National Aeronautics and Space Administration

Mission
Concept
Study

CERES

Exploration of Ceres' Habitability

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Pre-Decisional Information – For Planning and Discussion Purposes Only

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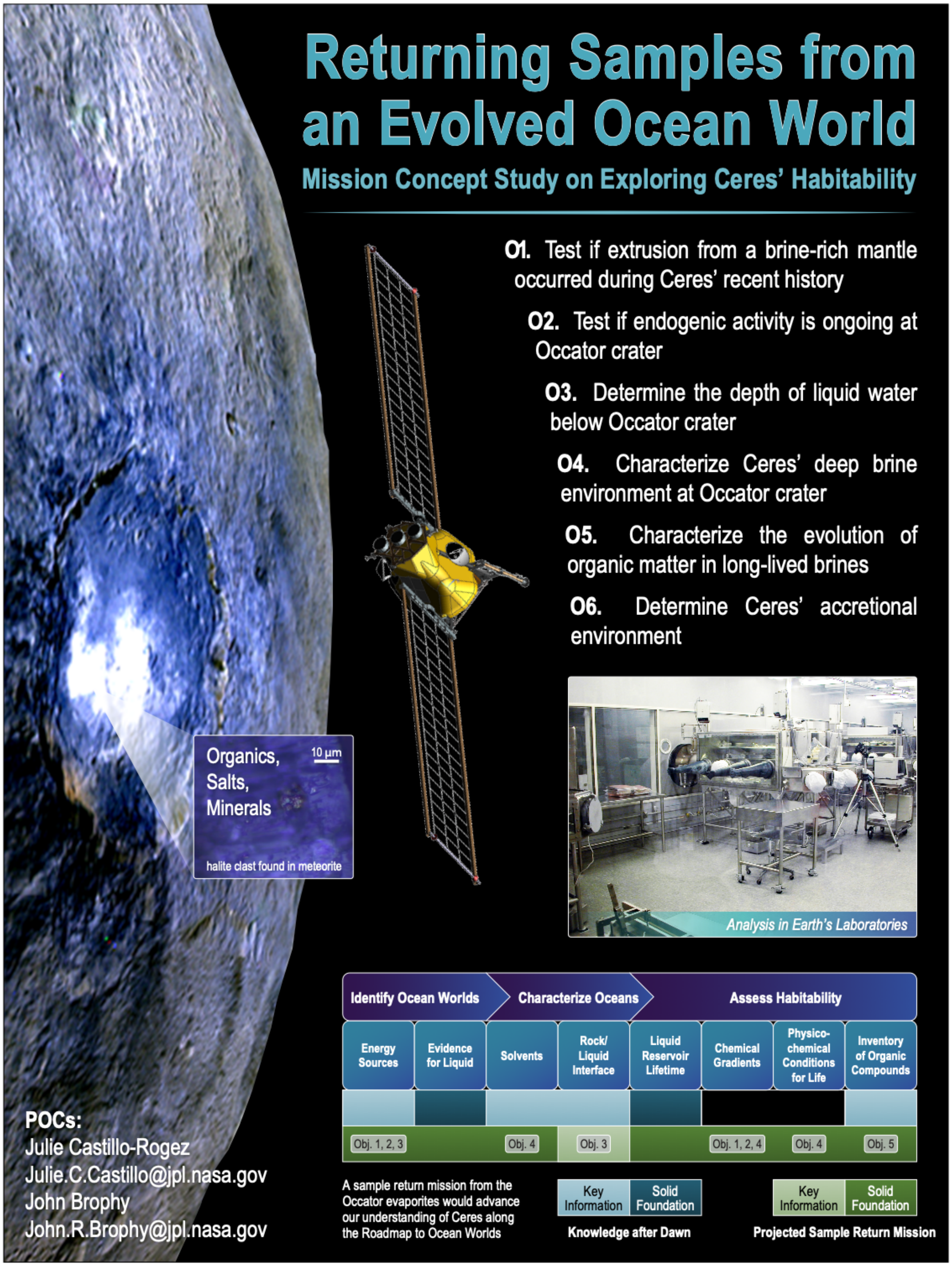
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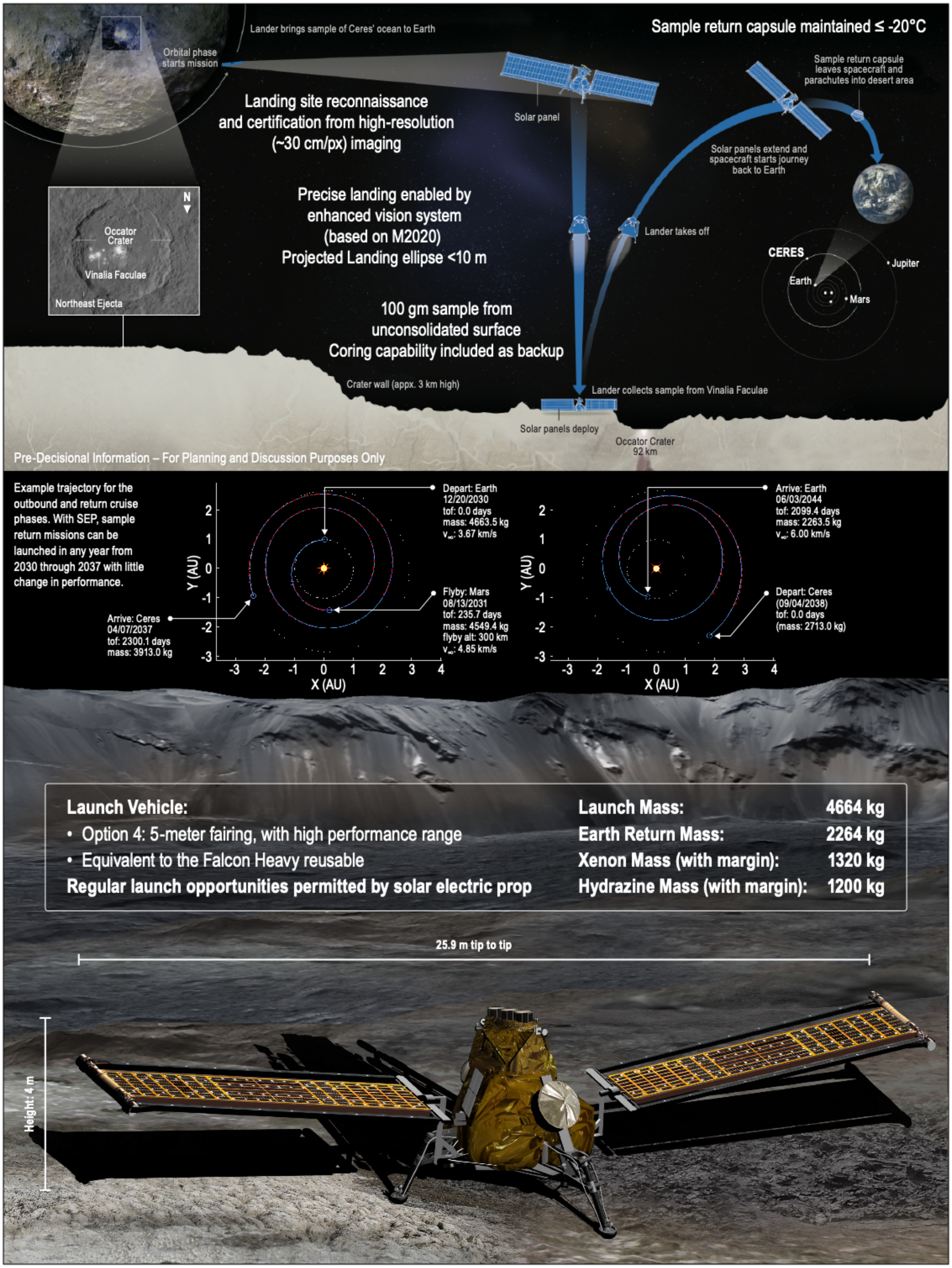
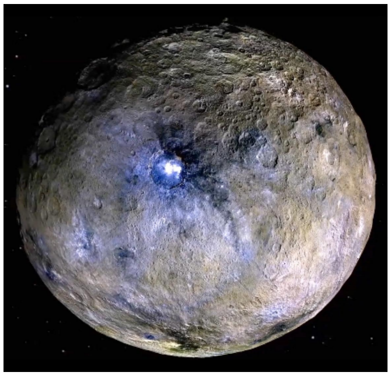

Lander brings sample of Ceres' ocean to Earth
Sample return capsule maintained ≤ -20°C
Orbital phase starts mission
Solar panel
Sample return capsule leaves spacecraft and parachutes into desert area
Landing site reconnaissance and certification from high-resolution (~30 cm/px) imaging
Solar panels extend and spacecraft starts journey back to Earth
N
Occator Crater
Vinalia Faculae
Northeast Ejecta
Precise landing enabled by enhanced vision system (based on M2020)
Projected Landing ellipse <10 m
Lander takes off
CERES
Jupiter
Earth
Mars
100 gm sample from unconsolidated surface
Coring capability included as backup
Crater wall (appx. 3 km high)
Lander collects sample from Vinalia Faculae
Solar panels deploy
Occator Crater 92 km
Pre-Decisional Information – For Planning and Discussion Purposes Only
Example trajectory for the outbound and return cruise phases. With SEP, sample return missions can be launched in any year from 2030 through 2037 with little change in performance.
Depart: Earth
12/20/2030
tof: 0.0 days
mass: 4663.5 kg
v∞: 3.67 km/s
Flyby: Mars
08/13/2031
tof: 235.7 days
mass: 4549.4 kg
flyby alt: 300 km
v∞: 4.85 km/s
Arrive: Ceres
04/07/2037
tof: 2300.1 days
mass: 3913.0 kg
Y (AU)
X (AU)
Arrive: Earth
06/03/2044
tof: 2099.4 days
mass: 2263.5 kg
v∞: 6.00 km/s
Depart: Ceres
(09/04/2038)
tof: 0.0 days
(mass: 2713.0 kg)
Launch Vehicle:
• Option 4: 5-meter fairing, with high performance range
• Equivalent to the Falcon Heavy reusable
Regular launch opportunities permitted by solar electric prop
Launch Mass: 4664 kg
Earth Return Mass: 2264 kg
Xenon Mass (with margin): 1320 kg
Hydrazine Mass (with margin): 1200 kg
25.9 m tip to tip
Height: 4 m

Executive Summary



This enhanced color mosaic of dwarf planet Ceres highlights the dramatic contrast between the fresh evaporites in Occator crater and the surrounding terrains. Image credit: NASA/JPL Caltech/ UCLA/ MPS/DLR/IDA

Dwarf planet Ceres is a compelling target as an evolved ocean world with, at least, regional brine reservoirs and potentially ongoing geological activity. As the most water-rich body in the inner solar system (in relative abundance), it is a representative of the population of planetesimals that brought volatiles and organics to the inner solar system. Situated in the Main Belt of asteroids, Ceres is accessible enough for a sample return with the resources of a typical medium-class (New Frontiers) NASA mission. Under the Discovery program, Dawn explored Ceres from 2015 to 2018. The extensive dataset revealed the presence of liquid, brine-driven activity, organic matter, and a rich salt chemistry. With this evidence, the overarching goals of the mission concept presented herein are to quantify Ceres' current **habitability potential** and **origin**.

Habitability is addressed through a combination of geological, geophysical, and compositional investigations by searching for evidence of past and ongoing geological activity via medium-resolution imaging and gravity science from orbit near landforms interpreted as brine-driven volcanic structures based on the Dawn observations, and by probing the depth of brines with electromagnetic sounding. Two approaches were considered for compositional measurements, which address both **habitability** and **origins**: (1) In situ exploration at two sites, and (2) Sample return from a single site with more limited in situ science investigations. Both concepts target material at Occator crater, which is one of the youngest features on Ceres (~20 My old) and a site rich in evaporites evolved from recently erupted brine sourced from a region > 35 km deep. The study concluded that a **sample return from these young evaporite deposits offers greater science return** than the in situ exploration mission by enabling high-resolution analysis of (1) organic matter expected from terrestrial and chondritic analogs that are trapped in salt minerals and (2) isotopes of refractory elements for a **similar cost and less science risk**.

Given these compelling aspects, this report focuses on the sample return concept. A concept for in situ–only exploration at two sites is included in the appendix for the Decadal Survey committee's consideration. The sample return concept can be executed with a **single flight system** due to Ceres' relative proximity to Earth and low gravity. **Solar electric propulsion** was identified as the most cost-effective for getting to Ceres and back, using an Option-4 launch vehicle (equivalent to Falcon Heavy Recoverable). De-orbiting, landing, and takeoff are performed with a throttleable monopropellant hydrazine system. The solar arrays are stowed prior to landing and takeoff. Sample acquisition builds on the pneumatic system designed by Honeybee Robotics for the Japan Aerospace Exploration Agency (JAXA) Martian Moons eXploration mission and NASA's Dragonfly mission, while the sample return capsule is inherited from the Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer (OSIRIS-Rex) mission. This concept relies on the availability of key technologies: an enhanced landing vision system leveraging investments from Mars 2020; retractable/redeployable solar arrays, which have been demonstrated on the International Space Station but not at Ceres' gravity; and an emerging design from upcoming missions for sample transfer from the pneumatic sampling system to the sample return capsule. Return of a sample of mass ~100 g from Ceres, acquired in pristine condition and returned at ≤-20°C, is without precedent for any currently advocated Ocean World mission, enabling a vast range of experimental techniques back on Earth with sensitivities and accuracies far beyond those feasible with in situ instruments. A sample of this size also enables analyses to benefit from techniques that will become available in the future.

This concept fits within the $1.1B New Frontiers cost target and we recommend that it be considered for the New Frontiers 6 portfolio.

1 SCIENTIFIC OBJECTIVES

1.1 SCIENCE MOTIVATIONS FOR CERES' EXPLORATION

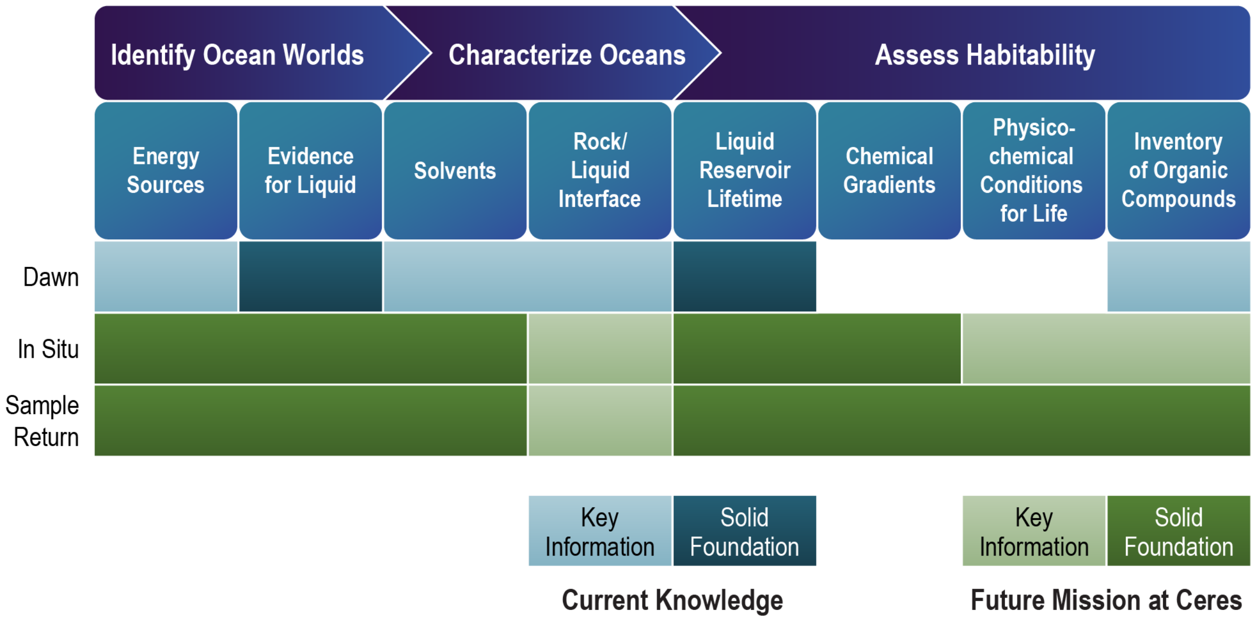


Figure 1-1. Knowledge of Ceres' astrobiological potential framed in the context of the Roadmap to Ocean Worlds (ROW) based on Dawn's results. A future New Frontiers–class mission (in situ or sample return) would significantly progress along the roadmap. (Adapted from Hendrix et al. 2019).

Dwarf planet Ceres is the largest object in the main belt and the most water-rich (~25 wt.%) object in the inner solar system (in relative abundance). Ceres had sufficient water and radioisotope-bearing silicates to host a deep ocean in its past, leading to a layered interior structure with a high degree of aqueous alteration (Ermakov et al. 2017). The Dawn mission revealed evidence of recent and possibly ongoing geologic activity on Ceres (De Sanctis et al. 2020), the presence of liquid below an ice-rich crust (Fu et al. 2017; Scully et al. 2020), local surface deposits of organic matter (De Sanctis et al. 2017), potentially super-chondritic concentrations of carbon in the regolith (Prettyman et al. 2018), and the presence of an exosphere and volatile transport (Raponi et al. 2018). Recent brine-driven exposure of material onto Ceres' surface can be found at Occator Crater (<2 My, Nathues et al. 2020) and the ~4 km tall, geologically recent Ahuna Mons (<100 My, Ruesch et al. 2016, 2019a). Multiple lines of evidence for deep liquid, at least regionally, and long-lived heat sources has led to Ceres being categorized as an ocean world (Castillo-Rogez 2020) (**Figure 1-1**). These observations suggest Ceres is a prime destination to study habitability in water-rich bodies. An origin of life in Ceres is discarded per the dwarf planet's limited heat budget (Castillo-Rogez et al. 2020). However, investigation of Ceres would provide a critical data point on understanding how ocean worlds work (by separating the tidal heating variable) to maintain habitability through billions of years. Furthermore, Ceres offers context for understanding how volatiles and organic compounds were generated and transported throughout the solar system and it might represent planetesimals at the source of (some of) Earth's volatiles (Budde et al. 2019). These scientific motivations are the drivers for this concept of a Ceres in situ and sample return explorer.

1.2 SCIENCE QUESTIONS AND OBJECTIVES

The overarching goals of this concept are to (1) assess Ceres' current habitability and use Ceres as a test case for determining the habitability of volatile-rich bodies over time; and (2) determine Ceres' origin and the relationship of its volatiles and organics to other inner solar system bodies. Goal 1 is addressed via **Objectives 1–5**, whereas Goal 2 is addressed via **Objective 6**.

Objective 1: Test if extrusion from a brine-rich mantle occurred during Ceres' recent history.

Assessing Ceres' habitability through time requires understanding the mechanisms of material exchange between the interior and the surface. Evidence for intrusion of deep mantle material into the shallow subsurface has been found in association with features likely of cryovolcanic origin, including Ahuna Mons (Ruesch et al. 2019a) and the Occator faculae (Cerealia Facula, Pasola Facula, Vinalia Faculae) (Nathues et al. 2020; Scully et al. 2020) and potentially Haulani crater (Nathues, pers. comm.). Ceres' numerous mounds and domes (e.g., Cosecha Tholus), which are observed across substantial portions of Ceres surface have also been attributed to cryovolcanism (Sori et al. 2017, 2018).

Such deeply sourced cryovolcanism provides a key mechanism for subsurface-surface exchange that might introduce chemical gradients in the crust over time and create transient habitable regions. However, alternative non-volcanic processes have also been proposed for the formation of the many mounds and domes (Bland et al. 2019). This mechanism requires a heterogeneous crust, but potentially only limited exchange between the deep mantle and the shallow subsurface. Characterizing the lateral structure of Ceres' crust is necessary to resolve this ambiguity.

Spatial variations in composition and structure can be inferred from spatial variations in subsurface density. This would be investigated through the determination of locally high-degree gravity in association with domes ($n > 40$ versus $n = 18$ for the global Ceres gravity field from Dawn, Park et al. 2016), as has been done for Ahuna Mons (Ruesch et al. 2019a). Medium-resolution (few m/px) color imaging can reveal structural features that inform on emplacement mechanism as recently published for the Occator faculae (e.g., Scully et al. 2020).

Objective 2: Test if endogenic activity is ongoing at Occator crater.

Results from the Dawn second extended mission (XM2, see Castillo-Rogez and Rayman 2020) suggest very recent (<2 My) and potentially ongoing activity at Cerealia Facula based on crater counting (Nathues et al. 2020) and the occurrence of hydrohalite ($NaCl \bullet 2H_2O$), which dehydrates within hundreds of years when exposed on Ceres' surface (De Sanctis et al. 2020). Ongoing activity at the Vinalia Faculae is also suspected but evidence is lacking. Seeking additional evidence for brine exposure at Occator crater, in combination with **Objectives 1**, **3** and **4** (brine depth and composition determination), would inform on the mechanism(s) driving recent and current activity.

Landscape modification since the Dawn observations (2015-2018) could be found from imaging the Occator faculae at a resolution similar to Dawn XM2 (<5 m/px). At Cerealia Facula, material exposure is expected to occur at the top of Cerealia Tholus (De Sanctis et al. 2020) where the addition of evaporites may not be detectable against the bright background. On the other hand, material exposure at Vinalia Faculae, if ongoing, is expected to be a ballistic process, hence resulting in a relative increase of evaporites against the dark floor. Based on eruption rates from Quick et al. (2019), the predicted volume of material that may be exposed over 20 years' time at Vinalia Faculae may be equivalent to a surface area 0.5 to 2 km^2 area. If all the bright material were exposed onto the dark floor, the change would fill $2\text{-}8.10^4$ pixels at 5 m/px. The large uncertainty is due to limited knowledge of the Vinalia fracture widths and brine ascension rate. It is possible, especially for the lower end of that range, that freshly exposed material would not be detectable because it overlaps with previous exposures. As there are multiple sources of evaporites at Vinalia Faculae, it is reasonable to assume that some of the recently deposited material would occur in an area that did not contain evaporites at the time of the Dawn observations. Nevertheless, a non-detection at 5 m/px resolution would set a bound on extrusion rate.

Imaging at 5 m/px enables the setting of the freshly exposed material to be analyzed and interpreted, which allows for mass-wasting to be differentiated from the ballistic and/or short-lived-flow emplacement of the endogenic material (e.g. Quick et al. 2019). For example, mass wasting is associated with specific topographic conditions (e.g., negative slope), while ballistic emplacement of endogenic materials results in characteristically diffuse deposits of bright material, such as those observed in Vinalia Faculae; these deposits are morphologically distinct from material emplaced via mass wasting, such as at

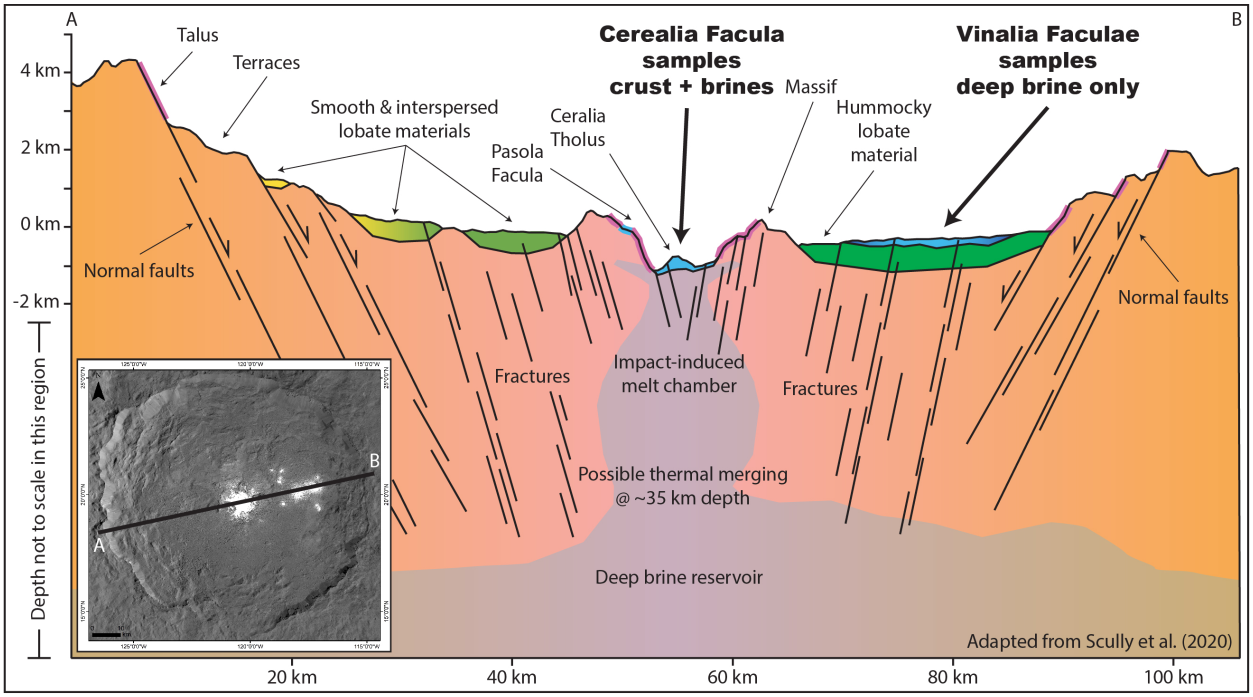


Figure 1-2. Geophysical context for the geological site investigated by this study. Medium-resolution imaging, compositional, and gravity data of the floor of Occator crater floor by the Dawn mission revealed the presence of a deep brine region that provides a long-lived source for evaporites found in the Vinalia Faculae (Raymond et al. 2020; Scully et al. 2020; Nathues et al. 2020). Adapted from Scully et al. 2020.

the narrow bright landslides that cascade into the fractures associated with Vinalia Faculae (see **Appendix C**). Color imaging would further help identify freshly emplaced carbonates and chlorides (Bu et al. 2019; Nathues et al. 2020; De Sanctis et al. 2020) by comparisons with the Dawn datasets.

Objective 3: Determine the depth of liquid water below Occator.

Recent activity (<2 My) at Occator crater is interpreted to stem from a deeply sourced brine rich in carbonates and chlorides (Quick et al. 2019; Raymond et al. 2020; **Figure 1-2**). An origin solely from a chamber generated by the Occator-forming impact heat is uncertain because the lifetime of such a chamber predicted by thermal modeling (<5 My, Hesse and Castillo-Rogez 2019) is substantially less than the age of the crater (~20 My, Nathues et al. 2019). Furthermore, an impact melt chamber in the central region of Occator crater is tens of kilometers away from the Vinalia Faculae, too far to represent a viable source (Scully et al. 2020). Medium-resolution gravity data returned during XM2 support the presence of a deep brine layer below Occator crater (Raymond et al. 2020), but its depth is poorly constrained. More precise knowledge of its depth and extent would provide a critical constraint on the thermal state of the crust and on the drivers of activity at Ceres. For example, it has been suggested that a high fraction of gas and salt hydrates in the crust could slow down heat transfer by preventing convection onset (Formisano et al. 2020) and decreasing the crust thermal conductivity (Castillo-Rogez et al. 2019), and thus help maintain deep liquid until present. A similar explanation has been suggested for the long-term preservation of a deep ocean in Pluto (Kamata et al. 2019). More generally, knowledge of the temperature gradient in the crust would put the broad Dawn geological results in context.

Geophysical sounding is required to address this question. Seismometry was initially considered but discarded due to geometric requirements and uncertainty in seismic sources. Furthermore, unknown/ambiguous crustal material properties might limit the interpretation of seismic sounding. Electromagnetic sounding was identified as the optimal approach for detecting brines because of the high inductive response of salty water and because the solar-wind source has been characterized.

Table 1-1. Range of values for habitability parameters, modified from Cockell et al. (2016).

Habitability Parameters	Range of Conditions Amenable to Life	Measurements by Future Mission
Temperature (T) and physicochemical conditions	T = from -25°C (limit for metabolic activity) to 122°C (limit for microbial growth) and up to 150°C (cell repair) Water activity > 0.605; Redox between -1 and +1.5 No known limit on pH	Brine eutectic water activity, redox (Eh), temperature inferred from mineralogy and isotopes of volatiles, and phase relationships
Available energy	e.g., NH_3, NH_4^+, Fe(II), Fe(III), SO_2, SO_4^{2-}	Occurrence and concentration of electron donors and acceptors
Presence of major elements	Carbon, Hydrogen, Nitrogen, Oxygen, Phosphorus, Sulfur (CHNOPS present), iron and other metals	Inventory of elemental compounds and form (mineral, organics)

Objective 4: Characterize Ceres' deep brine environment at Occator crater.

The evaporites exposed in Occator crater sample the deep brine (Nathues et al. 2020; Scully et al. 2020) and offer a unique opportunity to investigate the brine environment of an evolved ocean world. Dawn revealed abundant sodium carbonate and smaller fractions of ammonium chlorides and hydrohalite (De Sanctis et al. 2016, 2020; Raponi et al. 2019). These indicate an alkaline source with a temperature above 245 K (Castillo-Rogez et al. 2018). The next natural step in the exploration of Ceres is to test if the mud/brine is currently habitable via determination of attributes of the environment in which the brines formed, including temperature, pH, H_2 fugacity, chemical gradient (**Table 1-1**), and chemicals harmful to life. Some of these constraints exist for Ceres' early ocean environment from the mineralogical and elemental data from the Dawn mission (Castillo-Rogez et al. 2018), for example a temperature < 50°C, rather alkaline conditions, and a partial pressure of hydrogen log pH_2 >-5. The timeframe during which these conditions were present at Ceres is not well constrained. Obtaining this information for the current brine would help assess if Ceres was habitable throughout its history.

Furthermore, access to the deep brine of an evolved ocean world offers a unique opportunity to address many questions that pertain to most other ocean worlds, in particular e.g., "What environments possess redox disequilibria, in what forms, in what magnitude, how rapidly dissipated by abiotic reactions, and how rapidly replenished by local processes?" (Hendrix et al. 2019). For example, several processes that enable the long-term availability or replenishment of chemical energy have been suggested. Although ocean worlds that evolve as closed systems may reach chemical equilibrium early in their history under an environment with high partial pressures of hydrogen resulting from serpentinization (Vance et al. 2016), various processes have been suggested for introducing oxidants into the ocean, including crustal breach and potential overturn via large impacts (e.g., Chyba 2000), release of fluids from the mantle as a result of thermal metamorphism (Melwani Daswani et al. submitted), or local water radiolysis driven by radioisotope decay (Altair et al. 2018; Bouquet et al. 2018). In Ceres, uranium and thorium may be present in rock particles that remained in suspension in the ocean, and potassium is expected to be abundant in the ocean as a result of rock leaching (Neveu et al. 2017; Castillo-Rogez et al. 2020).

This objective is addressed by acquiring the full compositional inventory (mineralogical, elemental, isotopic, including for minor species: organic compounds are addressed in Objective 5) and analysis of the petrological relationships between mineral and chemical phases.

Objective 5: Characterize the evolution of organic matter in long-lived brines.

Ceres' regolith likely contains super-chondritic concentrations of carbon (Prettyman et al. 2017, 2018; Marchi et al. 2019) and there is direct evidence for organic matter in patches found at Ernutet crater (De Sanctis et al. 2017). The latter appear to be dominated by aliphatic compounds with less than 30% oxygen-rich functional groups (De Sanctis et al. 2019). However, information is lacking about the nature of that material and whether it was accreted early on, processed inside Ceres, and/or formed in situ.

In the context of ROW's Assess Habitability goal, determining the inventory of organic compounds falls under the theme of understanding the "availability (chemical form and abundance) of the biogenic elements, how does it vary throughout the ocean and time, and what processes control that distribution?" (Hendrix et al. 2019). The intent is to assess the sources, sinks, and stability of organic compounds as potential feedstock for biochemistry and the cycles of major elements, including inorganic carbon in the liquid environment. For example, laboratory analyses of carbonaceous chondrites (CC) indicate soluble organic matter (SOM) tends to associate with the rock (Le Guillou et al. 2014), so that a large fraction of these compounds could be removed from the ocean environment following rock settling. More generally, the evolution of accreted organic matter and potential prospect for synthesis of new compounds on water-rich planetesimals are topics of major interest for understanding prebiotic systems (e.g., Vinogradoff et al. 2018). Future observations of Ceres' organic matter may be compared with organic compounds found in various carbonaceous chondrites (Vinogradoff et al. 2017) to quantify the change in the nature of abiotic organic compounds exposed to a long-lived deep ocean environment.

Organo-carbonate relationships in evaporites would reveal diverse conditions driving the fate of carbon in ocean worlds, with the possibility of organic synthesis (e.g., Fischer-Tropsch type) or, alternately, degradation of the organics in an oxidizing environment (e.g., McSween et al. 2018). Both aspects have critical implications for framing the habitability and astrobiology potential of ocean worlds. Testing if Fischer-Tropsch or other C1 reactions (e.g., electrochemical CO_2 reduction, etc.) occurred has critical implications regarding the production of hydrocarbons from accreted CO and CO_2. An important finding from the Dawn observations is that the two sites on Ceres that are sourced from the deep brine reservoir, the Occator faculae and Ahuna Mons, display abundant carbonate compounds with no evidence of organic matter at the spatial resolution of the Dawn infrared spectrometer (10 m and 100 m, respectively). This may indicate that organic matter has been degraded in the conditions of the residual brine, a hypothesis that has major implications for assessing the long-term habitability of ocean worlds.

These questions are addressed by studying organic compounds expected to be trapped in the evaporite and in Occator's dark floor material. In terrestrial soda lakes, which are suggested to be analogous environments to Ceres' brine region (Castillo-Rogez et al. 2020), organic matter is found in carbonates (e.g., Benzerara et al. 2006). The two salt clasts (Zag and Monahans) found in collected meteorites also trapped organic species and a variety of other compounds, including fluid inclusions (Zolensky et al. 2015; Chan et al. 2018) on spatial scales of a few tens of nanometers.

Objective 6: Determine Ceres' accretional environment

Ceres' surface displays ammoniated clays and salts (De Sanctis et al. 2015; Raponi et al. 2019) as well as a large abundance of carbon, both of which have been interpreted as evidence for an origin of Ceres' volatiles in the outer solar system (De Sanctis et al. 2015; Marchi et al. 2019; Zolotov 2020). However, the ammonia has also been suggested to come from the thermal metamorphism of organic matter (McSween et al. 2018). Nevertheless, the source region of Ceres' volatiles (e.g., Kuiper Belt vs. Jupiter-Neptune, e.g., Gomes et al. 2005; Raymond and Izidoro 2017) remains unknown. Furthermore, the pebble accretion mechanism could potentially add to a proto-Ceres that formed in the main belt by accreting icy materials originating in the outer solar system (Johansen et al. 2015).

Many objects may be of interest for testing the origin of water in the inner solar system. Main belt comets in particular are associated with icy asteroids that may have preserved pristine ice (Meech and Raymond 2020). The interest in using Ceres for origin science stems from its large size as it allows testing, e.g., if 1000-km large planetesimals were present early on within the orbit of the giant planets; if pebble accretion was indeed a major process in planetary formation; and if large Kuiper Belt objects could be scattered and captured in the main belt of asteroids. Lastly, a Ceres-sized chondritic object has been suggested as a major contributor to Earth's water (Budde et al. 2019) and as being potentially at the origin of a major impact at Mars whose ejecta reaccreted to form Mars' moons (Canup and Salmon 2019).

Signatures of origin are generally found in elements and isotopes of volatiles and certain minor elements (e.g., Warren 2011; Kruijer et al. 2017). An example of a trade addressed during this study is whether constraints on origins are better approached by measuring isotopic ratios of volatile elements (O, N, H, C), which could be accomplished in situ, or from minor species (e.g., Cr, Ti), which requires Earth laboratories. Concerns were raised about the likely fractionation of these volatile elements as a consequence of hydrothermal processes, and thus the erasure or alteration of the signature of origin, except maybe in the case of nitrogen (Li et al. 2009, 2012). On the other hand, the past decade has highlighted the significant information contained in minor elements such as ε^{50}Ti vs. ε^{54}Cr and Δ^{17}O ($\equiv\delta^{17}$O – 0.52 δ^{18}O) vs. ε^{54}Cr that highlighted the existence of separate reservoirs for carbonaceous chondrites and ordinary chondrites in the early solar system (e.g., Warren 2011). More generally, the theoretical framework for interpreting elemental and isotopic composition in terms of formation conditions in the solar nebula and the genetic relationships to the terrestrial planets is continually evolving. This drives the requirement to return a sample that can benefit from extensive analyses on minor species, whereas in situ measurements are necessarily limited in extent (see **Appendix B**).

1.3 SCIENCE TRACEABILITY

Objectives 1 and 2: The search for ongoing activity at young geological features calls for medium-resolution resolution imaging from orbit for comparison with images returned during the Dawn second extended mission (~5 m/px). The narrow angle camera (NAC) selected for landing site characterization can be used for this purpose. Gravity fields with local degree strength up to 50 (which corresponds to a resolution of ~25 km or better) over regions of interest can be used to connect surface features to subsurface sources. This is achieved with radio tracking from ~30 km altitude, as demonstrated during the Dawn XM2 (Park et al. 2020).

