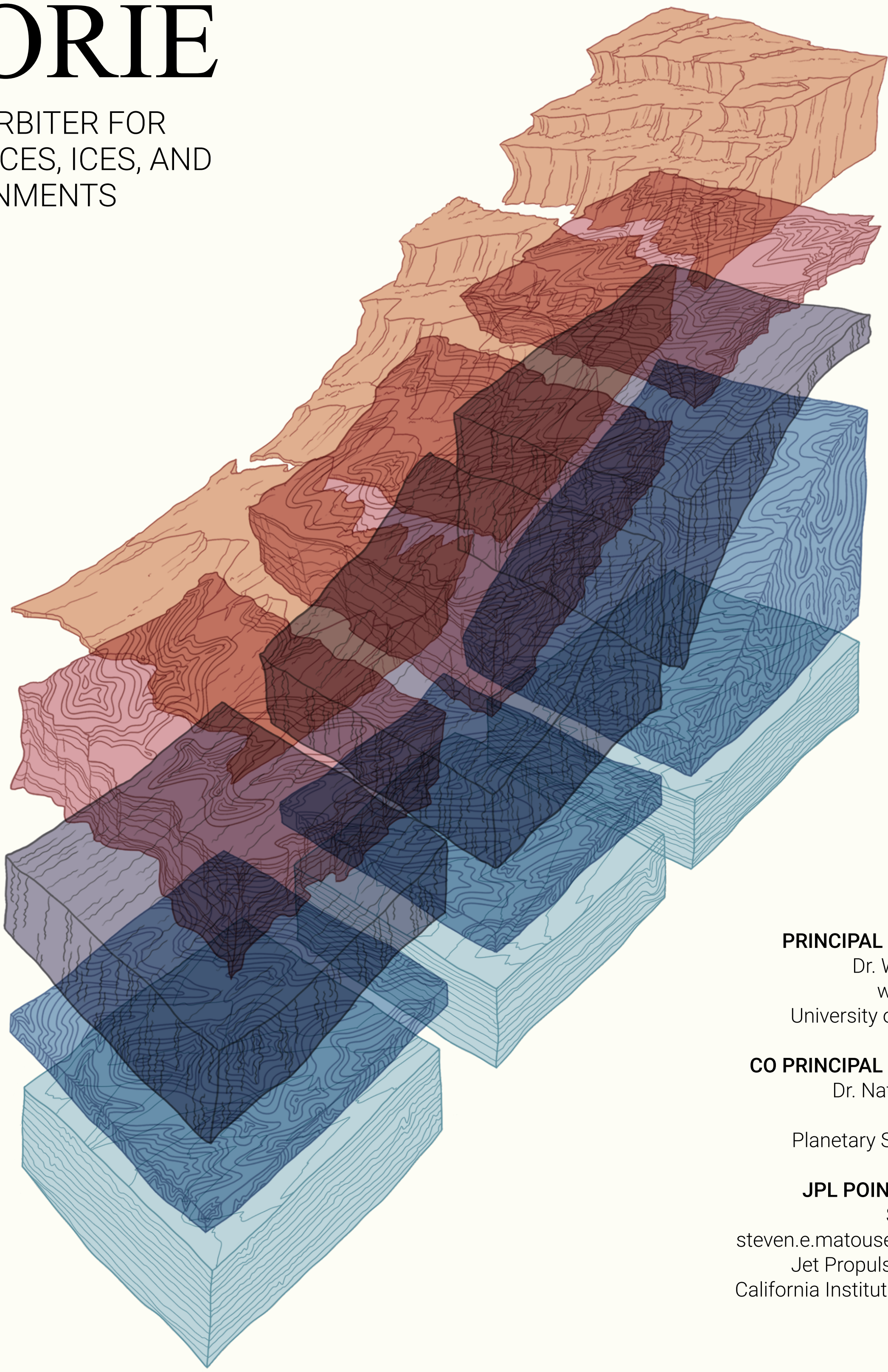
MORIE

MARS ORBITER FOR RESOURCES, ICES, AND ENVIRONMENTS



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AUGUST 2020
Mission Concept Study
Planetary Science Decadal Survey

National Aeronautics and Space Administration
www.nasa.gov

Disclaimers/Acknowledgements

JPL URS clearance number: CL#20-3461

Pre-Decisional Information—For Planning and Discussion Purposes Only

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

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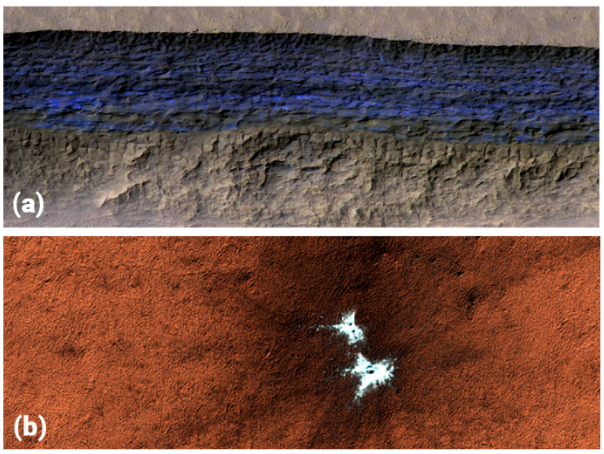
MORIE Mars Orbiter for Resources, Ices, and Environments

Water is the key to present and past habitability on Mars. MORIE will address key questions linked to water - where it is, where it was, and how it has modified the surface through time.

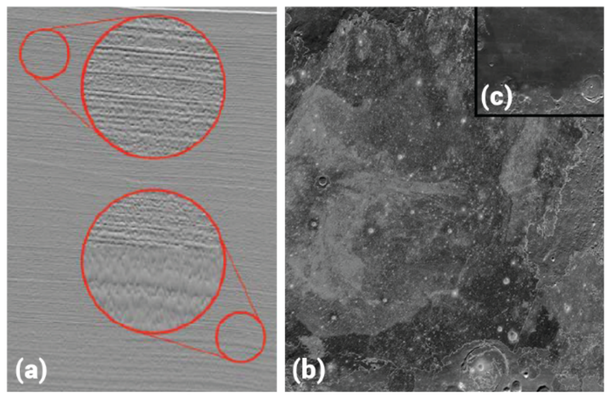
MORIE will determine the **extent and volume of subsurface water ice** and the **nature and timing of transitions** between ancient aqueous environments using radar, imaging, and spectral observations.

Additionally, the instrument complement can address goals relevant to the preparation for **human exploration of Mars** by mapping deposits of near-surface ground ice and hydrated minerals.

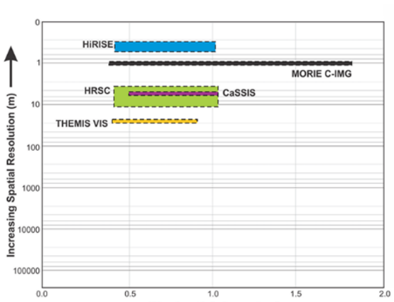
Recent discoveries on Mars include **(a) cliffs that expose the stratigraphy of thick ice** in the mid-latitudes and **(b) ice-exposing new impacts**.



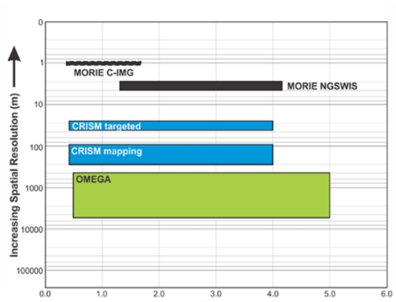
To obtain new science at Mars, MORIE will leverage new radar techniques as illustrated by **(a) sounding of the Greenland ice sheet in P-band with 0.5m vertical resolution** and **(b) SAR imaging of the Moon in P-band with 100m lateral resolution** (contrasted with visible imagery (c)).



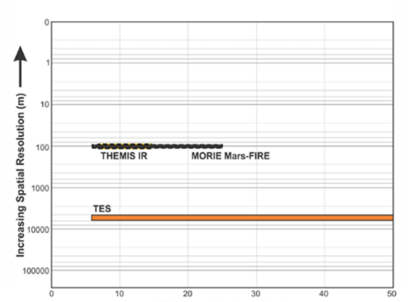
MORIE INCREASES COLOR RANGE/RESOLUTION



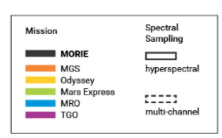
MORIE STEPS UP THE SCALE IN SWIR



MORIE ENHANCES LWIR SPECTRAL FIDELITY



MORIE's instruments will illuminate the evolution of Mars as a habitable world by returning the ***first synthetic-aperture radar (SAR) imaging from Mars orbit*****, fine-scale radar sounding of the depth to buried ice, and surface mineral mapping at unprecedented spatial scales** to unlock geologic sequence stratigraphy through time.



Science Questions	Polar-SAR	RaSo	C-IMG	NGSWIS + Mars-FIRE	MAVRIC	Mid-S-Cam
When did elements of the cryosphere form and how are ice deposits linked to current, recent and ancient climate?	✓	✓	✓	S	✓	✓
How does the crust record the evolution of surface environments and their transition through time?	✓		✓	✓	S	

✓ *indicates primary* **S** *indicates supportive*

MORIE Mars Orbiter for Resources, Ices, and Environments

PAYLOAD CHARACTERISTICS

Polar-SAR (Full Polarization Synthetic Aperture Radar)
100 m spatial resolution and the ability to detect the top of the ice within 3 m of the surface.

RaSo (Radar Sounder)
A sounder in a higher frequency range than MARSIS or SHARAD with a 100 m footprint and 0.5 to 1 m vertical resolution in buried ice from 1 to 20 m depth.

C-IMG (1-m Color Imager)
Observes from 0.4 to 1.7 µm, with 20 channels at 10–60 nm band pass.

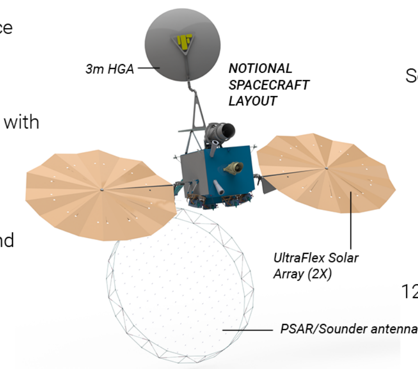
NGSWIS (Next Generation Short-Wave Infrared Imaging Spectrometer)
A 1.3 to 4.2 µm spectrometer, resolution of < 10 nm spectral, < 5 m spatial, and a swath from 5 to 10 km.

Mars-FIRE (Mars-Far Infrared Emission Imager)
Long wavelength infrared (IR) spectroscopy, spectral range from 6–25 µm, in 20 channels with < 1 µm bandpass, and < 100 m spatial resolution.

MAVRIC (Mars Atmosphere Volatile and Resource Investigation Camera)
Wide angle camera in 6 to 12 filters.

Mid-S-Cam (Dual Monochrome Cameras for Stereo DEM)
High resolution topography ~5 m per pixel and for radar clutter mitigation.

NOTIONAL MISSION CHARACTERISTICS



Medium class launch vehicle

New Frontiers class orbiter

Solar-electric propulsion (SEP)

Power-rich spacecraft enables radar

8000 m/s ΔV

3000 kg wet mass

Spiral down to 300 km orbit at Mars

12x MRO data return capability

MISSION COST ESTIMATE

FULL MISSION (FY25$M)

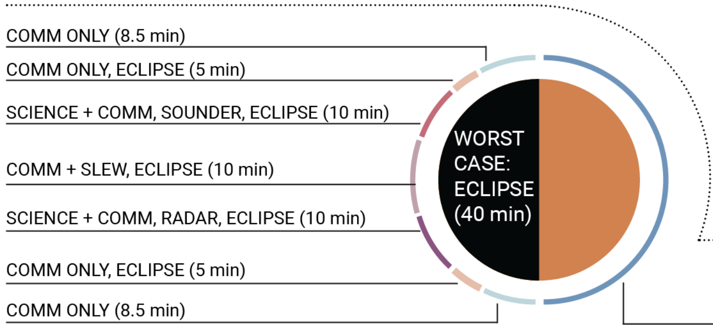
	Estimate	Reserves		Total	Reserves		Total
Development (A-D)*	929.4	30%	278.8	1208.2	50%	464.7	1394.1
Launch Vehicle	228.8	-	-	228.8	-	-	228.8
Operations (E/F)	216.0	15%	32.4	248.4	25%	54.0	270.0
Full Lifecycle Cost	1374.2	27%	311.2	1685.4	45%	518.7	1892.9

*New Frontiers comparable cost cap of $1,100M (FY25)

ICE-FOCUSED (FY25$M)

	Estimate	Reserves		Total	Reserves		Total
Development (A-D)*	730.5	30%	219.1	949.6	50%	365.2	1095.7
Launch Vehicle	228.8	-	-	228.8	-	-	228.8
Operations (E/F)	149.9	15%	22.5	172.4	25%	37.5	187.4
Full Lifecycle Cost	1109.2	27%	241.6	1350.8	46%	402.7	1511.9

*New Frontiers comparable cost cap of $1,100M (FY25)



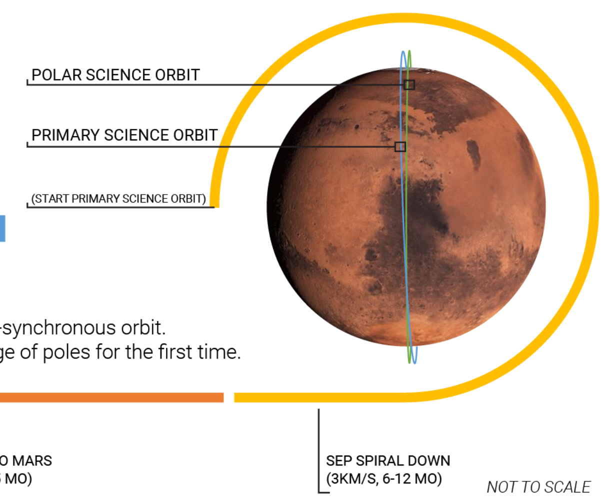
ORBIT PERIOD: 114 min

SCIENCE + COMM , DAY (57 min)

PHASE	DURATION	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	YEAR 6
Heliocentric	13.2 mo	cruise					
Spiral Down	9.7 mo		spiral				
3pm Sun Sync	23 mo			primary sci orbit			
Inc. Transfer	1.4 mo						
90 Degree	21.5 mo					polar science	
Inc. Transfer	1.4 mo						
3pm Sun Sync							

TWO MARS YEARS OF SCIENCE RETURNS.

YEAR 1 AT MARS: 92.7 degree inclination, 3pm sun-synchronous orbit.
YEAR 2 AT MARS: 90 degree inclination, full coverage of poles for the first time.



Executive Summary

The MORIE mission concept study examined the science and technical trade space to address high priority questions related to ice reservoirs and environmental transitions. The study team converged on a medium-class SEP-enabled orbiter with seven instruments to unlock the extent and volume of subsurface ice and geologic sequence stratigraphy through time. Observations would include the ***first radar imaging*** from orbit, the ***first radar sounding directly over the poles***, and ***surface mineral mapping at unprecedented spatial scales***.

Science Objectives: MORIE is a medium class orbiter to address high priority questions related to shallow subsurface ice, polar layer stratigraphy, and mineralogy of ancient environmental transitions linked to the past habitability of Mars. The mission would address three major objectives under the theme "Evolution of a Habitable World": 1) Determine when elements of the cryosphere formed and how ice deposits are linked to current, recent, and ancient climate; 2) Explore the evolution of surface environments and their transition through time; 3) Prospect for in situ resources necessary to support future human activities on the surface.

Instruments: These objectives are met by a payload complement of seven instruments: full polarization ultrahigh frequency (UHF) synthetic aperture radar (SAR), a dual-band radar sounder, a 1-m per pixel multiband imager, both short-wave and long-wave infrared (SWIR, LWIR) spectrometers, dual stereo cameras, and a wide-angle imager.

Preliminary designs suggest that the radar imager and sounder instruments can be combined with shared electronics and sensing at two different center frequencies (200 and 400 MHz). The SWIR and LWIR spectrometers can share a telescope to reduce overall mass. The spectrometers and imagers observe selected targets, where the radar, wide angle camera, and stereo imagers operate in a more continuous fashion to build up regional or global data sets. The imaging and spectral instruments have heritage from instruments that have flown and those that are being developed for near-term launch opportunities (Europa Imaging System (EIS), Earth Surface Mineral Dust Source Investigation (EMIT), Polar Radiant Energy in the Far Infrared Experiment (PREFIRE)).

Mission Scenario: MORIE is enabled by a large, solar electric propulsion (SEP) powered spacecraft. A 2026 launch is baselined, requiring ~ 2 years to cruise to Mars and spiral down into a 3 PM equator-crossing sun-synchronous orbit with an inclination of 92.7 degrees. The spacecraft spends a full Mars year in this orbit, then transitions over ~ 1 week to a 90-degree true-polar orbit to enable radar sounding of previously unobserved regions of the polar caps. The mission then spends one Mars year in the polar orbit before transitioning back to sun synchronous for an extended mission and communication relay activities.

The SEP-orbiter is characterized by a large 6-meter deployable SAR antenna, two flexible solar arrays, and an articulated 3-meter high-gain antenna. The SEP thrusters drive the power requirement, leading to 43 m^2 solar arrays that also provide ample power to run the radar and telecommunications system on orbit. The design does not present any major technical challenges or novel risks.

Data Acquisition and Coverage: Data downlink rates are strongly dependent on the Earth-Mars distance and are estimated from 3 to 75 Mbps for 2.5 to 0.5 AU. Using a mid-range average of 280 Gbits/day MORIE will generate > 300 Tb for the two Mars-year baseline mission. The SAR, radar sounder and stereo imagers will build global maps over the life of the mission. The imager and spectrometers will acquire > 50,000 targeted observations. Development of new technologies such as optical communication or advanced onboard data processing could substantially enhance targeted data volume.

Costs: Early trade space exploration used regression analysis based on past instrument analogies that allowed cost estimate ranges to inform payload and architecture decisions for final point designs. Point design costs used industry standard parametric models, system level estimates, and analogy. The team costed both the full mission and, due to the recent programmatic interest in a Mars Ice Mapper, an ice-focused radar version. Cost models suggest the full mission point design is larger than the current New Frontiers cost cap without instrument or hardware contributions or further design maturity.

1 Scientific Objectives

Water is the key to present and past habitability on Mars. MORIE will address key questions linked to water—where it is, where it was, and how it has modified the surface through time. Specifically, the mission will determine the lateral extent and volume of subsurface water ice as well as the nature and timing of transitions between ancient aqueous environments using radar, imaging, and spectral observations.

Science Questions and Objectives

MORIE is a medium class orbiter to address high priority science questions related to shallow subsurface ice, polar layer stratigraphy, and mineralogy of key stratigraphic environmental transitions. These questions have been articulated in numerous recent reports from the Mars Exploration Program Analysis Group (MEPAG) and the National Academies of Science, Engineering and Medicine (NASEM) and other community workshops (NEX-SAG, 2015; NASEM, 2017, 2018, 2019; ICE-SAG, 2019; Smith et al. 2020).

As part of this NASA Planetary Mission Concept Study (PMCS), the MORIE team crafted a modern set of objectives and an instrument complement that could synergistically address two primary scientific questions under the theme **"Evolution of a Habitable World"**.

1. *When did elements of the cryosphere form and how are ice deposits linked to current, recent, and ancient climate?*
2. *How does the crust record the evolution of surface environments and their transition through time?*

Additionally, MORIE will address goals relevant to the preparation for human exploration of Mars by identifying near-surface ground ice deposits and the extent of hydrated mineral deposits. **"Fueling the Future of Exploration"** these resource goals can be addressed with the same instruments and requirements that address the science.

This section briefly reviews the new discoveries and existing knowledge gaps that motivate the MORIE mission and payload and links the science objectives to measurement approach and requirements. The MORIE mission concept will reveal the lateral extent and volume of subsurface ice and geologic sequence stratigraphy through time.

1.1 Discoveries in Ice and Climate

Several major discoveries have provided new motivation for a next-generation Mars orbiter (Figure 1-1). SHAllow RADar (SHARAD) and Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) radar sounder detections have provided evidence for regional-scale buried ice sheets in the mid-latitudes (Bramson et al. 2015, Stuurman et al. 2016). Steep scarps expose ice in mid-latitudes, and ice exposures in new impact craters have been detected down to 39 °N (Byrne et al. 2009; Dundas et al. 2014, 2018). For landforms known as lobate debris aprons, recent radar and geomorphic analysis have shown them to be composed predominantly of water ice and thus constitute debris-covered glaciers (Holt et al. 2008; Plaut et al. 2009; Petersen et al. 2018). **For both glacial and non-glacial mid-latitude ices, the depth of burial remains poorly constrained, as the existing radar sounders have relatively coarse vertical resolution (~8–80 m).** The composition and origin of the Medusae Fossae Formation (MFF) is also contested, with different approaches offering contradictory interpretations as to whether the unit is a friable ash deposit or if it may offer an equatorial deposit rich in water ice (e.g., Watters et al. 2007; Carter et al. 2009; Campbell and Morgan 2018; Wilson et al. 2018; Ojha and Lewis 2018; Bradley et al. 2002; Kerber et al. 2012; Mandt et al. 2008). In the north polar layered deposits, a sequence of recent layers has been identified and suggested to be related to obliquity variations over the last 370 ka (Smith et al. 2016). Observations of surface change have proliferated, including Recurring Slope Lineae (RSL) (McEwen et al. 2011), hundreds of new impact craters (Daubar et al. 2013) including a major expansion of the number of known ice exposures (Dundas et al. 2014), dozens of active gullies (Dundas et al. 2017), and planet-wide dune movement (Bridges et al. 2013). The driving processes of many of these surface changes are controversial, with divergent interpretations for the role of recent liquid water.

1.2 Environmental Transitions

The success of orbital and landed missions has led to a new understanding of the variety of aqueous environments on Mars as evidenced

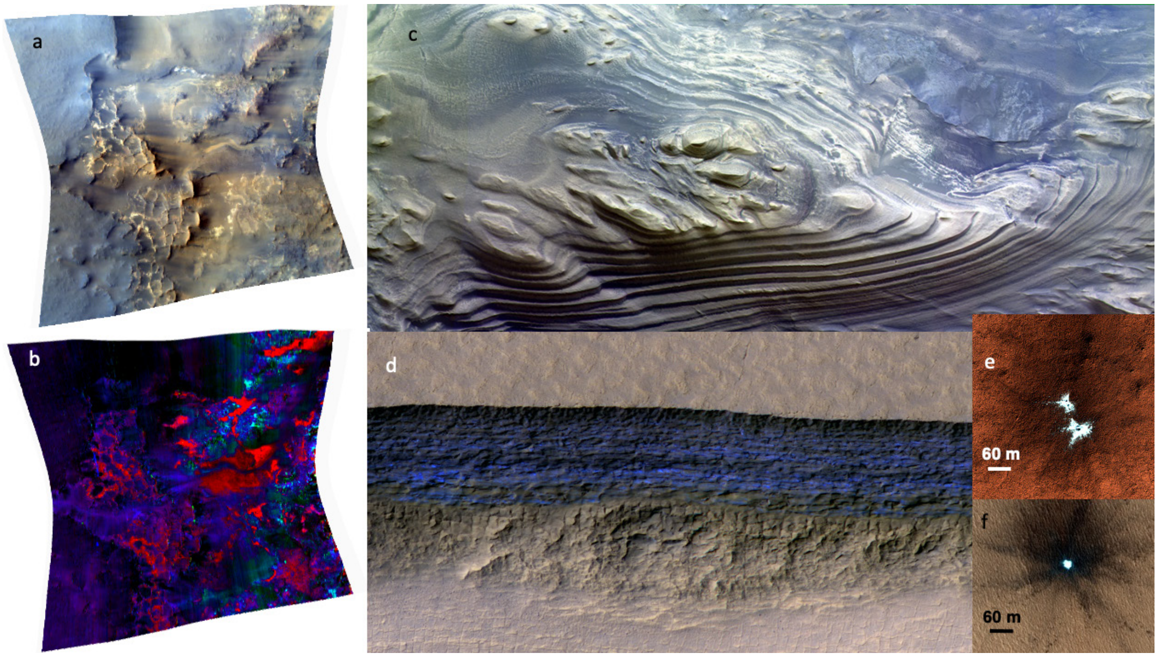


Figure 1-1. Environmental transitions and new ice exposures include (a, b) Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) image FRT00019DAA in NE Syrtis in true color and band parameters; (c) CaSSIS image of a layered mound in Juventae Chasma (2 Oct 2018, ESA/Roscosmos/CaSSIS, CC BY-SA 3.0 IGO); (d) cliffs that expose the stratigraphy of thick ice in the mid-latitudes, HiRISE ESP_022389_1230; (e, f) ice exposing new impacts, HiRISE images ESP_032340_1060 and ESP_025840_2240.

through mineral diversity (e.g., Squyres et al. 2004; Squyres et al. 2008; Bibring et al. 2006; Murchie et al. 2009; Boynton et al. 2009). These mineral detections were largely interpreted as indicating persistent warmer and wetter climates in the Noachian producing phyllosilicates followed by punctuated climates in the Hesperian producing salts (e.g., Bibring et al. 2006). However, recent work has shown that the history of major environmental transitions on Mars was much more complex. In the Noachian, paleoclimate models fail to produce persistently warm conditions (Wordsworth et al. 2013; Palumbo & Head 2018). They instead suggest that liquid water has been rare on Mars and that the surface may have been dominated by large ice sheets (Fassett & Head 2011; Kite et al. 2013; Cassanelli & Head 2014; Wordsworth 2016). However, clear physical or chemical evidence for this hypothesis has yet to be identified in Noachian terrains, where the mineralogy and geomorphology is most consistent with long-term surface and subsurface aqueous activity (Hynek et al. 2010; Ehlmann et al. 2011; Carter et al. 2015; Ramirez & Craddock 2018; Bishop et al. 2018). Results from Mars Science Laboratory (MSL) have demonstrated that a lake persisted continuously in Gale crater for up to millions of years during the Hesperian period, with limited evidence for significant hiatuses or major influence from glacial or periglacial processes, suggesting a locally stable climate (e.g., Grotzinger et al. 2014, 2015). Thus, while we have much better observational constraints on specific environments, **the nature and duration of major environmental transitions are still unclear, as is how these transitions may have affected the habitability of surface and subsurface environments.** Unlocking the geologic sequence stratigraphy and these transitions through time is crucial to interpreting the changing record at locations not yet visited by rovers.

1.3 Resource Knowledge Gaps

Both shallow ground ice and hydrated mineral deposits are of interest to NASA as potential resources for human missions (e.g., NEX-SAG 2015; MEPAG 2020). Recent work by Piqueux et al. (2019) used data from Mars Climate Sounder (MCS) and Thermal Emission Imaging System (THEMIS) to derive the depth to the water ice table within 1 m of the surface. This result and those of the ongoing project "Subsurface Water

Ice Mapping (SWIM) on Mars," (Putzig et al. 2019) are both pointing to near surface water ice at lower latitudes than previously identified (Figure 1-2). Regional studies and the SWIM project have leveraged multiple data sets in an effort to span the gap between shallow and deep ice detections, but **the 5–20 m depth range effectively remains a blind spot for current orbital assets.**

Two projects are underway to create global maps of hydrated minerals with data from the Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité (OMEGA) and the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) (Riu et al. 2019; Seelos et al. 2019). However, these global maps are at coarse regional scales and only able to map two-dimensional surface exposures where dust coverage is low. **To understand the potential for hydrated minerals as a future resource, mapping the subsurface, particularly under dust mantling will be important.** The MORIE payload will close this knowledge gap.

1.4 MORIE Science Traceability and Instruments

The MORIE team has traced our two primary science questions to eight objectives as shown in the Science Traceability Matrix (STM) foldout in Section 1.7. Three additional resource objectives are identified to close existing knowledge gaps relevant to fueling future Mars exploration. These objectives flow directly to desired observables and physical parameters, a measurement approach and the requirements on that measurement. Measurement requirements that flow from the science objectives are synergistic with those for resource objectives.

This set of objectives results in a seven instrument payload, where each measurement is primary (✓) for at least one objective and plays a supporting role (S) in other objectives, as shown in Table 1-1. Brief descriptions of the instruments and their requirements are:

- Full polarization P-band Synthetic Aperture Radar (**Polar-SAR**). With 100 m spatial resolution and the ability to detect the top of the ice within 3 m of the surface. Over the mission lifetime, acquire 80% coverage between latitudes of 25 and 60 (N/S), in full polarimetry, with a spotlight mode for higher resolution of selected locations.
- P-band Radar Sounder (**RaSo**). A radar sounder in a higher frequency range than MARSIS or SHARAD with a 100 m footprint and with 0.5 to 1 m vertical resolution in

Table 1-1. Science objectives linked to measurement approach ✓ indicates primary, S is supportive.

Science Objective	SAR Imager	Radar Sounder	1-m multi-band Visible and Near Infrared (VNIR) Imager	SWIR Spectrometer	LWIR Spectrometer	Wide-angle Color Camera	5-m Stereo Context Cameras
Determine the global distribution and volume of subsurface ice, especially near the surface (1-20m).	✓	✓	S		S		S
Identify the vertical and lateral structure of ice deposits at the poles and mid-latitudes.	✓	✓	✓				✓
Record the annual cycling of volatiles and dust between the surface and atmosphere.			✓	S	S	✓	
Link ice reservoirs to their formation processes and history.		✓	✓				S
Constrain the nature and timing of ancient aqueous deposits and major environmental transitions.	S	S	✓	✓	S		
Observe which intervals in the geologic record preserve environments that were conducive to the possible origin and evolution of life.	S		✓	✓	✓		
Identify how igneous rocks record the evolution of magmatic sources and crustal modification over time.	✓	S	✓	S	✓		
Observe how modern processes are reshaping the surface today.			✓			S	

buried ice from 1 to 20 m depth. Over the mission lifetime, acquire a track density of 10 tracks/1° longitude between latitudes of 25 and 60 both north and south.

- 1-m Color imager (**C-IMG**). Observes from 0.4 to 1.7 µm, with 20 channels at 10–60 nm band pass, including at least 6 wavelength bands in the spectral range from 1.2 to 1.7 µm at major absorption features in H_2O and CO_2 ices. A super-resolution mode from time delay integration (TDI) to achieve < 1 m per pixel at selected locations.
- Next Generation Short-Wave infrared Imaging Spectrometer (**NGSWIS**). A 1.3 to 4.2 µm spectrometer, to cover the wavelengths of a variety of alteration minerals, with a spectral resolution of < 10 nm, and spatial < 5 m, with a swath from 5 to 10 km. Targeted observations of high priority sites.
- Mars Far Infrared Emission (**Mars-FIRE**) imager. Long wavelength infrared (LWIR) spectroscopy is required for igneous petrology and minerals not detectable at shorter wavelengths. Spectral range from 6–25 µm, in at least 20 channels with < 1 µm bandpass, and < 100 m spatial resolution. Observe targets with higher spectral fidelity and better mineral detection capability than THEMIS.
- Mars Atmosphere Volatile and Resource Investigation Camera (**MAVRIC**). A wide angle camera with at least six wavelength bands, visible color plus bands at major absorption features in H_2O and CO_2 ices, with a large swath for daily global maps.
- Mid-resolution Stereo Camera (**Mid-S-Cam**). Dual monochrome cameras for stereo digital elevation models (DEM). High resolution topography ~5 m per pixel and for radar clutter mitigation. Also detect new ice exposing impacts in mid-latitudes and improve DEMs for Polar Layered Deposit (PLD) stratigraphy.

1.5 MORIE New Science

MORIE radar will resolve depths and near-surface stratigraphy in ice that are currently unobserved. High spatial resolution spectral instruments will detect minerals at unprecedented scales unlocking the evolutionary sequence of environmental transitions.

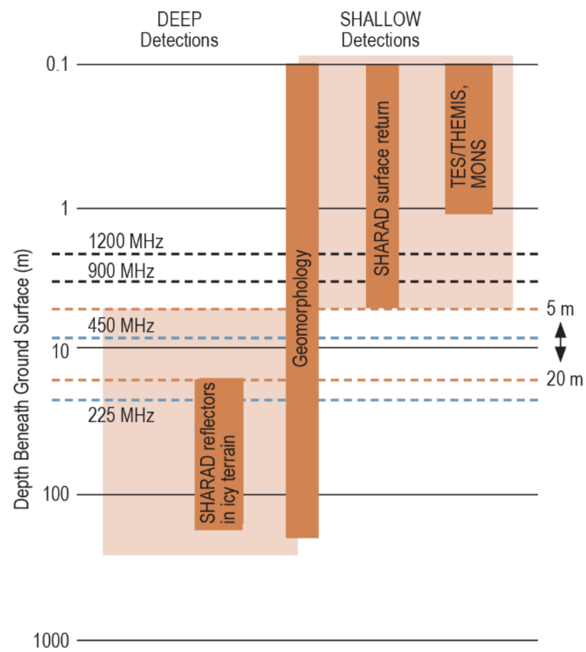


Figure 1-2. Current sensing gap (brown) with P-band (blue) versus L-band (black) penetration depths from Petinelli et al. 2007.

To optimize measurements of the ice table in the existing observational gap, this study concluded that both sounding and SAR in P-band are required, ideally at distinct center frequencies. P-band has also been advocated in various past studies (Campbell et al. 2004, 2012; Paillou et al. 2006; Pettinelli et al. 2007; Rincon et al. 2019). As noted in Figure 1-2, the lower frequencies of P-band are sensing directly in the current observation gap for ice and will determine ice lateral extent, volume and presence at latitudes nearer the equator where ice is expected to be buried under several meters of dry overburden. The ability to sound and image surfaces covered by dust or regolith will be highly valuable to geologic applications, providing information on buried features such as fluvial channels, volcanic flows and ash, and sedimentary deposits.

We gather spectral data from the visible through the thermal infrared using channels from the imager and both short- and long-wavelength infrared spectrometers. This allows detailed mapping of both alteration and primary mineralogy. NGSWIS will map alteration mineralogy at spatial scales that are a factor of three better than the best observations from CRISM. Finer spectral resolution will allow us to distinguish among many alteration minerals, including solid solution series with sufficient spatial resolution to understand evaporative sequences. Mars-FIRE will provide quantitative mineral abundance maps of igneous compositions with spectral fidelity and mineral discrimination similar to the Thermal Emission Spectrometer (TES), but with a significantly improved footprint (100 m rather than 6 km), revolutionizing our understanding of the primary mineralogy.

MORIE imagers provide new enhancements in high resolution multi-channel views and volatile ice discrimination. C-IMG contributes to observing modern processes and complements the spectral instruments by providing channels in the VNIR giving high resolution context for the detailed mineralogy. The spatial resolution will exceed Colour and Stereo Surface Imaging System (CaSSIS) and C-IMG will have 20 channels up through the near-infrared. MAVRIC will continue the existing record from the Mars Color Imager (MARCI). Both of these imagers include new channels that will be able to distinguish water and CO_2 volatile ices. Mid-S-Cam will provide stereo support for 3D modeling of surface minerals and help mitigate surface clutter in radar returns. By the end of the mission, the first global stereo map of Mars will be achieved at 5 m per pixel.

1.6 Full Mission vs an Ice Mapper

The mission design study focused on the full instrument complement. In the final point design several measurement approaches were combined into single instrument designs as described in Section 3.1. Based on the recent programmatic interest in a resource centered Mars Ice Mapper, and a mission that could launch as early as 2026, we also examined an option that addresses only the cryosphere and ice deposit goals, along with the ice resource objective, using the radar instruments and stereo imaging.

1.7 Science Traceability

Relation to NASA Goals	Theme	Key Question	Objectives	Observables and Physical Parameters	Measurement Approach	Requirement
MEPAG 2020 ICE-SAG NEX-SAG	*Science: Evolution of a habitable world*	When did elements of the cryosphere form and how are ice deposits linked to current, recent and ancient climate?	Determine the global distribution and volume of subsurface ice, especially near the surface (1-20m).	Determine the extent and volume of mid-latitude water ice at depth.	Sounding radar with stereo imaging for clutter mitigation.	~ 1m vertical resolution of buried ice from 1 to 20m depth, track density of 10 tracks / 1 deg long. between 25 and 60 latitudes, high resolution topography for clutter mitigation (dual CTX for stereo).
					Imaging radar (SAR) for mapping.	100m spatial resolution, detect top of ice within 3m of surface, 80% coverage between 25 and 60 latitudes, full polarimetry, a spotlight mode for select locations.
					Thermal inertia for shallow ice detection.	Surface temperature measured to 1K in day/night pairs over a wide range of Ls.
				Identify new impact craters in mid-latitudes.	Imaging.	CTX scale for detection (cover), SNR > current CTX, + 1m / pixel with color for characterization, mid-day, similar to MRO for consistency.
			Identify the vertical and lateral structure of ice deposits at the poles and mid-latitudes.	Observe shallow subsurface structure of water and CO_2 ice in the polar cap & layered terrain.	Sounding radar with stereo imaging for clutter mitigation.	With ~ 1m vertical resolution, to depth > 80m in ice, topo for clutter mitigation.
					Imaging radar (SAR).	No additional requirements than noted above.
				Improve mapping of ice cap and PLD surface composition.	Multi-band imaging with IR colors to distinguish H_2O and CO_2 ices at CTX or better scales.	At ~ 1m / pixel, at least 6 wavelength bands of (40-60 nm) spectral range from 1.2 to 1.7 μm at major absorption features in H_2O and CO_2 ices.
					Imaging radar (SAR) for penetration through PLD, mapping.	No additional requirements than noted above.
			Record the annual cycling of volatiles and dust between the surface and atmosphere.	Seasonal mapping of surface water, dust & CO_2 frost deposition and sublimation.	MARCI like imager with additional IR channels to distinguish H_2O and CO_2 ices.	At least 6 wavelength bands, visible color plus bands at major absorption features in H_2O and CO_2 ices, large swath for daily global coverage at poles, similar to MRO for data continuity.
				Monitor scarp avalanches, seasonal cap venting, and other processes that loft material into the lower atmosphere.	Color imaging at ~ 1m / pixel.	At ~ 1m / pixel, colors to distinguish ice and non-ice material, 6 wavelengths to distinguish H_2O vs CO_2 ices, track 10s of sites every few weeks.
			Link ice reservoirs to their formation processes and history.	Identify periodicity in stratigraphic layers and correlate those to climate cycles.	Combine old data with new imaging and higher resolution radar for improved stratigraphy.	No additional requirements than noted elsewhere.
MEPAG 2020 NEX-SAG		How does the crust record the evolution of surface environments and their transition through time?	Constrain the nature and timing of ancient aqueous deposits and major environmental transitions.	Determine composition of primary minerals and their alteration products across environments and ages.	Map mafic and alteration mineralogy at higher spatial resolution than currently available.	Survey well know sites from CRISM/OMEGA (not global). Stereo imaging better than CTX scale. 1000's of sites with swath of 5 -10 km. 0.4 to 1.7 μm – sufficient spectral channels to cover major, broad features, channel width of 40-60 nm, at <=5m spatial. 1.3 to 4.2 μm, < 10nm spectral resolution at <=5m spatial sampling. 6 to 25 μm with (<= 1 μm) resolution, with >= 20 channels to span the range, 10 – 100m/pixel.
				Investigate fine-scale composition & morphology in ancient terrain, especially aqueous alteration products.	Target high priority sites identified by CRISM/OMEGA/THEMIS.	
			Observe which intervals in the geologic record preserve environments that were conducive to the possible origin and evolution of life.	Use mineralogy as a proxy for clement and/or habitable environmental conditions.	VNIR for iron oxides, mafic minerals with sufficient channels to cover broad features. SWIR for distinguishing phyllosilicates, evaporative sequences, bound water, and sufficient spectral resolution for mineral discrimination and solid solution chemistry. TIR required for igneous petrology (e.g., feldspars) quantitative mineral abundances when combined with SWIR.	
			Identify how igneous rocks record the evolution of magmatic sources and crustal modification over time.	Measure compositional and structural changes in volcanic constructs and lava flows.	Same spectral requirements as above, plus imaging radar (SAR) for volcanic structures and composition in dust covered areas.	See spectral requirements above for mineralogy. SAR at 100m, P band, full polarization, a spotlight mode for 10's of meters at selected sites. 25% cover of 30S to 30N, minimum 10%.
			Observe how modern processes are reshaping the surface today.	Continued observation of dynamic processes such as RSL, gullies, avalanches, new craters.	Use "super resolution" mode to achieve near-HiRISE level imaging scales. Monitoring limited number of known sites. Observe potential changes in hydration and/or frosts at these locations.	1m scale imaging to detect changes, plus a mode to achieve super-resolution at 2 to 3x better, SNR > 100, 1000 to 2000 sites, at 10 km swath. Same spectral requirements as mineralogy / ices described above.
MEPAG 2020 NEX-SAG SKG: Water resources, ISRU, Civil Eng	Resources: Fueling Future Exploration	Where could ground ice serve as a resource for landed missions?	Determine the near-surface distribution and depth of mid-latitude ice.	Identification of regions with water ice present within 10 m of the surface.	Same techniques as Key Science Question 1.	These resource objectives and measurements use the same techniques as the science objectives. For a science-focused mission these do not levy additional requirements.
				Identification of regions where depth of dry overburden is < 2 m.		
		Can hydrated mineral deposits provide a viable resource for landed missions?	Determine the type, distribution, abundance and volume of hydrated minerals at the surface.	Identification of hydrous minerals exposed at the surface and estimate their subsurface distribution.	Same techniques as Key Science Question 2.	
		How do materials at the surface affect landing site trafficability and access to resources?	Constrain geotechnical properties of the near surface to characterize landing sites and resource accessibility.	Determine particle sizes, slopes, texture, thermal properties and estimate material thickness & consolidation over buried ice deposits.	Same techniques as Key Science Questions 1 and 2.	

2 High-Level Mission Concept

MORIE is a groundbreaking mission in both science and technology. It carries a unique P-band SAR/sounder instrument that investigates near-surface ice that is supported by complementary imaging and spectroscopy. MORIE's use of SEP enhances payload resources, facilitates an orbital plane-change, and enables large data volumes.

The medium-class orbiter designed provides MORIE's science return from low Mars polar orbit, with margin. The two Mars-year orbit has two phases – the first is a standard sun-synchronous, and the second is a direct-over-poles view not yet observed. A flexible system with few articulations, combined with abundant, SEP-enabled on-orbit power, allows high-volume data return and operational flexibility.

2.1 Overview

The MORIE orbiter is a medium-class, SEP-powered spacecraft. The fully-deployed orbiter includes a large 6-m SAR antenna, two solar arrays, and an articulated 3-m high-gain antenna (Figure 2-1). The SEP thrusters drive the power requirement, leading to 43-m^2 arrays that provide more than 12 kW at Earth and more than 5 kW at Mars. After arrival in the low-Mars science orbit, ample power will be available to run both the radar and telecommunications systems.

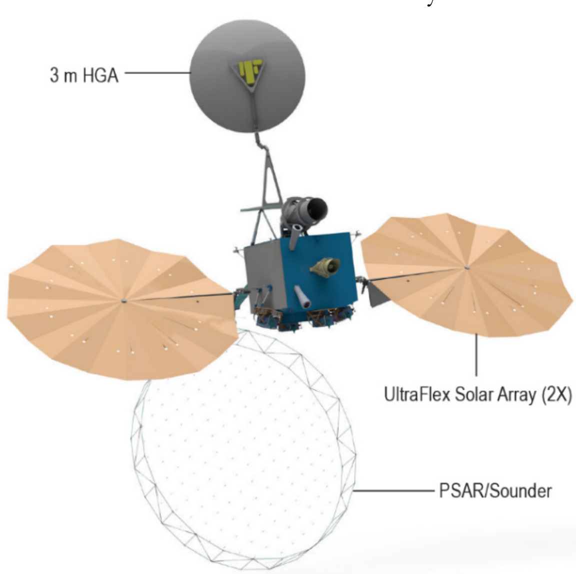


Figure 2-1. The MORIE flight system with two prominent solar arrays for SEP thrusting power and the large mesh antenna for radar/sounding provides operational flexibility.

MORIE's flight system is carried to a low C3 (~2–8 km^2/s^2) escape trajectory by a medium-class launch vehicle (e.g., Falcon 9 Recoverable). The SEP system provides thrust through the majority of the cruise and a circular capture spiral towards the first science orbit: 300 km x 92.7° sun-synchronous orbit with a 3 PM local solar time (LST) ascending node, similar to Mars Reconnaissance Orbiter (MRO). The cruise and spiral take approximately two years.

After one Mars year of science observations, the SEP system performs a plane change to a polar orbit (300 km × 90°). This new orbit will "walk backward" in local solar time at the rate of roughly 1-hour per month. This allows for observations at various times of day, and enables direct sounding of the poles and filling gaps that have never been observed. After a second Mars year and completion of the baseline mission, it is possible to return to the original sun-synchronous science orbit in its extended mission.

2.2 Concept Maturity Level

MORIE benefits from a large and diverse set of previous Mars orbiter studies. This study examined areas of the trade space (CML 3, see Section 5 for cost trades and Appendix B for architecture trade summary) not previously looked at in-depth for the combination of science, technical implementation, and cost. The resulting range of science and mission possibilities produced useful information for future Mars science orbiters such as MORIE.

JPL's Team X produced point designs (CML 4) for the areas identified in the trade space that best fit the science requirements in approximately a New Frontiers-size mission. CML is noted in Table 2-1 and throughout this study report.

Table 2-1. CML helps to describe the maturity of a concept. The MORIE PMCS is at CML 3 and 4.

Concept Maturity Level	Definition	Attributes
CML 4	Preferred Design Point	Point design to subsystem level mass, power, performance, cost, risk
CML 3	Trade Space	Architectures and objectives trade space evaluated for cost, risk, performance

2.3 Technology Maturity

All spacecraft subsystems, subassemblies, and components are mature to at least TRL 6, and many to TRL 9 (key spacecraft elements shown in Table 2-2). Advances in technologies such as solar electric propulsion (SEP) thrusters, power converters, and electronics could reduce mass and overall mission cost (Table 2-2). MORIE's payload benefits from technology developments (Table 2-3). Overall, almost all the technologies exist now (TRL 6 or greater) to fly MORIE. The payload technologies in Table 2-3 are further detailed with technology development plans in Section 4.2.

Table 2-2. Key spacecraft technologies are mature.

Spacecraft Element	Technology	TRL
Propulsion	SEP thruster SPT 140	6
Telecomm	TWTA (200 W)	6
Telecomm	Universal Space Transponder (UST)	6
C&DH	Computer	9
Power	UltraFlex solar arrays	6
Power	Power Processing Unit (PPU)	6
Mechanical	Solar array and HGA gimbals	>6

Table 2-3. Key payload technologies enable or enhance science data return.

Payload element	Technology	Performance Increase
SAR and sounder	Large dual-use mesh antenna for RaSo/Polar-SAR	6m diameter mesh antenna used for the first time at Mars for SAR and sounding. Reduces mass and cost of two separate SAR and sounder antennas
Thermal infrared	Thermal infrared detector array size increase for Mars-FIRE	Increased surface resolution per surface swath
Wide angle imager	Increased number of wavelength bands for MAVRIC	Greater wavelength resolution for a given surface swath
SWIR/TIR	50 cm telescope used by both NGSWIS/ Mars-FIRE	No gimbal or nodding. Mass, volume, and cost savings versus two separate instrument telescopes
Visible imaging	C-IMG Focal Plane Array (FPA)	Higher resolution for no increase in mass and volume
SWIR/TIR/Imaging Shared Instrument Optics	Combine NGSWIS/Mars-FIRE and C-IMG (or HiRise Lite)	No gimbal or nodding. Even greater mass, volume, and cost savings versus three separate instrument telescopes
Optical Communication	High data rate optical communication to Earth	2 to 10 times depending on flight system and Earth received assumptions

2.4 Key Trades

Spacecraft Propulsion

In order to deliver MORIE's flight system to low-Mars orbit, the Study Team considered various propulsive options:

- Monopropellant with a ballistic transfer and aerobraking (like MRO)
- Bipropellant with a ballistic transfer and direct orbit insertion (like Viking)
- Bipropellant with a ballistic transfer and aerobraking (like Mars Global Surveyor and Odyssey)
- SEP with spiral (*enhancing technology*)

Monopropellant has high heritage and requires a less costly propulsion system, but requires a large amount of propellant and an aerobraking campaign. A bipropellant mission with direct orbit insertion has the shortest time-of-flight, but requires a more complex propulsion system and a larger launch mass. Adding aerobraking to bipropellant transfer reduces the necessary ΔV and has the lowest launch mass. All three of these options are both limited in power and ΔV.

SEP allows for a completely different mission design. It is as much as ten times more efficient than chemical propulsion, greatly reducing the required propellant load. This allows MORIE to fit on a smaller launch vehicle (e.g., Falcon 9 Recoverable). While the transfer can be several months longer (Appendix C), there is more flexibility on transfer duration and launch period. The low, near-continuous thrust also means that there are no critical events, for example, Mars Orbital Insertion (MOI). SEP also offers the ability to change the orbit plane mid-mission. It provides the ΔV necessary to make a plane change from sun-synchronous to polar and back, eliminating the need to choose between the two potential science orbits and delivering on all of MORIE's objectives. SEP requires large amounts of power to run the thrusters out to 1.6 AU; once in MORIE's science orbit, this power will be used for the power-hungry SAR and telecom system that MORIE requires. Other special analyses that supported the trades were done (data return, flight system configuration and concept of operations, See Appendix C), but the key trade determined to impact MORIE's design was the propulsion system.

3 Technical Overview

The SEP-enhanced MORIE flight system is designed to achieve low Mars orbit and the first orbit plane change executed at Mars, as well as provide ample power for the radar, spectral, and imaging instruments and the high-data rate communication system during the two Mars-year mission.

Study Implementation Approach

Designed to provide sufficient thrust to get to Mars orbit, the SEP system will provide power to modern radar instruments, spectral imagers, cameras, and a high data-rate communications system to address high-priority science. SEP also allows an orbital plane change from 92.7 degrees to 90 degrees to obtain radar sounding data directly over the poles, addressing a longstanding gap in coverage. Full spacecraft redundancy increases longevity and aids full science data return. The flight system configuration, instrument fields of view (FOV), and pointing capabilities all meet payload requirements. The flight system has the added benefit of being able to relay data from other Mars surface and orbit assets. An Ice-Focused mission option was studied as well, with a significantly reduced payload.

3.1 Instrument Payload Description

The complete MORIE mission concept includes seven distinct measurements. In some instances, the payload envisioned to meet MORIE's science objectives is not yet at a technology readiness level that is necessary for entrance to JPL's Team X. In these cases, acceptable alternatives were used for the point designs generated by Team X, but the preferred technology is noted in the text, with the corresponding technology development plans in Section 4.2. The payload used for the Team X study is intended as a roadmap to MORIE science; the MORIE Study Team anticipates that technology advances, particularly those discussed here and in Section 4.2, will enable exchange of specific payloads to enhance the science return or alter the payload's footprint. Table 3-1 maps the preferred science payloads (described here and in Section 1.4) to the payload used in the Team X point design.

Table 3-1. MORIE preferred payloads map to alternative payloads used in Team X study.

Preferred Payload	Team X Payload Analogues
RaSo/Polar-SAR	*previous JPL radar studies*
Mid-S-Cam Context Imager	CTX
MAVRIC	MARCI
C-IMG	HiRISE Lite
NGSWIS/Mars-FIRE	HiRIS/PREFIRE

One of the outcomes of the study was the ability to combine specific instruments, resulting in substantial savings on mass and cost. The P-Band RaSo/Polar-SAR hybrid (Table 3-2, column 1) combines two observational modes into a single instrument. Two sounder frequencies (200 and 400 MHz) cover different maximum penetration depths (21–43 m and 6–15 m in icy soil, respectively (Pettinelli et al. 2007)), with the higher frequency and high bandwidth enabling higher resolution data at the more shallow penetration depths (Table 3-3), and the lower frequency offering data at deeper depths, particularly in ice-rich zones (~80–100 m). RaSo/Polar-SAR is based on prior JPL radar studies (e.g., Campbell et al. 2017), with additional electronics that enable the dual-frequency sounder mode (Section 4.2 for development plans and Appendix D for additional technology details).

There are two operational modes: Polar-SAR pointed at 30 degrees cross-track and RaSo pointing nadir, with spacecraft slews controlling which mode is active. The SAR images and radargrams are processed onboard; compressed data rates are 0.25 Mbps (100 m per pixel resolution) and 2.75 Mbps (30 m per pixel resolution) for Polar-SAR, and is 2.3 Mbps for RaSo (Appendix D for more on data compression). RaSo-measured reflections are correlated to surface and subsurface features and generate information on the electrical properties of the subsurface materials. These electrical properties inform on the presence, composition, and purity of ice, as well as the depth of the ice table.

In earlier instrument designs, only the 400 MHz sounder mode was included, incorporated into the full mission concept Team X point design. The 200 MHz mode was added later, and was included in the ice-only concept point design. The larger dual-mode instrument is preferred by the science team for both concepts, and could be accommodated in the full mission design.

Table 3-2. Instrument Payload Table.

	1	2	3	4	5	
Item	RaSo/Polar-SAR (using prior JPL radar study information)	Mid-S-Cam Context Imager (using CTX as analogue)	MAVRIC (using MARCI as analogue)	C-IMG (using HiRISE Lite as analogue)	NGSWIS/Mars-FIRE (using HiRIS/PREFIRE as analogues)	Units
Type of instrument	Hybrid SAR/Sounder Radar	Scanning Line Camera	Wide-Angle Camera	Panchromatic Hi-Res Imager	Hybrid SWIR/TIR Spectrometer Telescope	
Number of instrument copies	1	2	1	1	1	units
Number of channels	3	1	1	20	2	
Size/dimensions (for each instrument)	6-m antenna	0.242 m dia x 0.691	0.92 x 0.72 x 0.14	0.4 x 0.4 x 1.2	0.6 x 0.6 x 1.3	m × m × m
Instrument mass **without** contingency (CBE*)	90.9 / 109.2♦	3.37	1	19	45.7	kg
Instrument mass contingency	30	15	15	30	30	%
Instrument mass **with** contingency (CBE+Reserve)	118.2 / 142.0♦	3.9	1.2	24.7	59.4	kg
Instrument average payload power **without** contingency	110 / 185♦ (DC peak)	5.8	4.6	30	8	W
Instrument average payload power contingency	30	15	15	30	30	%
Instrument average payload power **with** contingency	184.5 / 240.5♦ (DC peak)	6.7	5.3	39	10.4	W
Instrument average science data rate^ **without** contingency	8300	40000	515	32000	120000	kbps
Instrument average science data^ rate contingency	N/A**	N/A**	N/A**	N/A**	N/A**	%
Instrument average science data^ rate **with** contingency	N/A**	N/A**	N/A**	N/A**	N/A**	kbps
Instrument Fields of View (if appropriate)	4.8	5.7	5.8	1.1	1.1	degrees
Pointing requirements (knowledge)	0.2	0.1	0.1	0.0017	2.3 x 10-4	degrees
Pointing requirements (control)	0.5	0.6	not driving	0.1	0.1	degrees
Pointing requirements (stability)	0.5	not driving	not driving	not driving	2.9 x 10-3	deg/sec

**CBE = Current Best Estimate.*
^Instrument data rate defined as science data rate prior to on-board processing.
***Contingencies on data rate were not applied to individual instruments; instead, contingency was built into the concept of operations (Sec 3 3.)*
♦The two options shown are the 400 MHz instrument and the later version with both 400 and 200 MHz sounder modes.

The Polar-SAR data is used to detect ice in the upper few meters, leveraging the polarization of the returned signal to further constrain the nature of surface and near-surface scatterers that might not be detected by the sounder (van Zyl et al. 1987; Raney 2007), completing the subsurface mapping objectives described in Section 1.7. For more information, see Appendix D.2.

The Mid-S-Cam (Table 3-2, column 2) is a heritage copy of the context camera (CTX) instrument onboard MRO. Mid-S-Cam is a 5000-pixel single-band visible charge-coupled device

(CCD) line array push-broom imager and will provide the necessary context imaging for sounding. Two copies, pointed at 22.5 degrees fore and aft, are included to meet high-resolution topography requirements for radar clutter mitigation, as well as enable stereo imaging for the generation of DEMs.

Table 3-3. RaSo/Polar-SAR instrument characteristics.

Radar Characteristic	Value
Center frequency	400 MHz
Bandwidth	100 MHz
Spatial Resolution	100 m SAR / 2 km Sounding
Vertical Resolution	1.5 m / 0.85 m (in water ice)
Polarimetry	Fully polarimetric
Orbital Altitude	350 km
Pulse repetition interval (usec)	740
Coverage	Mid latitudes for sounding, track density of 10 tracks / 1 deg long. between 30 and 60 latitudes
	SAR imagery, 80% coverage at 30 m/pixel between 30 and 90 degree latitudes.
	100 m between ± 30 degree latitude, no coverage requirements
Noise Equivalent σ_o	−40 dB
Swath Width (SAR, km)	25
SAR total looks	19-213
Incidence Angle Range	SAR at 30°, Sounder at nadir
Onboard processing compression factor	80-889

A color imager, MAVRIC, is a wide-angle push-frame ultraviolet/visible (UV-Vis) and SWIR (Figure 3-1) that will operate nadir-pointing. MAVRIC is a 2560 × 2160 Complementary Metal-Oxide Semiconductor (CMOS) focal plane array (FPA) for UV-Vis detection and a 1280 × 1080 Indium Gallium Arsenides (InGaAs) array for SWIR detection with twelve filters covering 340–1615 nm, supported by a customized data processing unit (DPU). A more detailed description of the instrument design and development plan can be found Appendix D and Section 4.2. Because MAVRIC is adapted from MRO/MARCI and because MAVRIC is not yet of appropriate TRL for a Team X study, a heritage copy of MARCI was used in Team X analyses as an analogue instrument (Table 3-2, column 3). MARCI only provides five filters versus MAVRIC's twelve. See Appendix D.5 for more information.

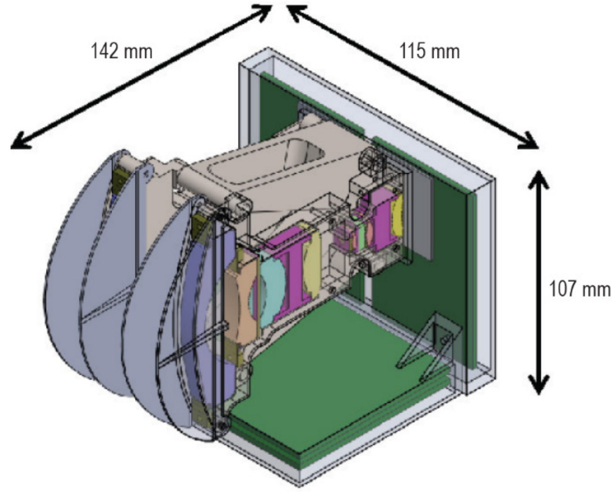


Figure 3-1. CAD rendering of MAVRIC instrument design.

C-IMG, a scaled-down version of MRO's HiRISE imager, is included to enable high-resolution visible-wavelength imaging of 6 km × 6 km targets of interest. This push-broom imager couples a detector array that covers the necessary spectral range with a 20-band filter array and a 30 cm telescope (see Section 4.2 for development plan). C-IMG covers from 0.4-1.7μm using 20 channels, with at least 6 channels in the 1.2 – 1.7 μm range to target specific absorption features. The calculated single pixel signal-to-noise ratio (SNR) for twelve filters is shown in Figure 3-2, showing that the predicted performance exceeds the science-driven instrument requirements. Similar to MARCI, C-IMG will also operate nadir-pointing. Due to the current TRL of C-IMG (Section 4.2 for development plan), High Resolution Imaging Science Experiment (HiRISE) Lite was used in the Team X point design (Table 3-2, column 4). Super-resolution via over-sampling is possible with digital TDI and can improve the image resolution beyond the native capabilities of the optics (e.g., McEwen et al., 2012; Gao et al., 2017). Carrying out super-resolution imaging in

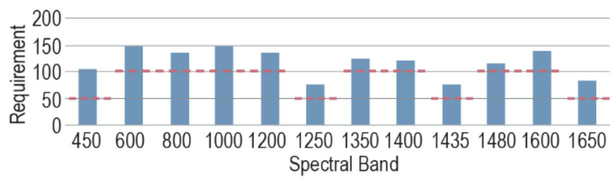


Figure 3-2. MAVRIC exceeds instrument requirements, with the predicted SNR performance of MAVRIC as compared with instrument requirements (Section 1.3).

flight enables all of the component images to be acquired simultaneously with identical lighting and viewing angles as well as known pixel offsets, improving image reconstruction, and enabling processing to be performed onboard the spacecraft. This method enables sub-meter pixel scales with a smaller, lighter imaging system. For more information on super resolution imaging, see Appendix D.3.

Another combined instrument that was the result of this study, NGSWIS/Mars-FIRE Imager, is included to characterize 6 km × 6 km targets of interest in the infrared spectrum. The instrument incorporates a MRO/HiRISE-based 50-cm telescope with SWIR and TIR spectrometers. The SWIR spectrometer is a 0.5-5 μm Dyson spectrometer that uses a 1280 × 480-pixel mercury cadmium telluride (MCT) Teledyne CHROMA detector, based on the M^3 design. The TIR spectrometer is a 6–25 μm grating spectrometer based on PREFIRE's design and uses a 128 × 64-pixel microbolometer array detector. These two measurements have similar telescope requirements (diffraction, signal-to-noise), making the combination into a single payload possible. One solution is to use an all-reflective telecentric beam splitter, sending half of the collected light to the Dyson spectrometer and half to the microbolometer array. The SWIR spectrometer operates as a push-broom spectrometer during dayside operations, while the TIR operates at both during the day as well as spot-checking at night. Because NGSWIS and Mars-FIRE are in development, instrument analogs HiRIS and PREFIRE were used in the Team X study (Table 3-2, column 5). For more information, see Appendix D.1.

In the primary mission, the RaSo/Polar-SAR collects data during night-side operations, while the remaining instruments operate during the day. This concept of operations (Section 3.3) was developed to handle the large amounts of data that will be generated from the proposed payload (total mission data volume > 300 Tb at 280 average Gb per day over two Mars years), while still meeting the science needs.

