetary seismology is comparatively small. The science team for InSight has done a superb job of extracting a tremendous amount of information out of a seismological data set that has many unique challenges.

That said, recent experiences on Earth with the EarthScope Transportable Array data (http://www.usarray.org/researchers/obs/transportable) have taught us that repeated assessments of a common data set using various modifications of existing analysis approaches results in more robust assessments of key structural parameters. As such, we encourage both the mission and NASA to consider all opportunities to expand the community of seismologists who use lunar and/or planetary seismic data. We commend the InSight mission for its plans for a martian seismic data analysis workshop at the 2022 AGU Fall Meeting. We hope that similar opportunities can be continued beyond the InSight mission, especially in light of future missions that include seismic instrumentation (*e.g.*, CLPS Farside Seismic Suite, ExoMars, Dragonfly).

On a similar note, we commend the InSight mission for making its seismic data analysis software open-source and openly available to the seismic community. We would encourage the InSight mission to consider sharing its analysis tools for the other InSight instruments in a similar fashion.

2022 NASA Planetary Mission Senior Review
Panel Evaluation

Proposal	**22-PMSR22-0008**
Title	**Lunar Reconnaissance Orbiter: Extended Science Mission 5**
Project Scientist	**Noah Petro / NASA GSFC**

Summary of Proposal

The Lunar Reconnaissance Orbiter (LRO) has generated the largest volume of data of any NASA planetary science mission and has captured the Moon in unprecedented detail, including critical information as to how the lunar surface changes over time. LRO is providing the planetary science community with the data to unravel the complex geologic history of the Moon. Extended Science Mission 5 (ESM5) would include a series of investigations focused on lunar volatiles, volcanism, tectonics, impact cratering, and regolith development processes. The proposal presents three broad scientific objectives, including conducting (1) new measurements to characterize regional and seasonal variability in the exosphere and the space environment, as well as focused measurements of regions of high interest in the north and south pole; (2) investigations to test models of magma generation, ascent, and eruption, degradation and space weathering of surface materials, and tectonism; and (3) new observations of space weathering and impact cratering to compare with previous data to assess for changes. The proposed strategy would be a coordinated, multi-instrument, nadir and off-nadir, multi-wavelength observing campaign of key targets for each science investigation. The instrument teams would strategically choose and observe high-value targets under a range of viewing and illumination geometries as those opportunities arise.

Overall Proposal Score: Excellent/Very Good

This reflects the Primary and Secondary criteria for the guideline proposed mission.

Primary Evaluation Criteria

Each section may have multiple findings, Please mark each finding as Major or Minor.

1. Scientific merit of the proposed investigations to be undertaken during the Extended Mission.

Strengths

Major: The proposal demonstrated the considerable scientific merit of the proposed observations to assess important processes on the Moon, including the volatile cycle, ongoing impacts, and tectonism. Previous LRO results have opened new lines of inquiry about active lunar processes over a range of timescales, and the proposed ESM5 objectives would improve understanding of these processes. The proposal convincingly demonstrated the merit of the majority of the proposed scientific investigations, and presented a multifaceted approach that would include combining observations from multiple instruments to address outstanding questions. New results from ESM5 would provide novel insights into the understanding of the formation and evolution of the Moon.

Major: Targeted analyses of Cabeus crater would greatly increase the understanding of the distribution and stability of volatiles in permanently shadowed regions (PSR) of the Moon. Previous LRO observations indicated that although many PSR environments are thermally suitable for the presence of volatiles, the actual distribution of volatiles in those spaces remains heterogeneous. Because the presence of volatiles within this south polar crater has been confirmed from Lunar Crater Observation and Sensing Satellite (LCROSS) data, temporal observations of this crater would help constrain the influence of seasonal variations, diurnal cycling, and illumination geometry on volatiles in PSRs. These factors are of high science priority as well as of interest for human exploration and In Situ Resource Utilization (ISRU).

Major: Higher-resolution analyses of the north pole would advance the understanding of volatile stability in permanently shadowed regions of the Moon. LRO has shown that there are differences in the distribution of volatiles between the north and south poles of the Moon, and the reason for this remains unclear. The orbital parameters of LRO during ESM5 would provide higher resolution coverage of the north pole than has been possible during past extended missions. These new observations would help in understanding why volatile distribution varies from pole to pole while providing insight into the general nature of volatile stability on the Moon.

Major: LRO would identify additional young tectonic features, including some that may be active, which would increase the understanding of lunar tectonism over time. Thousands of young lobate thrust fault scarps and hundreds of small-scale wrinkle ridges and graben have been revealed in NAC images acquired with optimum illumination geometry. Many of these features appear to be young, suggesting the possibility of active tectonism on the Moon. This conclusion is supported by the identification of 24 landslides that occurred during the time LRO has been in orbit that cannot be directly correlated with new impact craters. Additional images focused on lobate scarps proximal to landslides may provide evidence for active tectonism. Such evidence would fundamentally change our view of the lunar surface.

Major: Continued monitoring of new craters would further refine the current impact flux rate on the Moon, which would be critical for better constraining the ages of surfaces throughout the inner Solar System. The proposal demonstrated that empirical observations of new impact craters made by LRO would refine theoretical impact flux rates. This information would be fundamental for dating features and surfaces on the Moon, and it would form the basis for assigning relative ages to crater counts made on other planetary surfaces. Additionally, the proposed study of recent impacts would have value for understanding fundamentals of the impact process and how the Moon's surface evolves with time.

Minor: The proposal demonstrated the significance of how exposed lower crustal and mantle material would provide insight into the evolution of the Moon. Previous observations from LRO and other spacecraft showed that potential exposed mantle materials have a variety of compositions in terms of the amount of pure anorthosite, mafic minerals, and thorium, suggesting a heterogeneous mantle that is not completely understood. Mapping potential mantle deposits and characterizing them would be an important effort to advance the understanding and evolution of the lunar interior.

Minor: The proposal identified an important scientific objective regarding the determination of ages and distributions of wrinkle ridges and lobate scarps. Understanding if wrinkle ridge ages are progressively younger from the centers to the margins of mascon and non-mascon maria would help determine whether the lithosphere increased in thickness with time, expanding the understanding of lunar lithospheric evolution. High-resolution LRO imagery has demonstrated that it is possible to date individual wrinkle ridges using a variety of established crater counting techniques while placing them into temporal context with one another. Characterizing the dimensions, occurrences, and orientations of lobate scarp mega-clusters could enable further evaluation of the Moon's current state of stress and/or the mechanical properties where the mega-clusters formed.

Minor: The proposed analyses of polar regions as they emerge from shadows would provide a better understanding of lunar volatile generation and cycling. Observations made by LRO during ESM5 would test whether surface volatiles or porosity is responsible for low albedo measurements made by the LOLA and LAMP experiments. Because volatiles should sublimate as they emerge from the shadows and porosity should remain consistent regardless of illumination or surface temperature, the proposal presented a simple experiment to test competing hypotheses about the surface characteristics of craters in PSR.

Minor: LRO would quantify the breakdown and/or overturn of different types of impact ejecta materials, advancing the understanding of the evolution of the lunar surface. Recognition of the complexity of impact crater ejecta is a major LRO result, both in terms of the process of emplacement and the extent of its effect on the lunar regolith. Targeted investigations of at least 10 large (diameters >10 km) impact craters that display the clearest signs of diverse impact ejecta products would improve upon this previous result and provide a better understanding as to how different impact ejecta materials break down over time. These observations would also refine the understanding of the importance of processes such as solar wind bombardment, impacts over a broad range of scales, and cosmic ray exposure to the degradation of impact craters over time.

Weaknesses

Major: The proposal did not provide adequate details regarding the number and locations of new observations that would be needed to address several major scientific objectives. For example, LRO has already made a number of observations of wrinkle ridges, silicic deposits, and exposures of deep mantle material. The proposal did not adequately explain why these existing data would be insufficient to address the proposed scientific objectives, nor did it adequately explain how many more observations would be needed, where these observations should be made, or the acquisition conditions required to definitively answer such questions. This insufficient specificity made the potential value of several objectives unclear.

Major: The proposal did not adequately demonstrate that the data to be collected for several of the investigations would be sufficient to address the scientific goals. For example, the proposal did not sufficiently demonstrate that it would be possible to discriminate between mafic crustal and mantle materials as proposed in Objective 4.4.1**.** Thorium enhancements in Apollo samples are observed in specific types of secondary crustal rocks, like KREEP basalts and highlands alkali- and magnesian-suite rocks (e.g., Klima, Dyar & Pieters 2011; Klima, Pieters, Boardman, et al 2011). These samples are not mantle materials, but they could yield a Th enhancement, which suggests Th content may not be a diagnostic indicator. In addition, the proposal did not convincingly demonstrate that space weathering would cause significant changes in surface and optical properties on 10-year timescales, as would be targeted for investigation during this phase of the extended mission. In addition, the proposal did not adequately demonstrate that the experiment to determine if dust was responsible for degrading the Apollo Lunar Laser Ranging Retro Reflectors (LRRR) would provide definitive results. Lastly, the proposal mentioned "the mixing of silicic materials with non-silicic materials will be enabled by tying remote thermal observations to laboratory experiments." However, the proposal did not adequately explain what laboratory experiments, if any, would be funded by ESM5 or how the proposed Diviner observations would help address this question.

2. **Responsiveness of the proposal to goals described in the Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013-2022" (2011).**

   Missions originally proposed before the 2011 Decadal Survey may optionally also refer to goals in "New Frontiers in the Solar System: An Integrated Exploration Strategy" (2003). Missions which include substantial cross-divisional content, and identify goals from those divisions, may also be evaluated relative to those respective goals.

Strengths

Major: All the scientific investigations proposed for ESM5 were convincingly linked to specific goals and objectives from the Decadal Survey (Planetary Science Decadal Survey, Visions and Voyages, NRC, 2011) as well as The Scientific Context for Exploration of the Moon (SCEM) report. The Science Traceability Matrix (Foldout 1) represented a clear and convincing link between Decadal objectives and the scientific questions being proposed in ESM5. Specific Decadal Survey/SCEM objectives were also highlighted before each proposed task was introduced, making the relevance of the ESM5 objectives obvious.

Weaknesses

None noted.

3. **Capability of the spacecraft to achieve the proposed science.**

Strengths

Major: The proposal demonstrated the capability of the spacecraft to execute the proposed extended mission plan. The proposal reported that the spacecraft has performed nearly flawlessly in orbit since launch in June 2009 with a total of 99.04% operational uptime. Only 0.28% of the downtime has been due to spacecraft anomalies, while the remaining 0.68% downtime was due to routine thruster maneuvers and instrument calibration slews. The spacecraft has sufficient fuel reserves to accomplish ESM5. The proposal presented only two ‘low’ risks: the LRO Gyroless Safe and the LRO Battery Degradation, indicating that the LRO spacecraft is healthy and that the potential risks for the three years of ESM5 would be low. The spacecraft has also compensated for the degradation of the Miniature Inertial Measurement Unit (MIMU) with new star tracking capabilities, demonstrating strong operational problem solving qualities of the team.

Weaknesses

Minor: Since the Miniature Inertial Measuring Unit (MIMU) was turned off, spacecraft pointing uncertainty (‘noise’) has become an issue for generating high-resolution digital elevation models (DEMS) from the Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Cameras (NAC) images, the compensation for which was not adequately discussed in the proposal. The proposal lacked adequate quantification of the amount of degradation to the DEMs that this problem continues to represent. Although the team acknowledged a way to address this program, how well this would work remained an open question, and this issue is important because a large number of high-resolution NAC images and DEMs would need to be generated to support both the scientific and programmatic objectives of the proposed work.

4. **Merit of programmatic objectives.**

    Programmatic objectives may include goals such as data relay, preparation for future missions, or goals of relevance to other divisions or directorates at NASA. The PMSR will evaluate separately the objectives of relevance to PSD, and those of relevance to other divisions or directorates at NASA, and may assign different weights to each.

Strengths

Major: LRO is the only NASA asset currently positioned to acquire orbital data around the Moon, and hence it is a critical asset during this time of enhanced lunar exploration. The proposal demonstrated that LRO is a critical asset for mission planning for Artemis and CLPS during ESM5.

Weaknesses

None noted.