The remaining objectives require access to the surface. The focus on residual brines and organic matter led to the selection of the Vinalia Faculae, on the floor of Occator crater, as the baseline landing region (**Figure 1-2**). The main part of Vinalia Faculae extends over ~10 km and thus offers many possible accessible sites based on the 5 m/px images returned by the Dawn mission (**Appendix C**).

Objective 3: The magnetotelluric method is preferred, because joint measurement of electric and magnetic fields enables a complete sounding from a single station. Vinalia Faculae is hypothesized to overlay the deep brine region inferred from the Occator geology observations (Scully et al. 2020), which facilitates geophysical sounding. Modeling developed for this study (Grimm et al. 2020) shows that the response of brine in Ceres will be evident between 10^{-3} and 10 Hz. The ability to perform soundings over this frequency band can be determined from the joint signal-to-noise ratio of the magnetic and electric fields. The magnetometer and electrometer noise floors are taken from the Mars Atmosphere and Volatile EvolutioN (MAVEN) and Time History of Events and Macroscale Interactions During Substorms (THEMIS) missions, respectively. The electrometer noise improves with increasing measurement baseline and a 100-m deployment distance was specified and deemed feasible in the low-*g* Ceres environment, which yields 200-m baselines for a triangular configuration. Landed operations for 27 hours yield net SNRs >100.

Objective 4: Basic understanding of evaporites and rocky composition can be obtained with in situ analyses combining Raman spectroscopy or mass spectrometry, elemental spectroscopy (alpha particle induced X-ray and/or gamma-ray and neutron spectroscopy), and isotopic measurements (either mass spectrometry (MS) or tunable laser spectroscopy (TLS)). However, these techniques remain limited by their coarse spatial resolution (10s microns vs. 10s of nanometers required) and sensitivity to minor species. The context offered by medium-spatial resolution mapping of elements and isotope in a complex material is a major advantage of laboratory facilities over the bulk information obtained by in situ instruments.

Testable hypotheses driving the analyses include (**Figure 1-3**) [1] the existence of chemical gradient as a result of (1a) past/ongoing flux of oxidants from the mantle and (1b) concentration of certain radioisotopes (Altair et al. 2018; Castillo-Rogez et al. 2020). This is addressed via determination of the mineralogy (e.g., Castillo-Rogez et al. 2018), redox state of iron specie, and search for radioisotopes; [2] environmental conditions (projected ~245 K and pH ~7-11) via a combination of mineralogy and isotopic measurements, in particular the thermometer $^{18}O/^{16}O$; [3] the possible concentration of elements harmful to life (e.g., certain metals); and [4] rock composition for comparison with regolith composition inferred from the Dawn data. More generally, Earth-based analysis of evaporite samples would also yield the high-precision isotopic, elemental, and mineralogical observations required to fully comprehend the first-ever brine sample returned from a planetary body and address future questions that may arise as the scientific framework for ocean worlds keeps evolving.

Objective 5: Organic compounds can be investigated in situ with a combination of Raman spectroscopy or mass spectrometry, elemental spectroscopy (alpha particle induced X-ray and/or gamma-ray and neutron spectroscopy), and isotopic measurements (either MS or TLS). However, the perceived risk that organic compounds in bulk samples may be below detection limits for state-of-the-art in situ instrumentation drives the need for a returned sample (see details in **Appendix B**).

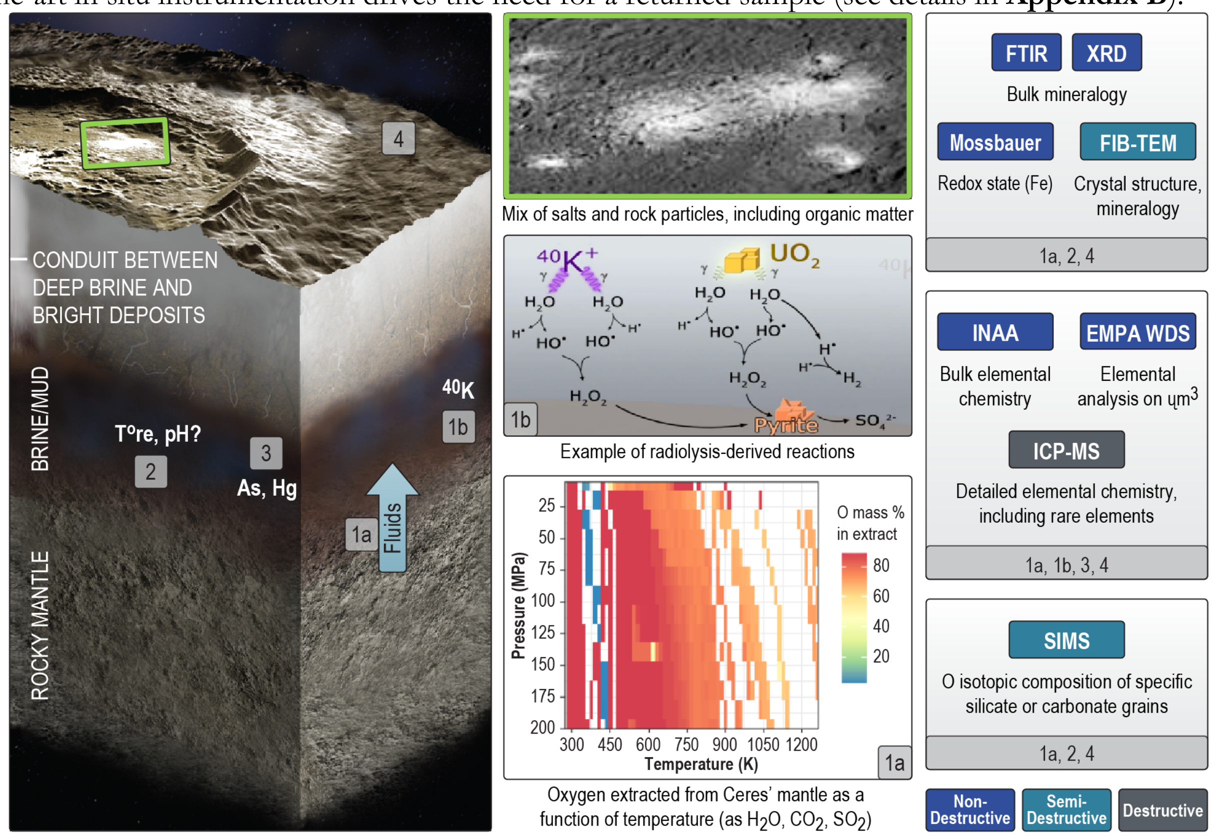


Figure 1-3. Characterization of Ceres' deep brine environment is addressed via a combination of elemental and mineralogical measurements and mapping of phase relationships. Possible techniques (among many others) are presented here: Fourier transform infrared (FTIR) spectroscopy and X-ray diffraction (XRD) for bulk identification of mineralogy; instrumental neutron activation analysis (INAA) for bulk elemental chemistry followed by inductively coupled plasma mass spectrometry (ICP-MS) for a more complete set of elements; electron microbe wavelength dispersive spectroscopy analyses (EMPA WDS for chemistry) and fast ion beam – transmission electron microscopy (FIB-TEM for crystal structure/mineral identification) for detailed phase relationships; secondary-ion mass spectrometry (SIMS) for isotopic measurements on, e.g., carbonate oxygen. Number refers to testable hypotheses mentioned in the text. Left: Ceres cutaway produced by Raoul Ranoa; Middle, top: NASA/JPL Caltech/ UCLA/ MPS/ DLR/IDA, middle: Altair et al. (2018), bottom: numerical modeling by Mohit Melwani Daswani (JPL).

Earth-based analysis of evaporite samples would also yield the high-precision isotopic, elemental, and mineralogical observations required to meet this objective. Constraints on the origin of the organics can be achieved via isotopic ratios, esp. $^{13}C/^{12}C$ and testing their degree of maturation (e.g., H/C). The relationship between the organics and the salts, in particular the carbonates, can be addressed via various high-resolution phase mapping techniques available only in Earth's labs (see also **Objective 4**). A model of our approach is the comprehensive analyses performed by Chan et al. (2018) on the Zag clast (**Figure 1-4**).

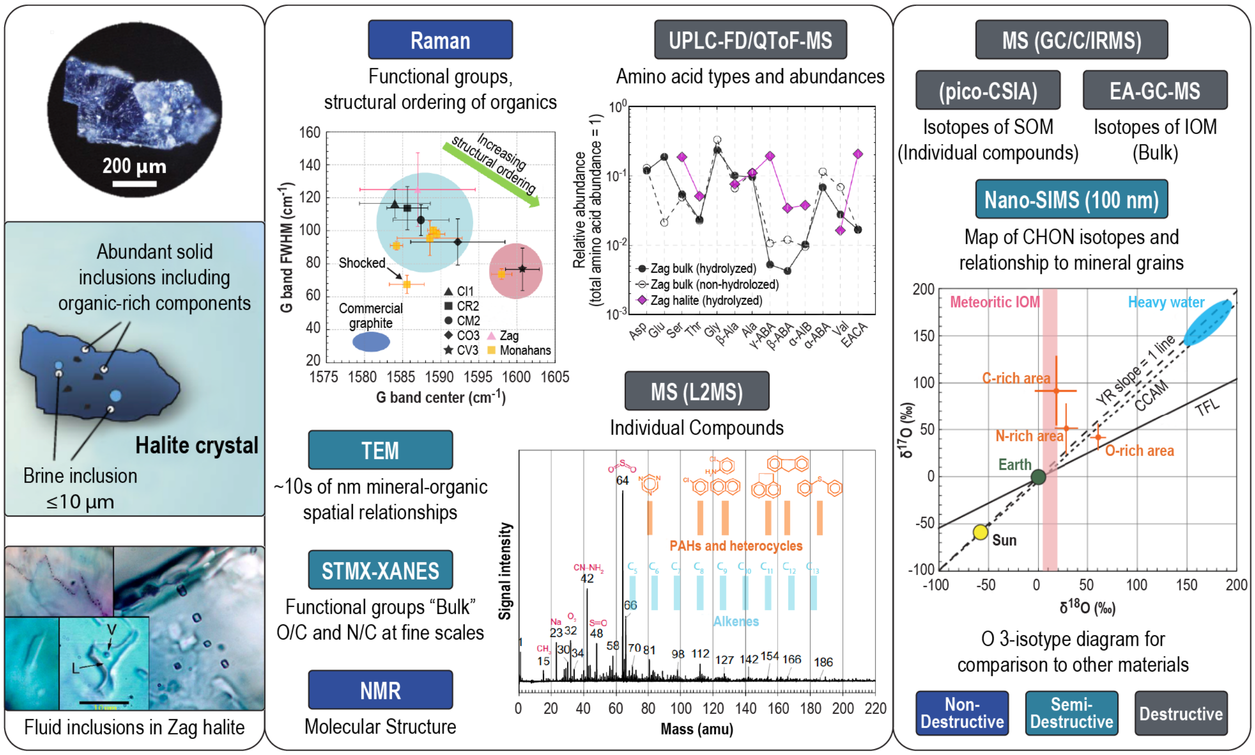


Figure 1-4. Characterization of organic matter that has been sitting in long-lived brines is addressed by a combination of elemental measurement, SOM and IOM characterization and relationships to minerals, and isotopic composition of C,H,O,N. Raman spectroscopy to identify functional groups, nano-SIMS for spatial distribution of C,H,O,N isotopes and relationship to mineral grains, transmission electron microscopy (TEM) for fine-scale (~10s of nanometers) mineral-organic spatial relationships and mineral identification, C, N, and O X-ray absorption near edge structure (XANES) for identification of organic functional groups and "bulk" O/C and N/C at fine scales; laser desorption laser ionization MS (L2MS) for identification of individual compounds; ultra-performance liquid chromatography fluorescence detection and quadrupole time-of-flight hybrid mass spectrometry (UPLC-FD/QToF-MS) for amino-acids; for IOM isotopes, demineralization followed by elemental analyzer (EA) GC-MS (C+N) and thermal conversion EA-GC-MS; for compound specific isotopic composition of soluble organics, GC-combustion -isotope ratio MS (GC/C/IRMS) or picomolar-scale compound-specific isotope analyses (pico-CSIA). Figures: Chan et al. (2018).

Objective 6: The isotopes necessary for this investigation require access to Earth-grade analytical facilities. Furthermore, origin science is an evolving field both in terms of the theoretical framework that isotopic and elemental ratios are compared against and in terms of finding the most informative combination of isotopic and elemental data (**Figure 1-5**). Hence, a sample return from Ceres' surface is required for this investigation to be successful.

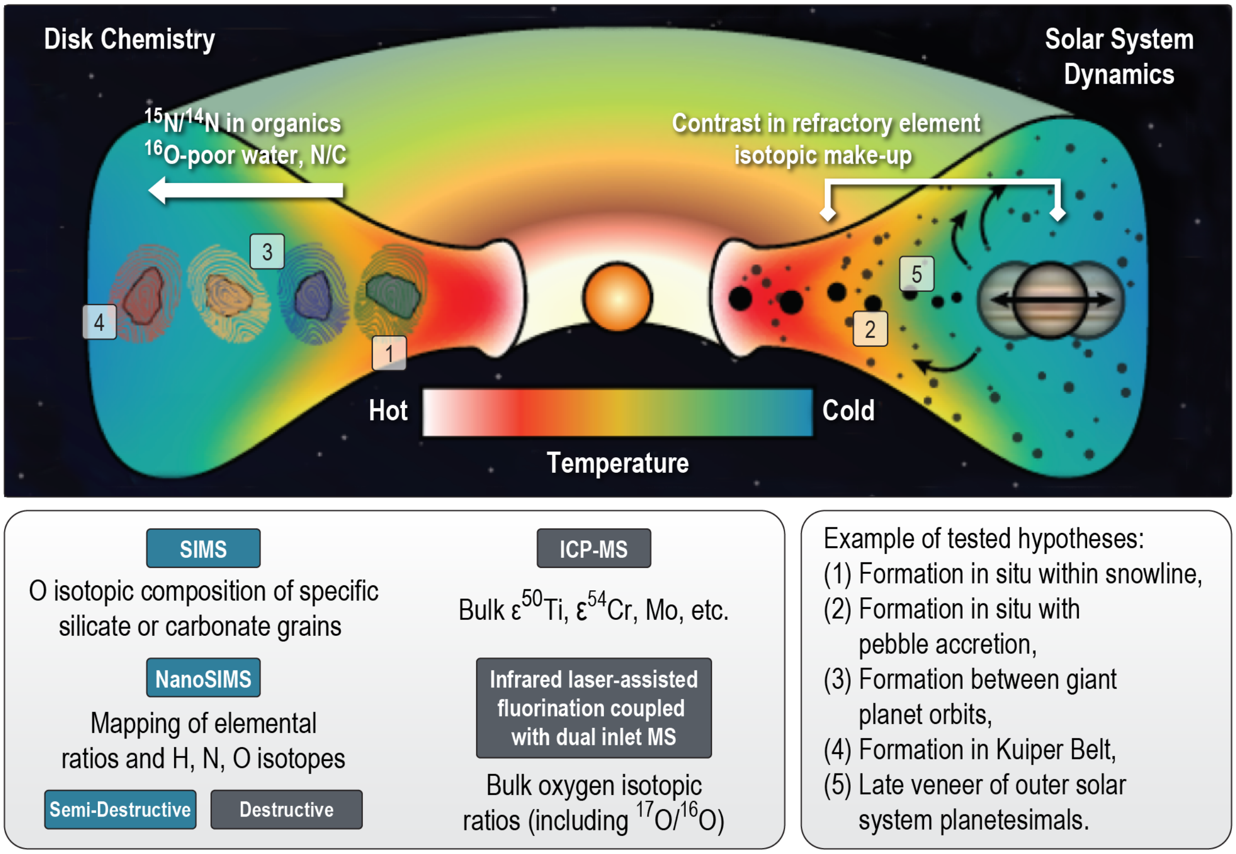


Figure 1-5. Hypotheses on the origin of Ceres can be tested by combining elemental ratios of light and heavy isotopes such as bulk $\varepsilon^{50}Ti$ and $\varepsilon^{54}Cr$ via multiple collection ICP-MS, bulk oxygen isotopic ratios (including calculation of $\Delta^{17}O$) with infrared laser-assisted fluorination coupled with dual inlet MS, secondary-ion mass spectrometry (SIMS) for O isotopic composition of specific silicate or carbonate grains, nano-SIMS for in situ analysis of, e.g., H, N, and O isotopic distribution. Figure courtesy of Karen Meech.

SUMMARY: A sample return of both the dark floor material forming the regolith and evaporites (i.e., bright material from Vinalia Faculae) in Occator crater would enable the investigation of Ceres' materials using the next generation of Earth-based analytical facilities. This report focuses on this science implementation option. An alternative option that utilizes an in situ payload only is also presented in Appendix B for consideration by the Decadal Survey committee.

At this point, we know of no other currently advocated ocean world sample return mission that would return a ~100 g sample acquired under nearly pristine conditions and preserved at cold temperatures (≤-20 deg C required) until Earth return. For comparison, a sample return from Enceladus' plume would return <1 g of material (Tsou et al. 2012). A ~100 g sample would enable the Planetary Science and Astrobiology community to take full advantage of the sample return curation and analysis capabilities currently being built up for Mars Sample Return, OSIRIS-Rex, MMX, and Artemis samples from the Moon, placing Ceres Sample Return in series with a long line of planned sample return missions NASA is involved in. A sample of this size would enable analyses to benefit from improved capabilities developed in the future.

Table 1-2. Science Traceability Matrix. The overarching goals of this concept are to (1) assess Ceres' current habitability and use Ceres as a test case for determining the habitability of volatile-rich bodies over time (Objectives 1-5); and (2) determine Ceres' origin and the relationship of its volatiles and organics to other inner solar system bodies (**Objective 6**.)

Science Objective	Measurement	Instrument Requirements	Functional Requirements
O1. Test if extrusion from a brine-rich mantle occurred during Ceres' recent history. Addresses the "Energy Sources" and "Chemical Gradients" objectives in ROW (**Fig. 1-1**).	• Imaging in the visible and 2 color filters with a spatial resolution <5 m/px to search for geological structure (exploratory) • Spacecraft acceleration via Doppler shift at 25 km half wavelength	• Narrow angle camera with two color filters (plus clear), e.g., 450±20 nm (blue) and 850±20 nm (red), iFOV of 10 µrad • Telecom subsystem (X-band); no additional hardware required • DSN Doppler accuracy: ≤0.1 mm/s for 60 s integration time • Transponder stability $\leq 10^{-13}$ at 1000 sec	• Polar orbit from < 500 km for imaging • 14 Gb • Polar orbit from altitude <30 km for radio science; two-way coherent Doppler tracking • Successive passes offset by ~1° to map targets of interest • Target Occator, Haulani craters; Ahuna Mons, Cosecha Tholus; expand over 20 to 300 km
O2. Test if endogenic activity is ongoing at Occator crater Addresses the "Energy Sources" and "Chemical Gradients" objectives in ROW.	• Imaging in the visible and 2 color filters with a spatial resolution <5 m/px for comparison with images returned by the Dawn mission	• Narrow angle camera with two color filters (plus clear), e.g., 450±20 nm (blue) and 850±20 nm (red), iFOV of 10 µrad	• Observe Occator crater from polar orbit from <500 km • 3 Gb (2 Gb of visible imaging included above)
O3. Determine the depth of liquid water below Occator crater Addresses the "Rock/Ocean Interface" and "Chemical Gradients" objectives in ROW.	• Electrical conductivity to >50 km depth (brine expected from 35 km depth)	• Electric field (electrodes) 1 µV/m, magnetic field (magnetometer) 0.1 nT (Magnetotelluric method)	• Deploy at Vinalia Faculae • Integrate for 50 h (27 h required + margin) • Data volume: 600 Mbit
O4. Characterize Ceres' deep brine environment at Occator crater Addresses the "Solvents", "Chemical Gradients" and "Physico-Chemical Conditions for Life" objectives in ROW.	• High-precision (<1%) and spatial resolution (submicron) mineralogy, including phase relationship mapping between minerals • Spatially resolved elemental composition • Spatially resolved C, H, O, N, isotopic composition	**Mineralogy – See Figures 1-3, 1-4, 1-5** • X-ray diffraction, Mössbauer spectroscopy • Raman spectroscopy with spatial resolution < 10 nm **Elemental Composition** • XANES and carbon-XANES • INAA **Organic Compounds** • Nuclear magnetic resonance spectroscopy • Amino-acid analysis, UPLC-FD/QtoF-MS • EA-GC-MS, pico-CSIA **Isotopes** • Mass spectrometry (various techniques depending on the material) • NanoSIMS • ICP-MS All three objectives require visible and in situ infrared imaging of the landing site for context and to assess the level of hydration of the material prior to its dehydration during return to Earth.	• Sample a mixture of bright (evaporite) and dark material at Vinalia Faculae • Sampling of surficial material • Sample mass: 100 g, driven by the use of destructive analysis techniques (10s mg an up to 1 g of sample per analysis) • Particulate contamination control to ISO 5 and non-volatile organic residue limited to level A/2; return at ≤-20°C to prevent water vapor release that would drive salt deliquescence and potential aqueous alteration of anhydrous in the sample return capsule (SRC) • No requirement to preserve the stratification of the sample • Prevent atmospheric leakage into the SRC during and after Earth entry until SRC recovery; Maintain internal pressure $<10^{-7}$ torr after SRC closure through SRC recovery • Storage at <-80°C • See **Figure 3-3** for sample processing flow chart
O5. Characterize the evolution of organic matter in long-lived ocean Addresses the "Inventory of Organic Compounds" as environmental markers and potential feedstock in ROW	• Elemental composition and nature and quantification of organic compounds and relationship to minerals (submicron scale) • Isotopic composition of C, N, O, H with accuracy and precision <1%		
O6. Determine Ceres' accretional environment Addresses the connection between Ceres, icy moons, and/or dwarf planets and puts the results of Objectives 1-5 in greater context.	• Elemental and isotopic ratios of volatile elements (e.g., H, N, O) and refractory minor species (e.g., ε^{50}Ti vs. ε^{54}Cr and Δ^{17}O vs. ε^{54}Cr) with <1% accuracy and precision		

2 HIGH-LEVEL MISSION CONCEPT

2.1 OVERVIEW

The total ΔV for a round-trip sample return mission Ceres is approximately 14 km/s, which could be achieved through the use of solar electric propulsion (SEP). In comparison, the ion propulsion system on the Dawn mission provided a total ΔV of 11.5 km/s. An additional 600 m/s would be required to land on and take off from the surface of Ceres. A monopropellant hydrazine propulsion system would be adequate for this. An example roundtrip, low-thrust trajectory is given in **Figure 2-1** for a December 2030 launch. The use of SEP would enable a launch any year from 2030 through 2037 with little change in the flight time, launch mass, and propellant mass. The total flight time would be about 13 years including a 500-day stay time at Ceres.

The sample return mission concept was developed to Concept Maturity Level (CML) 4 resulting in a detailed Master Equipment List (MEL), concept of operations, and driving power modes. Detailed low-thrust trajectory analyses were used determine the required solar array size and electric thruster type. Deorbit, descent, and landing analyses were used to determine the amount of hydrazine propellent needed to land in Occator crater. Similar analyses were performed to determine the propellent required to return to Ceres orbit. A single flight element, referred to as the SEP-lander, shown in **Figure 2-2** would be used to perform these functions.

The mission would begin with the launch on a high-performance launch vehicle with a 5 m fairing. The performance of the Falcon Heavy recoverable launch vehicle was used in the trajectory analyses. The spacecraft would be launched from Kennedy Space Center (KSC) to a C3 of approximately 13.4 km^2/s^2. Most of the 500 days at Ceres would be spent in orbit, identifying and characterizing landing sites as part of the landing site selection process and performing orbital science.

The solar arrays would be retracted and stowed for landing. A throttleable hydrazine propulsion subsystem would be used to deorbit the spacecraft from a 28 km-altitude orbit and land in Occator crater at the Vinalia Faculae. An enhanced lander vision system would be used to provide altimetry, velocimetry, and terrain relative navigation to guide the spacecraft to the preselected safe landing site. The solar arrays would be redeployed after landing providing ample energy over the course of each Ceres day to operate the flight system on the surface. The solar arrays would have a second axis of articulation that increases the clearance between the solar array wings and the surface after deployment as suggested in **Figure 2-2**.

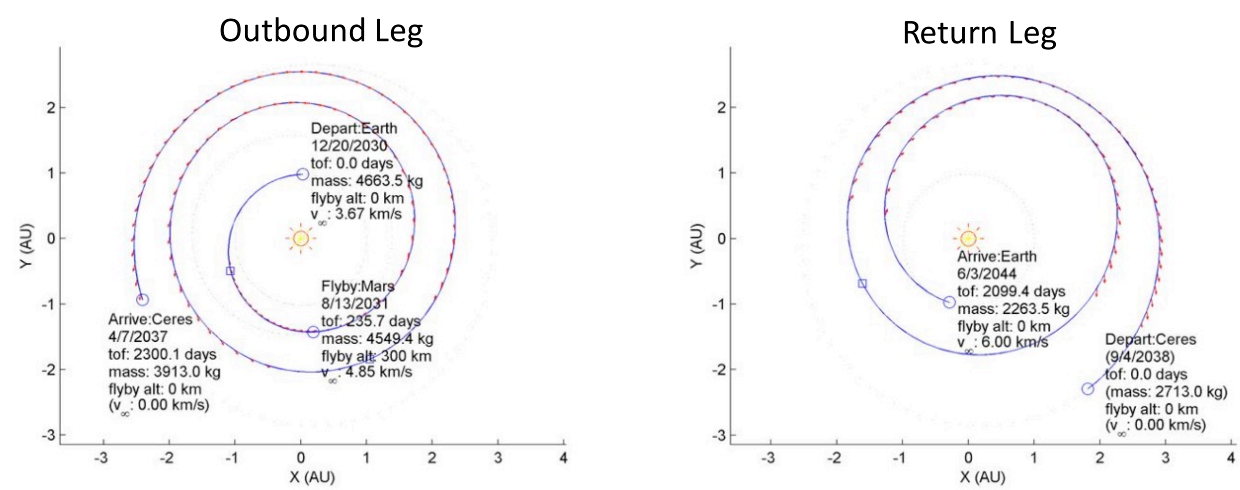


Figure 2-1. Example trajectory for the outbound and return cruise phases for a 2030 launch. With SEP, sample return missions can be launched in any year from 2030 through 2037 with little change in performance. For example, a 2033 launch decreases the total flight time from 12.8 years to 12.6 years and increases the Earth arrival mass from 2264 kg to 2269 kg. A Mars gravity assist flyby and stay time of 500 days at Ceres are included in all cases.

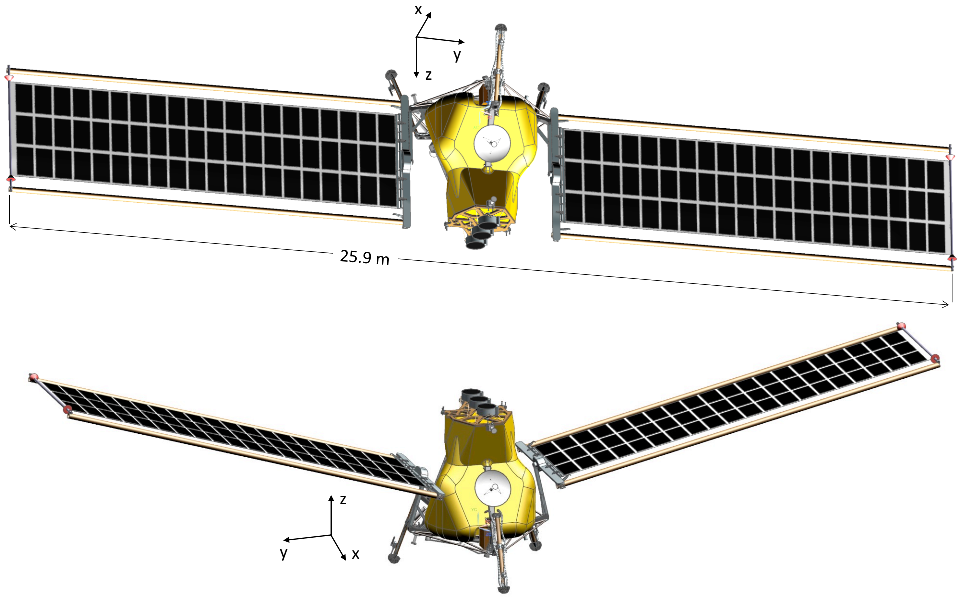


Figure 2-2. The SEP-lander spacecraft in the cruise configuration (top) and the landed configuration (bottom). In the cruise configuration the solar arrays are articulated about the y-axis to track the Sun during thrusting with the electric propulsion system. A second axis of articulation about the x-axis reduces the risk of the arrays contacting objects on the surface of Ceres in the landed configuration.

A sample acquisition system derived from that being developed for the JAXA MMX sample return mission would be used to collect material from the surface. There would be one sampling system in each of the three lander legs for robustness. Each sampling system would pneumatically deliver the acquired samples directly to the sample return capsule (SRC). Sampling would be verified optically during sample collection.

After successful sample acquisition, the solar arrays would be retracted and stowed a second time for takeoff. The hydrazine propulsion system would take the vehicle off from the surface and to return it to a 28 km-altitude Ceres orbit. Once back in orbit the solar arrays would be re-deployed for the third and final time. The SEP system would be used to depart from Ceres orbit and perform the heliocentric transfer back to Earth. The trajectory would be designed to release the sample return capsule with a hyperbolic excess velocity (V_∞) of ≤6 km/s and target landing at the Utah Test and Training Range (UTTR). After release of the SRC, the spacecraft would perform a divert maneuver. The SRC would be recovered at UTTR and the samples transferred to the Astromaterials Acquisition and Curation facility at Johnson Space Center (JSC).

The sample acquisition system would utilize the pneumatic *PlanetVac* technologies (**Figure 2-3**) for collection of materials from the surface of Ceres and for transfer to the SRC for return to Earth. Since the material was recently exposed, it has been subjected to little space weathering and micrometeorite contamination. Hence, there is no requirement to sample below the surface to access fresh material.

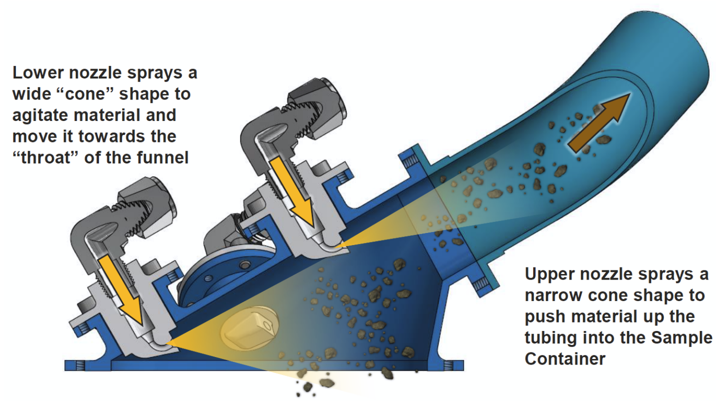


Figure 2-3. Example "PlanetVac" type sampler. Compressed gas is used to lift loose surface material and transport through a long tube leading to the Sample Canister in the SRC.

This system would use gas flow sourced from a compressed gas cylinder

(N_2) to move grains for both collection and transport from the Ceres surface to the SRC. The sampler for a conceptual Ceres sample return mission is derived from TRL 6 *PlanetVac* systems developed for multiple atmosphere-free planetary body applications (Zacny et al. 2020) including the JAXA MMX mission NASA sampler contribution. The pneumatic sampler would be augmented with a drill or other device to mechanically break apart the surface for increased robustness to a wide range of ground strengths.

The configuration of the conceptual Sample Chain elements is illustrated in **Figure 2-4**. Key aspects include: *PlanetVac* sampler heads integrated into each of the three lander footpads in a fixed location; debris deflection shields to direct sampling induced debris on a ballistic path away from the spacecraft; pneumatic transfer tubes to carry the sample to the sample canister located in the *SRC;* and the *SRC* pneumatic tube separations mechanism. Protection from contaminants during the outbound cruise is provided by ejectable contamination covers over the sampler collection heads.

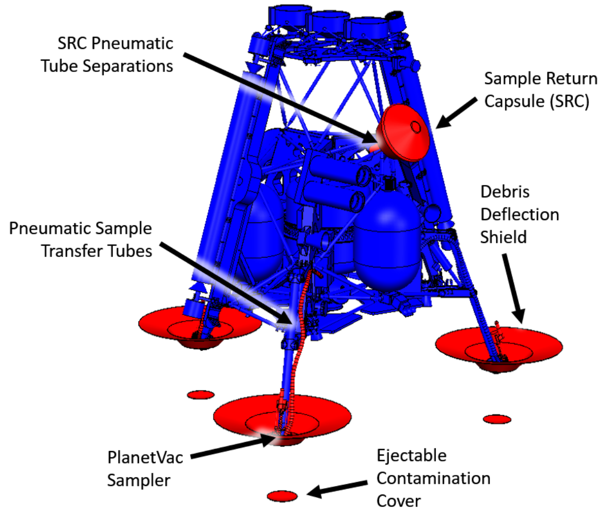


Figure 2-4. Sample Chain elements shown in red color.

2.2 SAMPLE RETURN CAPSULE

The SRC assumes the same capability as that used successfully on Stardust and Orex. Internal modifications would be made for the delivery of the sample material to the SRC and to maintain the samples in the desired environment for delivery all the way to UTTR. The SRC includes an aeroshell with ablative thermal protection system (TPS), a backshell, avionics, and the mechanisms to close and seal the sample delivery tubes. The SRC would be a passive, spin-stabilized capsule that would use a parachute system to land. A future trade study could examine the pros and cons of a landing approach that does not use a parachute. A mechanism mounted on the spacecraft bus would generate the required spin and separation rates. A preliminary assessment by NASA Langley has confirmed that the reentry conditions targeted by the low-thrust trajectories would result in stress and thermal loads within the capability of the Stardust SRC (White 2020).

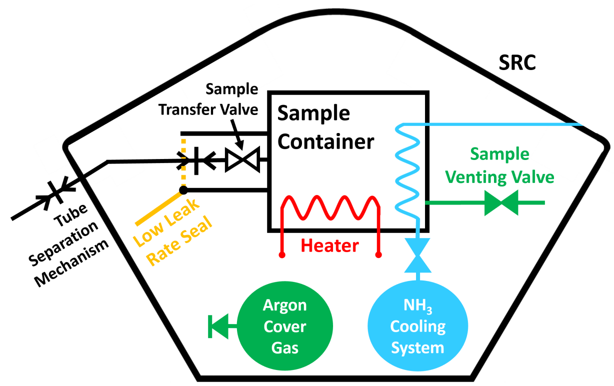


Figure 2-5. Conceptual SRC sample containment system architecture.

Function requirements for the *Sample Canister* are shown in **Table 2-1**. An approach to meeting these requirements using sample canister technologies of TRL 6-9 was identified that employs three main elements: argon cover gas; an ammonia cooling system via compressed gas expansion; and a low leakage rate seal that maintains internal pressure requirements during Earth entry and recovery. A diagram of this conceptual sample containment system architecture is given in **Figure 2-5**.

Table 2-1. Sample Container Functional Requirements

Sample Canister
Hold up to sample mass of: 200 g (100 g and 100% margin)
Particulate contamination control to >ISO 5 and non-volatile organic residue limited to level A/2
Return at ≤-20°C to prevent reaction between anhydrous material and liquid water in the spacecraft.
Prevent atmospheric leakage into the SRC during and after Earth entry until SRC recovery;
Maintain internal pressure < 10^{-7} torr after SRC closure through SRC recover

After the sample is delivered by the *PlanetVac* to the singular *Sample Container* located in the *SRC*, the *Sample Transfer Valve* is closed. Once the last sample attempt is completed, the pneumatic transfer system is separated from the SRC exterior via a *Tube Separation Mechanism*. Within the *SRC*, the sample transfer system is also separated from the *Sample Container*, and a *Low Leakage Rate Seal* is formed around the sample-side disconnect. The sealing system is TRL 6 technology from the TRL 6 CAESAR New Frontiers comet sample return mission concept (Zacny, 2016) and is capable of slowing the rate of sample pressure rise when in Earth atmosphere for the duration of entry/recovery.

An *Argon Cover Gas* is used to maintain positive pressure in the volume between the sealed sample container and the outer SRC walls, preventing atmospheric contamination. The cover gas is derived from SRC sample return technology heritage (Choukroun et al. 2017).

To prevent aqueous alteration the sample is maintained at -20 C early in the return cruise phase to sublimate and vent volatiles to space, then the sample is passively to cool to <-35 C for the remainder of cruise. Just before Earth entry, the Sample Venting Valve is closed, both the Ammonia Cooling System and Argon Cover Gas systems are initiated. The sample is actively cooled and maintained at approximately -35 C preventing sublimation and aqueous alteration while the Sample Venting Valve is closed during Earth entry/recovery. These systems provide at least 6 hours of both cooling and pressure maintenance of $<10^{-7}$ torr, to support recovery operations. The cooling approach is derived from TRL 9 technology from the Orion spacecraft.