As part of the Team X exercise, a second Ice-Focused option that included only three of these six instruments was explored. In this Ice-Focused mission, only RaSo/Polar-SAR and the two Mid-S-Cam instruments are included. In this descoped mission, RaSo/Polar-SAR and Mid-S-Cam can operate simultaneously on the day side.

The full payload meets MORIE's measurement requirements (Section 1.7), with projected mass and powers shown in Table 3-4. Thirty percent contingency is used on all payloads per JPL best practices, with the exception of MARCI and Mid-S-CAM. Due to the heritage design of these imagers, a lower contingency of 15% was deemed appropriate. Contingency on data rate was not applied individually by instrument; instead, the contingency was built into the concept of operations (Section 3.3), with significant margin.

Table 3-4. Payload mass and power.

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
RaSo/Polar-SAR (using prior JPL radar study information)	109.2	30	141.96	110 (peak)	30	184.5 (peak)
Mid-S-Cam Context Imager (using CTX as analogue)	3.37	15	3.8755	5.8	15	6.67
MAVRIC (using MARCI as analogue)	1	15	1.15	4.6	15	5.29
C-IMG (using HiRISE Lite as analogue)	19	30	24.7	30	30	39
NGSWIS/Mars-FIRE (using HiRIS/PREFIRE as analogues)	45.7	30	59.41	8	30	10.4
Total Payload Mass (Full Mission concept)	**163.3**		**211.2**			
Total Payload Mass (Ice-Focused Mission concept)	**115.9**		**149.8**			

The SAR will provide the first-ever radar imaging from Mars orbit while the sounder will deliver an order of magnitude improvement in sub-surface vertical resolution. The spectral and spatial resolution for MORIE's optical instruments offer improved capabilities over previous instrumentation.

3.2 Flight System

The MORIE flight system is a SEP-powered spacecraft bus with a design life of 70 months. The ΔV budget of 8000 m/s is sufficient for cruise, spiraling into orbit, station keeping, and two planes changes of 3 degrees each. (Table 3-5, and Appendix C).

Table 3-5. Flight system element characteristics.

Flight System Element Parameters (as appropriate)	MORIE Full Mission	MORIE Ice-focused
	Value/Summary, Units	Value/Summary, Units
General		
Design Life, months	70	70
Structure		
Structures material (aluminum, exotic, composite, etc.)	Aluminum	Aluminum
Number of articulated structures	4	3
Number of deployed structures	4	4
Aeroshell diameter, m	n/a	n/a
Thermal Control		
Type of thermal control used	Passive	Passive
Propulsion		
Estimated delta-V budget, m/s	8000	8000
Propulsion type(s) and associated propellant(s)/oxidizer(s)	Solar Electric Propulsion, Xenon Propellant	Solar Electric Propulsion, Xenon Propellant
Number of thrusters and tanks	4 thrusters; 3 tanks	4 thrusters; 3 tanks
Specific impulse (Isp) of each propulsion mode, seconds	1700	1700
Attitude Control		
Control method (3-axis, spinner, grav-gradient, etc.).	3-axis	3-axis
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Star tracker augmented by IMU	Star tracker augmented by IMU
Attitude control capability, degrees	0.1	0.1
Attitude knowledge limit, degrees	0.1	0.1
Agility requirements (maneuvers, scanning, etc.)	Orbit plane change by 3° halfway into mission, spacecraft; 30° pitch maneuver when using PolarSAR	Orbit plane change by 3°
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	Each solar array has a 2-axis gimbal; Telecom HGA 2-axis gimbal; SWIR/TIR 1-axis gimbal	Each solar array has a 2-axis gimbal; Telecom HGA 2-axis gimbal
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	Reaction Torque: 0.1–0.2 N-m; Momentum storage: 100 N-m-s;	Reaction Torque: 0.1–0.2 N-m; Momentum storage: 100 N-m-s;
Command & Data Handling		
Flight Element housekeeping data rate, kbps	400	100
Data storage capacity, Mbits	1024000	1024000
Power		
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	Flexible, deployed, and articulated	Flexible, deployed, and articulated
Array size, meters x meters	2.83 m radius per panel; 2 panels per s/c	2.71 m radius per panel; 2 panels per s/c
Solar cell type (Si, GaAs, Multi-junction GaAs, concentrators)	Multi-junction GaAs	Multi-junction GaAs
Expected power generation at Beginning of Life (BOL) and End of Life (EOL), watts	(BOL) 13321; (EOL) 11488	(BOL) 12147; (EOL) 10476
On-orbit average power consumption, watts	1016	1016
Battery type (NiCd, NiH, Li-ion)	Li-ion	Li-ion
Battery storage capacity, amp-hours	272	272

Two architecture options where studied. The full mission carried a 6 m deployable synthetic aperture radar antenna with radar sounding functionality, a dual channel short-wave and thermal imaging spectrometer with a 50 cm on a single-axis gimbal (Figure 3-3), a 25 cm body fixed near field imager, a wide field imager, and dual context cameras. The Ice-Focused concept had several instrument de-scopes but the overall flight system characteristics for (thermal, propulsion, ACS, CD&H, and energy storage remained unchanged between both architectures (Table 3-6).

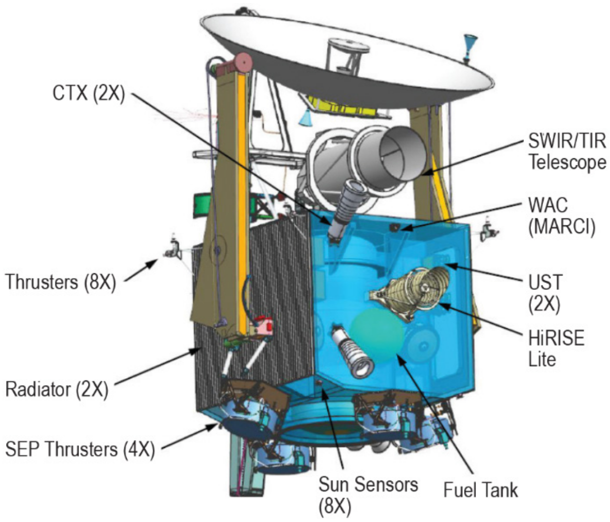


Figure 3-3. MORIE full mission stowed configuration.

The solar arrays on the full mission produced 13,321 watts of peak power at beginning of life; while the Ice-Focused concept generated 12,147 watts of peak power due to the reduction in payload.

The technical challenges of this spacecraft was the accommodation and simultaneous operation of the instrument payloads on the full mission. The large 6 m mesh antenna is on the port side of the spacecraft and must maintain an unobstructed from the other instrument.

The SAR has two modes SAR and sounding, during SAR mode the instrument must point cross track 30 degrees by rolling the spacecraft. The SAR instrument only runs at night while all the other instruments are not recording data. The 3 meter high-gain antenna is an analogue to the high-gain antenna (HGA) on MRO and is attached to a boom and on a two-axis gimbal mechanism to allow for data downlinking during science mission operations. Each option has two 5.5 m diameter solar array wings (Figure 3-4) deployed from the up and down track faces of the spacecraft and each wing is individually articulated on two-axis gimbals.

Table 3-6. MORIE flight system Full Mission element mass and power.

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Structures & Mechanisms	429.9	30%	558.9	n/a	n/a	n/a
Thermal Control	49.1	30%	63.8	175	30%	227
Propulsion (Dry Mass)	214.3	11%	237.4	7385	30%	9600
Attitude Control	69.6	10%	76.6	92	30%	120
Command & Data Handling	26.1	18%	30.9	47	30%	61
Telecomm-unications	59.8	16%	69.2	318	30%	414
Power	186.9	28%	238.3	104	30%	135
Total Flight Element Dry Bus Mass	1035.7	23%	1274.9			

To ensure clear fields of view the spacecraft has four articulated structures and four deployed structures. The four deployed structures include: the two solar arrays; the telecom antenna, and the SAR antenna. All of the imaging instruments were accommodated on the nadir deck of the spacecraft with the exception of the NGSWIS/MarsFIRE telescope on the body mounted on starboard side of the spacecraft with the entry pupil facing nadir. NGSWIS/MarsFIRE instrument requires pitching the instrument 5 to 20 degrees from the starboard face of the spacecraft. This was accomplished with a single-axis gimbal mechanism.

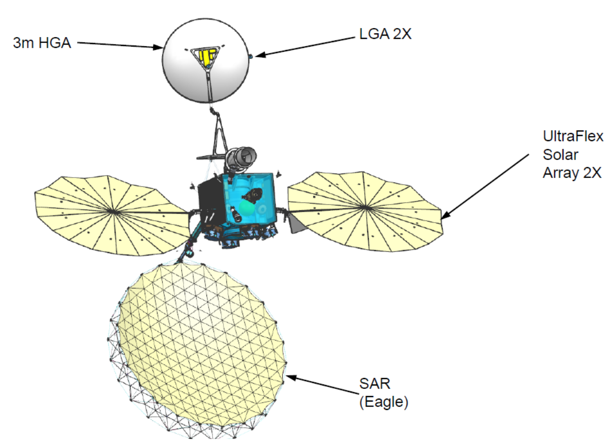


Figure 3-4. MORIE full mission deployed configuration.

The SEP system requires a 13.3 kW solar array at beginning of life (BOL). The solar array and battery system design assumed a maximum eclipse duration of 40 minutes per orbit (See appendix C for eclipse durations). The solar array area is 47.2 m^2 and can produce up to 11.5 kW. The spacecraft has 10 modes with the driving case occurring during Thrusting-Earth mode when the thrusters are at maximum power. Most of the power electronics design has heritage or could be built-to-print with the exception of the solar array which would be novel for a Mars orbiter which could present a potential cost upper to the design. For more technical details on the power subsystem see Appendix B.

Command and data handing (C&DH) design requirements are driven by the seven high-data throughput science instruments, the telecommunication subsystem, the solar electric propulsion system, and the attitude control system (ACS). The science instruments generate a maximum of 440 Gb of data per sol and are the driver for the subsystem. The C&DH is sized for 100% data margin and a data storage capacity of 1024 Tb. The spacecraft computer hardware is a dual-string design and is radiation tolerant up to 20 krad of radiation total dose.

The MORIE spacecraft is a rectangular bus (see Figure 3-5) designed to be launched on a Falcon 9 with three axis stabilization. During daytime operations six instruments operate facing nadir and limb while simultaneously capturing solar energy and downlinking data at times. The spacecraft has four deployed structures and four freely articulable structures to support clear fields of view for each of the instruments and the supporting flight subsystems requires during science operations. The four articulated structures are: the solar arrays have their own 2-axis gimbal to allow the arrays to freely articulate while the spacecraft is thrusting or gathering science; the 3 meter HGA is articulated with a 2 degree of freedom gimbal; and the NGSWIS/Mars-FIRE optical telescope scan platform articulates using a single-axis gimbal.

The Full Mission telecommunications subsystem design requires high data through-put with flexibility to downlink during science operations. For both options the telecom system is fully redundant X/Ka-band frequency system. They include hardware is a single three meter high

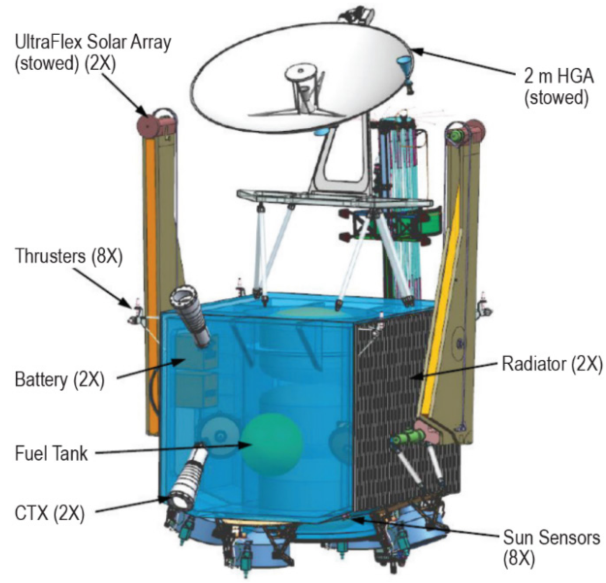


Figure 3-5. MORIE Ice-Focused stowed configuration.

gain antenna, two (2) X-band low gain antenna installed on the HGA gimbal, two (2) Universal Space Transponder (UST), two (2) 25 watt X-band traveling-wave-tube amplifiers (TWTA), two (2) 200 watt Ka-band TWTAs, and additional telecom hardware. The UST transponder allows for X/Ka-band downlink, X-band for safe mode and housekeeping downlink, Ka-band for high-rate science downlink, and X-Band for uplink. The only changes to the Ice-Focused telecommunications systems is a smaller two meter high-gain antenna and two (2) 100 watt Ka-band TWTAs, see Figure 3-6 and Figure 3-7.

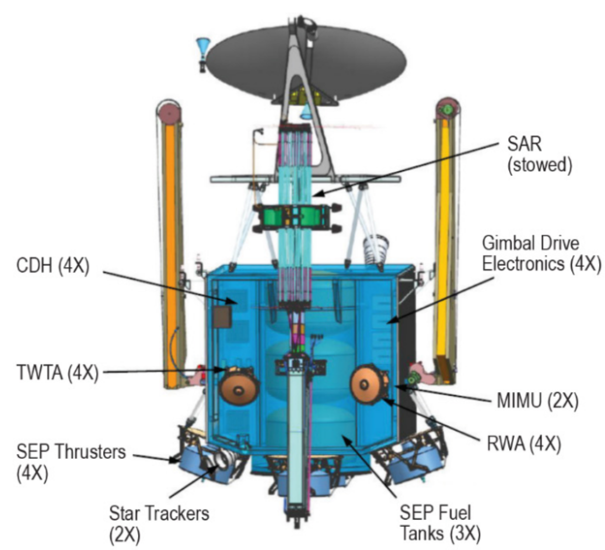


Figure 3-6. MORIE Ice-Focused stowed configuration.

The thermal design is a high flight heritage, passive design sized for an allowable temperate range of −20° C to +50° C. The system is cold biased with radiators sized for the worst case hot condition (SEP thrusting at 1 AU). Make up heater power is then used to maintain minimum allowable temperatures during cold scenarios. Propellant tanks and lines are covered with multilayer insulation (MLI). Payloads carry their own thermal control, but radiator sizing guidelines were provided by JPL design team thermal chair. The SEP power processing unit (PPU) is 85% efficient and drives the thermal system design.

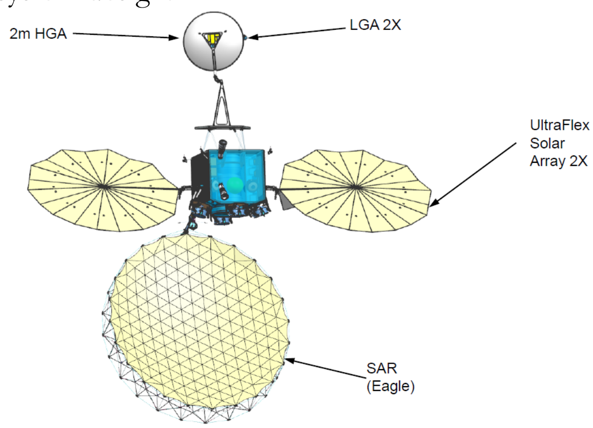


Figure 3-7. MORIE Ice-Focused deployed configuration.

The ground system design is based on a mission specific implementation of the standard JPL mission operations and ground data systems. The telecommunications link design enables data rates, see Table 3-7, to a 34 meter Deep Space Network (DSN) beam wave guide (BWG) antenna.

Nominal data volumes of 280 Gbit/day were assumed at a mid-range Mars to Earth distance of 1.5 AU. Total data volume for the entire four year mission is estimated to be 300 terabits.

The ACS subsystem requirements are driven by the C-IMG high resolution imager which will require 0.5 degree of pointing control and knowledge. The ACS hardware suite consists of eight sun sensors two star trackers, a two MIMUs, four 100 N-m-s reaction wheels, and hydrazine reaction control system (RCS) thrusters for momentum unloading, see Figure 3-8. The solar panels and HGA are on 2-axis gimbals.

The MORIE software mission level requirements are to map and quantify shallow ground ice deposits across Mars from a low Mars orbiter using SEP, support 400 Gb of maximum data generated per sol, have the file system management on flash memory, and manage uncompressed and compressed data. The MarsFire, C-IMG, PolarSAR, and RaSo data is assumed to be compressed. Core flight software (FSW) was used as an analogue for the baseline FSW architecture. The cost drivers the the software is the large data volumes generated by the full mission.

Table 3-7. MORIE flight system Ice-Focused element mass and power.

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Structures & Mechanisms	386.8	30%	502.8	n/a	n/a	n/a
Thermal Control	48.5	30%	63.1	385	30%	500.5
Propulsion (Dry Mass)	214.3	11%	237.4	4352	30%	5657.6
Attitude Control	69.6	10%	76.6	109	30%	141.7
Command & Data Handling	26.1	18%	30.9	55	30%	71.5
Telecomm-unications	52.6	16%	60.9	237	30%	308.1
Power	180	27%	229.4	122	30%	158.6
Total Flight Element Dry Bus Mass	977.9	23%	1200.9			

3.3 Concept of Operations and Mission Design

For power sizing purposes, the Concept of Operations is modeled using the power modes shown in Figure 3-8. The science orbit worst-case eclipse duration is 42 minutes. The solar array sizing was driven by the SEP-Thrusting mode. The large solar-array are driven by the SEP-Thrusting Mode shown in Figure 3-8. After thrusting to Mars the excess of power capacity can be shifted from the propulsion and allocated to high power-demand instruments and the large telecommunications system. The battery capacity was sized by the launch case.

Table 3-8. MORIE flight system telecom link rate.

Earth to Mars Range	Full Mission Data Rate	Ice-Focused Data Rate
Maximum Range (2.5AU)	3 Mbps	0.75 Mbps
Mid-Range (1.5AU)	8 Mbps	2 Mbps
Minimum Range (0.5 AU)	75 Mps	18 Mbps

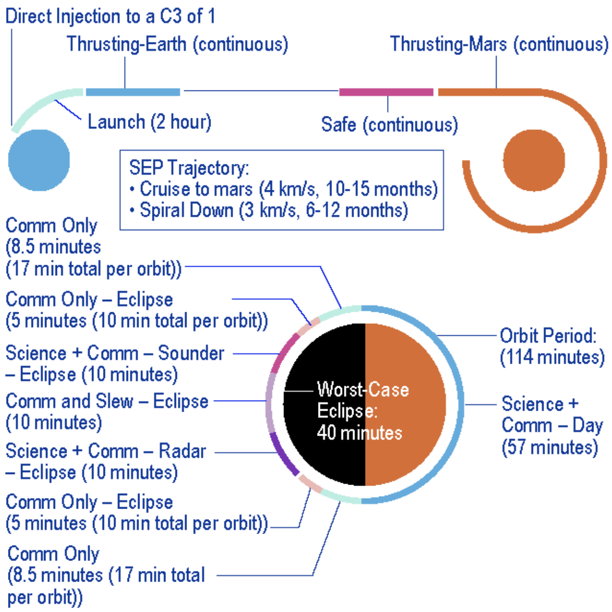


Figure 3-8. Concept of operations and modes.

The total mission duration is 70 months with the first launch opportunity occurring in late 2026. The cruise from Earth to Mars is expected to take 13 months delivering the spacecraft to the spiral-down phase. The spiral-down duration is 10 months until the spacecraft reaches its primary MRO-like orbit. The primary science orbit is sun-synchronous at 3 PM local standard time. The apoapsis and periapsis is 300 km with an inclination of 92.7°. The primary mission is expected to last 1 Mars year. After the primary mission is complete a plane change maneuver occurs to move the spacecraft 3 degrees into a 90° polar orbit.

This secondary orbit, Figure 3-9, has a drifting local standard time that shifts backward at one hour per month. The duration of the secondary orbit duration is 22 months. The propulsion system was sized for one additional 3° plane change back to 92.7° for an extended mission if desired.

The instrument payload for MORIE is very data intensive. The expected science data requires the capability to downlink 280 Gb of daily data volume. MORIE has the capability to downlink up to 460 Gb of data per day assuming 16 hours of daily downlink time at 1.5 astronomical unit Mars-Earth range (AU) providing 85% margin. The average cadence for downlinking on both options is 14 contacts per week, see Tables 3-9 and 3-10 for additional ground system details.

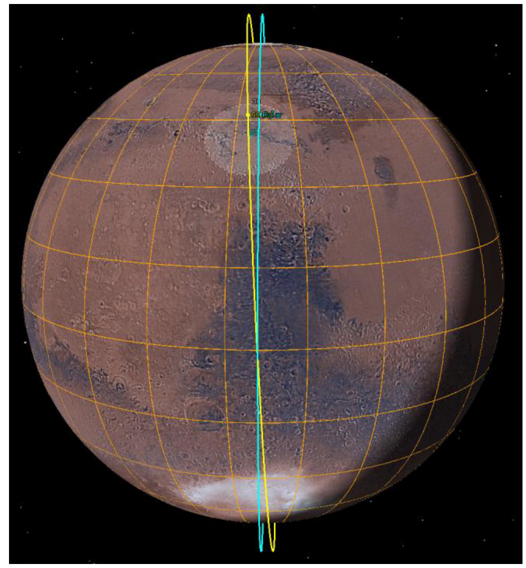


Figure 3-9. Primary (yellow) and Secondary (teal) science orbits

Assuming the mid-range data downlink capability Table 3-11 shows the notional daily measurement scenario for each instrument.

The Mid-S-Cam, NGSWIS, MarsFIRE, C-IMG, and MAVRIC, operate when the spacecraft orbits the illuminated or "day-side" of Mars, see Table 3-11.

The NGSWIS/MarsFIRE share a single optical telescope located on a deployed 0.5 meter boom. During NGSWIS measurements the optics can articulate to scan or "nod" 15 degrees in the direction of motion using a single axis scan platform. The two Mid-S-Cam imagers point fore and aft and are positioned for real time stereo taking 24 images per Sol. Both the MAVRIC and C-IMG imagers point nadir, see Figure 3-10. MAVRIC operates continuously, C-IMG is limited to 10 images per Sol.

During night side passes of each orbit, see Figure 3-11, the PolarSAR, RaSo, and MarsFIRE operate in an ad-hoc fashion. RaSo takes measurements by pointing the 6 meter mesh antenna nadir and taking 10 minute measurements. The MarsFIRE thermal spectrometer also points nadir when taking measurements. In order to take PolarSAR measurements and to avoid obstructing the antenna the spacecraft must perform two maneuvers the first is to rotate the spacecraft 90 degrees along the z-axis then roll the spacecraft 30 degrees along its axis of motion to point the mesh antenna 30-degrees off track, see Figure 3-11.

Table 3-9. Full mission operations and ground systems.

Downlink Information	Launch and Early Ops	Check out and first maneuver	SEP Cruise	Spiral Down	Science Orbit 1	Inclination Transfer 1	Science Orbit 2	Inclination Transfer 2
Number of Contacts per Week	14	14	2	4	14	4	14	4
Number of Weeks for Mission Phase, weeks	2	2	54	41	101	6	96	6
Downlink Frequency Band, GHz	32 (Ka-band); 8.4 (X-Band)							
Telemetry Data Rate(s), kbps	0.5 AU 76000 kbps; 1.5 AU 8300 kbps; 2.5 AU 3000kbps							
Transmitting Antenna Type(s) and Gain(s), dBi	(1) 3 m X/Ka-band HGA; 57 dBi gain @ K-Band; (2) X-band LGA; 8 dBi gain							
Transmitter peak power, Watts	200 W Ka-band; 25 W X-band							
Downlink Receiving Antenna Gain, dBi	79.37 in X/Ka Mode							
Transmitting Power Amplifier Output, Watts	18200							
Total Daily Data Volume, (Mb/day)	0.5 AU 2590000 Mb ; 1.5 AU 280000 Mb; 2.5 AU 100000 Mb							
Uplink Information	**Launch and Early Ops**	**Check out and first maneuver**	**SEP Cruise**	**Spiral Down**	**Science Orbit 1**	**Inclination Transfer 1**	**Science Orbit 2**	**Inclination Transfer 2**
Number of Uplinks per Day	14	14	2	4	14	4	14	4
Uplink Frequency Band, GHz	7.2							
Telecommand Data Rate, kbps	2							
Receiving Antenna Type(s) and Gain(s), dBi	34 m BWG							

Table 3-10. Ice Focused mission operations and ground systems.

Downlink Information	Launch and Early Ops	Check out and first maneuver	SEP Cruise	Spiral Down	Science Orbit 1	Inclination Transfer 1	Science Orbit 2	Inclination Tranfer 2
Number of Contacts per Week	14	14	2	4	14	4	14	4
Number of Weeks for Mission Phase, weeks	2	2	54	41	101	6	96	6
Downlink Frequency Band, GHz	32 (Ka-band); 8.4 (X-Band)							
Telemetry Data Rate(s), kbps	0.5 AU 19000 kbps; 1.5 AU 2000 kbps; 2.5 AU 750kbps							
Transmitting Antenna Type(s) and Gain(s), DBi	(1) 2 m X/Ka-band HGA; 54 dBi gain @ K-Band; (2) X-band LGA; 8 dBi gain							
Transmitter peak power, Watts	100 W Ka-band; 25 W X-band							
Downlink Receiving Antenna Gain, DBi	79.37 in X/Ka Mode							
Transmitting Power Amplifier Output, Watts	18200							
Total Daily Data Volume, (Mb/day)	0.5 AU 650000 ; 1.5 AU 70000 Mb; 2.5 AU 30000 Mb							
Uplink Information	**Launch and Early Ops**	**Check out and first maneuver**	**SEP Cruise**	**Spiral Down**	**Science Orbit 1**	**Inclination Transfer 1**	**Science Orbit 2**	**Inclination Tranfer 2**
Number of Uplinks per Day	14	14	2	4	14	4	14	4
Uplink Frequency Band, GHz	7.2							
Telecommand Data Rate, kbps	2							
Receiving Antenna Type(s) and Gain(s), DBi	34 m BWG							

Table 3-11. Full-Mission science instrument concept of operation at 1.5 AU Mars-Earth range.

Instrument	Observation Period	No. of Measurements Per Sol	Daily Data Volume (Gb)
Mid-S-Cam	Day	24	48.0
NGSWIS	Day	4	44.0
MarsFIRE	Day/Night	80	6.0
C-IMG	Day	10	110.0
MAVRIC	Day	Continuous	21.1
PolarSAR	Night	13	2.0
RaSo	Night	10	49.8
Spacecraft Total			**280.8**

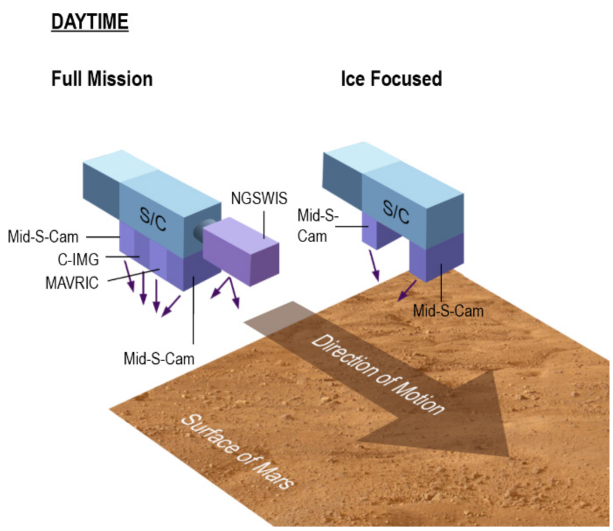


Figure 3-10. Full Mission and Ice-Focused Daytime Science Instrument Concept of Operations.

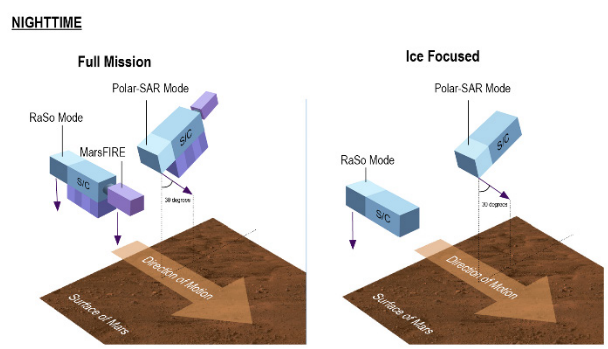


Figure 3-11. Full Mission and Ice-Focused Nighttime Science Instrument Concept of Operations.

The average cadence for downlinking on both options is 14 contacts per week, see Tables 3-9 and 3-10 for additional ground system details.

The mission design assumes a Falcon 9 launch from Cape Canaveral, Florida. The total dry-mass of the spacecraft including contingency is 1715 kg. The Xenon propellant mass is 1261 kg for a total wet mass of 3035 kg. The launch vehicle has a capability of 3195 kg, see Table-3-12. Further detailed mission design analysis can be found in Appendix D.

Table 3-12 Mission Design.

Parameter	Value	Units
Orbit Parameters	Primary Orbit: Apoapsis: 300 km Periapsis: 300 km Inclination: 92.6° Polar Orbit: Apoapsis: 300 km Periapsis: 300 km Inclination: 90°	
Mission Lifetime	70	mos
Maximum Eclipse Period	40	min
Launch Site	Cape Canaveral, Florida	
Total Flight Element Mass **with** contingency (includes instruments)	1715	kg
Propellant Mass **without** contingency	1146	kg
Propellant contingency	10	%
Propellant Mass **with** contingency	1261	kg
Launch Adapter Mass **with** contingency	59	kg
Total Launch Mass	3035	kg
Launch Vehicle	Falcon 9 Block 2	Type
Launch Vehicle Lift Capability	3195	kg
Launch Vehicle Mass Margin	160	kg
NASA Mass Margin (%)*	25	%

**Mass Margins were computed using both JPL and NASA standards*
Dry MPV (Max Possible Value) = Wet Allocation–Propellant & Pressurant.
Dry MEV (Maximum Expected Value) = Sum of spacecraft dry MEV values (CBE + contingency), including LV-side adapter MEV.
NASA Margin = (Dry MPV –Dry MEV)/(Dry MEV).

3.4 MORIE Concept Risk List

Overall, the MORIE concept has no risks of high likelihood and consequence and few risks of moderate likelihood and consequence. MORIE risks bin in two categories: development risk prior to launch, and mission risk post-launch. Risks are discussed and categorized here that a future project would have control over and that would impact science return or cost. Not included are risks that typical NASA projects mitigate such as instrument delivery schedule risks (mitigated by funded schedule margin, for example). Environmental or other risks that a project would not have control over are not listed. The top risks are included in Table 3-13.

Table 3-13. Risk category and mitigation.

#	Risk	Category Impl/Msn	L × C*	Mitigation	Residual L × C*
1	RaSo and Polar-SAR 6 meter mesh antenna development more difficult than planned	Imp	2 × 2	Early development of a high fidelity model including thermal, vibration, and vacuum deploy testing	1 × 2
2	NGSWIS/ Mars-FIRE combined instrument development more difficult than anticipated	Imp	2 x 2	Early design and EM test, if needed can split into two instruments early in development	1 × 2
3	Data return reduced in Mars orbit due to operational constraints (slewing, reaction wheel momentum dump, for example)	Imp	2 × 3	Telecom subsystem redundancy, operational backup plan for resiliency, over design system	2 × 1
4	Four deployments of large structures required before science data return	Imp	2 × 4	Early dynamic modeling of deployment, early EM testing	1 × 2
5	Mars orbit spacecraft safe mode causes loss of up to a week of science data	Msn	3 × 2	Design in capability to revisit data in missed swaths	3 × 1

Table 3-14 shows the definitions of likelihood of Occurrence (L) and the Consequence (C) for Table 3-13 Risk List. Table 3-15 shows the standard definitions of the Mission Risk Consequence of Occurrence used in Table 3-13.

Table 3-14. MORIE Concept Risk Likelihood of Occurrence.

Level	Description	Level Definition	Percentage
5	Very High	Almost certain	70% < × ≤ 100%
4	High	More likely than not	50% < × ≤ 70%
3	Moderate	Significant likelihood	10% < × ≤ 50%
2	Low	Unlikely	1% < × ≤ 10%
1	Very Low	Very unlikely	X ≤ 1%

Table-3-15. MORIE Concept Mission Risk Consequence of Occurrence.

Level	Description	JPL Mission Risk Definitions	Project Specific Clarification Related to Level-1 Requirement
5	Very High	Mission Failure	Does no acquire significant mission science (or meet other objectives).
4	High	Significant reduction in mission return	Acquires significant science (or meets other objectives) but does not meet Threshold Level-1 requirements.
3	Moderate	Moderate reduction in mission return	Meets Threshold Level-1 Requirements but does not meet Baseline Level-1 requirements.
2	Low	Small reduction in mission return	Meets Baseline Level-1 requirements.
1	Very Low	Minimal reduction in mission return	Only minor loss of mission science (or objectives).

4 Development Schedule and Schedule Constraints

MORIE uses a typical New Frontiers mission development schedule that might shorten due to previous Mars mission experience. Launch is in any year due to SEP.

4.1 High-Level Mission Schedule

MORIE follows a usual New Frontiers class development cycle spanning roughly five years. Phases A and B last one year, while Phase C and D run 22 months and 18 months, respectively (Table 4-1). Due to the nature of low-thrust Earth-Mars transfers, launch dates are not rigidly confined to the standard 26-month ballistic transfer cycle. Launches may occur almost any time, but the optimal arrival time follows a roughly 2-year cycle (Woolley et al. 2019). This means that a launch slip of one year likely means that the arrival at the science orbit is delayed by two years.

Table 4-1. MORIE Development timeline.

Phase	Duration (months)	Launch Relative Start Date
Phase A	12	L – 5.3 years
Phase B	12	L- 4.3 years
Phase C	22	L – 3.3 years
Phase D	18	L- 1.5 years
Phase E	70	L – 0 -6 years

Figure 4-1 shows the dates and durations associated with a reference trajectory to Mars. After launch, the spacecraft observes a checkout and calibration period, followed by a cruise of 13 months to the Martian sphere-of-influence. Once MORIE is loosely captured by the gravity of Mars, continual thrusts (with the exception of brief eclipses) cause spiral down for 10 months to the primary science orbit, arriving two years after launch. After one Mars year in sun-synchronous orbit, the SEP thrusters then fire to change the inclination by ~ 3° over the period of 1-2 months, to a 90° polar orbit. A second science phase ensues for another Mars year. At this point the LST of the orbit has drifted through one full 24-hour cycle, returning to the initial 3 PM node. ΔV is budgeted to halt precession to the original sun-synchronous orbit for extended mission.

4.2 Technology Development Plan

The TRL 5 payload technologies are listed in Table 4-2 (Section 2.3 has full list of technologies). Note that the SWIR/TIR (NGSWIS/Mars-FIRE) combined instrument sharing telescope and some optics, and the future possibility of a SWIR/TIR/Imaging combined instrument sharing telescope and some optics are not listed here since those are engineering developments.

Table 4-2. MORIE TRL 5 Payload Technologies.

Payload Element	Technology	Plan (Time, $ to TRL 6)
SAR and sounder	Large dual-use mesh antenna for RaSo/Polar-SAR	Adapt 6m diameter mesh antenna from Earth orbit for first time use at Mars for SAR and sounding. Analysis, modeling, thermal vacuum, and vibe test of engineering model. 1 yr, $1M
Thermal infrared	Thermal infrared detector array size increase for Mars-FIRE	See Appendix D, Table D-4. 2 yr, $2M
Wide angle imager	Increased number of wavelength bands for MAVRIC	SWIR focal plane array, 1 yr, $1M
Visible imaging	C-IMG Focal Plane Array (FPA)	FPA development, 1 yr, $1M

4.3 Development Schedule and Constraints

For the representative launch date of November 2026 the Team X point designs assumed the typical New Frontiers class development schedule of Table 4-1 starting in October 2020. Note that some past Mars orbiter mission development schedules are shorter than the representative schedule. MORIE can launch in any year due to the flexibility provided by SEP.

Phase	Duration [m]
Heliocentric	13.2
Spiral Down	9.7
3PM SS	23.0
Inc. Transfer	1.4
90 deg	21.5
Inc. Transfer	1.4
3PM SS	

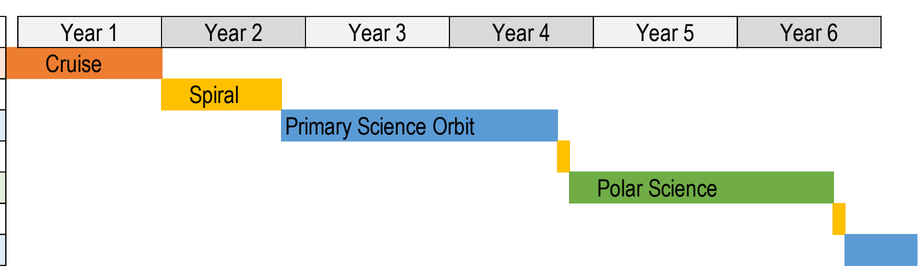


Figure 4-1. MORIE mission phases account for activities with margin.

5 Mission Life-Cycle Cost

The study team aimed to develop one or more concepts that fits within the cost of a New Frontiers mission, as well as one or more that are modestly higher in cost. This, combined with the CML 3 trade space exploration, allowed informed selections of the two CML 4 point designs investigated with Team X.

MORIE leverages currently flying mission actual cost estimates, combined with numerous previous Mars Program study cost estimates. This large set of cost data allows regression analysis and other cost models to be run and applied. The result is a conservative estimate with uncertainty that allows absolute and relative costs to be compared with New Frontiers (Table 5-1). The full mission option (known as Option 1) has a spacecraft bus plus seven instrument types and a full lifecycle Phase A–F cost with reserves (A–D at 50%, E/F at 25%) of $1,892.9M (FY25). A second, ice-focused option (known as Option 2) has a spacecraft bus plus three instrument types and a full lifecycle Phase A–F cost with reserves (A-D at 50%, E/F at 25%) of $1,511.9M (FY25).

5.1 Costing Methodology and Basis of Estimate

MORIE selected two options for further study from Team X architecture trades based upon different combination of instrument types that are driven by science objectives (see details in Appendix B Table B-5). Each CML 4 point design utilizes two or more independent cost methods to ensure a robust cost range. The desire to achieve one or more concepts that fits in the New Frontiers cost bin, as well as one or more concepts that are modestly more costly than New Frontiers, combined with the CML 3 trade space exploration, allowed informed selections of the two CML 4 point designs investigated with Team X (Figure 5-1).

JPL's Team X estimates have detail to level 3 across the Work Breakdown Structure (WBS), and level 4 for spacecraft and payload, with a described MEL (Master Equipment List), cost risk identified at subsystem level, and are based on various cost estimating techniques. Estimates used multiple methods and databases relating to past space systems so that no one model or database biases the results. Team X uses both system-level estimates as well as build-up-to-system-level estimates by appropriately summing subsystem data so as not to underestimate system cost and complexity; and use cross-checking tools to cross-check cost and schedule estimates for internal consistency and risk assessment.

In summary, an analogy-based methodology ties the estimated costs of future systems to the known cost of systems that have been built. The methodology, proven over more than 2,500 studies spanning 25 years, provides an independent estimate of the cost and complexity of new concepts anchored with respect to previously built hardware. The use of multiple methods such as analogies and standard cost models ensures that no one model or database biases the estimate. The use of system-level estimates and arriving at total estimated costs by statistically summing the costs of all individual WBS elements ensures that elements are not omitted and that the system-level complexity is properly represented in the cost estimate.

Team X final study reports (see Appendix B), include full details for costing assumptions and basis of estimate. The costs represented in this report are Rough Order of Magnitude (ROM) estimates and do not constitute an implementation or cost commitment.

Table 5-1. Shows both full mission and ice-focused life-cycle cost summaries including required cost reserves (FY25).

	Full Mission (FY25$M)							Ice-Focused (FY25$M)						
	Estimate	Reserves		Total	Reserves		Total	Estimate	Reserves		Total	Reserves		Total
Development (A-D)*	929.4	30%	278.8	1,208.2	50%	464.7	1,394.1	730.5	30%	219.1	949.6	50%	365.2	1,095.7
Launch Vehicle	228.8	-	-	228.8	-	-	228.8	228.8	-	-	228.8	-	-	228.8
Operations (E/F)	216.0	15%	32.4	248.4	25%	54.0	270.0	149.9	15%	22.5	172.4	25%	37.5	187.4
Full Lifecycle Cost	1,374.2	27%	311.2	1,685.4	45%	518.7	1,892.9	1,109.2	27%	241.6	1,350.8	46%	402.7	1,511.9

**New Frontiers comparable cost cap of $1,100M.*

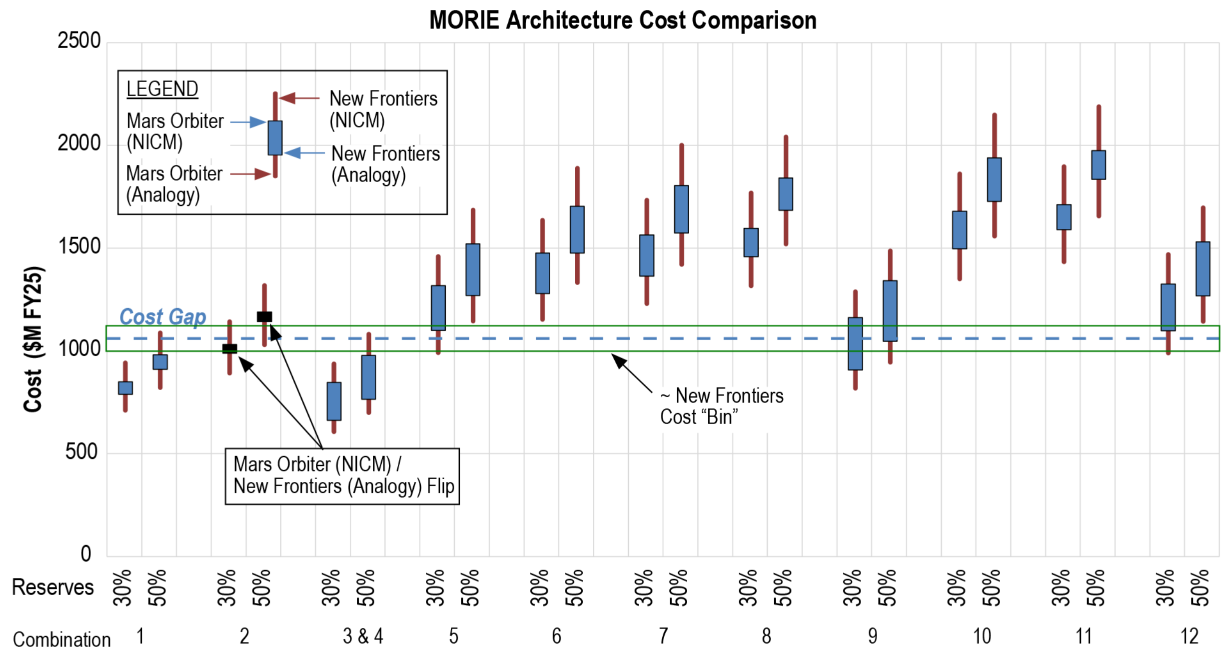


Figure 5-1. Trade space exploration for various payload combinations that helped select the full mission (Combination 7) and ice-focused (Combination 4 plus Mid-S-Cam) designs to study in Team X. See Appendix B Table B-5 for description of the payload instruments in these trade space options.

To validate these costs, JPL's business organization evaluated MORIE with parametric models supplemented with analogies and wrap factors based on historical data. The cost models used include SEER, TruePlanning, and Project Cost Estimating Capability (PCEC) for Phase A-D, and Space Operations Cost Model (SOCM) for Phase E.

5.2 Cost Estimates

Costs were estimated using the standard NASA WBS. Table 5-2 and Table 5-3 shows the total JPL Team X cost estimate, as well as the cost model estimates in FY25 dollars for full mission and ice-focused, including Development (Phases A–D) and Operations (Phases E–F). The instruments were estimated using the NASA Instrument Cost Model (NICM) System Tool which primarily relies on mass and power. Cost estimates do include Launch Vehicle Services, except for where comparisons are made to New Frontiers. Reserves were applied at 50% for Phases A–D and 25% for Phases E–F, as required by NASA Ground Rules for Mission Concept Studies. To complete the estimates the costs are also shown with more standard 30% for Phases A–D, and 15% for Phases E–F.

The primary objective of comparing Team X estimates with a set of parametric models are to assess the overall completeness and adequacy of the concept's Phase A–F cost and schedule, and evaluate potential cost and schedule risk through model benchmarking and historical analogies.

The parametric cost models provide Development and Operation cost estimates, and for comparison to Team X, Phase A costs were assumed to be $5M based on an escalated value of the Phase A cost from the New Frontier 4 Announcement of Opportunity (AO). (Model details in Appendix D.)

Based on these three model approaches (Methods 1 to 3), the validation ranges for full mission and ice-focused options are in the order of 4% and 7% respectively, which provides confidence that the estimated study costs are reasonable and realistic.

The MORIE study team uses the Team X cost estimate, and to create a mission cost funding profile, historical missions were analyzed to define representative profiles by phases. The analogous mission set includes the Mars Exploration Rover (MER) and MSL rovers, and a selection of competed Discover and New Frontiers missions.

The normalized percentage spreads were then used to phase the Team X estimate over the duration of 60 months for Phase B–D development and similarly for the four to five year duration for Phase E. The base year profile was then escalated to real year dollars using the JPL Composite Inflation Index. Table 5-4 and Table 5-5 shows the total mission cost funding profile for the MORIE options.

Table 5-2. Model Cost Assessment for MORIE Full Mission (FY25 $M).

WBS Element (Bus+7 Instruments)	Team X	Method 1 (SEER-H)	Method 2 (True-Planning)	Method 3 (PCEC)	Deltas Team X vs. Method 1 (%)	Deltas Team X vs Method 2 (%)	Deltas Team X vs Method 3 (%)	Models Average ($)	Deltas Team X vs. Models Avg. (%)
Phase A	Incl. in B–D	5.0	5.0	5.0					
Phase B–D Development	1158.2	1124.9	1153.4	1325.4	228.8	229.5	228.0	1201.3	−4%
WBS 01-03 PM/PSE/SMA/M&SD	112.8	133.6	61.9	177.5	−16%	82%	−36%	124.3	−9%
WBS 04,07/09 Science/MOS/GDS	80.0	76.3	78.7	102.0	5%	2%	−22%	85.7	−7%
WBS 05 PL System	314.9	322.9	337.8	341.1	−2%	−7%	−8%	333.9	−6%
WBS 06&10 FS & ATLO	421.7	363.4	446.3	476.1	16%	−6%	−11%	428.6	−2%
WBS 08 LV Services*	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.6	
Subtotal A–D w/o Reserve	**1158.2**	**1129.9**	**1158.4**	**1330.4**	**228.8**	**229.5**	**228.8**	**1201.3**	**−5%**
Phases A–D Res. (50% excl. LV)	464.7	450.6	464.8	550.8	3%	0%	−16%	488.7	−5%
Subtotal A–D with Reserve	**1622.9**	**1580.5**	**1623.3**	**1881.3**	**228.9**	**229.5**	**227.9**	**1690.0**	**−5%**
Phase E/F Operation	216.0	193.0	193.0	252.9	12%	12%	−15%	213.0	1%
Phase E/F Reserve (25%)	54.0	48.2	48.2	63.2	12%	12%	−15%	53.2	1%
Subtotal E/F with Reserve	**270.0**	**241.2**	**241.2**	**316.2**	**12%**	**12%**	−15%	**266.2**	**1%**
Total Mission w/ Reserve	**1892.9**	**1821.7**	**1864.5**	**2197.4**	**229.0**	**229.6**	**227.7**	**1956.2**	**−4%**

**WBS 08 estimates based on NASA PMCS Study Ground Rules. Note that this study assumed a potential use of Falcon 9 Recoverable.*

Table 5-3. Model Cost Assessment for MORIE Ice-Focused (FY25 $M).

WBS Element (Bus+3 Instruments)	Team X	Method 1 (SEER-H)	Method 2 (True-Planning)	Method 3 (PCEC)	Deltas Team X vs. Method 1 (%)	Deltas Team X vs Method 2 (%)	Deltas Team X vs Method 3 (%)	Models Average ($)	Deltas Team X vs. Models Avg. (%)
Phase A	Incl. in B–D	5.0	5.0	5.0					
Phase B–D Development	959.3	900.8	957.1	1137.6	229.0	229.4	227.8	998.5	−5%
WBS 01-03 PM/PSE/SMA/M&SD	105.2	99.5	59.4	170.0	6%	77%	−38%	109.6	−4%
WBS 04,07/09 Science/MOS/GDS	57.6	57.2	62.0	81.9	1%	−7%	−30%	67.0	−14%
WBS 05 PL System	170.3	176.5	176.8	203.2	−3%	−4%	−16%	185.5	−8%
WBS 06&10 FS & ATLO	397.3	338.9	430.1	453.7	17%	−8%	−12%	407.5	−3%
WBS 08 LV Services*	228.8	228.8	228.8	228.8	228.8	228.8	228.8	228.8	
Subtotal A–D w/o Reserve	**959.3**	**905.8**	**962.1**	**1142.6**	**229.0**	**229.4**	**227.8**	**998.5**	**−6%**
Phases A–D Res. (50% excl. LV)	365.2	338.5	366.6	456.9	8%	0%	−20%	387.3	−6%
Subtotal A–D with Reserve	**1324.5**	**1244.2**	**1328.7**	**1599.5**	**229.1**	**229.4**	**227.6**	**1385.8**	**−6%**
Phase E/F Operation	149.9	135.0	135.0	245.2	11%	11%	−39%	171.7	−13%
Phase E/F Reserve (25%)	37.5	33.8	33.8	61.3	11%	11%	−39%	42.9	−13%
Subtotal E/F with Reserve	**187.4**	**168.8**	**168.8**	**306.5**	**11%**	**11%**	−39%	**214.7**	**−13%**
Total Mission w/ Reserve	**1511.9**	**1413.0**	**1497.5**	**1906.1**	**229.2**	**229.5**	**227.2**	**1600.5**	**−7%**

**WBS 08 estimates based on NASA PMCS Study Ground Rules. Note that this study assumed a potential use of Falcon 9 Recoverable.*

Table 5-4. MORIE Full Mission Total Mission Cost Funding Profile. (FY costs in Real Year Dollars, Totals in Real Year and FY25 Dollars).

Item	FY 2021	FY 2022	FY 2023	FY 2024	FY 2025	FY 2026	FY 2027	FY 2028	FY 2029	FY 2030	FY 2031	FY 2032	FY 2033	Total RY$	Total FY25$
Cost															
Phase A Concept Study	4.5	–	–	–	–	–	–	–	–	–	–	–	–	**4.5**	**5.0**
Phase A Tech. Dev.	–	–	–	–	–	–	–	–	–	–	–	–	–	**–**	**–**
Phase B–D Development	–	67.3	229.8	290.3	177.5	98.2	40.2	–	–	–	–	–	–	**903.3**	**924.4**
Phase B–D Reserves	–	33.8	115.5	146.0	89.2	49.4	20.2	–	–	–	–	–	–	**454.1**	**464.7**
Total A–D Development Cost	**4.5**	**101.1**	**345.3**	**436.3**	**266.8**	**147.6**	**60.4**	**–**	**–**	**–**	**–**	**–**	**–**	**1361.9**	**1394.1**
Launch Services	–	–	36.2	37.1	38.1	39.2	40.3	41.4	–	–	–	–	–	**232.3**	**228.8**
Phase E Science	–	–	–	–	–	15.1	15.8	16.3	16.7	17.2	17.7	18.2	–	**117.1**	**104.7**
Other Phase E Cost	–	–	–	–	–	16.1	16.8	17.3	17.8	18.3	18.8	19.4	–	**124.5**	**111.3**
Phase E Reserves	–	–	–	–	–	7.8	8.2	8.4	8.6	8.9	9.1	9.4	–	**60.4**	**54.0**
Total Phase E Cost	**–**	**–**	**–**	**–**	**–**	**38.9**	**40.8**	**42.0**	**43.2**	**44.4**	**45.7**	**47.0**	–	**302.0**	**270.0**
Education/Outreach	–	–	–	–	–	–	–	–	–	–	–	–	–	**–**	**–**
EPO Phase B–D	–	–	–	–	–	–	–	–	–	–	–	–	–	**–**	**–**
EPO Phase E	–	–	–	–	–	–	–	–	–	–	–	–	–	**–**	**–**
Other (specify)	–	–	–	–	–	–	–	–	–	–	–	–	–	**–**	**–**
Total Cost	**4.5**	**101.1**	**381.5**	**473.4**	**304.9**	**225.7**	**141.5**	**83.4**	**43.2**	**44.4**	**45.7**	**47.0**		**1896.3**	**1892.9**
												Total Mission Cost		**1896.3**	**1892.9**

Table 5-5. MORIE Ice-Focused Total Mission Cost Funding Profile. (FY costs in Real Year Dollars, Totals in Real Year and FY25 Dollars).

Item	FY 2021	FY 2022	FY 2023	FY 2024	FY 2025	FY 2026	FY 2027	FY 2028	FY 2029	FY 2030	FY 2031	FY 2032	FY 2033	Total RY$	Total FY25$
Cost															
Phase A Concept Study	4.5	–	–	–	–	–	–	–	–	–	–	–	–	**4.5**	**5.0**
Phase A Tech. Dev.	–	–	–	–	–	–	–	–	–	–	–	–	–	**–**	**–**
Phase B–D Development	–	52.8	180.3	227.9	139.3	77.1	31.5	–	–	–	–	–	–	**709.0**	**725.5**
Phase B–D Reserves	–	26.6	90.8	114.7	70.1	38.8	15.9	–	–	–	–	–	–	**356.9**	**365.2**
Total A–D Development Cost	**4.5**	**79.4**	**271.1**	**342.6**	**209.5**	**115.9**	**47.4**	**–**	**–**	**–**	**–**	**–**	**–**	**1070.4**	**1095.7**
Launch Services	–	–	36.2	37.1	38.1	39.2	40.3	41.4	–	–	–	–	–	**232.3**	**228.8**
Phase E Science	–	–	–	–	–	–	5.1	9.8	10.0	10.3	10.6	10.9	–	**56.8**	**49.8**
Other Phase E Cost	–	–	–	–	–	–	10.2	19.6	20.2	20.8	21.4	22.0	–	**114.1**	**100.1**
Phase E Reserves	–	–	–	–	–	–	3.8	7.4	7.6	7.8	8.0	8.2	–	**42.7**	**37.5**
Total Phase E Cost	**–**	**–**	**–**	**–**	**–**	**–**	**19.1**	**36.8**	**37.8**	**38.9**	**40.0**	**41.1**	**–**	**213.7**	**187.4**
Education/Outreach	–	–	–	–	–	–	–	–	–	–	–	–	–	**–**	**–**
EPO Phase B–D	–	–	–	–	–	–	–	–	–	–	–	–	–	**–**	**–**
EPO Phase E	–	–	–	–	–	–	–	–	–	–	–	–	–	**–**	**–**
Other (specify)	–	–	–	–	–	–	–	–	–	–	–	–	–	**–**	**–**
Total Cost	**4.5**	**79.4**	**307.3**	**379.7**	**247.6**	**155.1**	**106.8**	**78.2**	**37.8**	**38.9**	**40.0**	**41.1**	**–**	**1516.3**	**1511.9**
												Total Mission Cost		**1516.3**	**1511.9**

5.3 Concept Maturity Level (CML) and Risk Assessment

The MORIE concept study developed by JPL initially started at CML 3, but evolved to CML 4 where the architecture design, system classification, and characterization of each subsystem have been expanded by the JPL's collaborative engineering that improved the technical and financial feasibility of the mission.

These final developed concepts reflects the incremental set of improved assessments that addressed the science objectives, mission design, technical risk, project organization, cost, risks, and mission performance.

Phase A–F unencumbered cost reserves are 45%: Phases A-D at 50%, and Phases E–F at 25%.

The project management plan encompasses the mitigation strategies for cost risk. Table 3-12 discusses the project's top risks; the mitigation plans are in the project costs and do not encumber the project cost reserves. Funded schedule reserves are included for early development of immature technologies.

5.4 Potential Cost-Saving Options

A commercial spacecraft (like MRO, for example) could provide cost savings. Commercial instruments could also provide cost savings where science requirements are satisfied without large changes to the standard product lines.

Appendix A Acronyms

ACS	Altitude Combustion Stand
AEPS	Advanced Electric Propulsion System
AO	Announcement of Opportunity
APL	Applied Physics Laboratory
ARR	Assembly Readiness Review
ASDS	Automated Spaceport Drone Ship
ATLO	Assembly, Test, and Launch Operations
AU	astronomical units
B&B	Burn & Break-up
BC	Band Center
BER	Bit Error Rate
BMW	Beam Wave Guide
BOL	Beginning of Life
BS	Band Shoulder
BTE	Battery Test Equipment
BWG	Beam Waveguide
C&DH	Command and Data Handling
C-IMG	Color Imager
CAD	Computer-Aided Design
CaSSIS	Colour and Stereo Surface Imaging System
CBE	Current Best Estimate
CCD	Charge-Coupled Device
CDR	Critical Design Review
CDS	Command and Data Subsystem
CG	Centre of Gravity
CHROMA	Configurable Hyperspectral Readout for Multiple Applications
CMD	Command
CML	Concept Maturity Level
CMOS	Complementary Metal-Oxide Semiconductor
CO_2	Carbon Dioxide
CPCI	Computer Program Configuration Item
CPU	Central Processing Unit
CRC	Controller System Control
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
CTX	Context Camera
DART	Double Asteroid Redirection Test
DC	Direct Current
DEM	Digital Elevation Model
DOF	Degree of Freedom
DPU	Data Processing Unit
DSN	Deep Space Network
DTE	Data Terminal Equipment
DV	delta-V

EFL	Effective Focal Length
EGSE	Electrical Ground Support Equipment
EIS	Europa Imaging System
EM	Engineering Model
EMIT	Earth Surface Mineral Dust Source Investigation
EOL	End of Life
EP	Electrical Power
EPD	Entrance Pupil Diameter
FB	Flyby
FER	Frame Error Rate
FFT	Fast Fourier Transform
FOV	Field of View
FPA	Focal Plane Array
FS	Flight System
FSW	Flight Software
FWHM	Full-Width at Half-Maximum
FWS	Flight Workstation
FY	Fiscal Year
GaA	Gallium Arsenide
Gbit	Gigabit
GDS	Ground Data Systems
GEO	Geostationary Earth Orbit
GID	Guidance Interface Driver
GNC	Guidance, Navigation, and Control
GSD	Ground Sample Distance
GSE	Ground Support Equipment
H/W	Hardware
HDR	Hard Data Rate
HEPA	High-Efficiency Particulate Air
HGA	High-Gain Antenna
HiRIS	High-Resolution Imaging Spectrometer
HiRISE	High Resolution Imaging Science Experiment
HMR	Heat Microbial Reduction
HPCU	Housekeeping Power Converter Unit
HVEA	High Voltage Electronics Assembly
I&T	Integration and Test
ICE-SAG	Ice and Climate Evolution-Science Analysis Group
IEEE	Institute of Electrical and Electronics Engineers
IFOV	Instantaneous Field of View
IMU	Inertial Measurement Unit
InGaA	Indium Gallium Arsenide
IR	Infrared
ISO	International Organization for Standardization
Isp	Specific impulse

ISRU	In Situ Resource Utilization
JHU	John Hopkins University
JPL	Jet Propulsion Laboratory
JSX	J-Series
ka	thousands of years
Kb	Kilobit
KBase	Knowledge Base
KSC	Kennedy Space Center
LCC	Life Cycle Cost
LDR	Low Data Rate
LGA	Low Gain Antenna
LOLA	Lunar Orbiter Laser Altimeter
LORRI	Long Range Reconnaissance Imager
LST	Local Solar Time
LV	Launch Vehicle
LWIR	Long Wavelength Infrared
MAHII	Mars Hyperspectral Infrared Imager
MARCI	Mars Color Imager
Mars-FIRE	Mars Far Infrared Emission
MARSIS	Mars Advanced Radar for Subsurface and Ionosphere Sounding
MAVRIC	Mars Atmosphere Volatile and Resource Investigation Camera
MC	Monte Carlo
MCS	Mars Climate Sounder
MCT	Mercury Cadmium Telluride
MDL	Microdevices Laboratory
MEL	Master Equipment List
MEPAG	Mars Exploration Program Analysis Group
MER	Mars Exploration Rover
MEV	Maximum Expected Value
MFF	Medusae Fossae Formation
MGA	Medium Gain Antenna
MGS	Mars Global Surveyor
MGSE	Mechanical Ground Support Equipment
MIMU	Miniature Inertial Measurement Unit
MISE	Mapping Imaging Spectrometer for Europa
MLI	Multilayer Insulation
MOC	Mars Observer Camera
MOC-MO	Mars Observer Camera-Mars Observer
MOC-NA	Mars Observer Camera-Narrow Angle
MOI	Mars Orbit Insertion
MOLA-MO	Mars Orbiter Laser Altimeter-Mars Orbiter
MORIE	Mars Orbiter for Resources, Ices and Environments
MOS	Mission Operation Systems
MPV	Max Possible Value

MREU	Multi mission Remote Engineering Unit
MRO	Mars Reconnaissance Orbiter
MSIA	Multi mission System Interface Assembly
MSL	Mars Science Laboratory
MSSS	Malin Space Science Systems
MST/ORT	Mission System Test/Operational Readiness Test
MT	Metric Ton
MTIF	Multi mission Telemetry InterFace
NAC	Narrow Angle Camera
NASEM	National Academies of Science, Engineering and Medicine
NE	Northeast
NeMO	Next Mars Orbiter
NEX-SAG	Next Orbiter Science Analysis Group
NEXT	NASA Evolutionary Xenon Thruster
NF	New Frontiers
NGST	Northrop Grumman Space Technology
NGSWIS	Next Gen Short-Wave Infrared Imaging Spectrometer
NICM	NASA Instrument Cost Model
NPR	NASA Procedural Requirements
NRC	National Research Council
NRE	Nonrecurring Engineering
NVMCAM	Non-Volatile Memory/Camera
OBP	Onboard Processor
OPD	Optical Path Difference
PAF	Payload Attach Fitting
PBC	Power Bus Controller
PCEC	Project Cost Estimating Capability
PDR	Preliminary Design Review
PEL	Powered Element List
PFM	Proto Flight Model
PFS	Pyro Firing Slice
PLD	Polar Layered Deposits
PMCS	Planetary Mission Concept Study
Polar-SAR	Full Polarization Synthetic Aperture Radar
PP	Pixel Pitch
PPO	Planetary Protection Officer
PPU	Power Processing Unit
PREFIRE	Polar Radiant Energy in the Far Infrared Experiment
PRF	Pulse Repetition Frequency
PRT	Platinum Resistance Thermometer
PSAR	P-band Synthetic Aperture Radar
PSE	Project System Engineer
PSI	Pounds per Square Inch
PSP	Parker Slope Probe

RaSo	Radar Sounder
RCS	Reaction Control System
RF	Radio Frequency
RIT	Radio-Frequency Ion Thruster
ROIC	Readout Integrated Circuit
ROM	Rough Order of Magnitude
ROT	Rules of Thumb
RSL	Recurring Slope Lineae
RW	Reaction Wheel
RWA	Reaction Wheel Assembly
RX	Receiver (Filter)
S/W	Software
SAR	Synthetic Aperture Radar
SEE	Single Event Effect
SEER	System Evaluation and Estimate of Resources
SEER-H	System Evaluation and Estimate of Resources-Hardware
SEP	Solar Electric Propulsion
SESAR	Space Exploration Synthetic Aperture Radar
SHARAD	SHAllow RADar (instrument on Mars Reconnaissance Orbiter)
SMAP	Soil Moisture Active Passive
SNR	Signal-to-Noise Ratio
SOCM	Space Operations Cost Model
SSR	Solid State Recorder
STM	Science Traceability Matrix
SVIT	System Verification, Integration, and Test
SWIM	Subsurface Water Ice Mapping
SWIR	Shortwave Infrared
SWOT	Strengths Weakness Opportunities Threats
TB	Terabyte
TDI	Time Delay Integration
TES	Thermal Emission Spectrometer
THEMIS	Thermal Emission Imaging System
TID	Total Ionizing Dose
TIR	Thermal Infrared
TJ	Tunnel Junction
TLM	Telemetry
TMCO	Technical, Management, Cost and Other
TOF	Time of Flight
TRL	Technology Readiness Level
TWTA	Traveling Wave Tube Amplifier
TX	Transmitter (Filter)
UHF	Ultrahigh Frequency
UST	Universal Space Transponders
UV	Ultraviolet

UV-Vis	Ultraviolet/Visible
V&V	Verification and Validation
VERITAS	Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy
VHPMR	Vapor H_2O_2 Microbial Reduction
VNIR	Visible and Near Infrared
VSWIR	Visible To Short-Wave Infrared
WAC	Wide Angle Camera
WBS	Work Breakdown Structure
WISPR	Wide-Field Imager for Solar Probe
XFC	Xenon Feed Controller
XIPS	Xenon Ion Propulsion System

Appendix B Design Team Study Report

Preface

- **Payloads chosen for the Team X study might differ from the ideal payloads envisioned by the MORIE science team. These differences are due to availability of necessary information for entrance into Team X as well as the fact that the MORIE study team continued to refine the notional payloads after the point design study. It is noted in the text where these differences arise and Table B-0 provides an overview of the payloads used for each design study as discussed in Appendix Sections B.1 to B.3. The payloads described in the Team X documents are intended as a roadmap to MORIE science, where other reasonable alternatives exist or are in development.**

Table B-0. Overview of payloads for MORIE design studies.