5. **Demonstrated scientific productivity of the mission team during the previous phase.**

Strengths

Major: The LRO mission team has continued to be highly productive through ESM4. ESM4 resulted in ~50 new papers published by the team. In particular, significant progress was made during ESM4 on questions related to the distribution of exospheric and surface volatiles as well as impact and tectonic processes. With over 375 peer-reviewed publications from the LRO team since 2006, the team has made significant contributions to the advancement of lunar and planetary science.

Weaknesses

Minor: A number of scientific objectives targeted in ESM4 were not completed as would be expected. In some instances, the proposal suggests that additional data would improve the fidelity or accuracy of the results, such as an ongoing monitoring of new impact craters. However, in other instances studies proposed in ESM4 were marked completed only to appear as “new” objectives this cycle. For example, ESM4 Objective 7 to “Identify previously unrecognized mare flow units and refine mare stratigraphy in targeted areas within Mare Imbrium and Oceanus Procellarum” was marked as completed, but is very similar to ESM5 Objective 4.4.4, which would address

“What is the distribution, ages, and extent of the youngest mare activity? When was the Moon last volcanically active?”

6. **Performance in archiving data to the PDS in the previous phase.**

Strengths

Major: With few exceptions, LRO dataset has been consistently delivered on time to the PDS throughout the mission. The volume of data archived in the PDS by LRO currently amounts to over 1.3 petabytes (PB) as of December 2021. This collection is the largest volume of data archived by any NASA planetary science mission and represents > 60% of the entire data volume of the PDS. With only a few minor exceptions, these data have also been consistently delivered on time to the PDS. A hallmark of the LRO PDS archive is its extensive set of data products, from level 0 data (raw) to higher-level reduced data record (RDRs) and gridded data record (GDRs) that include mosaics, maps, and derived products. The LRO instrument teams collaborated with the PDS to develop and implement plans to convert LRO data archived through ESM4, with the exception of radio science data, from the PDS3 standard to the current PDS4 standard. This effort is underway and on target to be completed on time.

Weaknesses

None noted.

Secondary Evaluation Criteria

7. **Extent to which the science community beyond the mission science team utilizes data and conducts published research**

Strengths

Major: Data from LRO have rejuvenated interest in lunar science over the lifetime of the mission. The planetary science community has produced over 600 peer-reviewed publications based on data collected by LRO. LRO data have enabled researchers to explore a wide range of processes that operate on the Moon and other Solar System bodies with unprecedented detail.

Weaknesses

None noted.

8. **Scientific merit of observations to be taken and archived to the PDS, for future use by the scientific community.**

Strengths

Major: The scientific community has made extensive use of LRO data since the mission launched, and the interest and use of LRO data is accelerating with time. It is likely that use of LRO data would increase during ESM5, particularly as a result of interest in the Commercial Lunar Payload Services (CLPS) and Artemis missions.

Minor: Solar maximum will occur in the latter half of ESM5, so the ESM4-ESM5 combined timeframe should encompass most of the Solar Energetic Particle (SEP) events of cycle 25, helping advance the understanding of the lunar exosphere and radiation environment under unique space weather conditions.

Weaknesses

Minor: The proposal did not adequately address the types, amounts, and characteristics of new data that would be collected. The proposed scientific objectives would often require a number of targeted observations to be made by multiple instruments; however, the spacecraft would also continue to collect data in a passive or untargeted mode. These data were not placed into context with the extremely large amount of data LRO has already collected.

9. **Science value**

   The PMSR will not perform a detailed cost analysis of each proposal. However, the panels may assess in broad terms the science return of the mission relative to its overall cost.

Strengths

Major: The proposed mission budget was consistent with the previous extended missions that resulted in additional data and new scientific findings. The proposal provided adequate justification for the requested funding at this level.

Weaknesses

None noted.

10. **Demonstrated capabilities, experience, and expertise of key personnel.**

Strengths

Major: The LRO team has a mature, experienced, and active leadership team. For over a decade, the team has shown its ability to both successfully manage LRO operations and support its science team in a way that optimizes science return while benefiting the planetary science community.

Weaknesses

None noted.

11. **Expected effectiveness of the proposed PDP in training future leaders.**

Strengths

Minor: The proposal presented a credible plan for developing the next generation of scientists three different ways. (1) They have implemented a system of "theme leads," which includes Drs. Catherine Elder, Julie Stopar, Angela Stickle, and Maria Banks. These theme leads were responsible for developing the concept and science questions presented in the proposal to completion of the proposal itself. As part of the execution of ESM5, these theme leads would support the project in the identification of targets, science planning, and team coordination. (2) The team would work with CLPS investigators, presumably many who are early-career scientists or new investigators. (3) The team would include 23 new Co-I's during ESM5. The addition of a diverse and talented set of early-career science team members to the mission team, even at this late phase, would provide highly valuable experience.

Weaknesses

Minor: The proposal did not demonstrate that "LRO 101," a series to provide an introduction to the engineering and operations for LRO, would provide information that was unique to the experience gathered by an experienced

investigator that was already on the team. The proposal did not describe a clear structure or set of topics for LRO 101.

12. Thoroughness and appropriateness of the PDMP.

Strengths

Major: The Planetary Data Management Plan (PDMP) is complete, thorough, and appropriate. The proposal articulated that the same procedures used to deliver the largest dataset to the PDS would be utilized in ESM5. As detailed by information provided by the PDS, LRO has delivered data to the PDS every 3 months for nearly 13 years.

Weaknesses

None noted.

Comments on Overguides and Descopes

Please list and comment explicitly on each Overgude and Descope

The proposal presented requests for three different overguides.

Overguide 1. Enhanced LRO support for CLPS landing site selection analyses and characterization. The proposal demonstrated that this overguide has significant merit, primarily because the LRO team has a substantial and unique capability in the type of analyses that the team proposed. In addition, CLPS providers will need these types of analyses, and NASA will to need to assure that these analyses are correct. Formalizing and managing this process through the existing LRO team, in coordination with the CLPS office, has the potential to ultimately save NASA and commercial companies resources by preventing duplication of work.

Overguide Score: Very Good.

Overguide 2. “Return to the Moon with LRO” website and visualization. The proposal demonstrated that this task would potentially be a useful and exciting product. Similar products produced by Co-I Ben Feist, such as Apollo in Real Time, are educational, informative, and entertaining. However, the proposal did not establish the scientific value of this effort. The PMSR Call for Proposals specifically excludes the evaluation of communications plans and activities. In addition, the proposal did not adequately address the potential that Artemis 3 surface activities may occur well past ESM5, which would make the timing of this Overguide inappropriate.

Overguide Score: Good.

Overguide 3. Enhancing use of LRO Data and Access Tools to Support Artemis Planning. The proposal demonstrated that this would be a useful, if not critical, product for supporting Artemis. The team has been proactive in identifying this need and devising a credible plan for supporting it.

Overguide Score: Very Good.

Additional Comments for the Mission

Comments here may include suggestions, or feedback about portions of the proposal which were not covered by the Evaluation Criteria. None of these comments affect the score.

The team might consider revitalizing the LRO Data User's Workshops. These workshops could focus on recent ESM4 and upcoming potential ESM5 measurements that the external science community, particularly early-career non-team members, may find useful and interesting. It is likely that LRO data will be in extremely high demand due to CLPS and Artemis, so these workshops would be especially timely.

NASA’s Heliophysics division operates the Heliophysics System Observatory (HSO), which joins heliospheric and space-science data from multiple missions. LRO could be positioned to contribute to this virtual observatory due to its unique location. LRO might contact the HSO to explore how it could contribute. Cross-portfolio and cross-division coordination could enhance the scientific return from this unique mission.

The team might consider updating the LOLA GDRs with recent data, since some of the products in the PDS are substantially out of date. The team is uniquely skilled to produce these GDRs, and even marginal improvements to this data would be widely used in the lunar community.

2022 NASA Planetary Mission Senior Review

Proposal	**22-PMSR22-0006**
Title	**2022 Planetary Mission Senior Review: MAVEN**
Principal Investigator	**Shannon Curry / University of California, Berkeley**

Summary of Proposal

The MAVEN mission began science observations at Mars in September 2014, and is currently executing its fourth extended mission (EM4). MAVEN was also incorporated into the Mars Relay Network in 2019, and the time devoted to relay activities is expected to increase from the present ~30% to ~45% in 2024 with the arrival of the ExoMars mission. The proposed fifth extended mission (EM5) would continue MAVEN's science and relay activities through FY25. This time period would be important because it encompasses the anticipated rise and peak of Solar Cycle 25, which should provide unique conditions not previously encountered during the mission. For example, MAVEN will have the opportunity to observe dust storms during intense solar activity, and will have the possibility of encountering high solar EUV flux at aphelion. The proposal laid out a set of eight objectives spanning three science themes which are driven by the 2013 NRC Planetary Science Decadal Survey and Mars Exploration Program Analysis Group (MEPAG) goals:

- How does solar maximum affect the Martian atmosphere and climate?
- How does the upper atmosphere system respond to Mars' seasons and dust?
- How does the hybrid magnetosphere control basic physical processes in the Mars-solar wind interaction?

Successful EM5 science observations would continue to improve our understanding of Martian aeronomy, the processes that lead to escape of atmospheric gasses, and how those processes might have varied over the age of the solar system. MAVEN's proposed EM5 science program would include several objectives related to NASA's Heliophysics and Human Exploration goals.

The MAVEN team has presented an outstanding record of significant and sustained scientific and technical accomplishment, including its exemplary role in the Mars Relay Network.

Overall Proposal Score: Excellent / Very Good

Primary Evaluation Criteria

1. **Scientific merit of the proposed investigations to be undertaken during the Extended Mission.**

Strengths

[MAJOR] The proposed MAVEN Extended Mission 5 (EM5) is poised to observe Mars with a unique set of instrumentation during the rise and peak of Solar Cycle 25, compared to its previous observations taken during the declining phase of Solar Cycle 24. MAVEN EM5 observations would also include geometries different from previously seen. MAVEN would capture the response of the upper atmosphere of Mars to higher solar activity levels than previously sampled, including during the expected dust season of 2024. Because energetic solar events are more common in the rising phase as compared to the declining phase of a solar activity cycle, MAVEN expects to see, e.g., three times more X-class solar flares during EM5 than it has witnessed previously. The EM5 observations would address compelling open science questions that have not been addressed earlier in the mission, and are critical to quantifying atmospheric loss at Mars during earlier periods in its history when the solar wind would have been more intense. The proposal articulated 3 science goals with 8 objectives to be achieved in EM5 - all specifically related to understanding the atmospheric response to increasing solar activity as coupled to Mars' seasonality and its hybrid magnetosphere. The measurement capabilities and existing expertise and body of work makes achieving these goals likely.

[MINOR] The MAVEN instruments continue to operate well, and the MAVEN team has proposed several enhancements in instrument capabilities. During EM5, IUVS would add a new nadir-viewing mode to investigate discrete aurora, and the SWEA instrument would add an increased time resolution mode enabling high-cadence electron pitch angle measurements for higher resolution near crustal magnetic fields.

[MINOR] The team has maximized science return in balance with MAVEN's increasingly critical role in the Mars Relay Network. Previously, any orbit used for relay could not be used for science, but the team has worked to improve this situation by sandwiching science observations around relay activities.

Weaknesses

[MINOR] Although beyond the control of the team, an inherent risk to the proposed science program is that Solar Cycle 25 may be a weak one. This would limit the upper range of solar activity levels for which MAVEN is able to characterize the Martian response, making the proposed EM5 science program less compelling.

2. **Responsiveness of the proposal to goals described in the Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013-2022" (2011).**

Strengths

[MAJOR] The proposed EM5 science program is strongly aligned with the 2013 NRC Planetary Science Decadal Survey, as shown clearly in the STM (Table 5.1) where Decadal Survey goals are directly linked to EM5 goals and objectives. For example, a noteworthy study from EM4 established the current escape rate of carbon from Mars (Lo et al., 2022), which follows directly from the Decadal Survey goal: "Photochemistry and dynamics are especially vigorous in the upper Martian atmosphere (thermosphere and ionosphere), and an understanding of these processes is critical to understanding the loss of Mars's upper atmosphere to space, which has probably controlled Mars's long-term climate evolution, and to testing Earth-based theories in meteorology and aeronomy" [2013 Decadal Survey, p. 148].

[MINOR] The MAVEN team also plans to address some Decadal Survey goals in Heliophysics and Human Exploration in EM5 including:

- Determine the origins of the Sun's activity and predict the variations of the space environment. [Heliophysics]
- Determine the interaction of the Sun with the solar system and the interstellar medium. [Heliophysics]
- Acquire information concerning potential resources and hazards … to support future human exploration activities [Human Exploration]

Weaknesses

None noted.