The organization for mission implementation (Phases A-D) assumes the spacecraft and SRC are provided by industrial partners under contract to JPL and separate organizations provide each of the three instruments and the sample acquisition system. The provider of the sample return capsule may or may not be the same as the spacecraft provider.

For Phase E the organization, in addition to the PI, project manager, mission manager, and chief engineer, includes phase leads, the science team, the navigation team, the spacecraft operations team, the ground data system operations team, the science data system operations team, the instrument operations team, and the curation team at Johnson Space Center. The spacecraft operations team is staffed primarily with representatives from the spacecraft provider.

2.3 TECHNOLOGY MATURITY

This concept includes one instrument currently at Technology Readiness Level (TRL) 5: the magnetotelluric sounder. A relevant product is being developed under NASA's Lunar Surface Instrument and Technology Payload at the Southwest Research Institute and also leverages development performed under the Instrument Concepts for Europa Exploration (ICEE-2) program. This instrument is expected to reach TRL 6 by 2021 before flight on one of the Commercial Lunar Payload Services (CLPS) (Task Order 19D). Since the instrument is low complexity and its maturation is funded with a path to flight, its TRL 5 at present is considered low risk for a New Frontiers 6 announcement of opportunity. All other instruments are at TRL 6 or above.

The spacecraft includes just one new technology, the retractable/redeployable solar array. **Appendix D** provides a TRL assessment flow chart from Hirshorn and Jefferies (2016) and Frerking and Beauchamp (2016) indicating that, even though this technology has been successfully demonstrated on the International Space Station, it is still considered a new technology for the intended use on the Ceres sample return mission. In addition, **Appendix D** provides assessments of the PlanetVac-derived sample acquisition system and the sample transfer system that sits between the PlanetVac and the SRC, indicating that both of these are considered engineering developments as opposed to new technologies.

The retractable/redeployable solar array is based on the Roll-Out Solar Array (ROSA) tested on the international space station in 2017. In this flight test, the ROSA was successfully deployed and retracted three times. The version of ROSA needed for the Ceres sampler return mission is a new technology according to the flow chart in **Appendix D** because the retractable/redeployable capability has not been used operationally and the environments that it will see for the Ceres sample return mission are sufficiently different that they are not bounded by the currently demonstrated capability. Specifically, these new environments include long-duration use (~6 years) in deep space before the first retraction, deployment in the $1/35^{th}$ *g* environment on the surface of Ceres, and retraction on the surface and redeployment in orbit after numerous Ceres day/night cycles. The solar array technology is assessed to be at TRL 5. The vendor ROM mass and cost inputs include the fabrication and test of an electromagnetic (EM) unit (partially populated with active solar cells). The development program will demonstrate the capability for multiple reliable deployment, retraction, and re-deployment events (in 0 *g* and in 0.028 *g* on Ceres).

2.4 KEY TRADES

The key trades performed to develop the mission concept are listed in **Table 2-2**. All the major trades have been closed in order to drive to a point design necessary for the generation of a MEL and configuration for costing. The study team recognizes that the conclusions identified in **Table 2-2** do not represent the only possible way do accomplish this mission. It is quite possible that other teams evaluating the same trades would come to different conclusions. **Table 2-3** discusses the trades that were closed, but would be revisited in a subsequent study.

Table 2-2. Key trades.

Key Trades Performed	Outcome	Rationale
Selection of scientific site (among 5 downselected)	Occator crater evaporite (Vinalia Faculae)	Occator crater display freshly exposed evaporites, which offer direct insights into the habitability of Ceres' residual ocean and would allow testing the occurrence of a number of processes predicted to take place in ocean worlds. [See **Appendix B** for additional information]
Sample return vs. in situ exploration	Sample return option preferred	Sample return enables searching for minor phases, including organic compounds, that may not be detectable with state-of-the-art in situ instruments, along with some in situ science for sample context characterization. [See **Appendix B** for additional information]
Single SEP-lander spacecraft vs Orbiter + Lander	Single SEP-lander spacecraft	Single spacecraft expected to be lower cost than two major flight elements.
Sample acquisition via legs vs. Deployable arm	Acquisition via legs	Sampling at discrete leg locations has less operational complexity than sampling from a deployed arm and would collect the necessary amount of material from the assumed weak surface. Collecting sample from locations other than the lander footpads would not be necessary to achieve science goals.
Deployment of solar arrays on Ceres' surface vs. batteries	Deployment of solar arrays	Surface operations on battery power severely limits the operational duration, increasing risk in an unfamiliar environment.
Transportation to Ceres: SEP vs. biprop. Vs monoprop vs. solid rocket motor	SEP	Sample return mission requires a delta-V of ~14 km/s. In situ mission requires a delta-V of ~7 km/s. Chemical, near-ballistic trajectories to Ceres are possible, but require flight times of approximately 10 years to deliver sufficient mass. Such long trip times negate the idea that Ceres is the most accessible candidate ocean world.
SEP thruster type: gridded ion thruster vs. Hall thruster	Gridded ion thruster	The ~14 km/s delta-V required for the sample return option requires gridded ion thrusters to keep the total propellant mass to a manageable level. Both Hall thrusters and gridded ion thrusters could be used for the one-way in situ mission.
Propulsion for landing: pulsed vs. throttleable	Throttleable	Pulsed operation may require an expensive testbed for validation.
eLVS vs. radar vs. light detection and ranging (LIDAR)	eLVS	The enhanced lander vision system (eLVS) is the lowest cost solution.
Solar power vs. radioisotope thermoelectric generator (RTG)	RTG	RTG-power lander is power-poor relative to large solar arrays. Still have to carry large solar arrays for SEP transportation.
Direct entry at Ceres vs. orbit first	Orbit first	SEP transportation provides an orbit-first capability for very little cost. Direct entry from a ballistic trajectory adds considerable risk for safe landing in a scientifically interesting location.
Solar array for landing/ takeoff: retractable vs. repositionable	Retractable	Retractable ROSA demonstrated on the International Space Station (ISS) and is believed to represent a lower risk than keeping large solar arrays deployed even if they are repositioned into a more favorable configuration for landing and takeoff.

Table 2-3. Outstanding trades.

Outstanding Trades	Pros	Cons	Path to Resolution
Landing thruster location	Locating them at the bottom of the S/C reduces plume interactions with the S/C. Locating them higher up on the S/C reduces plume interactions with the surface.	Locating them at the bottom increases plume interactions with the surface during landing. Locating higher up on the spacecraft makes it more difficult to avoid plume impingement on the S/C.	Rework spacecraft configuration to determine if the landing thrusters can be positioned near the top of the spacecraft without significant plume impingement on the vehicle.
Landing drop altitude	Dropping from higher altitudes reduces landing thruster plume interactions with the surface.	Dropping from higher altitudes increases the landing kinetic energy.	Determine maximum landing energy that the vehicle can tolerate. Perform detailed landing simulations with error propagation to determine range of landing energies vs nominal drop altitude.

Summary of Science Trades (Appendix B)

For a similar cost and risk, a sample return from the Occator evaporites was deemed of greater scientific merit than an in situ mission targeting two sites. Both missions would capture **Objectives 1-2** in orbit and **Objective 3** in situ. On top of this, the sample return would both quantify the habitability of Ceres' brines and inform the fate of organic matter in ocean worlds (**Objectives 4** and **5**). It would also enable long-term research on minor species and isotopes to determine the accretional environment of Ceres (**Objectives 6**). The in situ only mission concept would address **Objective 4** but would not provide the spatial resolution and sensitivity required to characterize organic matter trapped in evaporite grains. It would also investigate a limited set of isotopes (volatiles only) that would allow only limited comparison with the volatile isotopic make-up of meteorites. However, a lander equipped with hopping capability could investigate a second site, for example the Northeastern ejecta region of Occator crater (Homowo Regio) made of crustal material and bring additional information on Ceres' early oceanic environment and organic matter.

3 TECHNICAL OVERVIEW

3.1 INSTRUMENT PAYLOAD DESCRIPTION

The strawman payload includes a narrow-angle camera for medium- and high-resolution imaging of geological landmarks and for landing site contextual characterization and certification prior to landing. The spacecraft includes body-mounted context cameras for characterization of the landing site following landing. These are considered engineering cameras, included under the flight system. The landed phase uses an in situ infrared spectrometer for characterization of the sampled material, in particular to quantify its degree of hydration prior to return to Earth.

The second instrument used in situ and the main in situ science investigation is a combination of magnetometer and electrodes. All three instruments are based off TRL 5-6 products. The telecom subsystem is also used for gravity science observations (**Objective 1**) without any additional hardware required.

These instruments would be used during different phases of the mission. The NAC would be used during the orbital phase, in tandem with gravity science measurements. The point spectrometer would be used in situ prior to the sampling phase, and the electromagnetic sounding experiment would deploy after the sample has been acquired and needs to integrate for five Ceres days. The electrodes and magnetometer would be detached before take-off.

Table 3-1. Narrow angle camera characteristics.

Item	Value	Units
Type of instrument	Visible camera × 2 (block redundancy) with Sequence and Compression System (SCS)	
Number of channels	1 + 2 color filters	
Size/dimensions (for each instrument)	0.7 × 0.27 (dia) 0.17 × 0.11 × 0.45	m × m
Instrument mass without contingency (CBE*)	8.2 + 1.2 (SCS)	Kg
Instrument mass contingency	10%	%
Instrument mass with contingency (CBE + Reserve)	10.3 (total)	Kg
Instrument average payload power without contingency	6.4 + 4.0 (SCS)	W
Instrument average payload power contingency	10%	%
Instrument average payload power with contingency	11.44 (total)	W
Instrument average science data rate**	Pixel format: 1 × 5,064	kbps
Instrument fields of view	2.85	deg.
Pointing requirements (knowledge)	0.1	deg.
Pointing requirements (control)	0.1	deg.
Pointing requirements (stability)	0.46	deg/sec

**CBE = Current Best Estimate*
***Instrument data rate defined as science data rate prior to onboard processing*

3.1.1 NARROW-ANGLE CAMERA

The reference model is the narrow-angle camera (**Table 3-1**) on the Lunar Reconnaissance Orbiter developed by Malin Space Science Systems. This NAC provides imaging with an instantaneous field of view (FOV) of 10 μrad, or a pixel scale of 1 m from 100 km altitude. It was chosen because of its time-delay integration capability, which is necessary to achieve the imaging requirements under the high (~500 m/s) relative velocity of the spacecraft to Ceres' surface.

This instrument is at TRL 9 but should be augmented with color filters as part of the change detection campaign for Objective 2. It is also used for navigation; hence a duplicate is included for redundancy (the copy falls under the flight system). The NAC would be radiometrically and geometrically calibrated on the ground, during cruise using reference stars, and once again prior to data acquisition at Ceres.

The NAC includes a sequence and compression system for data processing prior to data transfer to the spacecraft command and data handling (C&DH). The analysis of images returned to the ground is low complexity and consists in regular orthocorrection. Images are used in different types of high-level (L3) products: color maps (**Objective 1**), topography maps for landing site certification. Topography maps are produced via stereo imaging using images acquired under five different phase angles, building on the approach applied by the Dawn mission (Raymond et al. 2011; Park et al. 2019). The total data volume for orbital imaging breaks down to: 1 Gb (color images) and 14 Gb (panchromatic imaging for topography) for **Objectives 1 and 2** and 24 Gb for landing site reconnaissance.

3.1.2 INFRARED POINT SPECTROMETER

This instrument (**Table 3-2**) covers the range 2–4 micron that encompasses carbonate, organic functions, and water signatures. Its spectral resolution of 10 nm adequate for the resolution of the various forms taken by water (hydration, hydroxyl).

This instrument is based on a new generation of low-mass, low-power infrared spectrometer (IRS) developed for CubeSat/smallsat applications and is costed as a Class B instrument. The version considered here is based on a line of IRS developed at JPL that benefits from miniaturized electronics. The IRS is body mounted and would be used to characterize the landing site. It requires a cryocooler to keep the focal plane array at <100 K. The cryocooler is turned on for four hours prior to data acquisition. Deployable covers are included in the design in order to prevent optics contamination upon landing.

Table 3-2. Infrared point spectrometer characteristics.

Item	Value	Units
Type of instrument	Point spectrometer	
Number of channels	200 (10 nm spectral resolution)	
Size/dimensions (for each instrument)	0.2 × 0.1 (dia)	m × m
Instrument mass without contingency (CBE*)	2	Kg
Instrument mass contingency	30	%
Instrument mass with contingency (CBE + Reserve)	2.6	Kg
Instrument average payload power without contingency	6	W
Instrument average payload power contingency	30	%
Instrument average payload power with contingency	7.8	W
Instrument average science data rate**	2.4	kbps
Instrument fields of view	0.2	degrees
Pointing requirements (knowledge)	0.05	degrees
Pointing requirements (control)	1	degrees
Pointing requirements (stability)	0.1	deg/sec

**CBE = Current Best Estimate*
***Instrument data rate defined as science data rate prior to onboard processing*

The data returned is in the form of a spectral cube. The instrument does not include any flight software. Only a few images are needed to characterize the working space, obtained at different times of the day for an estimated total of 6 Gb. Data analysis is low complexity and relies on spectral fitting using, e.g., the Reflectance Experiment Laboratory (RELAB) database. Narrowing down on a specific mixture composition can be a laborious process but builds on long-time expertise by various groups.

3.1.3 MAGNETOTELLURIC SOUNDER

The Ceres Magnetotelluric Sounder (CMS, **Table 3-3**) determines the depth-dependent electrical conductivity of the subsurface from frequency-dependent magnetic and electric fields. This instrument is—to within the fidelity of a concept study—identical to the Lunar Magnetotelluric Sounder developed at the Southwest Research Institute (Robert Grimm PI) and selected for lunar flight on the CLPS 19D mission.

Table 3-3. Electromagnetic sounding characteristics.

Item	Value	Units
Type of instrument	Ceres Magnetotelluric Sounder (CMS)	
Size/dimensions (for each instrument)	• 4x Electrodes and launchers (stowed): 22 × 12 (dia) • Fluxgate magnetometer and mast (stowed): 12 × 6 × 12 • Electronics: 15 × 12 × 12	cm × cm
Instrument mass without contingency (CBE*)	3.6	Kg
Instrument mass contingency	30	%
Instrument mass with contingency (CBE + Reserve)	4.7	Kg
Instrument average payload power without contingency	6.2	W
Instrument average payload power contingency	30	%
Instrument average payload power with contingency	8.1	W
Instrument average science data rate**	5	kbps

**CBE = Current Best Estimate*
***Instrument data rate defined as science data rate prior to on-board processing*

The four electrodes (**Figures 3-1** and **3-2**) are deployed at 90° azimuths and the mast is deployed vertically. Deployments are a one-time activity developing over five minutes at 30 W. The source signal is specified as the magnetic-field spectrum of the solar wind near the Earth, scaled to the distance of Ceres. The electric field due to induction is calculated from the model response for different assumptions on brine conductivity (1-10 S/m) and depths (> 35 km). Preliminary modeling indicates that brines can be detected by measuring ambient electric and magnetic fields over three Ceres days (~27 hrs) for a data volume < 1 Gbit.

The electrode deployments to 100 m enable a baseline of 200 m to guarantee probing down to >50 km. This means that is the brine is thinner than 25 km, then the interface with the mantle could be detected. Furthermore, the 2.5 m high mast stands off the magnetometer to alleviate any spurious magnetic signals produced by the spacecraft. Any remaining spacecraft noise identified by ground testing, analysis, or experience would be dealt with via relatively common techniques such as backwiring solar arrays, magnetically shielding individual components, and/or using operational knowledge to correct or ignore corrupted data. In this way, an experienced team (both spacecraft and instrument) could eliminate any magnetic cleanliness issues with modest effort. This approach has been successful on numerous previous missions (e.g., MAVEN, Juno, etc.).

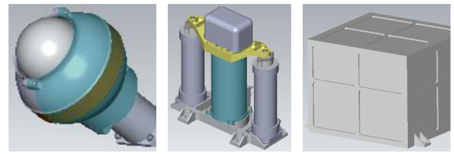


Figure 3-1. CMS components. *Left:* Electrode launcher (stowed, 22 L × 12 W cm). *Center:* Magnetometer mast (stowed, 12 L × 6 W × 12 H cm). *Right:* Electronics box: 15 L × 12 W × 12 H cm.

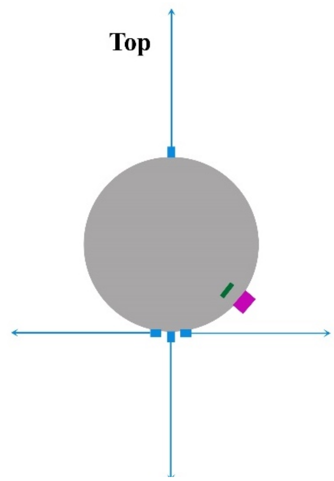


Figure 3-2. CMS configuration: three electrodes together (side-mounted) with 90° launch azimuths, with 4th on opposite side and also deploying perpendicular to lander to form orthogonal baselines. Additional cases could be developed by switching the mounting locations. Mast must deploy vertically from deck. Electronics box can in principle be anywhere, shown externally mounted here assuming appropriate thermal control.

The instrument has one operational mode with a few settings (sample rate, electrometer gain). Returned data are time series of the electric € and magnetic (B) fields. Data analysis requires editing, filtering, fast Fourier transform (FFT), calculation of impedances (E/B complex transfer functions), 1D inversion to conductivity-depth structure, and geological interpretation.

The total payload mass and power is summarized in **Table 3-4**.

3.1.4 CURATION AND HANDLING

The sample curation and analysis component of this concept was developed following the guidelines of the Planetary Science Decadal Survey provided by the National Academy of Sciences, Engineering, and Medicine (NASEM 2020), "Studies of meteorites and other extraterrestrial materials in terrestrial laboratories that further planetary science goals are in scope but findings and recommendations in this area should take into consideration the National Academies' report Strategic Investments in Instruments and Facilities for Extraterrestrial Sample Curation and Analysis (2019)."

The sample Curation Laboratory would be designed, constructed and completed at least 1 year prior to sample return. This would be an organically-clean ISO 5 cleanroom, whose design would take full advantage of 50 years of astromaterial curation experience at JSC and by JAXA.

Table 3-4. Payload mass and power.

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Instrument #1, Narrow Angle Camera × 1 The second NAC is included under the flight system: **Orbital Phase**	8.2	10	9.0	10.4	10	11.4
Instrument #2, Point Spectrometer: **Landed Phase**	2.0	30	2.6	6.0	30	7.8
Instrument #3, EM Sounding: **Landed Phase**	3.6	30	4.7	6.2	30	8.1
Total Payload Mass	**13.8**	**Variable**	**16.3**	**Instruments operate in sequence**		

The SRC will return to the Utah Test and Training Range (UTTR), where it is collected and stored in a temporary clean room before being transported to JSC for permanent curation of the returned samples. A maximum of 25% of the returned sample will undergo Preliminary Examination (PE) by an augmented mission Science Team (**Figure 3-3**). Contamination knowledge witness plates and portions of spacecraft hardware will also be subdivided and allocated for analysis during and after sample PE. The main goals of sample PE are to establish the basic nature and state of the collected samples, development of a sample database for the planetary science community, and elucidation of any sample contamination.

Ground curation and handling would be performed at or below the same temperature as the planned returned sample target temperature (≤-20ºC). The techniques and capabilities for that should be well developed at the Johnson Space Center by sample return date based on ongoing planning. This mission would leverage investments for the Asteroid Curation facilities as well as projected investments for the Mars sample returns.

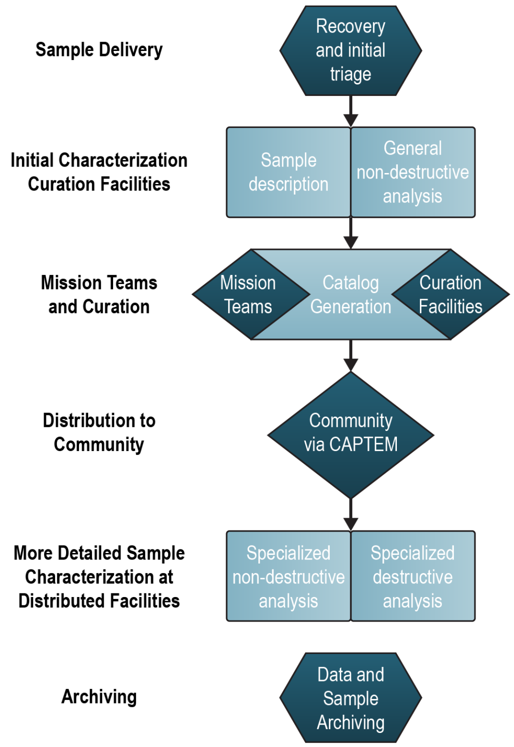


Figure 3-3. Returned sample processing flowchart. Source: CAPTEM, Curation and Analysis Planning Team for Extra-Terrestrial Material. See NASEM (2019)

The number of laboratory analyses planned during sample preliminary examination (PE), some of which being destructive and semi-destructive, lead to our sample mass requirement of ≥100 g. The mission plan prioritizes surfaces without exposed ice and with unconsolidated material, further increasing the likelihood of collecting ≥100 g of nonvolatile material. Analytical techniques in Earth-based laboratories measure the organic, elemental, isotopic, mineralogical, petrological, and spectral characteristics of the pristine samples in extraordinary detail, addressing the key mission science. This mission utilizes analytical techniques available at the time of sample return, many of which are likely yet to be developed, as was the case for Stardust, Hayabusa, etc. The PE period is 2 years, and as per NASA guidelines, ≤25% of the returned sample is employed for PE investigations, leaving ≥75% of the returned material for long-term curation to permit future investigations.

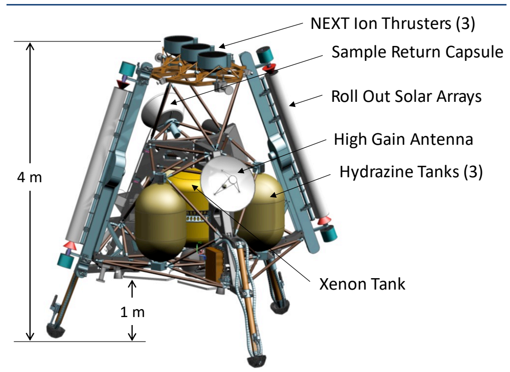


Figure 3-4. The flight system, shown in the stowed configuration with the multi-layer insulation (MLI) removed, has non-deployable landing legs and fits within a 5 m fairing. The 4 m tall vehicle provides approximate 1 m of ground clearance.

Since a major objective of this concept focuses on organic science, extra precautions should be applied to contain potential organic contamination while the samples are exposed to the terrestrial environment following return. The mission team should apply state-of-the-art contamination control protocols, for example analysis in a class-100 (i.e., ISO 5) clean laboratory. However, a review of lessons learned from past sample return missions by Chan et al. (2020) shows that contamination cannot be avoided. Fortunately, most terrestrial organics can be identified with laboratory techniques, based for example on their isotopic and molecular characteristics (see Chan et al. 2020 for more detail). Techniques such as etching the surface of studied grains with an ion beam can remove contaminants prior to analysis (e.g., Koike et al. 2020). Furthermore, Cerean organics trapped in salt grains would be protected from terrestrial contamination and remain uncontaminated when studied in a class 100 clean lab (e.g., Chan et al. 2018; Koike et al. 2020). Organic compounds collected from the dark floor material are expected to be abundant (Prettyman et al. 2018) and share distinct relationships with the rocky material. As a corollary, a major advantage of laboratory vs. in situ analysis is that various techniques can be employed to identify terrestrial organics, whereas in situ instrumentation is subject to stringent contamination control.

3.2 FLIGHT SYSTEM

There are two flight elements in the sample return mission concept, the SEP-lander spacecraft and the sample return capsule (**Figure 3-4**). For most of Phase E, these are combined into a single flight system. Only for the Earth-entry phase does the SRC separate from the SEP-lander spacecraft and fly on its own. A high-level mass summary of the flight system is given in **Table 3-5**. The systems level mass margin of 37% (as defined in this table) exceeds the JPL Design Principal margin of 30%.

Table 3-5. Flight system high-level mass summary.

	Mass		
	CBE (kg)	% Cont.	MEV (kg)
Instruments	61	26	76
Structures & Mechanisms	293	30	380
Thermal Control	61	24	75
Chemical Propulsion	138	6	146
Electric Propulsion	246	11	273
Attitude Control	72	10	79
Command & Data Handling	13	18	15
Telecommunications	23	15	26
Power	314	26	396
Harness (distribution losses)	70	30	91
Sample Return Capsule	54	20	65
Total Flight Element Dry Bus Mass	**1343**	**21**	**1662**
System Margin	---	---	516
Total Flight System Dry Mass (MPV)	**---**	**---**	**2138**
JPL DP Margin (MPV – CBE) / MPV	---	---	37%
Propellants			
Xenon Propellant	1200	10	1320
Hydrazine Propellant	1154	5	1211
Total Flight System Wet Mass (MPV)	**---**	**---**	**4669**

MPV = Maximum possible value

3.2.1 *SEP-LANDER SPACECRAFT*

Key flight elements of the SEP-lander spacecraft are summarized in **Table 3-6** and discussed below.

Ion Propulsion Subsystem (IPS). The 14 km/s ΔV required for the sample return mission drives the design to use the NASA Evolutionary Xenon Thruster (NEXT) gridded ion thruster because of their high specific impulse (*Isp*) capability instead of lower *Isp* Hall thrusters. The NEXT thruster produces an Isp of 4000 s at an input power to the power processing unit (PPU) of 7 kW (Soulas et al. 2009). A total useful propellant throughput capability of 600 kg per thruster is assumed (Herman et al. 2012). The entire round-trip mission can be performed with just two NEXT thrusters. A third thruster is carried for redundancy. The spacecraft can operate up to two thrusters operating simultaneously when sufficient power is available.

Electrical Power Subsystem (EPS). The EPS is dominated by the large solar arrays required for the ion propulsion system. The solar arrays provide 27.5 kW beginning of life (BOL) at 1 au. The ROSA technology from Deployable Space Systems (DSS) is used to provide the retraction and redeployment capability necessary to land on and take off from the surface of Ceres. The large arrays are deployed on the surface providing large energy margins per Ceres day for flight system operations. The solar arrays assume triple-junction ZTJ cells screened for low-intensity, low-temperature (LILT) performance. A Dawn-like power system architecture (Thomas et al. 2011) directs the high-voltage (~100 V) bus power to the IPS PPUs and down-converts the 100 V bus to 28 V to provide power for the instruments and the rest of the spacecraft.

Chemical Propulsion Subsystem. A throttleable monopropellant hydrazine system is used for deorbit, descent, and landing on Ceres, as well as for the takeoff and return to orbit functions. The system uses throttle valves derived from those used on the Mars Science Laboratory (MSL) and Mars 2020 missions to control six Aerojet MR-104 thrusters. An additional 18 Aerojet MR-106 thrusters make up the reaction control subsystem. The hydrazine system is a simple blowdown system.

Table 3-6. Flight system element characteristics.

Flight System Element Parameters (as appropriate)	Value/Summary, units
General	
Design life, months	120
Structure	
Structures material (aluminium, exotic, composite, etc.)	Aluminum, composite
Number of articulated structures	2 solar array wings, 1 HGA
Number of deployed structures	2 solar array wings, 1 HGA
Aeroshell diameter, m	0.8 m
Thermal Control	
Type of thermal control used	Heat pipes, MLI, thermal switches, heaters, temperature sensors
Propulsion	
Estimated delta-V budget, m/s	14 km/s SEP, 600 m/s hydrazine
Propulsion type(s) and associated propellant(s)/oxidizer(s)	• SEP (xenon); Chem (hydrazine)
Number of thrusters and tanks	• SEP: 3 NEXT ion thrusters; 1 Xe tank • Hydrazine: 6 MR104 thrusters; 18 MR106 thrusters; 3 N_2H_4 tanks
Specific impulse of each propulsion mode, seconds	• SEP NEXT: 1400 to 4100 s • Hydrazine: MR104: 220 s; MR106: 228 s
Attitude Control	
Control method (3-axis, spinner, grav-gradient, etc.).	3-axis
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Inertial
Attitude control capability, degrees	3.5 mrad
Attitude knowledge limit, degrees	0.3 mrad
Agility requirements (maneuvers, scanning, etc.)	Cruise: point SEP thrusters in direction of desired thrust and point solar panels at the sun Ceres Orbit: point NAC to nadir
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	Dual-axis solar arrays, dual-axis HGA
Power	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	Flexible blanket solar array, retractable/ redeployable, 2-axis articulation
Array size, meters x meters	95 m^2 (total of two wings)
Solar cell type (Si, GaAs, Multi-junction GaAs, concentrators)	ZTJ
Expected power generation at BOL and end of life (EOL), watts	27.5 kW BOL at 1 au
On-orbit average power consumption, watts	Varies with solar range and SEP thrusting state
Battery type (NiCd, NiH, Li-ion)	Li-ion
Battery storage capacity, amp-hours	126 amp-hour

Telecom Subsystem. Key components of the telecom subsystem include redundant UST-lite universal space transponders (Pugh et al. 2017), redundant 100-W, X-band traveling-wave tube amplifiers (TWTAs), a 1.5 m diameter High Gain Antenna (HGA), and three low-gain antennas (LGAs).

Attitude Determination and Control Subsystem (ADCS). The key feature of the ADCS is the use of an enhanced lander vision system (Sternberg et al. 2019) to provide the altimetry, velocimetry, and navigation information necessary to perform a precision landing. This approach eliminates the need for a radar or LIDAR. Sun sensors, inertial measurement units, star trackers, and reaction wheels round out the ADCS.

Structure and Mechanisms. A composite structure forms the primary spacecraft structure. Landing legs include crushables to manage the landing energy. Each solar array wing includes mechanisms to enable articulation about the y- and x-axes. The high-gain antenna (HGA) is equipped with a 2-axis gimbal to enable it to track the Earth while the spacecraft is on the surface of Ceres.

Command and Data Handling. The C&DH subsystem is based on the Sabertooth avionics under development at JPL.

Thermal Subsystem. The thermal subsystem must reject a significant amount of waste heat from the PPUs early in the mission when two NEXT thrusters are operated simultaneously at full power. It must also be able to minimize the amount of heater power required during thrusting with IPS in orbit at Ceres, and on while the spacecraft is on the surface. Thermal switches (Bugby and Rivera, 2020) are used instead of louvers to disconnect the PPUs from the radiators when not in use to minimize the amount of replacement heat required.

3.3 CONCEPT OF OPERATIONS AND MISSION DESIGN

The concept of operations for the sample return mission is divided into seven different phases as described below. The Cruise Phase is used for both the outbound and inbound heliocentric cruises.

Launch and Initial Checkout Phase. The sample return mission launches from KSC in any year from 2030 through 2037 with little change in overall mission performance. The initial checkout period is expected to be between 30 and 60 days, but no explicit checkout period was included in the trajectory analyses for this study since that level of detail is not warranted.

Cruise Phase. The cruise phase includes both the outbound cruise to Ceres and the inbound cruise back to Earth (**Figure 2-1**). The normal state of the vehicle during the cruise phase is thrusting with the IPS. An IPS duty cycle of 90% was assumed in the trajectory analyses. No missed thrust analysis has been performed. The SRC is nominally on the shade-side of the spacecraft during powered cruise facilitating its thermal management during the return leg. A summary of mission design parameters, power modes, and communications are given in **Tables 3-7 through 3-9**.

Table 3-7. Mission design parameters.

Parameter	Value	Units
Ceres Orbit Parameters		
Medium-Resolution Orbit		
Altitude	275	km
Eccentricity	Circular	N/A
Inclination	90	degrees
Period	4.5	hours
High-Resolution Orbit		
Altitude	28	km
Eccentricity	Circular	N/A
Inclination	90	degrees
Period	2.5	hours
Mission lifetime	161	months
Maximum eclipse period	0	min
Launch site	KSC	
Total flight element #1 mass with contingency (includes instruments)	1622	kg
Xenon propellant mass without contingency	1200	kg
Xenon propellant contingency	10	%
Xenon propellant mass with contingency	1320	kg
Hydrazine propellant mass without contingency	1154	kg
Hydrazine propellant contingency	5	%
Hydrazine propellant mass with contingency	1211	kg
Launch adapter mass with contingency	50	kg
Total launch mass	4664	kg
Launch vehicle	5 m high-performance	Type
Launch vehicle lift capability	4669	kg

Orbital Phase. Most of the 500-day stay time at Ceres is in the Orbital Phase. This phase includes two science orbits, both polar. The 275 km altitude orbit (1:2 resonance) allows imaging at <3 m/px required to address **Objectives 1** and **2**. Imaging is performed in the visible and two color filters (e.g., 450±20 nm and 850±20 nm). That phase is accomplished over 90 days. Imaging acquired in this phase is also used to develop a base map for landing/sampling site selection based on science criteria (from color data) and slopes (<15º). Current state of understanding based on the Dawn observations indicates the Vinalia Faculae present many opportunities for safe landing sites (**Appendix C**). Discussion within the science and engineering team, as well as input from the broad community, would lead to the identification of about ten possible landing areas, about 100 m in diameter based on the slope data and science value. These areas would then be imaged at <30 cm/px from a 28 km altitude orbit for landing/sampling site hazard mapping and certification and to enable precision landing to avoid hazards (i.e., landing within a ~20-m-diameter area), which is enabled by technologies such as hazard avoidance and terrain relative navigation (e.g., Johnson et al. 2007). This requirement is consistent with other in situ/sampling missions (e.g., Europa Lander assumes 50 cm/px, Hand et al. 2017). Texture information obtained at the sub-pixel level (mottled effect) brings further information on the suitability of the landing site for sampling (Mushkin and Gillespie 2006).

This 5:18 resonant orbit provides 30 flyovers every 1.9 days. This activity requires imaging under 5 different phase angles for topographic construction based on stereo imaging (1 additional angle as margin), for a total duration of 120 days. High-resolution gravity data are also obtained during this phase and additional imaging and gravity science for opportunistic science may be performed while the final landing site selection and certification activities are proceeding. The time margin for the orbital phase is four months. A total data volume of 39 Gbits is returned during the orbital phase.

Deorbit, Descent and Landing Phase. Deorbit begins from a 28 km orbit altitude with retraction of the solar arrays followed by a periapsis lowering maneuver. Terrain relative navigation is used to guide the spacecraft to the preselected landing site. Throttling of the hydrazine propulsion system provides the necessary control. This phase ends with the redeployment of the solar array wings on the surface.

Surface Phase. The surface phase obtains images of the SEP-lander surroundings with the context cameras including each of the three foot pads, operates the point spectrometer as part of addressing **Objectives 4, 5, 6**, and deploys and operates the electromagnetic sounder to achieve Objective 3. On the surface the Lander will have a mass of about 3400 kg. The surface gravity of Ceres is about 2.8% of Earth's resulting in a downward force of about 930 N so that no anchoring is needed. The PlanetVac system collects surface samples and stores them in the SRC. Science data from the Point Spectrometer and EM Sounder are transmitted back to Earth. The total duration of the surface phase is approximately three weeks.

Return to Ceres Orbit Phase. The return to orbit phase begins with retracting the solar arrays. The hydrazine propulsion subsystem provides the thrust to takeoff from the surface and return to a 28 km orbit altitude. This phase ends with the redeployment of the solar arrays.

SRC Earth Entry Phase. The Ceres sample return mission uses the UTTR landing site similar to NASA missions including Stardust, Genesis, and OSIRIS-REx. The U.S. Air Force tracks the SRC from atmospheric entry into the UTTR. After landing the SRC is recovered and the samples delivered to JSC.

Power Modes. Power modes are summarized in **Table 3-8** for three key mission phases. Powered cruise near 1 au early in the mission represents the highest power usage for the spacecraft. The system has the required 15% power contingency for the IPS loads (Oh et al. 2008) and 39% contingency for the rest of the spacecraft (non-EP) loads. Transfer between orbits at Ceres at 3 au with the IPS

Table 3-8. Power modes.

	SEP Cruise Near 1 au			SEP Cruise at Ceres (3 au)			Surface Operations		
	CBE (W)	Cont.	MEV (W)	CBE (W)	Cont.	MEV (W)	CBE (W)	Cont.	MEV (W)
Non-EP Loads									
Instruments	0	30%	0	0	30%	0	168	30%	218
Structures & Mechanisms	0	30%	0	0	30%	0	0	30%	0
Thermal Control	48	100%	96	123	50%	185	100	100%	200
Chemical Propulsion	1	30%	1	1	30%	1	0	30%	0
Attitude Control	108	30%	140	108	30%	140	41	30%	53
Command & Data Handling	24	30%	31	24	30%	31	12	30%	16
Telecommunications	10	30%	13	10	30%	13	195	30%	254
Power	161	30%	209	81	30%	105	50	30%	65
Sample Return Capsule	5	30%	7	5	30%	7	5	30%	7
Total Non-EP Loads	357	39%	497	352	37%	482	573	42%	813
EP Loads									
Electric Propulsion	14480	15%	16652	2000	15%	2300	0	15%	0
Harness (2% distribution loss)	301	0	301	47	0	47	11	0	11
Total EP loads and distribution losses	14781	15%	16953	2047	15%	2347	0	15%	0
Total Power Required	---	---	17150	---	---	2830	---	---	824
Power Available from Solar Array	---	---	27500	---	---	3056	---	---	1674*

MEV = Maximum expected value

**Provides 8360 W-hr per Ceres day compared to an energy requirement per Ceres day of 4300 W-hr.*

Table 3-9. Mission operations and ground data systems.