Science Measurement	Science Instrument	Team X Architecture Instrument Analogs	Team X Point Design 1 (Full mission)	Team X Point Design 2 (Ice-focused mission)
SAR Imager	Polar-SAR	Eagle (PSAR, previous JPL radar studies incl. SMAP)	PSAR/Sounder Combined JPL Inputs	PSAR/Sounder Combined JPL Inputs
Radar Sounder	RaSo	SHARAD MARSIS	PSAR/Sounder Combined JPL Inputs	PSAR/Sounder Combined JPL Inputs
1-m Color Imager	C-IMG	HiRISE-Lite HiRISE MOC-NA	HiRISE-Lite	
SWIR Spectrometer	NGSWIS	CRISM	HiRIS shared telescope	
LWIR Spectrometer	Mars-FIRE	THEMIS MAHII	PreFIRE shared telescope	
Wide Angle Camera	MAVRIC	MOC-WA MARCI	MARCI	
Moderate Resolution Stereo Camera	Mid-S-Cam	CTX	CTX	CTX

- The nomenclature "ATLO" is used throughout this Appendix B. It is equivalent to NASA's new nomenclature "AI&T".

To explore the trade space and then examine point designs, MORIE went through a series of design sessions intended to mature the concept. These activities are listed in time order, with brief explanations in Table B-1. Appendix Sections B.1, B.2, and B.3 provide reports distilled from the design sessions that give further insight into the trade space and point designs.

Table B-1. MORIE design team activities listed in time order with brief explanations.

Design Team Activity	Product
A Team science and architecture early trade space exploration	Science goals, objectives, measurements, instruments, mission and spacecraft architectures, and concept of operations CML 3 trade space initially defined.
Team X architecture	Further explore CML3 trade space through various payload combinations versus relative cost.
Team X	Mature two point designs identified through previous study team work and CML3 A Team and Team X architecture concurrent, collaborative sessions. One point design in New Frontiers cost bin. One point design modestly over New Frontiers cost bin.

Contents

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Tables

B.1 A Team Science and Architecture Early Trade Space Exploration Design Study Report Summary

In a one-day Architecture Team (A Team) study, the MORIE team discussed and defined the science goals, objectives, measurements, instruments, mission and spacecraft architectures, and concept of operations trade space. The study was carried out to examine the architecture options for the mission concept, analyzing the trade space, and defining architecture building blocks to take to a later Team X Architecture design study.

B.2 Team X Architecture Design Study Report Summary

In the Team X Architecture study, the MORIE study team further explored the concept maturity level (CML) 3 trade space through various payload options versus relative cost. It should be noted that the instruments considered in the Team X Architecture design study are analogs and are not necessarily used in the Team X design. Table B-0 provides an overview of the considered payloads for each design study.

B.2.1 Summary

The goal of the study was to produce rough order of magnitude (ROM) cost estimates for a Mars orbiter concept with a large number of payload options in order to help the MORIE study team choose the appropriate scope for a New Frontiers (NF) class mission. For each option, the MORIE study team provided a list of instruments in the desired payload. The mass and power of each instrument was either provided by the MORIE study team or taken from an appropriate analogy in the NICM catalog or past proposals. The cost of each instrument was estimated two ways:

- By analogy directly from the NICM catalog or previous proposals
- Using the mass and power in the NICM System Model

From the total cost of the payload, the cost of the spacecraft was estimated using a regression based on historical actuals for Mars orbiters. The resulting model cost estimates can be seen in Figure B-1.

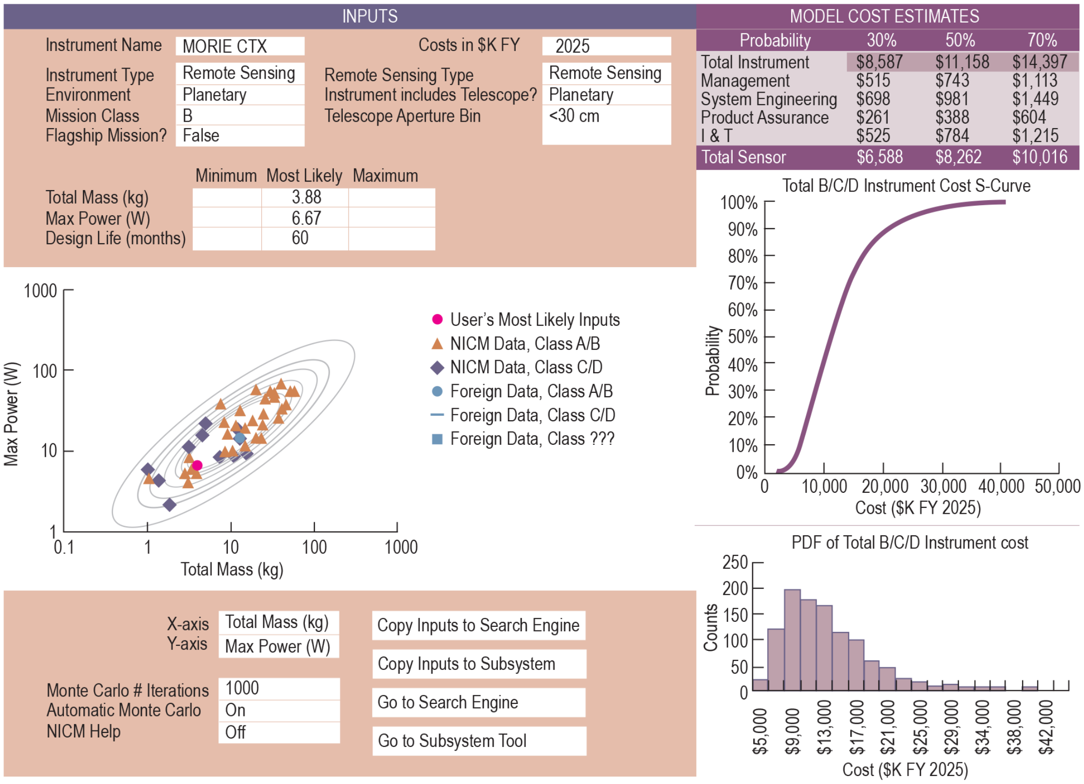


Figure B-1. Model cost estimate for MORIE provided by the Team X Architecture study.

From the total cost of the payload and spacecraft, the cost of each level 2 WBS line item was estimated for phases B-D and E-F using two sets of percentage breakdowns:

- One set derived from previous Mars orbiters. This sample size is small and includes only one competed mission. Results from this set are the lower bound, with very low levels of Project Management, Project Systems Engineering, and Mission Assurance. Typically, the combined percentage of WBS 1-3 must be > 10% for a successful competed proposal.
- One set derived from previous New Frontiers missions. Note that this set does not include any Mars orbiters, but does reflect the appropriate levels of Project Management, Project Systems Engineering, and Mission Assurance for a competed proposal.

The cost of MOS/GDS was first estimated using historical percentages. However, there are fixed costs associated with these WBSs that do not scale linearly with mission cost at the low end. The Team X GDS expert reviewed these costs and, using engineering judgement and experience with previous missions, recommended a fixed cost upper where necessary to bring the total MOS/GDS cost to a realistic level. The resulting breakdown can be seen in Table B-2.

Table B-2. MORIE cost breakdown by level 2 WBS line item, derived from previous Mars orbiters and previous New Frontiers missions.

	Mars Orbiters	Allocation per WBS
Project Manager	2%	2.7%
Systems Engineering	2%	2.9%
Safety and Mission Assurance	2%	2.6%
Science	1%	1.2%
Payload	27%	
Spacecraft	54%	
ATLO	6%	7.1%
MOS/GDS	6%	7.3%

In summary, eight different cost estimates were provided for each option. Note that the Team X cost models used in higher fidelity studies are based on a variety of historical missions and proposals, and are more likely to produce New Frontiers-like total mission cost breakdowns than Mars-orbiters-like mission cost breakdowns. A total of 12 architectures were evaluated with a FY25 NF cost cap of $1.1B as the discriminator assuming a 50% reserve as shown in Figure B-2.

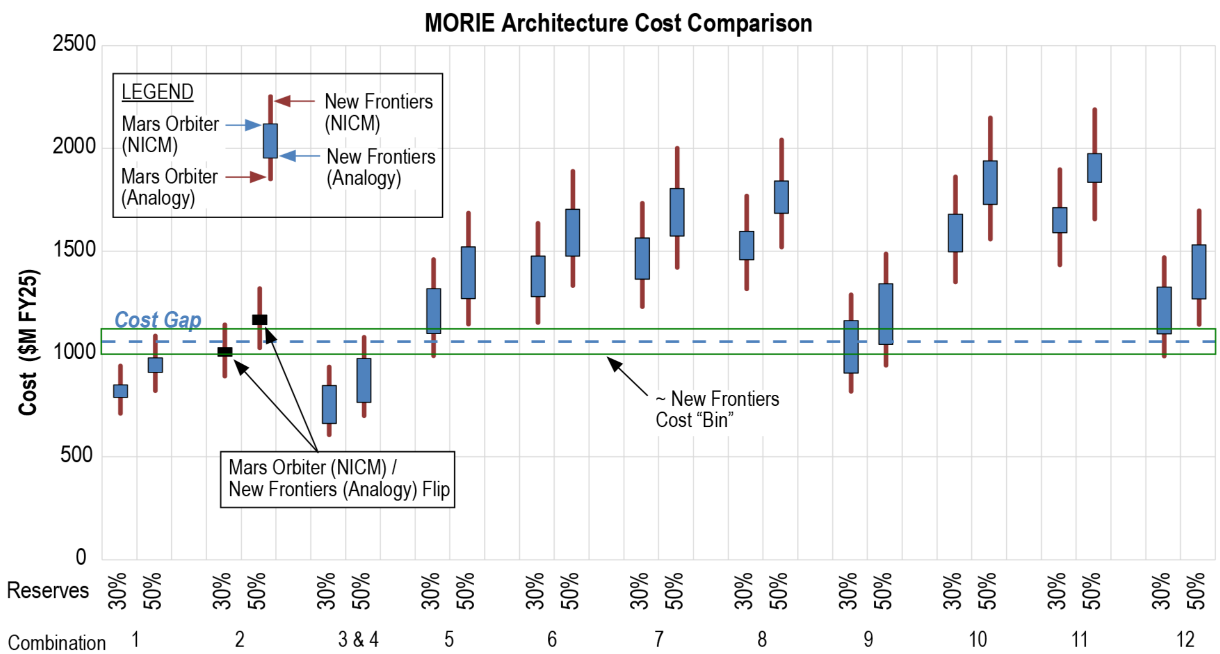


Figure B-2. MORIE Architecture Cost Comparison.

The Team X Architecture design study provided a range of cost estimates, derived from simple regressions and rules of thumb, using a variety of data sets and models. All of these estimates should be treated with large uncertainty bars; the cost may be even lower or higher than the bounds of the ranges.

- Identified instrument analogues:
  - Eagle (PSAR) → Polar-SAR
  - SHARAD (Sounder) → RaSo
  - CRISM (Short-wave IR spectrometer) → NGSWIS
  - THEMIS (Thermal IR Sounder) → MarsFIRE

- HiRISE(High Resolution Imaging Science Experiment) → C-IMG
- Mars Observer Camera-Narrow Angle (MOC-NA) (Wide Angle Camera) → MAVRIC
- CTX (Context Camera) → Mid-S-Cam

The Team X study recommended that the MORIE study team investigate some concepts that stretch the bounds of New Frontiers and may be more like a flagship mission since MORIE is a concept for the next Decadal Survey. However, Team X cautioned that any concept with the entire range of costs above the New Frontiers cost cap is highly unlikely to be proposable for the New Frontiers AO.

For the CRISM and PSAR instruments in particular, the NICM model estimates are much higher than the analogy estimates. The actual cost of CRISM reflects that it was a rebuild of a previous instrument. New instruments based on CRISM would likely not be able to realize these savings, and thus the NICM estimate is likely more accurate. On the other hand, NICM is known to produce very high costs for SAR instruments because of the high power input, and thus a case can be made that the analogy is more representative of PSAR than NICM. However, in all cases, reviewers typically run the NICM model and will question any lower costs in the proposal, unless there is a strong argument why NICM is not applicable.

B.2.2 Science

The MORIE design includes an orbit altitude of 300 km, with an orbit period of 114 hours and a ground velocity of 3123.4 m/s. The considered instruments are listed in Table B-3. Instrument parameters were derived from analogous instruments, with swath widths matched to the high resolution camera, where possible:

- "Data volumes (uncompressed)" represent global coverage at full instrument resolution and range (i.e. # bands).
- "Data rates (uncompressed)" represent Ground Sample Distance (GSD) (pixel size) acquired at MORIE ground velocity (no overlap, no adjustment for TDI).
- Note that tracking is normally 8 (or perhaps 16 hours)/day, so mission data return duration is longer than nominal tracking time.
- Global coverage for instruments highlighted in yellow cannot be returned (except, possibly for CTX, though the nominal design includes 2 CTX cameras for stereo), implying that coverage and/or #bands will have to be sub-sampled and that these instruments will increase sequencing complexity.

Table B-3. Considered instruments for MORIE.

Data generation	Max data rate	Data volume	Tracking	Tracking
300 km orbit, uncompressed data	Uncompressed	Global	Time	Time
Assumed telemetry 4 Mbps	Bits/sec	Bits	Hours	Years
"HiRISE" 1 m res, 20 km width, 20 bands	2.00E+10	4.62E+16	3.21E+06	366.2389
"CRISM" 5 m res, 20 km width, 3000 bands	1.20E+11	2.77E+17	1.92E+07	2197.434
"CTX" 5 m res, 30 km width, panchromatic	6.00E+07	2.77E+17	6.42E+03	0.732478
"WAC" 1–10 km res, limb-limb, 12 bands	6.00E+05	2.77E+10	1.92E+00	0.00022
"TIR" 100 m res, 20 km, width, 133 bands	1.33E+07	3.08E+13	2.14E+03	2.44E−01
"PSAR" 100 m res, 20 km width, 4 polarization	1.90E+07	1.85E+12	1.28E+02	0.01465
"Sounder" 300 m res, 3 km width, 7.5 m vres	2.02E+07	1.64E+12	1.14E+02	0.013022
"Altimeter" 30 m res, 150 m width, 1 band, ~12 cm vres	7.00E+05	2.57E+12	1.78E+02	0.020347
Sum of all small data sets	**5.38E+07**	**3.69E+13**	**2.56E+03**	**2.92E−01**

PSAR design and onboard processing not well constrained.
Some swath widths for were spec'd to match HiRISE.
SNR for "HiRISE" 20 bands may be problematic.
Data rates > 25 Mbps may require special solid-state recorder (SSR) design.
Data rates > 100 Mbps may require special bus design.

Comments on the considered instruments:

- High Res camera
  - Derivative of HiRISE/MOC
  - 1 m GSD, 20 bands, range up to 1.7 microns, InGaAs is nominal focal plane material, 20 km swath width desired
  - May be photometrically challenged (exposure time ~1/ground velocity ~0.3 ms)
  - If TDI, smear may additionally challenge achieving 1 m resolution
- SWIR
  - CRISM derivative, 5 m GSD, resolution (0.001), range (1-4micron), 20 km swath width achievable with modern focal planes
  - Exposure time (~1.5 ms) may be challenging
- Context camera
  - Similar to CTX, swath width (30 km) chosen to encompass high resolution camera
- Wide angle camera
  - Derivative of MARCI with 12 bands, 150 degree FOV, 1 km resolution nadir
- Thermal camera
  - Derivative of Mars Hyperspectral Infrared Imager (MAHII), 100 m resolution, swath width of 200 pixels assumed
- P-band Polarimetric SAR
  - Design is rather uncertain at this time, based on 10 year old proposal
  - Resolution 100 meters, 20 km "swath width", 4 polarizations returned, onboard processing
  - Bus data rates are based on exemplar numbers, but degree of onboard processing is unknown
  - Data volume is based on 100 meter resolution (MORIE requirement)
  - Currently, the antenna is separate from the telecom antenna
- Deep ground penetrating radar
  - Based on SHARAD
  - 300 m resolution, 3 km width, 7.5 m vertical resolution, pulse repetition frequency (PRF) of 700, 10 m Yagi antenna
  - Onboard processing, return word size 1024 bits/"pixel (probably an over-estimate), (min | max) data rates based on SHARAD (32 pulse sum 4 bit |, 1 pulse 8 bit) exemplar
  - Global coverage data volume base on 300 m horizontal resolution, 1024 bit word size
- Altimeter
  - Based on LOLA (note different orbit altitudes and albedos)
  - 30 meter spot size based on LOLA beam divergence, MORIE altitude
  - Swath width based on LOLA 5 beam design
  - Simple return assumed (differential return time, not complex return) for global coverage
  - Surface is under-sampled at LOLA 28 Hz rate (spot size 30 m, interval 111 m)
  - Global coverage based on full sampling
  - Swath width small, may drive orbit precession rate if full global coverage is desired
  - 0.5 nsec resolution = 12 cm vertical resolution

B.2.3 Instruments

Multiple heritage analogies were considered for each possible instrument. All analogies were found in NICM 8.5 except for three:

- Eagle SAR: From a 2010 Team X study.
- SHARAD: MRO sounder, provided by the Italian Space Agency.
- MAHII: A John Hopkins University/Applied Physics Laboratory (JHU/APL) instrument based on CRISM.

All NICM 8.5 Monte Carlo costs were close to the original NICM as-built costs except for the CRISM analogy. According to the Team X Science Chair, CRISM was an identical second rebuild of a flight instrument rocket failure, so the CRISM NICM cost is likely unrealistically low. A summary of the considered instruments is provided in Table B-4.

Table B-4. Summary of considered instruments.

Name	Analogy	NICM 8.5 Analog FY $25M	Heritage	Cont	Mass CBE (kg)	Mass MEV (kg)	Power CBE (W)	Power MEV (W)	NICM 8.5 FY $25M	NICM 8.5 Telescope Aperture	NICM vs NICM Ratio
CTX	CTX	9.55	Inherited	15%	3.37	3.88	5.80	6.67	11.16	No	117%
CTX Stereo	CTX ×2	13.56	Inherited	15%	6.74	7.75	11.60	13.34	15.84	No	117%
HiRISE	HiRISE	86.28	Inherited	15%	64.23	73.86	135.00	155.25	69.78	50 cm	81%
HiRISE Light	HiRISE	86.28	New	30%	64.23	83.50	135.00	175.50	73.34	50 cm	85%
HiRISE Light	MOC-MO	53.79	New	30%	23.6	30.68	21.00	27.30	57.00	No	106%
PSAR	SMAP	387.68	New	30%	234.62	305.00	316.92	412.00	339.13	No	87%
PSAR	Eagle SAR*	N/A	New	30%	75.46	98.10	180.00	234.00	167.07	No	
Sounder	SHARAD	N/A	New	30%	15	19.50	67.00	87.10	58.28	No	
Sounder	MARSIS	57.97	New	30%	18.04	23.45	39.00	50.70	47.65	No	82%
SWIR	CRISM	51.40	New	30%	33.1	43.03	46.00	59.80	93.02	No	181%
TIR	THEMIS	28.44	New	30%	13	16.90	14.00	18.20	34.90	No	123%
TIR	MAHII*	N/A	New	30%	25	32.50	30.00	39.00	68.86	No	
WAC	MARCI	5.75	Inherited	15%	1.04	1.20	4.60	5.29	6.01	No	105%
Laser Alt.	LOLA	45.51	Inherited	15%	12.58	14.47	31.30	36.00	46.75	No	103%
Laser Alt.	MOLA-MO	59.97	Inherited	15%	24.79	28.51	28.74	33.05	57.08	No	95%

**Eagle SAR is from 1137 Team X, *MAHII: JHU/APL microbolometer instrument.*

Legend for Table B-4

- Name: Approximation of MORIE Team name for instrument
- Analogy: Instrument used for cost basis; usually heritage
- NICM Analogy: Actual instrument build cost for Analogy from NICM, in FY25$M
- Heritage: "Inherited" means essentially having the same team remake the same instrument; "New" means significant changes to heritage
- Cont: Contingency on mass and power; numbers are from Team X tool
- Mass CBE: Heritage as-built mass, from NICM
- Mass MEV: Mass with contingency, used as an input to NICM Monte Carlo (MC) costing
- Power CBE: Heritage as-built peak power, from NICM
- Power MEV: Peak power with contingency, used as an input to NICM Monte Carlo (MC) costing
- NICM: Result of a single MC run, using the MEV mass and peak power (and aperture size)
- NICM Telescope: Has aperture diameter if heritage instrument in the NICM database specified an aperture diameter
- NICM Ratio: Ratio of MC cost vs NICM as-built cost; within 20% is good.

Eagle was a SAR (Synthetic Aperture Radar) for a Mars orbiter:

- All inputs for 1137 Team X provided by the original Eagle study team
- SAR included the antenna (telecom shared)
- SAR build at JPL
- P-band (300-350 MHz)
- Eagle Team X used grass root cost of FY2010 $64.7M
- Heritage (no flight)
- TRL 6 by PDR; most subcomponents demonstrated
- 46 months for phase C/B/D
- One Engineering Model (EM) and one Proto Flight Model (PFM)
- Mass: electronics 38.4 kg; antenna and supporting structure 44 kg
- Power: 180 W average; 480 W peak
- Data rates: 4 modes ranging from 1.5 – 19.4 Mbps after built-in data reduction
- Antenna: astro-mesh build by Northrop Grumman Space Technology (NGST)
- Folded and deployment mechanism
- Class B mission
- Thermal approach – passive: MLI, Radiators, Heaters, Temp Sensors, software (S/W) Controlled Thermostats

Figures B-3 to B-16 show NICM 8.5 runs for the various considered instruments.

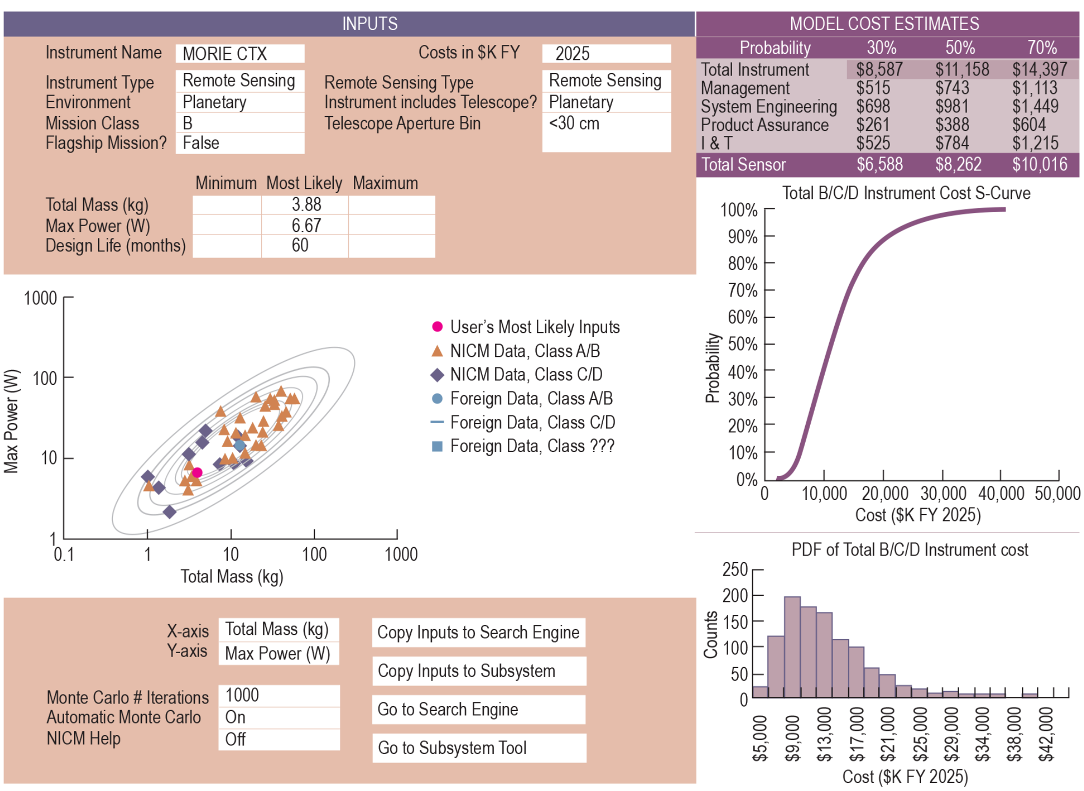


Figure B-3. NICM 8.5 run for CTX.

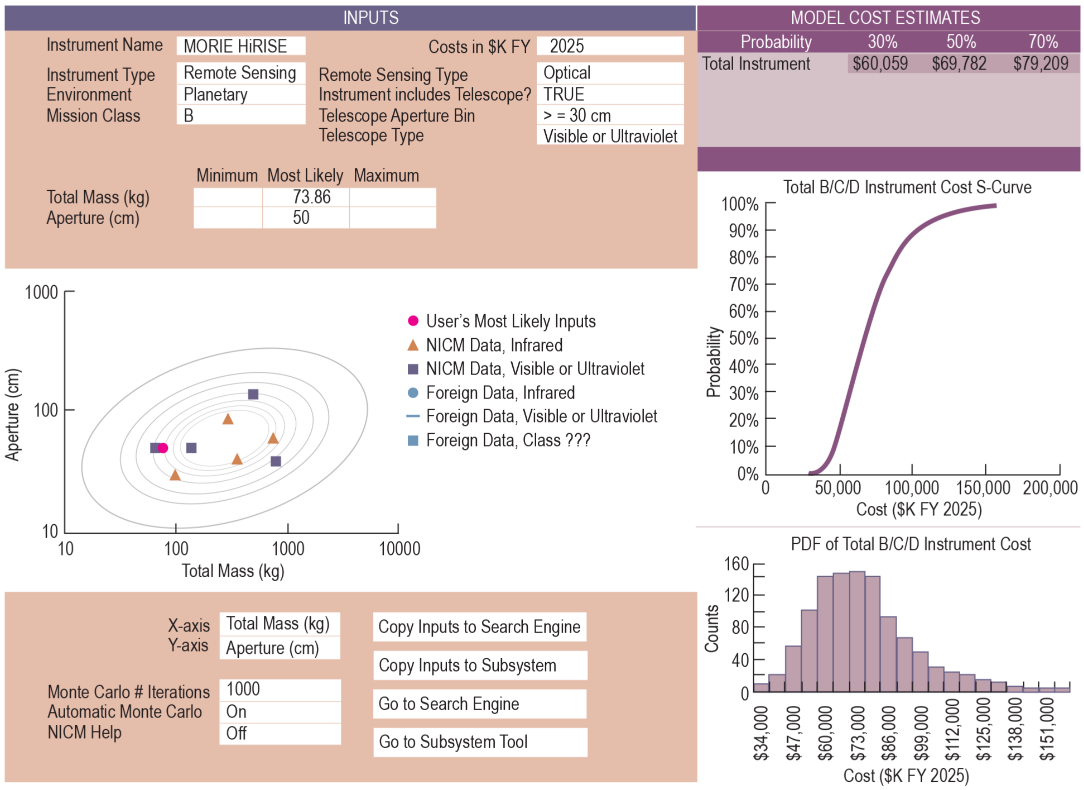


Figure B-4. NICM 8.5 run for HiRISE copy.

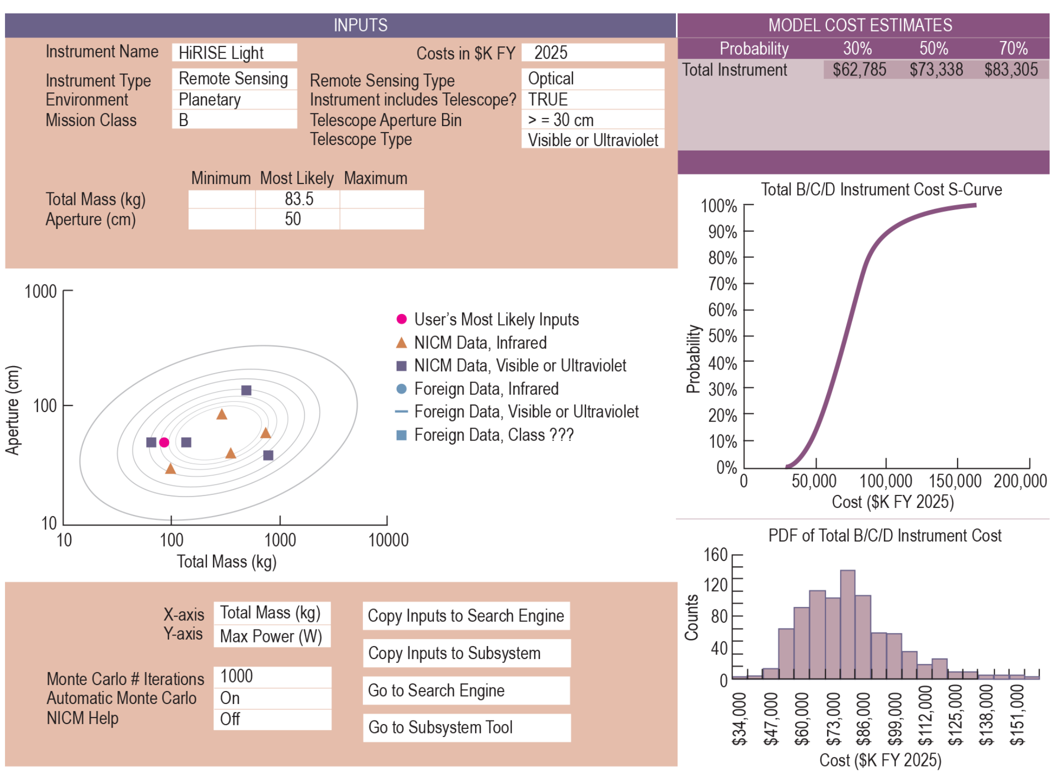


Figure B-5. NICM 8.5 run for HiRISE light. Costs slightly more than HiRISE copy due to loss of heritage. The aperture is the same since the shorter focal length was offset with a radiometry consideration.

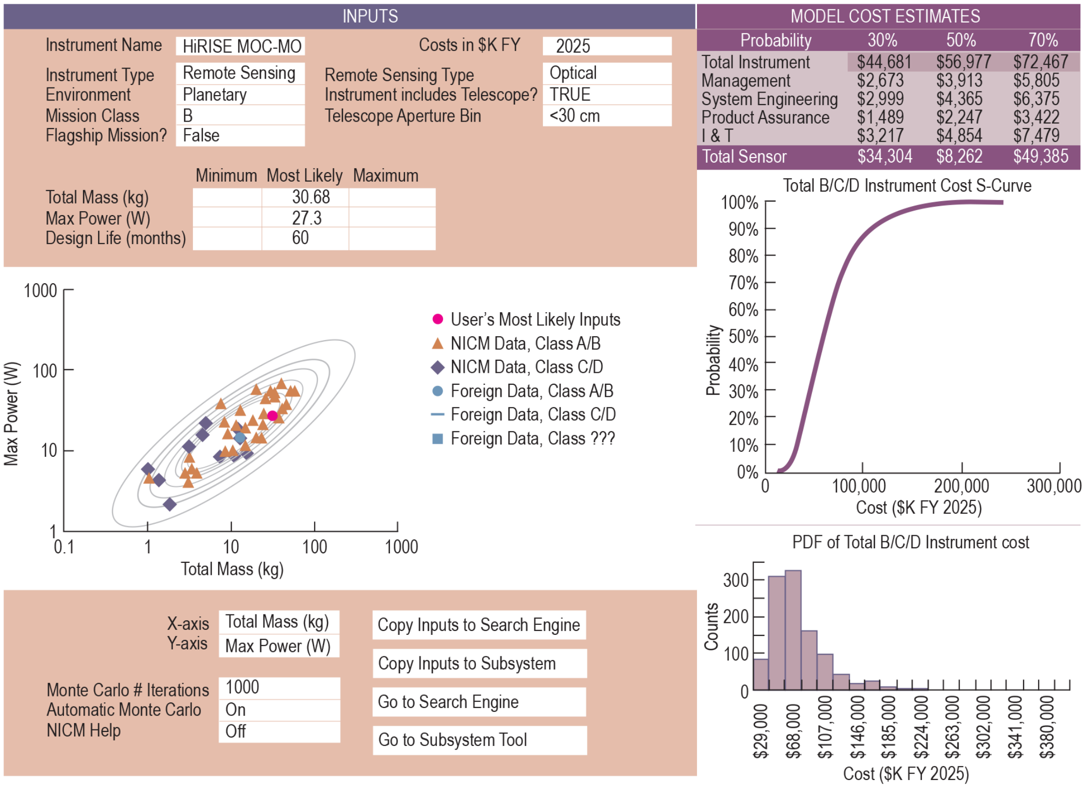


Figure B-6. NICM 8.5 run for HiRISE based on Mars Observer Camera-Mars Observer (MOC-MO)

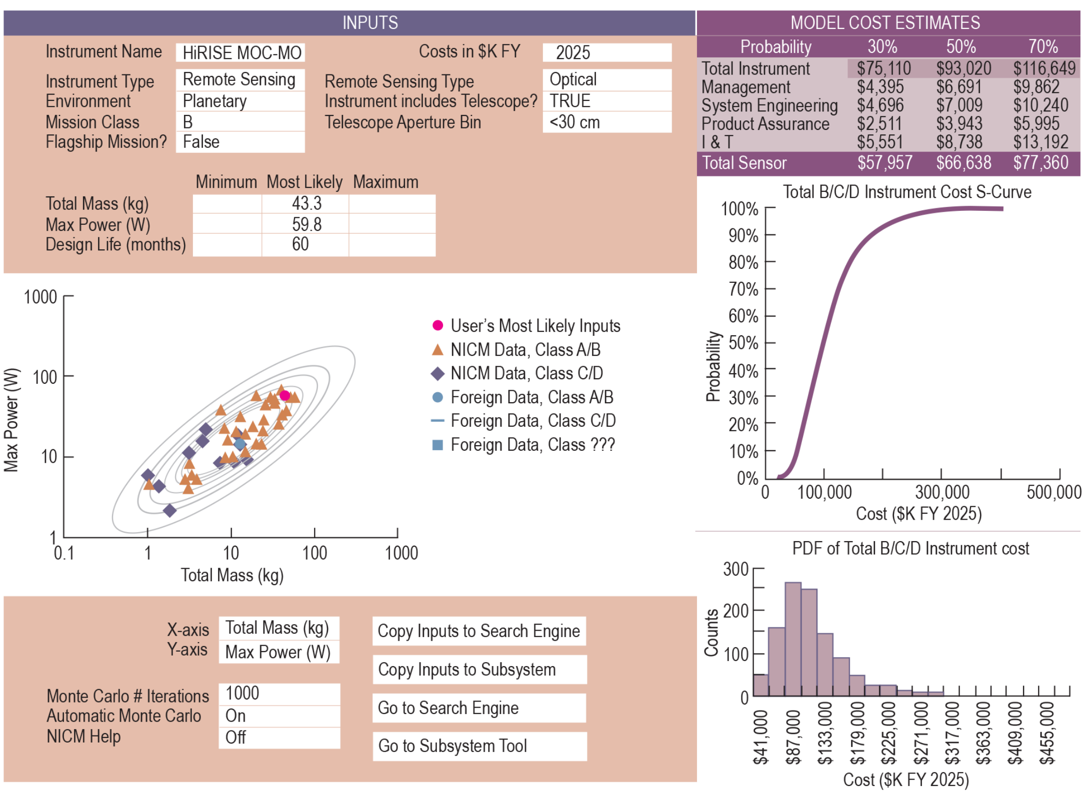


Figure B-7. NICM 8.5 run for SWIR based on CRISM.

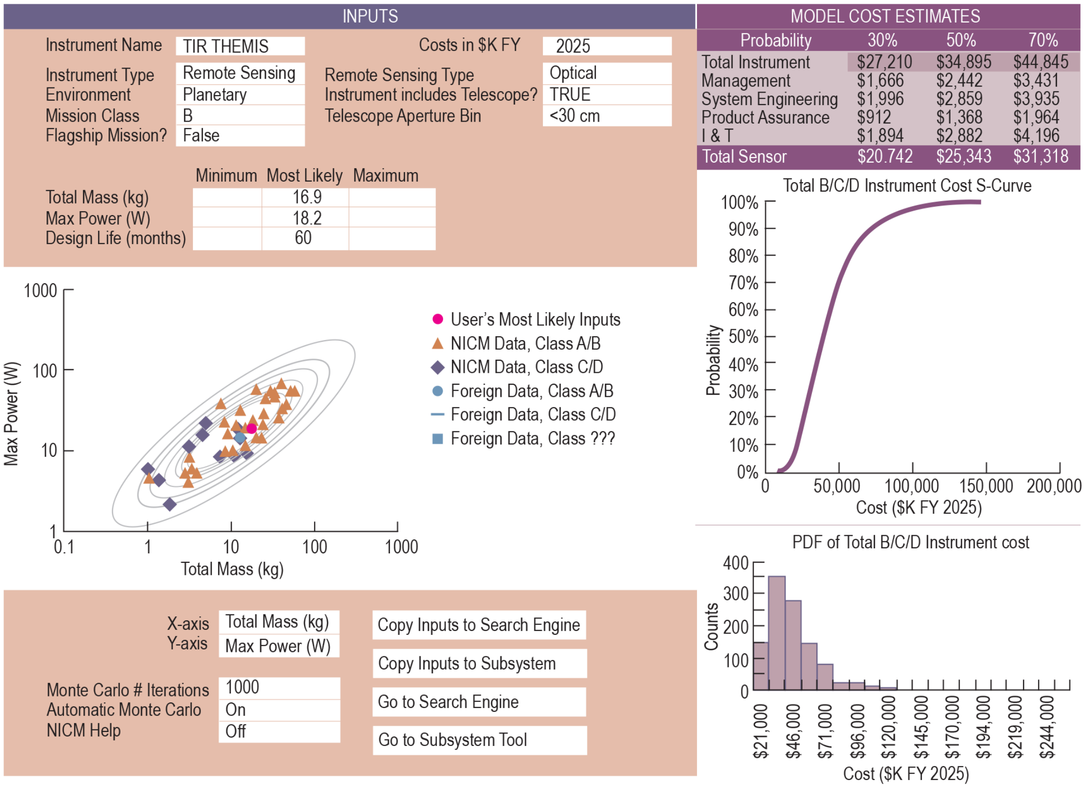


Figure B-8. NICM 8.5 run for TIR based on THEMIS.

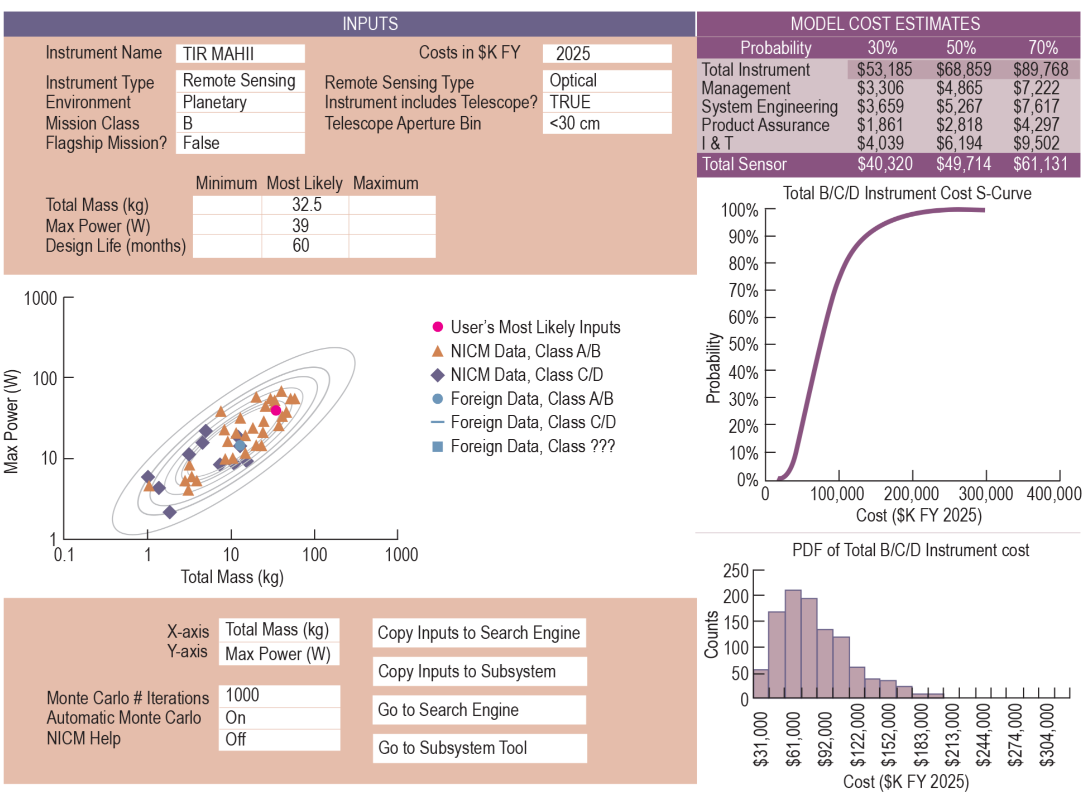


Figure B-9. NICM 8.5 run for TIR based on MAHII.

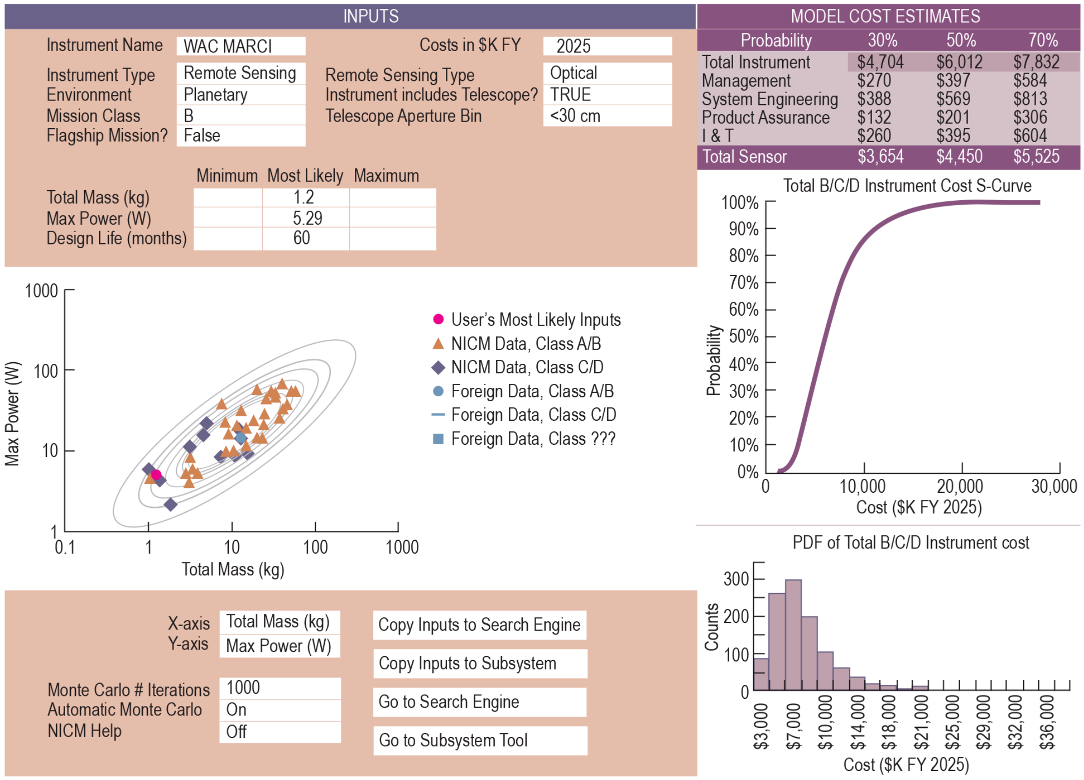


Figure B-10. NICM 8.5 run for WAC based on MARCI.

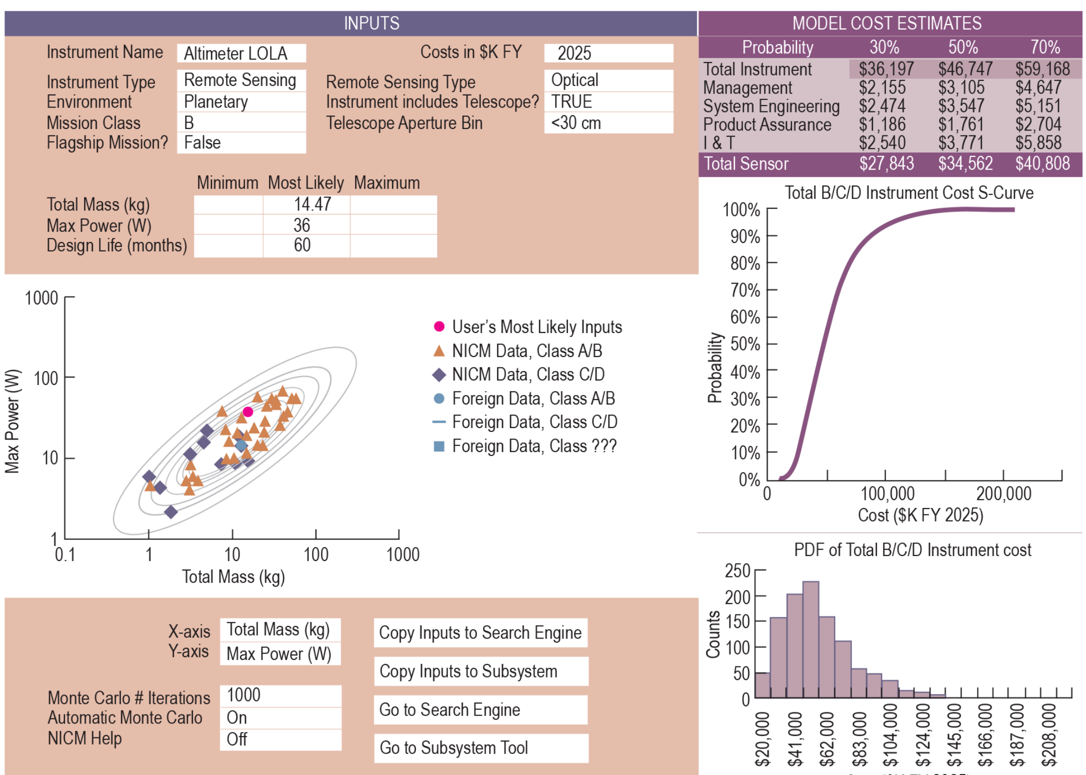


Figure B-11. NICM 8.5 run for Altimeter based on LOLA.

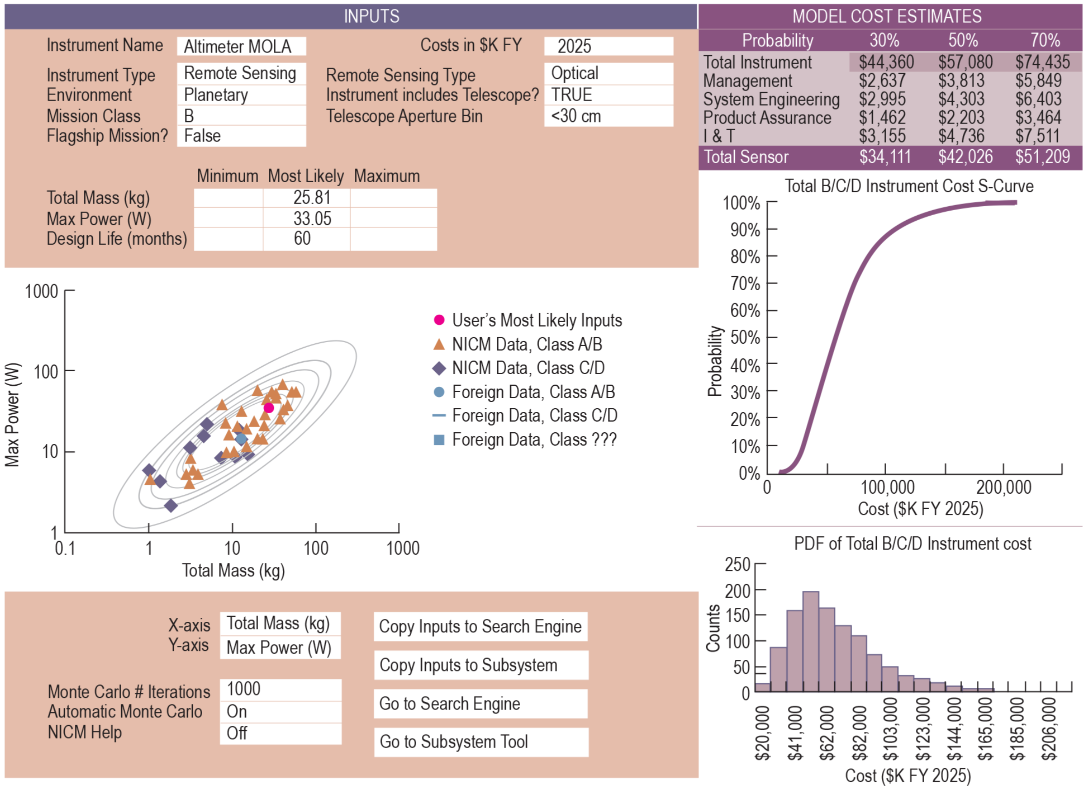


Figure B-12. NICM 8.5 run for Altimeter based on Mars Orbiter Laser Altimeter-Mars Orbiter (MOLA-MO).

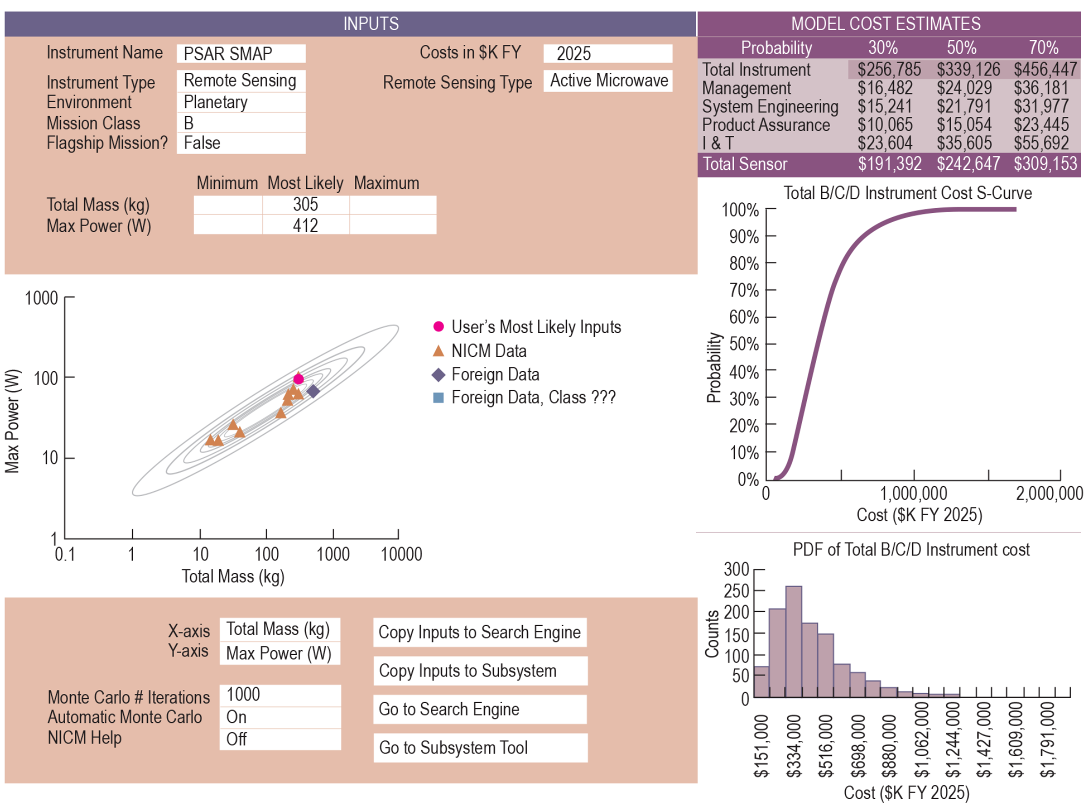


Figure B-13. NICM 8.5 run for PSAR based on Soil Moisture Active Passive (SMAP).

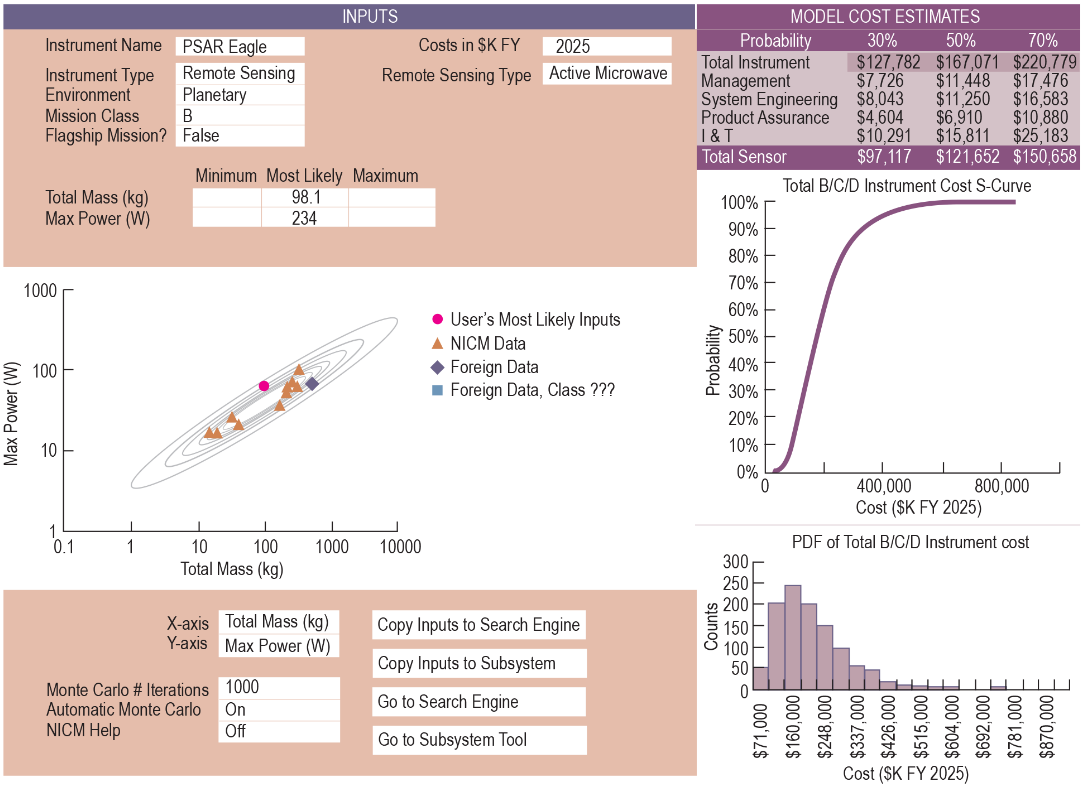


Figure B-14. NICM 8.5 run for PSAR based on Eagle (2010 Team X #1337).

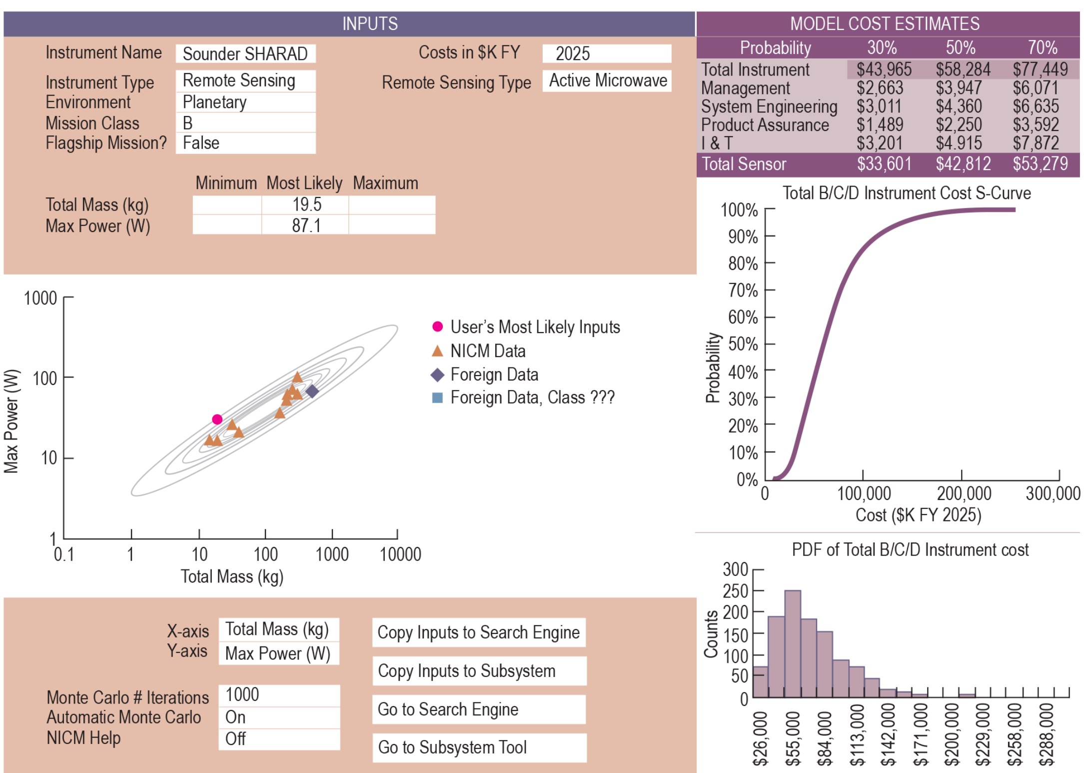


Figure B-15. NICM 8.5 run for Sounder based on SHARAD.

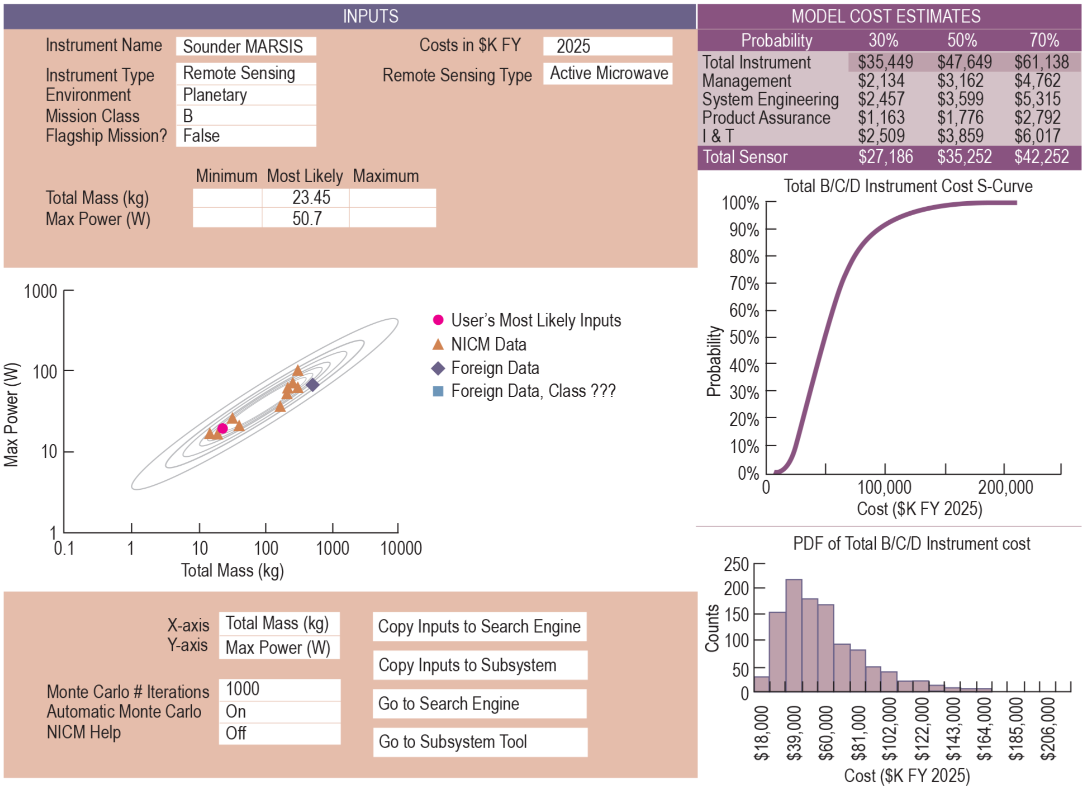


Figure B-16. NICM 8.5 run for Sounder based on MARSIS.