3. **Capability of the spacecraft to achieve the proposed science.**

Strengths

[MAJOR] The MAVEN spacecraft and instruments are largely healthy and operating well, with many years of expected lifetime remaining for major components and expendables. Some expected instrument degradation is being mitigated, while at the same time innovative new instrument capabilities and modes are being implemented. The risk of failure of both Inertial Measurement Units (IMUs) would be mitigated by the development of an “all stellar mode” (ASM) of operations. The schedule for implementation of ASM has been accelerated by several months, with a current readiness date of early March 2022.

The team has well-thought-out plans that would not push performance limits. The expected coverage of MAVEN periapsis in latitude, longitude, and local time during EM5 is very good. (Proposal Figure 7.2).

Weaknesses

[MINOR] Degradation and potential failure of the IMUs and the readiness of ASM to replace them remains a concern. The consequence of IMU failure is rated “5” in the LxC matrix (Table 8.1) and it is not clear this will be completely mitigated until ASM is fully implemented.

4. **Merit of programmatic objectives.**

Strengths

[MAJOR] MAVEN would continue to be an essential part of the Mars Relay Network in EM5. MAVEN currently carries about 22% of the relay load. Because all current missions have different capabilities, limitations and projected lifetimes, it is important to sustain as many of them as possible in the infrastructure at Mars. MAVEN is also budgeting fuel to support the upcoming Mars Sample Return program. MAVEN also adds significant value to the broad portfolio of Mars missions through its community space weather alerts. The proposal demonstrated how MAVEN has done an outstanding job of accommodating an increased amount of relay time in support of ExoMars without sacrificing important science.

[MINOR] The proposed EM5 is cross-divisional among Planetary, Heliophysics and Human Exploration, having added goals and measurement capabilities in Theme 3 that are relevant to Heliophysics and Human Exploration [Science Traceability Matrix, Table 5.1].

[MINOR] During the proposed EM5, the MAVEN team would continue to collaborate with other Mars missions, which includes bi-weekly meetings with MRO on dust observations; joint team membership between MAVEN and EMM/Hope; intercalibration of solar wind measurements between MAVEN and Mars Express; and cross calibration of observations between MAVEN and TGO. These activities enable direct collaboration between missions and aids in cross-training and skill development.

Weaknesses

None noted.

5. **Demonstrated scientific productivity of the mission team during the previous phase.**

Strengths

[MAJOR] During EM4, the MAVEN team has continued its excellent publication record, while non-team-led publications and community access of MAVEN data have also steadily increased. Non-team-led publications outnumbered team-led publications in both 2020 and 2021.
The MAVEN team has maintained a high level of productivity throughout the lifetime of the mission, including an exemplary publication rate in EM4 (Table 1, Appendix A3). Examples of recent high-impact papers produced during EM4 include:

- Stone et al.- “Hydrogen escape from Mars is driven by seasonal and dust storm transport of water,” Science, 2020.
- Schneider et al. - “Discrete Aurora on Mars: Insights into their distribution and activity from MAVEN/IUVS observations,” JGR, 2021.

[MINOR] The team continues to pursue the addition of new observing modes which could significantly enhance MAVEN’s science return. For example, the addition of Low Gain Antenna observations during EM4 tripled the number of ionosphere profiles obtained per week, improving the temporal resolution of the ionospheric response to varying input from solar storms and dust storms.

Weaknesses

None noted.

6. **Performance in archiving data to the PDS in the previous phase.**

Strengths

[MINOR] MAVEN has achieved an admirable on-time data archiving rate of 90%, with deviations justified and rectified to a successful conclusion with the MAVEN-related PDS nodes, Planetary Plasma Interactions, Atmospheres and NAIF.

[MINOR] The archiving of plasma data in the PDS4-compliant Common Data Format (CDF-A) has been beneficial to the heliophysics and planetary magnetospheres communities, as documented in the PDS report provided for the PMSR. MAVEN is the first mission to implement this format for plasma data in the PDS, which increases its compatibility with existing analysis packages and its overall usability by the community.

Weaknesses

None noted.

Secondary Evaluation Criteria

7. **Extent to which the science community beyond the mission science team utilizes data and conducts published research**

Strengths

[MAJOR] The number of non-team led publications has steadily increased over the course of the mission. In 2020 and 2021, the number of non-team led publications was larger than team-led publications, and this percentage was higher in 2021 than in 2020 (Table 1, Appendix A3). There has also been a marked increase in the community access of the PDS-archived MAVEN data, as discussed in the proposal and supported in the PDS usage report. All three categories of usage (data volume, files per month, unique internet users) tracked by the two MAVEN-data-hosting PDS nodes (ATM and PPI) showed steadily increasing numbers since 2016. These are healthy trends that indicate excellent community engagement with the mission data.

Weaknesses

None noted.

8. **Scientific merit of observations to be taken and archived to the PDS, for future use by the scientific community.**

Strengths

[MAJOR] The EM5 data set would be of great value and a unique resource for future researchers. The level of instrumentation at this location (1.5 AU) is very limited beyond what MAVEN currently provides. It is key to both the planetary and the heliophysics communities in that it provides a near constant solar wind monitor at 1.5 AU for benchmarking solar wind propagation models and forecasting intense interactions at the outer planets, and continuously tracks how planetary atmospheres are impacted by the evolution of the solar wind. The proposed EM5 observations would be utilized in collaboration with other Mars missions to achieve synergistic “system science,” for cross-divisional activities, for comparison to future observations, and in assessing long-term evolution of Mars' atmosphere with respect to solar and dust variability.

Weaknesses

None noted.

9. Science value

Strengths

[MINOR] The high-level budget presented in the proposal, showing modest increases in science and operations funding, is commensurate with and appropriate for the science and relay activities to be undertaken in EM5. Even with MAVEN's increasing relay duties, the team is working hard to adjust operations plans to maximize science return.

Weaknesses

[MINOR] The proposal provided high-level budget information split into Science and Ops, but did not provide cost data to WBS Level 2 as required by the call for proposals. This made it difficult to assess the budget.

10. Demonstrated capabilities, experience, and expertise of key personnel.

Strengths

[MAJOR] MAVEN has a strong team that has performed well, maintaining high science productivity, troubleshooting technical issues, and mitigating against future problems over the course of the prime and four extended missions. The recent transition to a new PI and the addition of two new deputy PIs appears to have been well executed.

Weaknesses

None noted.

11. Expected effectiveness of the proposed PDP in training future leaders.

Strengths

[MINOR] The MAVEN team has a well demonstrated record developing and advancing earlier career scientists into leadership positions. This includes appointment of a new PI (August 2021) and two new deputy PIs, as well as the addition of new deputy leads for nearly all instruments.The MAVEN mission has done a good job with mentorship and advancement of junior team members. The PDP discussed several opportunities available at all levels of the mission to support future leaders. The success of their model has been demonstrated by the transition of leadership roles to those initially in more junior team roles (e.g., postdocs now in PI and Deputy PI roles). Other instrument leads have transitioned as well, such as the lead for the LPW (Langmuir Probe and Waves instrument), and the lead for the Space Weather investigation.

Weaknesses

None noted.

12. Thoroughness and appropriateness of the PDMP.

Strengths

[MINOR] The PDMP is thorough and has been used successfully throughout the lifetime of the mission. They have archived all data in PDS4 format from the start of the mission, and are the first mission to archive plasma data in the more useful CDF-A format.

Weaknesses

None noted.

Comments on Overguides and Descopes

The proposal included no overguide or descopes.

NASA encouraged the team to offer a list of descopes. The team’s minimal explanation for not doing so was insufficient.

Additional Comments

In Table 10.1, which shows the deputy leads for the instruments, it would have been good to see where these scientists started out within the team, as was done in Table 10.2.

2022 NASA Planetary Mission Senior Review
Panel Evaluation

Proposal	**22-PMSR22-0002**
Title	**Mars Reconnaissance Orbiter 6th Extended Mission Proposal FY23-25: Mars Fundamentals for Future Exploration**
Project Manager	**Martin (Dan) Johnston / Jet Propulsion Laboratory**
Project Scientist	**Richard Zurek / Jet Propulsion Laboratory**

Summary of Proposal

This proposal is for the 6th Extended Mission (EM) for the NASA Mars Reconnaissance Orbiter (MRO), which has been studying Mars since 2006. MRO is a dual-purpose mission with both scientific and NASA programmatic objectives. In this EM, the MRO Science Team would examine key processes of change on Mars, from the evolution of ancient habitable environments to the modern climate. The scientific objectives are distributed in four broad goals that contain 17 investigations to be carried out in FY23-25 that are traceable to the high-level goals of Visions and Voyages (2011). These include: A) Mars Surface and Climate through Time (7 investigations), B) Evolution of Martian Ices (3 investigations), C) Active Geologic Processes (3 investigations), and D) Modern Mars Atmosphere and Climate (4 investigations). The NASA programmatic objectives include: i) relay communications with landed assets; ii) landing site characterization for science potential and engineering safety; iii) environmental data acquisition for future mission design and implementation, and iv) when possible, coverage of critical events of other spacecraft such as the Entry, Descent, and Landing (EDL) phase. Noteworthy for EM6 is that the CRISM instrument will be shut down (unless funded by an overguide). This is due in part to the failure of both cryocoolers that make IR observations no longer possible, and due in part to meet the funding limit imposed by the current NASA funding target.

An experienced, well-integrated team would operate MRO under tested procedures and mature processes. The proposed technical plan for EM6 leverages previously demonstrated capabilities and observing modes.

Overall Proposal Score: Excellent/Very Good

Primary Evaluation Criteria

1. **Scientific merit of the proposed investigations to be undertaken during the Extended Mission.**

Strengths

[Major] The MRO EM6 proposal is detailed, and in most cases it clearly describes a set of Goals and associated Investigations that build on past accomplishments. The four broad EM6 Goals are: A) Mars Surface and Climate through Time (7 investigations), B) Evolution of Martian Ices (3 investigations), C) Active Geologic Processes (3 investigations), and D) Modern Mars Atmosphere and Climate (4 investigations). The investigations identified for Goal A (Mars Surface and Climate Through Time) are timely and fundamental to a better understanding of Mars' geologic and climate history. Goal B investigations (Evolution of Martian Ices) would provide important information regarding quantity and distribution of ice in the martian surface and near-surface. Goal C investigations (Active Geologic Processes) depend on an ever-lengthening baseline of repeated observations; the proposed investigations of active slope processes and of active impacts are particularly compelling science. Goal D (Modern Mars Atmosphere and Climate) would increase the baseline for such observations and complement the data on vertical transport through the atmosphere from other spacecraft. Overall, this mission would continue to address questions of high scientific merit. In particular:

- EM6 would lead to improved understanding of upper atmosphere processes including ionospheric response to the crustal magnetic field and linkage of atmospheric escape to the dust and water in the middle atmosphere.
- EM6 would lead to better characterization of pre-Amazonian volcanic sequences using SHARAD and HiRISE data.
- EM6 would lead to better characterization of polar layered deposits, seasonal changes at the poles, and midlatitude ice.
- Continued MRO monitoring would improve our understanding of a variety of active processes, including those on slopes (RSLs, gullies, landslides), aeolian movements, and new impact craters.
- Continued MRO monitoring of atmospheric phenomena would help characterize a variety of atmospheric processes, such as gravity waves and associated clouds, dust storms, and the link of dynamics to chemistry (in concert with TGO).

[Major] Previously acquired data from all of the MRO instruments have revolutionized the understanding of Mars, and these past accomplishments lend confidence that the proposed EM6 investigations would be successful. For example, the images from the High Resolution Imaging Science Experiment (HiRISE) and Context Camera (CTX) have provided a wealth of data about the martian surface at a resolution and spatial coverage unmatched by any prior missions. The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) has provided compositional information of many interesting scientific targets that has led to an improved understanding of the martian surface chemical processes through time. The Shallow Radar sounder (SHARAD) has advanced the understanding of the shallow surface of Mars and provided detailed information about the interior structures of the martian polar caps. The Mars Climate Sounder (MCS) and the Mars Color Imager (MARCI) have provided many new insights into the functioning of the martian atmosphere, weather and climate over time. The continuation of this mission would support Mars science and NASA's Mars Exploration Program.