Downlink Information	Heliocentric Cruise	Ceres Orbit	Surface Operations	Return Approach
Number of contacts per week	1	2	7	2
Number of weeks for mission phase	630	71	3	8
Downlink frequency band, GHz	X-band	X-band	X-band	X-band
Telemetry data rate(s), kbps	>70	70	70	>70
Transmitting antenna type(s) and gain(s), DBi	1.5 m dia. HGA	1.5 m dia. HGA	1.5 m dia. HGA	1.5 m dia. HGA
Transmitter peak power, Watts	100	100	100	100
Earth range	0–4 au	3–4 au	3–4 au	0–4 au
Receiving antenna	34 m DSN	34 m DSN	34 m DSN	34 m DSN
Margin	3 dB	3 dB	3 dB	3 dB
Total daily data volume, (MB/day)	0.5	1	< 0.5	0.5
Uplink Information				
Uplink frequency band, GHz	X-band	X-band	X-band	X-band
Telecommand data rate, kbps	2	2	2	2
Receiving antenna type(s) and gain(s), DBi	1.5 m dia. HGA	1.5 m dia. HGA	1.5 m dia. HGA	1.5 m dia. HGA
Margin	≥11 dB	≥11 dB	≥11 dB	≥11 dB

represents the largest power demand at the greatest solar range. The 15% IPS power margin is maintained and the contingency for the non-EP loads is 37% plus a margin of 47%. Operation on the surface of Ceres represents the minimum energy case. The large solar arrays deployed after landing provide an energy margin of 94% even for the worst case conops in which sampling and telecom operations are conducted simultaneously.

Sample Curation and Analysis Phase. Samples are catalogued and curated following the approach described above (see **Figure 3-3**). A two-year period is dedicated to the analyses of the sample grains necessary to complete **Objectives 4, 5, 6**.

3.4 CRITICAL EVENTS

The sample return mission has four critical events: (1) Launch and solar array deployment; (2) Deorbit, Descent and Landing including solar array retraction and redeployment; (3) Takeoff and return to Ceres orbit including solar array retraction and redeployment; and (4) SRC separation and entry, descent, and landing (EDL). All of these critical events are done in view of a Deep Space Network (DSN) tracking station.

3.5 CONTAMINATION CONTROL FOR SURFACE OPERATIONS

Because of the organic science component of the mission, contamination control protocols have to be applied to the flight system prior to deployment to Ceres' surface. The approach used in establishing the contamination assessment and control for the Ceres sample return mission draws on experience from the Genesis, Stardust, Hayabusa, Hayabusa2 and OSIRIS-REx missions, addresses the need to minimize program resources, and maintains a low risk of contamination adversely impacting the collected samples. The controls implemented are as follows: (1) material outgassing limits and material compositional constraints will be imposed on all collection system materials, (2) typical spacecraft design features are imposed, (3) an archive of all spacecraft materials which could affect the collected sample will be maintained indefinitely by the JSC Curation Facility, (4) system level integration and testing shall be performed in an ISO Class 5 clean room environment or better, (5) personnel shall follow typical astromaterial cleanroom operational procedures, (6) contamination assessment of spacecraft surfaces that can possibly contact the collected sample will include observations by Scanning Electron Microscopy and Raman Microscopy rather than the inferior "visibly clean" standard of some past missions, (7) Contamination Control coupons shall be exposed in selected, critical fabrication, integration, testing and other ground-processing environments and analyzed when warranted to assist in evaluating anomalous events -these surfaces will be archived indefinitely at the JSC Curation Facility for future analysis, (8) the SRC interior surfaces and sampling system are precision cleaned through surface cleaning and bake-out, (9) the SRC interior and sampling system are vacuum conditioned prior to installation, (10) the payload fairing compartment shall be purged with Class 5,000 HEPA filtered air, until launch, (11) the SRC and sampling system are GN2 purged until fairing close-out, (12) airborne particulates and hydrocarbons, temperature and humidity levels are strictly controlled during ground processing activities, (13) sensitive optical surfaces are oriented to have minimal field of views to contaminant sources during flight, (14) critical hardware exposure during ground processing shall be minimized, (15) sensitive optical surfaces shall be covered continuously during ground processing prior to encapsulation with limited exceptions, e.g. System level thermal vacuum testing, (16) witness coupons will be flown with the sampling system to permit assessment of contamination of the collected samples during flight and recovery on Earth.

3.6 RISK LIST

The top five project risks have been identified and are listed below and in **Table 3-10**. The planned mitigations are indicated for each risk.

Table 3-10. Top risks for the sample return mission are all manageable. There are no currently identified red risks.

#	Risk Name	Pre-Mitigation		Mitigation
		C	L	
1	If the dust mitigation requirements grow, then additional, mass, cost, and schedule resources will be required (implementation risk).	2	3	1. Develop prototype and EM models of the retractable solar array prior to the flight model. 2. Covers for optical surfaces and the NEXT ion thrusters. 3. Use of debris deflection shields to direct sampling induced debris on a ballistic path away from the spacecraft.
2	If the adaptation of the retractable/redeployable ROSA solar array for the Ceres surface environment increases in scope because of poorly understood requirements, then additional mass, cost, and schedule reserves will be required (implementation risk).	3	3	1. Leverage the retractable/redeployable solar array flight tested on the International Space Station (ISS) and the ROSA arrays under development for deployment on the lunar surface. 2. Identify all of the driving environmental requirements including long-term operation in space prior to first retraction, thermal day/night cycling on the surface of the Ceres, deployment in a 0.028-*g* environment, and Ceres dust. 3. Perform trade study on alternate approaches for solar array management during landing and takeoff.
3	If one of the solar array wings fails to deploy or retract during the mission, then the mission probably will not meet all its Level 1 requirements (mission risk).	5	1	This is the residual mission risk after the successful development and risk mitigation in Risk #2.
4	If the uncertainty of the surface properties grows, then changes to the sample acquisition system will be required to meet the sample volume requirement (implementation risk).	2	3	Augment the pneumatic sampler with a drill or other device to mechanically break apart the surface for increased robustness to a wide range of ground strengths. The system may need technology development to enable adequate volume of sample to be excavated to support large volumes for sample return science requirements.
5	If determination of a safe, scientifically interesting landing site takes longer than expected, then s/c may miss the Earth return departure window (mission risk).	1	1	This is the residual mission risk after the following risk mitigation steps have been implemented: 1. Imaging at <30 cm pixel required for landing/sampling site hazard mapping and certification is completed during the second science orbit mapping phase, with 120 days of margin before the landing operations phase begins. 2. Margin has been built into the data return ops plan during the science orbit phases to minimize data drop-outs. 3. Landing error ellipse is designed to be very small (~20m) increasing the likelihood that multiple viable sites will be identified.

**Consequence criteria (C): cost impact complete Phases A–D): 1=Very Minimal; 2=Minimal; 3=Limited; 4=Moderate; 5=Very Significant. Likelihood criteria (L): % probability of occurrence: 1=Unlikely (<20%); 2=Possible (20–40%); 3=Likely (40–60%); 4=Very Likely (60–80%); 5=Almost Certain (>80%).*

3.7 PLANETARY PROTECTION

A working group composed of PMCS members and additional experts assessed the state of understanding of Ceres with the purpose to lay the ground for categorizing the concepts developed in this study, as well as future concepts. The full report is provided in **Appendix C** and it will also be submitted for peer review. The main findings from that activity are:

Forward Contamination: The working group concluded that there is no evidence for surface-to-subsurface material transfer anywhere on Ceres at present. Recent and potentially ongoing activity at

Occator crater is a one-way process and the source of the exposed material is >35 km deep. Hence forward contamination is not a concern for future landed missions to Ceres.

Backward Contamination: Planetary protection requirements for a sample return mission (Kminek et al. 2017) have been assessed, including a quantification of the radiation dosage accumulated by Ceres' surface material in order to determine whether a sample return mission should be Category V "restricted." Calculations by Dr. Tom Nordheim (JPL/Caltech) indicate that sterilization is achieved after about 1 My for surficial material down to 10 cm deep. Considering the large uncertainty on crater-based dating, especially when dealing with salt materials for which little relevant material literature is available, the working group concluded that the "restricted" classification is warranted for the sample return missions from the Occator faculae at this time. However, these concepts have not been officially categorized by NASA or COSPAR (Committee on Space Research) at this time. PI Castillo-Rogez is in contact with the chair of the COSPAR Planetary Protection Panel Athena Coustenis and NASA representative James Green regarding the categorization of future missions to Ceres. Progress on this matter is expected to develop in the 2020-2021 timeframe and will be shared with the Planetary Science Decadal Survey Committee as needed.

4 DEVELOPMENT SCHEDULE AND SCHEDULE CONSTRAINTS

4.1 HIGH-LEVEL MISSION SCHEDULE

A high-level schedule is given in **Fig. 4-1** for an assumed launch readiness date of December 2030. The corresponding key phase durations are given in **Table 4-1**. The critical path, not shown in **Fig. 4-1**, is assumed to go through the spacecraft structure and propulsion subsystem integration leading to spacecraft Assembly, Integration, and Test (AI&T). All instruments and subsystems are assumed to be delivered at the start of AI&T. The funded schedule margin indicated in **Table 4-1** is consistent with JPL's Flight Project Practices.

Table 4-1. Key phase duration.

Project Phase	Duration (Months)
Phase A – Conceptual Design	12
Phase B – Preliminary Design	12
Phase C – Detailed Design	18
Phase D – Integration & Test	16
Phase E – Primary Mission Operations	156
Phase F – Extended Mission Operations	24
Start of Phase B to PDR	11
Start of Phase B to CDR	24
Start of Phase B to Delivery of the NAC	31
Start of Phase B to Delivery of the Sampling System	31
Start of Phase B to Delivery of Point Spectrometer	31
Start of Phase B to Delivery of the EM Sounder	31
Start of Phase B to Delivery of Spacecraft to SIT	31
Start of Phase B to Delivery of the SRC	27
System Level Integration & Test	12
Launch Operations	4
Total Development Time Phases B–D	46

4.2 TECHNOLOGY DEVELOPMENT PLAN

As indicated above there are three components that are currently at a TLR < 6: the magnetotelluric sounder; the retractable/redeployable solar array; and the sample handling system.

Magnetotelluric Sounder. This instrument is currently at TRL 5 and is expected to reach TRL 6 by 2021 through an existing, funded technology maturation plan. This is well in advance of the TRL 6 need date ~March 2028 according to the schedule in **Figure 4-1**.

Retractable/Redeployable Solar Array. A retractable/redeployable roll-out solar array (ROSA) was developed by Deployable Space Systems, Inc. and flight tested on the International Space Station in 2017. This puts the flight demonstration unit at TRL 7. The larger size and significantly different environment required for the Ceres Sample Return mission reduces the technology readiness level to TRL 5. To bring this technology to TRL 6 a prototype unit would be fabricated and tested. The prototype unit would be used to demonstrate form and function at a scale representative of the final product in its operational environment. A prototype unit would provide sufficient fidelity to permit validation of analytical models capable of predicting the behavior of the full-scale system in the operational environment for the Ceres Sample Return mission.

If the retractable/redeployable ROSA technology cannot be realized, there are other approaches for solar array management during landing and takeoff. These approaches would likely involve articulation of the array wings into a more dynamically favorable configuration. They could also involve latching the array wings to improve the dynamic characteristics for landing and takeoff at Ceres.

4.3 DEVELOPMENT SCHEDULE AND CONSTRAINTS

The use of solar electric propulsion for the transportation to and from Ceres results in significant schedule robustness. As mentioned above, the same sample return flight system could be launched any year between 2030 and 2037 with little effect on the key performance margins.

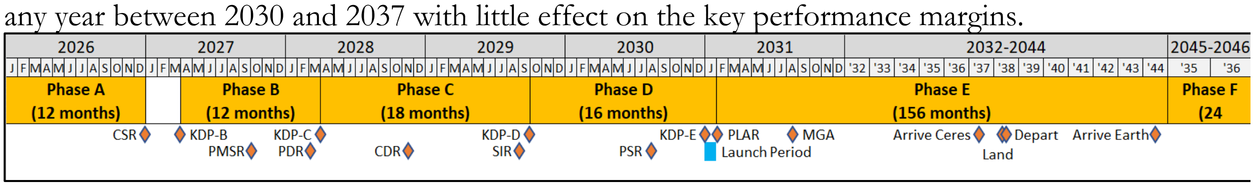


Figure 4-1. High-level schedule indicates key milestones for an assumed December 2030 launch consistent with the trajectory given in **Fig. 2-1**. The mission can launch in any year from 2030 through 2037 with little change in performance allowing the Phase A start year to range from 2026 through 2033. Sample analyses are performed in Phase F.

5 MISSION LIFE-CYCLE COST

5.1 COSTING METHODOLOGY AND BASIS OF ESTIMATE

The Ceres Pre-Decadal study team developed its cost estimate using JPL's cost estimation process for early formulation. The technical design and project schedule were used as the main inputs into the development of the cost estimate. Rather than providing a single point estimate, the Ceres study team developed a range estimate comprised of various cost estimation techniques appropriate for an early formulation study. 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.

The costs presented in this section are subject to change with the possibility of the estimates ranging from 20% higher or 10% lower dependent upon further definition of the mission and technical implementation.

The Ceres cost is organized, defined, and estimated according to the NASA Standard Work Breakdown Structure (WBS), which is compliant with NPR 7120.5E. Per study ground rules, costs presented in this section are in Fiscal Year 2025 dollars unless otherwise noted.

Based on science and technical trades, two main mission architectures were chosen for further study: Sample Return and In-Situ Lander with the Sample Return option identified as the main architecture. Based on this cost estimate study, both mission architectures should be categorized in New Frontiers cost bin. For In-Situ Lander architecture cost estimates, please refer to **Appendix B**.

Two main techniques were used to develop the Sample Return cost estimate: (1) Team X Institutional Cost Models (ICM). (2) Parametric hardware cost models, SEER-H and TruePlanning, were used to model the development cost.

Operations (Phase E-F) costs were modeled using the Space Operations Cost Model (SOCM) and Mission Operations Cost Estimation Tool (MOCET). In **Table 5-1**, the SOCM estimate has been applied to the system evaluation and estimate of resources (SEER) column and MOCET has been applied to the TruePlanning column. The TeamX estimate includes the operations costs generated from the ICMs.

Team X is a JPL concurrent engineering design environment created in 1995. Team members represent all JPL technical disciplines. The Team X ICM suite has been approved by JPL implementing organizations and is consistent with JPL institutional ground rules. The ICMs have been developed based on historical actuals and individual model runs are tailored to most closely represent the scope and complexity of the technical implementation. Additionally, the concurrent design environment of Team X enabled the team to perform design-to-cost trades. For purposes of this study, TeamX used an industry cost pass through for the PlanetVac, Spacecraft Bus, Mission Operations System/ Ground Data System (MOS/GDS), and AI&T estimates.

SEER-H and TruePlanning are parametric cost models which use hardware specifications (as noted in the Master Equipment List) as the primary input. These parametric models are used to estimate the development (Phase B-D) cost of a given mission concept. For WBS elements not estimated by the parametric cost models, wrap factors based on historical competed missions were used. Wrap factors were used for Science (4%), Spacecraft Management Oversight (6%), and Mission Operations/Ground Data System (8%).

SOCM and MOCET are cost models which estimate the operations (Phase E-F) cost by using mission characteristics like cruise time, mission target, number of scientific instruments, etc.

Reserves were applied at 50% for Phase A-D development (excluding LV) and 25% for Phase E-F operations (excluding tracking costs) as required by NASA for this study. A placeholder of $5M FY25 was used for Phase A based on the New Frontiers 4 AO (inflated to FY25 from FY15). The Ceres concept is baselining the Launch Service Option 4, which is identified as $240M in the Decadal Mission Study Ground Rules.

In addition to developing model-based estimates, the study team worked with industry providers to develop ROM estimates for unique, mission enabling Payload and Spacecraft hardware. Please note that these ROMs are strictly used for informational purposes only and are not to be considered as a commitment by any institution nor should it be considered as a selection of a potential supplier. **Table 5-2** presents the hardware and the industry provided ROM estimates for each compared against the average modeled costs.

The Phase E costs for Science are driven by the following activities, in chronological order:

Cruise:

1. NAC checkout.
2. NAC calibration during cruise (every 6-12 months).

Orbital Phase:

1. Science planning for medium resolution imaging (<3 m/px) and gravity science required to address Objectives 1 and 2.
2. Data analysis and production of 5 m scale basemap for the selection of possible landing sites in Vinalia Faculae based on material distribution, slopes and hazards visible at that scale (e.g., fractures). The basemap would also serve as a reference for the enhanced landing vision system. Preliminary landing site selection would involve the community in the form of a workshop, which would lead to downselecting ~10 reference sites for high-resolution imaging.
3. High-resolution imaging of the ~10 sites at <0.3 m/px under five different lightning conditions; development of digital elevation map (DEM); and downselection of landing site with input from the community (workshop or working group). This phase is very intensive and would require input and reviews from outside the science team (e.g., USGS) to ensure the DEM meets standards for landing site certification.
4. Characterization of the workspace with the point spectrometer and visible imaging from the engineering cameras.
5. Acquisition and analysis of the magnetotelluric sounding data. After the nominal data integration time of 50 hr, the science team would assess whether Objective 3 can be met with available data or schedule margin needs to be used.
6. Sample acquisition and verification.
7. All Level 1b data products would be archived in the Planetary Data System Small Bodies Node within 6 months following data acquisition.

Additional on-ground activities (in parallel to flight activities): Preparation for sample recovery and curation, e.g., rehearsals for end-to-end curation operational simulations.

5.2 COST ESTIMATE(S)

The cost estimates for the Sample Return architecture are presented in **Table 5-1.** In all cases, the sample return capsule costs are included in WBS 06.16. The industry-developed cost estimates for WBS 06.16, WBS 7/9, and WBS 10 were used in the Team X estimate as pass throughs consistent with the Team X process for mission costing with an industry-provided spacecraft. The A-D costs in Table 5-1 range from $0.968B to $1.30B with an average of $1.13B in FY'25 $.

Table 5-1. Ceres Sample Return Cost Estimate in FY25$M. The Phase A-D cost estimates span the range of the notional NF cost cap of $1.1B with an average estimate of $1.12B.

WBS	WBS Element	TruePlanning	SEER	Team X (industry S/C)
	Phase A	5	5	Incl in the below costs
WBS 1,2 ,3	Proj Mgmt, Proj SE, SMA	79	99	82
WBS 4	Science	26	30	22
WBS 5	Payload	100	98	113
05.01,05.02	PL Mgmt, PL SE	10	7	9
05.04	NAC	12	25	36
05.05	IR Point Spectrometer	24	20	14
05.06	EM Sounder	13	8	10
05.07	Transfer Mechanism	3	3	3
05.08	PlanetVac	38	35	41
WBS 06	Spacecraft	353	410	536
06.01,06.02	SC Mgmt, SC SE	23	27	39
06.16	Spacecraft Bus	330	383	497
WBS 7/9	MOS/GDS	52	59	60
WBS 10	I&T	31	39	52
	Phases A-D Subtotal	**646**	**740**	**864**
	A-D Reserves (50%)	323	370	432
	Total A-D	**968**	**1,110**	**1,296**
	Launch vehicle (LV)	240	240	240
	Phase E-F	325	278	320
	Phase E-F Reserves (25%)	81	70	80
	Total A-F	**1,615**	**1,698**	**1,935**

SEER
True Planning
Wrap
ROM Pass Thru
Rollup
SOCM
MOCET
Team X

Table 5-2. Industry Developed ROM Estimates FY25$M

Cost Element	Industry ROM Cost	Average Modeled Cost
IR Point Spectrometer	15	19
EM Sounder	12	10
Sample Return Capsule	32	26
NEXT Thruster & PPU	19	29
ROSA Solar Array	40	60
PlanetVac	41	37
Spacecraft Bus*	497	356
MOS GDS**	60	57
I&T	52	36

**Spacecraft ROM includes Team X modeled Lander Vision System*
***MOS GDS ROM includes Team X modeled managing center MOS GDS support costs*

APPENDIX A ACRONYMS

ADCS	Attitude Determination and Control Subsystem
AI&T	Assembly, Integration, and Test
AO	announcement of opportunity
APXS	Alpha Proton X-Ray Spectrometer
ASU	Arizona State University
BOL	beginning of life
C&DH	command and data handling
CAPTEM	Curation and Analysis Planning Team for Extra-Terrestrial Material
CBE	current best estimate
CC	Carbonaceous chondrite
CDR	Critical Design Review
CHNOPS	Carbon, Hydrogen, Nitrogen, Oxygen, Phosphorus, Sulfur
CIRS	Compact Integrated Raman Spectrometer
CLPS	Commercial Lunar Payload Services
CML	Concept Maturity Level
CMS	Ceres Magnetotelluric Sounder
COSPAR	Committee on Space Research
DEM	Digital Elevation Map
DSN	Deep Space Network
DSS	Deployable Space Systems
EA	Elemental Analyzer
EDL	entry, descent, and landing
eLVS	enhanced lander vision system
EM	electromagnetic
EMPA WDS	electron microprobe wavelength dispersive spectroscopy analyses
EOL	end of life
EP	electric propulsion
EPS	Electrical Power Subsystem
FIB-TEM	fast ion beam – transmission electron microscopy
FFT	fast Fourier transform
FOV	field of view
FTIR	Fourier transform infrared
GC/C/IRMS	Gas chromatography/combustion/isotope ratio MS
GDS	Ground Data System
GN2	Gaseous nitrogen
GSFC	Goddard Space Flight Center
HGA	high-gain antenna
I&T	Integration & Test
ICEE	Instrument Concepts for Europa Exploration
ICM	Institutional Cost Model
ICP-MS	inductively coupled plasma mass spectrometry

INAA	instrumental neutron activation analysis
IOM	insoluble organic matter
IPS	ion propulsion subsystem
IR	infrared
IRS	infrared spectrometer
ISO	International Organization for Standardization
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KSC	Kennedy Space Center
LGA	low-gain antenna
LIDAR	light detection and ranging
LILT	low-intensity, low-temperature
LV	launch vehicle
MA	Mission Assurance
MAVEN	Mars Atmosphere and Volatile EvolutioN
MEL	Master Equipment List
MEV	maximum expected value
MLI	multi-layer insulation
MMX	Martian Moons eXploration mission
MOCET	Mission Operations Cost Estimation Tool
MOS	Mission Operations System
MS	mass spectrometry
MSL	Mars Science Laboratory
MVP	maximum possible value
NAC	narrow angle camera
NASA	National Aeronautics and Space Administration
NASEM	National Academy of Sciences, Engineering, and Medicine
NEXT	NASA Evolutionary Xenon Thruster
NPR	NASA Procedural Requirement
ORCA	ORganic Composition Analyzer
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer Mission
pico-CSIA	picomolar-scale compound-specific isotope analyses
PDR	Preliminary Design Review
PE	preliminary examination
PI	Principal Investigator
PL	payload
PM	Project Manager
PMCS	Planetary Mission Concept Study
PPU	power processing unit
RELAB	Reflectance Experiment Laboratory

ROM	rough order of magnitude
ROSA	Roll-Out Solar Array
ROW	Roadmap to Ocean Worlds
RTG	radioisotope thermoelectric generator
S/C	spacecraft
SCS	Sequence and Compression System
SE	Systems Engineer
SEER	System Evaluation and Estimate of Resources
SEP	solar electric propulsion
SIMS	secondary-ion mass spectrometry
SMA	Safety and Mission Assurance
SOCM	Space Operations Cost Model
SOM	soluble organic matter
SRC	sample return capsule
SwRI	Southwest Research Institute
TEM	transmission electron microscopy
THEMIS	Time History of Events and Macroscale Interactions During Substorms mission
TLS	Tunable Laser Spectrometer
TPS	thermal protection system
TRL	Technology Readiness Level
TWTA	traveling-wave tube amplifier
UPLC-FD/QToF-MS	ultra-performance liquid chromatography fluorescence detection and quadrupole time-of-flight hybrid mass spectrometry
USGS	U.S. Geological Survey
UST	Universal Space Transponder
UTTR	Utah Test and Training Range
WBS	Work Breakdown Structure
XANES	X-ray absorption near edge structure
XM2	Dawn second extended mission
XRD	X-ray Diffraction

APPENDIX B DESIGN TEAM STUDY REPORTS

APPENDIX B.1 SUMMARY OF SCIENCE TRADES

Landing Site Trade (see Figure B-1)

- **Average surface:** Landing on the average surface of Ceres has the advantage that it does not require pinpoint (<20 m) landing. The average regolith may superchondritic concentrations of carbon in various forms (Prettyman et al. 2018; Marchi et al. 2019) along with a mixture of salts and other aqueous alteration products. However, it has also been suggested that Ceres' regolith may contain up to 70 vol.% of exogenic material (Marchi et al. 2019; see also Vernazza et al. 2017) delivered by impactors and micrometeorites. Although investigating the regolith would potentially confirm or invalidate these hypotheses, the PMCS team felt that separating endogenic material from a potentially overwhelming exogenic contributions would not lead to a compelling science concept.
- **Ernutet crater:** This crater hosts kilometer-scale areas rich in organic matter, between 7-50+% depending on the reference organic compound used for the inversion of the Dawn infrared data (De Sanctis et al. 2017, 2019; Kaplan et al. 2018). Although of greater interest and lending itself to in situ analysis with state of the art instrumentation for organic analysis, the team felt that the remaining uncertainty about the origin of this material (endogenic or exogenic, e.g., from a small P- or D-type asteroid) (Pieters et al. 2018) would create too much science risk. Furthermore, this site is dominated by average surface material that is likely to be heavily contaminated by infalls (see above).
- **Ahuna Mons:** The 4 km tall by 17 km long mountain was suggested, based on Dawn geophysical data, to stem from the briny mantle below the icy crust (Ruesch et al. 2019a). Furthermore, the emplacement of this large amount of material requires the presence of at least a small fraction of brines (Ruesch et al. 2016, 2019a). Hence, the investigation of Ahuna Mons material would provide an alternative way to address the habitability of Ceres' brine layer. However, a search for potential landing sites at the Mons revealed no viable, low slope site (Scully et al., available upon request).

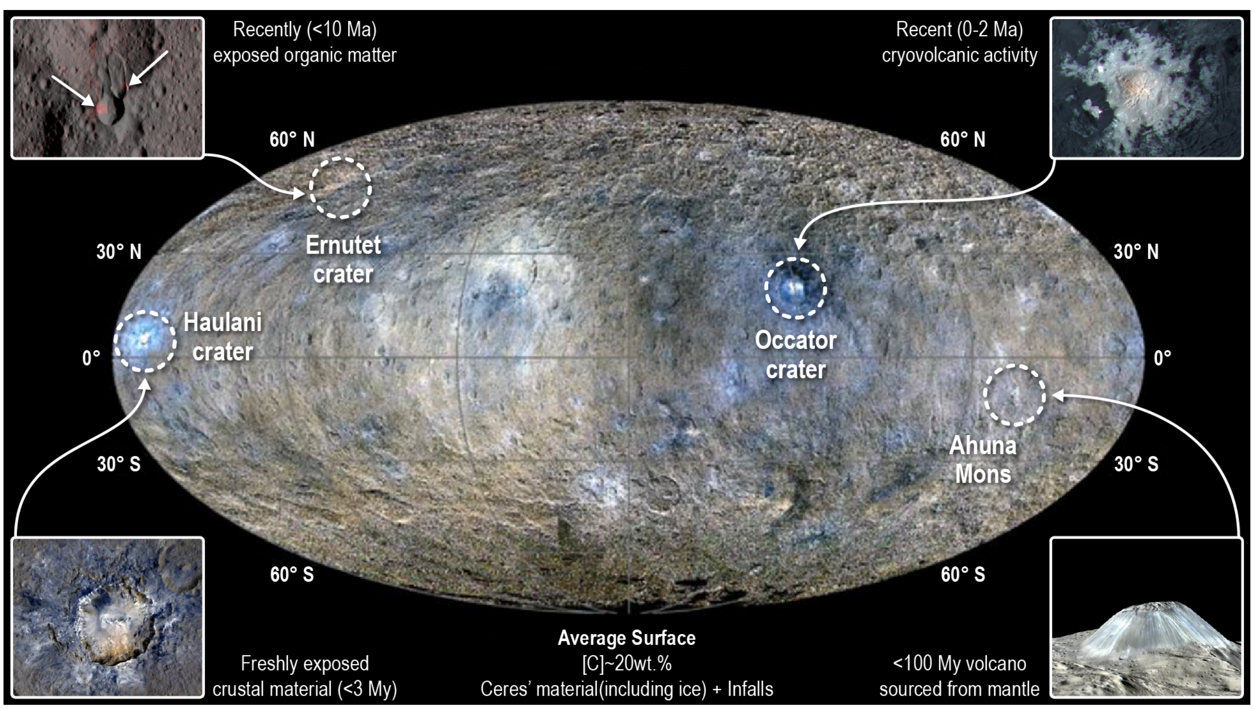


Figure B-1. The five regions of high scientific values considered in this study. The PMCS science team concluded Occator crater's evaporites offer the greatest opportunity to progress along the Roadmap to Ocean Worlds.

- **<u>Haulani crater</u>:** This young (<2.5 My) crater has exposed material from the shallow (<5 km) crust and thus would offer an opportunity to probe the early ocean now frozen in the crust. Per its young age, the exposed material has been weakly weathered and contaminated by infalls. However, a mission to that crater would uniquely focus on Ceres' early habitability, which was assessed by the science team and found to be less compelling enough for a follow-on mission to Ceres in the New Frontiers program and above.

Sample Return versus In Situ Exploration

Measurement Capability: For a concept focused on understanding Ceres' current habitability and origin, an in situ mission is limited by (1) the current performance of in situ instrumentation for organic matter characterization and isotopic measurements; (2) stringent contamination control requirements when looking for organics in very small abundance (nanogram). For instrument performance, we considered Raman spectroscopy and mass spectrometry. For Raman spectroscopy we considered the Compact Integrated Raman Spectrometer (CIRS) developed under the ICEE-2 program (J. Lambert PI). While that instrument spectral range and resolution is particularly well adapted for science objectives targeting salts and organics, its spatial resolution of 5-10 microns is too coarse to detect organic compounds that may be <<1 micron based on the Zag and Monahans clasts taken as reference (Chan et al. 2018). For Raman spectroscopy, we assumed the next generation ORganic Composition Analyzer (ORCA, based on Chris Glein pers. comm.) developed under NASA's ICEE-2 Program. This model has multiple front ends to separate the volatile and refractory components of planetary ices. However, discussion with the ORCA team, including PMCS Co-I Kelly Miller, indicated that this product would not be sensitive enough to detect organic compounds trapped in salt grains at the ppb level. ORCA has the capability to obtain the isotopic composition of CHNOPS. However, a high-level issue identified during the team discussions is that origin science is complex and requires combining elemental ratios and isotopes of many volatile and heavy elements. Ultimately, the study team concluded that an **in situ only mission would not be able to address Objectives 5 and 6**. On the other hand, state of the art instrumentation on Earth can achieve isotopic ratio measurements and organic detections by extracting and concentrating the materials of interest (see **Figure B-2**). Stated differently, a sample return mission would benefit from a cumulated ~billion-dollar level

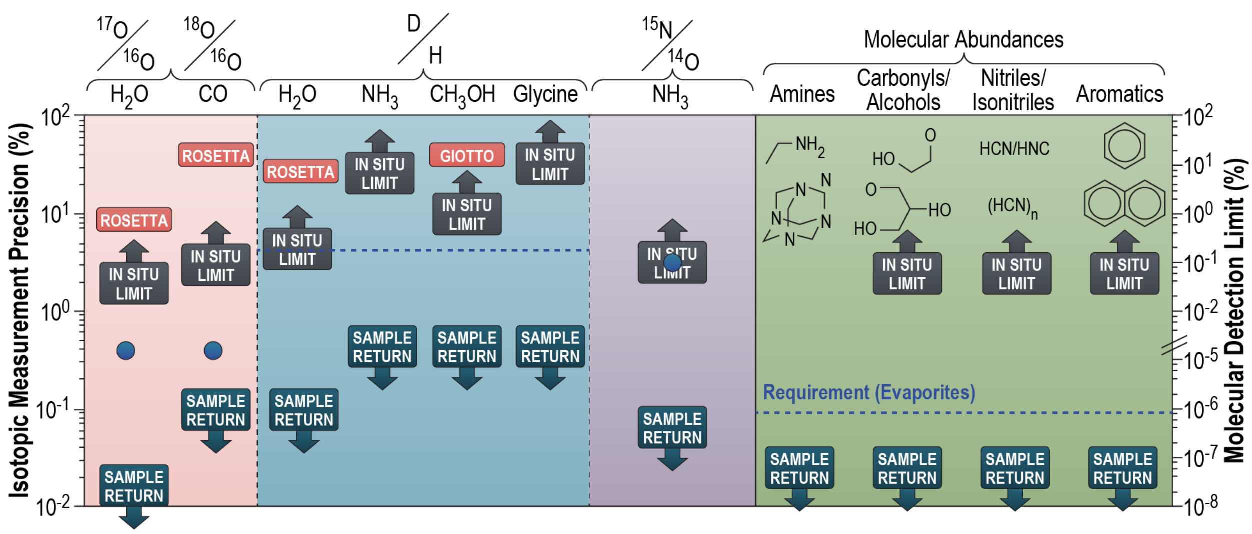


Figure B-2. Performance comparison between in situ measurement and Earth's laboratory measurement techniques against measurement requirements (blue circle and line). The requirement to measure $^{17}O/^{16}O$ and determine the nature of organic compounds believed to be highly diluted drives the need for high-grade facilities. Initial isotopic ratios depend on the mineral in which the reference element is incorporated (e.g., Willacy and Woods 2009 for D/H). Although high-precision D/H can be measured in water with available in situ payload, material ingestion techniques cannot separate minerals, resulting in a signal that is diluted and difficult or even impossible to interpret reliably. Based after Milam et al. (2020).

investment by NASA in facilities on Earth (NASEM 2019), as well as future investments, and engage a broad community in the analysis of the sample for several decades.

Single vs. Multi-Site Exploration: A major advantage of the in situ concept is that it can reach at least two sites (one additional after the first landing) for moderate additional cost (see **Figure B-3**). As hopping from one site to another is propellant intensive, the PMCS team explored possible sites of interest separated by a few tens of kilometers. The team converged on two sites located at Occator: the first site would be located in the dark ejecta material in the northeastern region of Occator (Homowo Regio) and the second one in the Vinalia Faculae. Originally present in the shallow subsurface, the dark ejecta represents Ceres' early ocean material captured in the crust upon freezing. The composition of that material is significantly different from the average Ceres surface (Raponi et al. 2019). In particular, it is richer in ammonium salts. Its dark color is attributed to a fine grain size of 10s microns, which may represent fine particles forming the matrix of accreted planetesimals (Neveu and Desch 2015). Hence, the analysis of the composition (elemental, isotopic, and mineralogic) can be used to quantify the environmental characteristics and thus the habitability of Ceres' *early* ocean. A two-site mission targeting Occator crater ejecta and evaporites would then address Ceres' past and current habitability. With this combination of lander-accessible ancient and recent surface material, Ceres may be the only ocean world where this kind of information can be gathered. **While this concept generated great interest in the study team, the potential risk of not identifying any organic matter with state of the art instrumentation led to rating it as a second favorite.**

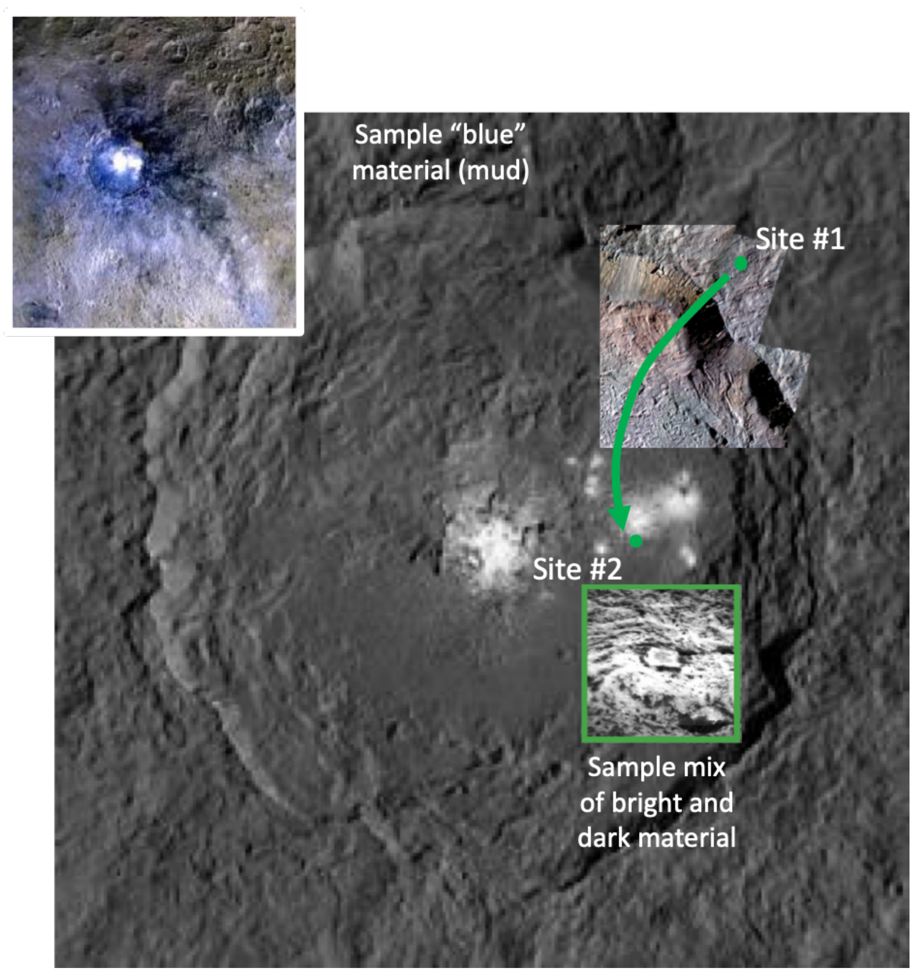


Figure B-3. The two landing regions identified of high value for the in situ concept: Homowo Region (Occator crater Northeastern ejecta) followed by Vinalia Faculae. The two regions are separated by about 40 km.