B.2.4 Ground System

The design assumptions for the ground system are as follows:

- Mission classes are roughly Discovery to New Frontier ($500M – $1B) also in terms of Mars Orbiter missions
- Spacecraft communication system is of similar size as MRO
  - Ka-band as primary data return path, with 100W TWTA
  - X-band as primary command and engineering data return path 35W TWTA
  - Same size HGA as MRO
  - DSN has deployed new receivers across the network enabling >6 Mb/s downlink (able to support whatever rates spacecraft can transmit at)
  - This design would provide ~4x the data rate of MRO X-band
  - MRO had minimum of 500 kbps at max Mars range and ~4 Mb/s at nominal Mars range

B.2.5 Cost

The costs presented in this Team X Architecture report are ROM estimates, not point estimates or cost commitments. It is likely that each estimate could range from as much as 20% percent higher to 10% lower. The costs presented are based on Pre-Phase A design information, which is subject to change.

The cost requirements are as follows:

- Constant/Real Year Dollars: FY25
- Cost Target: $1.1B
- Cost Phase: B-D (E/F not calculated for New Frontiers class)
- Studied 12 different architectures

The cost assumptions are as follows:

- Fiscal Year: 2025
- Mission Class: B
- Cost Category: 1
- Wrap Factors
  - Provided Phases B-D Reserves at both 30% and 50% (per New Frontiers call instructions). Not calculated on launch vehicle (LV) and Tracking costs
  - 2 different Payload cost estimates are provided:
    - □ Analogy: Comparing instruments mentioned in design study to previously flown
    - □ Parametric: NICMs model using instrument specs
  - Provided Rules of Thumb Wrap Factors from both Mars Orbiter historical actuals and New Frontiers historical actuals

The cost methodology is shown as a flow chart in Figure B-17.

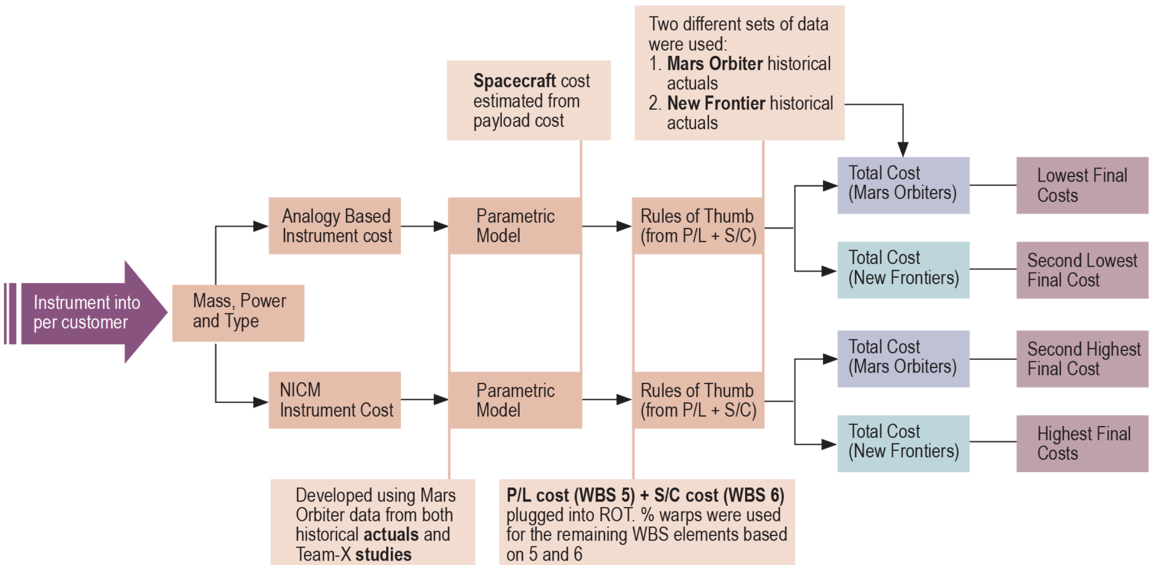


Figure B-17. Cost methodology.

The Team X Architecture study provided a range of cost estimates on 12 different architectures (Table B-5) based upon different combinations of science payloads driven by science descopes. The output of the Team X architecture study allowed the MORIE study team to down select to two concepts that were further matured in a JPL Team X Study (see Appendix Section B.3).

Table B-5. Cost comparison.

Included: Yes (✓) or No (X)	Option	Payload (Analog)										Reserve	B–D Mission Cost (Instrument Cost from NICM) ($M FY25)		B–D Mission Cost (Instrument Cost from Analog) ($M FY25)	
		CTX	HiRISE Lite	HiRISE Full	WAC MARCI	SWIR CRISM	TIR	PSAR EAGLE	Sounder SHARAD	Laser Altimeter LOLA	Telecom SAR		Mars Orbiters	New Frontiers	Mars Orbiters	New Frontiers
X	1	1			✓	✓			✓			30%	854	947	717	794
												50%	986	1092	827	916
X	2	2	✓		✓	✓			✓			30%	1036	1147	898	994
												50%	1195	1324	1036	1147
X	3							✓				30%	852	942	611	667
												50%	983	1087	705	770
X	4							✓				30%	SEP: Indistinguishable from 3		SEP: Indistinguishable from 3	
												50%				
✓	5	1			✓	✓		✓	✓			30%	1322	1465	997	1105
												50%	1525	1690	1150	1274
✓	6	2	✓		✓	✓		✓	✓			30%	1481	1641	1159	1284
												50%	1709	1893	1337	1481
✓	7	2	✓		✓	✓	✓	✓	✓			30%	1569	1738	1236	1369
												50%	1810	2005	1426	1579
✓	8	2		✓	✓	✓	✓	✓	✓			30%	1601	1773	1322	1464
												50%	1847	2046	1525	1689
✓	9	1			✓	✓		✓				30%	1166	1292	823	912
												50%	1346	1491	950	1053
✓	10	2	✓		✓	✓	✓	✓	✓	✓		30%	1685	1866	1356	1502
												50%	1944	2153	1564	1733
X	11	2		✓	✓	✓	✓	✓	✓	✓		30%	1716	1901	1439	1595
												50%	1980	2193	1661	1840
✓	12	2	✓		✓	✓		✓				30%	1331	1474	996	1103
												50%	1536	1701	1149	1273

Table B-6 shows the Rules of Thumb (ROT) wraps factors per WBS element. The 'Total Cost' column shows the percentage breakdown of the total cost. The 'Allocation per WBS' column shows the percentage breakdown in relation to the Payload and Spacecraft total cost.

Table B-6. ROT wraps factors by WBS element.

	Mars Orbiters Total Cost Breakdown	Allocation per WBS	NF Total Cost Breakdown	Allocation per WBS
Project Manager	2.2%	2.7%	5.1%	6.9%
Systems Engineering	2.2%	2.9%	3.6%	4.9%
Safety and Mission Assurance	2.2%	2.6%	3.8%	5.2%
Science	0.9%	1.2%	3.2%	4.4%
Payload	26.7%		20.0%	
Spacecraft	54.1%		52.9%	
ATLO	5.9%	7.1%	3.7%	5.0%
MOS/GDS	5.9%	7.3%	7.7%	10.6%

The following cost assumptions went into Table B-6:

- Management and Systems Engineering
  - Project: Project level management (WBS 1) and all subsequent WBS elements besides Payload (WBS 5) and Flight System (WBS 6) are calculated using Rules of Thumb percentage wraps based on the total cost of WBS 5 and 6.
  - Payload: The payload management and systems engineering costs are calculated by NICM. It calculates the cost of the raw hardware plus management and systems engineering.

- Flight System: Flight System Management and Engineering costs are built into the total cost of the spacecraft estimated by our regression model.

- ATLO (WBS 10) was calculated at the project level using Rules of Thumb wraps.

The Team X study identified the following potential cost savings:

- Purchasing off the shelf instruments will greatly reduce the cost.
- New vendors are increasingly offering cheaper and more flexible spacecraft solutions. This is especially true for SmallSats.

The Team X study identified the following potential cost uppers:

- Building the spacecraft and/or the instruments in-house can significantly drive up the cost. The biggest driver being labor.
- Reserves might be required to be calculated at 50% instead of the usual 30%. Both were assessed in the Team X study.

B.3 Team X Design Study Report Summary

This Team X design study was conducted to determine the technical and financial feasibility of the MORIE Mars Orbiter concept fitting within the constraints of a New Frontiers class mission as defined by the constraints given to the Planetary Mission Concept Studies. From the MORIE study team provided payload accommodation requirements, science mission profile (observation concept of operations), and mission design (trajectory), Team X produced a Master Equipment List, Power Equipment List, WBS Level 3 Cost Estimate, and calculate technical and financial margins for two mission concepts:

- Mission concept 1: the full mission concept, carrying 7 instrument types
- Mission concept 2: the ice-focused mission concept, carrying only 3 instrument types

The two studied mission concepts, the instruments and their respective analogs are shown in Table B-7.

Table B-7. Architecture concepts for the instrument payload.

Concept	Polar-SAR	RaSo	NGSWIS	MarsFIRE	C-IMG	MAVRIC	Mid-S-Cam
Full mission	1	1	1	1	1	1	2
Ice-focused mission	1	1	0	0	0	0	2

B.3.1 Mission architecture and assumptions

MORIE is a single SEP-enabled spacecraft on a dedicated launch that flies from Earth to a low Mars orbit, carrying a suite of instruments for studying ice. The spacecraft power and propulsion systems were sized using a SEP mission design provided by the MORIE study team's mission designer (with some iteration during the session, so that the design numbers shown below do not match the study team's input package).

- Total ΔV was provided (4500 m/s Cruise + 3000 m/s Spiral + 500 m/s at Mars = 8000 m/s)
- C3 = 1 km^2/s^2
- Average Isp was provided (1700 s)
- EP system input powers at Earth and Mars were provided (9600 W for two engines at Earth, 4800 W for one engine at Mars)
- A starting wet mass was provided (3000 kg)

In the ice-focused mission concept, when the total wet mass came down to a lower number, the electrical power (EP) input power was reduced proportionally, to maintain a fixed acceleration profile; this allowed the Power subsystem to scale down appropriately (along with all other related ripple effects).

Figure B-18 shows the schedule during a Team X point design total mission duration of 70 months.

Phase	Start	Duration [m]
Heliocentric	11/20/2026	13.2
Spiral Down	12/22/2027	9.7
3PM SS	10/7/2028	23.0
Inc. Transfer	8/27/2030	1.4
90 deg	10/8/2030	21.5
Inc. Transfer	7/14/2032	1.4
3PM SS	8/25/2032	

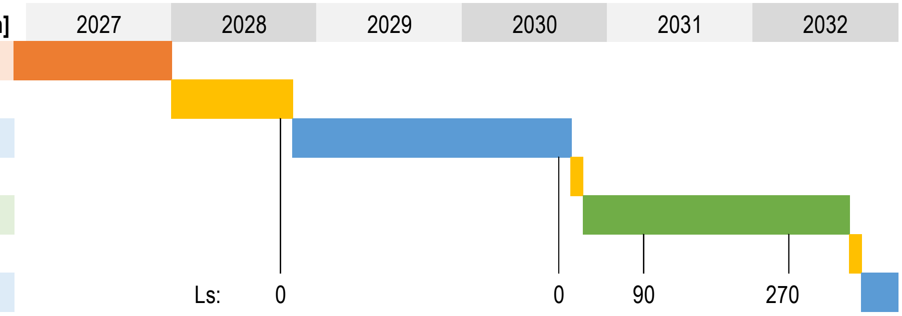


Figure B-18. Schedule for Team X point design total mission duration of 70 months.

For power sizing purposes, the concept of operations was modeled using the power modes shown in Figure B-19. In the Science Orbit, for sizing purposes, a worst-case eclipse of 40 minutes was assumed and communication was assumed to be turned on for the full orbit. The array size was driven by the SEP thrusting cases, the battery size was driven by the launch case, the spacecraft was power-rich in the science phase, and the science data volumes were driven by the cadence shown in the science orbit in Figure B-19.

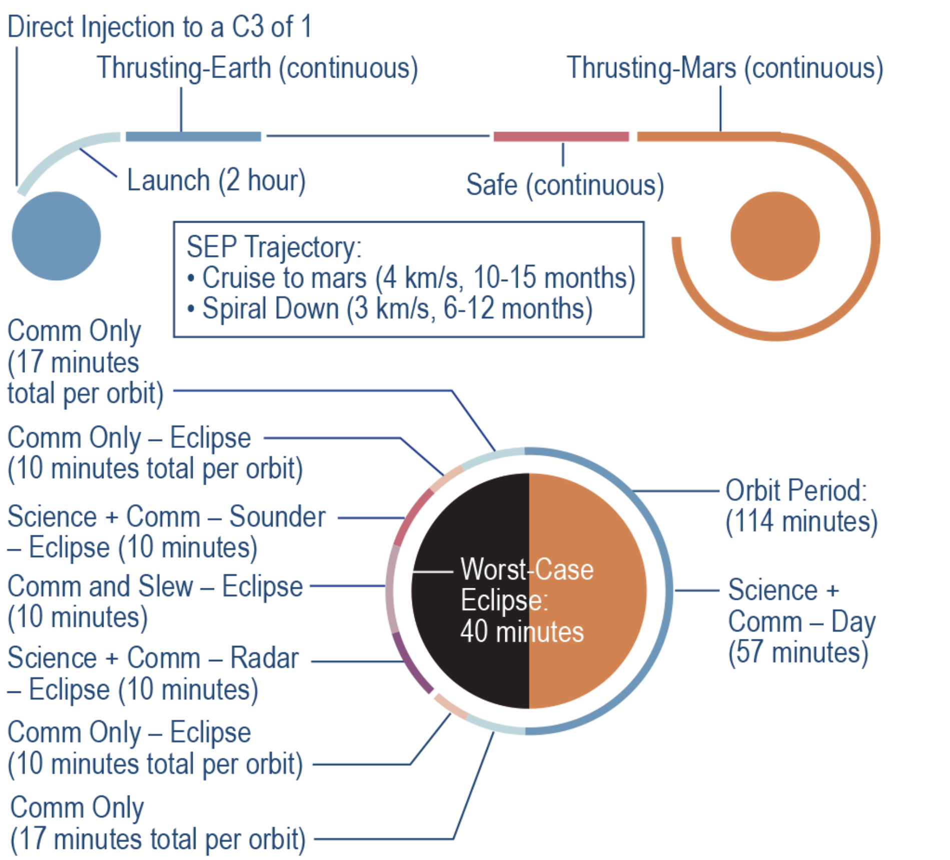


Figure B-19. Team X point design MORIE concept of operations. See Figure 3-8 in Section 3.3 for the final version.

The **full mission concept design** can be summarized as follows, and is visualized in Figure B-20:

- Instruments
  - CTX – Context Imagers
  - SWIR/TIR Spectrometer (on 1-axis platform)
  - HiRISE Lite – TDI imager
  - WAC – wide angle camera
  - PSAR/Sounder
- CDS
  - Fully dual-string
  - RAD750 avionics
  - 128 Gbytes memory card (1 per string)
- Ground Systems
  - Ground Network = DSN
  - Two 8-hr passes per day
- Telecom
  - 1 m Ka-band HGA, 2-axis gimbaled, with 200 WRFTWTA
  - X-band Medium Gain Antenna (MGA), with 25 WRFTWTA
- ACS
  - Sun sensors, star trackers, IMUs, reaction wheel assemblies (RWAs), gimbal drive electronics (for SAs, HGA, instrument scan platform)
- Structures
  - Primary Structure Mass MEV= 262 kg
  - Secondary Structure Mass MEV = 26 kg
  - Mechanisms
    - Solar array gimbals (2-axis)
    - HGA gimbals (2-axis)
    - Instrument scan platform (1-axis)
- Thermal
  - Passive thermal control (MLI, heaters, thermal surfaces)
  - Assume one bus face is always in shadow
- Power
  - Two deployable 5.7 m UltraFlex, total area = 47 m^2
    - Sized to “Thrusting at Earth” mode
  - Dual-string Li-Ion Battery
    - Sized for “Launch” mode
- Propulsion
  - SEP system with 4x SPT-140 engines
  - Small Hydrazine RCS system for reaction wheel (RW) desats and attitude control in safe mode

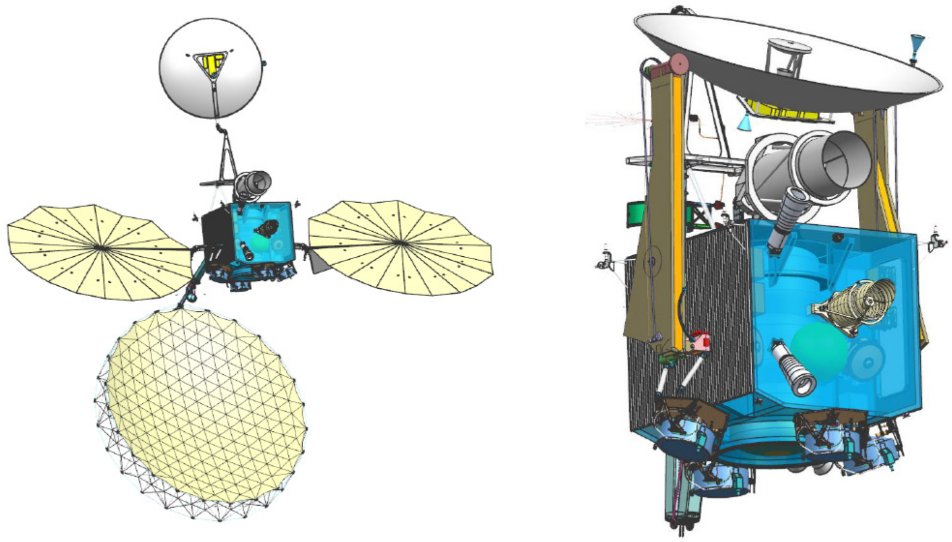


Figure B-20. Full mission design.

The **ice-focused mission concept design** can be summarized as follows, and is visualized in Figure B-21:

- Instruments
  - CTX – Context Imagers
  - PSAR/Dual frequency Sounder
- CDS
  - Fully dual-string
  - RAD750 avionics
  - 128 Gbytes memory card (1 per string)
- Ground Systems
  - Ground Network = DSN
  - Two 8-hr passes per day
- Telecom
  - 2 m Ka-band HGA, 2-axis gimbaled, with 100 WRFTWTA
  - X-band MGA, with 25 WRFTWTA
- ACS
  - Sun sensors, star trackers, IMUs, RWAs, gimbal drive electronics (for SAs, HGA)
- Structures
  - Primary Structure Mass MEV= 243 kg
  - Secondary Structure Mass MEV = 23 kg
  - Mechanisms
    - ☐ Solar array gimbals (2-axis)
    - ☐ HGA gimbals (2-axis)
- Thermal
  - Passive thermal control (MLI, heaters, thermal surfaces)
  - Assume one bus face is always in shadow

- Power
  - Two deployable 5.4 m UltraFlex, total area = 43 m^2
    - □ Sized to "Thrusting at Earth" mode
  - Dual-string Li-Ion Battery
    - □ Sized for "Launch" mode
- Propulsion
  - SEP system with 4x SPT-140 engines
  - Small Hydrazine RCS system for RW desats and attitude control in safe mode

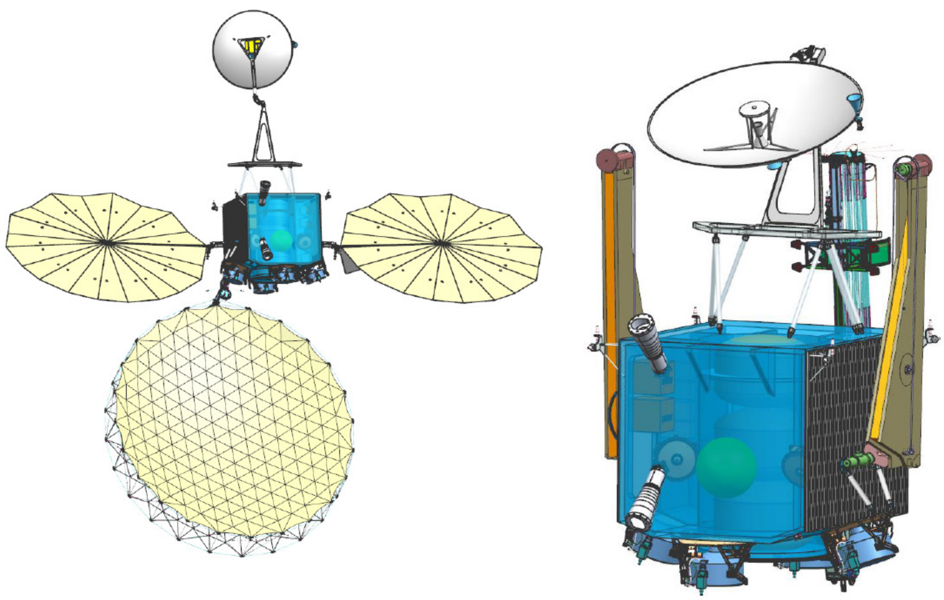


Figure B-21. Ice-focused mission design.

Summaries of the MORIE cost findings can be seen in Table B-8 and the MORIE mission concept comparison is given in Table B-9.

Table B-8. MORIE Cost Findings.

Full Mission						
Payload (Analog)						
CTX	HiRISE Lite	WAC	SWIR	TIR	PSAR	Sounder
2	✓	✓	✓	✓	✓	✓

Ice-focused Mission						
Payload (Analog)						
CTX	HiRISE Lite	WAC	SWIR	TIR	PSAR	Sounder
2					✓	✓

Full mission w/ 30% Reserves for A–D and 15% Reserves for E

	CBE	Res.	Total
Development Cost (Phase A–D)	$929.4M	30%	$1208.2M
Operations Cost (Phase E)	$216.0M	15%	$248.4M
Total A–E Project Cost (FY25 $M)	**$1145.4M**		**$1456.6M**

Ice-focused mission w/ 30% Reserves for A–D and 15% Reserves for E

	CBE	Res.	Total
Development Cost (Phase A–D)	$730.5M	30%	$949.6M
Operations Cost (Phase E)	$149.9M	15%	$172.4M
Total A–E Project Cost (FY25 $M)	**$880.4M**		**$1122.0M**

Full mission w/ 50% Reserves for A–D and 25% Reserves for E

	CBE	Res.	Total
Development Cost (Phase A–D)	$929.4M	50%	$1394.1M
Operations Cost (Phase E)	$216.0M	25%	$270.0M
Total A–E Project Cost (FY25 $M)	**$1145.4M**		**$1664.1M**

Ice-focused mission w/ 50% Reserves for A–D and 25% Reserves for E

	CBE	Res.	Total
Development Cost (Phase A–D)	$730.5M	50%	$1095.7M
Operations Cost (Phase E)	$149.9M	25%	$187.4M
Total A–E Project Cost (FY25 $M)	**$880.4M**		**$1283.1M**

**per New Frontiers guidelines, only A–D costs are considered for the $1.1B cap, while E/F costs are still estimated and reported on.*

Table B-9. MORIE Mission Concept Comparison.

	Full Mission	Ice-focused Mission
Cost (FY25, A–D, 50% res)	$1.4B	$ 1.1B
Launch Mass (at 30% JPL Margin)	3035 kg	2773 kg
Mass Margin (against 3195 kg allocation)	36% JPL, 25% NASA	44% JPL, 45% NASA
Instruments	CTX–context imagers (x2) SWIR Spectrometer TIR Spectrometer (shares telescope w/ SWIR) HiRISE Lite–TDI imager WAC-wide angle camera PSAR Sounder (shares hardware w/PSAR)	CTX–context imagers (x2) PSAR Dual frequency Sounder (shares hardware w/ PSAR)
Solar Array	2 wings, 5.7 m diam Ultraflex 11.5 kW EOL @ 1 AU	2 wings, 5.4 m diam Ultraflex 10.5 kW EOL @ 1 AU
Telecom Main Downlink	3 m Ka-band HGA 200 W TWTA (2x, redundant) 3 → 76 Mbps (0.5 → 2.5 AU link) 2x 8 hr DSN passes per day	2 m Ka-band HGA 100 W TWTA (2x, redundant) 0.75 → 19 Mbps (0.5 → 2.5 AU link) 2x 8 hr DSN passes per day
Launch Vehicle	Falcon 9 re-usable	Falcon 9 re-usable

The Team X study concluded that the MORIE design is fairly straightforward, and does not seem to present any novel technical risks:

- Mars orbiters with SEP and large deployable radars have not actually flown, but are well-studied and do not seem to present any major technical challenges
- It fits on a Falcon 9, with healthy margin

The Team X study concluded that:

- The full mission is significantly over the target New Frontiers cost cap
  – Its cost is mainly driven by the large number of instruments
- The ice-focused mission is estimated to fall right at the $1.1B FY25, A-D cap for New Frontiers (as per the Decadal Survey guidelines)

- The cost savings from the full mission are driven directly by the reduction in instrument and science costs
- The overall spacecraft bus mass and cost came down slightly as well, but for this concept, it is a second-order effect
  - As a SEP mission, its array size is driven by the mission design and total mass, rather than by the needs of the instruments or data downlink
  - The heaviest instrument (Radar/Sounder) stayed in the ice-focused mission, so the instrument mass reduction was only ~1/3
  - The 75% data volume reduction was enough to reduce the size of the Ka-band comm system (HGA size and amplifier power came down), but the effects on cost were minimal, because the data volumes are still far too high to use an X-band only system (which would entail more significant cost savings)
- If the Phase E costs were not considered "free" from the point of view of the cost cap, it would make more sense to keep a large Comm system (minimal mass and cost hit, and power is plentiful), and instead reduce the number of DSN passes by half (go to 1x 8hr passes instead of 2x 8hr passes)

B.3.2 Systems

The differences between the two studied mission concepts were driven entirely by the payload:

- The full mission carries 7 instrument types
  - One of the instruments has 2 copies (CTX)
  - Two of the instruments share optics (SWIR/TIR spectrometers)
  - The two radar instruments share hardware, including a 6 m deployable aperture (PSAR/Sounder)
- The ice-focused mission carries only 3 instrument types
  - The design objective for the ice-focused mission is to fit under a New Frontiers cost cap
  - The PSAR/Sounder was modified to add a sounder frequency, and was designated as the PSAR/Dual frequency Sounder, with an increase in mass

System Power Modes are used for the purposes of sizing the Power subsystem. They represent the ConOps at enough fidelity to model the power sizing cases, and are not necessarily a complete description of the ConOps. The Team X Power chair uses these modes to construct sizing scenarios, according to their judgement and in consultation with the Team X Systems chair. The ConOps assumptions for power sizing are shown in Table B-10.

Table B-10. ConOps assumptions for power sizing.

Mode Name	Launch	Safe	Thrusting - Earth	Thrusting - Mars	Science + Comm - Day	Science + Comm – Radar – Eclipse	Science + Comm – Sounder – Eclipse	Comm Only	Comm Only – Eclipse	Comm and Slew - Eclipse
Duration (hrs)	2	24 (continuous)	24 (continuous)	24 (continuous)	0.95	0.16667	0.16667	0.28333	0.16667	0.16667
Assumptions	At Earth. Comm in Receive Only, RCS	At Earth. Comm using X-band, ACS on wheels	At Earth. Comm using X-band, 2 EP engines active	At Mars. Comm using X-band, 1 EP engine active	Day side of science orbit. All inst. active except SAR/Sound. Full Ka-band downlink.	Night side, eclipse. Radar only. Full Ka-band downlink.	Night side, eclipse. Sounder only. Full Ka-band downlink.	Night side, but in Sun. No science inst. Full Ka-band downlink.	Night side, eclipse. No science inst. Full Ka-band downlink.	Night side, eclipse. No science inst. Full Ka-band downlink. Spacecraft is slewing to change observation orientation.

Mass Margins were computed using both JPL and NASA standards, as shown in Table B-11:

- Wet Allocation = Launch Vehicle capability (3195 kg)
- Dry MPV (Max Possible Value) = Wet Allocation – Propellant & Pressurant
- Dry CBE (Current Best Estimate) = Sum of spacecraft dry CBE values, including LV-side adapter CBE
- JPL Design Principles Dry Mass Margin = (Dry MPV – Dry CBE)/(Dry MPV)
  - JPL Design Principles require a dry mass margin of 30% for designs in Pre-Phase A and Phase A
- Dry MEV (Maximum Expected Value) = Sum of spacecraft dry MEV values (CBE + contingency), including LV-side adapter MEV
  - Note that this does not include the "System Contingency" shown on the Team X systems sheet
- NASA Margin = (Dry MPV – Dry MEV)/(Dry MEV)

Table B-11. Mass margins for studied mission concepts.

	Full mission concept	Ice-focused mission concept
Launch Vehicle	Falcon 9 re-usable	Falcon 9 re-usable
Launch Vehicle Mass Allocation (@C3 = 1 km^2/s^2	3195 kg	3195 kg
Spacecraft Dry CBE	1199 kg	1094 kg
Spacecraft Dry MEV	1486 kg	1350 kg
Propellant & Pressurant	1261 kg	1153 kg
Launch Mass (at 43% contingency, i.e., 30% JPL margin)	3035 kg	2773 kg
JPL Design Principles Margin	36%	44%
NASA Margin	25%	45%

After the Team X study, it was identified that the max throughput of the SPT140 thrusters should be 333 kg, rather than the 500 kg provided in the Team X study. If this is the case, the 4-thruster design is inadequate for an engine-out scenario.

- Max throughput for 3 thrusters: 333 kg x 3 thrusters = 999 kg
- The full mission required throughput: 1138 kg
- The ice-focused mission required throughput: 1036 kg

A thruster should be added, with all ripple effects accounted for. This is not reflected in this Team X report. It would result in a cost and mass increase in both mission concepts.

B.3.3 Science

The Team X study found that the full mission concept fulfills all stated science objectives. The measurements are centered about detecting water and hydrated materials are high (5 m) spatial resolution together with necessary geologic and stratigraphic context. The ice-focused mission concept fulfills the primary science objective "mapping the occurrence of near-surface ice," but does not include a similar visible and compositional context.

The Team X study noted that the utilization of the highly capable instruments is extremely low (approximately 6/10750 or about 0.05% for the 6 km patches and about 10/114 or about 9% for the radar). This is a consequence of the requisite high spatial resolution and the low telemetry availability.

Available telemetry (and lighting) are the only factors in principal limiting full utilization of the instruments. The science goals are met with the design utilization, however the science value of achieving full mapping and context at the payload resolution would be extremely large.

From a (NASA) programmatic standpoint, a technology investment in higher data return (larger aperture at Earth or improvement in optical communication or, perhaps interplanetary relay assets) would preclude the costs of missions and instruments to achieve coverage and would greatly improve the science return for unique launch opportunities (most outer planets missions). For example, MORIE could return global coverage at full resolution by increasing the Earth aperture diameter by a factor of 10.

Other technology developments that could enhance MORIE include onboard preprocessing data algorithm (to return key parameters in absence of more telemetry) and lower cost high-resolution instruments to enable retaining the mineralogic goals in the ice-focused mission concept.

The Team X study identified the following cost drivers:

- Instruments
- (Potentially) data analysis

Potential Cost Savings identified by the Team X study:

- Fly mission with one imaging team (NAC, WAC, CTX) and one radar team (PSAR/Sounder)
  - Can be difficult to convince TMCO this is valid, but makes sense for this mission
  - This will reduce modeled science costs (and size of team, so be careful) by three instruments, which is significant.

Potential Cost Uppers identified by the Team X study:

- Retrieval algorithms may be more complex than expected due to higher entropy at higher resolution. May affect any or all of the hi-res instrument teams. Challenges will be recognized in Phase E (mission risk).

B.3.4 Instruments

The mission is designed for a Mars orbit where in Year 1, it will be in a sun synchronous 3:00 PM orbit (as MRO) and where in Year 2, it will be in a polar orbit. The mission will use SEP, which means it is not highly power constrained. The ConOps consists of 57 minutes on the day side for CTX, HiRISE Lite, SWIR/TIR, and WAC, and 57 minutes on the night side for SAR/Sounder and TIR. Table B-12 shows an overview of the considered and selected instruments for the studied mission concepts.

Table B-12. Considered and selected instruments for the studied mission concepts.

Instrument	Full Mission	Ice-focused Mission
CTX–context imagers	Two	Two
SWIR/TIR Spectrometer	Yes	No
HiRISE Lite–TDI imager	Yes	No
WAC–wide angle camera	Yes	No
PSAR/Sounder	Yes, single sounder	Yes, dual frequency sounder

Tables B-13 and B-14 list the payload accommodations for studied mission concepts.

Table B-13. Payload accommodation for the full mission.

	CTX	HiRISE Lite	WAC	SWIR/TIR			PSAR/Sounder	
Measurement	Optical Context Imager	Hi-Resolution Optical Imager	Optical Wide Angle Imager	Shortwave IR Spectrometer	Thermal IR Spectrometer	IR Telescope	Polarimetric P-Band SAR	P-Band Sounder
Analogy or Heritage	MRO/CTX	MRO/HiRISE	MRO/MARCI	JPL/HiRIS	JPL/PREFIRE	HiRISE	JPL/EAGLE	
Mass (kg) (CBE)	3.37 each	19	1	1.5 (grassroots)	4.5 (PREFIRE + 50%)	39.7	90.9	
Power (W) (CBE)	5.8 each	30 (+30 W spacecraft heat)	4.6	Signal chain: 2 Cryocooler: 14	6 (PREFIRE +50%)		110 (direct current (DC) peak power) 500 (AC peak power)	
Dimensions (cm)			9.2 × 7.2 × 14	10 × 10 × 20 est.	10 × 10 × 20 est.	60 × 60 × 120 est.		
Configuration Constraints	Points fore & aft	Nadir pointing	Nadir pointing	Nadir point, but spacecraft nods instrument in direction of motion			On 0.5-m Boom	
Data Rate (Mbps)	40	32	.515	120 11 Gb/Patch (uncompressed)	0.16 17 Mb/Patch (uncompressed)		Raw: 219 Compressed: 0.25	Raw: 175.3 Compressed: 8.3
Thermal (C)	−35 to 27		−35 to 35	Active cryocooler Needs radiator surface or cold sink	Uncooled thermopile array			
Cost ($M FY25)	20 (NICM)	44 (NICM)	5.6 (NICM)					$170

Note: Costs shown are customer input values; costs used in studies were from independent NICM runs.

Table B-14. Payload accommodation for the ice-focused mission.

	CTX	PSAR/Dual Frequency Sounder		
Measurement	Optical Context Imager	Polarimetric P-Band SAR	P-Band Sounder	Sounder
Analogy or Heritage	MRO/CTX	JPL/EAGLE		SHARAD
Mass (kg) (CBE)	3.37 each	109.2		
Power (W) (CBE)	5.8 each	110 (DC peak power) 500 (AC peak power)		75 (DC peak power) 150 (AC peak power)
Dimensions (cm)				
Configuration Constraints	Points fore & aft	On 0.5-m Boom		
Data Rate (Mbps)	40	Raw: 219 Compressed: 0.25	Raw: 175.3 Compressed: 8.3	Raw: 350 Compressed: 1.6
Thermal (C)	−35 to 27			
Cost ($M FY25)	20 (NICM)	$170		

Note: Costs shown are customer input values; costs used in studies were from independent NICM runs.

Table B-15 gives more information on the instrument pointing requirements while Table B-16 provides information on the instrument measurement characteristics.

Table B-15. Instrument pointing requirements.

Parameter	CTX	HiRISE Lite	Wide Angle imager	SWIR/TIR spectrometer	PSAR/Sounder	PSAR/Dual Frequency Sounder
Control (deg) (Can we hit our target?)	0.6	0.1		0.1	0.5	0.5
Knowledge (Can we align our data with a coordinate system?)	0.1 deg 4 urad is ¼ pixel	ACS used MRO value of 29 urad		4urad is ¼ pixel	0.2 deg	0.2 deg
Stability (Is our image getting blurred?)				50 urad/s is ¼ pixel over exposure	0.5 deg	0.5 deg
Attitude	Spacecraft must fly such that two CTX tracks overlap	Pushbroom, so prefer spacecraft attitude fixed forward when taking data. Could angle TDI up to 20 degrees.	Pushbroom, so prefer spacecraft attitude fixed forward when taking data. Could angle up to 20 degrees.	Pushbroom, so prefer spacecraft attitude fixed forward when taking data. Could angle up to 20 degrees.	SAR looks 30 degrees to side. Must be side looking.	SAR looks 30 degrees to side. Must be side looking.

Table B-16. Instrument measurement characteristics.

Parameter	Context Imager	HiRISE Lite	Wide Angle imager	Shortwave IR	Thermal IR	Polarimetric SAR	Radar Sounder
Viewing Angle	Nadir	Nadir	Nadir	Nadir, nodding 20 deg (originally listed as 4.6 deg)	Nadir, nodding 20 degrees	30 degrees cross-track off nadir	Nadir
Spectral Angle	500–800 nm	400–1700 nm (Note: updated vs. customer inputs)	260 to 725 nm	1.3 to 4.2 µm (Note: updated vs. customer inputs)	6 to 25 µm (Note: updated vs. customer inputs)	Center Frequency 400 MHz; Bandwidth: 20 MHz	Center Frequency 400 MHz; Bandwidth: 100 MHz
Spatial Resolution	6 km/px	1 km/px	1 km–10 km/px	5 m/px sampling	50 m/px sampling	Spatial: 100m	
Swath Width (km)	30	6	1000–10000	6	6	25	25
Measurement Scenario	Day only	Day only, targeted imagery tracks, 10 s per week	Day only	Day only	Day only, spot checking at night	Nominally night only, but can operate day	Nominally night only, but can operate day

The following consists of a list of all instruments including a cost assessment with NICM 8.5.

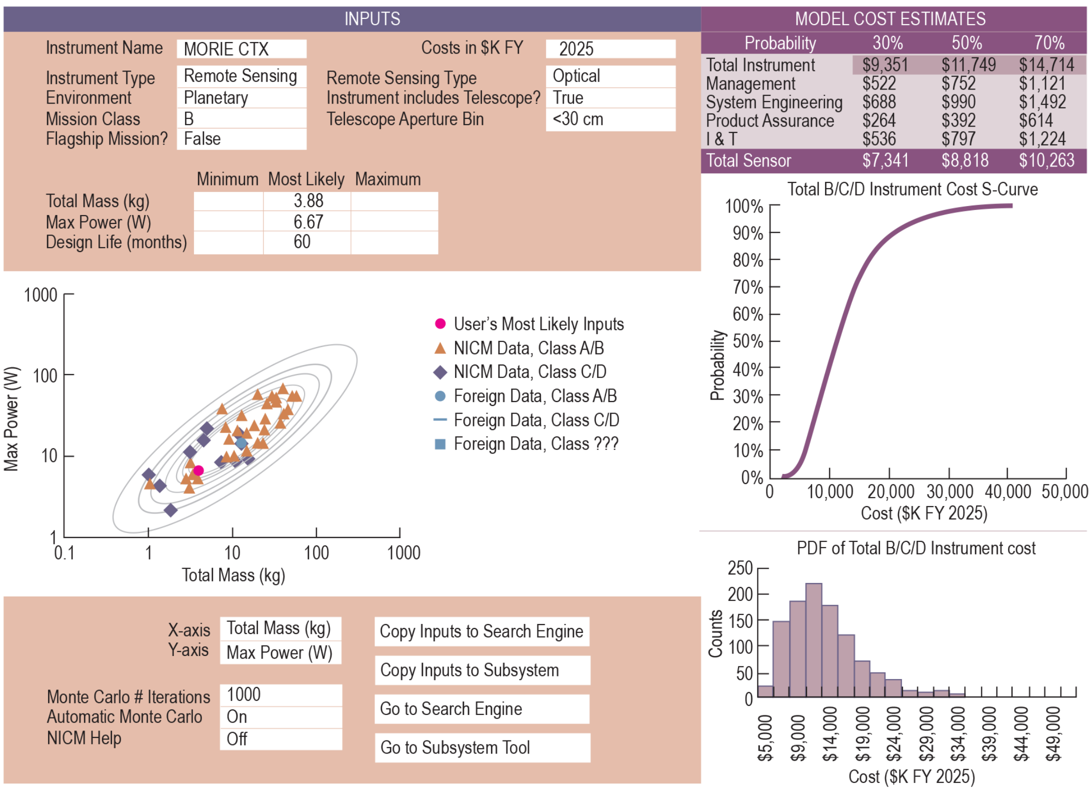
CTX

- Design Assumptions
  - Heritage copy of MRO/CTX
  - 5K-pixel single-band visible CCD line array
- Operational Overview
  - Pushbroom imager
  - Operates during dayside when sounding
- Rationale
  - Provides context imaging for sounder
  - Also stereo imaging

Strengths, Opportunities, Weaknesses, Threats (SOWT)

- Strengths
  - Heritage instrument
- Opportunities
- Weaknesses
- Threats
  - Malin Space Science Systems (MSSS) may not be a viable source in the future

The CTX cost summary is shown in Figure B-22. The CTX is assumed to be a heritage copy of the MRO/CTX camera. The contingency is not B2P since many electronics parts will no longer be available.



Notes: 1. Mass input is CBE + contingency. 2. Cost used in study is 50th percentile NICM result ($11.7M) for first unit cost; 2nd unit is assumed 42% of 1st unit, for total cost of $16.6M.

Figure B-22. CTX Cost with NICM 8.5.

Wide Angle Camera (WAC)

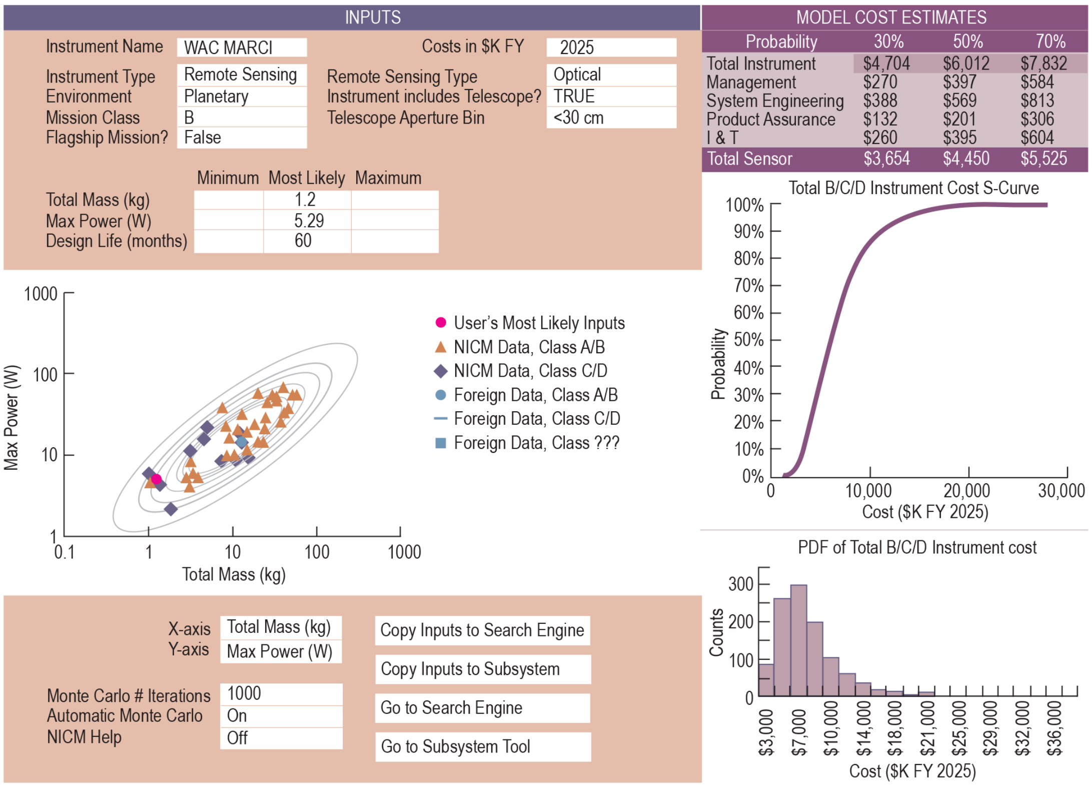
- Design Assumptions
  - Heritage copy of MRO/MARCI
  - 1K x [?]-pixel visible CCD array
- Operational Overview
  - Pushbroom imager
  - Nadir pointing
  - Operates continuously during dayside

SOWT

- Strengths
  - Heritage instrument

- Opportunities
- Weaknesses
- Threats
  - MSSS may not be a viable source in the future

The WAC cost summary can be seen in Figure B-23.



Notes: 1. Mass input is CBE + contingency. 2. Cost used in study is 50th percentile NICM result ($6M).

Figure B-23. WAC Cost with NICM 8.5.

High Resolution Imager (HiRISE) Lite

- Design Assumptions
  - Downscaled version of MRO/HiRISE
  - 30-cm telescope
  - 6k x 4k-pixel visible CCD array
  - 32 bands as an over-the-detector filter array
- Operational Overview
  - Pushbroom imager
  - TDI (Time Domain Integration)
  - Nadir pointing
  - Operates during dayside
  - Targets 6 km x 6 km patches of interest

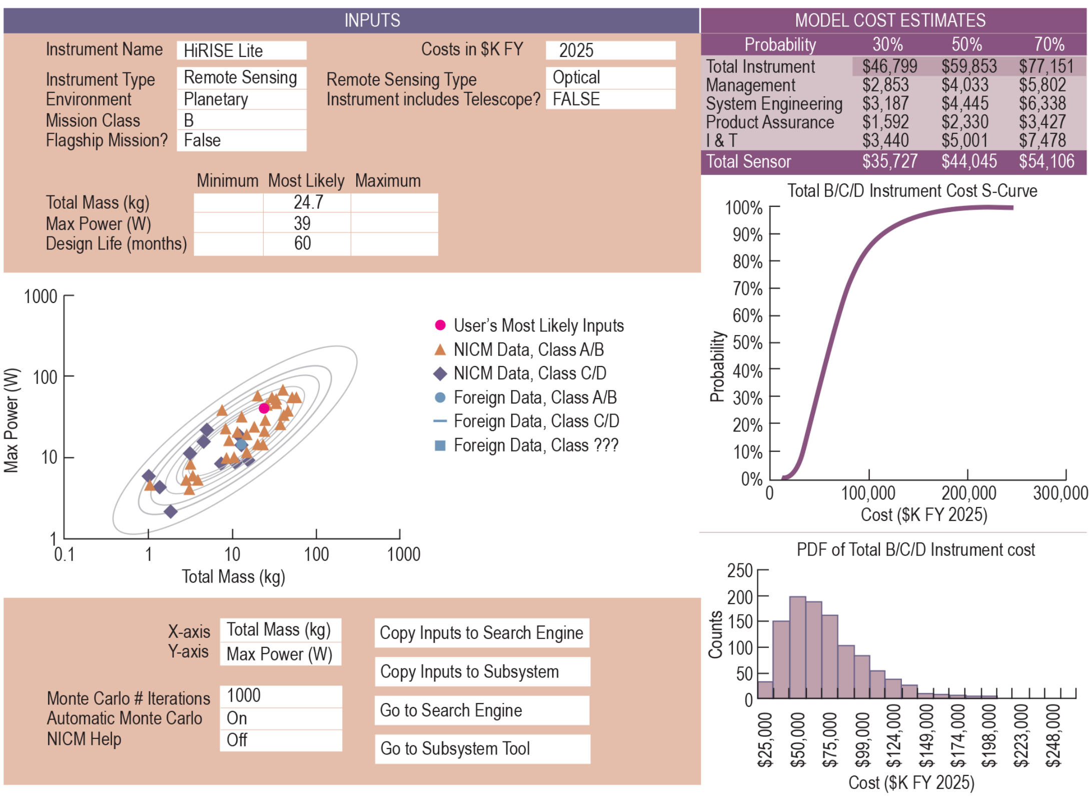
SOWT

- Strengths
  - Similar to heritage MRO/HiRISE instrument
- Opportunities
  - Telescope could be combined with SWIR/TIR, if the configuration allows, but large focal plane might be a challenge.
- Weaknesses
- Threats

Assumptions:

- 30% contingency (new design)
- CBE mass 19 kg (assumptions)
- CBE power 30 kg (assumptions)
- (30 W Heater power supplied by spacecraft)

The HiRISE Lite cost summary can be seen in Figure B-24.



Probability	30%	50%	70%
Total Instrument	$46,799	$59,853	$77,151
Management	$2,853	$4,033	$5,802
System Engineering	$3,187	$4,445	$6,338
Product Assurance	$1,592	$2,330	$3,427
I & T	$3,440	$5,001	$7,478
Total Sensor	$35,727	$44,045	$54,106

Notes: 1. Mass input is CBE + contingency. 2. Cost used in study is 50th percentile NICM result ($59.9M).

Figure B-24. HiRISE Lite Cost with NICM 8.5.

SWIR/TIR Spectrometer

- Design Assumptions
  - MRO/HiRISE based telescope
  - SWIR
    - □ 0.5-5 micron Dyson spectrometer, based on study team-provided design
    - □ 1280 x 480-pixel MCT Teledyne CHROMA detector

- TIR
    - ◻ 6-25 micron grating spectrometer, based on PREFIRE
    - ◻ 128 x 64-pixel microbolometer array
- Operational Overview
  - Pushbroom spectrometer
  - Operates during the dayside
  - Targets 6 km x 6 km patches of interest
  - TIR needs a space view, either through the telescope or off to side through a hole
- Rationale
  - SWIR and TIR have similar telescope needs (diffraction, SNR)

SOWT

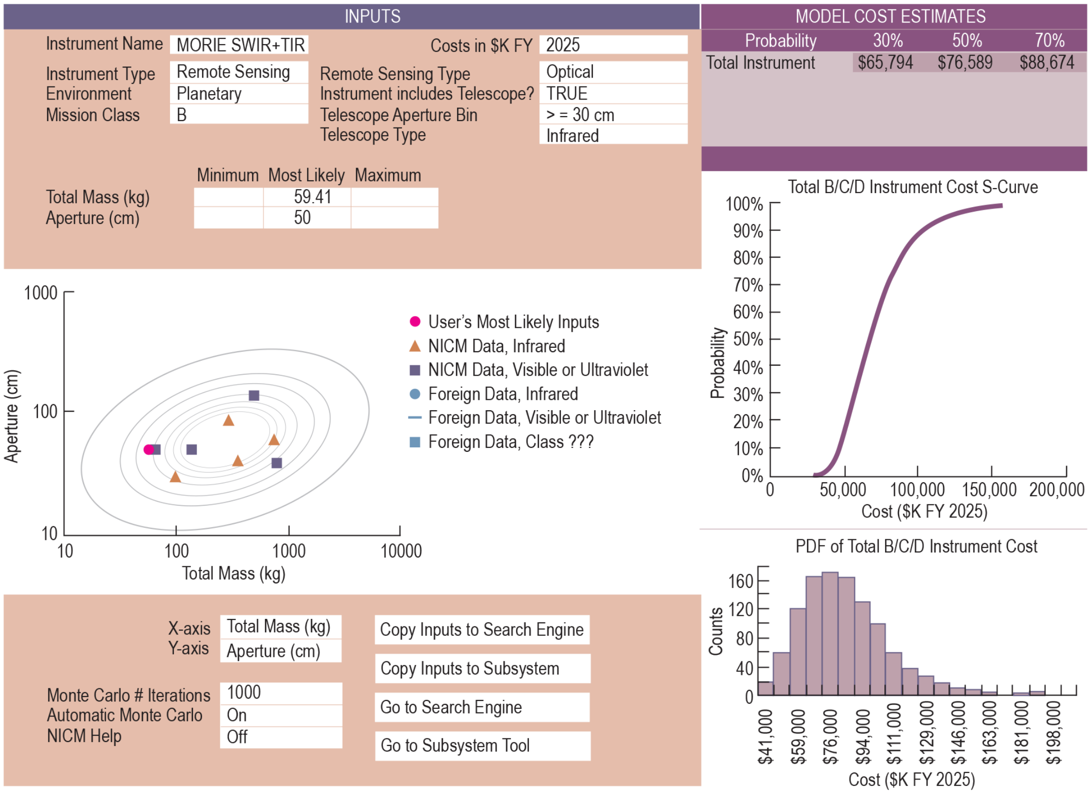
- Strengths
  - Telescope heritage MRO/HiRISE
  - Spectrometers based on ongoing JPL projects (Dyson airborne & PREFIRE)
- Opportunities
- Weaknesses
  - 50-cm telescope needs to nod to meet SNR of 100:1. Drives requirement for gimbal.
- Threats

Technology Development

- Need 128 x 64-pixel microbolometer arrays

The SWIR/TIR cost summary can be seen in Figure B-25.

Note that NICM model only depends on aperture size and mass. Since most of the mass is in the telescope, removing the TIR makes only a small difference. Telescope mass is from HiRISE.



Notes: 1. Mass input is CBE + contingency. 2. Cost used in study is 50th percentile NICM result ($76.6M).

Figure B-25. SWIR/TIR Cost with NICM 8.5.

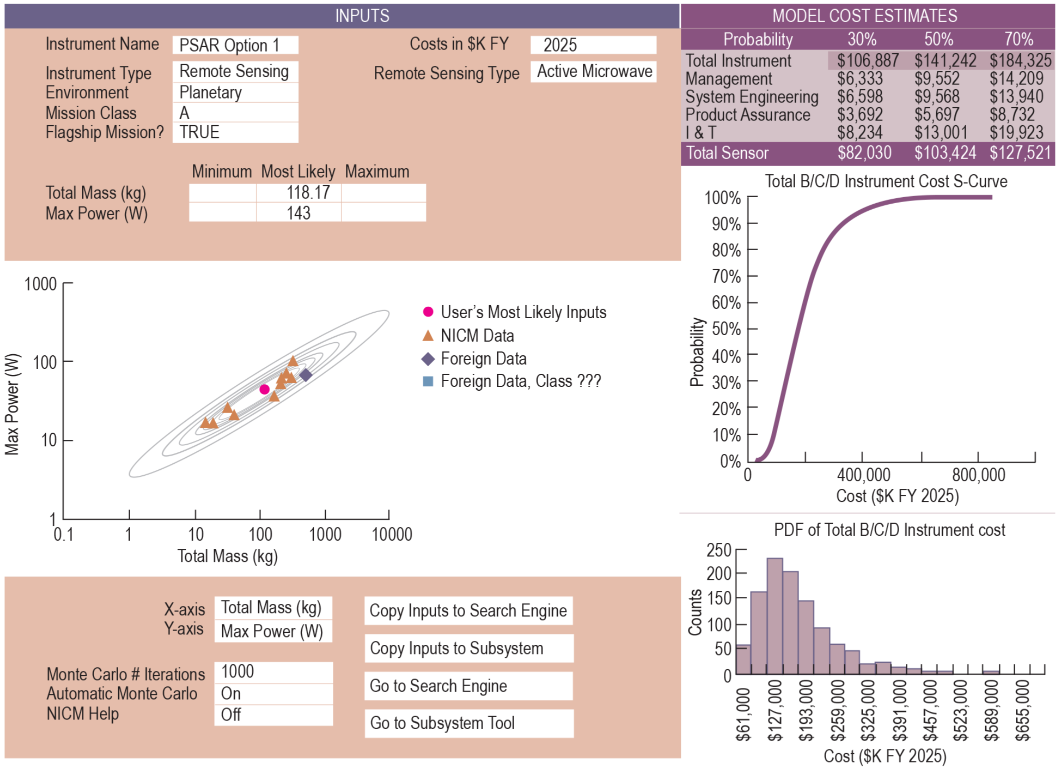
PSAR/Sounder

- Design Assumptions
  - Polarimetric P-Band SAR based on JPL/EAGLE
  - Additional electronics mass added for sounder mode
  - Option 2: Additional mass and power added for second SHARAD-based sounder at a different frequency
- Operational Overview
  - SAR side looking at 30 degree, sounder nadir; slews spacecraft to change modes.
  - Option 1: operates mainly during nightside, since optical instruments use day

SOWT

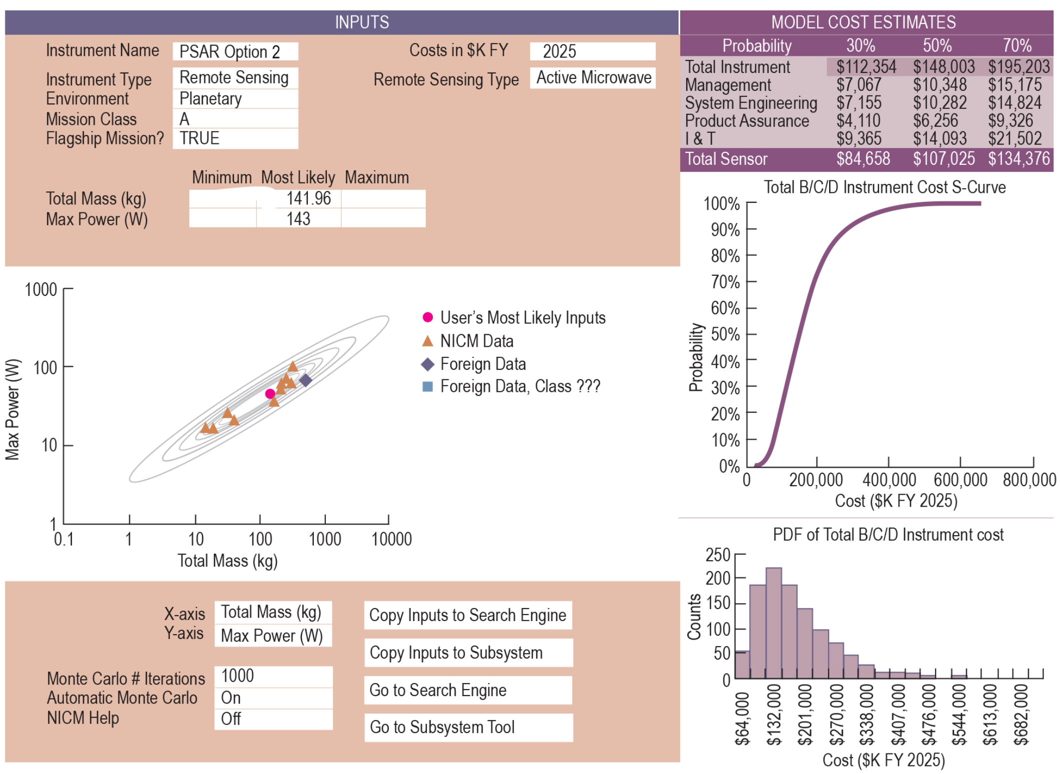
- Strengths
- Opportunities
- Weaknesses
  - Largely based on non-heritage Eagle SAR study from 2010
- Threats

The PSAR/Sounder cost summary is shown in Figure B-26 (option 1) and in Figure B-27 (option 2).



Notes: 1. Mass input is CBE + contingency. 2. Cost used in study is 50th percentile NICM result ($141.2M).

Figure B-26. PSAR/Sounder Option 1 Cost with NICM 8.5.



Notes: 1. Mass input is CBE + contingency. 2. Cost used in study is 50th percentile NICM result ($148.0M).

Figure B-27. PSAR/Sounder Option 2 Cost with NICM 8.5.

B.3.5 Mission Design

The mission design assumptions for the Team X are as follows:

- LV: Falcon 9 Recoverable
  - C3 = 1 km^2/s^2
  - Launch mass = 3,195 kg
- SEP from Earth to Mars, spiral down to LMO
  - ΔV – Heliocentric: 4.5 km/s, Spiral: 3.0 km/s, At Mars: 0.5 km/s
  - Total ΔV: 8 km/s
  - Possible thrusters: SPT-140, XR-5, Xenon Ion Propulsion System (XIPS), RIT 2x, (Advanced Electric Propulsion System)
- Solar power range – 12-25 kW BOL @ 1 AU
  - Must be optimized with thrusters, dry mass, and time of flight (TOF) targets
  - Rough ROT – 8 kW per Metric Ton (MT) dry mass
  - Secondary ROT – 75% of thruster saturation at Mars

EP power:

- EP system input powers: 9600 W for two engines at Earth, 4800 W for one engine at Mars
- Starting wet mass: 3000 kg
- EP power and wet mass were re-scaled for the ice-focused mission concept to keep the same acceleration profile

A Psyche-like SEP system was chosen for this Team X study:

- 4 x SPT140 (2 active)
- Max throughput: 500 kg ea.*
- Masses [kg]:
  - Thruster [x4] -10.1
  - PPU [x2] -13.7
  - Gimbal [x4]-3.9
  - Xenon Feed Controller (XFC) [x4] -1.1
- Arrays: 16 kW BOL @1AU
  - Psyche: 20 kW, 5-panel
  - Use 4-panel for Mars

Psyche info:

- SSL Commercial GEO Bus
- 2022 launch to asteroid (via Mars flyby)
- Masses
  - Wet: 2700 kg +/- 200 kg
  - Dry: 1900 kg (max allocation)
  - Xenon: 835 kg (up to 1085 kg in tanks)
- SEP ΔV: 6.1 km/s

After the study, it was identified that the max throughput of the SPT140 thrusters should actually be 333 kg, not 500 kg. If this is the case, the 4-thruster design is inadequate for an engine-out scenario (333 kg x 3 thrusters = 999 kg < 1138 kg (full mission), 1038 kg (ice-focused mission), and a thruster should be added, with all ripple effects accounted for. This is not reflected in this Team X study report.