[Major] The proposed science investigations for EM6 would be a natural extension of accomplishments from EM5, and would take advantage of, and continue to build, a long-lived temporal database that records surface and atmospheric changes on Mars since 2006. The ongoing collection of data from MRO instruments would provide information that is necessary to address questions about the evolution of Martian surface and atmospheric processes.

[Major] Expanded high resolution imaging and DTMs, in combination with the new CRISM hyperspectral maps to be produced from pre-EM6 data, would help improve the understanding of layered sediments, possible caves, fluvial deposits (aided with SHARAD radar), and the geology of hydrated mineral outcrops relevant for interpreting past Mars and its habitability.

[Major] Synergies in data collection among MRO instruments would enable accomplishment of the proposed investigations and are well described in the proposal. For example, the combination of HiRISE, CTX and SHARAD data would be ideal for identifying and characterizing near-surface ice deposits. Nearly all of the proposed investigations have similar redundancies across multiple instruments.

Weaknesses

[Minor] In several cases, the proposal lacked sufficient detail on which anticipated results would be incremental versus which would significantly advance the understanding of Mars. For example, mid-latitude ice has already been mapped by Mars Odyssey neutron spectroscopy, and mapping it again with thermal inertia (investigation #11), sensitive only to depths of <1 m, may not provide a new understanding of martian ices. Although it was mentioned that horizontal spatial resolution of thermal inertia would be improved, this may not provide a substantial improvement in scientific understanding. Additionally, it was not sufficiently described whether the proposed investigations would produce significant advancement in knowledge about interannual variability from the continual coverage of the meteorology over what is already known. Monitoring future, large-scale dust events as a key driver; however, in the upper atmosphere, EM5 results have already established that hydrogen escape can be modulated with dust activity, so it was not sufficiently clear how our understanding of Mars on this topic would improve substantially with additional observations in EM6.

2. Responsiveness of the proposal to goals described in the Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013-2022" (2011).

Strengths

[Major] As detailed in Table SR-2, the proposed investigations are strongly aligned to several topics in the Vision and Voyages for Planetary Science in the Decade 2013-2022 document, specifically:

- Objective 1: Assess past & present habitability (Aligned w/ EM6 Goals 1, 3)
- Objective 2.1: Characterize the climate and atmosphere (Aligned w/ EM6 Goals 2, 4)
- Objective 2.2: Ancient climate (Aligned w/ EM6 Goals 1, 3)
- Objective 3: Geologic processes and their evolution (Aligned w/ EM6 Goals 1, 2, 3)

Weaknesses

None noted.

3. Capability of the spacecraft to achieve the proposed science.

Strengths

[Major] The instrument capabilities, in general, are well characterized and are operated by experienced teams. Since the investigations are predominantly extensions or continuations of current work, there is generally high confidence that the instruments would carry out the proposed science.

[Major] Overall, the spacecraft and most science instruments are healthy, with sufficient operational reserves remaining. This was outlined in Section 8.3 and Table 8-1 of the proposal.

[Minor] The proposal described a plan to shut down the CRISM instrument in EM6, unless Overguide #1 is funded. This decision is made in part because the failure of both cryocoolers has rendered the IR imaging non-functional, though the VNIR capability remains functional. The Panel agrees with this decision.

Weaknesses

[Minor] It was not sufficiently demonstrated that putative caves and lava tubes would be as well characterized by SHARAD as described in the proposal.

[Minor] It was not sufficiently clear that the achievable gain and penetration of the SHARAD radar would allow characterization of putative subglacial lakes in the south polar layered deposits. The details provided in the Q&A session suggest that the MRO Team has low confidence in achieving the required radar penetration depth.

[Minor] MRO is an aging spacecraft, and there are four dominant risks identified as a result of this state. They include the batteries, IMU, high-gain antenna, and X-band downlink. All of these risks were categorized as low likelihood and high consequence, with potentially mission-ending consequences, however the MRO team is addressing these risks well, with mitigation plans in place for different types of component failures.

4. Merit of programmatic objectives.

Strengths

[Major]   The MRO Team has done an impressive job accommodating NASA's programmatic requests during the previous Extended Missions. NASA's Mars Exploration Program has assigned a set of Programmatic Objectives to the MRO Mission. These capabilities include: 1) operate as a relay satellite for lander data until 2031, potentially to support the Mars Sample Return Program; 2) critical event coverage of future Mars EDLs (e.g., ExoMars EDL in 2023); 3) future landing site reconnaissance (i.e., identification/characterization and certification); 4) resource identification for future human activities, and environmental data sets to assess times and locations for future landings; and 5) operations support (rover traverse planning). All of these programmatic objectives are important. For example, although the MRO relay capability represents only a small percentage of total data return, it does this for multiple missions, including InSight, Curiosity, and Perseverance (and is planned for the ExoMars rover). The past performance of the team, including Mars 2020 EDL support and data relay support for multiple lander missions, suggests that they would continue successfully during the proposed investigation.

Weaknesses

None noted.

5. **Demonstrated scientific productivity of the mission team during the previous phase.**

Strengths

[Major] This is an extremely competent and productive team, which has generated a monumental dataset and body of scientific literature. The productivity of the team, as measured by peer-reviewed publications, has varied over the lifetime of the mission, from a high of 77/year, to around 25/year in EM5. The recent decrease in publication activity may be influenced by the decreasing science budget.

Weaknesses

None noted.

6. **Performance in archiving data to the PDS in the previous phase.**

Strengths

[Major] The proposal demonstrated that the MRO Team has archived EM5 data in the NASA Planetary Data System in PDS3 format, similar to data products since the mission began. Although MRO instruments produce substantial amounts of data, the mission team has done a successful job in archiving. According to PDS delivery records, a backlog in pre-EM5 SHARAD data archiving was remediated during EM5.

Weaknesses

None noted.

Secondary Evaluation Criteria

7. **Extent to which the science community beyond the mission science team utilizes data and conducts published research**

Strengths

[Major] Community data use from the PDS has been consistently high, and file downloads peaked in 2020. Publications by the science community are 4 to 6 times higher than for the team, indicating very significant use of mission data outside of the immediate team.

Weaknesses

None noted.

8. **Scientific merit of observations to be taken and archived to the PDS, for future use by the scientific community.**

Strengths

[Major] The proposed new observations have high scientific merit, and would likely be used extensively by the broader community after they become available. The number of non-mission team publications during EM5 attests to this (see Table A4-1).

Weaknesses

None noted.

9. **Science value**

Strengths

[Minor] For the relatively modest cost of MRO, the productivity of the science team and the wider community is high, which cements NASA's leadership in Mars science.

Weaknesses

None noted.

10. **Demonstrated capabilities, experience, and expertise of key personnel.**

Strengths

[Major] The proposal demonstrated that the MRO team, including both original senior and newer members, have sufficient knowledge and experience to carry out the desired goals and investigations during EM6. Many new members of the science teams (see Table A5-2) are early- to mid-career scientists that started out using MRO data as graduate students and have been using mission data for the majority of their careers.

Weaknesses

None noted.

11. **Expected effectiveness of the proposed PDP in training future leaders.**

Strengths

[Minor] MRO has had an effective PDP to develop the next generation of leaders. The plan includes 1) leadership opportunities and mentoring of Team members to become deputy PIs, 2) promotion of Team members to DPIs or PIs when vacancies occur, 3) mentoring new Team members including Participating Scientists, investigation scientists, post docs, and research affiliates, and promoting to Co-I status when warranted, and 4) acquiring new students, post docs, and affiliates when funding permits. For example, MRO Investigation Scientist D. Nunes is now a Deputy Project Scientist on NASA's VERITAS mission. HiRISE Co-I S. Byrne was promoted to Deputy PI of HiRISE.

Weaknesses

[Minor] The promotion of younger scientists to Co-I and higher leadership has slowed over time, in part due to decreasing funding of the MRO science investigation.

12. Thoroughness and appropriateness of the PDMP.

Strengths

[Major] The PDMP (Appendix 6) is very complete and mature. The MRO Team has done a great job with data archiving and improving data usability outside of the immediate team, including the production of HiRISE and CTX DTMs. All new data acquired during EM6 will be archived in PDS4 format. The ability of the science community to request observations (e.g., through the HiWISH program for HiRISE) is highly valued by the community. Additionally, the production of science-ready, highly-usable data products are worthwhile, and are highly valued by the community.

Weaknesses

None noted.

Comments to Proposers

The MRO EM6 proposal did not sufficiently describe how science goals and investigations would be prioritized should failures occur to specific instruments or spacecraft subsystems. The team stated that the prioritization would be 'determined dynamically,' but did not give additional details for how the prioritization would be made. The Panel recommends that more thought be placed to prioritization of science goals/investigations proactively, because of the limited funding support available in the science reserves should a major failure occur.

The Review Panel shares the MRO Team's concerns about moving from the current ~3:00-3:15PM LMST orbit to a 4:30PM LMST orbit to accommodate additional downlink for Mars 2020. This change would compromise MRO's science related to long-term change detection, would reduce signal to noise, would impact HiRISE Bin-1 imaging, and would decrease latitudinal and seasonal imaging coverage. The loss to MRO science proposed for EM6 that would occur by moving MRO to the later orbit is too great, and should be avoided.

The MRO Team has developed and provided workshops to try to increase usage of the SHARAD data, because the data product is complicated and the barrier to usage is high. This effort is of value to the scientific community.

Comments on Overguides and Descopes

Overguide Request #1: CRISM polar cap mapping
Score: Good / Fair

This overguide request would fund the CRISM team during EM6 to acquire new VNIR observations of martian ices, with the goal of determining the distribution of CO_2 versus H_2O ices at the martian poles. If this overguide is not funded, the CRISM instrument would be turned off and no new observations would be acquired during EM6. The science case for the CRISM VNIR investigation of martian ices was poorly justified. The proposal and the team did not demonstrate how this investigation would make major advances in the knowledge of CO_2 and H_2O ice distribution in martian polar latitudes over previous studies accomplished by past missions and instruments.

Overguide Request #2: Conversion of previous data to PDS4
Score: Excellent

This overguide request would fund the MRO instrument teams to convert all data acquired prior to EM6 to PDS4 format. There is high demand for MRO data by the broader Mars science community, as noted both in the PDS Report of MRO data access, and in the statistics of non-MRO Team published papers (3-6 times the number of team papers). The conversion of MRO data from PDS3 to PDS4 is of extreme importance to maximize the usability of these data to future generations of Mars scientists and engineers. The proposal made an outstanding case for funding the instrument teams, who have the detailed knowledge of the data, to perform the PDS4 conversions efficiently and effectively now, rather than waiting until the future. The Panel strongly supports this overguide request, and recommends it be fully funded.

Descopes

No descopes were identified by the proposal.

2022 NASA Planetary Mission Senior Review
Panel Evaluation

Proposal	**22-PMSR22-0004**
Title	**MSL Extended Mission 4: Investigating the Persistence of Habitability through Dramatic Changes in Climate**
Project Manager	**Megan Richardson Lin / Jet Propulsion Laboratory**
Project Scientist	**Ashwin Vasavada / Jet Propulsion Laboratory**

Summary of Proposal

To date, NASA's Mars Science Laboratory (MSL) and its Curiosity rover have provided a compelling scientific investigation that has revealed the unique history of Gale Crater and evidence for habitability in earlier Martian epochs. The proposed Extended Mission 4 (EM4) would be centered on the long-anticipated advance up Mt. Sharp. EM4 investigation would be marked by a traverse across the clay/sulfate boundary and into the sulfate-bearing unit that was identified from orbit, informing how the Martian environment changed with time. Ground-truthing this orbital signature may help us better understand the nature of globally mapped sulfate deposits. The team proposes to continue moving forward in time through the sulfate-rich layering and climbing through Gediz Vallis ultimately to a region marked by "boxwork structure" (as observed from orbit), where underground, mineral-laden waters may have seeped through to the surface, cemented in cracks, and formed these unusual features. MSL would explore regions that have the potential to reveal major climate transitions archived in the sedimentary record. These explorations would have high science value for the understanding of the climate history of Mars. There would be few, if any, other places on Mars where a rover can investigate this time window and associated climatic/environmental transitions in similar detail and resolution.

Overall Proposal Score: Excellent/Very Good

This score represents the evaluation for the Guideline mission.