Table B-1. Science return comparison for the two concepts by assessing whether the science objectives are achieved in full (green), partially (yellow), or not at all (red).

Science Objectives	In Situ Homowo Regio only	In Situ Vinalia Faculae only	In Situ – Homowo and Vinalia	Sample Return Vinalia Faculae
O3. Determine the depth of liquid water below Occator crater	High science risk – Depth of brines in that area is not constrained	Depth of brine below Vinalia Faculae is constrained >~ 35 km		
O4. Characterize Ceres' deep brine environment at Occator crater	Homowo Regio does not sample current brine reservoir	Exposed evaporites are evolved from deep brines Composition can be determined with e.g., Raman spectroscopy, MS, elemental spectroscopy		Sample return enable full inventory quantification Requires sample to be preserved ≤ -20°C during return
O5. Characterize the evolution of organic matter in long-lived ocean	Homowo Regio does not sample current brine reservoir	Organic matter expected in abundance too small to be detectable with Raman spectroscopy and MS		Trace organic compounds can be fully studied on the ground
O6. Determine Ceres' accretional environment	Partially addressed with C, H, O, N isotopes; model-dependent (requires correcting for alteration by hydrothermal processing) Light volatile isotopes cannot be uniquely traced to formation in solar nebula, especially as ^{17}O cannot be measured with in situ techniques	Vinalia Faculae material is likely too processed for origin signature in volatiles to be easily interpreted based on limited analyses with in situ instruments		Addressed with a variety of measurements, including isotopes of Ti, Cr, Mg, and ^{17}O that are less affected by hydrpthermal processing
Additional objective: Constrain the environmental conditions and assess the evolution of organic matter in Ceres' early ocean	Can be addressed with micro-Raman imaging and isotopes (redox, pH, temperature from clumped isotopes) Organic matter expected in high abundance ([C] ⪷ 20 wt.%), can be characterized assuming compound structure has not been degraded by space weathering (~10 My timescale) Formation conditions of organic compounds with light isotopes (e.g., tunable laser spectroscopy, TLS)	Does not address this objective		Does not address this objective
SUMMARY Projected science return	Obj. 1, 2 fully addressed Obj. 6 partially addressed Obj. 3, 4, 5 not addressed Addresses past habitability only	Obj. 1, 2, 3, 4 fully addressed Obj. 5, 6 not addressed	Obj. 1, 2, 3, 4 fully addressed Obj. 6 partially addressed Obj. 5 not addressed	All objectives fully addressed

In summary, for a similar cost, an in situ mission and sample return from the Occator evaporites was deemed of greater scientific merit than an in situ mission only targeting two sites. Both missions would capture Objectives 1-3 in orbit and in situ. The sample return mission concept would be directly responsive to the Roadmap to Ocean Worlds by quantifying the habitability of Ceres' brines and address the fate of organic matter in ocean worlds.

APPENDIX B.2 SAMPLE RETURN VS. IN SITU CONCEPT AT A GLANCE

The projected science for the Sample Return mission concept is compared to that for the In Situ concept in **Table B-2**. This table also provides a comparison of the Project System, Development costs (for Phases A-D), and the mission operations costs (Phases E-F).

Table B-2. The Sample Return mission option provides better science at lower science risk and approximately the same Phase A-D cost as the In Situ option.

Parameter	Sample Return Concept	In Situ Concept
Science		
Science Goals	1. Assess Ceres' current habitability and use Ceres as a test case for unraveling the habitability, over time, of volatile-rich bodies; 2. Determine Ceres' origin and the relationship of its volatiles and organics to other inner solar system bodies.	1. Assess Ceres' current habitability and use Ceres as a test case for unraveling the habitability, over time, of volatile-rich bodies; 2. Assess Ceres' past habitability. 3. Determine Ceres' origin and the relationship of its volatiles and organics to other inner solar system bodies.
Projected Science Return	• Progresses along the roadmap to ocean worlds (ROW) – Assess extent of material transfer between mantle and surface – Determine depth of brines below Occator – Test if brines are habitable – Quantify extent of prebiotic chemistry • Determines Ceres' origin	• Partially progresses along ROW – Assess extent of material transfer between mantle and surface – Determine depth of brines below Occator – Partially test if brines are habitable (does not address prebiotic chemistry) • Partially addresses Ceres' origin (association with chondrite only) • Partially addresses habitability of Ceres' past ocean (does not address prebiotic chemistry)
Payload	• Narrow angle camera • Magnetotelluric sounder • Point IR spectrometer • Sample return capsule Sampling with PneumaVac system (Honeybee Robotics, HBR)	• Narrow angle camera • Magnetotelluric sounder • Raman imaging spectrometer • Tunable laser spectrometer • Elemental spectrometer Sampling with PneumaVac system (HBR)
Number of Sites	1 (Vinalia Faculae)	2 (Vinalia Faculae and Occator Northeastern ejecta), about 40 km apart
Project System		
Launch Vehicle	**Option 4 (e.g., Falcon Heavy Recovery)**	
Launch Mass	4664 kg	3775 kg
Flight System Dry Mass (MPV)	2149 kg	2234 kg
Xenon – Mass	1320 kg	800 kg
Hydrazine – Mass	1200 kg	701 kg
Cruise time (outbound)	6.5 yr	6.5 yr
Mars Gravity Assist	Yes	Yes
Orbital Phase	**Landing site reconnaissance, Objectives 1-2 for 500 days**	
In Situ Phase	2 mo	2 mo
Return Phase	4.7 yr	N/A
Total Phase E duration	12.6 yr	8 yr
Phase F duration	2 yr	6 mo after last data acquisition
Planetary Protection Categorization	V – restricted or unrestricted TBD	III – no forward contamination control requirement
Cost		
Payload Cost (WBS05)	$104M	$159M
Flight System Cost (WBS06)	$433M	$375M
Phase A-D Cost	$1125M	$1107M
Phase E-F Cost	$384M	$233M

APPENDIX B.3 DESIGN TEAM STUDY REPORT – SAMPLE RETURN MISSION

Key features of the Team X Report for the sample return mission are given below.

Ceres Pre-Decadal Sample Return Follow-On

PI: Julie Castillo-Rogez, Study Lead: John Brophy

Facilitator: Troy Hudson

April 21st to April 23rd, June 24th 2020 Wrap-Up

Study ID: 2326, 260

Jet Propulsion Laboratory
California Institute of Technology

Data Use Policy

TEAM X
Jet Propulsion Laboratory

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7. Mission Design – Reza Karimi
8. ACS – Aron Wolf
9. CDS – Roger Klemm
10. Ground Systems – Greg Welz
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12. Planetary Protection – Laura Newlin
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14. Cost – Sherry Stukes

Executive Summary

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Executive Summary

Study Overview

- Study Goals
  - To determine if an architecture for Ceres sample return meets the financial and programmatic constraints of a New Frontiers or Small Flagship class mission (Class B, $1.1B FY25 ØA-D incl. Launch Services w/ **50%** A-D, 25% E-F Reserves) for a **Planetary Mission Concept Study** to be provided by NASA as an input to the 2023 Planetary Decadal Survey for prioritization.

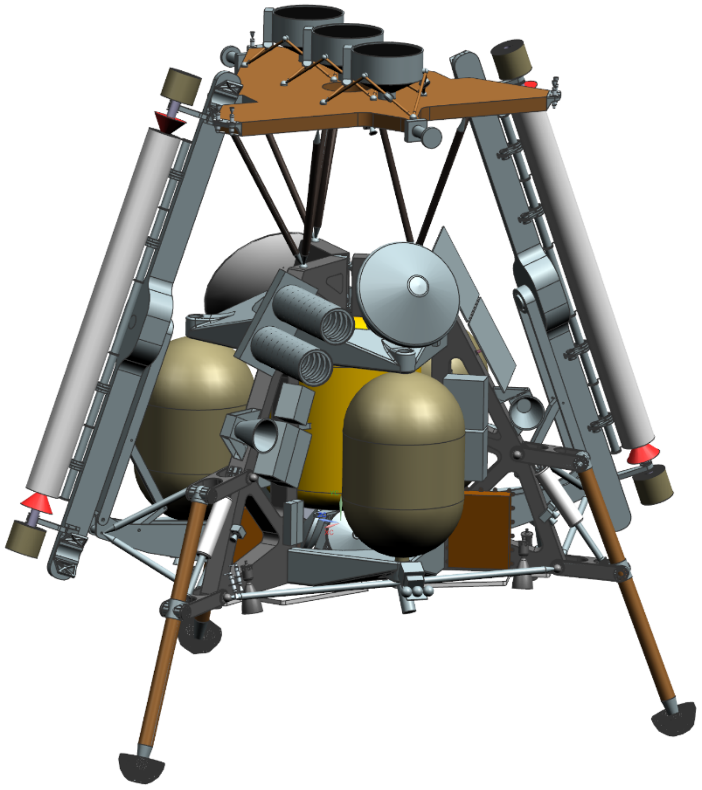
- Study Objectives
  - From customer provided spacecraft cost passthrough, Team-X shall provide an estimate of total mission cost.

- Architecture
  - Single flight element sample return, wherein the flight element lands, collects samples and performs some science investigations, then re-launches on Earth return trajectory with a ballistic sample capsule. Landing of the entire vehicle is enabled by retractable / re-deployable solar arrays.

Executive Summary

Mission Architecture and Assumptions

- Class B, Category 3, $1.1B FY25 (A-D) assumed NF cost cap
  - Launch in early 2030s (2030-12-20)
  - 6 year cruise to CERES with one Mars gravity assist
  - 16 month orbital science at Ceres
  - 2 month landed science phase
  - 6 year cruise back to Earth



- Assumptions
  - Passthrough costs:
    - WBS 6, 7, 9, and 10 - $466.2M FY25
    - Lander Vision System - $13.0M FY25
    - Payload costs: Per instrument plus PlanetVac sampling system (see cost report)

Executive Summary

Overview

- Team X provided the following cost outputs
  - Development (Phases A-D)
    - WBS 1, 2, 3, 4, 5, 6.01, 6.02, and 12
    - JPL portions of WBS 7 and 9
    - Costs for Lander Vision System using Team X ICMs
      - Note that the customer cost passthrough for the LVS was used in the complete cost roll-up, but the Team X costs are provided for reference
  - Operations (Phases E-F)
    - WBS 4
      - Including 2 years of sample analysis after return to Earth
    - WBS 7 and 9
      - Customer team did not provide spacecraft contractor operations costs, so the costs assuming all JPL operations were estimated and used in the cost roll-up
      - JPL-only costs are provided as reference, and should be **added** to the spacecraft contractor costs if they are provided in the future

Executive Summary

Total Mission Cost

COST SUMMARY (FY2025 $M)	Generate ProPricer Input	Team X Estimate CBE	Team X Estimate PBE
Project Cost		**$1180.6 M**	**$1687.1 M**
Launch Vehicle		**$0.0 M**	**$0.0 M**
Project Cost (w/o LV)		**$1180.6 M**	**$1687.1 M**
Development Cost		**$861.1 M**	**$1291.3 M**
Phase A		$8.6 M	$12.9 M
Phase B		$77.5 M	$116.2 M
Phase C/D		$775.0 M	$1162.1 M
Operations Cost		**$319.5 M**	**$395.8 M**

Total mission cost cap of $1.1B for Phases A-D exceeded by $191M, FY25

Systems Report

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Systems

Study Overview

- The goal of this study was to cost a mission to Ceres as part of the Pre-Decadal survey set of mission studies, using cost passthroughs for the spacecraft provided by the customer team.
  - This was a **cost only** study and did not assess the spacecraft technical design
- The mission travels to Ceres, lands, collects a set of samples, and returns them to Earth.
- Customer Inputs:
  - Reference MEL and CAD Configuration
  - Passthrough Costs:
    - WBS 6, 7, 9, and 10 contractor costs
    - Lander Vision System cost
    - Payload costs
- Team X Outputs:
  - Costs for JPL WBS elements
  - Mission cost using combination of customer team passthroughs and JPL Team X costs

Systems

Design Assumptions

- There is a single spacecraft element that performs all aspects of the mission
- The mission is desired to be "New Frontiers" class
  - Cost target of $1.1B FY25 (Phase A-D)
- Spacecraft is Class B risk posture, dual string redundancy
- Total mission duration is 13.5 years
  - 6 year cruise to Ceres
  - 16 month orbital science phase
  - 2 month landed science phase
  - 6 year cruise back to Earth

Systems

Customer Cost Passthroughs

- Customer provided the following cost passthroughs in FY25 $M
  - Costs do not include JPL procurement burden of 17.5% which was added by Team X

WBS	Cost FY25 $M	Note
06 Spacecraft Contract (Phase B-D)	411.5	Includes SRC
07/09 Contractor MOS/GDS (Phase B-D)	10.6	
10 I&T (Phase B-D)	44.1	
Total	466.2	

- Customer provided a cost passthrough for the JPL Lander Vision System of $11.5M FY20
  - Team X inflated this to $13.0M FY25
- Customer provided a cost passthrough for the sampling system of $40.7M FY25
  - This cost was fully burdened, so no additional costs were added

Systems

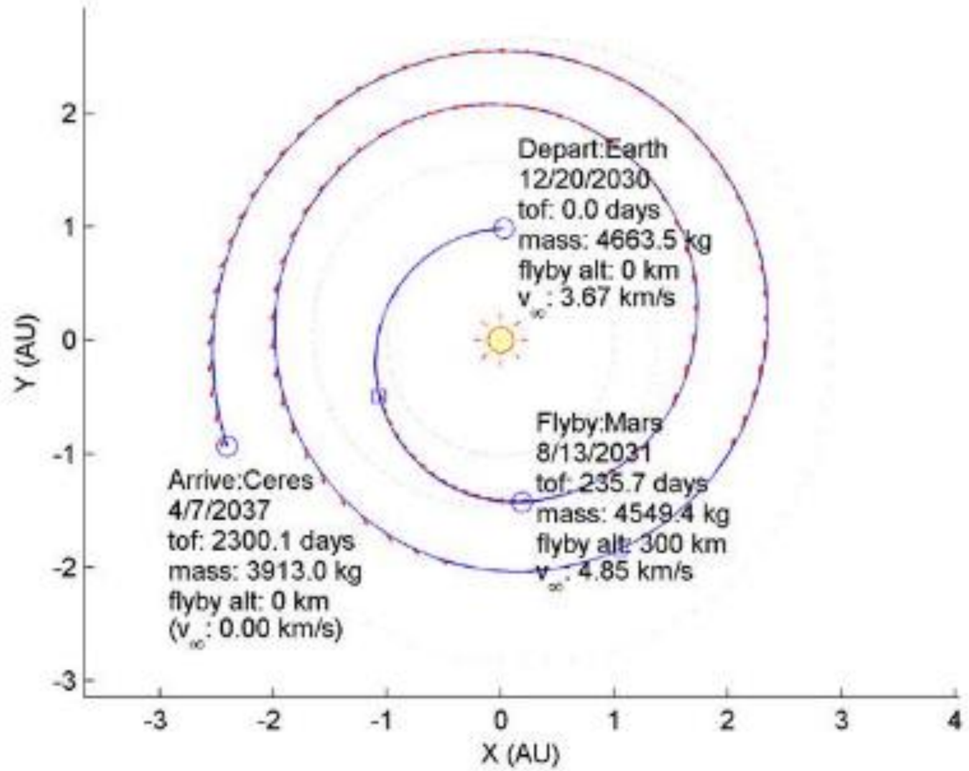
Summary of Team X Outputs

- Team X provided the following cost outputs
  - Development (Phases A-D)
    - WBS 1, 2, 3, 4, 5, 6.01, 6.02, and 12
    - JPL portions of WBS 7 and 9
    - Costs for Lander Vision System using Team X ICMs
      - Note that the customer cost passthrough for the LVS was used in the complete cost roll-up, but the Team X costs are provided for reference
  - Operations (Phases E-F)
    - WBS 4
      - Including 2 years of sample analysis after return to Earth
    - WBS 7 and 9
      - Customer team did not provide spacecraft contractor operations costs, so the costs assuming all JPL operations were estimated and used in the cost roll-up
      - JPL-only costs are provided as reference, and should be **added** to the spacecraft contractor costs if they are provided in the future

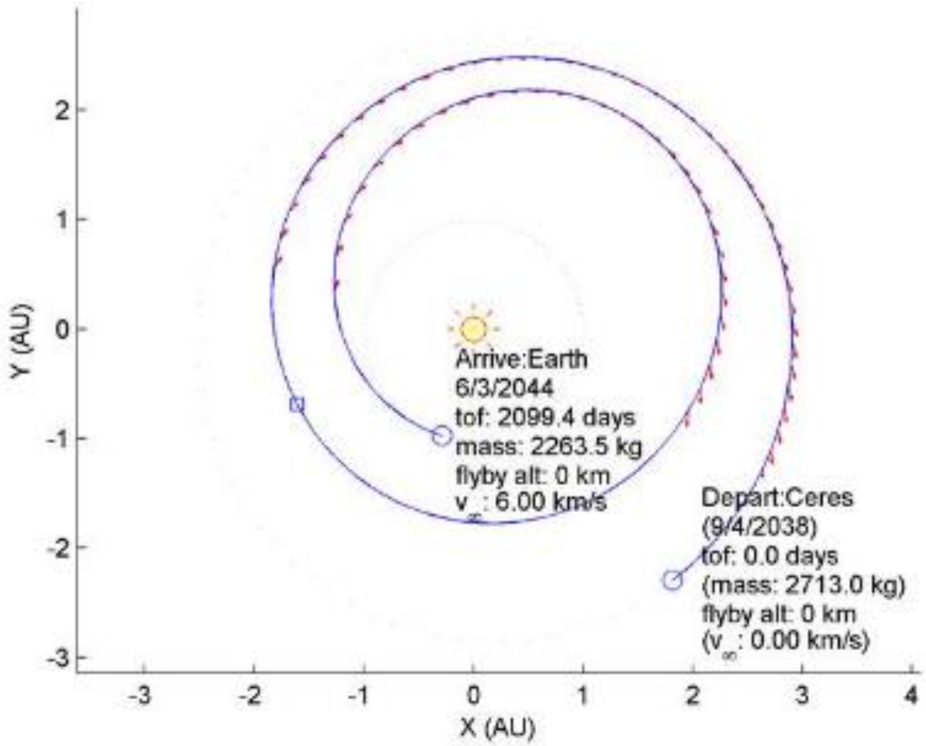
Concept of Operations – Interplanetary Trajectory

- Interplanetary trajectory provided by customer team

Outbound Leg



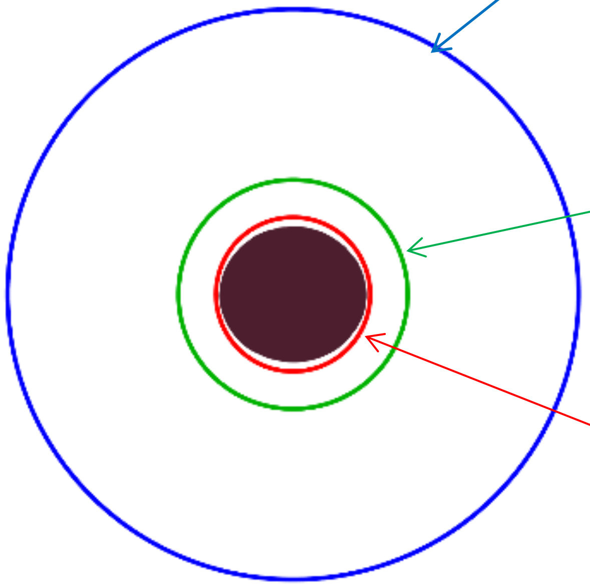
Return Leg



Systems

Concept of Operations – Ceres Orbit Phase

- Orbital Science CONOPs provided by customer team
- Science conducted at 3 orbit altitudes over approximately 12 months
  - 16 month orbital phase bookkept in schedule to provide margin
- Science data includes NAC imagery and gravity field radio science
- 39 Gb of science data returned during this phase
- NAC imagery is used to select a landing site and create a map for TRN during landing



Low-res:
- 120 days (18h period, 1400 km alt, 90º inc, circular)
- 2:1 resonance, 136 swaths every 0.75 days

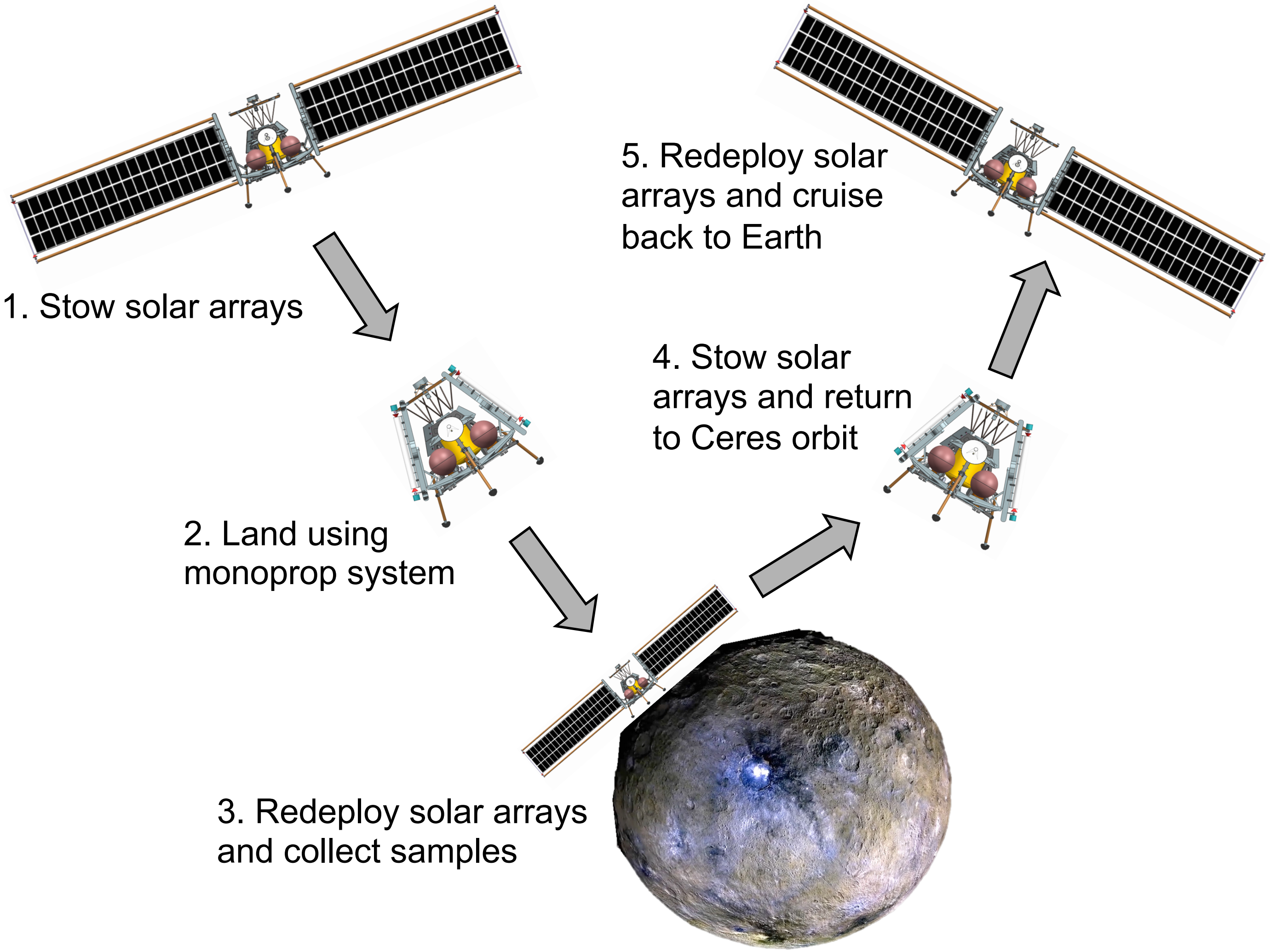
Medium-res:
- 90 days (4.5h period, 275 km alt, 90º inc, circular)
- 1:2 resonance, 50 passes every 0.38 days
- 2.8 m GSD (requirement for orbital science (Haulani, Ahuna Mons, Ernutet Crater, Cosecha Tholus) and basemap for TRN

High-res:
- 154 days (2.5h period, 28 km alt, 90º inc, circular)
- 5:18 resonance, 30 flyovers every 1.9 days
- 28-cm GSD (requirement)
- Gravity science (Haulani, Ahuna, Cosecha)
- Landing site selection

Systems

Concept of Operations – Landed Phase and Earth Return

- Once the orbital phase is complete, the spacecraft lands on Ceres:
  1. Stows solar arrays and lands using chemical propulsion system
  2. Redeploys solar arrays after landing
  3. Collects samples and conducts surface science for at least 5 Ceres days
- The spacecraft then returns to Ceres orbit and uses the EP system for the cruise back to Earth to return the sample container



Landed Operational Scenario

Sample Return Mission

- Operational Scenario
  - *Whole flight system lands*
  - *Solar arrays deploy*
  - *EECAMs take images of landing area + landscape*
  - *EECAM data return*
  - *Obtain IR data of surface between 2-4 microns (4 hr, including cooling)*
  - *Sampling – Takes < 1 Ceres day – operations from ground*
  - *Deploy EM sounding system - <30 min.*
  - *Integration for 5 Ceres days + EM data return in parallel*
  - *Take off to orbit*

Science

Cost Assumptions

- Costs include science team, science meetings, instrument accommodation analysis, sequence development, algorithm development, non-systematic data analysis and science management.
- Project support options were also selected, including data archiving and "environmental characterization" – which supports site selection activities with wide participation within the science community.
- Science team is quiescent (2 meetings/year) during cruise to Ceres (~75 months), and return cruise to Earth (~62 months)
- Team orbital training starts at arrival at Ceres (start of 16 month ops)
- Team sample analysis training starts 6 months before landing
- Sample analysis occurs for two years after return
- Analysis science team is approximately the same size as the orbital/landing science team
- Project-funded lab upgrades will be required for returned sample, some prior to sample return, some during sample analysis (costed using medium-priced flight instrument analog)
- Curation costs and analysis costs are managed within project

Science

Cost input – Sample Return Mission

Level_0 inputs	Basic Mission parameters			Model Value
Basic mission	Default	System	Override	Input
Target	Mars	Ceres		Ceres
Mission Cost Class	Large Flagship	B		B
Mission Design	Orbital			Orbital
Resource Interactions	None			None
Complex instrument#	0		1	1
Simple instrument#	0		3	3
Complex instrument # products (for IOS)	8			8
Simple instrument # products (for IOS)	5			5
Fraction external scientists	0.8			0.8
Mission Data Bits	1E+12	5.00E+08		5.00E+08
Analysis Complexity	Medium			Medium
Project Data Center	No			No
Project science visualization	No			No
Project data archiving	No		Yes	Yes
Project instrument support	No			No
Environmental characterization	No		Yes	Yes
Operations support	No		No	No

Phase	Default	System	Override	Input							
Fiscal year	2007	2025		2025							
Phase A start da	01/01/08	03/20/26		3/20/2026							
Duration A	0	12		12							
Duration B	0	12		12							
Duration C	0	18		18							
Duration D	0	16		16							
Duration Cruise	0	75.5333333		75.53333333							
Duration E	0	161		161	Override	Override	Input	Override	Input	Override	Input
Duration F	0	24		24	Subphase	#Complex	#Complex	# Simple	#Simple	Relative	Relative
Subphases				0	Activity description	Instruments	Instruments	Instruments	Instruments	Activity	Activity
Duration C1		9		9.00							
Duration C2		5		5.00							
Duration C3		4		4.00							
Duration D1		12		12.00							
Duration D2		4		4.00							
Duration E1	85.46666667	85.4666667	17	17	Orbital training and ops		1		3		1
Duration E2	0		62.46666667	62.46666667	Sample return cruise		1		3	0.05	0.05
Duration E3	0		6	6	Sample return training		1	1	1	3	3
Duration E4	0			0			1		3		1
Duration E5	0			0			1		3		1
Duration training	12	N/A	0	0							

Science

Cost model – Sample Return Mission

			A	B	C	D	E	F		
			12.00 M	12.00 M	18.00 M	16.00 M	17.00 M	24.00 M	Total	ABCD SUM
	WBS Costs		$K	$K	$K	$K	$K	$K	$K	$K
4		Science	711.6	2877.0	10441.1	7861.9	60566.3	26976.3	109434.2	21891.6
4.1		Science Management	220.8	975.4	1600.1	1422.3	12252.3	2495.7	18966.6	4218.6
	4.1.1	Science Office	220.8	975.4	1600.1	1422.3	12252.3	2495.7	18966.6	4218.6
4.2		Science Implementation	448.0	1535.9	7722.4	4576.2	32672.4	14500.7	61455.6	14282.5
	4.2.1	Participating Scientists	113.2	113.2	621.0	584.5	5972.9	2635.7	10040.4	1431.8
	4.2.T	Teams Summary	334.8	1422.7	7101.4	3991.7	26699.5	11865.0	51415.2	12850.7
4.3		Science Support	42.8	365.7	1118.6	1863.4	4641.6	979.9	9012.0	3390.5
	4.3.1	Science Data Visualization	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4.3.2	Science Data Archiving	0.0	143.7	215.6	336.8	2551.3	836.1	4083.5	696.1
	4.3.3	Instrument Support	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4.3.4	Science Environmental Characterization	42.8	222.0	903.0	1526.6	2090.4	143.8	4928.5	2694.4
	4.3.5	Operations Support	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.4		Spare	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.5		Technology Payload Implementation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Other Costs	Other cost description (includes 17.8 %burden)	$K	$K	$K	$K	$K	$K	$K	
	1	Sample archiving JSC customer input					7000.0	3000.0	10000.0	0.0
	2	Lab Equipment Upgrade					4000.0	6000.0	10000.0	0.0
	3								0.0	0.0
	4								0.0	0.0
	5								0.0	0.0

Science

Cost Discussion

- Curation cost based on JSC ROM, allocation between pre-/post return landing is to be negotiated
- Analysis staffing level, modeled here to be similar to science staffing for orbital ops, needs better definition to improve accuracy
- Analysis lab upgrades, assumed here to be the cost of an instrument, need better definition to improve accuracy
- Duration of analysis, assumed here to be 24 months, needs better definition to improve accuracy. Costs in this context are proportional to duration.
- One instrument was modeled as “complex” to emulate science staffing required to define sample capture and analyses during project phases a-d
- Some cost reduction might be achieved by reducing the level of science team participation during cruise to Ceres, though the modeled participation during cruise is already fairly small

Instruments Report

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Instruments

Design Requirements

- Mission Option:
  - Option 1: Ceres Orbit, Lander, and Sample Return

- Constraints
  - Observations on orbit in 3 different orbital altitudes
    - Identify landing location
      - Create basemap for Terrain Relative Navigation
    - Orbital science from optical observations
  - Observations when landed
    - Option 1: Context Imaging, local mineralogy, crust characteristics, and retrieve several samples
- Measurement (spectra, image, sounding, etc.)
    - Option 1: Color pushbroom imaging from orbit, IR Spectrum (minerology), EM Sounder (deployable electrodes) and magnetic field measurements (crust)

Instruments

Design Assumptions

- Instrument Suite
  - NAC
  - EM Sounder
  - IR Spectrometer (based off MLPS)
- Passthrough for the costs of the Sample Capture System in the Payload
  - PlanetVac
  - Note that the costs for the TBD sample return capsule closure system are not captured
    - Mass estimate from the provided MEL was added to PlanetVac mass
    - *Power estimate not provided*, and not WAG'ed either
- Engineering cameras in ACS include the 6 sample acquisition Context Cameras

Instruments

Design Assumptions

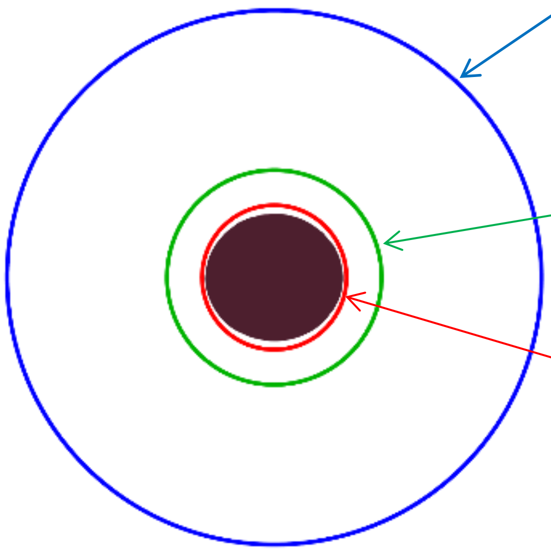
<table>
<tr><th></th><th>Mass CBE</th><th>Power CBE</th><th>Mass MEV</th><th>Power MEV</th><th>Other comments</th></tr>
<tr><td>NAC (2 units)</td><td>9.4</td><td>6.4</td><td>12.2</td><td>9.15</td><td>2 identical instruments, numbers are for 1</td></tr>
<tr><td>EM Sounder</td><td>3.9</td><td>6.2</td><td>5.07</td><td>8.9</td><td>Mass given as 3.0kg CBE for Opt 2</td></tr>
<tr><td>Infrared Spectrometer</td><td>5</td><td>15</td><td>6.5</td><td>21.45</td><td></td></tr>
<tr><td>Sample System PlanetVac</td><td>26</td><td>165</td><td rowspan="2">44.4</td><td>236</td><td>(mass lower than for Option 2)</td></tr>
<tr><td>Return Sample encapsulation Placeholder</td><td>8</td><td>0</td><td></td><td>Rolled mass into Sample System in Instrument sheet. Power impact not specified/included</td></tr>
<tr><td>Totals</td><td>62</td><td>Varies by mode</td><td>80.2</td><td>Varies by mode</td><td>Total mass includes 2 NAC units</td></tr>
</table>

Instruments

Operational View

- Orbital Phase: NAC observations:

16 months of orbital operations
(with margin)



Low-res:
- 120 days (18h period, 1400 km alt, 90º inc, circular)
- 2:1 resonance, 136 swaths every 0.75 days

Medium-res:
- 90 days (4.5h period, 275 km alt, 90º inc, circular)
- 1:2 resonance, 50 passes every 0.38 days
- 2.8 m GSD (requirement for orbital science (Haulani, Ahuna Mons, Ernutet Crater, Cosecha Tholus) and basemap for TRN

High-res:
- 154 days (2.5h period, 28 km alt, 90º inc, circular)
- 5:18 resonance, 30 flyovers every 1.9 days
- 28-cm GSD (requirement)
- Gravity science (Haulani, Ahuna, Cosecha)
- Landing site selection

- Landed Phase:
  - IR data of surface
    - about 4 hr including detector cooldown
  - Sample acquisition and encapsulation
    - takes <1 Ceres day
  - Deploy and perform magnetic and EM sounding measurements
    - Integrate for 5 Ceres days

Instruments

Cost

- Cost Assumptions
  - Assumed for this study that all instruments would be procured
- Cost Method
  - Customer supplied FY19 costs used for all but APXS and EM Sounder
    - Inflated FY19 dollars to FY25
    - Used NICM System runs for APXS and EM Sounder
    - Customer costs mostly higher than NICM System estimates using supplied mass/powers

	NICM Est.	Customer FY19 Costs	Passthru FY25	Other comments
NAC (2 units)	*25.5M*	19M for 2, 13.6M for 1	**16M for 1**	2 identical instruments, first unit costs used on sheet assuming usual NRE %
EM Sounder	**9.8M**	-	-	
IR Spectrometer	**14.1M**	-	**-**	
Sample System PlanetVac	N/A	N/A	**40.7M**	
Return Sample encapsulation Placeholder				Rolled mass into Sample System in Instrument sheet. Power and cost impact not specified/included
		Total Costs		**84M**

- Cost Drivers
  - None identified

- Potential Cost Savings
  - None identified

- Potential Cost Uppers
  - Cost risk associated with unknowns on the Sample Handling system
  - NAC costs provided by customer well under NICM estimate

Instruments

Design Analysis and Risks

- Strengths
  - Using high heritage instruments, starting from existing product lines
- Threats
  - Sample handling system may be more complicated than expected

Mission Design Report

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Mission Goals

- **This is an Asteroid (Ceres) sample return mission to :**

1. Constrain the environmental conditions in Ceres' early ocean and test whether they were amenable to prebiotic chemistry.