The mission timeline is shown in Figure B-18 with a planned launch in 2026-2035 and assuming typical durations for cruise (10-15 months), spiral (6-12 months), total (~2 years). More details can be seen in Figure B-28. The mission dates and durations are very sensitive to mass, power, and SEP assumptions.

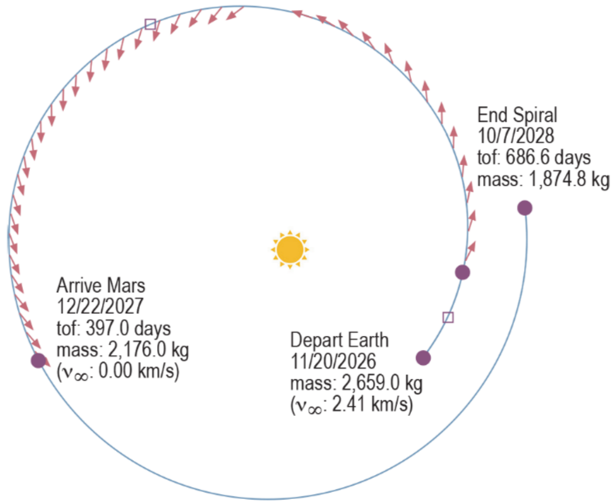


Figure B-28. Planned mission trajectory for MORIE.

The MORIE science orbits are planned as follows:

- Primary – 3 pm sun-synch (MRO-like)
  - 300 km x 92.7 deg, 114 min. period
  - Duration: 1 Mars year
- Secondary – Polar
  - 300 km x 90 deg
  - LST drifts backwards 1 hour per month

The SEP to change orbits encompasses 150-250 m/s ΔV over 3-6 weeks can duty cycle with science during transfer). The Team X study has budgeted 500 m/s for 2 transfers.

The mission design cost with a planned launch date of 11/20/2026 is shown in Tables B-17 and B-18.

Table B-17. Mission design cost based on a 11/20/2026 launch date broken down by Phase.

Phase	Duration (mo)	Cost ($M)
Phase A	12	3.39
Phase B	12	6.98
Phase C	22	10.47
Phase D1	14	7.38
Phase D2	4	1.50
Phase E	70	9.58
Total	**134**	**39.30**

Table B-18. Mission design cost based on a 11/20/2026 launch date broken down by Phase.

	12	12.01	12.02	12.03	12.04	07 and 09	9A.06	7.06	7.08	Total
Phase A Total Cost ($M)	3.39	0.41	1.60	0.00	1.37	0.00	0.00	0.00	0.00	3.39
Phase B Total Cost ($M)	6.57	0.41	1.60	0.42	4.13	0.41	0.41	0.00	0.00	6.98
Phase C Total Cost ($M)	9.82	0.75	1.73	0.78	6.56	0.65	0.65	0.00	0.00	10.47
Phase D1 Total Cost ($M)	4.35	0.48	1.03	0.50	2.34	3.03	0.69	2.34	0.00	7.38
Phase D2 Total Cost ($M)	0.71	0.14	0.43	0.14	0.00	0.79	0.00	0.79	0.00	1.50
Phase E Total Cost ($M)	0.00	0.00	0.00	0.00	0.00	9.58	0.29	8.93	0.37	9.58
Development Total (Phases A–D)	24.84	2.19	6.40	1.84	14.41	4.88	1.75	3.13	0.00	29.72
Ops Total	0.00	0.00	0.00	0.00	0.00	9.58	0.29	8.93	0.37	9.58
Total	24.84	2.19	6.40	1.84	14.41	14.47	2.04	12.06	0.37	39.30

B.3.6 Configuration

The Team X study made the following design requirements and assumptions:

- Full mission concept: Nadir pointing requirements for instruments; gimbal arms for SWIR & TIR telescope. SAR points 30 deg cross-track using spacecraft slew.
- Ice-focused mission concept: Nadir pointing requirements for CTX & Sounder. SAR points 30 deg cross-track using spacecraft slew.
- Launch Vehicle: Falcon 9
- Payload:
  - Full mission concept: 2 CTX, HiRISE Lite, WAC (MARCI), SWIR, TIR & SAR/Sounder
  - Ice-focused mission concept: 2 CTX & SAR/dual freq sounder
- Assumptions
  - Based on Next Mars Orbiter (NeMO) configuration
  - SAR based on 6 m aperture
  - Both mission concepts are configured similarly except for instruments
  - Baseline launch vehicle is Falcon 9 but have the option to increase in LV size if needed

The design configuration used in this Team X study has been inherited from the Mars Program formulation NeMO study.

- SEP propulsion tanks stacked vertically for better load lines and center of gravity
- Instrument placement driven by nadir pointing requirements
- Full mission concept: gimbal arms added for SWIR & TIR FOV requirements
- Telecom and ACS hardware placement based on pointing requirements

Table B-19 shows the configuration summary for the studied mission concepts.

Table B-19. Configuration summary for the studied mission concepts.

Concept	Launch Vehicle	Configuration	Comments
Full Mission	Falcon 9	2 CTX, SWIR, TIR, HiRISE Lite, WAC (MARCI), PSAR/Sounder	Based on NeMO study, gimbal arms for SWIR & TIR telescope
Ice-focused Mission	Falcon 9	2 CTX, PSAR/Dual Frequency Sounder	Based on NeMO study, same as full mission except for HGA diameter, battery size & Ultraflex Solar Array diameter

Figures B-29 to B-31 provide more information on the design configuration of the full mission concept and Figures B-32 to B-35 provide more information on the design configuration of the ice-focused mission concept. The Secondary support structure, cabling, thermal protection and prop line routing not shown in the figures but need to be accommodated. The location of the payload hardware may need to be optimized to fulfill stress and spin balance requirements.

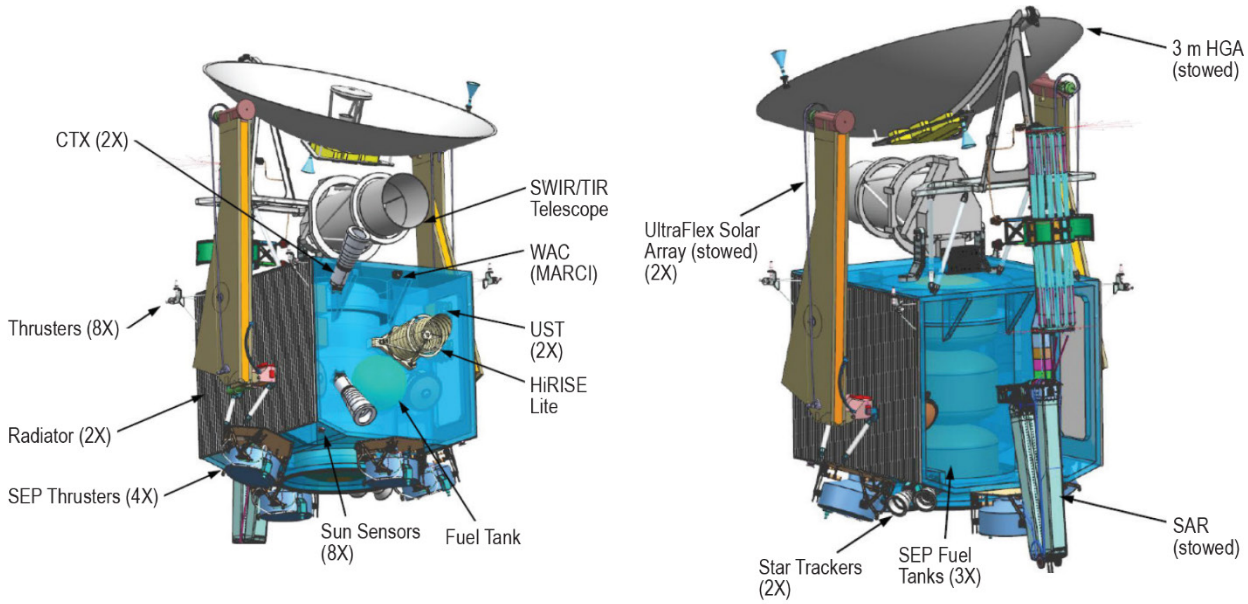


Figure B-29. Design configuration of the full mission concept (stowed).

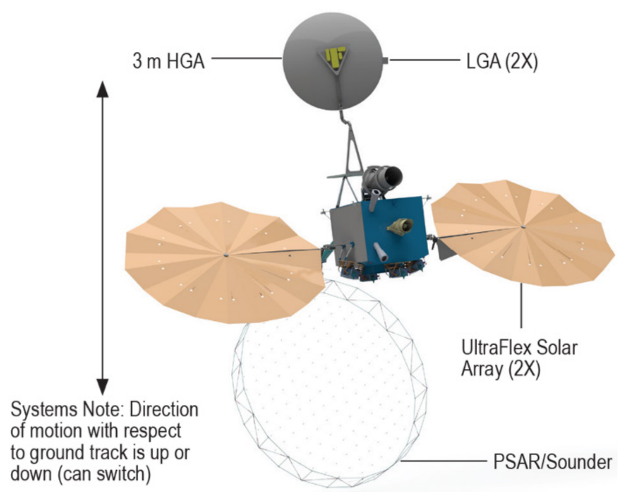


Figure B-30. Design configuration of the full mission concept (deployed).

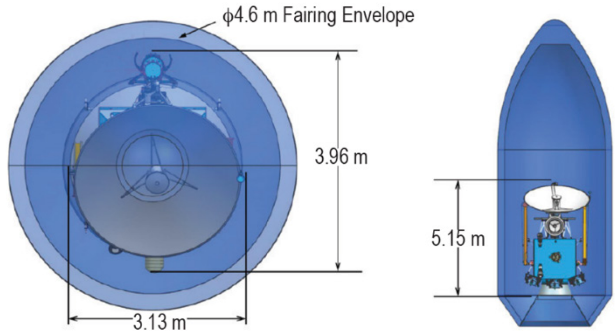


Figure B-31. Design configuration of the full mission concept.

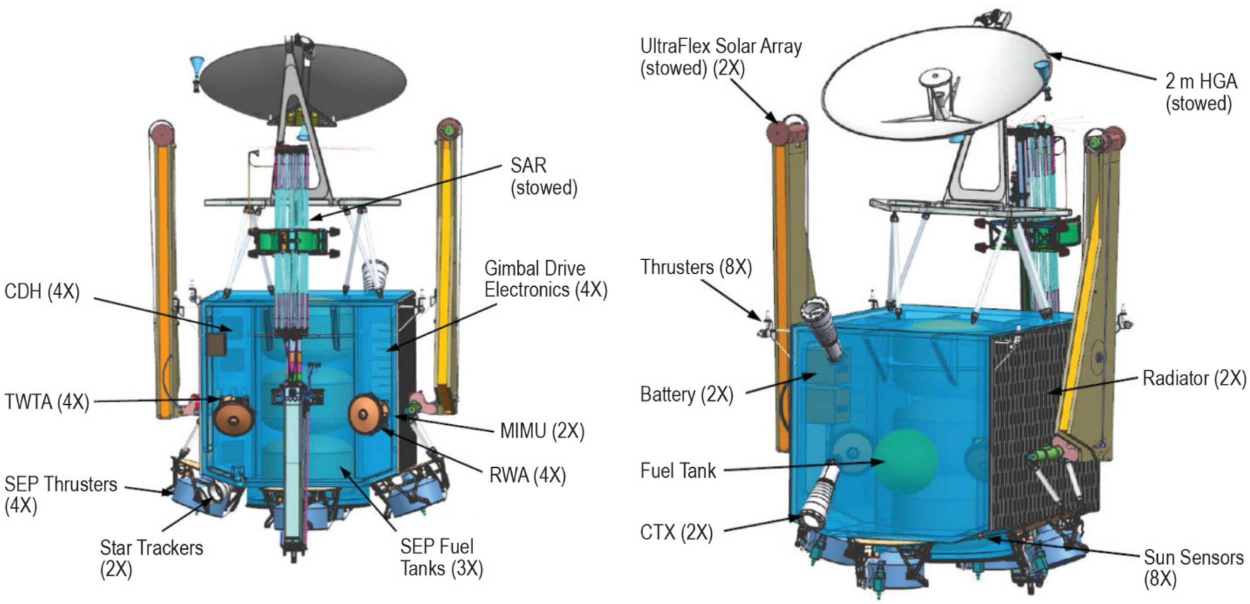


Figure B-32. Design configuration of the ice-focused mission concept (stowed).

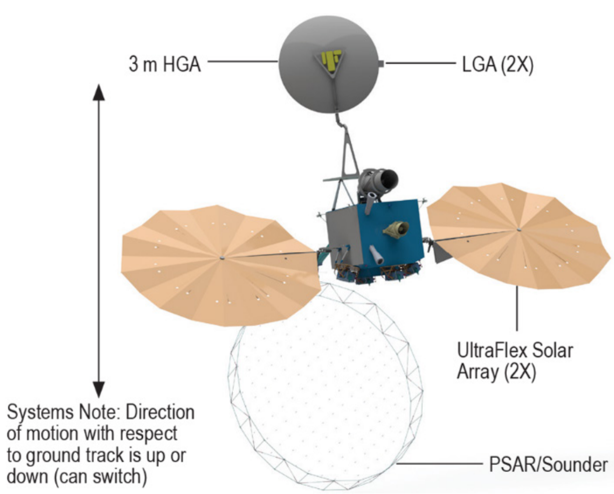


Figure B-33. Design configuration of the ice-focused mission concept (deployed).

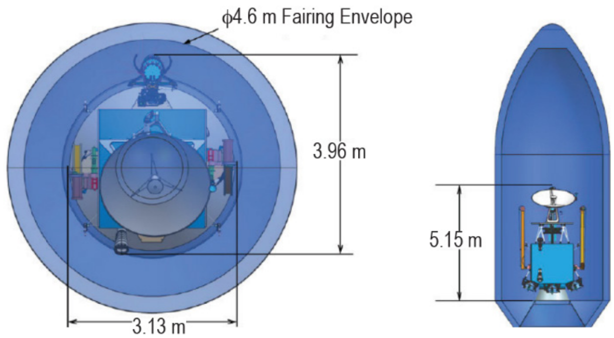


Figure B-34. Design configuration of the ice-focused mission concept.

B.3.7 Mechanical

The Team X study made the following design assumptions:

- Ultraflex structure costs carried by Power
- There are no carried elements
- Study team supplied base design
  - Design based on NeMO study
  - No provided MEL
- No non-standard materials
- Scan platform for SWIR (HiRISE) & TIR (PREFIRE).
  - Included in the full mission concept only

The bus shape was selected based on the NeMO study. Ultraflex arrays were used based on the NeMO study. Their size was set based on power requirements. A HGA boom is needed due to a 2-axis articulation and a scan platform is needed to articulate two instruments. The resulting Team X design is as follows:

- Spacecraft Bus: Rectangular Bus
- Power Source: Two (2) Ultraflex Solar Arrays
  - Each Array on a 2-degrees of freedom (DOF) Gimbal
- Telecom
  - 1 HGA on a 2-DOF Gimbal
  - 1 LGA
- Payload Support Structure
  - Scan Platform for SWIR (HiRIS) and TIR (PREFIRE)
  - Scan Platform on a 1-DOF Gimbal
- Other Items
  - Four (4) AerojetMR-111C engines for SEP system
  - Four (4) Reaction Wheels for Control

The mechanisms and deployments were designed as follows:

- Power Deployments
  - Spring driven Solar Array deployment
  - Ultraflex opening after spring deployment
- Telcom Deployments
  - HGA deploys on a single boom
  - HGA driven by 2-axis actuators

- Launch Vehicle Separation: Marmon clamp
- Other Separations
  - SAR Instrument deploys
    - Deployment mechanism contained in Instrument
  - Deployable Scan Platform
    - 1-DOF actuator to articulate

The mass drivers for this mechanical design are:

- The primary structure is the highest mass item
- The harness is the second highest mass item

Potential mass savings are identified as:

- Reducing the number of booms and actuators.
- Ballast could be reduced by considering mass properties during the initial design.

Potential mass uppers are identified as:

- As the details become more know the scan platform could be heavier than estimated.

The detailed mass list for the full mission concept is shown in Table B-20 and the detailed mass list for the ice-focused mission concept is shown in Table B-21.

Table B-20. Detailed mass list for the full mission concept.

Item	Type	Quantity	CBE	Contingency	CBE + Cont.
Primary Structure	Structure	1	201.7 kg	30%	262.2 kg
Secondary Structure	Structure	1	19.8 kg	30%	25.7 kg
Tertiary Structure	Structure	1	5.6 kg	30%	7.3 kg
Power Support Structure	Structure	1	2.8 kg	30%	3.7 kg
Power Mechanisms	Mechanism		10.4 kg	30%	13.5 kg
Telecom Support Structure	Structure	1	5.0 kg	30%	6.5 kg
Telecom Mechanisms	Mechanism		9.9 kg	30%	12.9 kg
Launch Vehicle Adapter–Structure	Structure	1	48.9 kg	30%	63.6 kg
Launch Vehicle Adapter–Mechanism	Mechanism		18.0 kg	30%	23.4 kg
Balance/Ballast	Structure	1	49.4 kg	30%	64.2 kg
Integration Hardware	Structure	1	15.9 kg	30%	20.7 kg
Scan Platform Base	Structure	1	5.0 kg	30%	6.5 kg
Scan Platform Bus Offset	Structure		3.0 kg	30%	3.9 kg
Scan Platform 1-DOF Actuator	Mechanism		4.5 kg	30%	5.9 kg
Harness	Cabling–Manufacturing	1	75.7 kg	30%	98.4 kg
Mechanical Total			**399.9 kg**	**30%**	**519.9 kg**
Harness Total			**75.7 kg**	**30%**	**98.4 kg**

Systems Note: "Mechanical Total" at left includes LV adapter mass, and thus differs from "Structures & Mechanisms" line item in Systems MEL.

Table B-21. Detailed mass list for the ice-focused mission concept.

Item	Type	Quantity	CBE	Contingency	CBE + Cont.
Primary Structure	Structure	1	186.2 kg	30%	242.1 kg
Secondary Structure	Structure	1	17.7 kg	30%	23.0 kg
Tertiary Structure	Structure	1	5.3 kg	30%	6.9 kg
Power Support Structure	Structure	1	2.6 kg	30%	3.4 kg
Power Mechanisms	Mechanism		10.4 kg	30%	13.5 kg
Telecom Support Structure	Structure	1	3.6 kg	30%	4.7 kg
Telecom Mechanisms	Mechanism		9.9 kg	30%	12.9 kg
Launch Vehicle Adapter–Structure	Structure	1	44.6 kg	30%	57.9 kg
Launch Vehicle Adapter–Mechanism	Mechanism		18.0 kg	30%	23.4 kg
Balance/Ballast	Structure	1	45.0 kg	30%	58.5 kg
Integration Hardware	Structure	1	14.6 kg	30%	19.0 kg
Harness	Cabling–Manufacturing	1	71.1 kg	30%	92.4 kg
Mechanical Total			**357.9 kg**	**30%**	**465.3 kg**
Harness Total			**71.1 kg**	**30%**	**92.4 kg**

Systems Note: "Mechanical Total" at left includes LV adapter mass, and thus differs from "Structures & Mechanisms" line item in Systems MEL.

The Team X study assumed that the solar array cost is split into power (costing the Ultraflex including the structure) and mechanical (costing the boom, gimbal, and the deployment motor). 1 STM/DTM/TDM, 1 Harness EM, 1 Harness Testbed, and no mechanical EM were assumed. The WBS cost breakdown is provided in Table B-22 for the full mission concept and in Table B-23 for the ice-focused mission concept.

Table B-22. WBS Breakdown Cost for the full mission concept.

WBS Title	NRE	RE	Labor	Procurement	Services	Total Cost
06.07–Mechanical Subsystem	**$34.40M**	**$16.69M**	**$17.12M**	**$23.58M**	**$10.40M**	**$51.09M**
06.07.01–Mechanical Subsystem Management	$1.73M	$0.42M	$1.52M	$0.28M	$0.34M	$2.14M
06.07.02–Mechanical Subsystem Engineering	$1.59M	$0.39M	$1.40M	$0.26M	$0.32M	$1.98M
06.07.03–Loads & Dynamics Analysis	$3.34M	$0.00M	$3.34M	$0.00M	$0.00M	$3.34M
06.07.04–Configuration & Mass Properties	$1.58M	$0.38M	$1.40M	$0.26M	$0.32M	$1.97M
06.07.05–Structural Hardware	$13.23M	$7.84M	$4.64M	$11.38M	$5.06M	$21.07M
06.07.06–Mechanisms	$8.98M	$5.32M	$3.43M	$8.01M	$2.86M	$14.31M
06.07.07–Mechanical Subsystem EGSE	$0.00M	$0.00M	$0.00M	$0.00M	$0.00M	$0.00M
06.07.08–Mechanical Subsystem MGSE	$2.11M	$1.25M	$0.74M	$1.81M	$0.81M	$3.36M
06.07.09–Mechanical Subsystem I&T	$1.84M	$1.09M	$0.64M	$1.58M	$0.70M	$2.93M
06.11–Harness	**$6.78M**	**$7.21M**	**$2.48M**	**$4.35M**	**$7.16M**	**$13.99M**
06.11.01–Harness Management	$0.70M	$0.17M	$0.51M	$0.13M	$0.24M	$0.87M
06.11.02–Harness Engineering	$1.22M	$0.30M	$0.88M	$0.23M	$0.41M	$1.51M
06.11.03–Harness Design	$0.27M	$0.07M	$0.20M	$0.05M	$0.09M	$0.34M
06.11.04–Harness Parts	$0.69M	$1.00M	$0.14M	$0.59M	$0.96M	$1.69M
06.11.05–Harness Fab & Assy	$2.29M	$3.34M	$0.45M	$1.97M	$3.21M	$5.63M
06.11.06–Harness I&T	$1.60M	$2.34M	$0.32M	$1.38M	$2.25M	$3.94M
06.13–Materials & Processes	**$4.04M**	**$0.45M**	**$4.37M**	**$0.13M**	**$0.00M**	**$4.49M**
02.07–Contamination Control	**$2.17M**	**$0.53M**	**$2.43M**	**$0.17M**	**$0.09M**	**$2.69M**

Table B-23. WBS Breakdown Cost for the ice-focused mission concept.

WBS Title	NRE	RE	Labor	Procurement	Services	Total Cost
06.07–Mechanical Subsystem	**$31.13M**	**$14.75M**	**$15.93M**	**$20.72M**	**$9.24M**	**$45.88M**
06.07.01–Mechanical Subsystem Management	$1.73M	$0.42M	$1.52M	$0.28M	$0.34M	$2.14M
06.07.02–Mechanical Subsystem Engineering	$1.59M	$0.39M	$1.40M	$0.26M	$0.32M	$1.98M
06.07.03–Loads & Dynamics Analysis	$3.34M	$0.00M	$3.34M	$0.00M	$0.00M	$3.34M
06.07.04–Configuration & Mass Properties	$1.58M	$0.38M	$1.40M	$0.26M	$0.32M	$1.97M
06.07.05–Structural Hardware	$11.73M	$6.95M	$4.11M	$10.09M	$4.49M	$18.69M
06.07.06–Mechanisms	$7.55M	$4.47M	$2.88M	$6.73M	$2.40M	$12.02M
06.07.07–Mechanical Subsystem EGSE	$0.00M	$0.00M	$0.00M	$0.00M	$0.00M	$0.00M
06.07.08–Mechanical Subsystem MGSE	$1.94M	$1.15M	$0.68M	$1.66M	$0.74M	$3.08M
06.07.09–Mechanical Subsystem I&T	$1.67M	$0.99M	$0.59M	$1.44M	$0.64M	$2.66M
06.11–Harness	**$6.48M**	**$6.78M**	**$2.42M**	**$4.09M**	**$6.74M**	**$13.25M**
06.11.01–Harness Management	$0.70M	$0.17M	$0.51M	$0.13M	$0.24M	$0.87M
06.11.02–Harness Engineering	$1.22M	$0.30M	$0.88M	$0.23M	$0.41M	$1.51M
06.11.03–Harness Design	$0.27M	$0.07M	$0.20M	$0.05M	$0.09M	$0.34M
06.11.04–Harness Parts	$0.64M	$0.94M	$0.13M	$0.55M	$0.90M	$1.58M
06.11.05–Harness Fab & Assy	$2.14M	$3.12M	$0.42M	$1.84M	$3.00M	$5.26M
06.11.06–Harness I&T	$1.50M	$2.19M	$0.29M	$1.29M	$2.10M	$3.69M
06.13–Materials & Processes	**$4.04M**	**$0.45M**	**$4.37M**	**$0.13M**	**$0.00M**	**$4.49M**
02.07–Contamination Control	**$2.17M**	**$0.53M**	**$2.43M**	**$0.17M**	**$0.09M**	**$2.69M**

The cost drivers are:

- The largest cost item is the Primary Structure.
- The Power and Telecom gimbals are the next highest cost items.

Potential cost savings are identified as:

- Reducing the mechanisms reduces the cost as the gimbals are large cost items.

Potential cost uppers are:

- There are no standout items that would drive the cost up. Any refinement or change in requirements could be a cost upper. Especially if complexity is high.

Table B-24 provides a mechanical comparison. The full mission concept was the baseline. The ice-focused mission concept removed the scan platform when SWIR and TIR were descoped.

Table B-24. Mechanical comparison.

Concept	Mechanical (06.07 Mass)	Mechanical (06.07 Cost)	Configuration	Comments
Full mission	399.9 kg	$51.09M	Baseline Configuration.	
Ice-focused mission	357.9 kg	$45.88M	Retained 2 CTX and SAR.	Removed Scan Platform when instruments were descoped.

B.3.8 Attitude Control System (ACS)

The Team X study defined the MORIE ACS architecture as follows:

- Stabilization: 3-Axis
- Attitude Determination
  - Star tracker measurements augmented by IMU
  - Sun sensor for safe modes / recovery

- Attitude Control
  - Cruise: attitude control provided by SEP thrusters (no analysis so far on configuration requirements)
  - Mars orbit: attitude control provided by reaction wheels (4 wheels for redundancy) with hydrazine RCS thrusters for momentum unloading
- Slewing
  - Slews on reaction wheels in normal operation
  - RCS thrusters can be used for slews in safe mode if needed
  - Solar panels and HGA are on 2-axis gimbals => slews in Mars orbit needed for safe modes only

The ACS design is the same for both studied concepts and its maintenance involves:

- Wheel momentum unloading: ~0.05 kg/burn, burn required every ~2.5 days => 580 burns over 4-year science mission = 30 kg prop
- 20 kg margin for future design changes (mass properties, configuration changes, etc.)

The ACS cost drivers identified by the Team X study are:

- Heritage is a major driver in ACS cost model (e.g. similar to previous mission with major mods vs similar with minor mods)

Potential cost savings are:

- Choose 3 reaction wheels instead of 4 (loss of redundancy / increased technical risk)
- Switch to a less expensive star tracker, e.g. SodernHydra 1.9 (cost $670k per unit compared to $1.4M per unit for the Jena-OptronikASTRO 15 which was used on Psyche – some risk of breaking Psyche heritage)

The ACS cost is shown in Table B-25. In particular, the full mission cost is assumed "similar with major modifications". This means that it is different from Psyche (e.g. built by an industry partner other than MAXAR). The ice-focused mission cost is assumed "similar with minor modifications". This assumption comes with some additional cost risk of not being able to apply sufficient heritage in either algorithms / flight software (FSW) or hardware (H/W) from previous mission to keep cost to this number. Minor modifications signifies "like Psyche" (e.g. built by the same contractor, the same FSW, built by the same people).

Table B-25. MORIE ACS Cost.

Full mission											
All Units Cost		Phase A	Phase B	Phase C (Subsystem Design, Fab & I&T)			Phase D		Phase E (Operations & Analysis)		Total ($K)
06.10 GN&C Subsystem		**3347**	**4251**	**7143**	**13740**	**1215**	**1086**	**310**	**-**	**-**	**31093**
06.10.01 GN&C Subsystem Management		307	307	281	153	128	358	102			**1637**
06.10.02 GN&C Subsystem Engineering		1033	1033	947	517	431	728	208			**4897**
06.10.03 GN&C Sensors AND			904	4075	12282						**17262**
06.10.04 GN&C Actuators AND											
06.10.05 GN&C I/F Electronics											
06.10.08 GN&C Control Analysis		2007	2007	1840	788	656				-	**7297**

Ice-focused mission											
All Units Cost		Phase A	Phase B	Phase C (Subsystem Design, Fab & I&T)			Phase D		Phase E (Operations & Analysis)		Total ($K)
06.10 GN&C Subsystem		**2149**	**2828**	**5838**	**13082**	**761**	**760**	**217**	**-**	**-**	**25636**
06.10.01 GN&C Subsystem Management		215	215	197	107	90	251	72			**1146**
06.10.02 GN&C Subsystem Engineering		711	711	652	355	296	509	146			**3380**
06.10.03 GN&C Sensors AND			678	3868	12169						**16715**
06.10.04 GN&C Actuators AND											
06.10.05 GN&C I/F Electronics											
06.10.08 GN&C Control Analysis		1224	1224	1122	450	375				-	**4395**

The estimated propellant required is 50 kg, see Table B-26. The main driver is the gravity gradient torque while pointed off-nadir for science observations (10 mins every other orbit). A potential concern is the thruster plume impingement on the solar panels or SAR antenna which could affect the thruster mounting angles or moment arms.

Table B-26. MORIE mission concept: Propellant estimation of 50 kg.

	Rate of momentum accumulation while pointed off-nadir	# orbits per day off-nadir pointed*	Time off-nadir pointed per day*	Momentum accumulation per day	Wheel momentum storage capacity	# desats per day	Prop per burn	# desats over 4-yr mission	Total prop over 4-yr mission
	Nms/min		Min	Nms	Nms		Kg		kg
Thruster config 6, Isp=226, alpha=30, beta=40	0.625	6.35	63.5	39.6875	75	0.52916667	0.11	772.58333	**84.9841667**
Thruster config 6, Isp=226, alpha=30, beta=40	0.625	6.35	63.5	39.6875	100	0.396875	0.11	579.4375	**63.738125**
Thruster config 6, Isp=226, alpha=30, beta=40	0.625	6.35	63.5	39.6875	150	0.26458333	0.11	386.291667	**42.4920833**
Thruster config 6, Isp=226, alpha=30, beta=60	0.625	6.35	63.5	39.6875	75	0.52916667	0.053	772.58333	**40.9469167**
Thruster config 6, Isp=226, alpha=30, beta=60	0.625	6.35	63.5	39.6875	100	0.396875	0.053	579.4375	**30.7101875**
Thruster config 6, Isp=226, alpha=30, beta=60	0.625	6.35	63.5	39.6875	150	0.26458333	0.053	386.291667	**20.4734583**
Thruster config 5b, Isp=226, beta=30	0.625	6.35	63.5	39.6875	75	0.52916667	0.04	772.583333	**30.9033333**
Thruster config 5b, Isp=226, beta=30	0.625	6.35	63.5	39.6875	100	0.396875	0.04	579.4375	**23.1775**
Thruster config 5b, Isp=226, beta=30	0.625	6.35	63.5	39.6875	150	0.26458333	0.04	386.291667	**15.4516667**

**12.7 orbits per day.*

B.3.9 Power

The Team X study made the following power assumptions:

- Because the solar electric propulsion (SEP) system dominates power demand, the array is sized to produce 120 V per the Team X Propulsion chair
- Included new assembly High Voltage Electronics Assembly (HVEA) with PPU i/f, downconverter, battery and power control functionality
  - This makes a Power Bus Controller (PBC) unnecessary.
  - The system is a array string switcher (like Europa Clipper)
- MREU is carried by CDS (C&DH)

The Powered Element List (PEL) summary is shown in Table B-27.

Table B-27. MORIE PEL summary.

Subsystem/ Instrument	Mode #	1	2	3	4	5	6	7	8	9	10
Full Mission	Mode Name	Launch	Safe	Thrusting–Earth	Thrusting–Mars	Science + Comm–Day	Comm–Radar–Eclipse	Comm–Sounder–Eclipse	Comm Only	Comm Only–Eclipse	Comm and Slew–Eclipse
ACS	W	43	109	109	109	123	120	120	120	120	203
C&DH	W	61	61	61	61	61	61	61	61	61	61
Instruments	W	0	0	0	0	68	126	126	16	16	16
Other Elements	W	0	0	0	0	0	0	0	0	0	0
Propulsion System 1	W	0	0	9600	4800	0	0	0	0	0	0
Propulsion System 2	W	17	17	1	1	1	1	1	1	1	1
Propulsion System 3	W	0	0	0	0	0	0	0	0	0	0
Structures	W	0	0	0	0	0	0	0	0	0	0
Telecomm	W	28	93	93	93	414	414	414	414	414	414
Thermal	W	684	545	93	93	219	217	217	227	227	142
Power Subsystem	W	125	124	136	108	130	135	135	126	126	125
Totals		**957**	**948**	**10092**	**5264**	**1016**	**1073**	**1073**	**963**	**963**	**961**

Subsystem/ Instrument	Mode #	1	2	3	4	5	6	7	8	9	10
Ice-focused Mission	Mode Name	Launch	Safe	Thrusting–Earth	Thrusting–Mars	Science + Comm–Day	Comm–Radar–Eclipse	Comm–Sounder 2–Eclipse	Comm Only	Comm Only–Eclipse	Comm and Slew–Eclipse
ACS	W	43	109	109	109	109	109	109	109	109	192
C&DH	W	58	58	58	58	58	58	58	58	58	58
Instruments	W	0	0	0	0	12	110	75	0	0	0
Other Elements	W	0	0	0	0	0	0	0	0	0	0
Propulsion System 1	W	0	0	8705	4352	0	0	0	0	0	0
Propulsion System 2	W	17	17	1	1	1	1	1	1	1	1
Propulsion System 3	W	0	0	0	0	0	0	0	0	0	0
Structures	W	0	0	0	0	0	0	0	0	0	0
Telecomm	W	28	93	93	93	237	237	237	237	237	237
Thermal	W	659	528	95	95	384	375	378	385	385	302
Power Subsystem	W	122	122	131	105	122	131	128	121	121	121
Totals		**926**	**926**	**9191**	**4813**	**922**	**1020**	**985**	**910**	**910**	**910**

The driving power mode for both mission concepts when sizing the solar array wings is the thrusting at Earth. The resulting design can be seen in Table B-28.

Table B-28. MORIE solar array sizing.

Full mission Solar Array Design Summary		
Mass–Cells, Coverglass, etc.	57.15 kg	
Mass–Structure	22.43 kg	
Mass–Total Array	79.59 kg	
Total Cell Area	37.11 m^2	18.55 m^2
Total Array Area	47.22 m^2	23.61 m^2
# Wings	2	0.79
Design Technology/Configuration	GaAs TJ UltraRex	
UltraFlex Radius	2.83	m/panel
UltraFlex Diameter	5.67	m/panel

Ice-focused mission Solar Array Design Summary		
Mass–Cells, Coverglass, etc.	52.16 kg	
Mass–Structure	20.55 kg	
Mass–Total Array	72.72 kg	
Total Cell Area	33.84 m^2	16.92 m^2
Total Array Area	43.26 m^2	21.63 m^2
# Wings	2	0.78
Design Technology/Configuration	GaAs TJ UltraRex	
UltraFlex Radius	2.71	m/panel
UltraFlex Diameter	5.43	m/panel

The battery design is shown in Figure B-35 for the full mission concept and in Figure B-36 for the ice-focused mission concept.

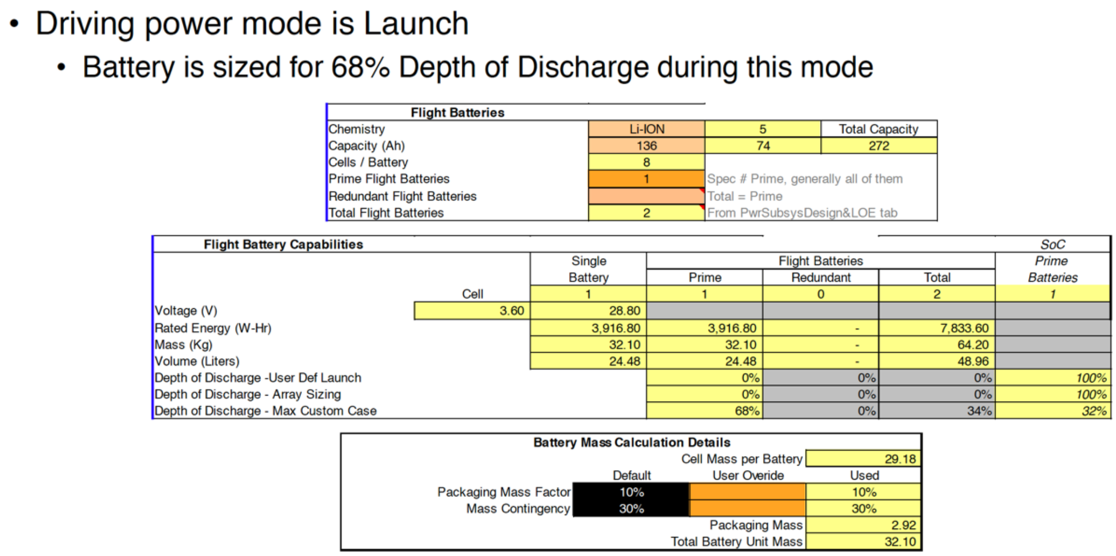
- Driving power mode is Launch
    - Battery is sized for 70% Depth of Discharge during this mode

Flight Batteries			
Chemistry	Li-ION	5	Total Capacity
Capacity (Ah)	136	74	272
Cells / Battery	8		
Prime Flight Batteries	1	Spec # Prime, generally all of them	
Redundant Flight Batteries		Total = Prime	
Total Flight Batteries	2	From PwrSubsysDesign&LOE tab	

Flight Battery Capabilities						*SoC*
		Single Battery	Flight Batteries			*Prime Batteries*
			Prime	Redundant	Total	
	Cell	1	1	0	2	*1*
Voltage (V)	3.60	28.80				
Rated Energy (W-Hr)		3,916.80	3,916.80	-	7,833.60	
Mass (Kg)		32.10	32.10	-	64.20	
Volume (Liters)		24.48	24.48	-	48.96	
Depth of Discharge -User Def Launch			0%	0%	0%	*100%*
Depth of Discharge - Array Sizing			0%	0%	0%	*100%*
Depth of Discharge - Max Custom Case			70%	0%	35%	*30%*

Battery Mass Calculation Details			
		Cell Mass per Battery	29.18
	Default	User Overide	Used
Packaging Mass Factor	10%		10%
Mass Contingency	30%		30%
		Packaging Mass	2.92
		Total Battery Unit Mass	32.10

Figure B-35. Battery design for the full mission concept.



- Driving power mode is Launch
  - Battery is sized for 68% Depth of Discharge during this mode

Flight Batteries			
Chemistry	Li-ION	5	Total Capacity
Capacity (Ah)	136	74	272
Cells / Battery	8		
Prime Flight Batteries	1	Spec # Prime, generally all of them	
Redundant Flight Batteries		Total = Prime	
Total Flight Batteries	2	From PwrSubsysDesign&LOE tab	

Flight Battery Capabilities		Single Battery	Flight Batteries – Prime	Flight Batteries – Redundant	Flight Batteries – Total	SoC Prime Batteries
	Cell	1	1	0	2	1
Voltage (V)	3.60	28.80				
Rated Energy (W-Hr)		3,916.80	3,916.80	-	7,833.60	
Mass (Kg)		32.10	32.10	-	64.20	
Volume (Liters)		24.48	24.48	-	48.96	
Depth of Discharge -User Def Launch			0%	0%	0%	100%
Depth of Discharge - Array Sizing			0%	0%	0%	100%
Depth of Discharge - Max Custom Case			68%	0%	34%	32%

Battery Mass Calculation Details	Default	User Overide	Used
Cell Mass per Battery			29.18
Packaging Mass Factor	10%		10%
Mass Contingency	30%		30%
Packaging Mass			2.92
Total Battery Unit Mass			32.10

Figure B-36. Battery design for ice-focused mission concept.

The total power cost is shown in Table B-29 for the full mission concept and in Table B-30 for the ice-focused mission concept. A potential cost upper is that the heritage or built-to-print assumption may fail as level 3 requirements become more project specific. The two power costs are compared in Table B-31.

Table B-29. Total power cost for the full mission.

2025 $K	Total Cost			
	Total	Labor ($k)	Services ($k)	Procurements ($k)
Subsystem Management	**3,742**	3,742	-	-
System Engineering	**7,616**	7,618	-	-
Power Source–Solar Array	**19,586**	799	-	18,787
Power Source–RPS	**-**	-	-	-
Energy Storage–Rechargeable Secondary Battery	**2,608**	299	-	2,308
Energy Storage–Primary Battery	**-**	-	-	-
Energy Storage–Thermal Battery	**-**	-	-	-
Electronics	**15,695**	5,294	4,055	6,346
Battery Test Equipment (BTE) / Ground Support Equipment (GSE) / I and T	**6,007**	6,007	-	-
Total	**55,256**	**23,759**	**4,055**	**27,441**

Table B-30. Total power cost for the ice-focused mission.

2025 $K	Total Cost			
	Total	Labor ($k)	Services ($k)	Procurements ($k)
Subsystem Management	**3,742**	3,742	-	-
System Engineering	**7,618**	7,618	-	-
Power Source–Solar Array	**17,930**	799	-	17,131
Power Source–RPS	**-**	-	-	-
Energy Storage–Rechargeable Secondary Battery	**2,608**	299	-	2,308
Energy Storage–Primary Battery	**-**	-	-	-
Energy Storage–Thermal Battery	**-**	-	-	-
Electronics	**15,695**	5,294	4,055	6,346
BTE / GSE / I and T	**6,007**	6,007	-	-
Total	**53,600**	**23,759**	**4,055**	**25,785**

Table B-31. Power comparison for MORIE.

Concept	CBE Mass (kg)	Cost ($M)	Total Solar Array Energy (W-Hrs)	Array Area (m^2)	Battery Capacity (A-Hrs)	Comments
Full Mission	186.9	55.2	11.5 k	47.2	272	
Ice-focused Mission	180	53.6	10.5 k	43.3	272	

B.3.10 Propulsion

The Team X study assumed a Psyche style Electric Propulsion design utilizing SPT-140 engines, gimbal, engine count and PPU cross linking and a Hydrazine ACS propulsion system which provides a longer life reliability over cold gas and lower overall mass due to reduced tank count and higher specific impulse.

Specifically, the SEP system was designed as follows:

- Electric Propulsion Hardware
  - Four SPT-140 Hall EP thrusters*, 1700 seconds Isp and .25 N thrust
  - Two PPUs
  - Two gimbals with two engines each
  - Four Xenon Flow Controllers, one for each engine
  - Three Cobham (Carleton) composite overwrapped Xenon tanks, P/N 7169, 1750 MDP, .9 m x 0.7 m
- Functionality
  - The SEP system provides primary propulsion to Mars, spiral to Mars orbit, and major plane change while in orbit

After the Team X study, it was identified that the max throughput of the SPT140 thrusters should be 333 kg, rather than the 500 kg provided in the study. If this is the case, the 4-thruster design is inadequate for an engine-out scenario (333 kg x 3 thrusters = 999 kg < 1138 kg (full mission), 1038 kg (ice-focused mission)), and a thruster should be added, with all ripple effects accounted for. This is not reflected in this report.

The chemical ACS system was designed as follows:

- Chemical Propulsion Hardware
  - Eight Aerojet Rocketdyne MR-103J, 0.9 N rocket engines
  - One PSI monolithic Titanium diaphragm tank, P/N 80259-1, 475 MDP, .56 m spherical with a mass of 6.35 kg
- Functionality
  - The Hydrazine ACS system provides momentum wheel unloading and three axis control in safe mode

The SEP propellant was estimated to be:

- 1210 kg Xenon for the full mission, and 1102 kg for the ice-focused mission
- Sized to 8.0 km/s ΔV with an initial spacecraft mass of 2987 kg and final dry mass of 1799 kg for the full mission, and 2720 kg initial and 1634 kg final for the ice-focused mission

The chemical propellant was calculated as:

- 50 kg Hydrazine
- Sized to 50 kg of ACS propellant (no ΔV) predominantly for momentum wheel unload

The SEP system was selected to provide highly efficient Isp to complete a large plane change while at Mars and high ΔV capability over the entire mission of 8.0 km/s. The Hydrazine ACS system is driven by the need for frequent momentum wheel unloads during Mars orbit mission phase. Initially, a cold gas ACS system was selected based on the study team's desire to use the Psyche propulsion baseline. Following ACS calculations, it was determined that a higher performance chemical system was required due to frequent momentum wheel unloads during Mars orbit phase.

SEP costs are based on recent cost from similar system, assuming in-house JPL build. The chemical propulsion costs are based on multiple JPL in-house builds with flight heritage.

The propulsion cost is shown in Table B-32 and comes to:

- Total cost for a SPT-140 EP system: $34.0M
  - Non-recurring cost: $13.0M
  - Recurring cost: $21.0M
- Total cost for a simple blowdown Hydrazine system: $13.1M
  - Non-recurring cost: $7.7M
  - Recurring cost: $5.4M

There is low risk when utilizing flight proven designs and hardware for both the SEP and Chemical systems and there was no design difference between the two studied concepts. The Team X study report noted that it may be possible to fly the entire mission without an ACS propulsion system, all on SEP, depending on creative ways to desaturate momentum wheel while in Mars orbit. There are techniques to fly during cruise/spiral with minimal momentum wheel loading.

Table B-32. Propulsion cost for MORIE.

Propulsion Systems Engineering Cost Summary ($K)									
Item	Type	Phase A	Phase B	Phase C1	Phase C2	Phase C3	Phase D1	Phase D2	Total
		12	12	11	6	5	14	4	$k
.01 & .02 Management, Engineering	Engr. Labor $	$2415.1k	$2415.1k	$2213.9k	$1207.6k	$1006.3k	$2817.7k	$805.0k	$12880.8k
.03 Components Engineering	Engr. Labor $	$0.0k	$779.3k	$1620.8k	$884.1k	$736.7k	$0.0k	$0.0k	$4020.8k
.04 GSE	Engr. Labor $	$0.0k	$0.0k	$0.0k	$482.7k	$482.7k	$0.0k	$0.0k	$965.5k
.05 I&T	Engr. Labor $	$0.0k	$0.0k	$0.0k	$1174.3k	$978.6k	$0.0k	$0.0k	$2152.9k
.06 Prop loading & ATLC Support	Engr. Labor $	$0.0k	$0.0k	$0.0k	$0.0k	$0.0k	$570.7k	$570.7k	$1141.4k
.04 GSE	Service $	$0.0k	$0.0k	$0.0k	$579.4k	$579.4k	$0.0k	$0.0k	$1158.8k
.05 I&T	Service $	$0.0k	$0.0k	$0.0k	$1902.2k	$1643.1k	$0.0k	$0.0k	$3545.3k
.06 Prop loading & ATLO Support	Service $	$0.0k	$0.0k	$0.0k	$0.0k	$0.0k	$877.2k	$877.2k	$1754.4k
Subtotal Labor and Services	**Labor and Services $**	**$2,415.1k**	**$3194.4k**	**$3834.6k**	**$6230.2k**	**$5426.8k**	**$4265.5k**	**$2252.9k**	**$27619.7k**
.03 Components	Subcontract Procurement $		$1518.1k	$5200.4k	$5200.4k	$5200.4k		$2442.3k	$19561.8k
Non-Recurring	$k	$2415.1k	$4712.5k	$4585.8k	$3191.4k	$2912.5k	$2254.1k	$644.0k	$20715.6k
Recurring	$k	$0.0k	$0.0k	$4449.3k	$8239.3k	$7714.7k	$2011.4k	$4051.2k	$26465.9k
Total	**$k**	**$2415.1k**	**$4712.5k**	**$9035.1k**	**$11430.7k**	**$10627.2k**	**$4265.5k**	**$4695.3k**	**$47181.5k**

B.3.11 Thermal

The Team X study made several assumption for the thermal design:

- Spacecraft shear panels are used as radiators (dual-use) and no mass or costs (other than coatings) are carried by the Team X Thermal Chair
- Radiator and heater sizing based on an allowable temperature range of -20 °C to +50 °C
- When sizing survival heaters, a worst case assumption of a 93 K radiative sink temperature is assumed (assumes a zenith-facing radiator in a 6 am – 6 pm orbit (beta angle = 90°)
- PPU is only 85% efficient, per Team X Propulsion Chair
- Solar array switching is used in a way that precludes the need for a shunt radiator

The thermal design is a high flight heritage, passive design. The system is cold biased with radiators sized for the worst case hot condition (SEP thrusting at 1 AU). Make-up heater power is then used to maintain minimum allowable temperatures during cold scenarios. Propellant tanks and lines are covered with MLI.

Hardware design considerations:

- Heaters are controlled using mechanical thermostats
- Platinum Resistance Thermometer (PRT) temperature sensors
- 17-layer MLI
- 3.9 m^2 of bus structure is left exposed and serves as the radiator
- 10-mil silverized Teflon coating on radiator
- Aluminum-ammonia constant conductance heat pipes embedded within panel used as the radiator

Thermal design does not significantly change between the two studied missions. Cost drivers are:

- Labor costs based on a Mars Orbiter labor profile (built into the cost model) are ~18.2 Work Years
- MLI costs are ~$1.9M due to large propellant-containing surfaces associated with SEP + cold gas systems
- Constant conductance heat pipe costs are ~$280K due to heat spreading needs under the PPU and other components

A potential cost upper has been identified: The design uses an inordinate amount of make-up heating during cold scenarios (i.e., the coldest scenario is launch mode where there is no SEP, dissipations are minimal, and radiator sink temperatures can be cold). Usually, JPL will utilize louvers that regulate the amount of heat rejected through radiators. But this design study shows large amounts of power available when not thrusting and battery costs are lower than louver costs. But should the modes change, which they often do, louvers may be needed. Cost is $350K per louver unit and we would need more than 10 units for a cost upper of at least $3.5M.

The thermal cost is shown in Table B-33 for the full mission and in Table B-34 for the ice-focused mission.

Table B-33. Thermal cost for the full mission.

	Thermal Control System Resources by Phase								Thermal Control System Cost		
Phase Duration	A 12 mo.	B 12 mo.	C1 11 mo.	C2 6 mo.	C3 5 mo.	D1 14 mo.	D2 4 mo.	Total 64 mo.	Total 64 mo.	NRE (A-C1) 35 mo.	RE (C2-D2) 29 mo.
06.08 Thermal Control System	1.4 FTE	4.2 FTE	5.9 FTE	4.0 FTE	4.2 FTE	2.7 FTE	1.0 FTE	18.2 WY	$11333.3 K	$5121.1 K	$6212.1 K
06.08.01 Mgmt and Sys. Eng.	1.4 FTE	2.0 FTE	2.4 FTE	2.1 FTE	2.1 FTE	1.6 FTE	1.0 FTE	9.8 WY	$5226.7 K	$2980.5 K	$2246.2 K
06.08.01.01 Management	0.1 FTE	0.4 FTE	0.5 FTE	0.4 FTE	0.4 FTE	0.2 FTE	0.1 FTE	1.7 WY	$1234.2 K	$743.4 K	$490.7 K
Management Support	0.1 FTE	0.4 FTE	0.5 FTE	0.4 FTE	0.4 FTE	0.2 FTE	0.1 FTE	1.7 WY	$716.8 K	$431.8 K	$285.0 K
Secretary Support	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
Computer HW/SW Support	$39.9 K	$119.0 K	$152.7 K	$57.5 K	$49.8 K	$88.7 K	$9.7 K	$517.4 K	$517.4 K	$311.7 K	$205.7 K
06.08.01.02 System Engineering	1.3 FTE	1.7 FTE	1.9 FTE	1.8 FTE	1.8 FTE	1.4 FTE	0.9 FTE	8.2 WY	$3992.5 K	$2237.1 K	$1755.4 K
Project Engineer	0.9 FTE	1.0 FTE	0.9 FTE	1.2 FTE	1.2 FTE	0.9 FTE	0.9 FTE	5.1 WY	$2692.2 K	$1394.4 K	$1297.8 K
Lead Engineer (Engineering 4)	0.4 FTE	0.7 FTE	0.9 FTE	0.6 FTE	0.6 FTE	0.5 FTE	0.0 FTE	3.1 WY	$1300.3 K	$842.7 K	$457.6 K
Sys Engineer (Engineering 3)	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
Sys Engineer (Engineering 1-2	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
06.08.02 Analysis/Design	0.0 FTE	2.0 FTE	3.0 FTE	0.7 FTE	0.7 FTE	0.6 FTE	0.0 FTE	6.1 WY	$2435.4 K	$1877.0 K	$558.5 K
Analysis Engineer (Engineerin	0.0 FTE	1.0 FTE	0.9 FTE	0.6 FTE	0.6 FTE	0.5 FTE	0.0 FTE	2.9 WY	$1220.7 K	$763.1 K	$457.6 K
Analysis Engineer (Engineerin	0.0 FTE	1.0 FTE	1.9 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	2.6 WY	$990.1 K	$990.1 K	$0.0 K
Analysis Engineer (Engineerin	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
Development Testing	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K
Planetary Protection	0.0 FTE	0.1 FTE	0.2 FTE	0.1 FTE	0.1 FTE	0.1 FTE	0.0 FTE	0.6 WY	$224.6 K	$123.8 K	$100.9 K
PP Lead Engineer	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
PP Analysis / Design	0.0 FTE	0.1 FTE	0.2 FTE	0.1 FTE	0.1 FTE	0.1 FTE	0.0 FTE	0.6 WY	$224.6 K	$123.8 K	$100.9 K
PP Testing / HW	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K
06.08.03 Hardware	0.0 FTE	0.1 FTE	0.2 FTE	0.6 FTE	0.1 FTE	0.0 FTE	0.0 FTE	0.7 WY	$3044.6 K	$179.0 K	$2865.6 K
HW Support Engineer (Enginee	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
HW Support Engineer (Enginee	0.0 FTE	0.1 FTE	0.2 FTE	0.6 FTE	0.1 FTE	0.0 FTE	0.0 FTE	0.7 WY	$256.6 K	$123.8 K	$132.8 K
HW Support Engineer (Enginee	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
Flight HW	$0.0 K	$0.0 K	$55.2 K	#######	$0.0 K	$0.0 K	$0.0 K	$2788.0 K	$2788.0 K	$55.2 K	$2732.8 K
Flight HW Testing HW	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K
06.08.04 BCE/AHSE/GSE	0.0 FTE	0.0 FTE	0.1 FTE	0.3 FTE	0.6 FTE	0.5 FTE	0.0 FTE	1.0 WY	$440.3 K	$45.0 K	$395.3 K
H/WTest Engineer (Engineerin	0.0 FTE	0.0 FTE	0.1 FTE	0.3 FTE	0.6 FTE	0.5 FTE	0.0 FTE	1.0 WY	$440.3 K	$45.0 K	$395.3 K
H/WTest Engineer (Engineerin	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
H/WTest Engineer (Engineerin	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
BCE/AHSE/GSE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K
06.08.05 Integration And Test	0.0 FTE	0.0 FTE	0.1 FTE	0.3 FTE	0.6 FTE	0.0 FTE	0.0 FTE	0.5 WY	$186.2 K	$39.7 K	$146.6 K
Subsystem Integration and Tes	0.0 FTE	0.0 FTE	0.1 FTE	0.3 FTE	0.6 FTE	0.0 FTE	0.0 FTE	0.5 WY	$186.2 K	$39.7 K	$146.6 K
I&T Engineer (Engineering 4)	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
I&T Engineer (Engineering 3)	0.0 FTE	0.0 FTE	0.1 FTE	0.3 FTE	0.6 FTE	0.0 FTE	0.0 FTE	0.5 WY	$186.2 K	$39.7 K	$146.6 K
I&T Engineer (Engineering 1-	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
System Integration and Test	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
I&T Engineer (Engineering 4)	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
I&T Engineer (Engineering 3)	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
I&T Engineer (Engineering 1-	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K

Table B-34. Thermal cost for the ice-focused mission.

	Thermal Control System Resources by Phase								Thermal Control System Cost		
Phase	A	B	C1	C2	C3	D1	D2	Total	Total	NRE (A-C1)	RE (C2-D2)
Duration	12 mo.	12 mo.	11 mo.	6 mo.	5 mo.	14 mo.	4 mo.	64 mo.	64 mo.	35 mo.	29 mo.
06.08 Thermal Control System	1.4 FTE	4.2 FTE	5.9 FTE	4.0 FTE	4.2 FTE	2.7 FTE	1.0 FTE	18.2 WY	$11287.1 K	$5121.1 K	$6166.0 K
06.08.01 Mgmt and Sys. Eng.	1.4 FTE	2.0 FTE	2.4 FTE	2.1 FTE	2.1 FTE	1.6 FTE	1.0 FTE	9.8 WY	$5226.7 K	$2980.5 K	$2246.2 K
06.08.01.01 Management	0.1 FTE	0.4 FTE	0.5 FTE	0.4 FTE	0.4 FTE	0.2 FTE	0.1 FTE	1.7 WY	$1234.2 K	$743.4 K	$490.7 K
Management Support	0.1 FTE	0.4 FTE	0.5 FTE	0.4 FTE	0.4 FTE	0.2 FTE	0.1 FTE	1.7 WY	$716.8 K	$431.8 K	$285.0 K
Secretary Support	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
Computer HW/SW Support	$39.9 K	$119.0 K	$152.7 K	$57.5 K	$49.8 K	$88.7 K	$9.7 K	$517.4 K	$517.4 K	$311.7 K	$205.7 K
06.08.01.02 System Engineering	1.3 FTE	1.7 FTE	1.9 FTE	1.8 FTE	1.8 FTE	1.4 FTE	0.9 FTE	8.2 WY	$3992.5 K	$2237.1 K	$1755.4 K
Project Engineer	0.9 FTE	1.0 FTE	0.9 FTE	1.2 FTE	1.2 FTE	0.9 FTE	0.9 FTE	5.1 WY	$2692.2 K	$1394.4 K	$1297.8 K
Lead Engineer (Engineering 4)	0.4 FTE	0.7 FTE	0.9 FTE	0.6 FTE	0.6 FTE	0.5 FTE	0.0 FTE	3.1 WY	$1300.3 K	$842.7 K	$457.6 K
Sys Engineer (Engineering 3)	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
Sys Engineer (Engineering 1-2	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
06.08.02 Analysis/Design	0.0 FTE	2.0 FTE	3.0 FTE	0.7 FTE	0.7 FTE	0.6 FTE	0.0 FTE	6.1 WY	$2435.4 K	$1877.0 K	$558.5 K
Analysis Engineer (Engineering	0.0 FTE	1.0 FTE	0.9 FTE	0.6 FTE	0.6 FTE	0.5 FTE	0.0 FTE	2.9 WY	$1220.7 K	$763.1 K	$457.6 K
Analysis Engineer (Engineering	0.0 FTE	1.0 FTE	1.9 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	2.6 WY	$990.1 K	$990.1 K	$0.0 K
Analysis Engineer (Engineering	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
Development Testing	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K
Planetary Protection	0.0 FTE	0.1 FTE	0.2 FTE	0.1 FTE	0.1 FTE	0.1 FTE	0.0 FTE	0.6 WY	$224.6 K	$123.8 K	$100.9 K
PP Lead Engineer	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
PP Analysis / Design	0.0 FTE	0.1 FTE	0.2 FTE	0.1 FTE	0.1 FTE	0.1 FTE	0.0 FTE	0.6 WY	$224.6 K	$123.8 K	$100.9 K
PP Testing / HW	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K
06.08.03 Hardware	0.0 FTE	0.1 FTE	0.2 FTE	0.6 FTE	0.1 FTE	0.0 FTE	0.0 FTE	0.7 WY	$2998.5 K	$179.0 K	$2819.5 K
HW Support Engineer (Enginee	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
HW Support Engineer (Enginee	0.0 FTE	0.1 FTE	0.2 FTE	0.6 FTE	0.1 FTE	0.0 FTE	0.0 FTE	0.7 WY	$256.6 K	$123.8 K	$132.8 K
HW Support Engineer (Enginee	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
Flight HW	$0.0 K	$0.0 K	$55.2 K	#######	$0.0 K	$0.0 K	$0.0 K	$2741.9 K	$2741.9 K	$55.2 K	$2686.7 K
Flight HW Testing HW	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K
06.08.04 BCE/AHSE/GSE	0.0 FTE	0.0 FTE	0.1 FTE	0.3 FTE	0.6 FTE	0.5 FTE	0.0 FTE	1.0 WY	$440.3 K	$45.0 K	$395.3 K
H/WTest Engineer (Engineerin	0.0 FTE	0.0 FTE	0.1 FTE	0.3 FTE	0.6 FTE	0.5 FTE	0.0 FTE	1.0 WY	$440.3 K	$45.0 K	$395.3 K
H/WTest Engineer (Engineerin	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
H/WTest Engineer (Engineerin	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
BCE/AHSE/GSE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K
06.08.05 Integration And Test	0.0 FTE	0.0 FTE	0.1 FTE	0.3 FTE	0.6 FTE	0.0 FTE	0.0 FTE	0.5 WY	$186.2 K	$39.7 K	$146.6 K
Subsystem Integration and Tes	0.0 FTE	0.0 FTE	0.1 FTE	0.3 FTE	0.6 FTE	0.0 FTE	0.0 FTE	0.5 WY	$186.2 K	$39.7 K	$146.6 K
I&T Engineer (Engineering 4)	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
I&T Engineer (Engineering 3)	0.0 FTE	0.0 FTE	0.1 FTE	0.3 FTE	0.6 FTE	0.0 FTE	0.0 FTE	0.5 WY	$186.2 K	$39.7 K	$146.6 K
I&T Engineer (Engineering 1-	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
System Integration and Test	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
I&T Engineer (Engineering 4)	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
I&T Engineer (Engineering 3)	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K
I&T Engineer (Engineering 1-	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 WY	$0.0 K	$0.0 K	$0.0 K

B.3.12 Command and Data Subsystem (CDS)

The Team X study assumed a Class B mission with dual string redundancy and assumed a JPL reference bus implementation.