Primary Evaluation Criteria

1. **Scientific merit of the proposed investigations to be undertaken during the Extended Mission.**

Strengths

Major

The proposal plans an excursion to explore the Gediz Vallis (GV) where the region's more recent water flows may have shaped the landforms and defined late stages of habitability, thus potentially extending our understanding of climate transitions and the search for life-favoring conditions. This hypothesized late-stage water flow has important implications for the possibility of a post-sulfate return to a wetter climate of at least regional significance. EM4 would explore landforms in GV to help decipher the relative roles of wind, fluvial erosion, perhaps glacial erosion, and downslope debris flows in forming GV and features within GV. GV also includes a transition from a channel to topographic inversion, which may be eroded channel fill. Such landform investigations are important as ground-truth for geomorphological interpretations that are uncertain from orbital data alone. Importantly, the erosion associated with GV, which cuts through the stratigraphy of Mt. Sharp, would provide a novel window to those older rocks and their climate implications. Insights gained from the study of GV could speak to the youngest potentially habitable environments accessible to the mission.

The EM would investigate a prominent landform seen from orbit —"boxwork structure"— which is inferred to have formed from subsurface fluid and cemented fractures, with potential implications for climate evolution and biosignature preservation. The boxwork structures described from two areas along the EM4 transect (referred to as the First and Second Boxwork Structure) are a puzzle for geomorphologists trying to understand the Mars surface, and they would provide an opportunity to observe post-depositional environments. Inferred associated fluid migration patterns and associated mineral formation could have relevance to climate controls and potentially similar features seen elsewhere on Mars. Further, boxwork structures may reveal a novel window of preservation of organic molecules tied to potentially rapid and early cementation and concomitant encasement of local organic materials.

The rover would continue to monitor the modern atmosphere during EM4 by acquiring systematic measurements of atmospheric composition, dust loading, meteorology, and UV and high-energy radiation through additional Mars years and in new geographic settings. Measurements would include the abundance and isotopic composition of atmospheric oxygen, carbon dioxide, and methane along with data on atmospheric circulation and aerosols that can vary with location and elevation. The transverse upslope would provide novel perspectives on possible vertical differences in the local atmospheric structure. EM4 would continue the daily weather reporting of the atmospheric instruments. In conjunction with the Perseverance weather station, these measurements would be a valuable contribution to understanding the surface conditions on Mars.

EM4 would enable the first in-depth and in situ investigation of the extensive hydrated Mg-sulfate-bearing unit (SBU) of Mount Sharp. Since the initial choice of the Gale Crater landing site, the origin of the sulfate-bearing unit has been a critically important science question that could be answered at last in EM4. The proposed transition in Gale Crater and other locations has been observed from orbit but can only be carefully characterized and understood through exploration on the ground. The transition from clays to sulfates occurs in different locations on Mars, and Curiosity is now poised to explore the implications of such changes, including climate controls and transitions. Determining the formation mechanism of these sulfates, including whether they are primary (evaporites) or secondary (diagenetic), is an essential first step and could inform our understanding of related climate change (e.g., patterns of aridity versus wetter regimes)—as expressed regionally and potentially planet-wide.

Important planned measurements include high-energy radiation observations that would capture activity during a Solar Maximum. Early data suggest that the next solar maximum will be different than the previous one—potentially much larger based on preliminary measurements—thus adding new insights, including relationships to atmospheric interactions and attenuation.

Weaknesses

Major

The proposal did not make clear how the mineralogical and textural relationships of the sulfate phases would be used to determine climate variations, given various plausible origins and complications. Those complicating factors include uncertainties about primary versus secondary formation. The origins of the Mg-sulfate minerals remain unknown, but the proposal carried a tacit assumption that these phases would provide important climate information without acknowledging fully that such interpretations may be difficult. For example, minerals can be deposited in one environment and then remobilized later into another (e.g., via dissolution/reprecipitation or eolian transport) so that sedimentological inferences may not give a direct answer to the original depositional environment of the minerals. While such complications may be unavoidable, the proposal did not clearly articulate a strategy for dealing with the complex array of possibilities that remain, given the unknown origins of these features and potential analytical challenges. Those complexities include the possibility of significant/dominant amorphous phases that would complicate instrumental characterizations and assessments of paleoenvironmental versus diagenetic (primary versus secondary) relevance of these sulfate phases.

EM4 would provide opportunity for further testing of previous, tantalizing, but tentative observations about atmospheric methane levels; however, the proposal and subsequent discussion lacked description of protocols to resolve discrepancies between orbiter and rover observations and to eliminate doubts about possible internal sources of methane on MSL. There is not a consensus in the wider community about how MSL measurements of appreciable methane levels, including some large spikes, can be reconciled with no methane detected by TGO. Possible atmospheric methane cycling on a variety of timescales (seasonal and shorter) has captured wide community interest in part because of possible biological contributions. The putative patterns (rapid variations) have required unusual models for rapid methane consumption. The proposal also lacked discussions about the potential for further coordinated efforts with TGO. The team acknowledged that methane contamination was found in the instrument foreoptics but expressed confidence in their approach because those amounts were small and stable. However, the 'small' amounts are at significant concentrations relative to the levels assumed to be real in the Martian atmosphere, and there was no discussion of whether similar methane contamination may exist elsewhere in the rover and could affect ingested samples. The proposal and subsequent discussion did not address the full range of possibilities for internal contamination nor possible variations that could scale with varying rover operations. Because spikes and rapidly disappearing atmospheric methane are difficult to explain with conventional understanding of methane chemistry and given the disconnect with TGO non-detection, the possibility of contamination remains a concern in the wider community.

Minor

Although the present hydration states observed for the sulfate minerals may carry important implications for climate (wet versus dry), the proposal did not adequately acknowledge that mineral hydration is often a transient and dynamic feature that may not reflect the controls present at the time of initial mineral formation. Minerals, particularly salts such as Mg-sulfates, experience hydration/rehydration reactions during burial and uplift/re-exposure and changing surface conditions. As such, present hydration states may be telling us little about surface environments in the past.

The proposal did not adequately explain in scientific terms why a stop at the First Boxwork Structure would be necessary, given the stated higher exposure quality of the Second, the feasibility of reaching the Second within the guideline mission, and lack of clear stated advantages or unique aspects suspected for the First.

2. **Responsiveness of the proposal to goals described in the Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013-2022" (2011).**

Strengths

Major

EM4 would be highly responsive to the Planetary Science Decadal goals. The major question addressed by EM4—did habitability persist through dramatic changes in the ancient climate?—is clearly identified in the Vision and Voyages Decadal Survey (2011). A considerable number of specific Decadal Survey goals, as identified in the Science Traceability Matrix provided in the proposal, are addressed directly in the planned rover traverse and associated instrumental measurements and science questions. The four goals of the EM4 investigations (surface evolution, past habitability and prebiotic chemistry, process and history of climate, and interconnections and radiation environment) are linked strongly to primary goals articulated in the survey. The radiation measurements also have value in anticipation of future human exploration.

Weaknesses

None noted.

3. **Capability of the spacecraft to achieve the proposed science.**

Strengths

Major

Most of Curiosity's scientific payload is presently achieving measurements of the same quality and quantity as those obtained at the end of the prime mission. As presented, the spacecraft and instruments are healthy with substantial remaining margins on most life metrics and tested performance. The vast majority of the instruments, particularly those required for the stated goals of the mission, are still returning high-value scientific data. Although the rover's power source and batteries have degraded in line with predictions, efforts in EM3 to improve efficiency through operations modeling and corresponding reductions in power usage have ensured adequate power for at least the duration of EM4. Energy available is sufficient to achieve the stated EM4 objectives. Overall, usage of consumable resources and mechanism life should proceed with additional scrutiny but without expected impact to EM4 objectives.

Minor

The mission has implemented a number of measures to minimize wear and extend wheel lifetimes. All six wheels are expected to maintain nominal operation through EM4.

The drill feed actuator redesign appears to be functioning well. Failures in the turret and wrist brake solenoids have required substitution of the backup solenoid, but it is functioning nominally.

One of the most highly diminished components, the DAN (Dynamic Albedo of Neutrons) instrument, is not essential to meet EM4 objectives but will have extended utility through operations in passive neutron mode.

Weaknesses

Minor

The wind sensor is no longer operational, which limits some meteorological studies.

It is unclear whether the remaining number of pristine cells on CheMin at the end of EM3 (ca. 5-7 of 27) would be sufficient to analyze the sulfate-bearing unit, especially given the difficulty in distinguishing the many interrelated sulfates species, the likelihood of encountering significant amorphous materials, and the corresponding importance of CheMin in these characterizations. The MSL team noted this concern and would work to conserve usage leading up to the sulfate unit.

Due to instrumental aging and an attempt to preserve its limited remaining life, the ability of the ChemCam laser to produce a high energy pulse capable of generating a plasma would be significantly reduced during EM4. As such, ChemCam would not be operating nominally, which would limit the number of laser shots. The importance of this concern is elevated because ChemCam is one of the prime instruments used/needed to characterize the sulfate phases.

4. Merit of programmatic objectives

Strengths

Major

MSL mission results have demonstrated the critical value that comes with integrating rover-scale, in situ measurements with complementary observations from orbit (including geomorphology, spectral, atmospheric composition, meteorology, dust, and water vapor). These integrated measurements have improved the scientific value of each, and the resulting contributions to ground-truthing, site characterization, EDL analysis, etc., would continue during EM4. This approach can lead to a full understanding of paleoenvironments and their evolution over time, as well as insights into globally relevant phenomena. For example, detailed characterization of sulfate phases first identified through orbital measurements would present a novel and important opportunity during EM4. These combined, ground-truthed datasets would address fundamental scientific questions and logistical concerns, including EDL risk analysis in future landed missions.

Continued coordinated observations involving MSL's Radiation Assessment Detector (RAD) remain among the important contributions of EM4. The proposal made a strong case for using RAD as an "outpost" for NASA's Heliophysics System Observatory during EM4. RAD measurements of radiation are partly supported by the Heliophysics Division and Human Exploration and Operations and are critical to understanding space weather and the radiation risks for future human exploration. Opportunities for real-time comparisons with Perseverance data elevate the value of the EM4 measurements.

Weaknesses

None noted.

5. **Demonstrated scientific productivity of the mission team during the previous phase.**

Strengths

Major

The team appears to have maintained a reasonably high level of publication during EM3 (~50/year) despite expected challenges related to the COVID-19 pandemic, and these contributions remain important to the broader community. The paper count for the most recent year is elevated by 25 in-press papers scheduled to appear in a special volume that is not included in the 2021 count. The papers remain largely of very high quality, with measurable large impact (e.g, as expressed in citations).

Weaknesses

Major

In the absence of specific, detailed goals (deliverables) for EM3, it was difficult to assign levels of completion and thus evaluate overall productivity in operations. Table 3-1 lists the ten objectives from EM3, but the status of each was simply listed as "expected to be completed." During the team's presentation and Q&A, they expressed optimism about completing those goals before the scheduled start of EM4. However, given a history of delays in reaching stated MSL targets throughout the mission, as well as the importance of EM4 objects (the sulfate zone in particular) and the age of the rover and its waning resources and capabilities, the team is encouraged to move in a timely fashion to the EM4 start and to define clear benchmarks throughout to create a structure for completion of goals. Assessing accomplishments in general was difficult because of the lack of specificity and/or open-endedness of many goals for EM3, such as "determine energy sources that could be used to sustain biological processes," "characterize organic compounds and potential biomarkers in rocks and regolith," and "identify potential biosignatures (chemical, textural, isotopic) in rocks and regolith."

6. Performance in archiving data to the PDS in the previous phase.

Strengths

Major

MSL has done an outstanding job with data archiving over the last cycle. The project met all of its delivery deadlines in EM3, with ample details provided in the proposal. EM4 and future data products would be archived using the PDS4 data standard. The MSL team are meeting PDS data delivery expectations and are doing so efficiently, within 3-8 months of acquisition. The quantity of data downloads from the PDS by users increased dramatically during EM3 (Fig. 9-1) .

Weaknesses

None noted.

Secondary Evaluation Criteria

7. **Extent to which the science community beyond the mission science team utilizes data and conducts published research**

Strengths

Major

The proposal thoroughly demonstrated extensive use of the data outside the team as expressed in downloads and publications, which was presented graphically and through appended bibliographical details. A large number of publications, in particular, confirmed the outside utility and impact of the data. The number of publications resulting from MSL data by those outside the team is not significantly smaller than those coming from within the team, and this encouraging trend is expressed in recent statistics.

Minor

The Analyst's Notebook is elevating the accessibility of MSL data to researchers outside the team, thus further enhancing the importance of the EM4 data. Such applications would otherwise be hampered by the lack of context that often limits outside use.