2. Determine the origin of the organic material found on Ceres' surface and its significance for prebiotic chemistry.

3. Confirm the presence of liquid in Ceres' deep interior or in local seas. Determine the nature and composition of the liquid.

4. Determine where Ceres originated from

Mission Design

- **Orbit/Trajectory Parameters**
  - SEP trajectory from Earth to Ceres with a Mars Gravity Assist
  - SEP trajectory from Ceres to Earth

- **Max distance from the sun**: 3 AU

- **De-orbit Approach**:
  - Hydrazine mono-prop DDL at Ceres (400 m/s)
  - Direct entry for the Sample Return Capsule (SRC) at Earth (Vinf < 6 km/s)

- **Takeoff Approach**
  - Hydrazine mono-prop at Ceres (370 m/s)

- **Total Delta V**:
  - 14 km/s SEP
  - 770 m/s hydrazine

Mission Design

- **Launch**: 12/20/2030
- **LV**: Falcon Heavy Recovery
- **Electric Propulsion Subsystem**: NEXT, 2 thrusters at a time, 600 kg throughput each
- **Solar Array**: 27.5 kW BOL at 1 au, 68.5 m^2 of active cell area
- **TOF from launch to Ceres Capture**: 6.3 yr
- **Stay Time at Ceres**: 500-day minimum
- **TOF (return leg from Ceres to Earth)**: 5.75 yr
- **Xenon Propellant**: 1320 kg (including 10% margin)
- **Hydrazine Propellant**: 1200-kg used at Ceres
- **Earth Return Velocity**: 6 km/s
- **Planetary Protection**: Unrestricted Return

- **Note**: No checkout modeled / xenon throughput required for orbital transfers not included, but are expected to be small

Cost

Land and Return

- **Sample Return**: In this option, Spacecraft lands on Ceres followed by a return to Earth trajectory leg

Phase	Duration (Months)	Cost ($M)
Phase A	12	1.09
Phase B	12	2.63
Phase C	18	4.94
Phase D1	12	3.86
Phase D2	4	1.41
Phase E	161	16.48

Total Cost = $30.42M

ACS Report

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Status: ready

ACS

Architecture

- Stabilization: 3-Axis
- Attitude Determination
  - LVS Camera (LCAM) for onboard terrain-relative navigation during descent and landing
- Attitude Control
  - (provided by contractor)

ACS

Cost Assumptions

Cost Parameter	Parameter Option
Include Phase D Costs	Yes
ADCS Heritage Factor	Similar w/ Minor Mods
Mission Class from Guidelines: B	B
S/C Performance Pointing Control & Stability	0.1 deg

Number of Pieces of ADCS Equipment	2
Number of Types of ADCS Equipment	1
Hardware Quantity Factor (for Engineering support sized with subsystem)	0.7

Optional ACS Control Functions

- [ ] Star Identification (not delivered with HW)
- [ ] Mars Pathfinder Style EDL
- [ ] Mars Exploration Rover Style EDL
- [ ] Mars Science Laboratory Style EDL
- [ ] Aero-manuevering During Entry
- [x] Pin-point Landing (~100 Meter Accuracy)
- [ ] Hazard Detection and Avoidance
- [ ] Terrestrial Planet Finder Class Formation Flying (3+ Spacecraft)
- [ ] 2 - Spacecraft Rendezvous
- [ ] Target - Relative Tracking (Small Body Target)
- [x] Small Body Landing
- [ ] Small Body "Touch-and-Go" (Approach & Touch While Passing By)
- [ ] SMAP Style Dynamics and Control
- [ ] Extensive Field Testing

ACS

Cost

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		2,284	2,436	3,713	5,669	714	733	244	-	-	**15,793**
06.10.01 GN&C Subsystem Management		243	243	182	101	81	243	81			**1,175**
06.10.02 GN&C Subsystem Engineering		804	804	603	335	268	490	163			**3,466**
06.10.03 GN&C Sensors AND		-	153	2,000	4,777	-					**6,930**
06.10.04 GN&C Actuators AND											
06.10.05 GN&C I/F Electronics											
06.10.08 GN&C Control Analysis		1,237	1,237	928	456	365				-	**4,223**

Hardware Costs (with spares, EM's)

Systems Note: The customer team's cost passthrough for the LVS was used, but the Team X costs across ACS, CDS, and Software are provided for reference.

	Flight Models	#	Engineering Models	#	Qualification Units	#	Models for Current Study ($K)	H/W Engr Equip. Dev (Wm)	Flight Spares	#	Off-the-Shelf Cost ($K)	Cost for Flight Units	Cost for Spares	Cost for Qual Units	Cost for EM's	Development Type
LVS LCAM	4000	2	1600	1	0	0			0	0	2000	100%	100%	120%	80%	Out-of-House
		0		1		0				0		100%	100%	120%	80%	Out-of-House
				1		0				0		100%	100%	120%	80%	Out-of-House
		0		1		0				0		100%	100%	120%	80%	Out-of-House
		0		1		0				0		100%	100%	120%	80%	Out-of-House
		0		1		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
												100%	100%	120%	80%	Out-of-House
												100%	100%	120%	80%	Out-of-House
Subtotals in FY2025 $K	4000		1600		0		0	0	0							

CDS Report

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Status: Ready

CDS

Design Requirements

- Mission:
  - Lander Vision System (LVS) for a Ceres Sample Return mission
  - Contractor provided spacecraft bus including CDS
- Data Volumes
  - N/A
- Interfaces
  - Lander Vision System
- Radiation
  - Radiation environment at Ceres is not problematic

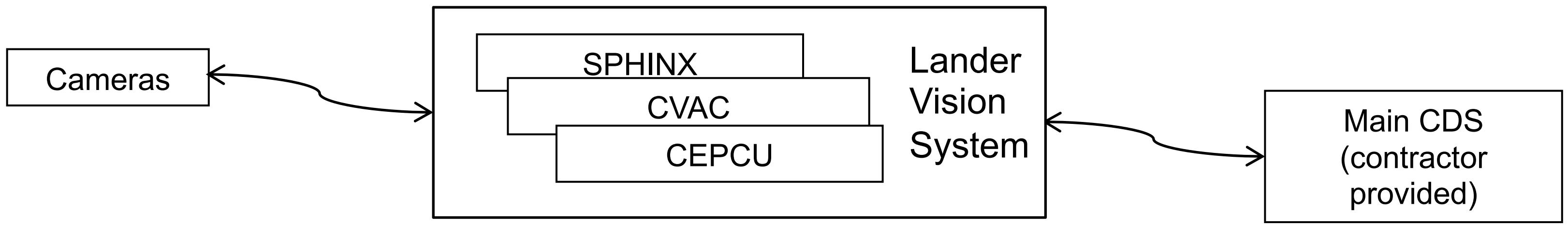
CDS

Design Assumptions, Rationale, Cost Assumptions

- Spacecraft built by vendor
  - This study is only a Sphinx-based Lander Vision System
- Heritage Assumptions
  - Sphinx is current SmallSat CDS system, in process of being certified for Class B missions
  - Lander Vision System has heritage from Mars 2020, but the version for this study is based on a Sphinx processor, in a smaller form factor than the M2020 package
- Sphinx hardware chosen for low mass and power consumption
- Cost Assumptions
  - Discovery Slice mission category (one piece of a larger system)
  - In-house build, single FM hardware, no spares;
  - Single EM, Prototype, and Testbed; single each BTE and GSE

CDS

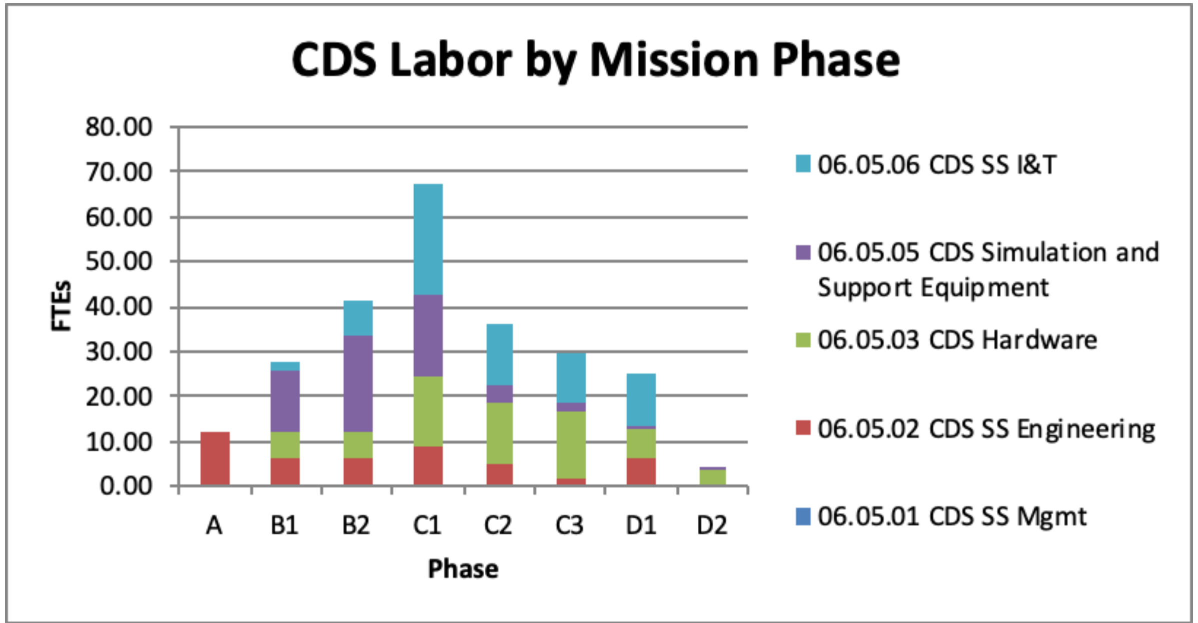
Block Diagram



CDS

Cost

- 1ST Unit Cost : $10.3M
- Nth Unit Cost: $3.7M



Systems Note: The customer team's cost passthrough for the LVS was used, but the Team X costs across ACS, CDS, and Software are provided for reference.

Task ID	260 Ceres Sample Return Wrap-Up	A	B	C1	C2	C3	D1	D2	E	F	Total
06.05	Total Cost (K$)	424.5	3172.0	3167.0	1287.1	1186.5	894.6	127.4	0.0	0.0	10259.1
	Labor Total (FTE)	12.00	68.63	67.58	36.21	29.84	25.29	3.60	0.00	0.00	20.26
06.05.01	Subtotal Cost - Subsystem Management	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Labor (FTE)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
06.05.02	Subtotal Cost - Subsystem Engineering	424.5	424.5	318.3	176.9	70.7	212.2	0.0	0.0	0.0	1627.1
	Labor (FTE)	12.00	12.00	9.00	5.00	2.00	6.00	0.00	0.00	0.00	3.83
.06.05.03	Subtotal Cost - C&DH Hardware	0.0	935.7	1023.4	478.5	645.0	241.5	121.1	0.0	0.0	3445.1
	Labor (FTE)	0.00	11.80	15.54	13.53	14.53	6.83	3.42	0.00	0.00	5.47
06.05.05	Subtotal Cost - Simulation & Support Equipment (SSE)	0.0	1493.5	949.8	145.5	81.7	16.4	6.3	0.0	0.0	2693.2
	Labor (FTE)	0.00	35.83	18.28	3.93	2.31	0.46	0.18	0.00	0.00	5.08
06.05.06	Subtotal Cost - I & T	0.0	318.3	875.4	486.4	389.1	424.5	0.0	0.0	0.0	2493.7
	Labor (FTE)	0.00	9.00	24.75	13.75	11.00	12.00	0.00	0.00	0.00	5.88

Ground Systems Report

Author: Greg Welz
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Phone: (818) 393-4978

Status: ready

Ground Systems

Design Requirements

- Mission:
  - Ceres Exploration
  - SEP cruise to Ceres, circular orbit to landing and option for sample return
- Data Volumes
  - Orbiter/sample return option has 39 Gb during orbit, 6 Gb on surface
- 1 Option
  - Sample return – Contractor provided S/C and ops support

Ground Systems

Design Assumptions

- Ground system is based on a mission specific implementation of the standard JPL mission operations and ground data systems
- Surface Ops mostly preprogrammed with no planned tactical operations,

- Phase E Activity Description
  - Launch and check-out
  - SEP Cruise with Mars Gravity Assist to Ceres
  - Ceres Approach
  - Approach science
  - Orbit Science + landing site selection
  - Landing activities
    - Prep for landing
    - Landing
    - Surface deployments
    - Science observations
    - Option 1 sample collection
    - Launch
  - SEP Return to Earth cruise
  - Sample delivery to UTTR
  - End of Flight Ops

Ground Systems

Design

- Ground Network
  - DSN 34m BWG Subnet, all communications via X-band
  - At max range average data rate 75Kb/s
  - Data rate and tracking plan more than adequate for basic mission needs

DSN Profile

	Support Period		Antenna	Service	Hours per	No. Tracks	No. Weeks
	No (#)	Name (description)	Size (meters)	Year (year)	Track (hours)	per Week (# tracks)	Required (# weeks)
Phase D	1	Launch & Early Ops	34BWG	2030	8	21.0	2.0
Phase D	2	Check out and first maneuver	34BWG	2030	8	14.0	2.0
Phase E	3	Crusie to MGA	34BWG	2030	8	1.0	28.0
Phase E	4	MGS coverage	34BWG	2030	8	14.0	4.0
Phase E	5	Cruise to Ceres	34BWG	2030	8	1.0	296.0
Phase E	6	Ceres Orbital Ops part 1	34BWG	2030	8	7.0	75.0
Phase E	7	Ceres Surface Ops	34BWG	2030	8	21.0	1.0
Phase E	8	Ceres orbital Ops part 2	34BWG	2030	8	7.0	2.0
Phase E	9	Cruise to Earth - 3 momths	34BWG	2030	8	1.0	274.0
Phase E	10	Cruise to Sample Return endgame	34BWG	2030	8	3.0	13.0
Phase E	11	Earth End Game	34BWG	2030	8	21.0	4.0

Ground Systems

Cost Assumptions – Option 1

- Mission is Sample return from Ceres
- Has 3 instrument types, or which one type is a series of engineering cameras. Radio science uses the telecom system and not considered a separate instrument
- Selected One of a kind science operation for this mission, surface portion is not tactical nor is it routine. The orbital operations would be routine complex.
- Contractor provides S/C Team and Mission Control Team – zero the relevant costs for JPL

Number of Commandable Spacecraft	1
Type of Spacecraft	Sample Return
Domain	Deep Space
Number of Instruments	4
Nature of Science Operations	One of a kind
Number of Partners	1
Number of Foreign Partners	0
Lowest Experience of Partners	Significant
S/C Builder	Contrator
S/C Operator	JPL & S/C Vendor
Science Operations	JPL
Launch Date	12/20/2030
Phase E LOE Distribution	Duration (Months)
Heavy Support	24
Moderate Support	137
Light Support	0
Phase E Total	161
	Duration (Months)
Science Ops	22
Non-Science Ops	139

Ground Systems

Cost

- $M BY2025
  - Does not include MD/Nav related costs found in WBS 07/09, these are reported in MD/Nav section and summed together in the Cost section.
  - JPL **with** contractor related work for phase **B-F**

$M BY 2025	Total Dev	Total Ops	Total A-F
07 MOS	$ 20.68	$ 50.86	$ 71.54
09 GDS	$ 24.07	$ 30.82	$ 54.89
09A Flt Sys GDS	**$ 21.50**	**$ 25.39**	**$ 46.89**
09B SDS/IDS	**$ 2.57**	**$ 5.43**	**$ 8.00**

  - JPL **without** contractor related work for phase **B-D**. Since contractor cost not provided for Phase E, substituting in JPL numbers for Phase E. If contractor costs are available for Phase E, subtract 102.6 from the 07 MOS cost and add in the contractor costs

$M BY 2025	Total Dev	Total Ops	Total A-F
07 MOS	$ 20.68	$ 153.45	$ 174.13
09 GDS	$ 24.07	$ 30.82	$ 54.89
09A Flt Sys GDS	**$ 21.50**	**$ 25.39**	**$ 46.89**
09B SDS/IDS	**$ 2.57**	**$ 5.43**	**$ 8.00**

Software Report

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Status: ready

Software

Design Requirements

- Mission:
  - LVS for use on a contractor built spacecraft
  - Does not include any software on the spacecraft flight computer, ONLY the VCE FSW

- Team Graphical Distribution
  - Assume JPL co-located development

Software

Cost Assumptions

- TeamX has costed VCE software before. This estimate was reused.
  - Estimated 70K lines of code
    - M2020 VCE FSW 93K LOC * 0.75
  - Assume M2020 heritage with major modifications
  - M2020 VCE FSW costs:
    - $7.4M
    - 17.2 WY
  - Approximate cost for VCE software on this spacecraft: $3.2M
  - Note: This $3.2M does not include GNC algorithm development or FPGA development effort

Software

Cost – Option 1

- NRE: $3.4mm
- RE: $0.2mm
- Total: $3.6mm
- NOTE: the "Development Infrastructure Support" line (1.8M) is too high – this is an artifact of the software estimate tool. The real number is 0.8M total, the other 1.0M should be distributed proportionally among the remaining categories.

WBS	Title	Cost ($M) Phase A	PMSR-PDR Phase B	PDR-ARR Phase C	ARR-Launch Phase D	Total $M
06.12.01	Flight Software Management	$ 0.0	$ 0.0	$ 0.1	$ 0.1	**$ 0.2**
06.12.02	Flt SW System Engineering	$ 0.0	$ 0.1	$ 0.1	$ 0.1	**$ 0.3**
06.12.03	C&DH	$ -	$ 0.1	$ 0.5	$ 0.1	**$ 0.7**
06.12.04	GN&C FSW	$ -	$ -	$ -	$ -	**$ -**
06.12.05	Engineering Applications FSW	$ -	$ -	$ -	$ -	**$ -**
06.12.06	Payload Accommodation FSW	$ -	$ -	$ -	$ -	**$ -**
06.12.07	System Services	$ -	$ -	$ -	$ -	**$ -**
06.12.08	Flt SW Development Testbed	$ -	$ -	$ 0.1	$ 0.0	**$ 0.1**
06.12.09	Flt SW - Integration and Test	$ -	$ -	$ 0.3	$ 0.2	**$ 0.5**
	Total Cost of Labor	**0.0**	**$ 0.2**	**$ 1.1**	**$ 0.4**	**$ 1.7**
06.12.01	Development Infrastructure Procurements	$ 0.0	$ 0.0	$ 0.0	$ 0.0	**$ 0.1**
06.12.01	Travel	$ -	$ -	$ -	$ -	**$ -**
06.12.01	Development Infrastructure Support	$ -	$ 0.3	$ 0.7	$ 0.7	**$ 1.8**
	Total Cost (including Procurements, etc.)	**$ 0.0**	**$ 0.5**	**$ 1.9**	**$ 1.2**	**$ 3.6**
	Percent by Phase	1%	14%	53%	33%	

Systems Note: The customer team's cost passthrough for the LVS was used, but the Team X costs across ACS, CDS, and Software are provided for reference.

Planetary Protection Report

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Phone: 818 354 0130

Planetary Protection

Mission Category and Justification

- Option 1
  - This is a Category V mission according to the official NASA Planetary Protection guidelines, “NPR 8020.12D Planetary Protection Provisions for Robotic Extraterrestrial Missions.” Category V includes all sample return mission from any solar system body.
    - Outbound: This mission must meet the requirements of a Category III mission.
    - Inbound: This mission must meet the requirements of a Category 5-Unrestricted mission.

Planetary Protection

Requirements

- Documentation:
  - Request for Planetary Protection Mission Categorization
  - Planetary Protection 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
  - *Note: Subsidiary Plans should not be required for this mission*

Planetary Protection

Requirements (cont'd)

- 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

Planetary Protection

Requirements (cont'd)

- Mars Impact Avoidance:
  - Probability of impact of Mars by the launch vehicle (or any stage thereof) shall not exceed 10^{-4} for 50 years following launch
  - 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

Planetary Protection

Requirements (cont'd)

- Mars Impact Avoidance (cont'd):
  - If probability of Mars impact exceeds requirement then (cont'd):
    - Biological Contamination Control:
      - Bioassays to establish the microbial bioburden levels
      - Independent verification bioassays by NASA Planetary Protection Officer
  - *Note: it will be assumed that the Ceres mission will meet the Mars probability of impact requirement*

- Spacecraft assembled in Class 100,000 / ISO Class 8 (or better) clean facilities, with appropriate controls and procedures

Planetary Protection

Requirements (cont'd)

- Project shall demonstrate a probability of less than 10^{-4} that one or more Earth micro-organisms might survive to contaminate an ocean or other liquid water body on Ceres
  - The calculation of this probability shall include a conservative estimate of poorly known parameters, and address the following factors, at a minimum:
    a. Bioburden at launch
    b. Cruise survival for contaminating organisms
    c. Organism survival in the radiation environment adjacent to the target
    d. Probability of encountering/landing on the target, including spacecraft reliability
    e. Probability of surviving landing/impact on the target
    f. Mechanisms and timescales of transport to the subsurface
    g. Organism survival and proliferation before, during, and after subsurface transfer

- Option 1:
  - No additional requirements on the sample handling hardware and the earth return portion of the mission

Planetary Protection

Implementing Procedures

- 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 accidental impact of Mars due to Failure during the cruise phase
  - Flight System microbial burden estimation at launch
  - Final disposition of all hardware
  - Probability that a spacecraft failure prevents a soft landing on Ceres
  - Option 1: Probability of accidental impact of Mars due to Failure during Earth return
- Spacecraft assembly performed in Class 100,000 / ISO Class 8 (or better) clean facilities, with appropriate controls and procedures

Planetary Protection

Subsystem Design Requirements

- Launch vehicle trajectory must be biased to meet Mars probability of impact requirement
- Flight System trajectory must be biased to meet Mars probability of impact requirement

Planetary Protection

Assumptions

- The Ceres asteroid will be re-categorized to a PP Category II* body
- Mission will meet both Mars probability of impact requirements and Ceres probability of contamination requirement by analysis
  - No cleaning and/or microbial reduction of flight system or launch vehicle hardware will be required
  - No bioassay sampling of flight system or launch vehicle hardware will be required
- No cleaning/microbial reduction or bioassay sampling of sample-handling hardware will be required
- The planned final disposition of the Lander will be acceptable to the NASA PP Officer

Planetary Protection

Cost Assumptions / Rationale

- The Ceres asteroid will be re-categorized to a PP Category II* body
- This Cost includes the following:
  - All PP documentation and review support:
  - Required analyses

Planetary Protection

Cost – Sample Return Mission

	FTE (yrs)	Cost (FY25 M$)
Development Phase	**1.73**	**0.73**
Operations Phase	**0.76**	**0.32**
TOTAL	**2.49**	**1.05**

Planetary Protection

Risks

- Mars probability of impact requirements may not be met, requiring cleaning/microbial reduction, bioassay sampling, and additional analyses
- Ceres probability of contamination requirement may not be met, requiring cleaning/microbial reduction, bioassay sampling, and additional analyses
- Stringent biological cleanliness requirements may be placed on the sample handling hardware, requiring cleaning/microbial reduction, bioassay sampling, and a biobarrier

Cost Report

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Cost

Disclaimer

The costs presented in this 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 costs presented are heavily dependent on the customers teams cost passthroughs for the payload, spacecraft, and LVS. Team X is not able to validate the costs for these elements.

Cost

Cost Requirements

- Constant/Real Year Dollars: FY$2025 by WBS element
- Cost Target: $1.1B (FY$2025)
  - Estimates are generated using the current JPL Institutional Cost Models (ICM) with 2025 rates and factors for the JPL effort
  - Pass thru values obtained from the customer include a 17.5% burden (JPL)
  - Subsystem reports include estimates in FY$2025
- Cost estimates are lifecycle costs provided at WBS levels 2 and 3
- Assume Out-House development for Spacecraft using a Product Line development
- There is no cost included for de-orbit activities
- Launch Vehicle cost is excluded
- Launch date is 12/20/2030
  - Based on a schedule provided in Customer briefing package

Cost

Cost Assumptions

- Fiscal Year: FY$2025
- Mission Class: B
- Mission duration: 13.5 years of operations, plus 24 months for Phase F
- Cost Category: Large

- Wrap Factors
  - Mission Assurance (Less Reserves)
    - Development 3.0%
    - Operations 0.9%
  - E&PO – no cost is included
  - Reserves (Not calculated on Tracking costs)
    - Phases A-D 50%
    - Phases E-F 25%

Cost

Cost Assumptions – Schedule

- Development schedule is **58 months**, assumes significant flight system heritage consistent with a December 2030 launch date
- Mission Operations duration
  - **185 months**, includes a 24 month Phase F

Phase	Duration
Phase A	**12 mo.**
Phase B	**12 mo.**
Phase C	**18 mo.**
Design	9 mo.
Fabrication	5 mo.
Subsystem I&T	4 mo.
Phase D	**16 mo.**
System I&T	12 mo.
Launch Operations	4 mo.
Phase E	**161 mo.**
Phase F	**24 mo.**

Cost

Basis of Estimate (1 of 5)

WBS #	Title	Description	Estimating Method
01.0	Program Management	The business and administrative planning, organizing, directing, coordinating, controlling, and approval processes used to accomplish overall Project objectives that are not associated with specific hardware (HW) or software (SW) elements.	JPL ICM
02.0	Project Systems Engineering	The technical and management efforts of directing and controlling an integrated engineering effort for the project. Includes the effort to define the Project space-ground system, conducting trade studies; the integrated planning and control of the technical program efforts of design engineering, specialty engineering, and integrated test planning; the effort to transform Project objectives into a description of system requirements and a preferred system configuration; the technical oversight and control effort for planning, monitoring measuring, evaluating, directing, and replanning the management of the technical program. Documentation products include Level 2 Project Requirements; Design Report; Interface Control Documents (ICDs); CADRe; Project Verification and Validation (V&V) Plan; Information & Configuration Management Plan; Project Software Management Plan; Project Risk Management Plan; Planetary Protection Plan; Contamination Control Plan; and several launch services deliverables. Excludes any design engineering costs (which are in elements 06 and 07).	JPL ICM
03.0	Mission Assurance	The technical and management efforts of directing and controlling the Safety & Mission Assurance Elements of the project. Includes design, development, review, and verification of practices and procedures intended to assure that the delivered Spacecraft System and Instruments/payloads meet performance requirements and function for their intended lifetimes. Excludes Mission and Product Assurance efforts at partners/ subcontractors other than a review/oversight function, and the direct costs of environmental testing.	JPL ICM

Cost

Basis of Estimate (2 of 5)

WBS #	Title	Description	Estimating Method
04.0	Science	The technical and management efforts of directing and controlling the Science investigation aspects of the project. Includes the efforts associated with defining the science requirements; ensuring the integration of the science requirements with the Instruments, Payloads, Flight and Ground Systems; providing the algorithms and software for science data processing and analyses; science data analysis and archiving. Products include the Level 2 Science Requirements; Science Management Plan; Science Data Management & Archive Plan; and MOU with science data archive provider. Technology: The technical and management efforts of directing and controlling the Technology Demonstration aspects of the project. Includes the efforts associated with defining the technology demonstration requirements, integrating those requirements with the other project systems, and the team(s) associated with planning and analyzing the results of the technology payload demonstration(s). Excludes hardware and software for on-board science Instruments / Payloads and technology demonstration payloads.	Estimated by Science Chair running the JPL ICM
05.0	Payload System	The equipment provided for special purposes in addition to the normal equipment integral to the spacecraft. Includes experimental, scientific data gathering, and technology demonstration equipment placed on board the flight system.	Customer-provided and NICM model

Cost

Basis of Estimate (3 of 5)

WBS #	Title	Description	Estimating Method
06.0	Flight System Management	The Spacecraft System serves as the platform for carrying payload, instruments and other mission-oriented equipment in space to the mission destination(s) to achieve the mission objectives. May be a single module Spacecraft System; or multiple modules that comprise the Spacecraft System such as cruise stage, orbiter, lander, or rover. Each module of the Spacecraft System includes subsystems such as: power, C&DH, telecom, mechanical, thermal, propulsion, GN&C, harness and flight software. Includes all design, development, production, assembly, and test efforts to deliver the completed Spacecraft System for integration with the Payload, Launch Vehicle, MOS and GDS Systems. NOTE: The term Flight = SC + Payload and either 'SC' or 'S/C' is used as an acronym for spacecraft. Documentation products include the S/C System Implementation Plan; S/C Operating Scenarios; Level 3 S/C System Requirements; S/C System Design; various software documents; S/C System Block Dictionary; Flight Rules & Constraints; Command and telemetry dictionaries; and other documents listed in elements below. Does not include support to the Project level I&T activity (ATLO). Note that Payload/Instrument only projects are not required to use this element of the standard WBS Template.	FSM and FSE estimated by JPL ICM, Spacecraft and LVS customer-provided

Cost

Basis of Estimate (4 of 5)

WBS #	Title	Description	Estimating Method
07.0	Mission Operations	The Mission Operations System (MOS) is the ground-based system required to conduct project mission operations and consists of the following key components: a) Human resources: Trained and certified personnel b) Processes and Procedures: Documented, tested procedures to ensure that operations are conducted in a reliable, consistent and controlled manner c) Facilities: Offices, conference rooms, operations areas, testbeds and other space to house the personnel and perform the operations d) Hardware: Ground-based communications and computing hardware and associated documentation required to perform mission operations e) Software: Ground-based software and associated documentation required to perform mission operations f) Networks: Ground-based networks utilized during mission operations g) Tracking stations of the Deep Space Network and NEN/SN Note that some of these components are developed and maintained under WBS Element 09, Ground Data System.	Estimated by MOS/ GDS Chair running the JPL ICM, customer-provided contractor costs
08.0	Launch Vehicle	The primary means for providing initial thrust to place the flight system directly into its operational environment or on a trajectory towards its intended target. Includes launch Vehicle; associated launch services.	Not included
09.0	GDS	The grouping of the Flight Engineering Ground Data System (GDS) and the Science Data System accounts under a single roll-up account.	Same as 07.0
10.0	ATLO	The human resources, equipment, data, services, and facilities required to assemble, integrate, test, and deliver the Integrated Spacecraft, Payload, Launch Vehicle, MOS and GDS systems that meet Project requirements. Includes mechanical and electrical assembly; functional testing; performance testing and environmental testing; transportation/logistics; Launch Site support.	Customer-provided

Cost

Basis of Estimate (5 of 5)

WBS #	Title	Description	Estimating Method
11.0	Education and Public Out-reach	Provide for the Education and Public Outreach (EPO) responsibilities of JPL's missions, projects, and programs in alignment with NASA's Strategic plan for Education. Includes management and coordinated activities, formal education, informal education, public outreach, media support, and web site development.	Not included in estimate
12.0	Mission and Navigation Design	Mission Design: Manage and develop the project mission and navigation designs. Includes all mission analysis; mission engineering; and navigation design. Also includes management of Mission Design schedules, cost and performance, liaison with all elements of the project, and support of Project design teams and reviews.	Estimate provided by Navigation Chair running the JPL ICM
-	Re-serves	Project reserves	% provided by customer

Systems

Customer Cost Passthroughs

- Customer provided the following cost passthroughs in FY25 $M
  - Costs do not include JPL procurement burden of 17.5% which was added by Team X

WBS	Cost FY25 $M	Note
06 Spacecraft Contract (Phase B-D)	411.5	Includes SRC
07/09 Contractor MOS/GDS (Phase B-D)	10.6	
10 I&T (Phase B-D)	44.1	
Total	466.2	

- Customer provided a cost passthrough for the JPL Lander Vision System of $11.5M FY20
  - Team X inflated this to $13.0M FY25
- Customer provided a cost passthrough for the sampling system of $40.7M FY25
  - This cost was fully burdened, so no additional costs were added

Cost

Cost Summary

COST SUMMARY (FY2025 $M)	Generate ProPricer Input	Team X Estimate CBE	Team X Estimate PBE
Project Cost		$1180.6 M	$1687.1 M
Launch Vehicle		$0.0 M	$0.0 M
Project Cost (w/o LV)		$1180.6 M	$1687.1 M
Development Cost		$861.1 M	$1291.3 M
Phase A		$8.6 M	$12.9 M
Phase B		$77.5 M	$116.2 M
Phase C/D		$775.0 M	$1162.1 M
Operations Cost		$319.5 M	$395.8 M

Phase A-D development Cost with Reserves: $1291.3 M FY25

Cost

Phases A-D, including Reserves

WBS Elements	NRE	RE	1st Unit
Project Cost (including Launch Vehicle)	$1267.8 M	$419.3 M	$1687.1 M
Development Cost (Phases A - D)	$872.3 M	$418.9 M	$1291.3 M
01.0 Project Management	$17.7 M		$17.7 M
1.01 Project Management	$8.1 M		$8.1 M
1.02 Business Management	$7.4 M		$7.4 M
1.04 Project Reviews	$1.3 M		$1.3 M
1.06 Launch Approval	$0.9 M		$0.9 M
02.0 Project Systems Engineering	$17.8 M	$0.4 M	$18.3 M
2.01 Project Systems Engineering	$5.4 M		$5.4 M
2.02 Project SW Systems Engineering	$3.5 M		$3.5 M
2.03 EEIS	$0.6 M		$0.6 M
2.04 Information System Management	$1.8 M		$1.8 M
2.05 Configuration Management	$1.6 M		$1.6 M
2.06 Planetary Protection	$0.3 M	$0.1 M	$0.4 M
2.07 Contamination Control	$1.4 M	$0.3 M	$1.7 M
2.09 Launch System Engineering	$1.0 M		$1.0 M
2.10 Project V&V	$1.9 M		$1.9 M
2.11 Risk Management	$0.4 M		$0.4 M
03.0 Mission Assurance	$22.9 M	$11.0 M	$33.9 M
04.0 Science	$21.9 M		$21.9 M
04.01, 04.02, & 04.03 Science Teams	$21.9 M		$21.9 M
05.0 Payload System	$61.3 M	$48.6 M	$109.9 M
5.01 Payload Management	$4.7 M		$4.7 M
5.02 Payload Engineering	$4.4 M		$4.4 M
Spacecraft	$52.3 M	$48.6 M	$100.8 M
NAC	$14.8 M	$21.4 M	$36.2 M
PlanetVac and Tube closure system	$23.6 M	$17.1 M	$40.7 M
Infrared Spectrometer	$8.2 M	$5.9 M	$14.1 M
EM Sounder	$5.7 M	$4.1 M	$9.8 M

WBS Elements	NRE	RE	1st Unit
06.0 Flight System	$337.2 M	$198.6 M	$535.8 M
6.01 Flight System Management	$12.2 M		$12.2 M
6.02 Flight System Systems Engineering	$27.1 M		$27.1 M
6.03 Product Assurance (included in 3.0)			$0.0 M
JPL Lander Vision System	$7.8 M	$5.2 M	$13.0 M
Spacecraft	$290.1 M	$193.4 M	$483.5 M
6.14 Spacecraft Testbeds	$0.0 M	$0.0 M	$0.0 M
07.0 Mission Operations Preparation	$35.6 M		$35.6 M
JPL Mission Operations Preparation	$23.2 M		$23.2 M
7.0 MOS Teams	$20.7 M		$20.7 M
7.03 Tracking (Launch Ops.)	$0.7 M		$0.7 M
7.06 Navigation Operations Team	$1.7 M		$1.7 M
7.07.03 Mission Planning Team	$0.0 M		$0.0 M
LM Mission Operations Preparation	$12.5 M		$12.5 M
09.0 Ground Data Systems	$24.6 M		$24.6 M
9.0A Ground Data System	$21.5 M		$21.5 M
9.0B Science Data System Development	$2.6 M		$2.6 M
9A.03.07 Navigation H/W & S/W Development	$0.6 M		$0.6 M
10.0 ATLO	$31.1 M	$20.7 M	$51.8 M
11.0 Education and Public Outreach	$0.0 M	$0.0 M	$0.0 M
12.0 Mission and Navigation Design	$11.6 M		$11.6 M
12.01 Mission Design	$1.7 M		$1.7 M
12.02 Mission Analysis	$4.1 M		$4.1 M
12.03 Mission Engineering	$1.6 M		$1.6 M
12.04 Navigation Design	$4.2 M		$4.2 M
Development Reserves	$290.5 M	$139.6 M	$430.2 M

Cost

Phases E-F, including Reserves

WBS Elements	NRE	RE	1st Unit
Operations Cost (Phases E - F)	$395.4 M	$0.4 M	$395.8 M
01.0 Project Management	$19.3 M		$19.3 M
1.01 Project Management	$13.0 M		$13.0 M
1.02 Business Management	$5.5 M		$5.5 M
1.04 Project Reviews	$0.6 M		$0.6 M
1.06 Launch Approval	$0.2 M		$0.2 M
02.0 Project Systems Engineering	$0.0 M	$0.3 M	$0.3 M
2.06 Planetary Protection	$0.0 M	$0.3 M	$0.3 M
Spacecraft	$0.0 M	$0.3 M	$0.3 M
03.0 Mission Assurance	$4.1 M	$0.0 M	$4.1 M
04.0 Science	$80.8 M		$80.8 M
4.02 Science Team	$80.8 M		$80.8 M
06.0 Flight System	$0.0 M		$0.0 M
6.02 Flight System Systems Engineering	$0.0 M		$0.0 M
07.0 Mission Operations	$183.6 M		$183.6 M
7.0 MOS Teams	$153.5 M		$153.5 M
7.03 Tracking	$14.3 M		$14.3 M
7.06 Navigation Operations Team	$14.6 M		$14.6 M
7.07.03 Mission Planning Team	$1.3 M		$1.3 M

WBS Elements	NRE	RE	1st Unit
09.0 Ground Data Systems	$31.4 M		$31.4 M
9.0A GDS Teams	$25.4 M		$25.4 M
9.0B Science Data System Ops	$5.4 M		$5.4 M
9A.03.07 Navigation HW and SW Dev	$0.6 M		$0.6 M
11.0 Education and Public Outreach	$0.0 M	$0.0 M	$0.0 M
12.0 Mission and Navigation Design	$0.0 M		$0.0 M
12.01 Mission Design	$0.0 M		$0.0 M
12.02 Mission Analysis	$0.0 M		$0.0 M
12.04 Navigation Design	$0.0 M		$0.0 M
Operations Reserves	$76.2 M	$0.1 M	$76.3 M
8.0 Launch Vehicle	$0.0 M		$0.0 M

Cost

Cost Potentials

- Potential Cost Savings
  - Reducing the level of science team participation during the cruise phase.
  - Phase E GDS was costed as JPL workforce since contractor passthrough cost was not provided. Is expected to be a lower cost if the effort is performed by the spacecraft contractor.