- Hardware
  - JPL Reference Bus Design
  - MREU bookkept in CDS but physically located in Power subsystem
- Functionality
  - Interface with other spacecraft subsystems
    - Telecom, Guidance, Navigation, and Control (GNC), Power, Propulsion, etc.
  - Handle data from instruments
    - 55 Gbytes max generated per sol
    - Compress instrument data (less instrument activity during night side of orbit)

The instrument data volume is a driver:

- JPL Reference Bus Design
- Including a memory card to store a sol's worth of data
  - Memory card can hold 128 Gbytes
  - Maximum instrument generation is 55 Gbytes/sol

- Data compression done in CDS

Data story

- Max data generation 55 Gbytes/sol (= 436 Gbits), uncompressed
  - Compression expected to reduce volume to 36 Gbytes(= 286 Gbits)
- Data rates vary over orbital geometry
- Max 400 Gbits/day over telecom

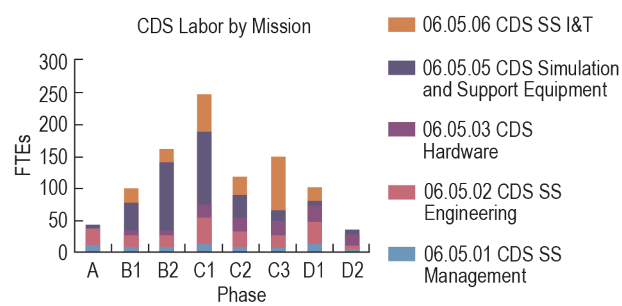
A dual string CDS is assumed:

- Two copies each of flight, EM, and prototype hardware, single flight spare
- Two testbeds (one for Avionics, one for System test)
- Two GSE, single BTE

The CDS cost for both mission concepts is given in Figure B-37.

1st Unit Cost: $50.0M

Nth Unit Cost: $31.5M



Task ID		A	B	C1	C2	C3	D1	D2	E	F	Total
06.05	Total Cost (K$)	1485.6	16066.7	16312.3	4467.1	7989.0	3483.1	1136.3	0.0	0.0	50.940.1
	Labor Total (FTE)	42.00	260.98	247.36	118.14	150.27	98.47	32.12	0.00	0.00	79.11
06.05.01	Subtotal Cost–Subsystem Management	424.5	424.5	389.1	212.2	176.9	495.2	141.5	0.0	0.0	2263.8
	Labor (FTE)	12.00	12.00	11.00	6.00	5.00	14.00	4.00	0.00	0.00	5.33
06.05.02	Subtotal Cost–Subsystem Engineering	848.9	1485.6	1556.3	848.9	707.4	1238.0	283.0	0.0	0.0	6968.1
	Labor (FTE)	24.00	42.00	44.00	24.00	20.00	35.00	8.00	0.00	0.00	16.42
06.05.03	Subtotal Cost–C&DH Hardware	0.0	6681.3	7462.7	1125.8	3474.8	735.4	689.1	0.0	0.0	20169.0
	Labor (FTE)	0.00	11.40	16.72	25.81	22.65	20.79	19.48	0.00	0.00	9.74
06.05.05	Subtotal Cost–SSE	212.2	5919.0	4746.6	1242.6	544.5	61.9	22.7	0.0	0.0	12749.5
	Labor (FTE)	6.00	151.58	114.63	33.00	15.39	1.75	0.64	0.00	0.00	26.92
06.05.06	Subtotal Cost–I&T	0.0	1556.3	2157.6	1037.6	3085.5	952.7	0.0	0.0	0.0	8789.7
	Labor (FTE)	0.00	44.00	61.00	29.33	87.23	26.93	0.00	0.00	0.00	20.71

Figure B-37. CDS cost for both studied mission concepts.

B.3.13 Telecom

The Team X study identified these telecom design requirements for both mission concepts:

- General telecom requirements
  - Support a two-way link with Earth through all mission phases
- Downlink/Return Requirements
  - Two eight-hour passes every two days
- Uplink/Forward Requirements
  - Support an uplink of 2 kbps
- Link Quality Requirements
  - Bit Error Rate (BER) of 1E-05 for command (CMD) links

  - Frame Error Rate (FE of 1E-04 for telemetry (TLM) links
  - Minimum 3 dB margin on all data terminal equipment (DTE) links
- Specific requirements from the MORIE study team
  - Fully redundant
  - Use 3 m HGA and 200 W Ka-band TWTA (full mission) and 2 m HGA and 100 W Ka-band TWTA (ice-focused mission). In other words, not terribly constrained by power or mass in the Telecom subsystem in order to achieve high data rates from Mars

The resulting telecom design assumptions are:

- Operational Assumptions
  - Spacecraft is 3-axis stabilized
  - Spacecraft will continue to take science data of Mars during downlink passes. This is possible through a gimbaled HGA
- Antenna Assumptions
  - HGA is gimbaled and will be pointed within 0.1 degrees
  - Two LGAs will be positioned on opposite sides of the spacecraft to provide 2 π steradian coverage
- Ground Station Assumptions
  - 34 m BWG DSN ground stations with 20 kW transmitters
- Coding Assumptions
  - Assumed Turbo rate 1/6 encoding for links
- Link Assumptions
  - 95% weather for all Ka-band links

The resulting telecom design for the full mission:

- Overall system description
  - For all mission concepts, telecom is a fully redundant X/Ka-band system
- Hardware includes:
  - One 3 m X/Ka-band HGA, gimbaled
    - □ 57 dBi gain at Ka-band
  - Two X-band low gain antennas (are installed on the HGA gimbal as well)
    - □ 8 dBi gain
  - Two X/Ka-band Universal Space Transponders (UST)
    - □ X and Ka-band downlink, X-band for safe mode and housekeeping downlink (lower power), Ka-band for high-rate science downlink
    - □ X-band uplink
  - Two 25 W X-band TWTAs
  - Two 200 W Ka-band TWTAs
  - Filters, diplexers, waveguide transfer switches, waveguide, and coax cabling
- Estimated total mass of 59.84 kg (CBE), 69.21 kg (MEV)

The resulting telecom design for the ice-focused mission:

- Overall system description
  - For both studied mission concepts, telecom is a fully redundant X/Ka-band system
- Hardware includes:
  - One, 2 m X/Ka-band HGA, gimbaled
    - □ 54 dBi gain at Ka-band

- Two X-band low gain antennas (are installed on the HGA gimbal as well)
  - 8 dBi gain
- Two X/Ka-band UST
  - X and Ka-band downlink, X-band for safe mode and housekeeping downlink (lower power), Ka-band for high-rate science downlink
  - X-band uplink
- Two 25 W X-band TWTAs
- Two 100 W Ka-band TWTAs
- Filters, diplexers, waveguide transfer switches, waveguide, and coax cabling

- Estimated total mass of 52.64 kg (CBE), 60.94 kg (MEV)

The telecom design rationale for both studied mission concepts is shown in Table B-35 and is:

- Rationale for Frequencies
  - Ka-band needed for data rates required, X-band used for uplink and housekeeping and/or backup downlink capability
- Rationale for Hardware
  - Using next generation transponding technology
    - UST is reprogrammable in flight, offering flexibility
    - Advanced signal processing capabilities for anomaly investigation and resolution
  - 200 W TWTA (with 377 W DC consumption) acceptable on a SEP mission
- Link Capabilities:
  - Downlink data rates at Ka-band outlined below for both mission concepts
  - Uplink data rate of 2 kbps supported through all mission phases (at X-band)

Table B-35. MORIE telecom design rationale for both studied mission concepts.

Link Description	0.5 AU–Ka-band Downlink	1.5 AU–Ka-band Downlink	2.5 AU–Ka-band Downlink
Full mission data rate (3 m HGA, 200 TWTA)	76 Mbps	8.3 Mbps	3 Mbps
Ice-focused mission data rate (2 m HGA, 100 W TWTA)	19 Mbps	2 Mbps	750 kbps

The telecom costing assumptions are as follows and are summarized in in Table B-36 and Table B-37:

- Development for 100 W and 200 W Ka-band TWTA included
- No spares
- Costs and mass for antenna gimbal carried by the Team X Mechanical chair
- Costs for telecom support to ATLO carried by the Team X Systems chair
- No telecom hardware or support is included for testbeds

The Team X study identified a low telecom mission risk:

- Most components have heritage from MRO
- Small development needed for 200 W Ka-band TWTA
- Includes X-band backup for science downlink, in the event of weather affecting Ka-band downlink transmission
- Spares not included in this cost
- Cost increase for single spares for major components (radio, TWTAs, LGAs) is approximately $4M in FY2025 dollars

The Team X study also identified telecom technology development opportunities:

- Design includes next-generation UST for telecom radio, includes development for this (albeit small)
- Design includes 200 W Ka-band TWTA, which is at TRL 6, and costs are included to develop this technology further. Flying a 200 W Ka-band TWTA would advance Ka-band technology at Mars considerably (many concepts look to using a 200 W Ka-band TWTA at Mars)
- Further opportunity exists in exploring Optical Communication vs. radio frequency (RF)-only Telecom for even higher data returns

Table B-36. Full mission telecom cost.

	Phase A	Phase B	Phase C			Phase D		Total
			Subsystem Design	Subsystem Fabrication	Subsystem I&T	System Level IA&T	Launch Operations	
WBS	12.0 months	12.0 months	11.0 months	6.0 months	5.0 months	14.0 months	4.0 months	$43,009
6.06 Telecom Subsystem	$469	$11,837	$20,532	$4,302	$3,677	$1,957	$235	$43,009
06.06.01 Telecom Management	$214	$608	$608	$325	$318	$399	$147	$2,619
06.06.02 Telecom System Engineering	$255	$637	$584	$318	$265	$743	$85	$2,886
06.06.03 Radios	$0	$6,211	$4,511	$902	$278	$11	$3	$11,917
06.06.04 Power Amplifiers	$0	$1,857	$6,220	$448	$18	$0	$0	$8,543
06.06.05 Antennas	$0	$2,007	$3,740	$1,336	$1,814	$0	$0	$8,897
06.06.06 Optical Comm Assembly	$0	$0	$0	$0	$0	$0	$0	$0
06.06.08 Microwave Components	$0	$0	$2,502	$210	$0	$0	$0	$2,712
06.06.09 RFS I&T	$0	$517	$2,367	$763	$984	$804	$0	$5,435
06.06.10 Telecom Support to ATLO	$0	$0	$0	$0	$0	$0	$0	$0

Table B-37. Ice-focused mission telecom cost.

	Phase A	Phase B	Phase C			Phase D		Total
			Subsystem Design	Subsystem Fabrication	Subsystem I&T	System Level IA&T	Launch Operations	
WBS	12.0 months	12.0 months	11.0 months	6.0 months	5.0 months	14.0 months	4.0 months	$41,948
6.06 Telecom Subsystem	$469	$11,248	$20,061	$4,302	$3,677	$1,957	$235	$41,948
06.06.01 Telecom Management	$214	$608	$608	$325	$318	$399	$147	$2,619
06.06.02 Telecom System Engineering	$255	$637	$584	$318	$265	$743	$85	$2,886
06.06.03 Radios	$0	$6,211	$4,511	$902	$278	$11	$3	$11,917
06.06.04 Power Amplifiers	$0	$1,857	$6,220	$448	$18	$0	$0	$8,543
06.06.05 Antennas	$0	$1,418	$3,269	$1,336	$1,814	$0	$0	$7,836
06.06.06 Optical Comm Assembly	$0	$0	$0	$0	$0	$0	$0	$0
06.06.08 Microwave Components	$0	$0	$2,502	$210	$0	$0	$0	$2,712
06.06.09 RFS I&T	$0	$517	$2,367	$763	$984	$804	$0	$5,435
06.06.10 Telecom Support to ATLO	$0	$0	$0	$0	$0	$0	$0	$0

B.3.14 Ground Systems

The ground system is based on a mission specific implementation of the standard JPL mission operations and ground data systems. The telecom link design enables the data rates to DSN 34 m BWG shown in Table B-38.

Table B-38. Data rates to DSN 34 m BWG.

	Full mission	Ice-focused mission
Max Range (~2.5 AU)	3 Mbps	0.75 Mbps
Mid Range (~1.5 AU)	8 Mbps	2 Mbps
Min Range (~0.5 AU)	75 Mbps	18 Mbps

The ground systems design assumes:

- Ground Network
  - DSN 34 m BWG subnet, X-band engineering telemetry/command, Ka-band science return
- Discuss Details of the Design
  - During Science collection phase budgeting 2x 8-hour passes/day
  - Out of the 16-hour of DSN coverage expect, worst case 60% in view of Earth, this is used for sizing the data return

The resulting daily average data volumes can be seen in Table B-39.

Table B-39. MORIE daily average data volumes.

Earth–Probe Range (AU)	Full mission Daily average data volume (Tb)	Ice-focused mission Daily average data volume (Tb)
0.5	2.59	0.65
1.5	0.28	0.07
2.5	0.10	0.03

The ground systems cost is based on a standard implementation with no deviations from the base model. Costs are in FY2025 $M and given in Table B-40.

Table B-40. MORIE ground systems cost.

Concept	MOS Dev	MOS Ops	GDS Dev	GDS Ops	SDS Dev	SDS Ops	Total Dev	Total Ops	DSN
Full Mission	22.3	43.2	21.9	9.1	0.4	7.4	44.7	59.8	33.4
Ice-focused Mission	19.9	37.6	17.4	7.9	0.2	3.2	37.5	48.7	33.4

"MOS" corresponds to WBS 7.0 excluding 7.03, 7.06, and 7.07.03. It is shown in the full WBS as "7.0 MOS Teams", as a sub-line under "07.0 Mission Operations"
"GDS" corresponds to WBS 9A.0, excluding "09A.03.07 Navigation H/W and S/W Dev". It is shown in the full WBS as "9.0A GDS Teams"

B.3.15 Software

The Team X design study assumed that a Flight Workstation (FWS) core will be used as the base architecture for software development, see Table B-41.

Table B-41. Software design assumptions.

Instrument	Obs Mode	Data Rate	Images
CTX (Context Imager)	Continuous (dayside)	40 Mbps (uncompressed)	2 GB/image; 24 images / sol => 4866/day
SWIR (Shortwave Infrared)	(dayside)	120 Mbps	16 Gb/patch (uncompressed) 11 Gb/patch (SWIR)
TIR (Thermal Infrared)	(night/day)	1.6 Mbps	75 Mb/night time (compressed) 112 Mb/strip (compressed)
HiRISE-Lite	(dayside)	32 Mbps	11 Gb/image (compressed) 20 Gb/image (uncompressed)
MARCI	Continuous (dayside)	0.5 Mbps	
SAR	10 minutes / Orbit (dayside)	0.25 Mbps (compressed)	
Sounder	10 minutes / Orbit (dayside)	8.3 Mbps (compressed)	

The software design is as follows:

- ACS Features
  - Moderate complexity Spacecraft Attitude Control
    - □ 3-axis stabilized with gyros, IMUs, and star trackers
    - □ High pointing accuracy
  - 1 articulated High Gain Antenna with 2 degrees of freedom, 2 fixed Low Gain Antennas
  - High complexity thrust vector control
    - □ High rates of change and high accuracy requirements similar to Cassini and MSL
- Deployments
  - Simple one-time deployment of Articulated Solar Array
  - SAR Reflector deployment
- CDS Features
  - Dual String – single computer processing unit for redundancy
  - Flash Memory for FSW Image storage and Science data storage
    - □ 128 GB for both mission concepts
- Engineering Subsystems Moderately complex Thermal Control
  - Moderately complex Power Control
  - Telecomm capability (DTE and Relay) is similar to MRO and Difficult to implement
- Payload
  - Instruments with Simple Interface Complexity
    - □ Context Imager (CTX)
    - □ Shortwave-IR (SWIR)
    - □ Thermal-IR Spectrometer (TIR)
    - □ Wide Angle Camera (WAC)
    - □ HiRISE type Imager –image data procession performed by FSW management and control
  - Science Data Processing
    - □ WAC (MARCI) Image data processing (both lossy and lossless compression) by FSW
    - □ Polarimetric SAR
- Heritage
  - JPL Reference Bus with Core FSW

The software cost for the full mission concept with seven instruments are shown in Table B-42.

- NRE: $24.1M
- RE: $1.3M
- Total: $25.4M

The software cost for the ice-focused mission concept with three instruments are shown in Table B-43.

- NRE: $22.6M
- RE: $1.2M
- Total: $23.8M

Table B-42. Software cost for the full mission concept with seven instruments.

WBS	Title	Phase A	Cost ($M) PMSR–PDR Phase B	PDR–ARR Phase C	ARR–Launch Phase D	Total $M
06.12.01	Flight Software Management	$0.1	$0.6	$1.0	$0.8	**$2.5**
06.12.02	Flt S/W System Engineering	$0.1	$0.7	$1.8	$0.7	**$3.3**
06.12.03	C&DH	$-	$0.2	$2.2	$0.4	**$2.8**
06.12.04	GN&C FSW	$-	$-	$1.4	$0.6	**$2.0**
06.12.05	Engineering Applications FSW	$-	$-	$1.0	$0.2	**$1.2**
06.12.06	Payload Accommodation FSW	$-	$-	$1.3	$0.8	**$2.1**
06.12.07	System Services	$-	$-	$0.6	$0.4	**$1.0**
06.12.08	Flt S/W Development Testbed	$-	$-	$0.8	$0.2	**$1.0**
06.12.09	Flt S/W–Integration and Test	$-	$-	$4.5	$2.1	**$6.6**
	Total Cost of Labor	**$0.2**	**$1.4**	**$14.7**	**$6.2**	**$22.5**
06.12.01	Development Infrastructure Procurements	$0.0	$0.1	$0.6	$0.2	**$0.8**
06.12.01	Travel	$-	$-	$-	$-	**$-**
06.12.01	Development Infrastructure Support	$-	$0.3	$0.8	$0.8	**$2.0**
	Total Cost (including Procurements, etc.)	**$0.2**	**$1.8**	**$16.1**	**$7.2**	**$25.4**
	Percent by Phase	1%	7%	63%	29%	

Table B-43. Software cost for the ice-focused mission concept with three instruments.

WBS	Title	Phase A	Cost ($M) PMSR–PDR Phase B	PDR–ARR Phase C	ARR–Launch Phase D	Total $M
06.12.01	Flight Software Management	$0.1	$0.5	$1.0	$0.7	**$2.3**
06.12.02	Flt S/W System Engineering	$0.1	$0.6	$1.7	$0.7	**$3.1**
06.12.03	C&DH	$-	$0.2	$2.2	$0.4	**$2.8**
06.12.04	GN&C FSW	$-	$-	$1.4	$0.6	**$2.0**
06.12.05	Engineering Applications FSW	$-	$-	$0.9	$0.2	**$1.1**
06.12.06	Payload Accommodation FSW	$-	$-	$1.1	$0.6	**$1.7**
06.12.07	System Services	$-	$-	$0.6	$0.4	**$1.0**
06.12.08	Flt S/W Development Testbed	$-	$-	$0.7	$0.2	**$0.9**
06.12.09	Flt S/W–Integration and Test	$-	$-	$4.2	$1.9	**$6.2**
	Total Cost of Labor	**$0.2**	**$1.3**	**$13.8**	**$5.8**	**$21.0**
06.12.01	Development Infrastructure Procurements	$0.0	$0.0	$0.5	$0.2	**$0.8**
06.12.01	Travel	$-	$-	$-	$-	**$-**
06.12.01	Development Infrastructure Support	$-	$0.3	$0.8	$0.8	**$2.0**
	Total Cost (including Procurements, etc.)	**$0.2**	**$1.7**	**$15.1**	**$6.8**	**$23.8**
	Percent by Phase	1%	7%	63%	29%	

The main cost driver for the software cost is the large volume of data (55 Gbytes per sol) generated from various instruments in the full mission. This will be managed by the flight software.

B.3.16 Planetary Protection

This is a Category III mission according to the official NASA Planetary Protection guidelines, "NPR 8020.12D Planetary Protection Provisions for Robotic Extraterrestrial Missions." Category III includes flyby and/or orbiter missions to targets of significant interest relative to the process of chemical evolution and/or the origin of life or for which scientific opinion provides a significant chance of contamination, which would jeopardize a future biological experiment or exploration program(s).

Several planetary protection requirements are identified:

- Documentation
  - Request for Planetary Protection Mission Categorization
  - Planetary Protection Plan
  - Subsidiary Plans:
    - Biological Contamination Analysis Plan
    - Microbiological Assay Plan
    - Microbial Reduction Plan
  - Planetary Protection Implementation Plan
  - Pre-Launch Planetary Protection Report
  - Post-Launch Planetary Protection Report
  - Extended Mission Planetary Protection Report (only required for extended mission)
  - End-of-Mission Planetary Protection Report
- Periodic formal and informal reviews with the NASA Planetary Protection Officer (PPO), including:
  - Project Planetary Planning Review (PPO Option)
  - Pre-Launch Planetary Protection Review
  - Launch Readiness Review
  - Others as negotiated with the PP Officer, typically coinciding with major project reviews
- Impact Avoidance:
  - Probability of impact of Mars by the launch vehicle (or any stage thereof) shall not exceed 10^{-4}
  - The probability of entry into the Martian atmosphere and impact on the surface of Mars shall not exceed the following levels for the specified time periods:
    - 10^{-2} for the first 20 years from date of launch
    - 5×10^{-2} for the period of 20 to 50 years from date of launch
  - If probability of Mars impact exceeds requirement then:
    - Total (all surfaces, including mated, and in the bulk of non-metals) bioburden at launch of all hardware 5×10^5 viable spores
    - Organic Inventory: An itemized list of bulk organic materials and masses used in launched hardware
    - Organic Archive: A stored collection of 50 g samples of organic bulk materials of which 25 kg or more is used in launched hardware
- Spacecraft assembled in Class 100,000 / International Organization for Standardization (ISO) Class 8 (or better) clean facilities, with appropriate controls and procedures
- Biological Contamination Control:
  - Bioassays to establish the microbial bioburden levels

  - Independent verification bioassays by NASA Planetary Protection Officer

The following implementing procedures are identified:

- Preparation of the required PP documentation
- Periodic formal and informal reviews with the NASA PPO
- Trajectory biasing
- Analyses:
  - Probability of impact of Mars by the launch vehicle
  - Probability of impact of Mars by the spacecraft during the prime mission
  - Spacecraft microbial burden estimation at launch
  - Entry heating and break-up analysis (also known as the Burn & Break-up (B&B) analysis)
- Spacecraft assembly performed in Class 100,000 / ISO Class 8 (or better) clean facilities, with appropriate controls and procedures
- Microbial burden reduction:
  - Alcohol-wipe cleaning
  - Precision cleaning
  - Heat microbial reduction (HMR)
  - Vapor H_2O_2 microbial reduction (VHPMR)

Subsystem design requirements are identified as follows:

- Orbital lifetime approach:
  - Trajectory must be biased to meet probability of impact requirements
- Biological cleanliness approach:
  - Launch vehicle fairing, Payload Attach Fitting (PAF), upper stage must be cleaned/microbially reduced to 1000 spores/m^2
  - All hardware must be compatible with damp-swab sampling
  - All hardware must be compatible with alcohol-wipe cleaning
  - Use of HMR &/or VHPMR for hardware items with large surface area and not demonstrated to be sterilized on entry

The cost rationale and assumptions are the same for both studied mission concepts. They are the same relative to planetary protection:

- Flight system will not meet orbital lifetime/probability of impact requirement (due to low periapsis)
- Entry heating and break-up analysis will demonstrate that most of the flight system hardware will be sterilized on entry
- Includes the following activities required for a Mars Orbiter mission not meeting orbital lifetime:
  - Includes all PP documentation and review support
  - Includes required analyses
  - Bioassay sampling of:
    - □ All flight system hardware surfaces that will not sterilize on entry, or are a recontamination risk to hardware that will not sterilize on entry
    - □ Bulk bioassay sample of key/driving materials that will not sterilize on entry
    - □ Assembly facilities and ground support equipment that are a recontamination risk
    - □ Launch vehicle hardware
    - □ Genomic inventory sampling will not be required

- Limited microbial reduction procedures are required for hardware, as the majority of hardware should be sterilized on entry. If required, the cost of performing the microbial reduction procedures are to be carried by hardware subsystems.
- The costs of biobarriers/bioshields and High-Efficiency Particulate Air (HEPA) filters, if required, to be carried by hardware subsystems.
  - Some of the development costs may be covered under technology development

  Cost Rationale / Assumptions (cont'd)

The cost for both studied mission concepts is shown in Table B-44. The planetary protection risks are twofold:

- Entry heating and break-up analysis may indicate that no flight system hardware will be sterilized upon entry, therefore requiring cleaning and microbial reduction procedures and additional bioassay sampling not currently planned (~$2-5M cost to project)
- Genomic inventory sampling may be required (~$1-3M cost to project)

Table B-44. Planetary protection cost for both studied mission concepts.

	FTE (yrs)	Cost (FY25 M$)
Development Phase	9.01	3.76
Operations Phase	0.42	0.18
Total	**9.43**	**3.94**

B.3.17 System Verification, Integration, and Test (SVIT)

The Team X study identified the following key verification and validation aspects:

- Instruments performance will be verified at sub-system level
- Instruments will perform interface testing with system test bed prior to ATLO
- System test bed and/or ATLO will be used for ALL level 3 verification activities
- System test bed will be used for ALL Mission System Test/Operational Readiness Test (MST/ORT)
- System test bed will be used for ALL off-nominal scenarios
- Ops products

The verification and validation (V&V) cost is the same for both studied mission concepts: $2.2 M, see Table B-45.

Table B-45. V&V cost for studied mission concepts.

Project Verification & Validation Cost By Phase								
Phase	**A**	**B**	**C1**	**C2**	**C3**	**D1**	**D2**	**Total**
Duration	12 mo.	12 mo.	11 mo.	6 mo.	5 mo.	14 mo.	4 mo.	64 mo.
Total	**$0.0 K**	**$132.6 K**	**$247.6 K**	**$374.8 K**	**$312.3 K**	**$874.5 K**	**$249.9 K**	**$2191.7 K**
Lead	$0.0 K	$132.6 K	$247.6 K	$212.2 K	$176.9 K	$495.2 K	$141.5 K	$1406.0 K
Deputy	$0.0 K	$0.0 K	$0.0 K	$162.6 K	$135.5 K	$379.3 K	$108.4 K	$785.7 K

The MORIE project will develop 2 test beds to facilitate the V&V program:

- Mission System Test Bed
  - Dual string, high-fidelity, used for mission scenario, fault protection, cross-cutting, special focus on aligning the two spacecraft
- Flight Software Test Bed
  - Single string, software development and regression testing

The cost for the testbeds in the full mission concept is $10.0M with a breakdown shown in Table B-46. The cost for the test beds in the ice-focused mission concept is $9.7M with a breakdown shown in Table B-47.

Table B-46. System testbed cost for the full mission concept.

Testbed Cost by Phase								
Phase	A	B	C1	C2	C3	D1	D2	Total
Duration	12 mo.	12 mo.	11 mo.	6 mo.	5 mo.	14 mo.	4 mo.	64 mo.
Total	$0.0 K	$278.2 K	$1428.1 K	$1836.4 K	$1530.3 K	$4285.0 K	$632.3 K	$9990.4 K
General	$0.0 K	$278.2 K	$704.7 K	$462.2 K	$385.1 K	$1078.4 K	$308.1 K	$3216.8 K
PEM	$0.0 K	$172.1 K	$315.6 K	$172.1 K	$143.4 K	$401.6 K	$114.8 K	$1319.7 K
Lead TB Eng	$0.0 K	$106.1 K	$389.1 K	$212.2 K	$176.9 K	$495.2 K	$141.5 K	$1521.0 K
Maintenance	$0.0 K	$0.0 K	$0.0 K	$77.8 K	$64.8 K	$181.6 K	$51.9 K	$376.1 K
Set-up	$0.0 K	$0.0 K	$705.1 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$705.1 K
Set-up 3	$0.0 K	$0.0 K	$377.3 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$377.3 K
Set-up 1-2	$0.0 K	$0.0 K	$327.8 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$327.8 K
Testbed Ops	$0.0 K	$0.0 K	$0.0 K	$1337.6 K	$1114.6 K	$3121.0 K	$299.7 K	$5872.9 K
System Events 3	$0.0 K	$0.0 K	$0.0 K	$134.7 K	$112.3 K	$314.3 K	$0.0 K	$561.3 K
System Events 1-2	$0.0 K	$0.0 K	$0.0 K	$117.0 K	$97.5 K	$273.1 K	$0.0 K	$487.7 K
CDH 3	$0.0 K	$0.0 K	$0.0 K	$44.9 K	$37.4 K	$104.8 K	$0.0 K	$187.1 K
CDH 1-2	$0.0 K	$0.0 K	$0.0 K	$39.0 K	$32.5 K	$91.0 K	$0.0 K	$162.6 K
GNC	$0.0 K	$0.0 K	$0.0 K	$203.7 K	$169.8 K	$475.4 K	$0.0 K	$848.9 K
Power 3	$0.0 K	$0.0 K	$0.0 K	$44.9 K	$37.4 K	$104.8 K	$0.0 K	$187.1 K
Power 1-2	$0.0 K	$0.0 K	$0.0 K	$39.0 K	$32.5 K	$91.0 K	$0.0 K	$162.6 K
Telecom 3	$0.0 K	$0.0 K	$0.0 K	$59.9 K	$49.9 K	$139.7 K	$0.0 K	$249.5 K
Telecom 1-2	$0.0 K	$0.0 K	$0.0 K	$52.0 K	$43.3 K	$121.4 K	$0.0 K	$216.7 K
Payload	$0.0 K	$0.0 K	$0.0 K	$152.8 K	$127.3 K	$356.5 K	$0.0 K	$636.7 K
FSW 3	$0.0 K	$0.0 K	$0.0 K	$193.6 K	$161.3 K	$451.6 K	$129.0 K	$935.5 K
FSW 1-2	$0.0 K	$0.0 K	$0.0 K	$168.2 K	$140.1 K	$392.4 K	$112.1 K	$812.8 K
Fault Protection	$0.0 K	$0.0 K	$0.0 K	$87.8 K	$73.2 K	$204.9 K	$58.5 K	$424.5 K
Services (Burdened)	$0.0 K	$0.0 K	$18.3 K	$36.7 K	$30.6 K	$85.6 K	$24.4 K	$195.6 K
Cleanroom	$0.0 K	$0.0 K	$5.2 K	$10.5 K	$8.7 K	$24.4 K	$7.0 K	$55.9 K
Loanpool	$0.0 K	$0.0 K	$10.5 K	$21.0 K	$17.5 K	$48.9 K	$14.0 K	$111.8 K
Training/Certification	$0.0 K	$0.0 K	$2.6 K	$5.2 K	$4.4 K	$12.2 K	$3.5 K	$27.9 K

Table B-47. System testbed cost for the ice-focused mission concept.

Testbed Cost by Phase								
Phase	A	B	C1	C2	C3	D1	D2	Total
Duration	12 mo.	12 mo.	11 mo.	6 mo.	5 mo.	14 mo.	4 mo.	64 mo.
Total	$0.0 K	$278.2 K	$1428.1 K	$1760.0 K	$1466.7 K	$4106.7 K	$632.3 K	$9672.0 K
General	$0.0 K	$278.2 K	$704.7 K	$462.2 K	$385.1 K	$1078.4 K	$308.1 K	$3216.8 K
PEM	$0.0 K	$172.1 K	$315.6 K	$172.1 K	$143.4 K	$401.6 K	$114.8 K	$1319.7 K
Lead TB Eng	$0.0 K	$106.1 K	$389.1 K	$212.2 K	$176.9 K	$495.2 K	$141.5 K	$1521.0 K
Maintenance	$0.0 K	$0.0 K	$0.0 K	$77.8 K	$64.8 K	$181.6 K	$51.9 K	$376.1 K
Set-up	$0.0 K	$0.0 K	$705.1 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$705.1 K
Set-up 3	$0.0 K	$0.0 K	$377.3 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$377.3 K
Set-up 1-2	$0.0 K	$0.0 K	$327.8 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$327.8 K
Testbed Ops	$0.0 K	$0.0 K	$0.0 K	$1261.2 K	$1051.0 K	$2942.7 K	$299.7 K	$5554.5 K
System Events 3	$0.0 K	$0.0 K	$0.0 K	$134.7 K	$112.3 K	$314.3 K	$0.0 K	$561.3 K
System Events 1-2	$0.0 K	$0.0 K	$0.0 K	$117.0 K	$97.5 K	$273.1 K	$0.0 K	$487.7 K
CDH 3	$0.0 K	$0.0 K	$0.0 K	$44.9 K	$37.4 K	$104.8 K	$0.0 K	$187.1 K
CDH 1-2	$0.0 K	$0.0 K	$0.0 K	$39.0 K	$32.5 K	$91.0 K	$0.0 K	$162.6 K
GNC	$0.0 K	$0.0 K	$0.0 K	$203.7 K	$169.8 K	$475.4 K	$0.0 K	$848.9 K
Power 3	$0.0 K	$0.0 K	$0.0 K	$44.9 K	$37.4 K	$104.8 K	$0.0 K	$187.1 K
Power 1-2	$0.0 K	$0.0 K	$0.0 K	$39.0 K	$32.5 K	$91.0 K	$0.0 K	$162.6 K
Telecom 3	$0.0 K	$0.0 K	$0.0 K	$59.9 K	$49.9 K	$139.7 K	$0.0 K	$249.5 K
Telecom 1-2	$0.0 K	$0.0 K	$0.0 K	$52.0 K	$43.3 K	$121.4 K	$0.0 K	$216.7 K
Payload	$0.0 K	$0.0 K	$0.0 K	$76.4 K	$63.7 K	$178.3 K	$0.0 K	$318.3 K
FSW 3	$0.0 K	$0.0 K	$0.0 K	$193.6 K	$161.3 K	$451.6 K	$129.0 K	$935.5 K
FSW 1-2	$0.0 K	$0.0 K	$0.0 K	$168.2 K	$140.1 K	$392.4 K	$112.1 K	$812.8 K
Fault Protection	$0.0 K	$0.0 K	$0.0 K	$87.8 K	$73.2 K	$204.9 K	$58.5 K	$424.5 K
Services (Burdened)	$0.0 K	$0.0 K	$18.3 K	$36.7 K	$30.6 K	$85.6 K	$24.4 K	$195.6 K
Cleanroom	$0.0 K	$0.0 K	$5.2 K	$10.5 K	$8.7 K	$24.4 K	$7.0 K	$55.9 K
Loanpool	$0.0 K	$0.0 K	$10.5 K	$21.0 K	$17.5 K	$48.9 K	$14.0 K	$111.8 K
Training/Certification	$0.0 K	$0.0 K	$2.6 K	$5.2 K	$4.4 K	$12.2 K	$3.5 K	$27.9 K

The MORIE system will be assembled and tested at JPL. Launched from KSC. Instrument deliveries are assumed as JPL deliverables:

- JPL build
- JPL environmental test lab
- All Mechanical Ground Support Equipment (MGSE) and electrical ground support equipment (EGSE) are delivered to ATLO by sub-systems

The cost for System Integration and Test (I&T) for the full mission concept is $32.8M as shown in Table B-48. The cost for system I&T for the ice-focused mission concept is $31.0M as shown in Table B-49.

Table B-48. System I&T cost for the full mission concept.

	System Integration & Testing 1st UNIT Workforce by Phase							System Integration & Testing 1st UNIT Cost by Phase							
Phase	A	B	C1	C2	C3	D1	D2	A	B	C1	C2	C3	D1	D2	Total
Duration	12 mo.	12 mo.	11 mo.	6 mo.	5 mo.	14 mo.	4 mo.	12 mo.	12 mo.	11 mo.	6 mo.	5 mo.	14 mo.	4 mo.	64 mo.
1st Unit Cost	0.0 FTE	0.3 FTE	4.8 FTE	4.8 FTE	11.1 FTE	30.8 FTE	30.8 FTE	$0 K	$132 K	$2189 K	$1194 K	$2285 K	$22395 K	$4562 K	$32757 K
10.01 ATLO Management	0.0 FTE	0.3 FTE	1.3 FTE	1.3 FTE	2.0 FTE	3.2 FTE	3.2 FTE	$0.0 K	$131.6 K	$640.0 K	$349.1 K	$499.6 K	$1985.9 K	$567.4 K	$4173.6 K
ATLO Management (Phase B-D)	0.0 FTE	0.3 FTE	1.0 FTE	1.0 FTE	1.0 FTE	1.1 FTE	1.1 FTE	$0.0 K	$131.6 K	$482.7 K	$263.3 K	$219.4 K	$649.7 K	$185.6 K	$1932.3 K
Documentarian	0.0 FTE	0.0 FTE	0.3 FTE	0.3 FTE	1.0 FTE	1.1 FTE	1.1 FTE	$0.0 K	$0.0 K	$153.1 K	$83.5 K	$278.3 K	$824.0 K	$235.4 K	$1574.2 K
System Administrator	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	1.1 FTE	1.1 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$506.8 K	$144.8 K	$651.6 K
Doc Services			4.2 $K	2.3 $K	1.9 $K	5.4 $K	1.5 $K	$0.0 K	$0.0 K	$4.2 K	$2.3 K	$1.9 K	$5.4 K	$1.5 K	$15.4 K
10.02 ATLO System Engineering	0.0 FTE	0.0 FTE	2.0 FTE	2.0 FTE	2.0 FTE	2.1 FTE	2.1 FTE	$0.0 K	$0.0 K	$965.4 K	$526.6 K	$438.8 K	$1264.0 K	$361.1 K	$3556.0 K
Mechanical Lead	0.0 FTE	0.0 FTE	1.0 FTE	1.0 FTE	1.0 FTE	1.0 FTE	1.0 FTE	$0.0 K	$0.0 K	$482.7 K	$263.3 K	$219.4 K	$614.4 K	$175.5 K	$1755.3 K
Electrical Lead	0.0 FTE	0.0 FTE	1.0 FTE	1.0 FTE	1.0 FTE	1.1 FTE	1.1 FTE	$0.0 K	$0.0 K	$482.7 K	$263.3 K	$219.4 K	$649.7 K	$185.6 K	$1800.7 K
Flight System ATLO Product Assurance															
Included in 3.0 Mission Assurance															
10.03 System Test Facilities	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$639.1 K	$182.6 K	$821.7 K
Facility/Cleanroom						639.1 $K	182.6 $K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$639.1 K	$182.6 K	$821.7 K
10.04 Flight System Enviromental Testing	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$3101.9 K	$0.0 K	$3101.9 K
Enviromental Testing						3101.9 $K		$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$3101.9 K	$0.0 K	$3101.9 K
10.05 Subsystem Engineering Support	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	3.8 FTE	3.8 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$1885.2 K	$538.6 K	$2423.8 K
Subsystem Support	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	3.8 FTE	3.8 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$1885.2 K	$538.6 K	$2423.8 K
10.07 Instrument and Payload Support	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	2.1 FTE	2.1 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$1047.3 K	$299.2 K	$1346.6 K
Instrument Support	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	2.1 FTE	2.1 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$1047.3 K	$299.2 K	$1346.6 K
10.08 Flight and Payload System I&T	0.0 FTE	0.0 FTE	1.5 FTE	1.5 FTE	5.8 FTE	18.0 FTE	18.0 FTE	$0.0 K	$0.0 K	$583.6 K	$318.3 K	$1106.9 K	$8887.8 K	$2380.4 K	$13277.1 K
Test Conductor	0.0 FTE	0.0 FTE	1.0 FTE	1.0 FTE	1.0 FTE	1.1 FTE	1.1 FTE	$0.0 K	$0.0 K	$389.1 K	$212.2 K	$176.9 K	$523.7 K	$149.6 K	$1451.4 K
Command	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.3 FTE	1.1 FTE	1.1 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$44.2 K	$523.7 K	$149.6 K	$717.5 K
Flight Software	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.3 FTE	1.1 FTE	1.1 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$44.2 K	$523.7 K	$149.6 K	$717.5 K
Mechanical Engineer	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.8 FTE	1.6 FTE	1.6 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$132.6 K	$785.5 K	$224.4 K	$1142.6 K
Electrical Engineer	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	1.2 FTE	1.3 FTE	1.3 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$212.2 K	$628.4 K	$179.5 K	$1020.2 K
Electrical Technician	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	1.8 FTE	1.9 FTE	1.9 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$408.3 K	$1208.9 K	$345.4 K	$1962.5 K
System Engineer	0.0 FTE	0.0 FTE	0.5 FTE	0.5 FTE	0.5 FTE	0.5 FTE	0.5 FTE	$0.0 K	$0.0 K	$194.5 K	$106.1 K	$88.4 K	$261.8 K	$74.8 K	$725.7 K
Mechanical Tech Services						9.5 FTE	9.5 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$3876.0 K	$1107.4 K	$4983.4 K
Equipment/Loan Pool Rental						258.1 $K		$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$258.1 K	$0.0 K	$258.1 K
Fabrication Services						298.2 $K		$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$298.2 K	$0.0 K	$298.2 K
10.09 EGSE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$861.4 K	$0.0 K	$861.4 K
EGSE Cables						861.4 $K		$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$861.4 K	$0.0 K	$861.4 K
10.10 MGSE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K
System MGSE						0.0 $K		$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K
10.11 Logistics and Transportation	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	1.4 FTE	1.5 FTE	1.5 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$239.7 K	$1004.0 K	$213.0 K	$1456.7 K
Packing and Transport	0.0 $K	0.0 $K	0.0 $K	0.0 $K	0.0 $K	258.4 $K		$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$258.4 K	$0.0 K	$258.4 K
Logistics	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	1.4 FTE	1.5 FTE	1.5 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$239.7 K	$745.6 K	$213.0 K	$1198.3 K
10.12 Launch Operations	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.2 FTE	0.2 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$1718.9 K	$19.8 K	$1738.7 K
Launch Site Support	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.2 FTE	0.2 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$69.4 K	$19.8 K	$89.2 K
Travel and Lodging						1649.5 $K		$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$1649.5 K	$0.0 K	$1649.5 K

Table B-49. System I&T cost for the ice-focused mission concept.

	System Integration & Testing 1st UNIT Workforce by Phase							System Integration & Testing 1st UNIT Cost by Phase							
Phase	A	B	C1	C2	C3	D1	D2	A	B	C1	C2	C3	D1	D2	Total
Duration	12 mo.	12 mo.	11 mo.	6 mo.	5 mo.	14 mo.	4 mo.	12 mo.	12 mo.	11 mo.	6 mo.	5 mo.	14 mo.	4 mo.	64 mo.
1st Unit Cost	0.0 FTE	0.3 FTE	4.8 FTE	4.8 FTE	11.0 FTE	28.2 FTE	28.2 FTE	$0 K	$132 K	$2189 K	$1194 K	$2266 K	$20942 K	$4188 K	$30910 K
10.01 ATLO Management	0.0 FTE	0.3 FTE	1.3 FTE	1.3 FTE	2.0 FTE	3.0 FTE	3.0 FTE	$0.0 K	$131.6 K	$640.0 K	$349.1 K	$499.6 K	$1878.2 K	$536.6 K	$4035.2 K
ATLO Management (Phase B-D)	0.0 FTE	0.3 FTE	1.0 FTE	1.0 FTE	1.0 FTE	1.0 FTE	1.0 FTE	$0.0 K	$131.6 K	$482.7 K	$263.3 K	$219.4 K	$614.4 K	$175.5 K	$1886.9 K
Documentarian	0.0 FTE	0.0 FTE	0.3 FTE	0.3 FTE	1.0 FTE	1.0 FTE	1.0 FTE	$0.0 K	$0.0 K	$153.1 K	$83.5 K	$278.3 K	$779.2 K	$222.6 K	$1516.6 K
System Administrator	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	1.0 FTE	1.0 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$479.3 K	$136.9 K	$616.2 K
Doc Services			4.2 $K	2.3 $K	1.9 $K	5.4 $K	1.5 $K	$0.0 K	$0.0 K	$4.2 K	$2.3 K	$1.9 K	$5.4 K	$1.5 K	$15.4 K
10.02 ATLO System Engineering	0.0 FTE	0.0 FTE	2.0 FTE	2.0 FTE	2.0 FTE	2.0 FTE	2.0 FTE	$0.0 K	$0.0 K	$965.4 K	$526.6 K	$438.8 K	$1228.7 K	$351.1 K	$3510.6 K
Mechanical Lead	0.0 FTE	0.0 FTE	1.0 FTE	1.0 FTE	1.0 FTE	1.0 FTE	1.0 FTE	$0.0 K	$0.0 K	$482.7 K	$263.3 K	$219.4 K	$614.4 K	$175.5 K	$1755.3 K
Electrical Lead	0.0 FTE	0.0 FTE	1.0 FTE	1.0 FTE	1.0 FTE	1.0 FTE	1.0 FTE	$0.0 K	$0.0 K	$482.7 K	$263.3 K	$219.4 K	$614.4 K	$175.5 K	$1755.3 K
Flight System ATLO Product Assurance															
Included in 3.0 Mission Assurance															
10.03 System Test Facilities	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$639.1 K	$182.6 K	$821.7 K
Facility/Cleanroom						639.1 $K	182.6 $K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$639.1 K	$182.6 K	$821.7 K
10.04 Flight System Enviromental Testing	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$3101.9 K	$0.0 K	$3101.9 K
Enviromental Testing						3101.9 $K		$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$3101.9 K	$0.0 K	$3101.9 K
10.05 Subsystem Engineering Support	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	3.6 FTE	3.6 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$1782.7 K	$509.3 K	$2292.1 K
Subsystem Support	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	3.6 FTE	3.6 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$1782.7 K	$509.3 K	$2292.1 K
10.07 Instrument and Payload Support	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	1.0 FTE	1.0 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$495.2 K	$141.5 K	$636.7 K
Instrument Support	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	1.0 FTE	1.0 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$495.2 K	$141.5 K	$636.7 K
10.08 Flight and Payload System I&T	0.0 FTE	0.0 FTE	1.5 FTE	1.5 FTE	5.8 FTE	17.0 FTE	17.0 FTE	$0.0 K	$0.0 K	$583.6 K	$318.3 K	$1106.9 K	$8434.9 K	$2251.0 K	$12694.8 K
Test Conductor	0.0 FTE	0.0 FTE	1.0 FTE	1.0 FTE	1.0 FTE	1.0 FTE	1.0 FTE	$0.0 K	$0.0 K	$389.1 K	$212.2 K	$176.9 K	$495.2 K	$141.5 K	$1414.8 K
Command	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.3 FTE	1.0 FTE	1.0 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$44.2 K	$495.2 K	$141.5 K	$680.9 K
Flight Software	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.3 FTE	1.0 FTE	1.0 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$44.2 K	$495.2 K	$141.5 K	$680.9 K
Mechanical Engineer	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.8 FTE	1.5 FTE	1.5 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$132.6 K	$742.8 K	$212.2 K	$1087.7 K
Electrical Engineer	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	1.2 FTE	1.2 FTE	1.2 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$212.2 K	$594.2 K	$169.8 K	$976.2 K
Electrical Technician	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	1.8 FTE	1.8 FTE	1.8 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$408.3 K	$1143.2 K	$326.6 K	$1878.0 K
System Engineer	0.0 FTE	0.0 FTE	0.5 FTE	0.5 FTE	0.5 FTE	0.5 FTE	0.5 FTE	$0.0 K	$0.0 K	$194.5 K	$106.1 K	$88.4 K	$247.6 K	$70.7 K	$707.4 K
Mechanical Tech Services						9.0 FTE	9.0 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$3665.3 K	$1047.2 K	$4712.5 K
Equipment/Loan Pool Rental						258.1 $K		$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$258.1 K	$0.0 K	$258.1 K
Fabrication Services						298.2 $K		$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$298.2 K	$0.0 K	$298.2 K
10.09 EGSE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$861.4 K	$0.0 K	$861.4 K
EGSE Cables						861.4 $K		$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$861.4 K	$0.0 K	$861.4 K
10.10 MGSE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K
System MGSE						0.0 $K		$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K
10.11 Logistics and Transportation	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	1.2 FTE	1.4 FTE	1.4 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$220.2 K	$943.5 K	$195.7 K	$1359.4 K
Packing and Transport	0.0 $K	0.0 $K	0.0 $K	0.0 $K	0.0 $K	258.4 $K		$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$258.4 K	$0.0 K	$258.4 K
Logistics	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	1.2 FTE	1.4 FTE	1.4 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$220.2 K	$685.1 K	$195.7 K	$1101.1 K
10.12 Launch Operations	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.2 FTE	0.2 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$1576.1 K	$19.8 K	$1595.9 K
Launch Site Support	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.2 FTE	0.2 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$69.4 K	$19.8 K	$89.2 K
Travel and Lodging						1506.7 $K		$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$1506.7 K	$0.0 K	$1506.7 K

B.3.18 Cost

The total cost is shown in Table B-8. The cost breakdown for A-D and E-F for the full mission concept are shown in Table B-50 and Table B-51, respectively.

Table B-50. Cost A-D for the full mission.

WBS Elements	NRE	RE	1st Unit
Development Cost (Phases A - D) (w/o reserves)	**$610.4 M**	**$319.1 M**	**$929.4 M**
01.0 Project Management	**$21.0 M**		**$21.0 M**
1.01 Project Management	$8.9 M		$8.9 M
1.02 Business Management	$10.2 M		$10.2 M
1.04 Project Reviews	$1.4 M		$1.4 M
1.06 Launch Approval	$0.4 M		$0.4 M
02.0 Project Systems Engineering	**$26.3 M**	**$2.8 M**	**$29.1 M**
2.01 Project Systems Engineering	$8.9 M		$8.9 M
2.02 Project SW Systems Engineering	$5.2 M		$5.2 M
2.03 EEIS	$1.5 M		$1.5 M
2.04 Information System Management	$1.7 M		$1.7 M
2.05 Configuration Management	$1.6 M		$1.6 M
2.06 Planetary Protection	$1.5 M	$2.3 M	$3.8 M
2.07 Contamination Control	$2.2 M	$0.5 M	$2.7 M
2.09 Launch System Engineering	$1.1 M		$1.1 M
2.10 Project V&V	$2.2 M		$2.2 M
2.11 Risk Management	$0.5 M		$0.5 M
03.0 Mission Assurance	**$24.9 M**	**$13.0 M**	**$37.9 M**
04.0 Science	**$29.8 M**		**$29.8 M**
05.0 Payload System	**$185.9 M**	**$129.0 M**	**$314.9 M**
5.01 Payload Management	$8.2 M		$8.2 M
5.02 Payload Engineering	$6.4 M		$6.4 M
Element 01	$171.3 M	$129.0 M	$300.3 M
CTX	$6.8 M	$9.8 M	$16.6 M
SWIR	$0.0 M	$0.0 M	$0.0 M
TIR	$0.0 M	$0.0 M	$0.0 M
IR Telescope	$44.4 M	$32.2 M	$76.6 M
HiRISE Lite	$34.7 M	$25.2 M	$59.9 M
WAC (MARCI)	$3.5 M	$2.5 M	$6.0 M
SAR/Sounder	$81.9 M	$59.3 M	$141.2 M
06.0 Flight System	**$228.9 M**	**$160.0 M**	**$388.9 M**
6.01 Flight System Management	$5.2 M		$5.2 M
6.02 Flight System Systems Engineering	$33.7 M		$33.7 M
6.03 Product Assurance (included in 3.0)			$0.0 M
Element 01	$182.5 M	$157.5 M	$340.0 M
6.04 Power	$21.3 M	$34.0 M	$55.3 M
6.05 C&DH	$19.4 M	$31.5 M	$50.9 M
6.06 Telecom	$29.2 M	$18.1 M	$47.2 M
6.07 Structures (includes Mech. I&T)	$34.4 M	$16.7 M	$51.1 M
6.08 Thermal	$5.1 M	$6.2 M	$11.3 M
6.09 Propulsion	$20.7 M	$26.5 M	$47.2 M
6.10 ACS	$17.5 M	$15.6 M	$33.1 M
6.11 Harness	$6.8 M	$7.2 M	$14.0 M
6.12 S/C Software	$24.1 M	$1.3 M	$25.4 M
6.13 Materials and Processes	$4.0 M	$0.4 M	$4.5 M
6.14 Spacecraft Testbeds	$7.5 M	$2.5 M	$10.0 M
07.0 Mission Operations Preparation	**$26.1 M**		**$26.1 M**
7.0 MOS Teams	$22.3 M		$22.3 M
7.03 Tracking (Launch Ops.)	$0.6 M		$0.6 M
7.06 Navigation Operations Team	$3.1 M		$3.1 M
7.07.03 Mission Planning Team	$0.0 M		$0.0 M
09.0 Ground Data Systems	**$24.1 M**		**$24.1 M**
9.0A Ground Data System	$21.9 M		$21.9 M
9.0B Science Data System Development	$0.4 M		$0.4 M
9A.03.07 Navigation H/W & S/W Development	$1.7 M		$1.7 M
10.0 ATLO	**$18.4 M**	**$14.3 M**	**$32.8 M**
11.0 Education and Public Outreach	**$0.0 M**	**$0.0 M**	**$0.0 M**
12.0 Mission and Navigation Design	**$24.8 M**		**$24.8 M**
12.01 Mission Design	$2.2 M		$2.2 M
12.02 Mission Analysis	$6.4 M		$6.4 M
12.03 Mission Engineering	$1.8 M		$1.8 M
12.04 Navigation Design	$14.4 M		$14.4 M

SWIR &TIR costs captured under IR Telescope

Table B-51. Cost E-F for the full mission.

WBS Elements	NRE	RE	1ST Unit
Operations Cost (Phase E–F (w/o Reserves)	**$215.8M**	**$0.2M**	**$216.0M**
01.0 Project Management	**$8.9M**		**$8.9M**
1.01 Project Management	$5.2M		$5.2M
1.02 Business Management	$3.5M		$3.5M
1.04 Project Reviews	$0.3M		$0.3M
1.06 Launch Approval	$0.0M		$0.0M
02.0 Project Systems Engineering	**$0.0M**	**$0.2M**	**$0.2M**
2.06 Planetary Protection	$0.0M	$0.2M	$0.2M
03.0 Mission Assurance	**$0.0M**	**$0.0M**	**$0.0M**
04.0 Science	**$104.7M**		**$104.7M**
4.02 Science Team	$104.7M		$104.7M
06.0 Flight System	**$0.0M**		**$0.0M**
6.02 Flight System Systems Engineering	$0.0M		$0.0M
07.0 Mission Operations	**$85.3M**		**$85.3M**
7.0 MOS Teams	$43.2M		$43.2M
7.03 Tracking	$32.8M		$32.8M
7.06 Navigation Operations Team	$8.9M		$8.9M
7.07.03 Mission Planning Team	$0.4M		$0.4M
09.0 Ground Data Systems	**$16.8M**		**$16.8M**
9.0A GDS Teams	$9.1M		$9.1M
9.0B Science Data Systems Ops	$7.4M		$7.4M
9.A.03.07 Navigation H/W and S/W Dev	$0.3M		$0.3M
11.0 Education and Public Outreach	**$0.0M**	**$0.0M**	**$0.0M**
12.0 Mission and Navigation Design	**$0.0M**		**$0.0M**
12.01 Mission Design	$0.0M		$0.0M
12.02 Mission Analysis	$0.0M		$0.0M
12.04 Navigation Design	$0.0M		$0.0M

The cost breakdown for A-D and E-F for the ice-focused mission concept are shown in Table B-52 and Table B-53, respectively.

Table B-52. Cost A-D for the ice-focused mission.

WBS Elements	NRE	RE	1st Unit
Development Cost (Phases A - D) (w/o Reserve)	**$478.5 M**	**$252.0 M**	**$730.5 M**
01.0 Project Management	**$21.0 M**		**$21.0 M**
1.01 Project Management	$8.9 M		$8.9 M
1.02 Business Management	$10.2 M		$10.2 M
1.04 Project Reviews	$1.4 M		$1.4 M
1.06 Launch Approval	$0.4 M		$0.4 M
02.0 Project Systems Engineering	**$26.3 M**	**$2.8 M**	**$29.1 M**
2.01 Project Systems Engineering	$8.9 M		$8.9 M
2.02 Project SW Systems Engineering	$5.2 M		$5.2 M
2.03 EEIS	$1.5 M		$1.5 M
2.04 Information System Management	$1.7 M		$1.7 M
2.05 Configuration Management	$1.6 M		$1.6 M
2.06 Planetary Protection	$1.5 M	$2.3 M	$3.8 M
2.07 Contamination Control	$2.2 M	$0.5 M	$2.7 M
2.09 Launch System Engineering	$1.1 M		$1.1 M
2.10 Project V&V	$2.2 M		$2.2 M
2.11 Risk Management	$0.5 M		$0.5 M
03.0 Mission Assurance	**$19.8 M**	**$10.4 M**	**$30.3 M**
04.0 Science	**$14.6 M**		**$14.6 M**
05.0 Payload System	**$98.3 M**	**$72.0 M**	**$170.3 M**
5.01 Payload Management	$3.3 M		$3.3 M
5.02 Payload Engineering	$2.4 M		$2.4 M
Element 01	$92.6 M	$72.0 M	$164.6 M
CTX	$6.8 M	$9.8 M	$16.6 M
SAR/Dual freq Sounder	$85.8 M	$62.2 M	$148.0 M
06.0 Flight System	**$212.9 M**	**$153.5 M**	**$366.4 M**
6.01 Flight System Management	$5.2 M		$5.2 M
6.02 Flight System Systems Engineering	$33.7 M		$33.7 M
6.03 Product Assurance (included in 3.0)			$0.0 M
Element 01	$166.7 M	$151.1 M	$317.8 M
6.04 Power	$21.3 M	$32.3 M	$53.6 M
6.05 C&DH	$19.4 M	$31.5 M	$50.9 M
6.06 Telecom	$24.4 M	$17.6 M	$41.9 M
6.07 Structures (includes Mech. I&T)	$31.1 M	$14.8 M	$45.9 M
6.08 Thermal	$5.1 M	$6.2 M	$11.3 M
6.09 Propulsion	$20.7 M	$26.3 M	$47.0 M
6.10 ACS	$11.6 M	$14.1 M	$25.6 M
6.11 Harness	$6.5 M	$6.8 M	$13.3 M
6.12 S/C Software	$22.6 M	$1.2 M	$23.8 M
6.13 Materials and Processes	$4.0 M	$0.4 M	$4.5 M
6.14 Spacecraft Testbeds	$7.3 M	$2.4 M	$9.7 M
07.0 Mission Operations Preparation	**$23.7 M**		**$23.7 M**
7.0 MOS Teams	$19.9 M		$19.9 M
7.03 Tracking (Launch Ops.)	$0.6 M		$0.6 M
7.06 Navigation Operations Team	$3.1 M		$3.1 M
7.07.03 Mission Planning Team	$0.0 M		$0.0 M
09.0 Ground Data Systems	**$19.3 M**		**$19.3 M**
9.0A Ground Data System	$17.4 M		$17.4 M
9.0B Science Data System Development	$0.2 M		$0.2 M
9A.03.07 Navigation H/W & S/W Development	$1.7 M		$1.7 M
10.0 ATLO	**$17.7 M**	**$13.2 M**	**$30.9 M**
11.0 Education and Public Outreach	**$0.0 M**	**$0.0 M**	**$0.0 M**
12.0 Mission and Navigation Design	**$24.8 M**		**$24.8 M**
12.01 Mission Design	$2.2 M		$2.2 M
12.02 Mission Analysis	$6.4 M		$6.4 M
12.03 Mission Engineering	$1.8 M		$1.8 M
12.04 Navigation Design	$14.4 M		$14.4 M

Table B-53. Cost E-F for the ice-focused mission.

WBS Elements	NRE	RE	1ST Unit
Operations Cost (Phase E–F (w/o Reserves)	**$149.8M**	**$0.2M**	**$149.8M**
01.0 Project Management	**$8.9M**		**$8.9M**
1.01 Project Management	$5.2M		$5.2M
1.02 Business Management	$3.5M		$3.5M
1.04 Project Reviews	$0.3M		$0.3M
1.06 Launch Approval	$0.0M		$0.0M
02.0 Project Systems Engineering	**$0.0M**	**$0.2M**	**$0.2M**
2.06 Planetary Protection	$0.0M	$0.2M	$0.2M
03.0 Mission Assurance	**$0.0M**	**$0.0M**	**$0.0M**
04.0 Science	**$49.8M**		**$49.8M**
4.02 Science Team	$49.8M		$49.8M
06.0 Flight System	**$0.0M**		**$0.0M**
07.0 Mission Operations	**$79.7M**		**$79.7M**
7.0 MOS Teams	$37.6M		$37.6M
7.03 Tracking	$32.8M		$32.8M
7.06 Navigation Operations Team	$8.9M		$8.9M
7.07.03 Mission Planning Team	$0.4M		$0.4M
09.0 Ground Data Systems	**$11.3M**		**$11.3M**
9.0A GDS Teams	$7.9M		$7.9M
9.0B Science Data Systems Ops	$3.2M		$3.2M
9.A.03.07 Navigation H/W and S/W Dev	$0.3M		$0.3M
11.0 Education and Public Outreach	**$0.0M**	**$0.0M**	**$0.0M**
12.0 Mission and Navigation Design	**$0.0M**		**$0.0M**

The cost drivers have been identified as:

- Spacecraft drives the cost of the development with Mechanical/Structures, C&DH, ACS and Propulsion (see the subsystems reports)
- In-house development labor is one of the main drivers
- The number and types of instruments have been the cost driver for this study.

Potential cost savings are identified as:

- If possible, a commercially development spacecraft or instrument offers savings as they typically don't charge for NRE.
- Seek vendors with space qualified flight heritage

Potential cost uppers are identified as:

- Spacecraft development from a vendor that has little to no experience may cause a schedule impact, thus increase costs
- Added procurement burden for all out-of-house purchases and contracts (17.5%)

Table B-54 shows the cost comparison. The WBS breakdown is using 50% reserves. The biggest difference between the two studied mission concepts are the number and types of instruments: $314.9M vs $170.3 M (WBS 5.0).

Table B-54. Cost comparison.