Weaknesses

Note noted.

8. **Scientific merit of observations to be taken and archived to the PDS, for future use by the scientific community.**

Strengths

Major

The proposed EM4 observations would expand the vertical stratigraphy and timeline accessed by this rover and include important targets that would speak to the enigmatic but potentially important SBU and GV. The appreciable rate at which prior MSL data are used suggests that EM4 data would also be of considerable value to Mars scientists outside of the mission. EM4 would finally reach the SBU of Mount Sharp, which was an important science driver for sending the rover to Gale Crater.

Minor

Data collected would find significant future use in comparing geology at different landing sites, particularly as more Perseverance data are collected and comparisons become possible.

The team would use integrated archives to help the external community understand the context and coordination of the observations to be taken. The new data would be important for the scientific community to understand how in situ measurements compare with inferences from orbit, by other missions. The ground-truth observations would support the orbital assessment of a transition from clay features to sulfate deposits, which have relevance to other regions of Mars.

Continuous sets of atmospheric observations and radiation measurements throughout the solar cycle would have broad and long-lived value.

Weaknesses

None noted.

9. **Science value**

Strengths

Major

The budget was consistent with previous obligations during EM3 and the scope of the newly proposed EM4; it was reasonable and well-justified within the framework of the proposed science. The proposal provided helpful details to justify why science operations require 50 scientists and engineers every planning day. The Guideline budget ($45M, $40M, $35M during FY23-FY25) supports 408 planning cycles. Although costly, this mission offers high science return for that cost.

Weaknesses

None noted.

10. **Demonstrated capabilities, experience, and expertise of key personnel.**

Strengths

Major

The team is strong and well suited to address the full range of science needs. It has the experience needed to manage a complex system and produce essential data for the community, while also optimizing the mission's potential despite the advanced age of the rover and its instruments. This is an outstanding team at all levels, readily able to coordinate the proposed measurements, choose which sites to sample, analyze the data returned, and publish the results. The team has managed the mission and data effectively to date, even under the limitations imposed by the pandemic, which gives confidence that the same will continue. During the team's presentation and Q&A, they expressed their commitment to adequate coverage of the important targets of this EM.

Weaknesses

Minor

Delays in progress during EM3 point to different operational priorities between management and the science team that should be addressed, particularly given the intriguing science prospects of EM4 and the aging nature of the rover and its instruments and consumables. Delays to targeted goals within the proposed timeframe have been a persistent problem for the mission, including EM3. The challenge is always finding the balance between the extra time needed for something exciting and unexpected along the way and the fully stated primary objectives, but there remains a history of delays in rover traverse progress and deliverables. Further, the operational targets/milestones of EM3 were mostly vaguely defined, to the point that accountability becomes difficult.

11. **Expected effectiveness of the proposed PDP in training future leaders.**

Strengths

Major

MSL has a strong track record of training and promoting early career people within the team to take on additional responsibilities and leadership roles, including efforts at improved gender diversity, and the proposal indicated that

EM4 would follow this tradition. The proposal demonstrated how key personnel on the mission grew into their positions from within the team, ensuring their capability and long experience with the mission. The team is outstanding in terms of inclusion and nurturing of early career scientists, including those who have been primed to take over major leadership roles. MSL has a strong record of professional development for students and postdocs during the operational period. The MSL Project Science Group would continue facilitating career development for potential future mission leaders by providing opportunities for leadership experience via encouragement, mentoring, and increased project responsibilities. The project would continue to recruit scientists to elevate to Science Theme Group Leads, Science Operations Working Group Chairs (lead tactical scientist), and Long-Term Planner (lead strategic scientist).

The MSL team has a cadre of 67 students and 32 postdocs, thus providing training for a younger generation of planetary scientists, and periodic rotations mean that hundreds of trainees participate in operations and science discoveries.

Weaknesses

None noted.

12. Thoroughness and appropriateness of the PDMP.

Strengths

Major

The Data Management Plan was very well structured and described; it is exceptional in its high quality. Its level of detail and traceability were outstanding. Among other strengths, the PDMP outlined plans to convert the project's data for delivery in PDS4-compliant format during EM4.

Weaknesses

None noted.

Comments on Proposed Overguides

Overguide: Deliver Previous Mission Data in PDS4 Standard

The proposal makes a compelling case for funds for converting previous data to PDS4, including its accompanying Solid Sample Catalog (SSC). This is a laudable, essential step that would increase the community accessibility, utility, and impact of the results. (The proposal identified this Overguide as a subtask within the main Overguide related to Additional Planning Cycles. The panel chose to vote on it as a separate task.)

Overguide: Additional Planning Cycles

The Overguide request for additional operations cycles was not adequately justified and is likely not necessary if the team heads directly to the Second Boxwork Structure, skipping the First. The panel was unanimously in favor of this option. The Second is on a slope and better exposed, and the proposal did not provide arguments for the unique value of stopping at the First, nor did it argue against its redundancy relative to the Second. Similarly, sufficient arguments for going to the First Boxwork Structure first were also not provided during the mission's presentation or Q&A.

The proposal stated that the Overguide is largely in support of investigating the habitable environments potentially represented by Second Boxwork Structure, but this goal could be achieved by only visiting the Second Structure and without Overguide funding. The proposal did not make clear that an 18% increase in planning cycles would produce science that would justify the 18% increase in cost. Moreover, the proposal did not make a strong case for why the team could not accomplish all three objectives to a lesser but adequate extent via the 408 cycles requested within the Guideline request. Further, the SBU and GV are likely more relevant to the project's umbrella goal of exploring habitability in Gale Crater and relationships to climate change on a variety of time scales and should not be compromised to explore both boxwork structure locations.

The boxwork structure is nonetheless a fundamental part of the proposal and is thus not expendable. It should be reachable within Guideline funding.

Comments on Proposed Descopes

No descopes were proposed.

Additional Comments

None noted.

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Proposal	**22-PMSR22-0005**
Title	**2001 Mars Odyssey Ninth Extended Mission**
Project Scientist	**Jeffrey Plaut / Jet Propulsion Laboratory**

Summary of Proposal

The Mars Odyssey Extended Mission 9 (E9) proposes to take advantage of the spacecraft's shifting orbit to acquire additional Thermal Emission Imaging System (THEMIS) multispectral images at early morning and post-sunset times. E9 would use this changing orbit to conduct new surveys of thermophysical properties of the Martian surface, including rock abundance and subsurface ice. E9 would extend the already comprehensive record of climate monitoring, adding new limb observations of atmospheric properties and concurrent observations with the Emirates Mars Infrared Spectrometer (EMIRS) instrument. Mars Odyssey would continue collecting High Energy Neutron Detector (HEND) and Neutron Spectrometer (NS)data to monitor the seasonal CO_2 ice, map hydrogen (water) abundance and measure the radiation environment at Mars. Programmatic support includes data relay for surface assets (InSight, Curiosity, and Perseverance).

Overall Proposal Score: Very Good

This score and the findings below refer to the Guideline mission.

Primary Evaluation Criteria

Any individual finding may be Major or Minor. Please mark as 'Minor' if appropriate; findings not so marked are assumed to be Major.

1. **Scientific merit of the proposed investigations to be undertaken during the Extended Mission.**

Major Strengths

The planned observing campaign would increase the accuracy of thermal models derived from THEMIS data over selected targets, enabling new applications for these models that address high priority science and exploration goals. Many of the E9 THEMIS studies would leverage the extensive record of existing observations and combine them with new observations acquired at different local times, so as to enable a detailed understanding of diurnal, seasonal, and interannual surface and atmospheric processes. The focus here would be to match previous observations at different times of day and solar longitude (Ls) in order to create more accurate thermal models. These observations would allow the creation of new types of data products from the THEMIS instrument, including rock abundance maps and maps of very shallow ice depths, which would support future landing site selection and more accurate assessment of shallow ice resources.

Data collected during E9 would enable the creation of new rock abundance maps that would provide higher spatial resolution than current global maps. This campaign would develop new maps showing the proportion of rocks and fines by using targeted data near the terminator. E7 and E8 focused on data collection in the early morning and the E9 campaign would identify pre-dawn images to match with post-sunset new data collections. Preliminary analysis shows excellent agreement with the time- and labor- intensive method using HiRISE imagery. E9 data would allow regional studies over possible future landing sites, including human mission exploration zones. Developing and testing this new approach to rock abundance mapping would lay the groundwork for more extensive observing campaigns by THEMIS or future thermal imagers.

Mars Odyssey E9 would advance the understanding of very shallow subsurface ice at mid-latitudes. The proposed new investigation to map subsurface ice in northern mid-latitudes would provide a pilot study using autumn observations to characterize the top surface layer, enabling better discrimination of very shallow ice (< ~ 6 cm). This would fill an important existing gap in the ability to resolve very shallow ice, and would provide a dataset that could be compared with eventual results from the International Mars Ice Mapper mission. The proposal demonstrated that data from the desired Ls ranges and times of day have not yet been acquired, and demonstrated the need to collect new data in E9.

The proposed atmospheric science objectives include both new observations of vertical structure and continued atmospheric monitoring that would help construct a unified climatology for Mars. Limb observations taken by Mars Odyssey during E9 would provide important constraints for numerical modeling. The proposed long-term atmospheric monitoring during E9 would build upon an existing, extensive dataset and would retrieve the vertical profiles of dust aerosol, water ice cloud, and atmospheric temperature. The long temporal baseline of Odyssey, when synthesized with the observations from other spacecraft, can provide new knowledge on the state of the atmosphere. These observations would be complementary to ongoing studies by MRO's Mars Climate Sounder (MCS) instrument. The E9 mission would collect data that expand diurnal coverage to a different LST from MCS and at the interesting dawn/dusk local times when rapid changes occur in surface and atmospheric conditions. THEMIS would also obtain coordinated nadir observations with EMIRS, making many simultaneous observations each week. This synergy would improve the higher order datasets from both missions.

Minor Strengths

The proposal justified continued data collection by the HEND and NS instruments during E9 adding to a robust high-energy event detection network across the Solar System.

Major Weaknesses

The proposal did not sufficiently demonstrate that all of the planned investigations would be scientifically compelling. In particular, the proposal did not adequately justify how several of the proposed investigations would contribute to the broader understanding of Mars' geologic evolution. For example, the impact of the surface roughness study is not sufficiently described, and the proposal did not demonstrate that roughness would be a unique constraint on the nature or origin of volcanic units. The proof-of-concept study for surface roughness would examine two targets, Jezero crater and NW Arabia Terra, but the pilot study over Apollinaris conducted in E8 has not substantially changed any geologic interpretations in this region. Rock abundance would be determined and mapped for a limited number of sites, and the proposal did not demonstrate how these maps would deepen the understanding of regolith evolution. Many investigations are continuations of efforts from E8, for example crater rim degradation, and source-to-sink sediment transport, but the proposal does not state how additional observations will significantly advance the understanding of surface age or fan depositional style.

Minor Weaknesses

The proposed effort would provide modest expansion of the catalog of alluvial fans, and the proposal does not provide a strong justification for why new data would be needed for this investigation. The pilot study conducted in E8 has not demonstrated quantitative or diagnostic links between the thermal data and such things as grain size characteristics or grain size sorting, which are necessary to evaluate emplacement processes, hydrology or formation timescales of alluvial fans.

The proposal did not demonstrate that the search for thermal anomalies in response to seismic activity detected by InSight would identify active hydrothermal environments. THEMIS has already observed such seismically active regions, and the proposal does not offer sufficient evidence that additional monitoring would yield different results. Therefore, the connection of this study to habitability is tenuous.

The proposal does not identify vertical range, vertical resolution, nor accuracy of the limb profile observations that will be used to retrieve dust aerosols, water ice clouds, and atmospheric temperature.

The small thermal contrast between the surface and atmosphere near sunrise and sunset in E9 could lead to large uncertainties in dust and ice aerosol retrievals.

2. **Responsiveness of the proposal to goals described in the Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013-2022" (2011).**

   Missions originally proposed before the 2011 Decadal Survey may optionally also refer to goals in "New Frontiers in the Solar System: An Integrated Exploration Strategy" (2003). Missions which include substantial cross-divisional content, and identify goals from those divisions, may also be evaluated relative to those respective goals.

Minor Strengths

The investigations related to polar processes and climate are linked to Decadal Survey questions in the Science Traceability Matrix.