- Potential Cost Uppers
  - Lander Vision System costed by Team X totaled $30M, which is 2.3X higher than the customer provided $13M.
  - Team X did not assess the technical feasibility of the contractor spacecraft design. Changes could result in a cost upper.
  - Sample Handling System cost still needs to be included and may be more complicated than expected.

APPENDIX B.4 DESIGN TEAM STUDY REPORT – IN SITU EXPLORATION MISSION

Key trades specific to the in situ mission option are given in **Table B-3**. Cost estimates are presented in **Table B-4.** Two Team X costs estimates are provided, one that assumes an in-house build of the spacecraft and one that assumes an out-of-house spacecraft build. The key features of the Team X report complete this appendix.

Table B-3. Key trades.

Key Trades Performed	Outcome	Rationale
Transportation to Ceres	Solar Electric Propulsion (SEP)	SEP is the only propulsion technology capable of delivering the required mass at a reasonable trip time. The trade space included monopropellant hydrazine propulsion, space-storable bi-propellant systems, and solid rocket motors in various combinations. Trajectory options included low-thrust trajectories, ballistic trajectories, and near-ballistic trajectories. The near-ballistic trajectories included one or two deep space maneuvers. Ballistic trajectories with flight times of ~10 years were found that could deliver the required mass, but were rejected as undesirable due to the long flight time.
Gridded ion thrusters vs Hall thrusters	Grid ion thrusters	Both Hall thrusters and gridded ion thrusters can be used. Hall thrusters typically provide shorter flight times at the expense of a larger xenon load. Gridded ion thrusters were selected to maintain configuration similarity with the Sample Return mission option.
Number of Hops	Single Hop	Multiple hops multiply the risk associated with the state of the vehicle after each landing.
Hop distance of 100's of km vs. 10's of km	10's of km	Hop distances of hundreds of km adds considerable additional propellant. Scientifically valuable sites within tens of km are known to exist around Occator crater (see **Appendix B-1**).

Table B-4. The average total In Situ Mission option development costs (Phases A-D) of $1.11B is comparable to that for the Sample Return option.

WBS	WBS Element	TruePlanning	SEER	Team X (Out of House)	Team X (In-House)
	Phase A	5	5	Incl below	Incl below
WBS 1,2 ,3	Proj Mgmt, Proj SE, SMA	83	102	73	76
WBS 4	Science	27	30	25	25
WBS 5	Payload	165	156	155	155
05.01,05.02	PL Mgmt, PL SE	17	12	13	13
05.04	NAC	15	25	23	23
05.05	Planet Vac	47	44	41	41
05.06	Micro-Raman (CIRS)	33	20	39	39
05.07	TLS	18	24	24	24
05.08	APXS	13	24	8	8
05.09	EM sounder	22	8	9	9
WBS 06	Spacecraft	318	365	373	442
06.01,06.02	SC Mgmt, SC SE	21	24	36	36
06.16	Spacecraft Bus	297	341	337	406
WBS 7/9	MOS/GDS	55	61	60	60
WBS 10	I&T	32	41	31	31
	Phases A-D Subtotal	**685**	**761**	**717**	**789**
	A-D Reserves (50%)	343	381	359	394
	Total A-D	**1,028**	**1,142**	**1,076**	**1,183**
	LV	240	240	240	240
	Phase E-F	181	166	212	212
	Phase E-F Reserves (25%)	45	42	53	53
	Total A-F	**1,494**	**1,590**	**1,580**	**1,688**

TP	SEER	ROM Pass Thru	NICM	Wrap	Rollup	SOCM	MOCET	Team X

Ceres Pre-Decadal – Option 2

PI: Julie Castillo-Rogez, Study Lead: John Brophy
Facilitator: Troy Hudson

April 21st to April 23rd
Study ID: 2326

Jet Propulsion Laboratory
California Institute of Technology

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21. Cost – Sherry Stukes

Table of Contents

Executive Summary

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Executive Summary

Study Overview

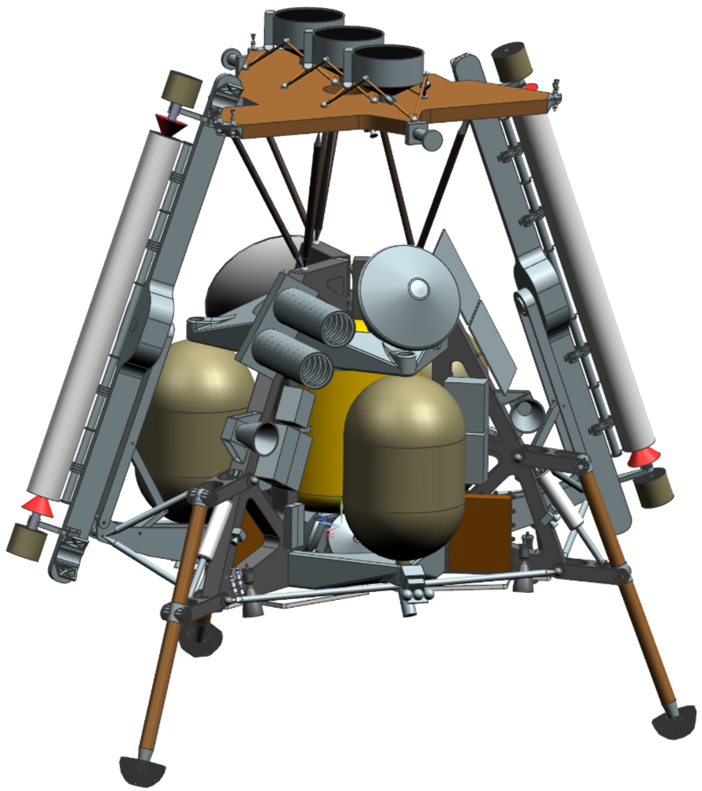
- Study Goals
  - To determine if an architecture studying Ceres surface materials in situ meets the financial and programmatic constraints of a New Frontiers or Small Flagship class mission (Class B, $1.1B FY25 ØA-D incl. Launch Services w/ **50%** A-D, 25% E-F Reserves) for a **Planetary Mission Concept Study** to be provided by NASA as an input to the 2023 Planetary Decadal Survey for prioritization.

- Study Objectives
  - From customer provided design of a single flight-element system, Team-X shall provide a technical assessment (fixing where necessary), produce a MEL, and estimate mission cost.
    - Architecture is a single flight element that lands and performs in-situ science with one point-to-point hop on Ceres' surface. No re-launch, no return to Earth. Landing of the entire vehicle is enabled by retractable / re-deployable Solar Arrays

Executive Summary

Mission Architecture and Assumptions

- Class B, Category 3, $1.1B FY25 (A-D) assumed NF cost cap
  - Launch in early 2030s (2030-12-20)
  - 6 year cruise to CERES with one Mars gravity assist
  - SEP Propulsion using NEXT ion thrusters in addition to hydrazine thrusters
  - Orbital science, mapping, and landing site selection (~500 days at Ceres)
  - Retractable / re-deployable solar arrays (27.5 kW@1AU)
  - 1.5 m HGA for DTE comms.
  - Precision landing
  - Honeybee PlanetVac sampling system built into legs

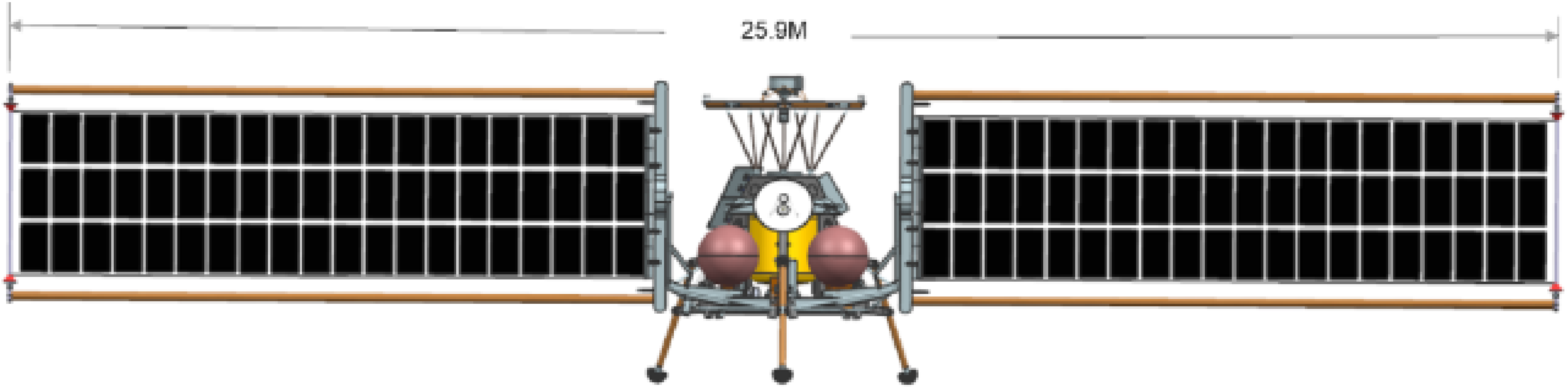


- Assumptions
  - Re-categorization of Ceres as Planetary Protection class II*
  - Pass-thru costs for NEXT EP thrusters, PlanetVac, and ROSA solar arrays include 17.5% JPL burden
  - Sphinx Class B certification and Sabertooth availability

Executive Summary

Overview

- Ceres lander @ Occator Crater for In Situ science + one hop; no Sample Return
  - 2 month landed phase (including hop)
  - EM sounding (last site only), Micro-Raman (CIRS), Mini-TLS, APXS, Sample Carousel
  - In situ analysis of collected samples



Executive Summary

Technical Detail

- Instruments
  - NAC (2 units)
  - EM Sounder
  - Micro-Raman (CIRS)
  - Mini-TLS
  - APXS
  - PlanetVac Sampling System and Sample Carousel
- CDS
  - Sabertooth and Sphinx dual-string avionics
  - Includes main compute element, lander vision system compute element, motor controllers, REU processors
- Ground Systems
  - Ground Network = DSN
  - Up to one 8 hour DSN pass per day
- Telecom
  - Dual-string UST-Lite transponders with 100W TWTA
  - 1.5-m X band gimbaled HGA for DTE downlinks
  - Three X-band LGAs for safe modes and uplinks
- ACS
  - Sun sensors, star trackers, IMUs, RWAs
  - 9 context cameras
  - 2 lander vision system cameras
- Structures
  - Primary Structure Mass MEV= 405.2 kg
  - Secondary Structure Mass MEV = 26.8 kg
  - Landing Gear = 109.2 kg MEV
  - Mechanisms
    - HGA gimbals
    - NEXT thruster gimbals
- Thermal
  - Passive and active thermal control
- Power
  - Two deployable ROSAs, total area = 95.4 m^2
  - Battery sized for launch mode (126 Ah)
  - Dawn-heritage electronics
- Propulsion
  - SEP system with 3 NEXT Ion engines
    - 701 kg Xenon for cruise to Ceres and orbital phase
  - Monoprop hydrazine system with six 445 N main engines and 2 redundant branches of 12 RCS thrusters
    - 800 kg hydrazine for landing and surface hop

Executive Summary

Technical Findings

Mass and Contingency Summary

Payload Mass CBE	68.5 kg
Spacecraft Dry Mass CBE	1494 kg
Spacecraft & Payload Subsystem Contingency	335 kg
Spacecraft & Payload Dry Mass CBE + Contingency	1898 kg
Additional Systems Contingency	336 kg
Propellant	1502 kg
Spacecraft & Payload Wet Mass MEV	3736 kg

Total dry mass contingency = 43% (per JPL Design Principles)

COST SUMMARY (FY2025 $M)	Generate ProPricer Input	Team X Estimate CBE	Team X Estimate PBE
Project Cost		$1004.6 M	$1451.1 M
Launch Vehicle		$0.0 M	$0.0 M
Project Cost (w/o LV)		$1004.6 M	$1451.1 M
Development Cost		$793.0 M	$1189.1 M
Phase A		$7.9 M	$11.9 M
Phase B		$71.4 M	$107.0 M
Phase C/D		$713.7 M	$1070.2 M
Operations Cost		$211.7 M	$262.1 M

Cost Drivers:

- Large Solar Array mass
- Primary structure mass
- Number and cost of EECAM cameras
- Software complexity

Executive Summary

Risks

Customer inputs for Structures & Mechanisms mass estimates are lower than heritage missions. A more thorough structural analysis would be required to produce vetted mass pass-through that Team X could use.

- Complex sample handling yields poorly-constrained cost and development schedule
- Sphinx Class B certification and Sabertooth availability is assumed
- Software complexity – significant modifications may drive cost and/or schedule
- Having the TWTA on during landing requires additional qualification and V&V

Executive Summary

Additional Comments

- The single flight-element architecture is capable of performing Ceres orbital and in-situ science (including one hop) for a cost close to the *assumed* FY25 New Frontiers cap. This assumption must be refined when possible.

Systems Report

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Systems

Study Overview

- The goal of this study was to design and cost a mission to Ceres as part of the Pre-Decadal survey set of mission studies. Two options were considered:
    - A sample return mission
    - A lander mission
- Customer Inputs:
    - Reference MEL and CAD Configuration
    - Passthrough Costs:
        - NEXT EP thrusters from NASA GRC: **$19.2M FY25**
        - PlanetVac Sampling System from Honeybee Robotics: **$40.7M FY25**
        - Retractable ROSA Array from DSS: **$40M FY25**
- Team X Outputs:
    - Technical point design
    - Mission cost

Systems

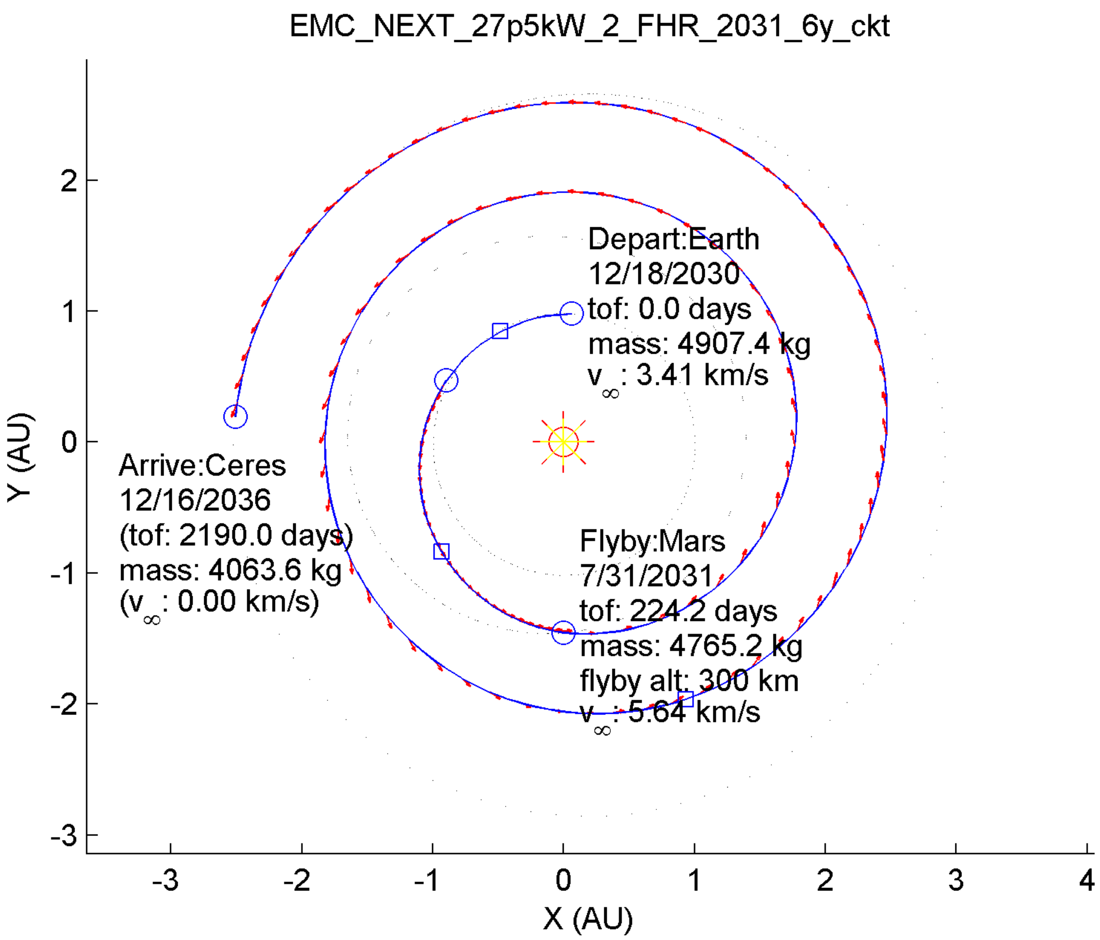
Design Assumptions – Option 2

- The spacecraft launches on a Falcon Heavy Recovery launch vehicle with a maximum mass capability of 4,665 kg to the required C3
- Spacecraft is Class B risk posture, dual string redundancy
- Total mission duration is 7.5 years
  - 6 year cruise to Ceres
  - 16 month orbital science phase
  - 2 month landed science phase

Systems

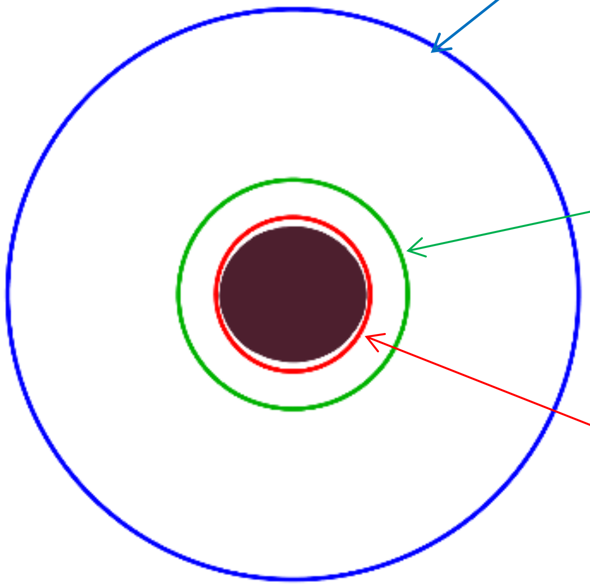
Concept of Operations – Option 2 – Interplanetary Trajectory

- Interplanetary trajectory provided by customer team
- Launch date: 12/18/2030
- Launch vehicle capability: 4,665 kg
- 6 year cruise to Ceres using electric propulsion



Concept of Operations – Option 2 – Orbital Phase

- Orbital Science CONOPs provided by customer team
- Science conducted at 3 orbit altitudes over approximately 12 months
  - 16 month orbital phase bookkept in schedule to provide margin
- Science data includes NAC imagery and gravity field radio science
- 39 Gb of science data returned during this phase
- NAC imagery is used to slelect a landing site and create a map for TRN during landing



Low-res:
- 120 days (18h period, 1400 km alt, 90º inc, circular)
- 2:1 resonance, 136 swaths every 0.75 days

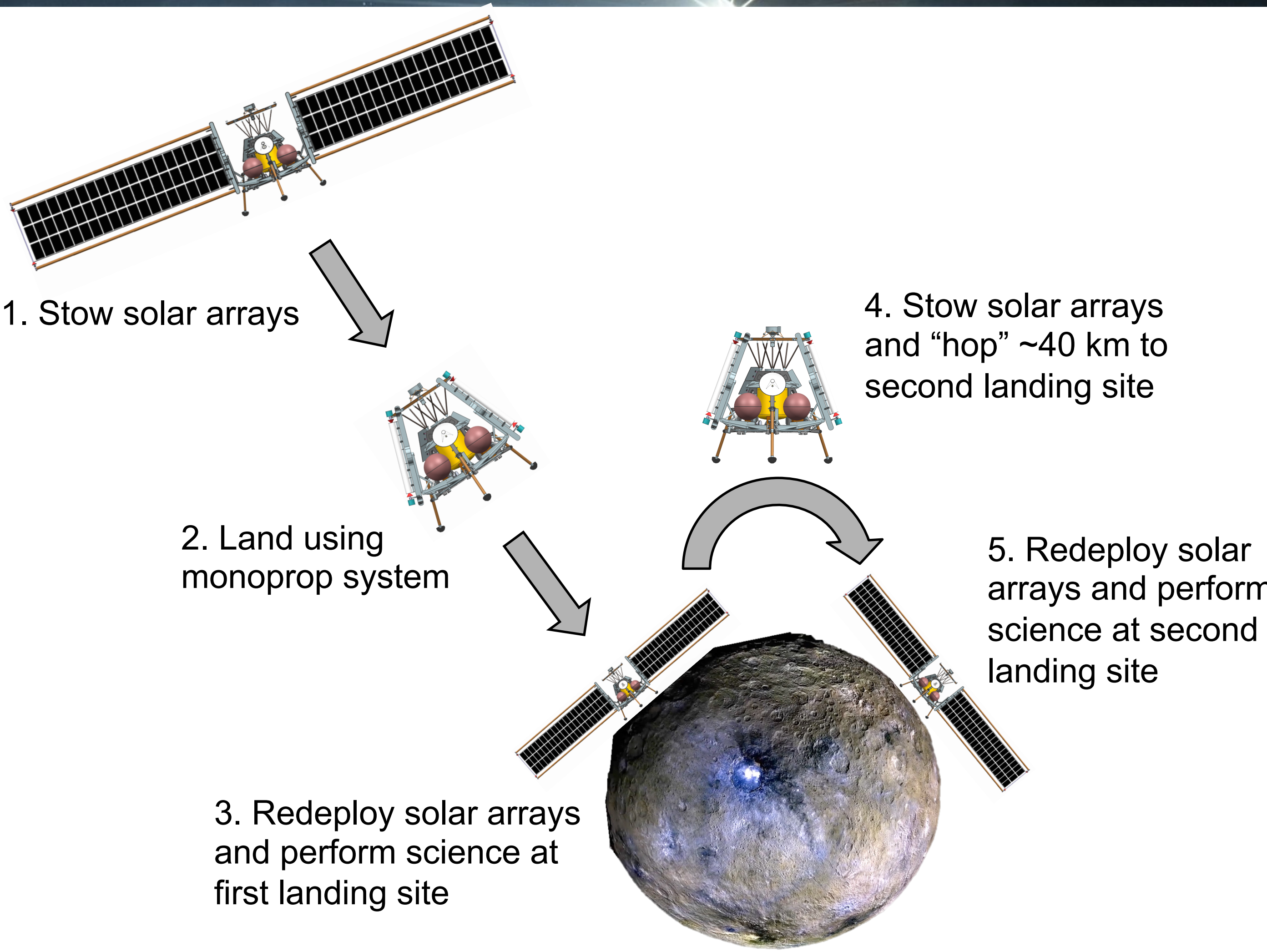
Medium-res:
- 90 days (4.5h period, 275 km alt, 90º inc, circular)
- 1:2 resonance, 50 passes every 0.38 days
- 2.8 m GSD (requirement for orbital science (Haulani, Ahuna Mons, Ernutet Crater, Cosecha Tholus) and basemap for TRN

High-res:
- 154 days (2.5h period, 28 km alt, 90º inc, circular)
- 5:18 resonance, 30 flyovers every 1.9 days
- 28-cm GSD (requirement)
- Gravity science (Haulani, Ahuna, Cosecha)
- Landing site selection

Systems

Concept of Operations – Option 2 – Landed Phase

- Once the orbital phase is complete, the spacecraft lands on Ceres:
    1. Stows solar arrays and lands using chemical propulsion system
    2. Redeploys solar arrays after landing
    3. Collects samples and conducts surface science for at least 5 Ceres days
- The spacecraft then "hops" ~40 km to a second landing site:
    1. Stows solar arrays and uses the chemical propulsion system to "hop"
    2. Redeploys solar arrays after landing
    3. Collects samples and conducts surface science for at least 5 Ceres days



Systems

System Guidelines – Option 2

Team X Study Guidelines

2326 Ceres Pre-Decadal
Orbiter & Lander

Project - Study

Customer	John Brophy
Facilitator	Troy Hudson
Study Type	Solar System Exploration Roadmap
Report Type	PPT

Project - Mission

Mission	2326 Ceres Pre-Decadal
Target Body	Ceres
Science	Ceres orbiter that lands and hops
Launch Date	20-Dec-30
Mission Duration	7.5 years
Mission Risk Class	B
Technology Cutoff	2028
Minimum TRL at End of Phase B	6 TBR
Planetary Protection	Outbound: III, Inbound: N/A
Flight System Development Mode	Out-of-House

Launch Vehicle	Falcon Heavy Recovery
Trajectory	SEP cruise to Ceres
L/V Capability, kg	4665 kg to a C3 of 13 with 0% contingency taken out
Tracking Network	DSN
Contingency Method	Apply Total System-Level

Spacecraft

Spacecraft	Orbiter & Lander
Instruments	NAC,PlanetVac and Tube closure system,CIRS Micro-Raman,EM Sounder,Mini-TLS,APXS
Primary Element?	TRUE
Redundancy	Dual (Cold)
Stabilization	3-Axis
Heritage	Dawn
Radiation Total Dose	23.5 krad behind 100 mil. of Aluminum, with an RDM of 2 added.
Type of Propulsion Systems	System 1-Monoprop, System 2-SEP
Post-Launch Delta-V, m/s	7600
P/L Mass CBE, kg	68.5 kg Payload CBE
P/L Power CBE, W	165
EDL Type	Precision Landing

Project - Cost and Schedule

Cost Target	$1100MPhas A-D
Mission Cost Category	Large - e.g. New Frontiers
FY$ (year)	2025
Include Phase A cost estimate?	Yes
Phase A Start	March 2026
Phase A Duration (months)	12
Phase B Duration (months)	12
Phase C/D Duration (months)	34
Review Dates	PDR - March 2028, CDR - December 2028, ARR - September 2029
Phase E Duration (months)	90
Phase F Duration (months)	4
Project Pays Tech Costs from TRL	6
Spares Approach	Selected
Parts Class	Commercial + Military 883B
Launch Site	Cape Canaveral

Systems

Power Modes – Option 2

- Solar Array is an input from the customer team (27.5 kW at 1 AU)
- Battery sized by launch mode

9 hour Ceres day

Mode Name	Launch	SEP Cruise @ Earth	SEP Cruise @ Ceres	Orbital Science	Telecom	Landing or Hopping	Surface Ops - Sampling	Surface Ops - Day	Surface Ops - Night
Duration (hrs)	4	24	24	2.3	8	1	1	4.5	4.5
	• Avionics • Telecom receive • Attitude Control sensors • Thruster heaters	• Avionics • Telecom receive • Attitude Control sensors • Reaction Wheels • SEP Engines @ 14.5kW	• Avionics • Telecom receive • Attitude Control sensors • Reaction Wheels • SEP Engines @ 2kW	• NAC • Avionics • Telecom receive • Attitude Control sensors • Reaction Wheels	• Avionics • Telecom transmit/ receive • Attitude Control sensors • Reaction Wheels	• LVS Cameras • Avionics • Telecom transmit/ receive • Attitude Control sensors • Monoprop thrusters	• Context cameras • PlanetVac System • Avionics • Telecom transmit/ receive	• Context cameras • CIRS • EM Sounder • Mini-TLS • APXS • Avionics • Telecom transmit/ receive	• Avionics • Telecom receive

Systems

Design Summary – Option 2

- Instruments
  - NAC (2 units)
  - EM Sounder
  - Micro-Raman (CIRS)
  - Mini-TLS
  - APXS
  - PlanetVac Sampling System and Sample Carousel
- CDS
  - Sabertooth and Sphinx dual-string avionics
  - Includes main compute element, lander vision system compute element, motor controllers, REU processors
- Ground Systems
  - Ground Network = DSN
  - Up to one 8 hour DSN pass per day
- Telecom
  - Dual-string UST-Lite transponders with 100W TWTA
  - 1.5-m X band gimbaled HGA for DTE downlinks
  - Three X-band LGAs for safe modes and uplinks
- ACS
  - Sun sensors, star trackers, IMUs, RWAs
  - 9 context cameras
  - 2 lander vision system cameras
- Structures
  - Primary Structure Mass MEV= 405.2 kg
  - Secondary Structure Mass MEV = 26.8 kg
  - Landing Gear = 109.2 kg MEV
  - Mechanisms
    - HGA gimbals
    - NEXT thruster gimbals
- Thermal
  - Passive and active thermal control
- Power
  - Two deployable ROSAs, total area = 95.4 m^2
  - Battery sized for launch mode (126 Ah)
  - Dawn-heritage electronics
- Propulsion
  - SEP system with 3 NEXT Ion engines
    - 701 kg Xenon for cruise to Ceres and orbital phase
  - Monoprop hydrazine system with six 445 N main engines and 2 redundant branches of 12 RCS thrusters
    - 800 kg hydrazine for landing and surface hop

Systems

Summary Sheet – Option 2

		Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Launch	Mode 2 Power (W) SEP Cruise @ Earth	Mode 3 Power (W) SEP Cruise @ Ceres	Mode 4 Power (W) Orbital Science	Mode 5 Power (W) Cruise/Orbit Telecom	Mode 6 Power (W) Landing or Hopping	Mode 7 Power (W) Surface Ops - Sampling	Mode 8 Power (W) Surface Ops - Science Day	Mode 9 Power (W) Surface Ops - Night
Power Mode Duration (hours)						*4*	*24*	*24*	*2.3*	*8*	*1*	*1*	*4.5*	*4.5*
Payload on this Element														
Instruments		4%	68.5	30%	89.1	0	0	0	2	0	0	165	86	0
Payload Total		4%	**68.5**	30%	**89.1**	**0**	**0**	**0**	**2**	**0**	**0**	**165**	**86**	**0**
Spacecraft Bus														
Attitude Control		4%	68.7	9%	74.8	42	108	108	74	74	58	49	41	0
Command & Data		1%	20.3	19%	24.3	24	24	24	24	24	28	24	24	24
Power		18%	277.0	29%	358.4	70	161	74	67	74	97	92	84	56
Propulsion1 ☐ SEP1		9%	143.0	2%	145.7	37	1	1	1	1	217	1	1	1
Propulsion2 ☑ SEP2		17%	262.2	5%	275.3	0	14480	2000	0	0	0	0	0	0
Structures & Mechanisms		34%	538.0	29%	695.1	0	0	0	0	0	0	0	0	0
S/C-Side Adapter		2%	29.8	30%	38.7									
Cabling		5%	79.1	30%	102.8									
Telecom		2%	29.8	18%	35.0	10	10	10	10	205	205	205	205	10
Thermal		3%	46.1	28%	59.0	193	48	123	163	48	108	108	108	108
Bus Total			1493.9	21%	1809.1	375	14831	2339	339	425	713	478	463	198
Thermally Controlled Mass					1809.1									
Spacecraft Total (Dry): CBE & MEV			**1562.4**	21%	**1898.1**	375	14831	2339	341	425	713	643	548	198
Subsystem Heritage Contingency	21%		335.7	SEP Cont	10%	0	1448	200	0	0	0	0	0	0
System Contingency	22%		336.1			161	151	146	146	183	307	276	236	85
Total Contingency ☐ Include Carried?	**43%**		671.8											
Spacecraft with Contingency:			**2234**	of total	w/o addl pld	**536**	**16430**	**2684**	**487**	**608**	**1020**	**919**	**784**	**283**
Propellant & Pressurant with residuals1		21%	801.1		For S/C mass =	3900.0		Delta-V, Sys 1	600.0	m/s	residuals =	7.9	kg	
Propellant & Pressurant with residuals2		19%	700.9		For S/C mass =	3900.0		Delta-V, Sys 2	7000.0	m/s	residuals =	63.7	kg	
Spacecraft Total with Contingency (Wet)			**3736**											
L/V-Side Adapter			38.7					BOL Power:	29096.5	W				
Launch Mass			**3775**					EOL Power:	27500.0	W				
Launch Vehicle Capability			**4665**	Falcon Heavy Recovery										
Launch Vehicle Margin			**890.1**											
Dry Mass Allocation: MPV			**3163.0**											
JPL Design Principles Margin			**1570.8**	**50%**	(MPV – CBE)/MPV									
NASA Margin			**1226.2**	**63%**	(MPV – MEV)/MEV									

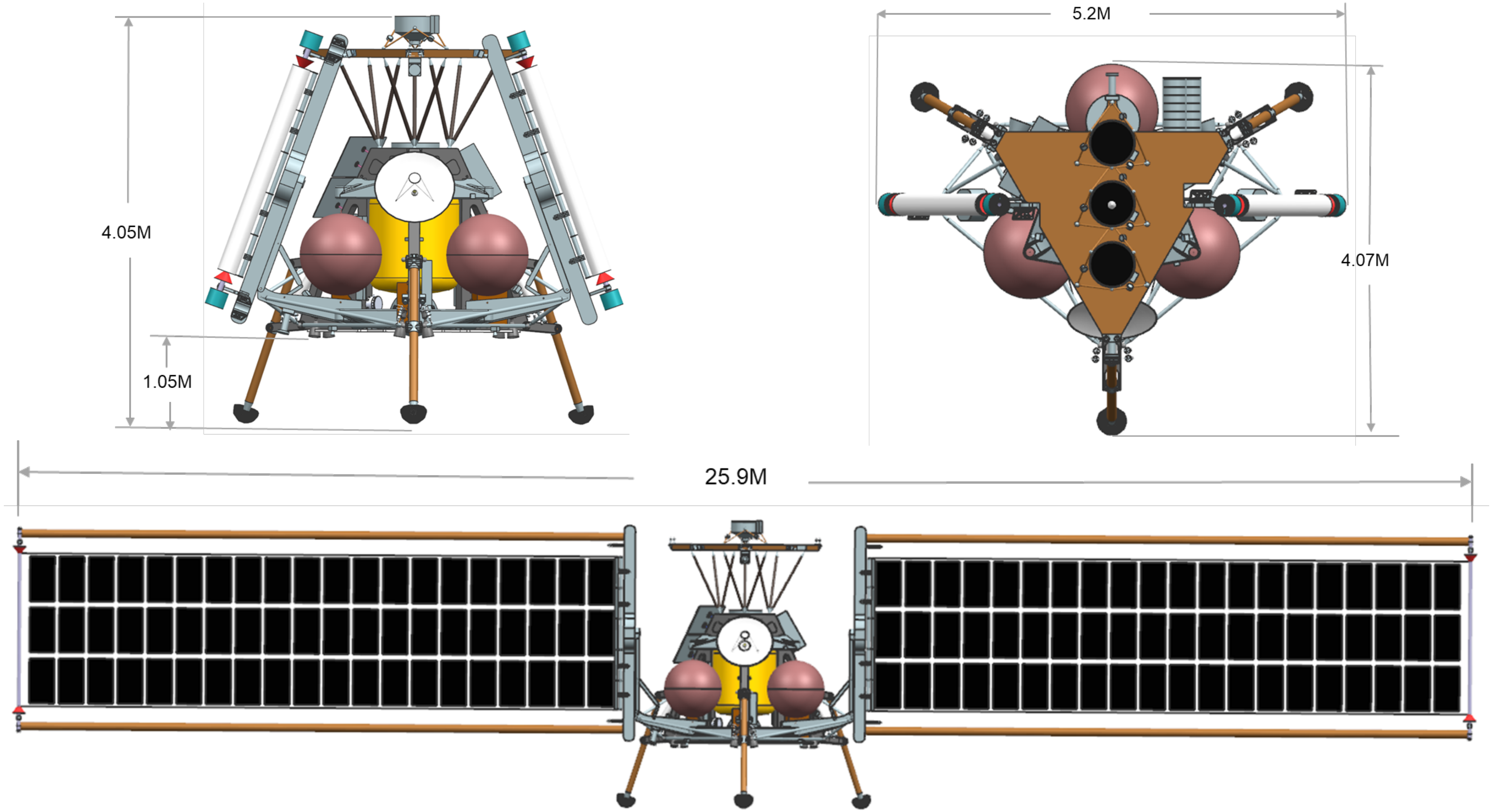
Mass and Contingency Summary

Payload Mass CBE	**68.5 kg**
Spacecraft Dry Mass CBE	**1494 kg**
Spacecraft & Payload Subsystem Contingency	**335 kg**
Spacecraft & Payload Dry Mass CBE + Contingency	**1898 kg**
Additional Systems Contingency	**336 kg**
Propellant	**1502 kg**
Spacecraft & Payload Wet Mass MEV	**3736 kg**

Total dry mass contingency = 43% (per JPL Design Principles)

Systems

Configuration – Option 2



Systems

Margin and Contingency Guidelines

- Contingencies applied to spacecraft dry mass include subsystem contingencies (applied based on part heritage) and additional systems contingency
  - Per JPL Design Principles, total contingency applied is 43%
  - Propulsion sized to MEV mass with all contingencies applied, allowing for growth in dry mass to the MEV without affecting propellant required

- Margin to launch vehicle computed according to NASA principles for dry mass margin from MEV mass of the spacecraft
  - NASA Margin = (MPV – MEV)/MEV
  - MPV = Launch Vehicle Capability – Propellant = **3,163 kg**
  - MEV = Spacecraft & Payload Dry Mass CBE + Contingency + LV Adapter = **1,937 kg**
  - NASA Margin = **63%**

Systems

Conclusions, Risks, and Recommendations

- The system closes within the launch vehicle capability with adequate mass and power margins
- Phase A-D cost is **$1.2B FY25** with 50% reserves
  - ~9% over the cost target of $1.1B FY25, but close to the assumed New Frontiers cost cap
- Risks and Recommendations:
  - Customer team's structures & mechanisms mass estimates were lower than heritage missions. Recommend completing a more thorough structural analysis and/or carrying higher mass estimates at this early stage of the design.
  - Sampling system and sample carousel require further design consideration and represent a cost and complexity upper.
  - In general, the mission is complex and could grow in scope and cost as it moves forward.