	CBE	Res.	Total	CBE	Res.	Total
Development Cost (Phase A–D)	**$929.4M**	**50%**	**$1394.1M**	**$730.5M**	**50%**	**$1095.7M**
Operations Cost (Phase E)	**$216.0M**	**25%**	**$270.0M**	**$149.9M**	**25%**	**$187.4M**
Total A–E Project Cost (FY25 $M)	**$1145.4M**		**$1664.1M**	**$880.4M**		**$1283.1M**
WBS Elements	**NRE**	**RE**	**1st Unit**	**NRE**	**RE**	**1st Unit**
Development Cost (Phase A–D) (w/o reserves)	**$610.4M**	**$319.1M**	**$929.4M**	**$478.5M**	**$252.0M**	**$730.5M**
01.0 Project Management	$21.0M		$21.0M	$21.0M		**$21.0M**
02.0 Project Systems Engineering	$26.3M	$2.8M	$29.1M	$26.3M	$2.8M	**$29.1M**
03.0 Mission Assurance	$24.9M	$13.0M	$37.9M	$19.8M	$10.4M	**$30.3M**
04.0 Science	$29.8M		$29.8M	$14.6M		**$14.6M**
05.0 Payload System	$185.9M	$129.0M	$314.9M	$98.3M	$72.0M	**$170.3M**
06.0 Flight System	$228.9M	$160.0M	$388.9M	$212.9M	$153.5M	**$366.4M**
07.0 Mission Operations Preparation	$26.1M		$26.1M	$23.7M		**$23.7M**
09.0 Ground Data Systems	$24.1M		$24.1M	$19.3M		**$19.3M**
10.0 ATLO	$18.4M	$14.3M	$32.8M	$17.7M	$13.2M	**$30.9M**
11.0 Education and Public Outreach	$0.0M	$0.0M	$0.0M	$0.0M	$0.0M	**$0.0M**
12.0 Mission and Navigation Design	$24.8M		$24.8M	$24.8M		**$24.8M**
Operations Cost (Phase E–F) (w/o reserves)	**$215.8M**	**$0.2M**	**$216.0M**	**$149.8M**	**$0.2M**	**$149.9M**
01.0 Project Management	$8.9M		$8.9M	$8.9M		**$8.9M**
02.0 Project Systems Engineering	$0.0M	$0.2M	$0.2M	$0.0M	$0.2M	**$0.2M**
03.0 Mission Assurance	$0.0M	$0.0M	$0.0M	$0.0M	$0.0M	**$0.0M**
04.0 Science	$104.7M		$104.7M	$49.8M		**$49.8M**
06.0 Flight System	$0.0M		$0.0M	$0.0M		**$0.0M**
07.0 Mission Operations Preparation	$85.3M		$85.3M	$79.7M		**$79.7M**
09.0 Ground Data Systems	$16.8M		$16.8M	$11.3M		**$11.3M**
11.0 Education and Public Outreach	$0.0M	$0.0M	$0.0M	$0.0M	$0.0M	**$0.0M**
12.0 Mission and Navigation Design	$0.0M		$0.0M	$0.0M		**$0.0M**

B.3.19 Master Equipment Lists

The Team X Master Equipment List is shown in Table B-55 (full mission) and Table B-56 (ice-focused mission).

Table B-55. Full mission MEL.

Full mission: Mars Pre-Decadal MORIE 2020–02							
Launch Vehicle: Falcon 9 re-usable							
Attitude Control		**# Of Units**			**Flight Hardware Masses**		
Subsystem/Component	**Current Best Estimate (CBE) Unit Mass (kg)**	**Flight Units**	**Flight Spares**	**EMs & Proto-types**	**Total CBE Mass (kg)**	**Cont. (%)**	**Total Mass w/ Cont. (kg)**
Sun Sensors	0.13	8	0	1	1.04	10%	1.14
Star Trackers	4.30	2	0	1	8.60	10%	9.46
IMUs	4.00	2	0	1	8.00	10%	8.80
RWAs	12.00	4	0	1	48.00	10%	52.80
Gimbal Drive Electronics	0.99	4	0	1	3.96	10%	4.36
Total Mass/Power					**69.6**	**10%**	**76.6**
C&DH		**# Of Units**			**Flight Hardware Masses**		
Subsystem/Component	**Current Best Estimate (CBE) Unit Mass (kg)**	**Flight Units**	**Flight Spares**	**EMs & Proto-types**	**Total CBE Mass (kg)**	**Cont. (%)**	**Total Mass w/ Cont. (kg)**
Processor: RAD750	0.55	2	1	5	1.10	5%	1.16
Memory: NVM	0.71	2	1	5	1.42	5%	1.49
Telecom_I_F: MTIF	0.73	2	1	5	1.46	5%	1.53
General_I_F: MSIA	0.71	2	1	5	1.42	5%	1.49
General_I_F: LEU-D	0.67	2	1	5	1.34	5%	1.41
Analog_I_F: LEU-A	0.55	2	1	5	1.10	5%	1.16
Custom_Board: CRC	0.26	2	1	5	0.52	5%	0.55
Analog_I_F: MREU	0.82	2	1	5	1.64	5%	1.72
Power: CEPCU	1.15	2	1	5	2.30	5%	2.42
Backplane: CPCI backplane (6 slots)	0.60	4	2	9	2.40	30%	3.12
Chassis: C&DH chassis (6 slot)	2.85	4	2	9	11.40	30%	14.82
Total Mass/Power					**26.1**	**18%**	**30.9**
Power		**# Of Units**			**Flight Hardware Masses**		
Subsystem/Component	**Current Best Estimate (CBE) Unit Mass (kg)**	**Flight Units**	**Flight Spares**	**EMs & Proto-types**	**Total CBE Mass (kg)**	**Cont. (%)**	**Total Mass w/ Cont. (kg)**
Solar Array, GaAs TJ UltraFlex, Two Deployable Wings, 47.22m²	79.59	1	0	0	79.59	30%	103.46
Battery, Secondary BatteryLi-ION	32.10	2	1	0	64.20	30%	83.46
High Voltage Down Converter (aka High Voltage Electronics Assy (HVEA)	20.00	1	1	1	20.00	30%	26.00
Dual Str. Reference Bus Pyro Firing Slice (PFS)	1.80	2	0	2	3.60	5%	3.78
Dual Str. Reference Bus Power Switch Slice - High Side (MPSS-HS)	1.85	6	0	2	11.10	5%	11.66
Dual Str. Reference Bus Guidance Interface Driver Card (GID)	0.77	2	1	2	1.54	5%	1.62
Dual Str. Reference Bus Housekeeping Power Converter Unit (HPCU)	1.20	2	1	2	2.40	5%	2.52
6-slot power chassis	1.50	2	0	1	3.00	30%	3.90
CPCI backplane (6 slots)	0.63	2	0	1	1.25	30%	1.63
Diodes Assembly	0.20	1	1	1	0.20	30%	0.26
Total Mass/Power					**186.9**	**28%**	**238.3**

Table B-55. Full mission MEL.

Full mission: Mars Pre-Decadal MORIE 2020–02							
Launch Vehicle: Falcon 9 re-usable							
Propulsion–SEP		**# Of Units**			**Flight Hardware Masses**		
Subsystem/Component	**Current Best Estimate (CBE) Unit Mass (kg)**	**Flight Units**	**Flight Spares**	**EMs & Proto-types**	**Total CBE Mass (kg)**	**Cont. (%)**	**Total Mass w/ Cont. (kg)**
EP Xenon Feedsystem	0.32	1	0.25	0	0.32	10%	0.35
XFC	0.00	4	1	0	0.00	10%	0.00
Lines, Fittings, Misc.	3.00	1	1	0	3.00	50%	4.50
PPU	16.30	2	1	0	32.60	10%	35.86
Thruster Gimbals	3.90	2	0.25	0	7.80	10%	8.58
Deployment module & thruster support	28.00	2	0.25	0	56.00	10%	61.60
EP Main Engine	8.81	4	1	0	35.24	10%	38.76
Pressurant Tanks	22.00	3	1	0	66.00	10%	72.60
Total Mass/Power					**201.0**	**11%**	**222.3**
Propulsion–Monoprop		**# Of Units**			**Flight Hardware Masses**		
Subsystem/Component	**Current Best Estimate (CBE) Unit Mass (kg)**	**Flight Units**	**Flight Spares**	**EMs & Proto-types**	**Total CBE Mass (kg)**	**Cont. (%)**	**Total Mass w/ Cont. (kg)**
Gas Service Valve	0.23	2	1	0	0.46	2%	0.47
Temp. Sensor	0.01	1	1	0	0.01	5%	0.01
Liq. Service Valve	0.28	1	1	0	0.28	2%	0.29
LP Transducer	0.27	2	1	0	0.54	2%	0.55
Liq. Filter	0.45	1	1	0	0.45	2%	0.46
LP Latch Valve	0.35	2	1	0	0.70	2%	0.71
Temp. Sensor	0.01	10	1	0	0.10	5%	0.11
Lines, Fittings, Misc.	1.80	1	1	0	1.80	50%	2.70
Monoprop Main Engine	0.33	8	1	0	2.64	5%	2.77
Fuel Tanks	6.35	1	1	0	6.35	10%	6.99
Total Mass/Power					**13.3**	**13%**	**15.1**
Mechanical		**# Of Units**			**Flight Hardware Masses**		
Subsystem/Component	**Current Best Estimate (CBE) Unit Mass (kg)**	**Flight Units**	**Flight Spares**	**EMs & Proto-types**	**Total CBE Mass (kg)**	**Cont. (%)**	**Total Mass w/ Cont. (kg)**
Primary Structure	201.69	1	0	0	201.69	30%	262.19
Secondary Structure	19.80	1	0	0	19.80	30%	25.74
Tertiary Structure	5.59	1	0	0	5.59	30%	7.27
Integration Hardware: Fasteners, etc.	15.90	1	0	0	15.90	30%	20.66
Power Support Structure	2.84	1	0	0	2.84	30%	3.69
Power Mechanisms	10.40	1	0	0	10.40	30%	13.52
Telecom Support Structure	5.01	1	0	0	5.01	30%	6.52
Telecom Mechanisms	9.90	1	0	0	9.90	30%	12.87
Scan Paltform Base	5.00	1	0	0	5.00	30%	6.50
Scan Platform Bus Offset	3.00	1	0	0	3.00	30%	3.90
Scan Platform 1-DOF Actuator	4.50	1	0	0	4.50	30%	5.85
Balance/Ballast	49.36	1	0	0	49.36	30%	64.17
Adapter, Spacecraft side	21.23	1	0	0	21.23	30%	27.60
Harness	75.69	1	0	0	75.69	30%	98.40
Total Mass/Power					**429.9**	**30%**	**558.9**
Telecom		**# Of Units**			**Flight Hardware Masses**		
Subsystem/Component	**Current Best Estimate (CBE) Unit Mass (kg)**	**Flight Units**	**Flight Spares**	**EMs & Proto-types**	**Total CBE Mass (kg)**	**Cont. (%)**	**Total Mass w/ Cont. (kg)**

Table B-55. Full mission MEL.

Full mission: Mars Pre-Decadal MORIE 2020–02							
Launch Vehicle: Falcon 9 re-usable							
Ka-band HGA, Reflector Only, 3m	19.10	1	0	0	19.10	15%	21.96
Dual Band X-Ka Band HGA Feed	1.60	1	0	0	1.60	10%	1.76
X-band LGA, JUNO Toroidal	1.95	2	0	0	3.90	10%	4.29
UST Single RX, Dual TX	4.50	2	0	0	9.00	15%	10.35
Ka-band TWTA RF=100-200W	5.20	2	0	1	10.40	15%	11.96
X-band TWTA, RF=25W	3.00	2	0	0	6.00	10%	6.60
X-band Diplexer, moderate isolation	0.35	2	0	0	0.70	15%	0.81
Ka-Band Filters Tx / Rx	0.60	2	0	0	1.20	15%	1.38
Ka-band Isolator	0.50	2	0	0	1.00	15%	1.15
Ka-Band Waveguide Transfer Switch	0.15	3	0	0	0.45	15%	0.52
X-Band Waveguide Transfer Switch	0.45	6	0	0	2.70	15%	3.11
X-band Isolator	0.50	2	0	0	1.00	15%	1.15
Coax Cable, flex (190)	0.05	6	6	0	0.33	50%	0.49
WR-112 WG, rigid (Al)	0.19	10	10	0	1.90	50%	2.85
WR-34 WG, rigid (Al)	0.07	8	8	0	0.56	50%	0.84
Total Mass/Power					**59.8**	**16%**	**69.2**
Thermal		**# Of Units**			**Flight Hardware Masses**		
Subsystem/Component	**Current Best Estimate (CBE) Unit Mass (kg)**	**Flight Units**	**Flight Spares**	**EMs & Proto-types**	**Total CBE Mass (kg)**	**Cont. (%)**	**Total Mass w/ Cont. (kg)**
Multilayer Insulation (MLI)	0.38	72	1	0	27.00	30%	35.10
General Thermal Surfaces	0.03	36	11	0	0.90	30%	1.17
Paints/Films	0.60	4	1	0	2.40	30%	3.12
General Conduction Control	1.28	1	0	0	1.28	30%	1.66
Catalogue (make-up heaters) Heaters	0.05	10	3	0	0.50	30%	0.65
Custom Heaters	0.05	12	4	0	0.60	30%	0.78
Propulsion Tank Heaters	0.10	4	1	0	0.40	30%	0.52
Propulsion Line Heaters	0.10	50	15	0	5.00	30%	6.50
PRT's	0.01	300	90	0	3.00	30%	3.90
Mechanical Thermostats	0.02	100	30	0	2.00	30%	2.60
Thermal Radiator (Area=m2)	0.00	4	0	0	0.00	30%	0.00
CCHP (Straight) Heat Pipes	0.15	40	12	0	6.00	30%	7.80
Total Mass/Power					**49.1**	**30%**	**63.8**
Payload		**# Of Units**			**Flight Hardware Masses**		
Subsystem/Component	**Current Best Estimate (CBE) Unit Mass (kg)**	**Flight Units**	**Flight Spares**	**EMs & Proto-types**	**Total CBE Mass (kg)**	**Cont. (%)**	**Total Mass w/ Cont. (kg)**
CTX	3.37	2	0	0	6.74	15%	7.75
SWIR	1.50	1	0	0	1.50	30%	1.95
TIR	4.50	1	0	0	4.50	30%	5.85
IR Telescope	39.70	1	0	0	39.70	30%	51.61
HiRISE Lite	19.00	1	0	0	19.00	30%	24.70
WAC (MARCI)	1.04	1	0	0	1.04	15%	1.20
SAR (Eagle)	90.90	1	0	0	90.90	30%	118.17
Total Mass/Power					**163.4**	**29%**	**211.2**

Table B-56. Ice-focused mission MEL.

Ice-focused mission: Mars Pre-Decadal MORIE 2020–02							
Launch Vehicle: Falcon 9 re-usable							
Attitude Control		**# Of Units**			**Flight Hardware Masses**		
Subsystem/Component	**Current Best Estimate (CBE) Unit Mass (kg)**	**Flight Units**	**Flight Spares**	**EMs & Proto-types**	**Total CBE Mass (kg)**	**Cont. (%)**	**Total Mass w/ Cont. (kg)**
Sun Sensors	0.13	8	0	1	1.04	10%	1.14
Star Trackers	4.30	2	0	1	8.60	10%	9.46
IMUs	4.00	2	0	1	8.00	10%	8.80
RWAs	12.00	4	0	1	48.00	10%	52.80
Gimbal Drive Electronics	0.99	4	0	1	3.96	10%	4.36
Total Mass/Power					**69.6**	**10%**	**76.6**
C&DH		**# Of Units**			**Flight Hardware Masses**		
Subsystem/Component	**Current Best Estimate (CBE) Unit Mass (kg)**	**Flight Units**	**Flight Spares**	**EMs & Proto-types**	**Total CBE Mass (kg)**	**Cont. (%)**	**Total Mass w/ Cont. (kg)**
Processor: RAD750	0.55	2	1	5	1.10	5%	1.16
Memory: NVM	0.71	2	1	5	1.42	5%	1.49
Telecom_I_F: MTIF	0.73	2	1	5	1.46	5%	1.53
General_I_F: MSIA	0.71	2	1	5	1.42	5%	1.49
General_I_F: LEU-D	0.67	2	1	5	1.34	5%	1.41
Analog_I_F: LEU-A	0.55	2	1	5	1.10	5%	1.16
Custom_Board: CRC	0.26	2	1	5	0.52	5%	0.55
Analog_I_F: bookkept here but physically in Power	0.82	2	1	5	1.64	5%	1.72
Power: CEPCU	1.15	2	1	5	2.30	5%	2.42
Backplane: CPCI backplane (6 slots)	0.60	4	2	9	2.40	30%	3.12
Chassis: C&DH chassis (6 slot)	2.85	4	2	9	11.40	30%	14.82
Total Mass/Power					**26.1**	**18%**	**30.9**
Power		**# Of Units**			**Flight Hardware Masses**		
Subsystem/Component	**Current Best Estimate (CBE) Unit Mass (kg)**	**Flight Units**	**Flight Spares**	**EMs & Proto-types**	**Total CBE Mass (kg)**	**Cont. (%)**	**Total Mass w/ Cont. (kg)**
Solar Array, GaAs TJ UltraFlex, Two Deployable Wings, 43.26m²	72.72	1	0	0	72.72	30%	94.53
Battery, Secondary BatteryLi-ION	32.10	2	1	0	64.20	30%	83.46
High Voltage Down Converter (aka High Voltage Electronics Assy (HVEA)	20.00	1	1	1	20.00	30%	26.00
Dual Str. Reference Bus Pyro Firing Slice (PFS)	1.80	2	0	2	3.60	5%	3.78
Dual Str. Reference Bus Power Switch Slice - High Side (MPSS-HS)	1.85	6	0	2	11.10	5%	11.66
Dual Str. Reference Bus Guidance Interface Driver Card (GID)	0.77	2	1	2	1.54	5%	1.62
Dual Str. Reference Bus Housekeeping Power Converter Unit (HPCU)	1.20	2	1	2	2.40	5%	2.52
6-slot power chassis	1.50	2	0	1	3.00	30%	3.90
CPCI backplane (6 slots)	0.63	2	0	1	1.25	30%	1.63
Diodes Assembly	0.20	1	1	1	0.20	30%	0.26
Total Mass/Power					**180.0**	**27%**	**229.4**
Propulsion–SEP		**# Of Units**			**Flight Hardware Masses**		
Subsystem/Component	**Current Best Estimate (CBE) Unit Mass (kg)**	**Flight Units**	**Flight Spares**	**EMs & Proto-types**	**Total CBE Mass (kg)**	**Cont. (%)**	**Total Mass w/ Cont. (kg)**
EP Xenon Feedsystem	0.32	1	0.25	0	0.32	10%	0.35
XFC	0.00	4	1	0	0.00	10%	0.00

Table B-56. Ice-focused mission MEL.

Ice-focused mission: Mars Pre-Decadal MORIE 2020–02							
Launch Vehicle: Falcon 9 re-usable							
Lines, Fittings, Misc.	3.00	1	1	0	3.00	50%	4.50
PPU	16.30	2	1	0	32.60	10%	35.86
Thruster Gimbals	3.90	2	0.25	0	7.80	10%	8.58
Deployment module & thruster support	28.00	2	0.25	0	56.00	10%	61.60
EP Main Engine	8.81	4	1	0	35.24	10%	38.76
Pressurant Tanks	22.00	3	1	0	66.00	10%	72.60
Total Mass/Power					**201.0**	**11%**	**222.3**
Propulsion - Monoprop		**# Of Units**			**Flight Hardware Masses**		
Subsystem/Component	**Current Best Estimate (CBE) Unit Mass (kg)**	**Flight Units**	**Flight Spares**	**EMs & Proto-types**	**Total CBE Mass (kg)**	**Cont. (%)**	**Total Mass w/ Cont. (kg)**
Gas Service Valve	0.23	2	1	0	0.46	2%	0.47
Temp. Sensor	0.01	1	1	0	0.01	5%	0.01
Liq. Service Valve	0.28	1	1	0	0.28	2%	0.29
LP Transducer	0.27	2	1	0	0.54	2%	0.55
Liq. Filter	0.45	1	1	0	0.45	2%	0.46
LP Latch Valve	0.35	2	1	0	0.70	2%	0.71
Temp. Sensor	0.01	10	1	0	0.10	5%	0.11
Lines, Fittings, Misc.	1.80	1	1	0	1.80	50%	2.70
Monoprop Main Engine	0.33	8	1	0	2.64	5%	2.77
Fuel Tanks	6.35	1	1	0	6.35	10%	6.99
Total Mass/Power					**13.3**	**13%**	**15.1**
Mechanical		**# Of Units**			**Flight Hardware Masses**		
Subsystem/Component	**Current Best Estimate (CBE) Unit Mass (kg)**	**Flight Units**	**Flight Spares**	**EMs & Proto-types**	**Total CBE Mass (kg)**	**Cont. (%)**	**Total Mass w/ Cont. (kg)**
Primary Structure	186.51	1	0	0	186.51	30%	242.46
Secondary Structure	17.81	1	0	0	17.81	30%	23.15
Tertiary Structure	5.32	1	0	0	5.32	30%	6.91
Integration Hardware: Fasteners, etc.	14.67	1	0	0	14.67	30%	19.08
Power Support Structure	2.60	1	0	0	2.60	30%	3.37
Power Mechanisms	10.40	1	0	0	10.40	30%	13.52
Telecom Support Structure	3.62	1	0	0	3.62	30%	4.70
Telecom Mechanisms	9.90	1	0	0	9.90	30%	12.87
Balance/Ballast	44.98	1	0	0	44.98	30%	58.47
Adapter, Spacecraft side	20.14	1	0	0	20.14	30%	26.19
Harness	70.86	1	0	0	70.86	30%	92.12
Total Mass/Power					**386.8**	**30%**	**502.8**
Telecom		**# Of Units**			**Flight Hardware Masses**		
Subsystem/Component	**Current Best Estimate (CBE) Unit Mass (kg)**	**Flight Units**	**Flight Spares**	**EMs & Proto-types**	**Total CBE Mass (kg)**	**Cont. (%)**	**Total Mass w/ Cont. (kg)**
Ka-band HGA, Reflector Only, 2m	12.90	1	0	0	12.90	15%	14.84
Dual Band X-Ka Band HGA Feed	1.60	1	0	0	1.60	10%	1.76
X-band LGA, JUNO Toroidal	1.95	2	0	0	3.90	10%	4.29
UST Single RX, Dual TX	4.50	2	0	0	9.00	15%	10.35
Ka-band TWTA RF=100-200W	4.70	2	0	1	9.40	15%	10.81
X-band TWTA, RF=25W	3.00	2	0	0	6.00	10%	6.60
X-band Diplexer, moderate isolation	0.35	2	0	0	0.70	15%	0.81
Ka-Band Filters Tx / Rx	0.60	2	0	0	1.20	15%	1.38
Ka-band Isolator	0.50	2	0	0	1.00	15%	1.15

Table B-56. Ice-focused mission MEL.

Ice-focused mission: Mars Pre-Decadal MORIE 2020–02							
Launch Vehicle: Falcon 9 re-usable							
Ka-Band Waveguide Transfer Switch	0.15	3	0	0	0.45	15%	0.52
X-Band Waveguide Transfer Switch	0.45	6	0	0	2.70	15%	3.11
X-band Isolator	0.50	2	0	0	1.00	15%	1.15
Coax Cable, flex (190)	0.05	6	6	0	0.33	50%	0.49
WR-112 WG, rigid (Al)	0.19	10	10	0	1.90	50%	2.85
WR-34 WG, rigid (Al)	0.07	8	8	0	0.56	50%	0.84
Total Mass/Power					**52.6**	**16%**	**60.9**
Thermal		**# Of Units**			**Flight Hardware Masses**		
Subsystem/Component	**Current Best Estimate (CBE) Unit Mass (kg)**	**Flight Units**	**Flight Spares**	**EMs & Proto-types**	**Total CBE Mass (kg)**	**Cont. (%)**	**Total Mass w/ Cont. (kg)**
Multilayer Insulation (MLI)	0.38	71	1	0	26.63	30%	34.61
General Thermal Surfaces	0.03	34	10	0	0.85	30%	1.11
Paints/Films	0.58	4	1	0	2.32	30%	3.02
General Conduction Control	1.21	1	0	0	1.21	30%	1.57
Catalogue (make-up heaters) Heaters	0.05	10	3	0	0.50	30%	0.65
Custom Heaters	0.05	12	4	0	0.60	30%	0.78
Propulsion Tank Heaters	0.10	4	1	0	0.40	30%	0.52
Propulsion Line Heaters	0.10	50	15	0	5.00	30%	6.50
PRT's	0.01	300	90	0	3.00	30%	3.90
Mechanical Thermostats	0.02	100	30	0	2.00	30%	2.60
Thermal Radiator (Area=m2)	0.00	4	0	0	0.00	30%	0.00
CCHP (Straight) Heat Pipes	0.15	40	12	0	6.00	30%	7.80
Total Mass/Power					**48.5**	**30%**	**63.1**
Payload		**# OF UNITS**			**FLIGHT HARDWARE MASSES**		
Subsystem/Component	**Current Best Estimate (CBE) Unit Mass (kg)**	**Flight Units**	**Flight Spares**	**EMs & Proto-types**	**Total CBE Mass (kg)**	**Cont. (%)**	**Total Mass w/ Cont. (kg)**
CTX	3.37	2	0	0	6.74	15%	7.75
SAR (Eagle+)	109.20	1	0	0	109.20	30%	141.96
Total Mass/Power					**115.9**	**29%**	**149.7**

Appendix C Special Technical Analyses

This appendix summarizes some of the mission design analyses that were performed while evaluating the MORIE mission concept. Much of the materials herein are inputs or design points from earlier in the trade space exploration and do not represent the final design.

Contents

Figures

Tables

C.1 Launch Vehicles

In the coming decade there will be a number of medium- and heavy-lift launch vehicles available, many of which are slated to have their inaugural launches in the next few years. This will potentially drive competition, increase availability, and reduce costs. Launch vehicles such as Falcon 9, Falcon Heavy, Vulcan, and New Glenn can meet the needs of a MORIE launch. This is true whether a SEP or a traditional chemical propulsion system is ultimately chosen. A SEP propulsion system typically requires a lower launch C3 (5–15 km^2/s^2, subject to optimization). In Figure 1 below, the lowest-cost, lowest-performance launch vehicle (Option 2) relates to the Falcon 9 Recoverable (Automated Spaceport Drone Ship (ASDS)). It can accommodate up to 2700 kg at a C3 of 5 km^2/s^2 and was the target for this study.

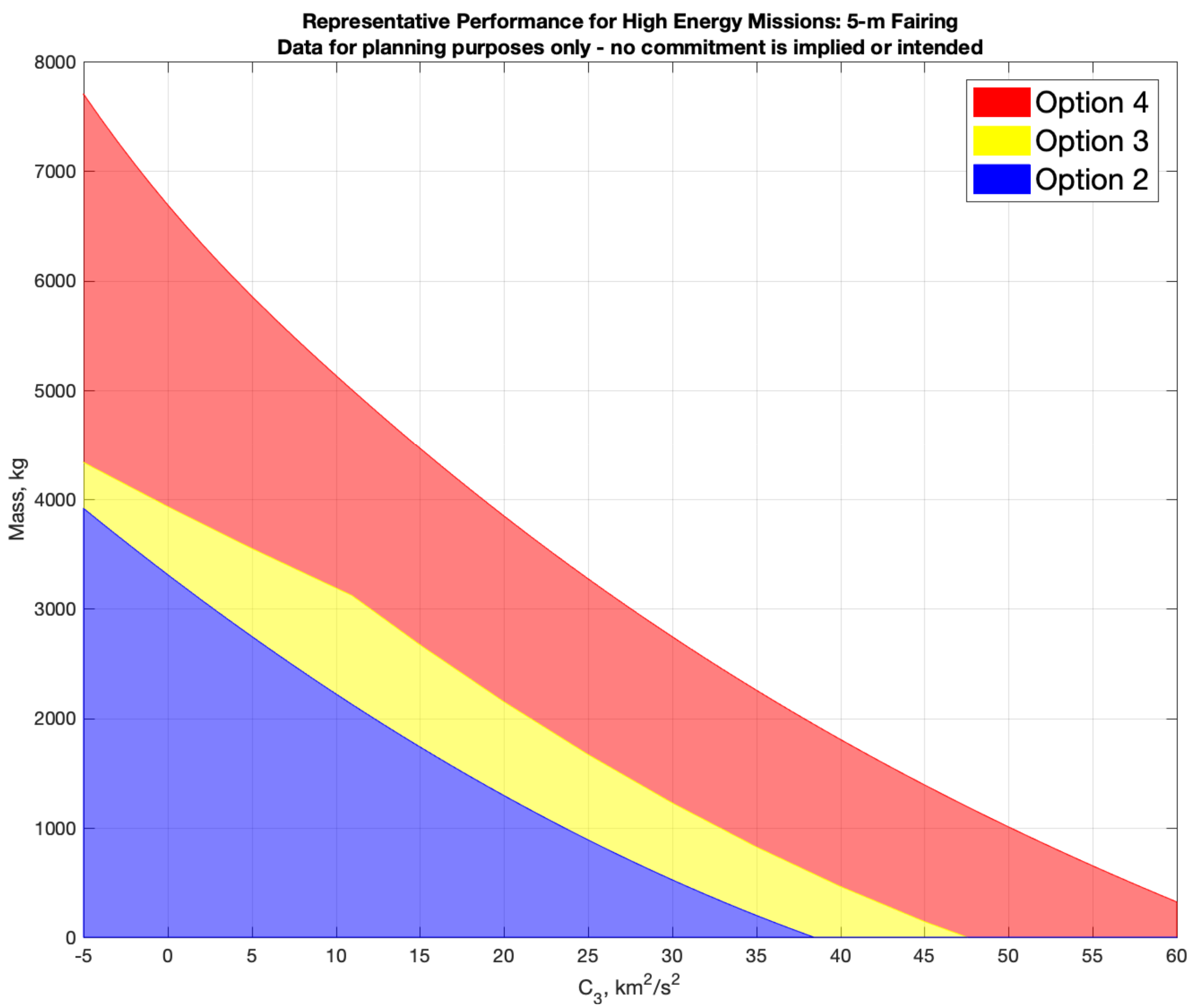


Figure C-1. Launch Vehicle Performance Curves.

C.2 Low-Thrust Trajectory Design

Low-thrust trajectories from Earth to Mars differ from ballistic transfers in that there is not a unique solution for each launch/arrival date pair. Every trajectory must be optimized to determine a control law based on thruster characteristics, mass, power, and other constraints. Optimization for this study was carried out using simulations in MALTO–a robust, medium-fidelity optimizer developed at JPL. MALTO is particularly adept at parametric trade space exploration. Power, mass, and time-of-flight were varied to create large databases of optimized trajectories from which to choose. To first order, a low-thrust trajectory from Earth escape to Mars orbit typically requires:

- 3.5–4 km/s of ΔV for the heliocentric cruise
- 2.6–3 km/s of ΔV for the spiral down to low-Mars orbit
- ~1 km/s for maneuvers in orbit including a 3-degree plane change
- Total: 7–8 km/s

The exact numbers are determined through an iterative process that considers the thruster characteristics, power available, total mass, launch vehicle performance, launch dates, times-of-flight, etc. The following targets were used:

- Launch years: 2026–2035 (with 2026 used for reference)
- Typical Durations:
  - Cruise: 10–15 months
  - Spiral: 6–12 months
  - Total: ~ 2 years
- Falcon 9 Recoverable (ASDS)
- Power: 8–20 kW

Figure C-22 shows a reference trajectory generated in MALTO. Launch occurs in late 2026 to a C3 of 5.8 km^2/s^2 with a mass of under 2700 kg. (Note: in the Team X study the launch mass grew to 3000 kg, which was accommodated by launching to a lower C3). Launch is followed by a 30-day check-out coast. The red arrows depict the direction and magnitude of the thrust vector throughout the cruise. Note that thrusting occurs for ~90% of the duration with only a short ballistic coast near the middle. Upon arrival at the Mars sphere-of-influence in late 2027, the spacecraft begins a 10-month circular spiral to reduce its altitude to the final orbit. The full transfer requires about 800 kg of xenon propellant.

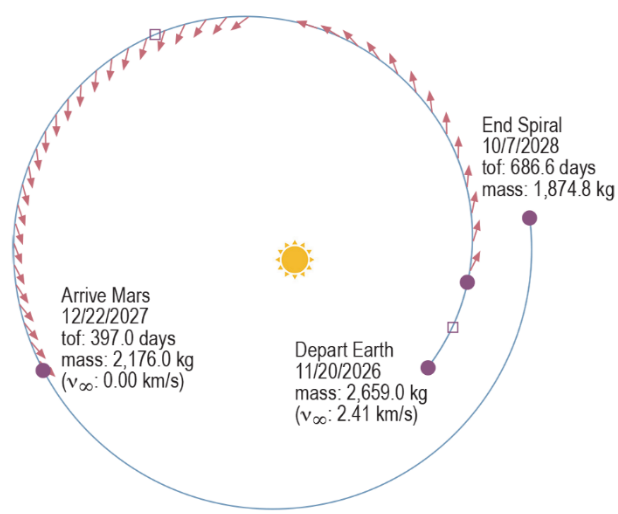


Figure C-2. Reference trajectory for MORIE

C.3 SEP Thrusters

There are many large SEP thrusters (see Table 1) that could be considered for a mission to Mars. These include both Hall-effect (such as SPT-140 and XR-5) and ion thrusters (such as Radio-Frequency Ion Thruster (RIT), Xenon-Ion Propulsion System (XIPS), and NASA Evolutionary Xenon Thruster (NEXT)). Suitable thrusters would need to be able to operate at 2–8 kW and have a lifetime more than 200 kg of xenon in total throughput. Multiple thrusters would be required for redundancy, throttling, and throughput.

Table C-1. Potential SEP Thrusters

Thruster	Type	Thrust*	Specific Impulse*	Power*
---	---	[mN]	[s]	[kW]
SPT-140	Hall	260	1720	5.5
XR-5	Hall	280	2000	4.8
NEXT-C	Ion	220	4000	6.8
RIT 2X	Ion	250	4100	8.5
XIPS	Ion	175	3500	5

** Representative numbers, consult manufacturers for current specs*

The propulsion system for the MORIE reference concept used a system very similar to that of Psyche. Reasonable solutions can be found using any of the thrusters shown in Table 1. For the system chosen, >10 kW of power is available to operate 2 SPT-140 thrusters as the spacecraft leaves Earth. At Mars, the power is reduced to ~5 kW and only 1 thruster is used at a time. At 0.25 N and 1700 s of specific impulse, the SEP system can provide approximately 12.5 m/s of ΔV per day, and using 1 kg of xenon per 10 m/s.

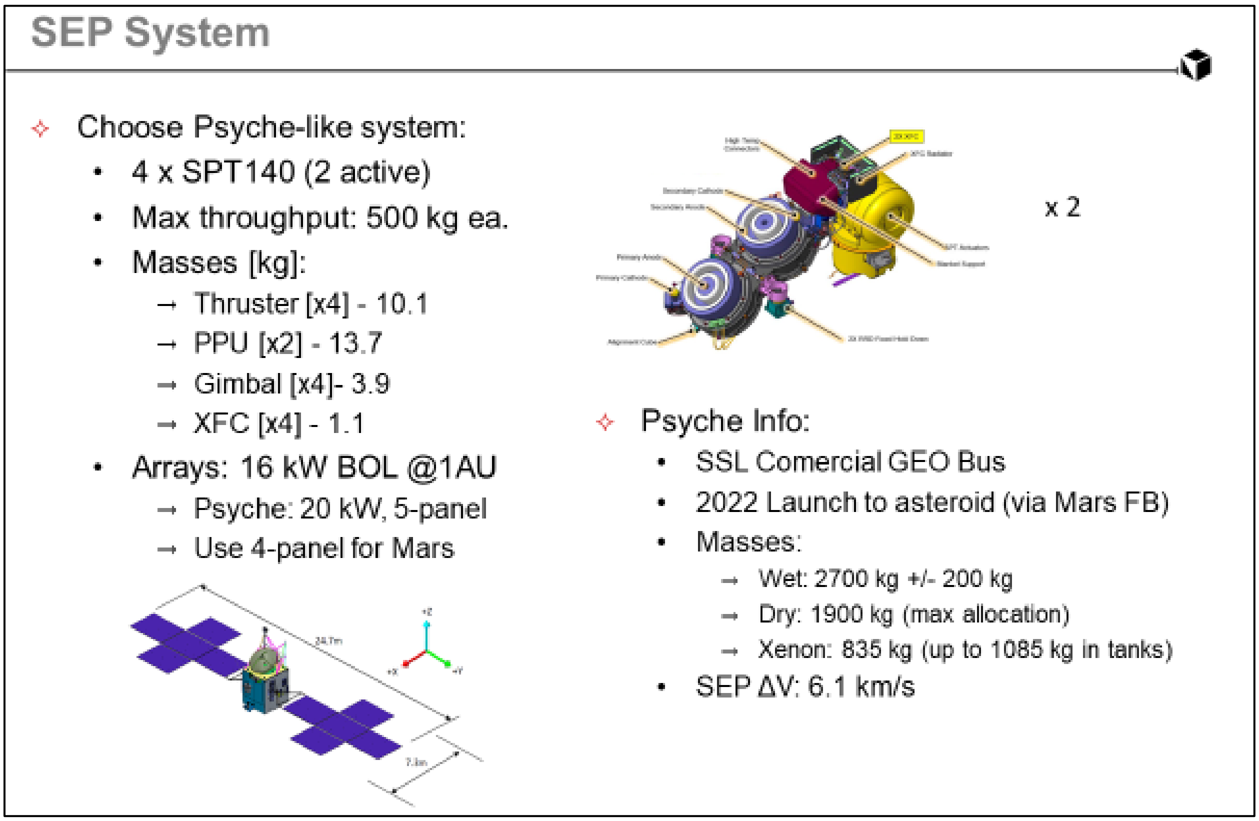


Figure C-3. The Psyche propulsion system offered a valuable starting point for the MORIE SEP system, with similar propulsion requirements.

C.4 Science Orbits

MORIE's primary orbit used the Mars Reconnaissance Orbiter (MRO) as a reference point (sun-synchronous with a 3 PM LST ascending node). For simplification, the orbit was taken to be circular with a mean altitude of 300 km (as opposed to 255 km × 320 km for MRO). At this altitude the sun-synchronous inclination is 92.7 degrees and the period is 114 minutes. Further refinement would be needed to accommodate higher-order gravity field perturbations and find suitable ground track repeat cycles, if desirable.

After one Mars year in the sun-synchronous orbit, a plane change will be executed to bring the orbit to pass directly above the poles (90° inclination). This will be done using the SEP thrusters. The minimum duration transfer (thrusting continuously minus eclipse periods) would take 3–4 weeks and ~ 250 m/s of ΔV. It is more efficient to thrust primarily near equatorial crossings, at the expense of a longer transfer. This could take as much as 6-8 weeks, but save 100 m/s or more. An additional benefit is that some power would be available for science when not thrusting.

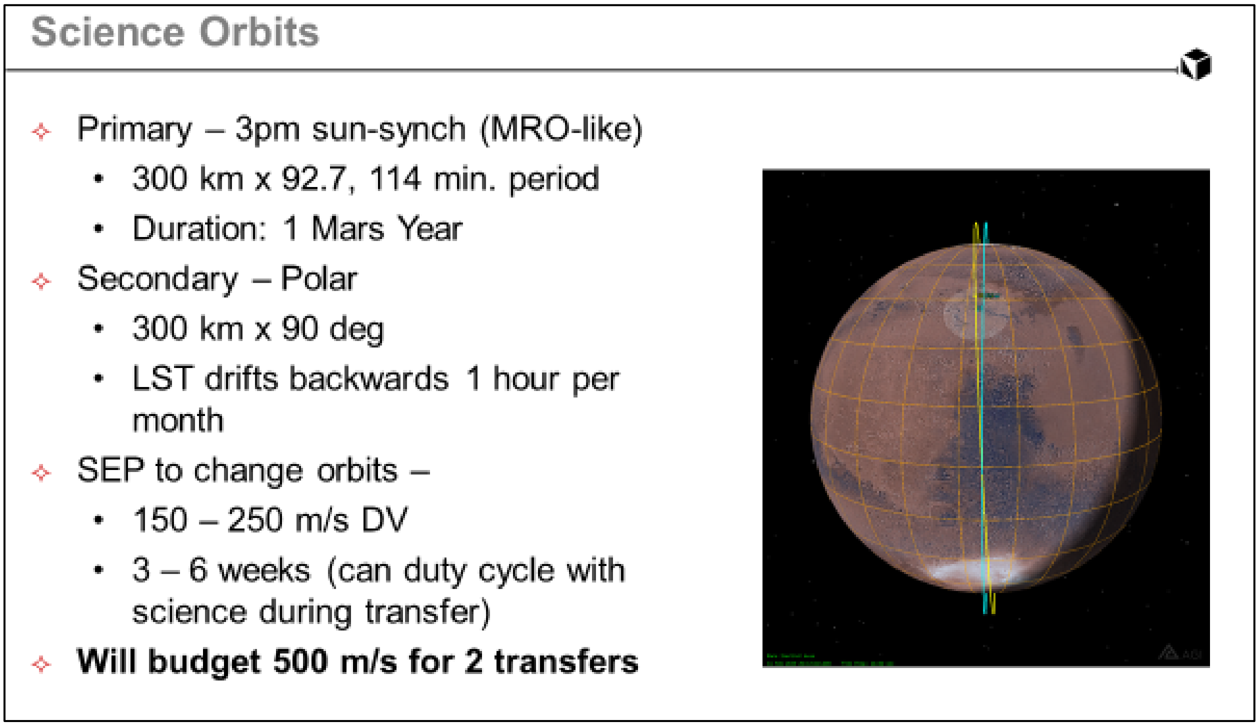


Figure C-4. Characteristics of Primary Science Orbits.

Some consequences of a 3 PM LST orbit are that there are always sun eclipses and nearly always Earth occultations (see Figures 5-7, and note that they are for the MRO timeframe, but are applicable to any Mars year). Solar ellipses vary in length from 30 to 39 minutes, with an average near 36 minutes (Figure C-5). Eclipse duration will vary in the polar orbit phase with durations up to 42 minutes, and many months with no eclipses at all. Earth occultations cause the orbiter to lose contact with the DSN, affecting the downlink data volume capability of the mission. There is also a period of 3 months with continuous visibility to Earth (Figure C-6).

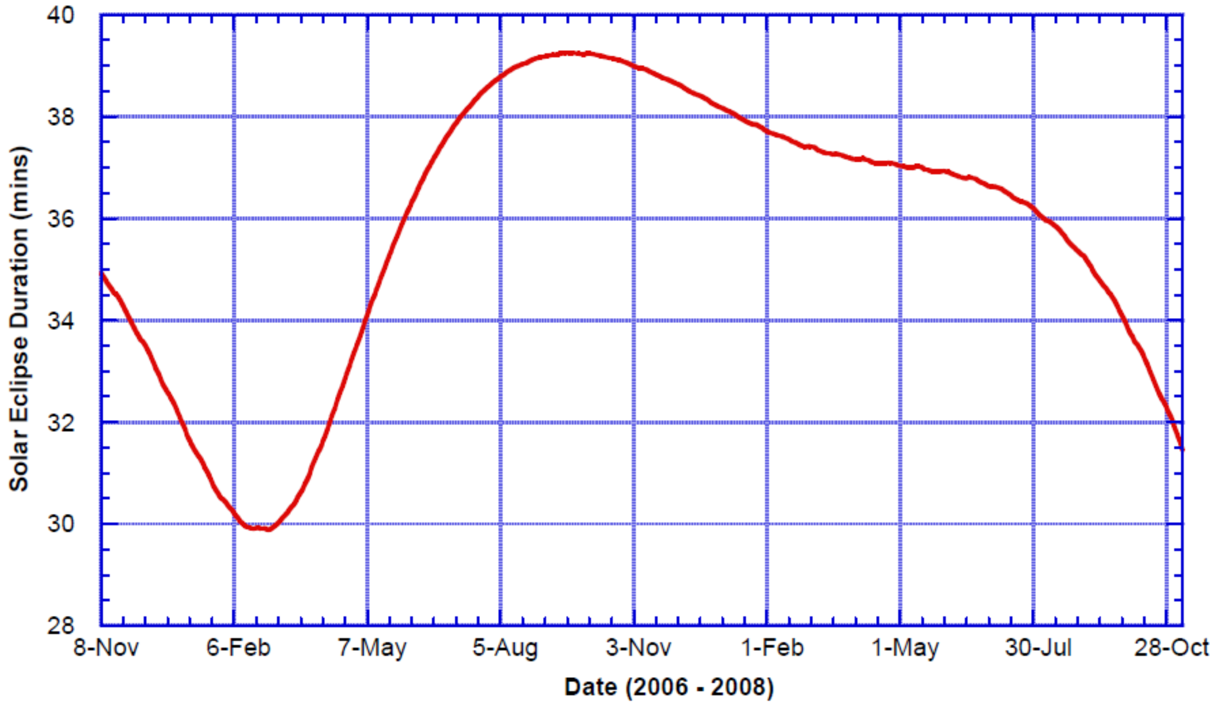


Figure C-5. Solar Eclipse Durations over 1 Mars Year for 3 PM Sun-Synchronous Orbit.

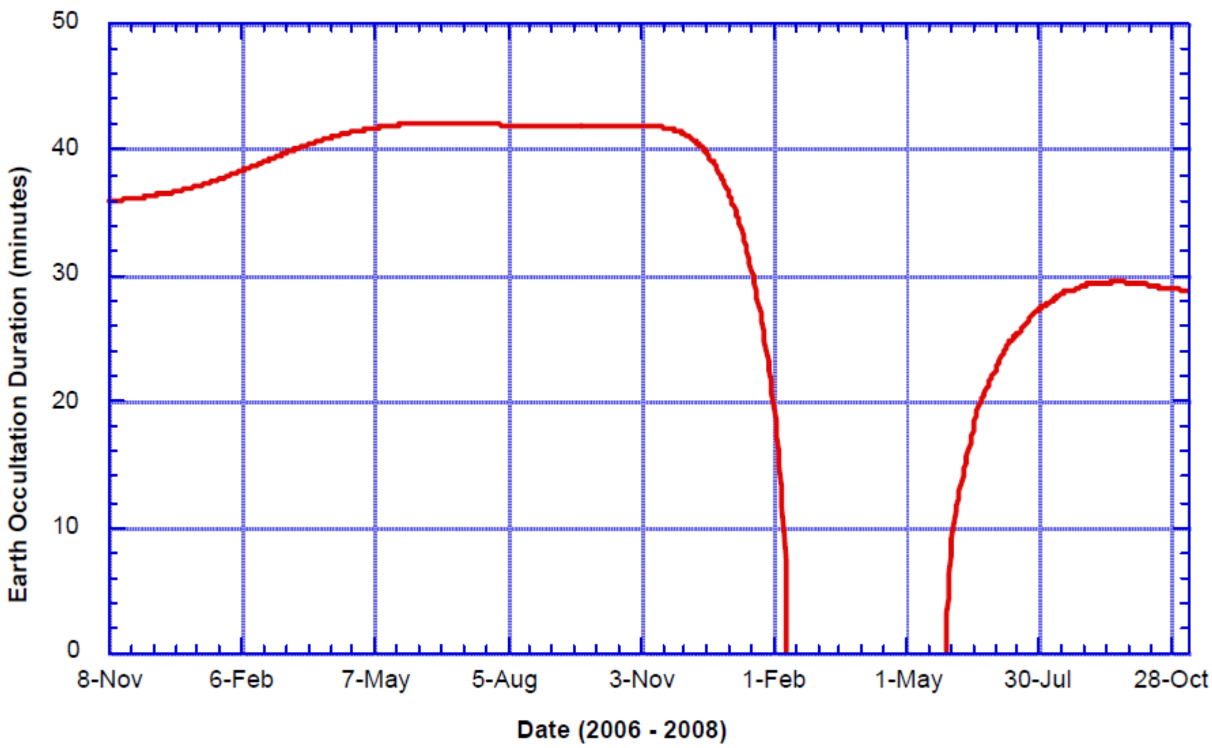


Figure C-6. Earth Occultation Durations over 1 Mars Year for 3 PM Sun-Synchronous Orbit.

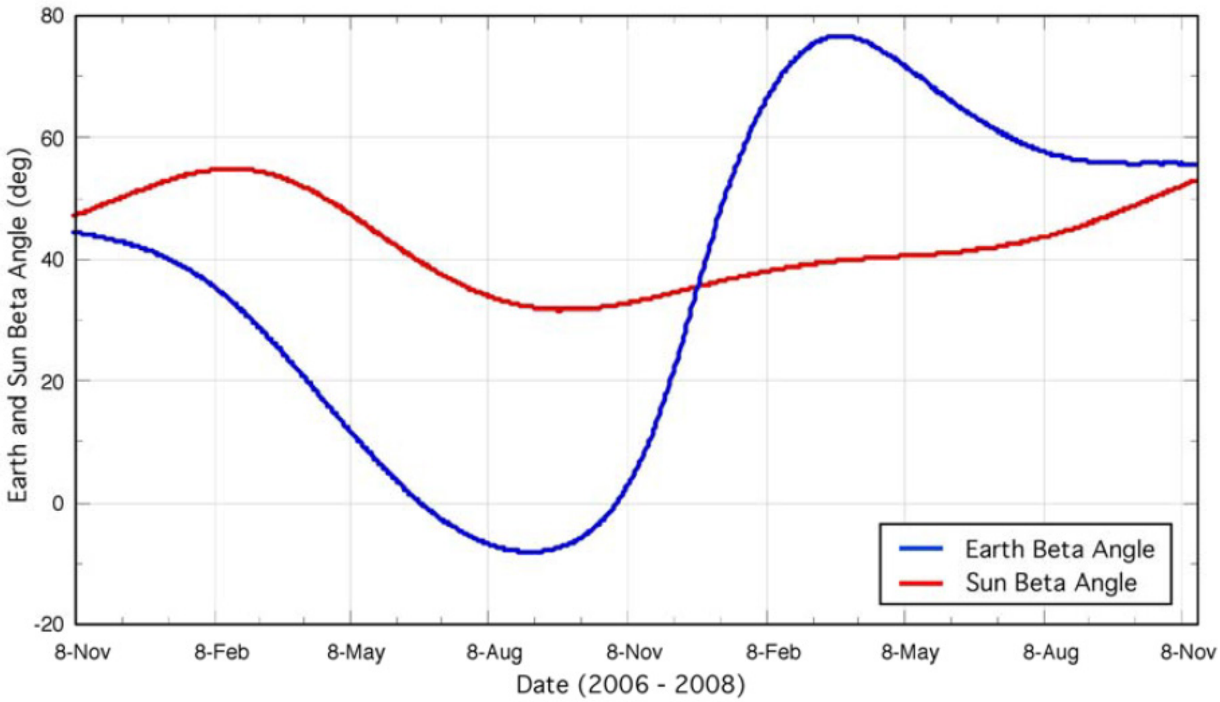


Figure C-7. Earth and Sun Beta Angles over 1 Mars Year.

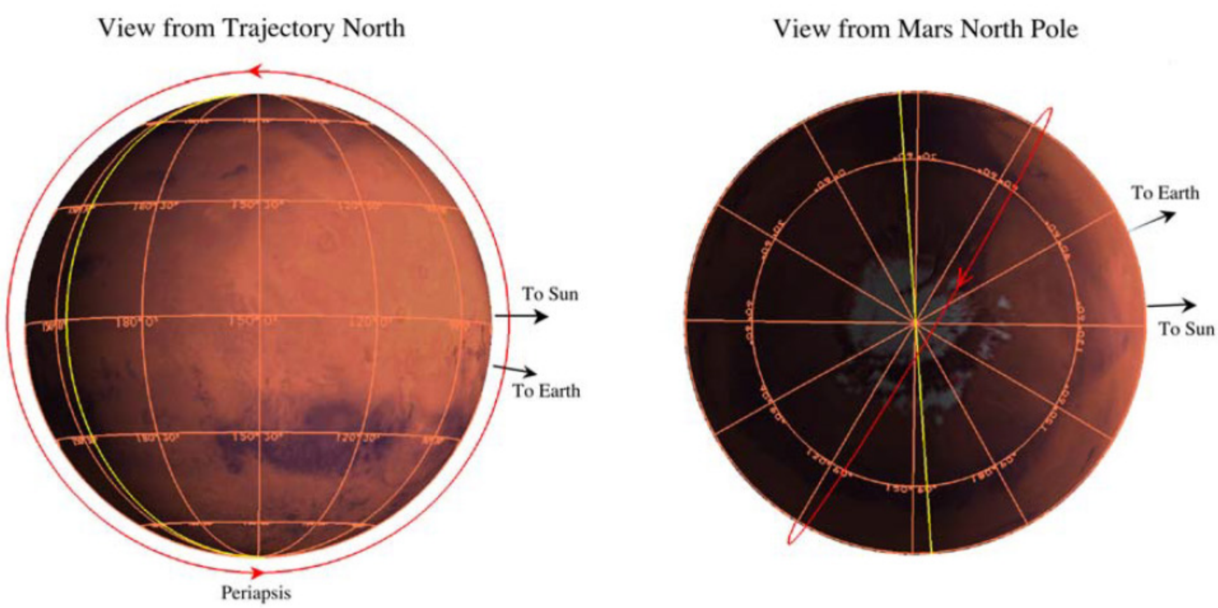


Figure C-8. Views of 3 PM Sun-Synchronous Science Orbit.

Eclipses and occultations are related to the orientation of the orbit with respect to the Sun and the Earth respectively. The Beta Angle is defined as the angle between the orbit plane and the body in question (Earth or Sun, Figure C-8). Beta angles for Earth and Sun are shown in Figure C-7. Figure C-9 shows the ground track patterns for one sol for both the sun-synchronous and polar orbits, with the former leaving a ~6° gap at the poles.

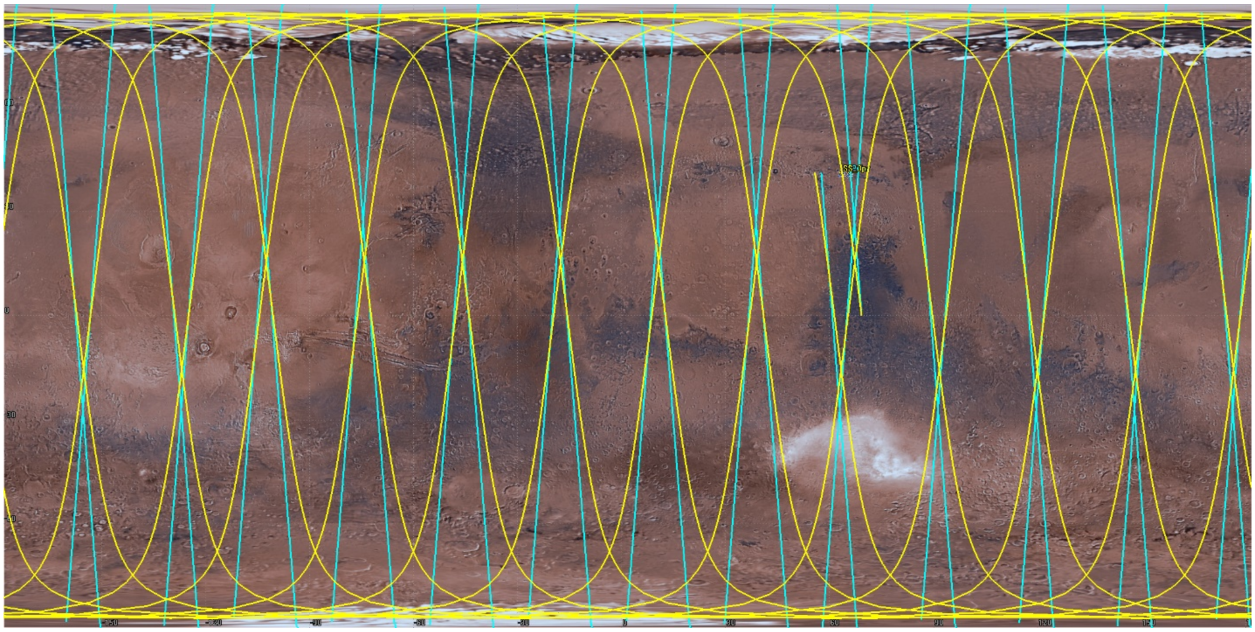


Figure C-9. Ground tracks for sun-synchronous (yellow) and polar (blue) orbits.

Appendix D Additional Information on Technologies and Techniques

Contents

Figures

Tables

D.1 SWIR / TIR Instrument Technology

D.1.1 Introduction

One of the outcomes of the JPL Team X Architecture design study the week of 2020-03-03 was the recognition that the Shortwave Infrared (SWIR) spectrometer and the Thermal Infrared (TIR) spectrometer had requirements for a similar sized telescope as well as similar operational requirements. Because the large telescope (50 cm aperture) would be the cost driver for both instruments, sharing the telescope was an obvious cost saving measure. The combined telescope was the approach taken in the Follow-On Team X design study the week of 2020-03-31. This combined instrument concept was applied to instrument analogs HiRIS and PREFIRE with the HiRISE IR telescope, and can also be applied to the MORIE science team's preferred payloads NGWIS and Mars-FIRE (Section 1.4).

D.1.2 Requirements

Tables D-1, D-2 and D-3 are extracted and adapted from the Team X design study slides.

Table D-1. SWIR/TIR spectrometer key parameters.

	SWIR/TIR Spectrometer		
Measurement	Shortwave IR Spectrometer	Thermal IR Spectrometer	IR Telescope
Analogy or Heritage	JPL/HiRIS	JPL/PREFIRE	HiRISE
Mass [kg]	1.5 (grassroots)[1]	4.5 (PREFIRE + 50%)	39.7
Power [W]	Signal chain: 2 Cryocooler: 14[3]	6 (PREFIRE + 50%)[2]	
Dimensions [cm]	10 × 10 × 20 est.	10 × 10 × 20 est.	60 × 60 × 120 est.
Configuration Constraints	Nadir point, but spacecraft nods instrument in direction of motion		
Data Rate [Mbps]	120 11 Gb/Patch (uncompressed)	0.16 17 Mb/Patch (uncompressed)[4]	
Thermal [C]	Active cryocooler Needs radiator surface or cold sink	Uncooled thermopile array	

Table D-2. Additional SWIR/TIR spectrometer key parameters.

Parameter	SWIR/TIR Spectrometer
Control [°] (Can we hit our target?)	0.1
Knowledge (Can we align our data with a coordinate system?)	4 μrad is ¼ pixel[5]
Stability (Is our image getting blurred?)	50 μrad/s is ¼ pixel over exposure
Attitude	Pushbroom, so prefer spacecraft attitude fixed forward when taking data. Could angle to track up to 20°

1. Assumes extreme light-weighting. Estimated by Rob Green as 3 kg. Prototype is 7 kg.

2. PREFIRE is 8 × 64 and FPA takes 1 W. Redesign would use a different 2D Readout Integrated Circuit (ROIC) for 128 × 64, so power may not be equivalent.

3. Detector 80 K, spectrometer 120 K. 14 W is an estimated peak for cool-down. Steady state might be more like 3-4 W.

4. 128 × 64 × 16 bits / (0.8 s) = 0.16 Mb/s. 128 × 128 × 64 × 16 bits = 16.8 Mb/patch.

5. Upper limit. There is no point to being tighter than this.

Table D-3. SWIR/TIR key parameters.

Parameter	Shortwave IR	Thermal IR
Viewing Angle	Nadir, nodding > 4.6°	Nadir, nodding 20°
Spectral Range	0.5 to 5 µm	6 to 25 µm
Spatial Resolution	5 m/px sampling	50 m/px sampling
Spectral Resolution	9 nm per pixel	0.35 microns per pixel
Swath Width [km]	6	6
Measurement Scenario	Day only	Day only, spot checking at night

D.1.3 Operations

Both spectrometers have a 6 km long slit at the ground and operate in pushbroom mode, with the slit perpendicular to the spacecraft ground track. Both spectrometers are designed to use reflected sunlight from the Mars dayside. The SNR requirement was 100:1 per pixel while observing a 6 km × 6 km patch of surface with approximately square pixels. This SNR would not be reached with a nadir-observing telescope, as the exposure time, set by the image motion smear, would be too short. The chosen solution was to gimbal the entire instrument and then "nod". Nodding means that the gimbal moves in such a way that the apparent speed of the observation point on the ground moves slower than the nadir speed. The required nod for the SWIR spectrometer to reach 100:1 was found to be a gimbal range of ±4.6°, while the TIR spectrometer required ±20°. When both instruments are observing simultaneously, the SWIR attains significantly better SNR, while a SWIR-only instrument requires less total observation time to reach 100:1. The TIR spectrometer performs a calibration before or after each observation by taking a cold space exposure. This is most easily handled by a side-port and a mirror mechanism.

D.1.4 SWIR Instrument

The JPL Team X architecture study collected a set of analogous instruments for the SWIR spectrometer. From that study, the MORIE team chose to base the SWIR instrument on Rob Green's High-Resolution Imaging Spectrometer (HiRIS) SIMPLEx proposal. HiRIS is based on a JPL Dyson spectrometer design (Earth Surface Mineral Dust Source Investigation (EMIT), Mapping Imaging Spectrometer for Europa (MISE), which allows for a very compact spectrometer, see Figures D-1 and D-2.

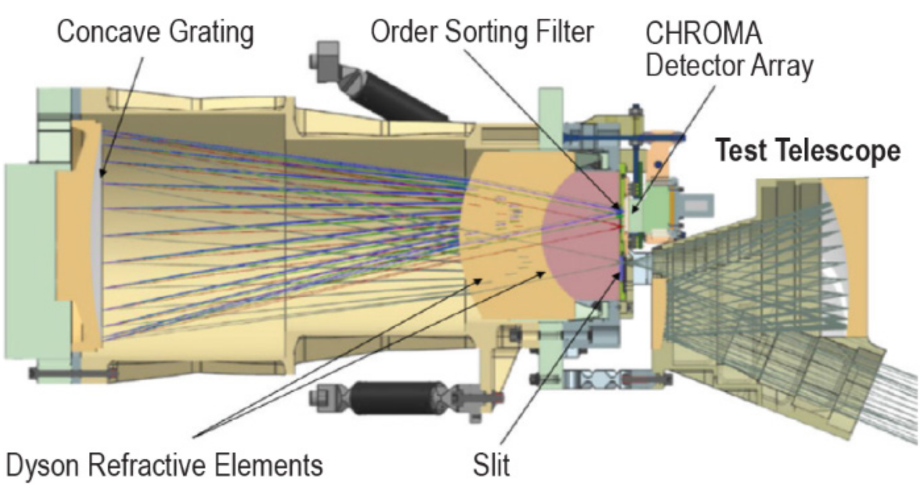


Figure D-1. HiRIS Spectrometer optical and mechanical design. For scale, the height shown for the CHROMA detector is 14.4 mm.