Major Weaknesses

The proposal did not sufficiently respond to the goals of the Decadal Survey. The majority of investigations are only obliquely related to high priority Decadal Survey goals with regard to habitability (both past and present), aqueous environments over time, and the geologic record of climate change.

3. **Capability of the spacecraft to achieve the proposed science.**

Minor Strengths

The Mars Odyssey team has managed the spacecraft well so as to protect hardware for future extended missions. The proposed plan is credible given the state of the hardware, and most subsystems are in a healthy condition.

Mars Odyssey has no redundancy with regard to the reaction wheels. Should this fail, the backup plan would use thruster-only operation. There would be a reduction in targeting accuracy for THEMIS but no anticipated impact to relay support. The additional fuel consumption would reduce remaining mission life to ~ 8 months.

Minor Weaknesses

The presentation made clear that the Mars Odyssey team does not have a solid model for how much fuel remains aboard the spacecraft. Further study is necessary to refine these estimates. In a worst-case scenario, of the 4.6 kg +/- 1.2 kg available for E9 (presentation table). At a burn rate of 1 kg/year, this could leave no fuel available at the end of E9.

4. **Merit of programmatic objectives.**

   Programmatic objectives may include goals such as data relay, preparation for future missions, or goals of relevance to other divisions or directorates at NASA. The PMSR will evaluate separately the objectives of relevance to PSD, and those of relevance to other divisions or directorates at NASA, and may assign different weights to each.

Minor Strengths

Odyssey will continue to provide data relay services between the surface of Mars and Earth for both nominal passes and critical event support. As an example, 21% of Perseverance passes and 36% of Curiosity passes were provided by Odyssey, albeit transmitting only a modest amount of the total data for these missions. The availability of Odyssey at 6:30 pm LMST is unique and fits well into the overpass plans of NASA's landed missions. Additionally, the architecture of the Odyssey relay system provides real time relay service (bent pipe), which is valuable during critical events and currently not available from other relay orbiters; albeit critical events are not currently called for in E9.

THEMIS data has been used during EDL and Aerobraking activities to provide advanced warning of atmospheric conditions, and during the extended mission will continue to be a valuable asset.

The continued Mars environmental monitoring by HEND and NS is part of the Mars Space Weather alert system, which provides timely warnings to the operations of surface spacecraft.

Weaknesses

None noted.

5. **Demonstrated scientific productivity of the mission team during the previous phase.**

Minor Strengths

The team completed multiple successful projects in E8, the vast majority of which were led by student collaborators. These included efforts using full mission datasets to investigate olivine enrichments in Noachian bedrock, using E8 multispectral data to characterize the ExoMars landing site, a pilot alluvial fan study, mapping layered igneous complexes in Hellas, new studies of crater rim thermal inertias, using E8 data to investigate current landing sites, ground truthing thermal inertia at landing sites, new studies of CO_2 frost and mid-latitude H_2O ice, and new models for the north polar CO2 cycle.

Mars Odyssey continued to monitor the atmosphere, providing a continuous record over 10 Martian years.

Mars Odyssey continued to monitor the local radiation environment, providing a key dataset that has been used in synergy with other simultaneous radiation detection experiments at Mars and to assist with localization of gamma ray emission events.

Although no funding was provided to HEND/NS for science analysis in E8, there were several publications from the team utilizing this data set.

Minor Weaknesses

Several investigations did not produce publishable results. In particular, technical challenges and unexpected personnel changes limited progress on the Phobos calibration pipeline, and orbital and mission planning constraints prevented the completion of the ROTO activities proposed in E8 for surface roughness.

The number of publications are down in E8, and many investigators listed as “substantially involved” in Table A5-1 did not participate as co-authors on any publications that are listed in Appendix A3 over the last three years.

6. **Performance in archiving data to the PDS in the previous phase.**

Minor Strengths

As of October 2021, THEMIS has delivered 38.1 terabytes (TB) of data to the PDS and GRS has delivered 1.7 TB. Total PDS delivered volume, including earlier data sets and ancillary data is 40.2 TB. The Odyssey science team delivers both THEMIS and GRS data every three months according to schedule, and deviations have been extremely rare.

Due to increasing noise in higher energy channels later in the mission, NS data processing code initially used by the mission required an updated approach. The code was completely rewritten during the E8 time frame and the entire data set from 2001 through the present was reprocessed by the GRS science operations team and delivered to the PDS.

Weaknesses

None noted.

Secondary Evaluation Criteria

7. **Extent to which the science community beyond the mission science team utilizes data and conducts published research**

Minor Strengths

A large number of publications written by non-team members (outlined in Appendix A4) have utilized Odyssey data. THEMIS data continues to be used extensively in the science community beyond the mission science team.

The ASU team has made it easy for the community to access THEMIS data through JMARS and ASU web sites, so PDS download statistics do not reflect the strong use of this data by the broader community. As noted in Section 9, during the first two years of E8 THEMIS data websites were visited by nearly 150,000 unique IP addresses, downloading 46.2 TB of data.

Important science results were obtained using data from the neutron detectors HEND and NS in investigations by outside researchers. GRS and Radio science data continue to be downloaded and utilized in publications.

Weaknesses

None noted.

8. **Scientific merit of observations to be taken and archived to the PDS, for future use by the scientific community.**

Minor Strengths

Continued collection of GRS data will be valuable as the sun moves away from solar minimum, and will contribute to the network of spacecraft that are monitoring high energy events.

Minor Weaknesses

Judging by the titles of papers listed in Appendix A4, it appears most of the THEMIS data being used for publications in E8 were from previously archived data acquired at an earlier orbit time of day. Therefore, it is not clear if the broader community is using the early am / late pm data of E7 and E8. The proposal does not provide sufficient information to assess if E9 data will be useful to the community or not, given the lack of evidence that E8 data were used outside the team.

9. **Science value**

   The PMSR will not perform a detailed cost analysis of each proposal. However, the panels may assess in broad terms the science return of the mission relative to its overall cost.

Minor Strengths

Science return is consistent with the proposed science budget, especially considering the extra ~30 papers/year from the community.

Weaknesses

None noted.

10. **Demonstrated capabilities, experience, and expertise of key personnel.**

Minor Strengths

The Mars Odyssey team will continue its well-established management approach. The team is experienced and has a long history on this project as well as other relevant missions.

Weaknesses

None noted.

11. Expected effectiveness of the proposed PDP in training future leaders.

Minor Strengths

The proposal identified several individuals who have transitioned to leadership roles. Dr. Laura Kerber became Deputy Project Scientist in 2018, Dr. Vicki Hamilton was promoted to THEMIS Deputy PI in 2016, and former Deputy Project Scientist (DPS) Dr. Dave Senske is now DPS for the Flagship Europa Clipper mission.

The THEMIS investigation has supported numerous students and postdocs including strong representation of traditionally underrepresented groups. THEMIS continues to support early career scientists through Co-Is and Participating Scientists who support students. Early career scientists and students have led science investigations and many first-authored papers that were published in E7 and E8.

The NASA Equal Employment Opportunity Medal was awarded to Odyssey Project Manager Joseph Hunt for his commitment to the recruitment, nurturing, and mentorship of summer students, academic part-time, and early career hires.

Minor Weaknesses

The proposal presented no plan for specific leadership transitions to occur in E9 and it is noted that the mission has not provided science advancement to PI / full leadership levels. In particular, Christensen, Boynton and Plaut have been in their roles for >20 years (Table 8-1).

12. Thoroughness and appropriateness of the PDMP.

Minor Strengths

The PDMP would convert each Odyssey science team's data processing pipeline to generate and deliver data in PDS4-compliant format beginning in E9.

The Mars Odyssey team will release data in both PDS3 and PDS4 formats so that users in the community will not have to redesign analysis tools in order to include E9 data.

Weaknesses

None noted.

Comments and Scores on Overguides and Descopes

Please list and comment explicitly on each Overgude and Descope

No descopes or overguides were proposed.

Additional Comments

Comments here may include suggestions, or feedback about portions of the proposal which were not covered by the Evaluation Criteria. None of these comments affect the score.

In general, the proposal left out many important details. In particular, the proposal did not adequately explain why more THEMIS data would be necessary to achieve specific scientific objectives. The proposal lacked a clear exposition about the amount of existing THEMIS data that would be utilized versus the amount of new data that would be collected and how new data will differ from that already archived. Some of the proposed objectives (e.g., B4) weren't discussed in the text of the proposal. The rock abundance model was inconsistent with previously published methods, and the proposal text was vague as to whether global or site specific-models at 100m /pixel were the objective. The team did a better job addressing these issues in their presentation.

The panel had concerns regarding the lack of reserves at the project level. Although it was stated that they have 800 hours in the pool at Lockheed Martin to undertake an anomaly investigation, a rough calculation suggests that is as little as ~$240K. If an anomaly happens it was said that Mars Odyssey would request funds from the Mars Program Office (MPO) (and the approach was confirmed by Joe Parrish). However, MPO did not provide solid reassurance that such funds would be there or be sufficient as a reserve equivalent.

The proposal text did not make direct connections to Decadal Survey goals and objectives, only those from MEPAG. The Decadal Survey goals were listed in the Science Traceability Matrix, but not the text. The proposal does not specifically say which investigations address specific Decadal Survey questions, and to what degree.

2022 NASA Planetary Mission Senior Review
Panel Evaluation

Proposal	**22-PMSR22-0001**
Title	**OSIRIS-APEX: An OSIRIS-REx Extended Mission to Apophis**
Principal Investigator	**Daniella DellaGiustina / University of Arizona – OSIRIS-APEX**
Principal Investigator	**Dante Lauretta / University of Arizona – OSIRIS-REx**

Summary of Proposal

Following release of the OSIRIS-OREx sample return capsule to Earth in 2023, the spacecraft would divert to an orbit that allows it to encounter near-Earth object (NEO) Apophis during its close approach to Earth in 2029. The science goals for the OSIRIS-APEX extended mission would be: (1) To understand the evolution of rubble-pile asteroids, by studying tidal effects on Apophis. This study would obtain information about gravitational and non-gravitational physical disturbances, mass shedding, and changes in spin state and orbital parameters. (2) To establish the link between the NEO and its parent asteroid family, and its dynamical evolution from the main belt. This goal includes determination of the asteroid's mass, structure, and composition, and may strengthen the identification of the parent bodies of chondritic meteorites. (3) To examine the geotechnical properties of an S-complex NEO, with an eye towards mitigating hazard from collision of such objects with our planet. (4) To observe Earth as an exoplanet analog during cruise. This goal involves repeated imaging of Earth at various wavelengths and phase angles, to expand understanding of observable discriminants for habitable environments.

Overall Proposal Score: Excellent / Very Good

This reflects the Primary and Secondary criteria for the guideline proposed mission.

Primary Evaluation Criteria

Each section may have multiple findings, Please mark each finding as Major or Minor.

1. **Scientific merit of the proposed investigations to be undertaken during the Extended Mission.**

Strengths

(1) [Major] APEX would characterize an S-complex asteroid from close orbit using New Frontiers-class instruments, and this new knowledge of a chondritic asteroid could resolve important questions such as the connection between ordinary chondrites and S-type asteroids, the role of space weathering, mass movements and dust shedding from tidal effects, as well as serve as "space truthing" for ground-based observations of Apophis.

(2) [Major] Obtaining geotechnical data for an S-asteroid (the most common type of potentially hazardous NEOs) would be important for understanding and modeling impact hazards.

(3) [Major] In situ high-resolution observations of an asteroid as it passes within 32,000 km of Earth would offer a unique, once-in-a-lifetime opportunity to gain scientific knowledge about tidal effects on rubble-pile bodies and to compare data with ground-based observations.

(4) [Minor] Measuring the change in the Yarkovsky acceleration on Apophis to within 1% uncertainty in the Guideline mission would provide a better assessment of the orbital evolution and long-term impact hazard Apophis poses to the Earth.

(5) [Minor] Using the spacecraft's Earth flybys as an opportunity to image the planet as an exoplanet analog is a creative use of those necessary encounters, and may help inform direct imaging searches for Earthlike planets.

Weaknesses

(1) [Major] A number of investigations were not fully explained or justified in the proposal. Examples include: the Yarkovsky acceleration has been previously measured for a number of NEOs including high-precision measurements for Apophis based on stellar occultations, but no explanation is provided as to how the data for Apophis will improve upon current understanding; the proposal did not explain how observations of craters and of exogenic material could be used to construct the population of impactors before re-accumulation, or to constrain the source family and dynamic evolution of Apophis.