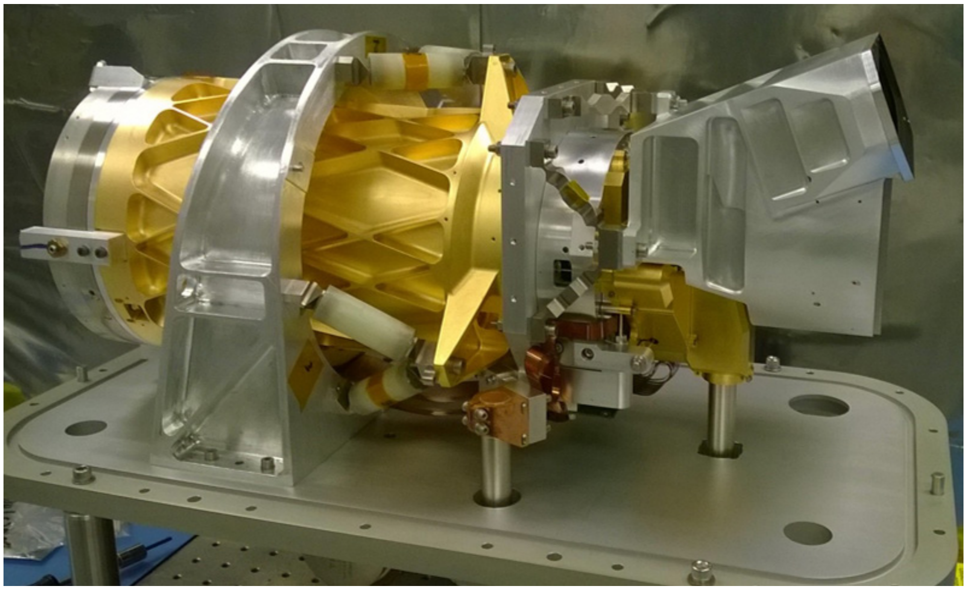


Figure D-2. HiRIS prototype. HiRIS has been qualified for space (vibed and thermal cycled).

D.1.5 TIR Instrument

The JPL Team X architecture study collected a set of analog instruments for the TIR spectrometer. From that study, the MORIE team chose to base the TIR instrument on Matt Kenyon's PREFIRE instrument (launch 2022), see Figures D-3 and D-4. PREFIRE uses a grating for dispersion and uncooled micro-thermopile arrays from JPL/Microdevices Laboratory (MDL). Since thermopiles measure a difference in temperature rather than an absolute measurement, cooling is not required. Thermopiles also do not have 1/f noise, unlike bolometers. A comparison of PREFIRE and MORIE is shown in Table D-4.

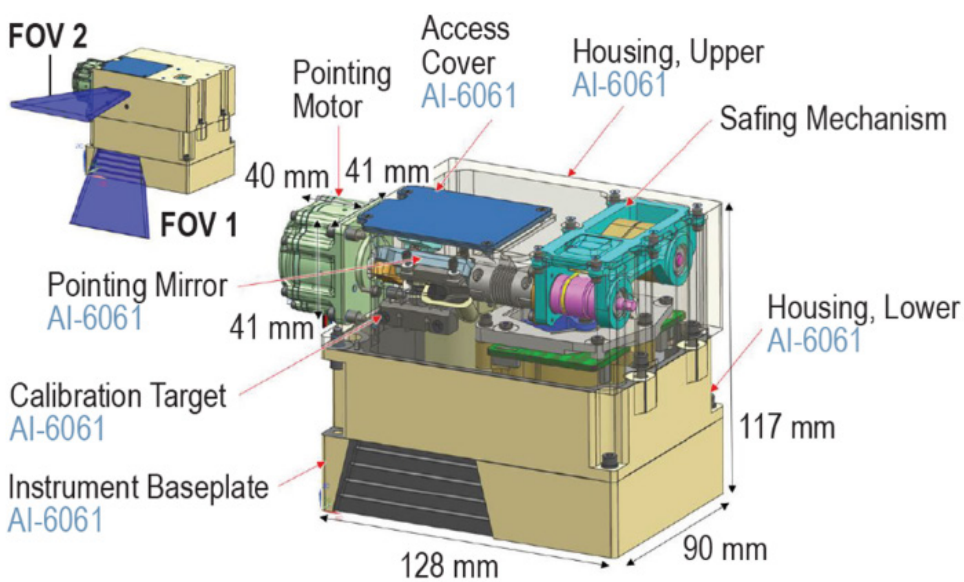


Figure D-3. The PREFIRE instrument is compacted and already contains the calibration mechanism.

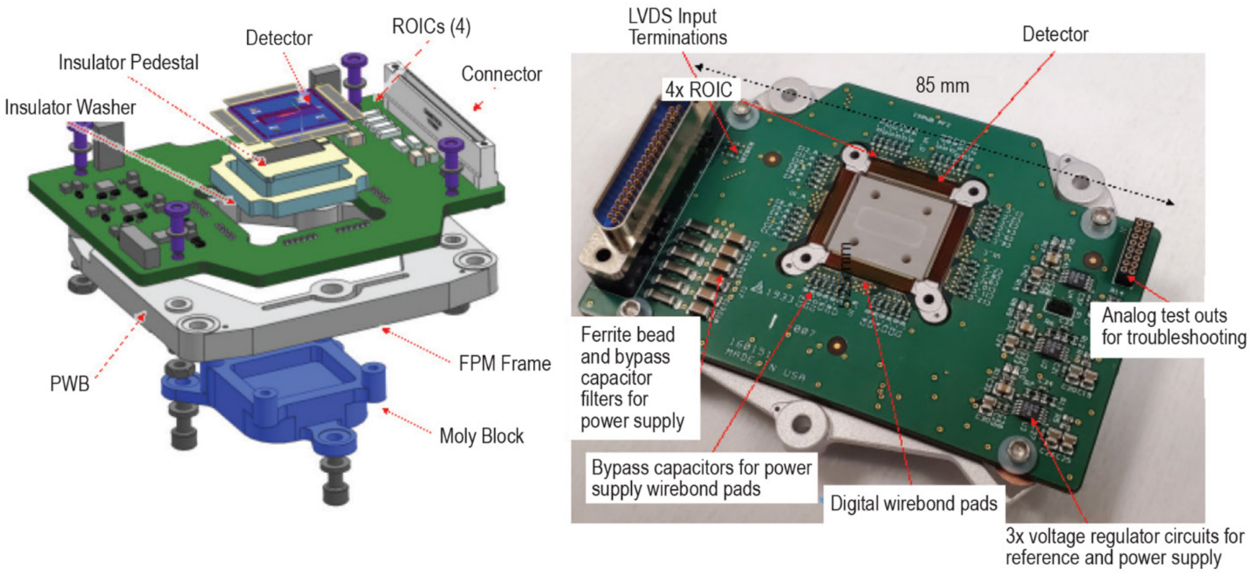


Figure D-4. The PREFIRE FPA can be seen in Figure D-3, just below the safing mechanism.

Table D-4. PREFIRE and MORIE key parameter comparison.

Characteristic	PREFIRE Value	MORIE Value
Thermopile array (uncooled)	64 × 8 pixels, 0.18 mm square	64 × 128 pixels, 0.3 mm square
Spectral resolution	0.7 µm from 5-50 µm	0.35 µm from 6-25 µm
Spatial coverage	8 cross-track pixels with 1° footprints	128 cross-track pixels with 70 m footprints
Mass	3 kg	+50% contingency[1]
Data rate	11 kbps	163 kbps
Power (avg)	4 W	+50% contingency
f/#	2	3.6
Integration Time (s)	0.7	0.8

1. F number is larger, so smaller optics, but focal plane array is larger.

D.1.6 Telescope

Both the SWIR and TIR spectrometers require a large telescope. The MORIE study team specified that the telescope would be no larger than 50 cm aperture. A survey of 50-cm aperture telescopes (Table D-5) shows that the lowest cost 50-cm telescope is from HiRISE. The HiRISE telescope has an identical target environment and was chosen as the closest analog, see Figures D-5 and D-6.

Table D-5. “Small Telescope Cost Model,” JPL, February 2011.

Instrument	Lowest Wavelength (µm)	Mass (kg)	Aperture ⌀ (cm)	Cost (FY04$K)
GALEX	0.135	36.3	50	15,960
IRAS	8.0	130	50	30,959
HiRISE	0.4	39.7	50	19,744

Figure D-5. HiRISE Telescope. (https://mars.nasa.gov/mro/mission/instruments/hirise/)

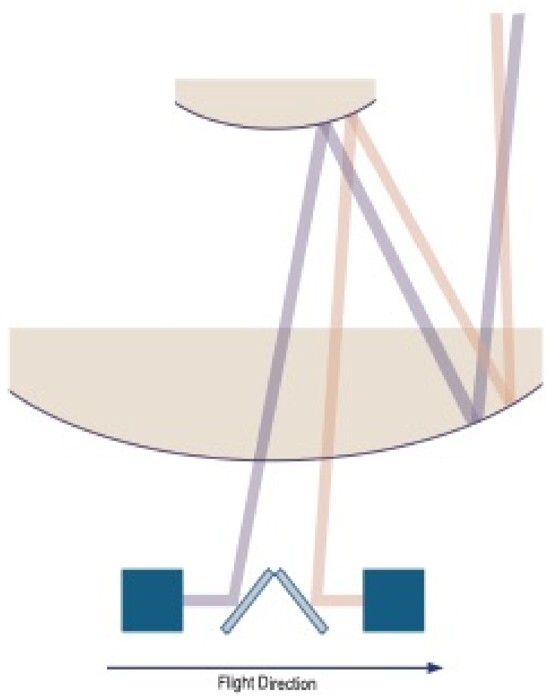


Figure D-6. The SWIR and TIR spectrometers share the focal plane. The two instruments have slightly different pointing, spaced in the flight direction.

D.2 P-band Polar-SAR / Radar Sounder (RaSo) Hybrid Instrument

Polar-SAR and RaSo Onboard Compression

Polar-SAR / RaSo is based on prior JPL radar studies with additional electronics that enable the dual-frequency sounder mode. The block diagram for the hybrid instrument encompassing Polar-SAR and RaSo is shown in Figure D-7.

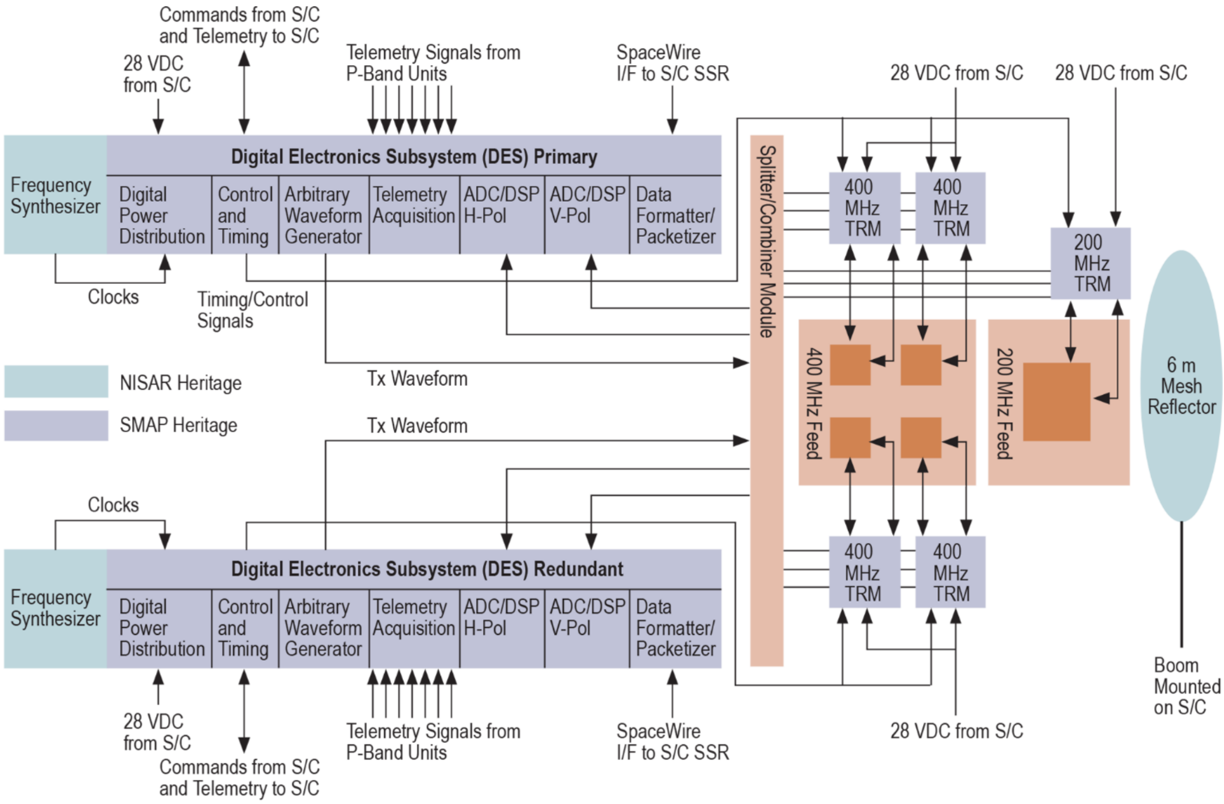


Figure D-7. MORIE block diagram for hybrid Polar-SAR + Radar Sounder.

Polar-SAR and RaSo Onboard Compression

To reduce the data rate due to the radar payload, the combined Polar-SAR and RaSo instrument will include an onboard processor (OBP) for the radar data. Range compression, azimuth compression, and multi-look processing will be completed onboard and only the processed radar images and radargrams will be downlinked to Earth in the nominal case. For performance analysis, calibration, and detailed science investigations, the option to send full data products will remain open. The OBP is similar to the OBP proposed on Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy (VERITAS) (Freeman et al., 2016), and the compression algorithms have already successfully been employed on other radar missions (UAVSAR, SMAP, SWOT, etc.).

All onboard processing will employ the standard radar imaging algorithms. The azimuth and range compression describe SAR image formation. Range compression is a correlation of the transmitted signal with the returned signal to increase signal-to-noise and range resolution. Azimuth compression, or synthetic aperture processing, coherently sums all returns from a given point within the scene over the target illumination time (which is determined by the radar beam width). The result of azimuth and range compression is a two-dimensional radar image of the planetary surface. Multi-look processing then combines the returns of multiple resolution cells into one pixel, trading resolution for improved signal-to-noise ratio and reduced data rates. An additional feature of the OBP (derived from VERITAS) is that the processing parameters may be changed during the mission. If inflight validation finds that an updated set of processing parameters would improve SAR data quality, they may be uploaded to the OBP.

There are two main data products for the Polar-SAR: high data rate (HDR), (30 m/pixel) and low data rate (LDR), (100 m/pixel) modes. The LDR mode is the nominal mode, and the HDR mode will be used in "postage-stamp" fashion over features of interest. Tables D-6 and D-7 provide information on the downlinked processed image data rate for Polar-SAR for the two main data products. Table D-8 provides information on the data rate for RaSo.

Table D-6. MORIE Processed Image Data Rate for the Polar-SAR instrument at 30 m/pixel.

Processed Image Data Rate for SAR, 30 m/pixel	
Downlinked Ground Projected Cross-Track Pixel Size (m)	30
Downlinked Azimuth Pixel Size (m)	30
Number of Range Looks	2
Number of Azimuth Looks	8
Total Number of Looks	19
Bits per Complex Sample	16
Strip Length for 1 Second (m)	3093
Number of Image Pixels Per Second	85918
Downlinked Processed Image Data Rate (Dual pol, Mbs)	1.37
Downlinked Processed Image Data Rate (Quad pol, Mbs)	2.75

Table D-7. MORIE Processed Image Data Rate for the Polar-SAR instrument at 100 m/pixel.

Processed Image Data Rate for SAR, 100 m/pixel	
Downlinked Ground Projected Cross-Track Pixel Size (m)	100
Downlinked Azimuth Pixel Size (m)	100
Number of Range Looks	8
Number of Azimuth Looks	38
Total Number of Looks	213
Bits per Complex Sample	16
Strip Length for 1 Second (m)	3093
Number of Image Pixels Per Second	7733
Downlinked Processed Image Data Rate (Dual pol, Mbs)	0.12
Downlinked Processed Image Data Rate (Quad pol, Mbs)	0.25

Table D-8. MORIE Processed Image Data Rate for the RaSo instrument.

Processed Image Data Rate for Sounder	
Expected along-track resolution: Fresnel zone radius [meters]	362
Number of integration time [seconds]	0.1
Number of pulses to average (PRF = 2800 Hz)	150
Number of additional bits to carry [bits]	2
Data bits in I/Q domain	10
Number of complex Fast Fourier Transform (FFT) data points	4096
Number of bits for each look [kbits per frame per look]	81.92
Number of looks	3
Frame update rate	9
Data rate (per second) [Mbps]	2.3

D.3 Super Resolution for Imaging

Super-resolution via over-sampling is possible with digital TDI and can improve the image resolution beyond the native capabilities of the optics (e.g., McEwen et al., 2012; Gao et al., 2017). In this approach the target is imaged repeatedly by multiple TDI columns in series with sub-pixel cross-track offsets to permit over-sampling, either with designed cross-track offsets or via diagonal target motion across the detector. One way to achieve the latter approach could be a purpose-designed super-resolution detector with a slight "twist" relative to the ground-track motion. Carrying out super-resolution imaging in flight enables all of the component images to be acquired simultaneously with identical lighting and viewing angles and known pixel offsets, improving image reconstruction, and enabling processing to be performed onboard the spacecraft. This method potentially enables sub-meter pixel scales with smaller, lighter imaging systems.

D.4 SNR Assessment for 1 m/pixel Visible to Short-Wave Infrared (VSWIR) Multispectral Imager: C-IMG

An analysis was conducted to answer the question if sufficient SNR can be attained for 1 m/pixel color using ~20 bands for C-IMG to discriminate minerals and ices.

Background

- A major science objective of imaging is to distinguish minerals and ices at meter scales
- Queries to the EIS team (EIS uses a 2K x 4K detector, multiple strip filters and TDI) suggests that a detector 2K pixels in the along-track direction could accommodate up to 24 filters

Filters from earlier study

- Fairly wide, evenly spaced bands will capture ferric and ferrous Fe-bearing mineral variability
- Narrower bands needed for ~1.4 µm-region hydration absorptions
- Sharp absorption features of CO_2 ice may necessitate additional narrow bands
- Starting assumption: 14 bands ≤60 nm wide + 3 bands ≤30 nm wide around 1.4 µm + 2-3 bands ≤10 nm wide @ 1.2, 1.435 (Å}1.6 µm) = 20 filters (only 12 bands are shown in Figure D-8)

Assumed detector

- 3K x 3K (or wider in cross-track direction) substrate-removed HgCdTe array (could be Rockwell or Teledyne)
- 18-µm pixel pitch, ≥30,000 e- full well, 14 e- read noise
- 1.7-µm wavelength cutoff
- Passively cooled to -75C using radiator similar to CRISM cryoradiator (dark current ~1000 e-/s)
- 20 filter strips, images collected under each strip in TDI mode, using HiRISE-like approach (TDI in stages of 2N up to 128)
- 80% QE, falling off at wavelengths <700 nm

Assumed camera

- Long Range Reconnaissance Imager (LORRI)-like: 20-cm aperture, 5.4-m focal length (f/27)
- 3.33 µrad/pixel instantaneous field of view (IFOV), 3000x3000 pixels, 0.57° x 0.57° FOV
- TDI direction aligned with vector product of spacecraft velocity and ground track velocity due to planet rotation
- Reflective design with 80% cumulative reflectivity of optical elements
- 10% obscuration
- HgCdTe detector with fixed filters operating in TDI mode; some band passes narrowed from starting assumption to balance SNR across wavelengths

Assumed operational scenario

- Mars at apoapsis (1.62 AU)
- SNR evaluated on reference material with a dust-like spectrum and 0.3 SWIR albedo
- SNR evaluated with illumination at solar incidence angle of 45° (i.e., 3 PM orbit)

- SNR evaluated at representative filter wavelengths
- TDI uses 64 stages (leaving margin)

Requirement / evaluation

- SNR required to be ≥100 in all filters except shortest and longest wavelengths, and the 10-nm filters. 2x2 pixel binning allowed to meet SNR ≥100 in latter filters
- Evaluation performed using Applied Physics Laboratory (APL)-proprietary spreadsheet that has been validated on previous missions

Summary of assessment

- SNR requirements are exceeded at apoapsis for reference materials as can be seen in Figure D-8. The investigated spectral bands are shown in Table D-9.
- 10-nm and longest-wavelength filters need 2x2 binning to attain SNR ≥100 for reference materials
- Dark materials may also require additional pixel binning or more TDI stages
- NOTE: Alternative detectors have 30,000 e- and 80,000-100,000 e- full wells. This analysis assumed the worst case 30,000 e-. The larger full well together with more TDI stages could provide better performance overall especially on dark materials.

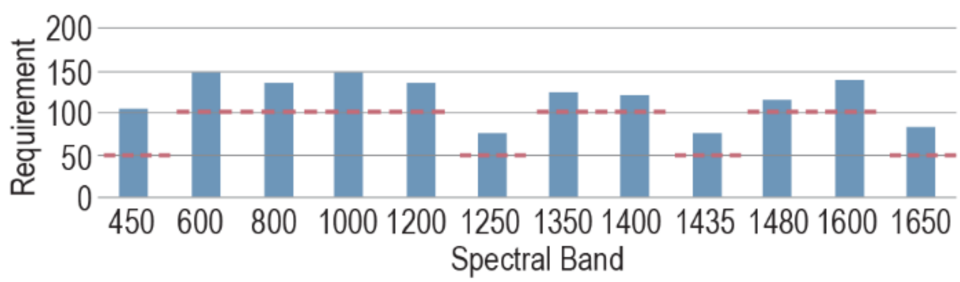


Figure D-8. MORIE single pixel SNR and requirement over twelve spectral bands (red).

Table D-9. Spectral bands investigated in SNR assessment study.

Filter Label	Center Wavelength (µm)	Full Width Bandpass (µm)
450	0.450	0.060
600	0.600	0.030
800	0.800	0.020
1000	1.000	0.030
1200	1.200	0.030
1250	1.250	0.010
1350	1.350	0.030
1400	1.400	0.030
1435	1.435	0.010
1480	1.480	0.030
1600	1.600	0.060
1650	1.650	0.060

D.5 Additional Information on MAVRIC Camera

The Mars Atmospheric, Volatile, and Resource Investigation Camera (MAVRIC) is wide-angle, push-frame dual ultraviolet/visible (UV-Vis) and short-wave infrared (SWIR) camera, see Figure D-9. MAVRIC is mounted nadir and images the daylit hemisphere in a continuous swath.

MAVRIC collects data in 12 filters from 340-1615 nm and is supported by a Data Processing Unit (DPU). UV-Vis and SWIR cameras are 8-element refractive telescopes, identical to each other except for the figures of 2 aspherical surfaces. The two cameras are co-boresighted with "taco shell" baffling to block scattered light from along-track geometries while providing a 150° cross-track FOV (Figure D-9).

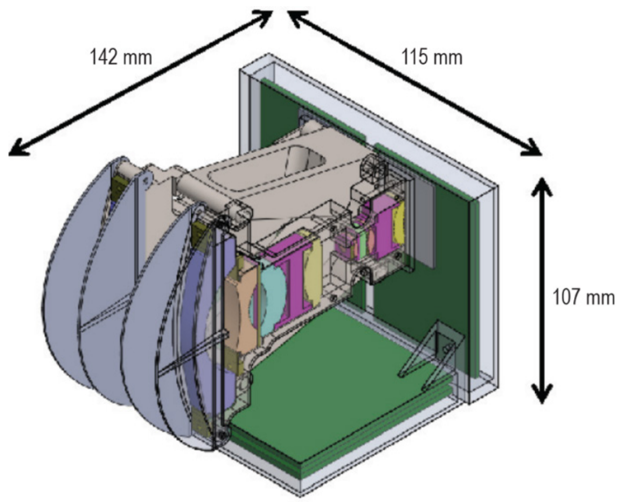


Figure D-9. CAD rendering of the MAVRIC dual camera assembly.

Table D-10. MAVRIC Parameters.

Attribute	UV-Vis	SWIR
Wavelength	340-673 nm	1080-1615 nm
Filters	6	6
Detector	BAE CIS2521	Sensors Unlimited 1280JSX
Detector type	CMOS	InGaAs
Array dimensions	2560x2160 (2x2 binnable to 1280x1080; 1280x116 pix used)	1280x1024 (1280x 116 pix used)
Pixel pitch	6.5 μm (13 μm 2x2 binned)	12.5 μm
Full well	30,000 e-	$6x10^6$ e-
Read noise	4 e- after 13 krad Total Ionizing Dose (TID)	35 e-
Focal length	8.33 mm	8.01 mm
Aperture	1.4 mm	1.35 mm
Pixel IFOV	780/1560 μrad 1x1/2x2 binned	1560 μrad
Pixel scale @ 300 km	234 m /468 m 1x1/2x2 binned	468 m
@ limb	3 km full-res.	6 km
FOV	150° x 1.43°	
Operating/ Survival T	CAMERA: operating -40/+50° C (FPAs controlled to –30°C ±2K); survival -55/+70°C. DPU: operating -40/+85° C; survival -55/+85° C	
Mass (CBE)	CAMERA: 0.97 kg DPU, mounts, cables, harness, therm. blankets: 2.3 kg	
Volume	CAMERA: 16x11.9x10 cm DPU: 21.2 x 11.6 x 11 cm	
Power	CAMERA: 2.1 W CBE DPU: 8.3 W CBE	

The UV-Vis camera uses a 2560x2160 BAE CIS2521 CMOS focal plane array (FPA) with 6.5-µm pixels, typically binned 2x2 operationally to match the SWIR footprint, with on-chip analog-to-digital converter. This detector is baselined for the Double Asteroid Redirection Test (DART) mission, and APL has radiation tested its performance and developed the protection circuitry to mitigate Single Event Effect (SEE) issues. The SWIR camera uses a 1280x1080 Sensors Unlimited 1280JSX InGaAs array with 13-µm pixels that provide analog outputs. Camera focal lengths differ slightly to provide a common 1560-µrad pixel IFOV with the UV-Vis detector 2x2 binned, resulting in a nadir pixel scale of 0.47 km from a 300 km orbit. The outer 280 pixels on each side are binned 2x1 in the along-track direction to preserve vertical resolution at the limb.

Table D-11. Filter Rationale: (BS/BC = Band Shoulder/Center). Min. required in bold.

	Center (FWHM) nm	Rationale
UV-Vis	370 (60)	Ultraviolet (UV) for ice haze
	437 (60)	Blue
	546 (60)	Hematite 530-nm band
	604 (40)	Red
	653(40)	Hematite 600-nm band
	718 (40)	Reflectance peak
SWIR	1100 (40)	1250-nm H_2O BS
	1250 (40)	1250-nm H_2O BC
	1390 (40)	Shoulder to all 3 bands
	1435 (60)	1435-nm CO_2 BC
	1525 (50)	1500-nm H_2O BC 1535-nm CO_2 BS
	1595 (40)	1500-nm H_2O BC 1535-nm CO_2 BS

Six filter strips bonded to each detector are chosen to distinguish ices and dust. Strips are 16 SWIR detector elements (detels; 16 UV-Vis 2 × 2 binned detels) wide with 4-detel opaque masks between them. Each filter sees a 1.43°-wide strip along-track. The total along-track FOV in each camera is 10.4° to limit photometric variations between filters. Varying the combination of filters acquired or downlinked can address specific science goals such as cloud monitoring, seasonal ice mapping, and full spectral profiles.

Heritage and Development: The MAVRIC optical camera design is adapted from MRO/MARCI, with the visible camera extended into the UV to better detect ice aerosols, and the UV camera replaced with a SWIR camera to distinguish ices. The DPU provides power, command and control, and data management, and is a copy of the Lucy/L-LORRI DPU which is adapted from the Parker Solar Probe (PSP) Wide-Field Imager for Solar Probe (WISPR) DPU. Components are TRL 7 except for the TRL 5 SWIR focal plane array.

D.6 Additional Cost Model Techniques Information

JPL's business organization assessed the MORIE pre-decadal study using several techniques to ensure completeness:

1. Historical wrap factors for level-of-effort activities such as science, mission operations system, and ground data system that are level of effort, based on previous Mars missions (MRO, MER, Phoenix, MSL, Insight).
2. System Evaluation and Estimate of Resources-Hardware (SEER-H), and TruePlanning for the spacecraft system.

3. PCEC for the project Life Cycle Cost (LCC) at subsystem levels of NASA WBS.
4. The Space Operations Cost Model (SOCM) for Phases E-F mission operations and data analysis costs.

MORIE Instruments are included in the assessment as pass-through from Team X's NICM results.

Phase A costs were added to the cost model estimates. As a gauge for the amount to apply, the previous New Frontiers 4 AO from 2016 was used as the basis. New Frontiers had a value of $4M Real Year for Phase A with a start date in FY2018. Taking this same value of $4M and inflating it to FY2025 dollars using the NASA New Start Inflation Index, the cost rounds up to $5M.

Phase B-D validations are based first estimating the spacecraft system, then combining it with independent payload estimates and historical wrap factors.

Phase E-F are validated using SOCM (in combination with SEER and TruePlanning models).

The cost results from these parametric estimates are summarized in Table D-12 for the full mission concept and Table D-13 for the ice-focused mission concept.

Table D-12. Cost model results for the full mission (FY22 $M). Highlighted cells represent Wrap and SOCM

WBS Element	Team X Full Mission	SEER (Per Space Guidance v3.1)	TruePlanning	PCEC	Models Average	Delta ($)	Delta (%)
Phase A	**incl. below**	**5.0**	**5.0**	**5.0**	**5.0**		
Phase B/C/D	**929.4**	**896.1**	**924.6**	**1,096.6**	**972.5**		
01 Proj Mgmt	21.0			6.3			
02 Proj System Eng/MD	53.9	133.6	61.9	123.7	124.3	-11.5	-9%
03 S&MA	37.9			47.4			
04 Science & Technology	29.8	18.5	19.1	25.9	21.2	8.6	41%
05 Payload(s)	314.9	322.9	337.8	341.1	333.9	-19.0	-6%
06 Flight Sys + 10 Sys I&T	421.7	363.4	446.3	476.1	428.6	-6.9	-2%
06 Spacecraft System	388.9	300.1	423.0	415.4	379.5	9.4	2%
10 Systems I&T (ATLO)	32.8	63.3	23.3	60.7	49.1	-16.3	-33%
07 MOS + 09 GDS	50.2	57.8	59.6	76.1	64.5	-14.3	-22%
Phases A-D w/o Reserve	**929.4**	**901.1**	**929.6**	**1,101.6**	**977.5**	**-48.1**	**-5%**
01 Proj Mgmt	8.9	15.3	15.3				
02 Proj System Eng	0.2	Incl. in PM	Incl. in PM				
04 Science & Technology	104.7	17.6	17.6	252.9			
07 Mission Operation System	85.3	102.5	102.5				
09 Ground Data System	16.8	57.6	57.6				
Phases E/F w/o Reserve	**216.0**	**193.0**	**193.0**	**252.9**	**213.0**	**3.0**	**1%**
Total Cost (w/o reserves)	**1,145.4**	**1,094.1**	**1,122.6**	**1,354.6**	**1,190.4**	**-45.0**	**-4%**
Phases A/D @ 30% reserves	278.8	270.3	278.9	330.5	293.2	-14.4	-5%
Phases E/F @ 15% reserves	32.4	28.9	28.9	37.9	31.9	0.5	1%
Total Cost + Reserves	**1,456.6**	**1,393.4**	**1,430.5**	**1,723.0**	**1,515.6**	**-59.0**	**-4%**
Phases A/D @ 50% reserves	464.7	450.6	464.8	550.8	488.7	-24.0	-5%
Phases E/F @ 25% reserves	54.0	48.2	48.2	63.2	53.2	0.8	1%
Total Cost + Reserves	**1,664.1**	**1,592.9**	**1,635.7**	**1,968.6**	**1,732.4**	**-68.3**	**-4%**

Table D-13. Cost model results for the ice-focused mission (FY25 $M). Highlighted cells represent Wrap and SOCM

WBS Element	Team X Ice-focused Mission	SEER (Per Space Guidance v3.1)	TruePlanning	PCEC	Models Average	Delta ($)	Delta (%)
Phase A	**Incl. below**	**5.0**	**5.0**	**5.0**	**5.0**		
Phase B/C/D	**730.5**	**672.0**	**728.3**	**908.8**	**769.7**		
01 Proj Mgmt	21.0	99.5	59.4	6.3	109.6	-4.4	-4%
02 Proj System Eng/MD	53.9			117.8			
03 S&MA	30.3			45.9			
04 Science & Technology	14.6	13.9	15.0	21.4	16.8	-2.2	-13%
05 Payload(s)	170.3	176.5	176.8	203.2	185.5	-15.1	-8%
06 Flight Sys + 10 Sys I&T	397.3	338.9	430.1	453.7	407.5	-10.2	-3%
06 Spacecraft System	366.4	292.9	407.7	397.4	366.0	0.4	0%
10 Systems I&T (ATLO)	30.9	46.0	22.3	56.3	41.5	-10.6	-26%
07 MOS + 09 GDS	43.0	43.3	46.9	60.5	50.3	-7.3	-14%
Phases A/D subtotal	**730.5**	**677.0**	**733.3**	**913.8**	**774.7**	**-44.2**	**-6%**
01 Proj Mgmt	8.9	11.2	11.2	245.2			
02 Proj System Eng	0.2	Incl. in PM	Incl. in PM				
04 Science & Technology	49.8	14.1	14.1				
07 Mission Operation System	79.7	65.6	65.6				
09 Ground Data System	11.3	44.2	44.2				
Phases E/F	**149.9**	**135.0**	**135.0**	**245.2**	**171.7**	**-21.8**	**-13%**
Total Cost (w/o reserves)	**880.4**	**812.0**	**868.3**	**1,159.0**	**946.4**	**-66.0**	**-7%**
Phases A/D @ 30% reserves	219.1	203.1	220.0	274.1	232.4	-13.3	-6%
Phases E/F @ 15% reserves	22.5	20.3	20.3	36.8	25.8	-3.3	-13%
Total Cost + Reserves	**1,122.0**	**1,035.3**	**1,108.5**	**1,470.0**	**1,204.6**	**-82.6**	**-7%**
Phases A/D @ 50% reserves	365.2	338.5	366.6	456.9	387.3	-22.1	-6%
Phases E/F @ 25% reserves	37.5	33.8	33.8	61.3	42.9	-5.5	-13%
Total Cost + Reserves	**1,283.1**	**1,184.2**	**1,268.7**	**1,677.3**	**1,376.7**	**-93.6**	**-7%**

In addition to these parametric model validations, a top-level crosscheck of spacecraft/ System I&T (WBS 06 & 10) is shown in Figure D-10 and D-11, comparing mass vs. cost ($/kg). The two MORIE mission concepts are shown to be below the trend line of both set of comparable missions: Mars missions only (MRO, Maven, MSL, Insight, and Phoenix) and the selected planetary historical missions.

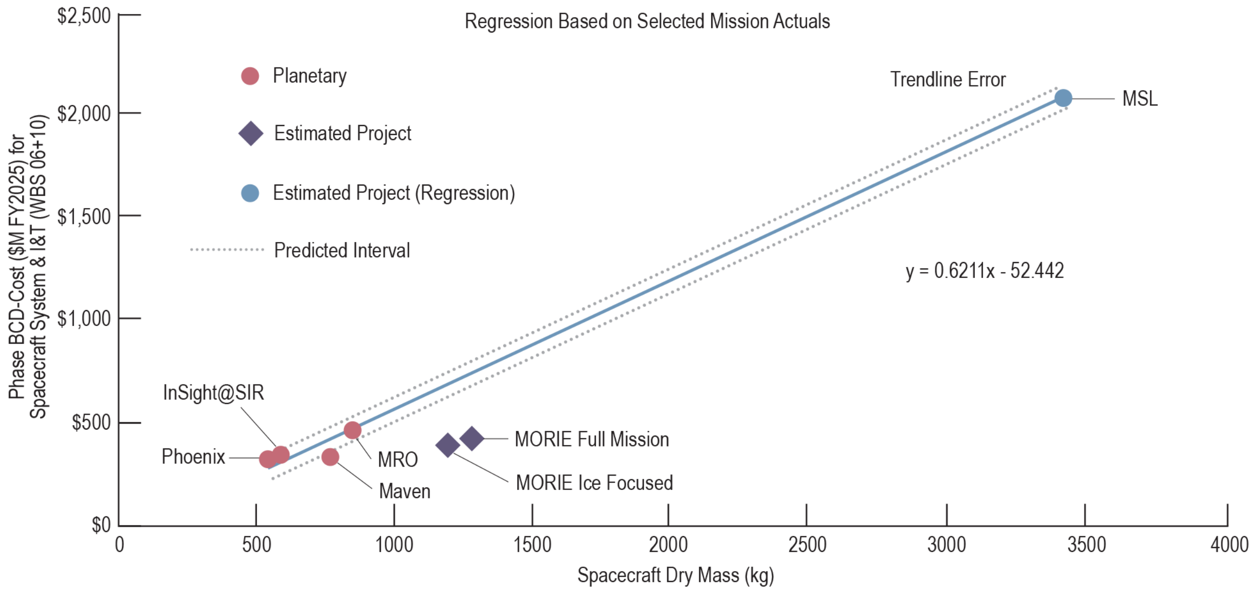


Figure D-10. Mars Missions vs MORIE ($/kg).

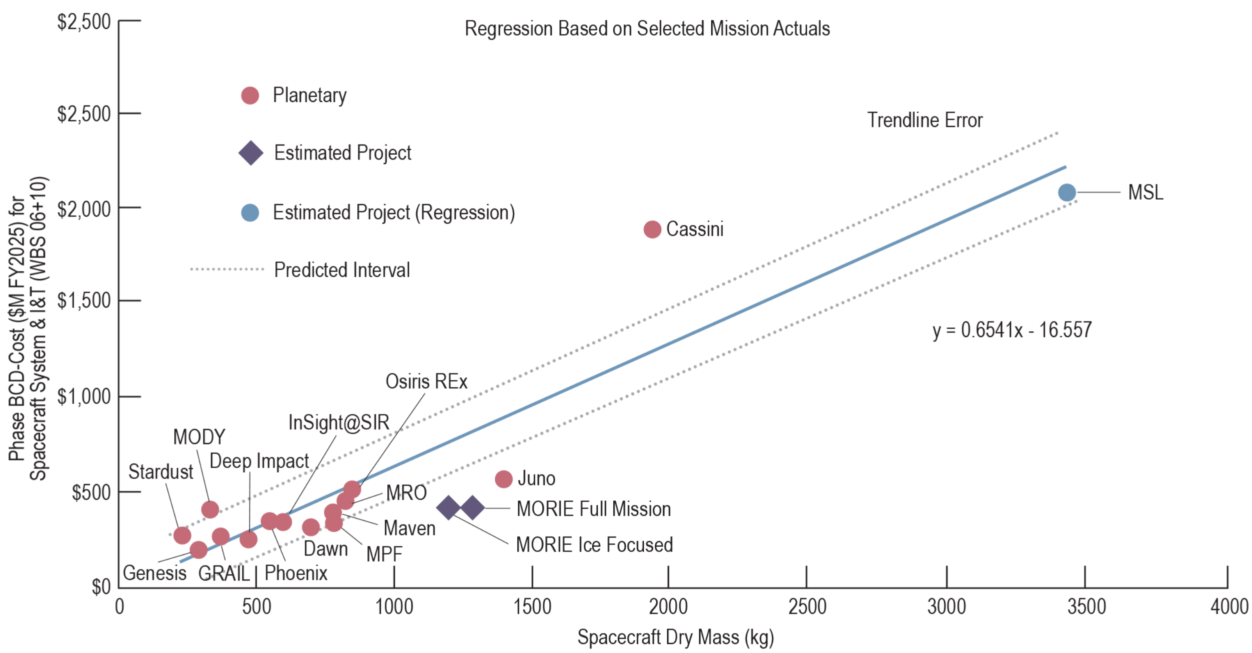


Figure D-11. Planetary Missions vs MORIE ($/kg).

D.6.1 Wrap factors

Wrap factors were developed from historical costs of selected JPL missions. Historical cost data comes from the NASA Cost Analysis Data Requirement (CADRe) for Launch or End of Mission. Wrap factors for WBS 04, 07, and 09 are computed as a percentage of total Phase B/C/D cost without LV or Reserves. Table D-14 shows the calculated historical wrap factor for each WBS that was applied to the SEER and TruePlanning models which do not estimate these costs.

Table D-14. Historical wrap factors for WBS 04, 07 and 09

	MRO	MER	Phoenix	MSL	Insight	Averages
WBS 04 Science	0.9%	2.1%	3.9%	1.0%	2.4%	2.1%
WBS 07 MOS	4.0%	3.2%	3.8%	1.5%	4.7%	3.4%
WBS 09 GDS	1.8%	3.4%	3.6%	3.0%	3.4%	3.0%

D.6.2 SEER-H

SEER-H (version 7.4.13) is a component level cost tool that is recognized for its built-in Knowledge Bases (KBases) that pre-populate most inputs with appropriate industry values and optional calibration adjustments. SEER's built-in capabilities along with recommendations in the SEER-H Space Guidance v.3.1 were used to estimate the separate electrical and mechanical costs of each subsystem/assembly. SEER-H Space Guidance recommends that Class B instruments should set certification level to (Hi, Hi, Hi+) for mechanical/electronic components. The guidance also recommends the design complexity should set at (Hi-, Hi, Hi+) for Power and Propulsion subsystems.

Table D-15 lists the application settings, acquisition category (heritage), and other pertinent settings for SEER-H. Software costs were added using a wrap factor of 10% on the hardware cost, which is based on historical data.

Table D-15. SEER-H Settings and Model Inputs for MORIE Spacecraft.

					Full Mission			Ice-focused Mission	
Work Element Name	Application	Acquisition Category	Prototype Qty	Production Qty Yr 1	# Circuit Boards	Weight		# Circuit Boards	Weight
GN&C									
Sun Sensors	Sun Sensor - Space	Space Procure To Print	0.65	8		0.14			0.14
Star Trackers	Star Tracker - Standard, Space	Space Procure To Print	0.65	2		4.73			4.73
IMUs	Inertial Measurement Unit - Space	Space Procure To Print	0.65	2		4.4			4.4
RWAs	Reaction Wheel - Space	Space Procure To Print	0.65	4		13.2			13.2
Gimbal Drive Electronics	Controller - Electro-Mechanical Control	Space Procure To Print	0.65	4	1			1	
Command & Data									
Processor: RAD750	Processor - Central Processing Unit	Modification - Average	3.25	2	1			1	
Memory: NVMCAM	Memory	Modification - Average	3.25	2	1			1	
Memory: SKR 192 Gb Flash	Memory	Modification - Average	3.25	2	1			1	

Table D-15. SEER-H Settings and Model Inputs for MORIE Spacecraft.

					Full Mission			Ice-focused Mission	
Work Element Name	**Application**	**Acquisition Category**	**Prototype Qty**	**Production Qty Yr 1**	**# Circuit Boards**	**Weight**		**# Circuit Boards**	**Weight**
Telecom_I_F: Multi mission Telemetry InterFace (MTIF)	!~Communications General	Modification - Average	3.25	2	1			1	
General_I_F: Multi mission System Interface Assembly (MSIA)	!~Communications General	Modification - Major	3.25	2	1			1	
General_I_F: LEU-D	Processor - Data Processor	Modification - Average	3.25	2	1			1	
Analog_I_F: LEU-A	Processor - Data Processor	Modification - Average	3.25	2	1			1	
Custom_Board: CRC	Controller - System Control	Modification - Average	3.25	2	1			1	
Analog_I_F: Multi mission Remote Engineering Unit (MREU)	Interconnect - Interconnect Board	Modification - Average	3.25	2	1			1	
Power: CEPCU	Controller - System Control	Modification - Average	3.25	2	1			1	
Backplane: CPCI backplane (6 slots)	Interconnect - Interconnect Board	Modification - Major	5.85	4	1			1	
Chassis: C&DH chassis (6 slot)	Electronic Enclosure - Space	Modification - Major	5.85	4		14.8			14.8
Power									
Solar Array, GaAs TJ UltraFlex, Two Deployable Wings, 47.22m²	Solar Array - Panel, Space	Modification - Major	1.5			103.5			94.53
Battery, Secondary BatteryLi-ION	Battery - Lithium, Space	Modification - Major	1.5	1		41.73			41.73
High Voltage Down Converter (aka High Voltage Electronics Assy)	Power Supply - Electrical	Modification - Average	0.65	1		26			26
Dual Str. Reference Bus Pyro Firing Slice (PFS)	Power Supply	Modification - Average	1.3	2	1			1	
Dual Str. Reference Bus Power Switch Slice - High Side (MPSS-HS)	Power Supply	Modification - Average	1.3	6	1			1	
Dual Str. Reference Bus Guidance Interface Driver Card (GID)	Power Supply	Modification - Average	1.3	2	1			1	
Dual Str. Reference Bus Housekeeping Power Converter Unit (HPCU)	Power Supply	Modification - Average	1.3	2	1			1	
6-slot power chassis	Electronic Enclosure - Space	Modification - Major	0.65	2		1.95			1.95
CPCI backplane (6 slots)	Interconnect - Interconnect Board	Modification - Major	0.65	2	1			1	
Diodes Assembly	Power Supply	Modification - Major	0.65	1	1			1	
Propulsion									
System 1: SEP			1.5	1					
EP Xenon Feedsystem	Power Supply	Modification - Average	1.75	1	2			2	
Lines, Fittings, Misc.	Propulsion Components - Electric, Space	Make	1.5	1		4.5			4.5
PPU	Power Supply - Electrical	Modification - Average	1.5	2		17.93			17.93

Table D-15. SEER-H Settings and Model Inputs for MORIE Spacecraft.

					Full Mission			Ice-focused Mission	
Work Element Name	Application	Acquisition Category	Prototype Qty	Production Qty Yr 1	# Circuit Boards	Weight		# Circuit Boards	Weight
Thruster Gimbals	Gimbal Mechanism	Modification - Average	1.75	1		4.29			4.29
Deployment module & thruster support	Propulsion Thruster - Electric, Space	Modification - Average	1.75	1		30.8			30.8
EP Main Engine	Propulsion Thruster - Electric, Space	Modification - Average	1.5	4		9.69			9.69
Pressurant Tanks	Propulsion Tankage - Electric, Space	Modification - Average	1.5	3		24.2			24.2
System 2: Monoprop			0.65	1					
Gas Service Valve	Propulsion Components - Single Mode, Space	Make	1.5	1		2.59			2.59
Lines, Fittings, Misc.	Propulsion Components - Single Mode, Space	Make	1.5	1		2.7			2.7
Monoprop Main Engine	Propulsion Thruster - Single Mode, Space	Modification - Average	1.5	8		0.35			0.35
Fuel Tanks	Propulsion Tankage - Single Mode, Space	Modification - Average	1.5	1		6.99			6.99
Mechanical & Structure									
Primary Structure	Primary Structure	Modification - Major	1.5			262.19			242.46
Secondary Structure	Secondary Structure	Modification - Major	1.5			80.13			57.22
Power/Telecom Mechanism	!~Mechanism General	Modification - Major	1.5			26.39			26.39
Balance/Ballast	Secondary Structure	Modification - Major	1.5			64.17			58.47
Adapter, Spacecraft side	Adapter	Modification - Major	1.5			27.6			26.19
Harness									
Harness	Harness - Space	Make	0.65	1		98.4			92.12
Telecom									
Ka-band HGA, Reflector Only, 3m	Antenna - Dish, Space	Modification - Average	1.5			21.96			14.84
Dual Band X-Ka Band HGA Feed	Antenna - Dish, Space	Modification - Average	1.5			1.76			1.76
X-band LGA, JUNO Toroidal	Antenna - Conical/Horn, Space	Modification - Average	1.5	1		2.15			2.15
UST Single RX, Dual TX	Transponder - X-Band, Deep Space	Modification - Average	1.5	1	4			4	
Ka-band TWTA RF=100-200W	Traveling Wave Tube Amplifier	Modification - Average	0.65	2		5.98			5.41
X-band TWTA, RF=25W	Traveling Wave Tube Amplifier	Modification - Average	1.5	1		3.3			3.3
X-band Diplexer, moderate isolation	RF Components - Space	Make	1.5	1		0.4			0.4
Ka-Band Filters Tx / Rx	RF Components - Space	Make	1.5	1		0.69			0.69

Table D-15. SEER-H Settings and Model Inputs for MORIE Spacecraft.

					Full Mission			Ice-focused Mission	
Work Element Name	**Application**	**Acquisition Category**	**Prototype Qty**	**Production Qty Yr 1**	**# Circuit Boards**	**Weight**		**# Circuit Boards**	**Weight**
Ka-band Isolator	RF Components - Space	Make	1.5	1		0.57			0.57
Ka-Band Waveguide Transfer Switch	RF Components - Space	Make	1.5	2		0.17			0.17
X-Band Waveguide Transfer Switch	RF Components - Space	Make	1.5	5		0.52			0.52
X-band Isolator	RF Components - Space	Make	1.5	1		0.57			0.57
Coax Cable, flex (190)	Harness - Space	Make	1.5	11		0.08			0.08
WR-112 WG, rigid (Al)	Waveguide	Make	1.5	19		0.28			0.28
WR-34 WG, rigid (Al)	Waveguide	Make	1.5	15		0.11			0.11
Thermal									
Multilayer Insulation (MLI)	Thermal Control - MLI/Paint/Coating	Modification - Major	1.5	72		0.49			0.49
Thermal Surfaces	Thermal Control - MLI/Paint/Coating	Modification - Major	1.5	1		4.29			4.12
Thermal Conduction Control	Thermal Control - Active	Modification - Major	1.5			1.66			1.57
Heaters	Thermal Control - Active	Modification - Major	0.65	1		8.45			8.45
Temperature Sensors	Thermal Control - Active	Modification - Major	1.5	389		0.01			0.01
Thermostats	Thermal Control - Active	Modification - Major	1.5	129		0.03			0.03
Heat Pipes	Radiator/Heat Pipe - Space	Modification - Major	1.5	51		0.2			0.2

Application KBases abide with Acquisition Category settings in SEER's Space Guidance v3.1 Table 7.2

D.6.3 TruePlanning

TruePlanning (version 16.1 SR1) was chosen as an additional validation of the MORIE project LCC. JPL has validated the TruePlanning framework against actuals for past missions and, as a result, uses the following settings: a) Operating Specification is 2.2 for planetary missions, and b) Project complexity is 40 for the top-level system, and 25 for the payload and spacecraft system. Like SEER-H, TruePlanning is a mass-based model with additional inputs for operational environment, component functions, and heritage.

Table D-16 shows the model inputs used for each component in the MEL include Function, Equipment types, heritage and mass (kg).

Table D-16. TruePlanning Setting and Model Inputs for MORIE Spacecraft.

				Full Mission	Ice-focused Mission
Work Element Name	**Function**	**Equipment Type**	**Heritage**	**Mass (kg)**	**Mass (kg)**
GN&C					
Sun Sensors	Spacecraft Attitude Control	Sun Sensor	Copy/ Build to Print	1.14	1.14
Star Trackers		Star Tracker		9.46	9.46
IMUs		IMU/IRU		8.80	8.80
RWAs		Momentum/Reaction Wheel		52.80	52.80
Gimbal Drive Electronics		ACS Control Electronics		4.36	4.36
Command & Data					
Processor: RAD750	Communications and Telemetry Tracking and Control	Spacecraft Control Processor	Minimal Mod	0.58	1.16
Memory: NVMCAM		Memory(Space)		0.75	1.49
Memory: SKR 192 Gbyte Flash					1.53
Telecom_I_F: MTIF		Data Interface		0.77	
General_I_F: MSIA		Data Interface		0.75	1.49
General_I_F: LEU-D		Premodulator Processor		0.70	1.41
Analog_I_F: LEU-A		Premodulator Processor		0.58	1.16
Custom_Board: CRC		Data Handling (Space)	Significant Mod	0.27	0.55
Analog_I_F: MREU		Demodulator (Space)	Minimal Mod	0.86	1.72
Power: CEPCU		Power Conditioner/ Controller	Minimal Mod	1.21	2.42
Backplane: CPCI backplane (6 slots)		Data Interface	Significant Mod	0.78	3.12
Chassis: C&DH chassis (6 slot)		Electronic Chassis/Housing	Significant Mod	3.71	14.82
Power					
Solar Array, GaAs TJ UltraFlex, Two Deployable Wings, 47.22m²	Electrical Power	Solar Array	Minimal Mod (50% New Design)	103.46	94.53
Battery, Secondary BatteryLi-ION		Battery		83.46	83.46
High Voltage Down Converter (aka High Voltage Electronics Assy)		Power Supply Electronics(Space Electrics)		26.00	26.00
Dual Str. Reference Bus Pyro Firing Slice (PFS)		Pyrotechnics	Copy/Build to Print	3.78	3.78
Dual Str. Reference Bus Power Switch Slice - High Side (MPSS-HS)		Switching Unit		11.66	11.66

Table D-16. TruePlanning Setting and Model Inputs for MORIE Spacecraft.

				Full Mission	Ice-focused Mission
Work Element Name	**Function**	**Equipment Type**	**Heritage**	**Mass (kg)**	**Mass (kg)**
Dual Str. Reference Bus Guidance Interface Driver Card (GID)		Power Supply Electronics(Space Electrics)		1.62	1.62
Dual Str. Reference Bus Housekeeping Power Converter Unit (HPCU)		Power Supply Electronics(Space Electrics)		2.52	2.52
6-slot power chassis		Electronic Chassis/Housing	Minimal Mod	3.90	3.90
CPCI backplane (6 slots)		Data Interface		1.63	1.63
Diodes Assembly		Power Supply Electronics(Space Electrics)		0.26	0.26
Propulsion					
System 1: SEP					
EP Xenon Feedsystem	Propulsion	Thruster, XIPS	Minimal Mod	0.35	0.35
Lines, Fittings, Misc.		Lines/Fittings,Latch/ Isolation Valves	Significant Mod	4.50	4.50
PPU		Power Processor	Minimal Mod (40% New Design)	35.86	35.86
Thruster Gimbals		Mechanisms	Minimal Mod	8.58	8.58
Deployment module & thruster support		Thruster, XIPS	Minimal Mod (40% New Design)	61.60	61.60
EP Main Engine		Thruster, XIPS	Minimal Mod	38.76	38.76
Pressurant Tanks		Tank, Pressurant		72.60	72.60
System 2: Monoprop					
Gas Service Valve	Propulsion	Lines/Fittings,Latch/ Isolation Valves	Copy/Build to Print	2.59	2.59
Lines, Fittings, Misc.		Lines/Fittings,Latch/ Isolation Valves	New	2.70	2.70
Monoprop Main Engine		Thruster, Liquid	Copy/Build to Print	2.77	2.77
Fuel Tanks		Tank, Liquid		6.99	6.99
Mechanical & Structure					
Primary Structure	Structures and Mechanisms	Structure, Primary	Significant Mod	262.19	242.46
Secondary Structure		Structure, Panel	Minimal Mod	80.13	57.22
Power/Telecom Mechanism		Mechanisms	Significant Mod	26.39	26.39
Balance/Ballast		Structure, Panel	Minimal Mod	64.17	58.47
Adapter, Spacecraft side		Structure, Panel		27.60	26.19
Harness					
Harness	Electrical Power	Cabling/Wiring Harness	New	98.40	92.12
Telecom					
Ka-band HGA, Reflector Only, 3m	Communications and Telemetry Tracking and Control	Antenna, Hi-Gain	Minimal Mod	21.96	14.84
Dual Band X-Ka Band HGA Feed		Antenna, Horn		1.76	1.76
X-band LGA, JUNO Toroidal		Antenna, Low/Medium Gain		4.29	4.29
UST Single RX, Dual TX		Transponder(Space)		10.35	10.35
Ka-band TWTA RF=100-200W		TWTA		11.96	10.81
X-band TWTA, RF=25W		TWTA		6.60	6.60

Table D-16. TruePlanning Setting and Model Inputs for MORIE Spacecraft.

				Full Mission	Ice-focused Mission
Work Element Name	**Function**	**Equipment Type**	**Heritage**	**Mass (kg)**	**Mass (kg)**
X-band Diplexer, moderate isolation		Diplexer(Space)		0.81	0.81
Ka-Band Filters Tx / Rx		Filter/Coupler		1.38	1.38
Ka-band Isolator		RF Plumbing		1.15	1.15
Ka-Band Waveguide Transfer Switch		Harness/Cabling/Waveguide		0.52	0.52
X-Band Waveguide Transfer Switch		Harness/Cabling/Waveguide		3.11	3.11
X-band Isolator		RF Plumbing		1.15	1.15
Coax Cable, flex (190)		Harness/Cabling/Waveguide	New	0.49	0.49
WR-112 WG, rigid (Al)		Harness/Cabling/Waveguide	New	2.85	2.85
WR-34 WG, rigid (Al)		Harness/Cabling/Waveguide	New	0.84	0.84
Thermal					
Multilayer Insulation (MLI)	Thermal Control	MLI Blanket/Insulation/Paint/Shroud	Significant Mod	0.49	0.49
Thermal Surfaces	Thermal Control	MLI Blanket/Insulation/Paint/Shroud	Significant Mod	4.29	4.12
Thermal Conduction Control	Thermal Control	MLI Blanket/Insulation/Paint/Shroud	Significant Mod	1.66	1.57
Heaters	Thermal Control	Heater/Thermister/Thermostat	Significant Mod	8.45	8.45
Temperature Sensors	Thermal Control	Heater/Thermister/Thermostat	Significant Mod	0.01	0.01
Thermostats	Thermal Control	Heater/Thermister/Thermostat	Significant Mod	0.03	0.03
Heat Pipes	Thermal Control	Heat Pipes	Significant Mod	0.20	0.20

D.6.4 PCEC

PCEC model comprises of "Global Inputs" and "Subsystem Inputs". Table D-17 provides the settings of the model for the MORIE mission concepts. In PCEC model, Phase E estimated Mission Ops and Science Data Analysis together, therefore, project manager (PM) and project system engineer (PSE) estimates are considered as a pass-thru from Team X values.

Table D-17. PCEC Model Inputs Settings for the MORIE Spacecraft.

Global Inputs	Full Mission	Ice-focused Mission
Project Lead Organization	NASA Center	
Flight System Organization	NASA Center	
Flight System Type (Robotic SC)	Flyby Spacecraft or Orbiter	
Mission Risk Class (Robotic SC)	Class B	
Mission Target/Type (Robotic SC)	Mars	
Mission Destination	Mars	
Operating Environment	Nominal Deep Space	
Radiation Environment (krad)	20.34	
End of Life Power (watts)	11488.8	10476
Flight System Power (watts)	10098	9188
Total Flight System Dry Mass (kg)	1275	1201
Total Payload / Instrument Mass (kg)	211.08696	149.71
Total Consumables Mass (kg)	1260	1153
Design Phase Duration (months)	23.3	
Fabrication Phase Duration (months)	11.2	
Integration & Test Phase Duration (months)	15.2	
Launch Ops & Checkout Phase Duration (months)	3.1	
Subsystem Inputs mass (kg)	**Full Mission**	**Ice-focused Mission**
Structures & Mechanisms	460	411
Cable	98	92
Thermal Control	64	63
Electrical Power & Distribution	238	229
GN&C	77	77
Propulsion	237	237
C&DH	31	31
Communications	69	61

D.6.5 SOCM

The Space Operations Cost Model (SOCM) was used for the validation of Phase E/F. SOCM estimates the costs and staffing for space operations projects using high-level project characteristics that are typically known at the early stages of a project's lifecycle. Running the cost model at Level 1 generates an estimate with an accuracy of ± 30%. The Level 1 Planetary inputs selected to reflect the MORIE mission are identified in Figure D-12. The only different input between the two mission concepts are the instrument payloads.

PLANETARY - LEVEL 1 INPUTS	Value ->	1	2	3	4	5	6
MISSION CHARACTERIZATION							
Mission Type	6	Planet Flyby	Atmospheric Probe	Satellite Flyby	Planet Flyby with Atmos Prb	Satellite Flyby with Atmos Prb	Orbiter
Target	3	Inner Planets (M,V)	Small Bodies	Mars	Outer Planets (J,S,U,N,P)		
# of Identical Flight Systems	1	1	2	3	4	5	6
Cruise Mission Duration (mo)	24						
Encounter Mission Duration (mo)	46						
Post-Flight Data Analysis Duration (mo)	3						
PROGRAMMATICS CHARACTERIZATION							
Mission Risk Class	4	Technology Demo (tech > sci)	Discovery, moderate risk	Medium, low risk	Major, minimum risk		
Development Schedule	3	Fast (< 2.5 yrs)	Moderate (2.5-4 yrs)	Long (> 4 yrs)			
GDS/MOS CHARACTERIZATION							
Lead Organization Level of Experience	3	Low	Average	Extensive			
MOS S/W Maturity/Heritage	2	Low	Average	Extensive			
# of Supporting Organizations	1	1	2	3	4	5	
PAYLOAD CHARACTERIZATION							
Enter # of Instruments by Type:							
Heat Probes			Science				
Accelerometers			Instrument	**56**			
Lightning & Radio Emis Det.			Score				
Atmospheric Structures Instr.							
Dust Detectors							
Magnetometers							
In Situ Mass Spectrometers							
Point Spectrometers							
Laser Altimeters							
Alpha Proton X-Ray Spectr.							
Radio Experiments							
Radar Altimeters							
Gamma Ray Spectrometers							
X-Ray Spectrometers							
Sample Acquisition Devices							
Imaging X-Ray Spectr.	5						
Electron Ion Mass Spectr.							
Multi-Spectral Imaging Systems							
Mapping Spectro. Systems							
Synthetic Aperture Radar	2						
S/C DESIGN CHARACTERIZATION							
S/C Design Implementation	2	High Heritage	Cost-Capped	Requirements-Driven			
Design Complexity	3	Low (minimal # of flight rules)	Medium	High (several unique engrng reqs)			

Figure D-12. SOCM Level 1 Cost Input for MORIE Phase E.

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