(2) [Minor] The utility of observations of Apophis' physical state during and after close encounter with the Earth would be compromised by the limited observations before the encounter.

(3) [Minor] In regard to Earth observations, the proposal was unclear about whether MapCam and OTES would be sufficiently stable to measure diurnal, phase, and seasonal variations, whether the SNR and spectral resolution in OVIS are sufficient to detect gaseous O2, H2O, CH4, and CO2, or how the pixel-level data of the resolved Earth would be processed into a full-disk light curve for use in comparing with exoplanet data.

2. Responsiveness of the proposal to goals described in the Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013-2022" (2011).

Missions originally proposed before the 2011 Decadal Survey may optionally also refer to goals in "New Frontiers in the Solar System: An Integrated Exploration Strategy" (2003). Missions which include substantial cross-divisional content, and identify goals from those divisions, may also be evaluated relative to those respective goals.

Strengths

(1) [Major] Planetary Science Decadal (Visions and Voyages 2011) goals of deciphering the record in primitive bodies of epochs not observable elsewhere, and understanding the role of primitive bodies in building planets and life are addressed in part by the proposed observations of Apophis.

Weaknesses

None noted.

3. **Capability of the spacecraft to achieve the proposed science.**

Strengths

(1) [Major] The spacecraft continues to operate nominally and has sufficient reserves to accomplish the proposed science.

(2) [Major] The New Frontiers-class instruments offer more investigative capabilities at Apophis than smaller missions could.

(3) [Minor] The proposal presents a thoughtful and detailed technical plan for Apophis proximity operations, which are well informed by the team's experience at Bennu.

(4) Continued use of the same instrument suite used at Bennu will aid in comparing different asteroids.

Weaknesses

(1) [Major] The mission requires six perihelion passages close (0.5 AU) to the Sun. Although the spacecraft hibernation configuration and fig-leaf attitude are calculated to achieve survivability of the spacecraft, the risks to both spacecraft and instruments have been addressed only by computational models with unknown margins and uncertainties for those models. The possibility of outgassing and the cumulative effects of repeated heating were not discussed. Other issues - blistering and flaking of paint that could reattach to instruments and bubble formation in hydrazine lines - were discussed in Q&A, but remain concerns.

4. **Merit of programmatic objectives.**

Programmatic objectives may include goals such as data relay, preparation for future missions, or goals of relevance to other divisions or directorates at NASA. The PMSR will evaluate separately the objectives of relevance to PSD, and those of relevance to other divisions or directorates at NASA, and may assign different weights to each.

Strengths

(1) [Major] In situ characterization of a NEO during close approach clearly contributes to PDCO strategic knowledge gaps, which in turn would assist in preparedness to respond to a future NEO on collision course with Earth.

(2) [Minor] Imaging of Earth as an exoplanet analog would be potentially useful to the exoplanet community.

Weaknesses

None noted.

5. Demonstrated scientific productivity of the mission team during the previous phase.

Strengths

(1) [Major] The OSIRIS-OREx science team has published 137 papers that reveal significant discoveries and insights into the structure and evolution of a small asteroid. Of those, 111 have been published since asteroid operations at Bennu began in 2018.

Weaknesses

None noted.

6. Performance in archiving data to the PDS in the previous phase.

Strengths

(1) [Major] OSIRIS-OREx has delivered 3.9 TB of raw-to-calibrated instrument data on schedule. The PDS report indicates no problems with data deliveries.

(2) [Minor] OREx has delivered a PDS4-compliant archive. OREx and the SBN instituted an early process of peer review for data formats and metadata that resulted in changes to the PDS4 standards.

(3) [Minor] Ground-based spectral observations of Bennu that complement spacecraft observations have been provided to the PDS by the team.

Weaknesses

None noted.

Secondary Evaluation Criteria

7. Extent to which the science community beyond the mission science team utilizes data and conducts published research

Strengths

(1) [Minor] The community has downloaded 54 TB of OSIRIS-OREx data from the PDS and has published 39 papers using those data. The discovery of

particle ejection events and the high-resolution imagery of the surface of Bennu are motivating new studies of small body regoliths and comparative studies with other asteroids. Use of the data for sampling context will increase once samples are returned to Earth and allocated to the community.

Weaknesses

None noted.

8. Scientific merit of observations to be taken and archived to the PDS, for future use by the scientific community.

Strengths

(1) [Major] The planetary science community is expected to make extensive use of new high-resolution observations of an S-class asteroid.

(2) [Major] The NEO geotechnical data obtained by the mission would find wide use in hazard mitigation studies and models.

(3) [Minor] The observations of Earth as an exoplanet analog respond to a priority of the exoplanet community.

Weaknesses

None noted.

9. Science value

The PMSR will not perform a detailed cost analysis of each proposal. However, the panels may assess in broad terms the science return of the mission relative to its overall cost.

Strengths

(1) [Major] OSIRIS-APEX would cost only a fraction of a similarly equipped spacecraft mission to explore a S-complex asteroid. The integrated staffing for APEX is roughly two-thirds of OREx, further reducing cost. This mission's scientific observations would be of considerable value not only to PSD, but also to other divisions of NASA. Mounting separate missions to determine in situ geotechnical properties of a NEO or to make exoplanet analog observations of Earth would be much more costly.

Weaknesses

None noted.

10. **Demonstrated capabilities, experience, and expertise of key personnel.**

Strengths

(1) [Major] Key personnel have ample experience, gained through the OREx phase, to conduct the APEX operations and science. The team has proved especially adaptable during the OREx phase. The OSIRIS-OREx team has already completed 11 of 15 objectives from its primary mission, with the remainder expected to be completed upon successful return of the sample capsule. The proposed use of a Science Advisory Council including the OREx PI and other senior mission leadership would provide a valuable ‘safety net’ for the newly constituted APEX team.

Weaknesses

None noted.

11. **Expected effectiveness of the proposed PDP in training future leaders.**

Strengths

(1) [Major] This long-duration mission presented an effective professional development plan which would transition junior scientists into more senior roles as the mission progresses. In fact, most of the major roles for OREx science personnel, including the PI, are transitioning for the APEX phase.

(2) [Minor] Specific training and effective team-building exercises are outlined. Team-building activities are not commonly described in PDPs, and this is especially important for a science team that has so many new members for the extended mission.

Weaknesses

None noted.

12. **Thoroughness and appropriateness of the PDMP.**

Strengths

(1) [Minor] The PDMP is thorough and aligned with community standards.

Weaknesses

None noted.

Comments on Overguides and Descopes

Please list and comment explicitly on each Overgude and Descope

Overguides

The proposal described three possible Overguides.

L1: Extending proximity observations beyond November 2030; these include additional reconnaissance, forward scatter observations, extended particle size observations, descent to a super low orbit, and high-risk endgame activities, costing $4.4M to $17.2M depending on duration.

L2: Developing new capabilities that would enable autonomous operations or enhanced science return; these include reconnaissance hover observations, low-altitude hover observations, and autonomous navigation demonstrations, costing $4M.

L3: Upgrading PDS labels, costing $0.45M, and archival of science software, costing $0.76M.

The proposers only request Senior Review evaluations on the proposed activities in Overguide L3, as the mission enhancements described in Overguides L1 and L2 would be better made in 2029 after the initial encounter with Apophis. The Panel agrees that decisions on Overguides L1 and L2 are not needed now and should await completion of risky high-temperature periapse passes early in the extended mission. However, as presently formulated, the mission will not be subject to additional Senior Reviews. Before the in-guide mission is completed, NASA might conduct a special review to consider these Overguide requests. This is a long-duration extended mission, and the science justifications behind these Overguides may evolve. Some of the proposed activities are not science, but rather are technical and operations activities and demonstrations, and those could more properly be evaluated by spacecraft engineers.

Overguide L3.1 and L3.2 are reasonable and would likely allow more use of PDS data by the community. They are supported by the Panel.

Descopes

Descope scores are defined such that a high score (e.g., Excellent) indicates that the panel is in favor of taking the proposed descope, reducing the overall mission cost.

The proposal described two possible Descopes:

(1) Deleting the exoplanet analog observations during cruise, saving ~$1.7M.

(2) Removing the last 4 months of quiet, post-encounter orbital operations, which would degrade Yarkovsky science by increasing orbital uncertainty from 0.3% to 4%, saving ~$9.5M.

The exoplanet analog observations would exceed whole-Earth observations by all previous spacecraft missions. This activity is viewed as inspirational, and will have value as public interest. It also provides some training activity for the team prior to Apophis encounter. However, some weaknesses were identified in the Earth observation plan, and the usefulness of the data in recognizing exoplanet habitability was not established. **Score of Descope option: Fair.**

The post-encounter orbital operations would measure changes in Yarkovsky acceleration after the Earth encounter, which could be used to test models. New measurements of the Yarkovsky effect using stellar occultations of Apophis can measure orbital uncertainty to within 0.5%, almost the same as the 0.3% cited in the proposal. Also, understanding the Yarkovsky effect does not just require measuring changes with high accuracy, but also constraining what is causing the changes. That is difficult if thermal models cannot be constructed because of limited pre-encounter observations. Apophis presents no impact hazard for the next hundred years, so refining its orbital changes due to Yarkovsky acceleration is not a pressing concern. **Score of Descope option: Good.**

Additional Comments for the Mission

Comments here may include suggestions, or feedback about portions of the proposal which were not covered by the Evaluation Criteria. None of these comments affect the score.

The mission team is encouraged to develop interactions with the ground-based telescope community so that coordination of observations can be done effectively.

Additional Comments

Comments here may include suggestions, or feedback about portions of the proposal which were not covered by the Evaluation Criteria. None of these comments affect the score.

In regards to the budget, it is not clear if sufficient reserves are available for the proposed software development.

PMSR22 -- Panelist List

Reviewer	Institution	MAVEN	MRO	ODY	MSL	NH	OSIRIS	LRO	InSight
Jim Adams	Ret.	P	P	P	P	P	P	P	P
Amanda Brecht	Ames	P							
Daniel Britt	UCF		P		P				P
Debra Buczkowski	APL			P	P				
Wendy Calvin	UNR			GC	P				
David Catling	UW		P		P				
Anita Cochran	UT					P			
Robert Craddock	Smithsonian		P	P				GC	
Andrew Dombard	U Illinois							P	
Daniel Durda	SwRI						P		
Darby Dyar	Holyoke / PSI				P				
Caleb Fassett	MSFC							P	
Vladimir Florinski	UAH					P			
Edward Garnero	ASU								P
Scott Gaudi	Ohio State					P			
Randy Gladstone	SwRI	P							
Sarah Greenstreet	UW						P		
Briony Horgan	Purdue			P				P	
Erica Jawin	Smithsonian							P	
Harald Krueger	Max Planck					P			
Lucille Le Corre	PSI					P			
Jian-Yang Li	PSI					P			
Jonathan Lunine	Cornell					P			
Jane Luu	U Oslo / MIT					P			
Tim Lyons	UCR				GC				
Renu Malhotra	UA					P			
Simone Marchi	SwRI						P		
Francis McCubbin	JSC							P	
Lucy McFadden	Ret.						P		
Melissa McGrath	SETI	GC							
Hap McSween	UTK		P		P		GC		
Carol Paty	U Oregon	P							
Frank Postberg	Freie U Berlin					P			
Alice Quillen	Rochester						P		
Ramses Ramirez	UCF							P	
Melissa Rice	WWU			P					
Peter Smith	Ret.				P				
Alejandro Soto	SwRI								P
Michelle Thompson	Purdue							P	
John Vidale	USC								P
Faith Vilas	PSI					GC			
Lara Wagner	Carnegie								GC
Helen Wang	Smithsonian			P					
Jennifer Whitten	Tulane							P	
David Williams	ASU		GC						
Paul Withers	BU			P					
Anonymous			ER						
Anonymous							ER		
Anonymous							ER		
Anonymous									ER
Total Reviewers (P + GC + ER)		5	7	8	9	12	9	10	7

P = Panelist
GC = Group Chief
ER = External Reviewer
RC = Review Chair
ES = Executive Secretary

Doug McCuistion	McQTech	RC	RC	RC	RC	RC	RC	RC	RC
Lisa Pratt	Indiana U	RC	RC	RC	RC	RC	RC	RC	RC
Samuel Birch	Cornell			ES	ES	ES	ES		
Travis Gabriel	USGS	ES	ES					ES	ES

PMSR Lead: Henry Throop, NASA HQ
PMSR Deputy Lead: Lindsay Hays, NASA HQ