Science Report

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Science Goals & Implementation (option: no sample return)

- Science Goals
  - Constrain the environmental conditions in Ceres' early ocean and test whether they were amenable to prebiotic chemistry.
  - Determine the origin of the organic material found on Ceres' surface and its significance for prebiotic chemistry.
  - Confirm the presence of liquid in Ceres' deep interior or in local seas. Determine the nature and composition of the liquid.
  - Determine Ceres location of origin
- Implementation
  - NAC (+ 6 engineering cameras)
  - EM Sounder (particles and fields)
  - Micro-Raman (CIRS)
  - Mini-Tunable Laser Spectrometer (Mini-TLS)
  - Alpha Particle and X-Ray Spectrometer (APXS)
  - Gravity Science
- Science operations
  - Select and characterize safe landing site(s) from orbit.
  - Retract solar arrays and land outside of Occator Crater
  - Deploy solar arrays and perform landed ops
  - Retract solar arrays and hop inside Occator Crater
  - Deploy solar arrays and perform landed ops

Science

Design Requirements

- Science Measurements
  - Raman, APXS and TLS require proximity operations (arm, sampling, or both)

- Data
  - Science data volumes 39 Gbit orbit, 4 Gb ground

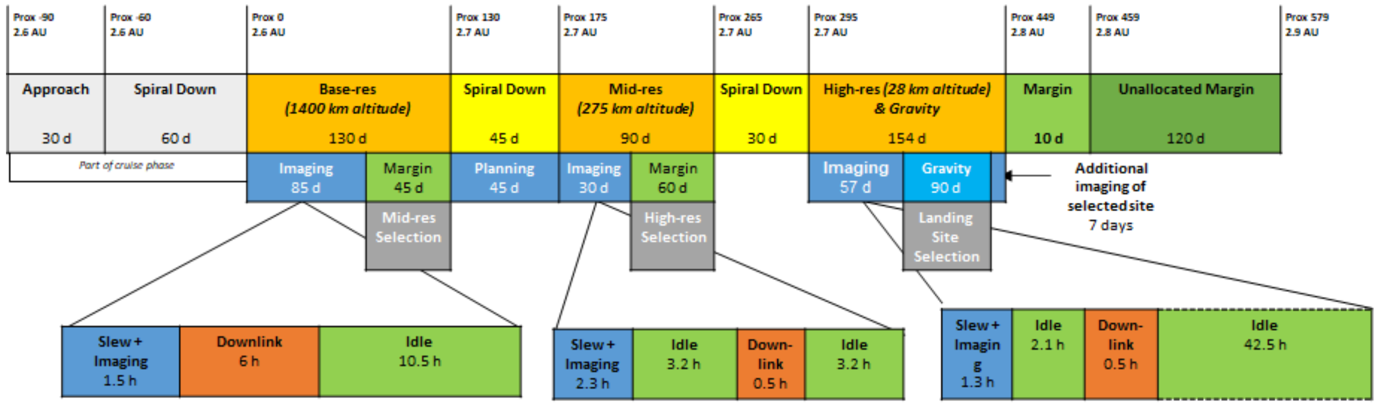
- Option studied has landing + 1 hop

Science

Design Assumptions

- Instrument
  - The instruments are not complex, though the surface sequencing will require dedicated effort by the science team over a short period of time
- Operations
  - Surface operations include ground-in-the-loop sequencing
- Science team
  - This option was designed as a PI-led mission

Orbit Operational Scenario



- Surface Operational Scenario
  - *Whole flight system lands*
  - *Solar arrays deploy*
  - *EECAMs take images of landing area + landscape*
  - *EECAM data return*
  - *APXS, TLS and CIRS operations TBS*
  - *Deploy EM sounding system - <30 min.*
  - *Integration for 5 Ceres days + EM data return in parallel*
  - *Hop and repeat*

Science

Cost Assumptions

- Costs include science team, science meetings, instrument accommodation analysis, sequence development, algorithm development, non-systematic data analysis and science management.
- Project support options were also selected, including data archiving and "environmental characterization" – which supports site selection activities with wide participation within the science community.

- Phase E science workforce assumed 7 FTEs per each of six science investigations.
- Phase E cost includes 12 month training for science team to prepare for proximity operations and outside team to inform landing site selection.

- Potential cost savings
  - Reduce the size of the science team to reflect the low data volumes
  - Reduce the training period for proximity operations
  - Reduce duration and activity during Phase F

Science

Cost

Basic mission	Default	System	Override	Input
Target	Mars	Ceres		Ceres
Mission Cost Class	Large Flagship	B		B
Mission Design	Orbital			Orbital
Resource Interactions	None			None
Complex instrument#	0		1	1
Simple instrument#	0		4	4
Complex instrument # products (for IOS)	8			8
Simple instrument # products (for IOS)	5			5
Fraction external scientists	0.8			0.8
Mission Data Bits	1E+12	5.00E+08		5.00E+08
Analysis Complexity	Medium			Medium
Project Data Center	No			No
Project science visualization	No			No
Project data archiving	No		Yes	Yes
Project instrument support	No			No
Environmental characterization	No		Yes	Yes
Operations support	No			No

Time & Phase Definition				
Phase	**Default**	**System**	**Override**	**Input**
Fiscal year	2007	2025		2025
Phase A start da	01/01/08	03/20/26		3/20/2026
Duration A	0	12		12
Duration B	0	12		12
Duration C	0	18		18
Duration D	0	16		16
Duration Cruise	0	75.5333333		75.53333333
Duration E	0	90		90
Duration F	0	4	6	6
Subphases				0
Duration C1		9		9.00
Duration C2		5		5.00
Duration C3		4		4.00
Duration D1		12		12.00
Duration D2		4		4.00
Duration E1	14.46666667	14.4666667		14.46666667
Duration E2	0			0
Duration E3	0			0
Duration E4	0			0
Duration E5	0			0
Duration training	12	N/A		12

			A	B	C	D	E	F		
			12.00 M	12.00 M	18.00 M	16.00 M	14.47 M	6.00 M	Total	ABCD SUM
	WBS Costs		$K	$K	$K	$K	$K	$K	$K	$K
4		Science	829.8	3320.5	12166.5	9050.5	53625.2	5815.1	84807.7	25367.4
4.1		Science Management	240.1	1046.7	1745.7	1551.8	10497.8	660.0	15742.1	4584.4
	4.1.1	Science Office	240.1	1046.7	1745.7	1551.8	10497.8	660.0	15742.1	4584.4
4.2		Science Implementation	546.9	1886.3	9269.5	5577.4	38969.0	4875.8	61124.8	17280.0
	4.2.1	Participating Scientists	135.8	135.8	767.1	714.3	6414.7	815.2	8983.0	1753.0
	4.2.T	Teams Summary	411.1	1750.5	8502.4	4863.0	32554.3	4060.6	52141.9	15527.0
4.3		Science Support	42.8	387.5	1151.3	1921.4	4158.4	279.4	7940.8	3503.0
	4.3.1	Science Data Visualization	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4.3.2	Science Data Archiving	0.0	165.5	248.2	394.8	2413.0	241.7	3463.2	808.6
	4.3.3	Instrument Support	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4.3.4	Science Environmental Characterization	42.8	222.0	903.0	1526.6	1745.5	37.7	4477.5	2694.4
	4.3.5	Operations Support	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Instruments Report

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Instruments

Design Requirements

- Mission Options:
  - Option 1: Ceres Orbit, Lander, and Sample Return (option will be completed at a later date)
  - Option 2: Ceres Orbit and Lander/Hopper

- Constraints
  - Observations on orbit in 3 different orbital altitudes
    - Identify landing location
      - Create basemap for Terrain Relative Navigation
    - Orbital science from optical observations
  - Observations when landed
    - Option 1: Context Imaging, local mineralogy, crust characteristics, and retrieve several samples
    - Option 2: Context Imaging, crust characteristics, in-situ sample analysis, and elemental determination near lander leg

- Measurement (spectra, image, sounding, etc.)
    - Option 1: Color pushbroom imaging from orbit, IR Spectrum (minerology), EM Sounder (deployable electrodes) and magnetic field measurements (crust)
    - Option 2: Color pushbroom imaging from orbit, EM Sounder (deployable electrodes) and magnetic field measurements (crust), Sample analysis imaging and spectral response using Raman spectrometer and water/CO2 abundance using Tunable Laser Spectrometer, Alpha Particle and X-Ray Spectrometer elemental measurements (next to leg)

Instruments

Design Assumptions Option 2

- Instrument Suite
  - NAC
  - EM Sounder
  - Micro-Raman (CIRS)
  - Mini-Tunable Laser Spectrometer (Mini-TLS)
  - Alpha Particle and X-Ray Spectrometer (APXS)

Systems note: the customer team could not confirm that the sample handling system/carousel were included in the cost estimate from Planetvac so it remains a cost risk

- Passthrough for the costs of the Sample Capture System in the Payload
  - PlanetVac
  - Note that the costs for the not yet defined sample handling system are not captured
    - Mass estimate from the provided MEL was added to PlanetVac mass
    - Power estimate not provided, and not WAG'ed either

- Engineering cameras in ACS include the 6 sample acquisition Context Cameras

Instruments

Design Assumptions Option 2

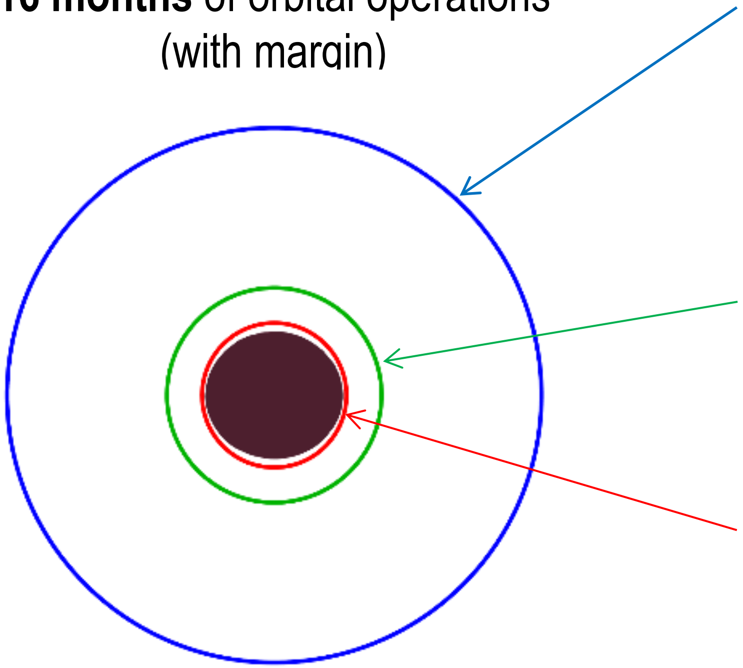
	Mass CBE	Power CBE	Mass MEV	Power MEV	Other comments
NAC (2 units)	9.4	6.4	12.2	9.15	2 identical instruments
EM Sounder	3	6.2	3.9	8.9	Had 3.9kg CBE in Opt 1
Micro-Raman (CIRS)	4.6	18	5.98	25.7	
Mini-TLS	2.3	24	2.99	34.3	
APXS	1.75	7.5	2.34	10.7	
Sample System PlanetVac	28	165	49.4	236	
Sample handling Placeholder	10	0			Rolled mass into Sample System in Instrument sheet. Power impact not specified/included
Totals	68.5	Varies by mode	89.1	Varies by mode	Total mass includes 2 NAC units

Instruments

Operational View, Option 2

- Orbital Phase: NAC observations:

16 months of orbital operations (with margin)



Low-res:
- 120 days (18h period, 1400 km alt, 90º inc, circular)
- 2:1 resonance, 136 swaths every 0.75 days

Medium-res:
- 90 days (4.5h period, 275 km alt, 90º inc, circular)
- 1:2 resonance, 50 passes every 0.38 days
- 2.8 m GSD (requirement for orbital science (Haulani, Ahuna Mons, Ernutet Crater, Cosecha Tholus) and basemap for TRN

High-res:
- 154 days (2.5h period, 28 km alt, 90º inc, circular)
- 5:18 resonance, 30 flyovers every 1.9 days
- 28-cm GSD (requirement)
- Gravity science (Haulani, Ahuna, Cosecha)
- Landing site selection

- Landed Phase (2 sites):
  - Both Sites:
    - Sample acquisition
    - Sample measurements
      - CIRS Raman spectrum on solid
      - TLS measurements of volatiles
    - APXS elemental measurements
  - Second site only:
    - Deploy and perform magnetic and EM sounding measurements
    - After chemical analysis complete

Instruments

Design Rationale

- These instruments provided by customer team

- No Trade Studies were performed

Instruments

Cost

- Cost Assumptions
  - Assumed for this study that all instruments would be procured
- Cost Method
  - Customer supplied FY19 costs used for all but APXS and EM Sounder
    - Inflated FY19 dollars to FY25
    - Used NICM System runs for APXS and EM Sounder
    - Customer costs mostly higher than NICM System estimates using supplied mass/powers

	NICM Est.	Customer FY19 Costs	Passthru FY25	Other comments
NAC (2 units)	-	19M for 2, 13.6M for 1	**16M for 1**	2 identical instruments, first unit costs used on sheet assuming usual NRE %
EM Sounder	**9M**	-	-	
Micro-Raman (CIRS)	-	33M	**39M**	$33M FY'19 proposed for Flagship
Mini-TLS	-	20M	**23.6M**	$20M FY'19 proposed for Discovery
APXS	**8M**	-	-	
Sample System PlanetVac	-	N/A	**40.7M**	
Sample handling Placeholder				Rolled mass into Sample System in Instrument sheet. Power and cost impact not specified/included
		Total Costs		**143M**

Instruments

Cost

- Cost Drivers
  - None identified
- Potential Cost Savings
  - None identified
- Potential Cost Uppers
  - Cost risk associated with unknowns on the Sample Handling system
  - NAC costs provided well under NICM estimate

Instruments

Design Analysis and Risks

- Strengths
  - Using high heritage instruments, starting from existing product lines
- Threats
  - Sample handling system may be more complicated than expected

Mission Design Report

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Mission Goals

➢ **This is an Ceres mission to :**

1. Constrain the environmental conditions in Ceres' early ocean and test whether they were amenable to prebiotic chemistry.

2. Determine the origin of the organic material found on Ceres' surface and its significance for prebiotic chemistry.

3. Confirm the presence of liquid in Ceres' deep interior or in local seas. Determine the nature and composition of the liquid.

4. Determine where Ceres originated from

Mission Design

Option 2

- **Orbit/Trajectory Parameters**
  - SEP trajectory from Earth to Ceres with a Mars Gravity Assist
- **Max distance from the sun**: 3 AU
- **De-orbit Approach**:
  - Hydrazine mono-prop DDL at Ceres (400 m/s)
- **Total Delta V**:
  - 7 km/s SEP
  - 600 m/s hydrazine

Mission Design

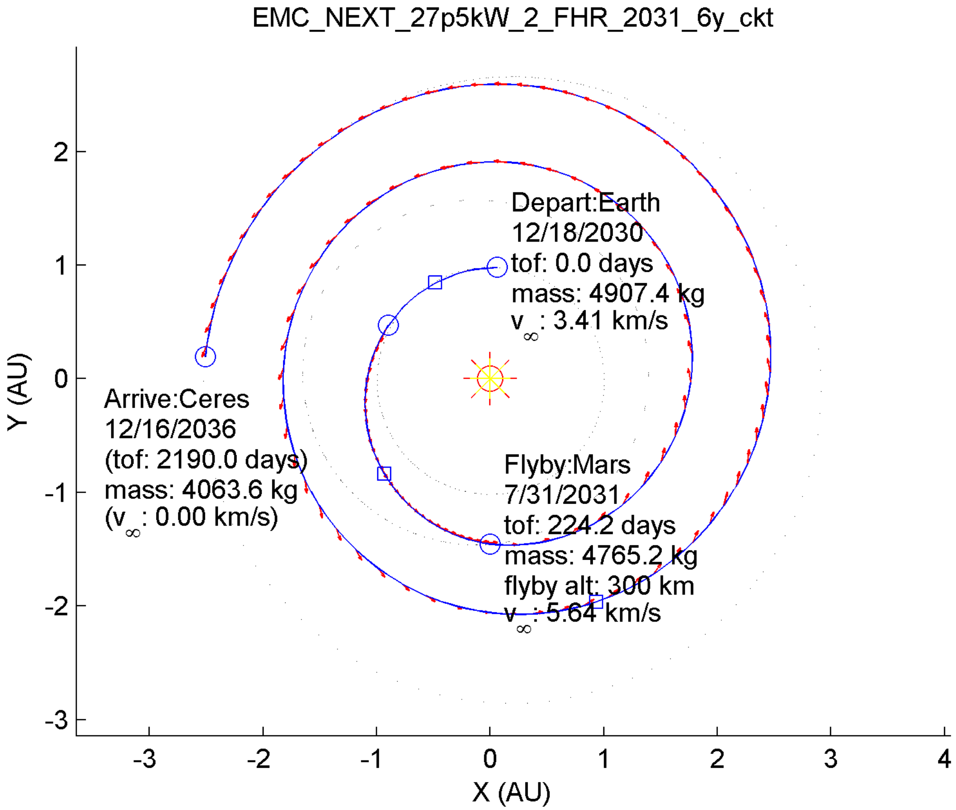
Option 2

- **Launch**: 12/20/2030
- **LV**: Falcon Heavy Recovery
- **Electric Propulsion Subsystem**: NEXT, 2 thrusters at a time, 600 kg throughput each
- **Solar Array**: 27.5 kW BOL at 1 au, 68.5 m^2 of active cell area
- **TOF from launch to Ceres Capture**: 6.3 yr
- **Xenon Propellant**: 701 kg (including 10% margin)
- **Hydrazine Propellant**: 800-kg used at Ceres

- **Note**: No checkout modeled / xenon throughput required for orbital transfers not included, but are expected to be small

Mission Design

Option 2

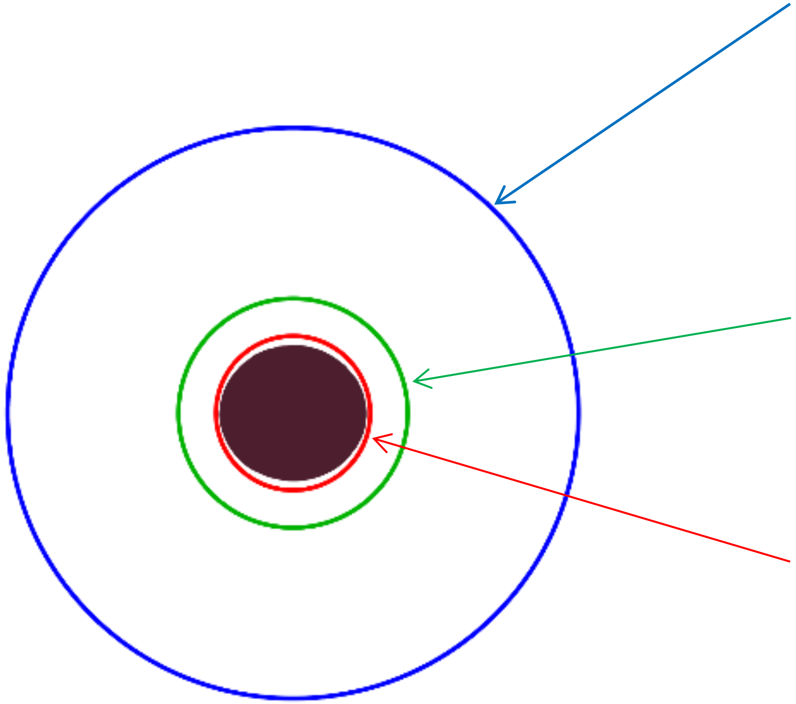


Launch Mass:	4665 kg
Xenon Mass (with margin):	701 kg
Hydrazine Mass (with margin):	800 kg

Mission design

Ceres Orbital Phase Overview

16 months of orbital operations
(with margin)



Low-res:
- 120 days (18h period, 1400 km alt, 90º inc, circular)
- 2:1 resonance, 136 swaths every 0.75 days

Medium-res:
- 90 days (4.5h period, 275 km alt, 90º inc, circular)
- 1:2 resonance, 50 passes every 0.38 days
- 2.8 m GSD (requirement for orbital science (Haulani, Ahuna Mons, Ernutet Crater, Cosecha Tholus) and basemap for TRN

High-res:
- 154 days (2.5h period, 28 km alt, 90º inc, circular)
- 5:18 resonance, 30 flyovers every 1.9 days
- 28-cm GSD (requirement)
- Gravity science (Haulani, Ahuna, Cosecha)
- Landing site selection

Cost (Option 2)

Orbiter and Lander

➢ **Options 2**: In this option, Spacecraft only lands on Ceres

Phase	Duration (Months)	Cost ($M)
Phase A	12	1.01
Phase B	12	2.19
Phase C	18	4.38
Phase D1	12	3.38
Phase D2	4	1.28
Phase E	90	14.09

Total Cost = $26.33M

Configuration Report

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Configuration

Design Requirements and Assumptions

- Requirements
  - Package the provided Spacecraft.
  - Launch Vehicle: Falcon Heavy
  - Payload:
    - Replace Sample Return, IR with Sample Carousel, CIRS, Mini-TLS, APXS.

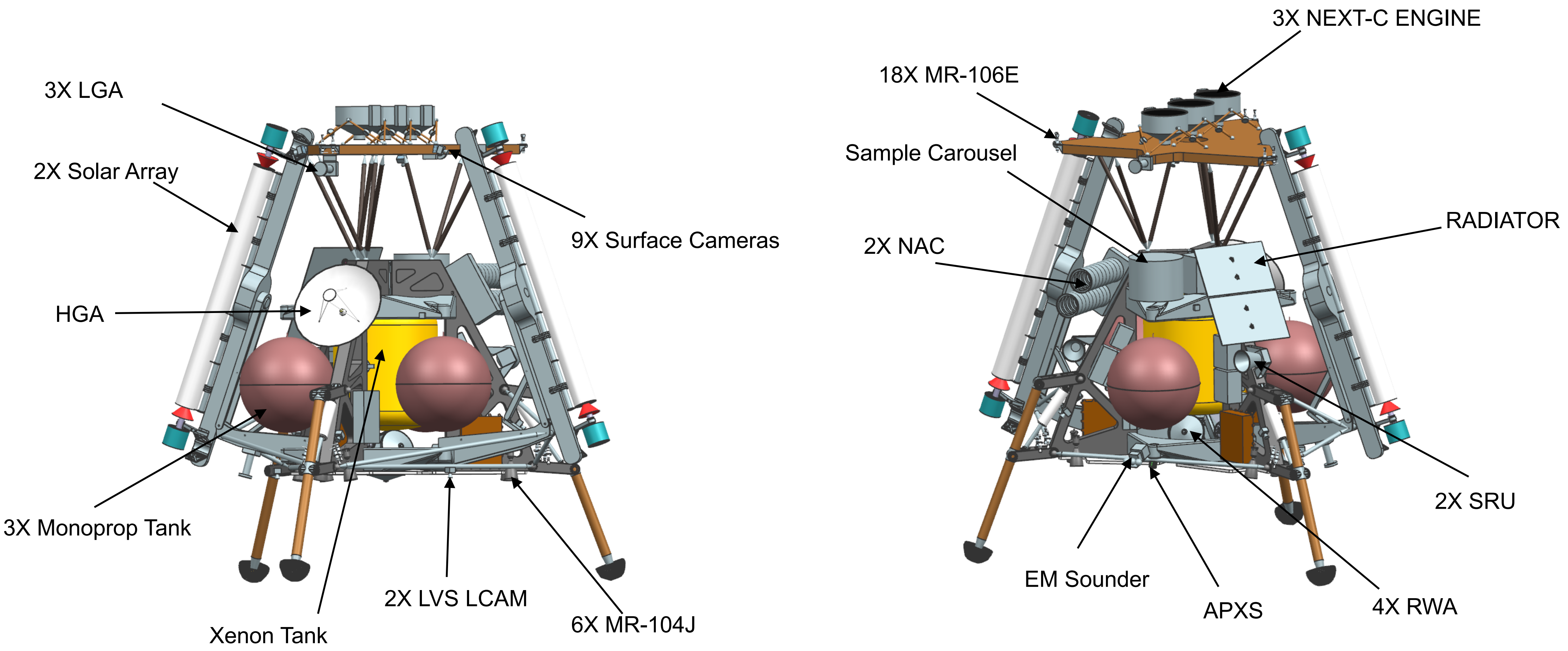
- Assumptions
  - Spacecraft provided.

- No Sample return, 40-km hop to inside Occator crater.

Configuration

Design Configuration Option 2

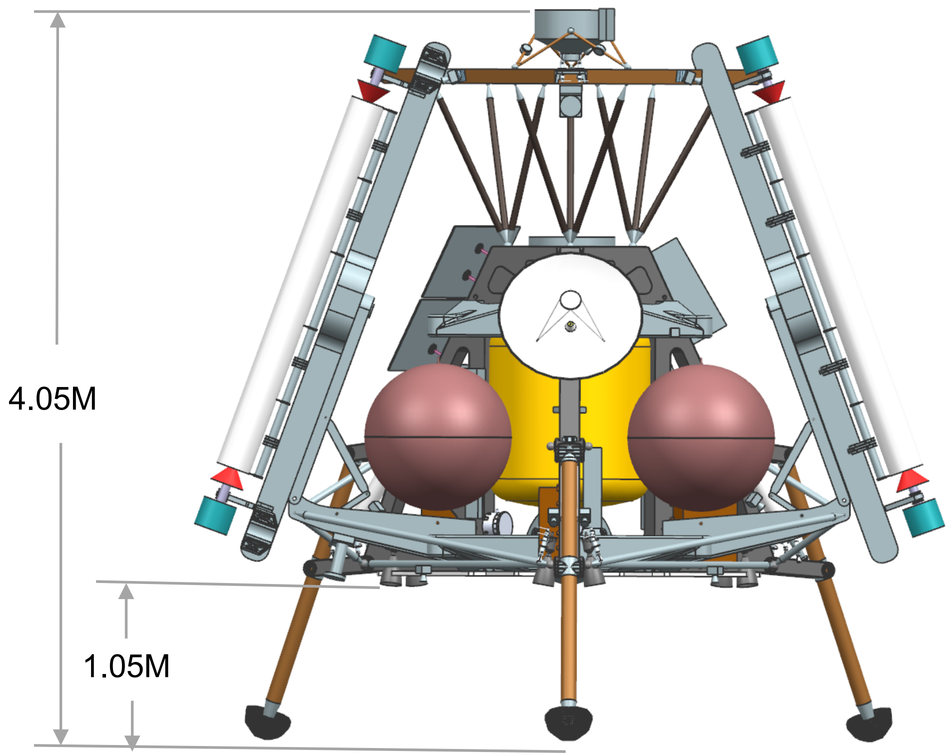
- Configuration Drawings – Stowed

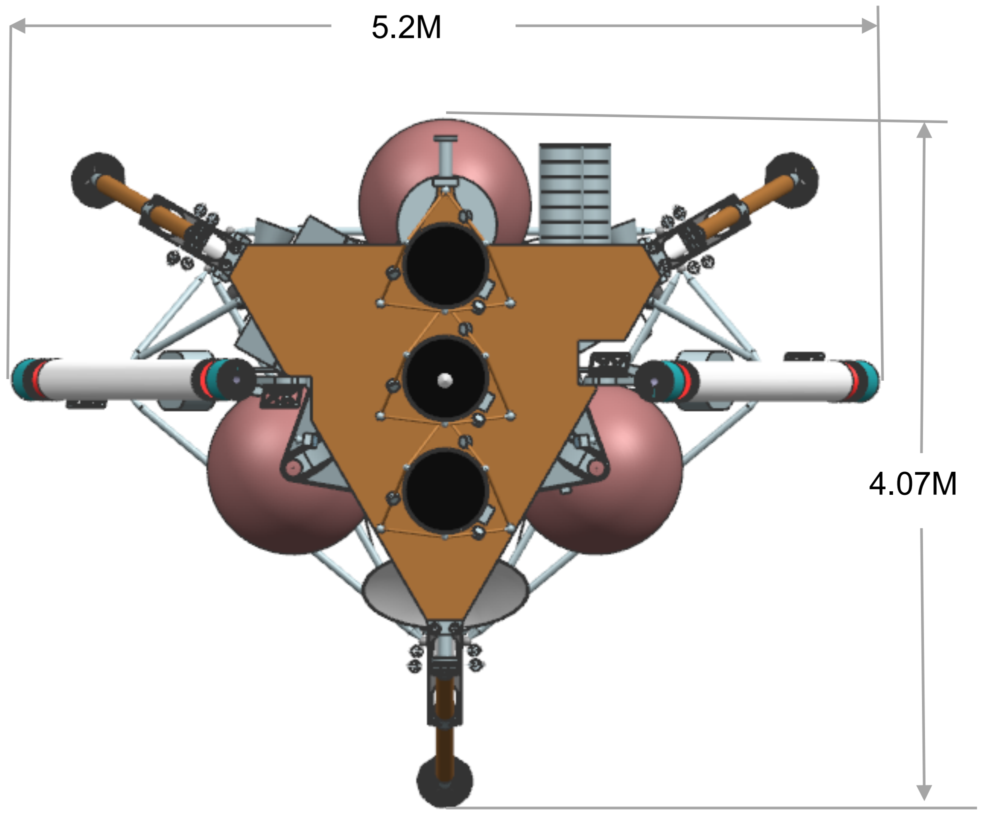


Configuration

Design Configuration Option 2

- Configuration Drawings – Stowed

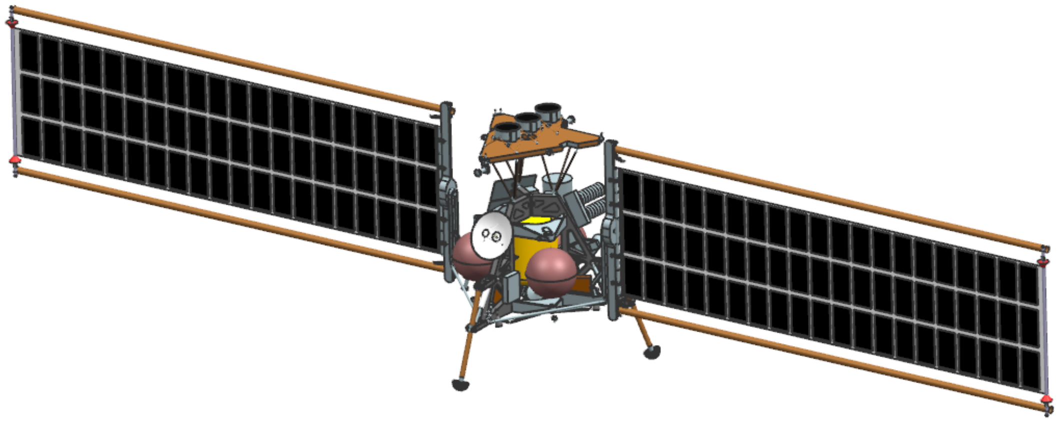


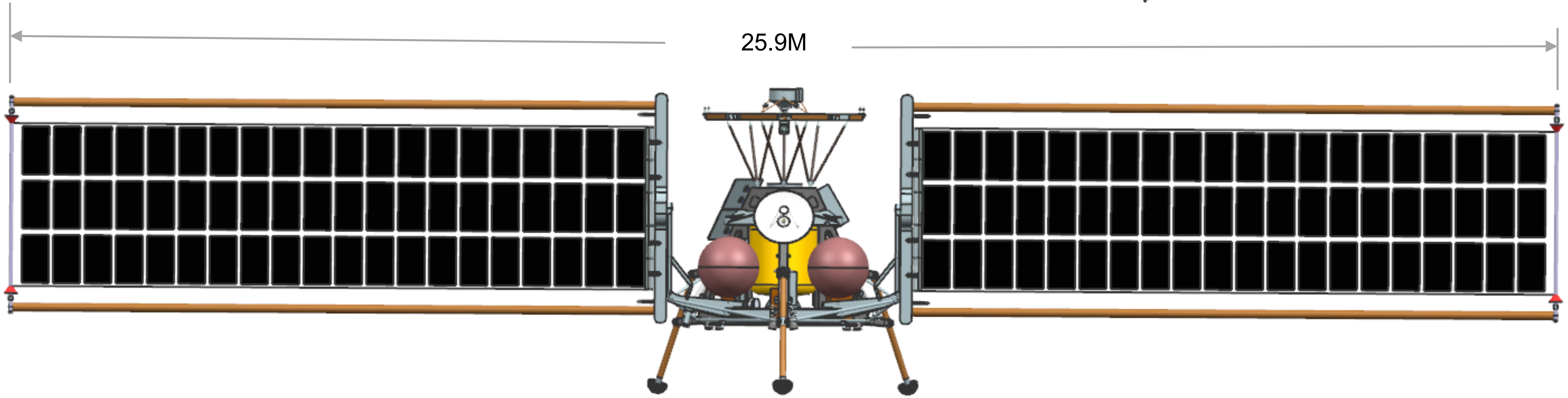


Configuration

Design Configuration Option 2

- Configuration Drawings – Deployed-Cruise

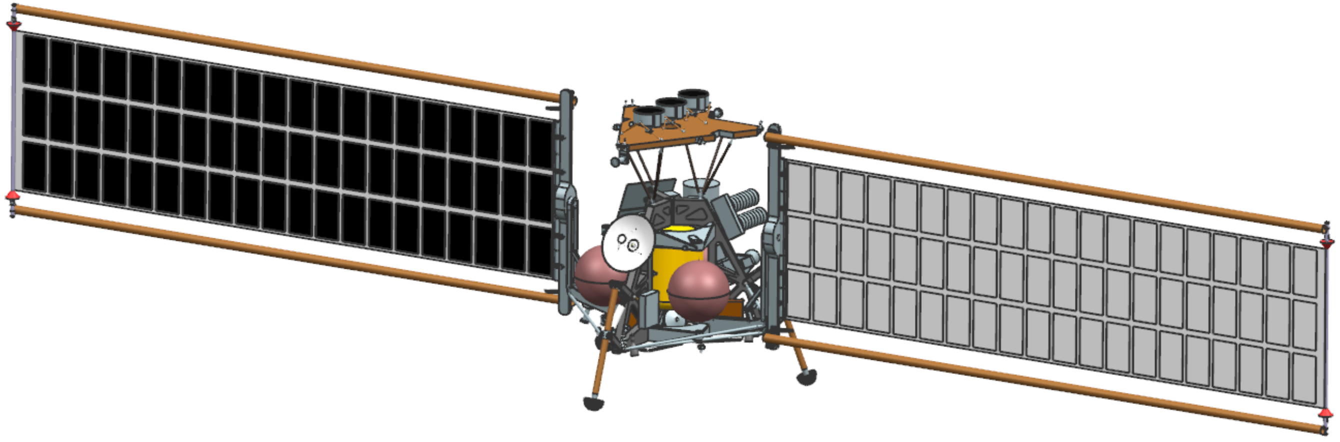


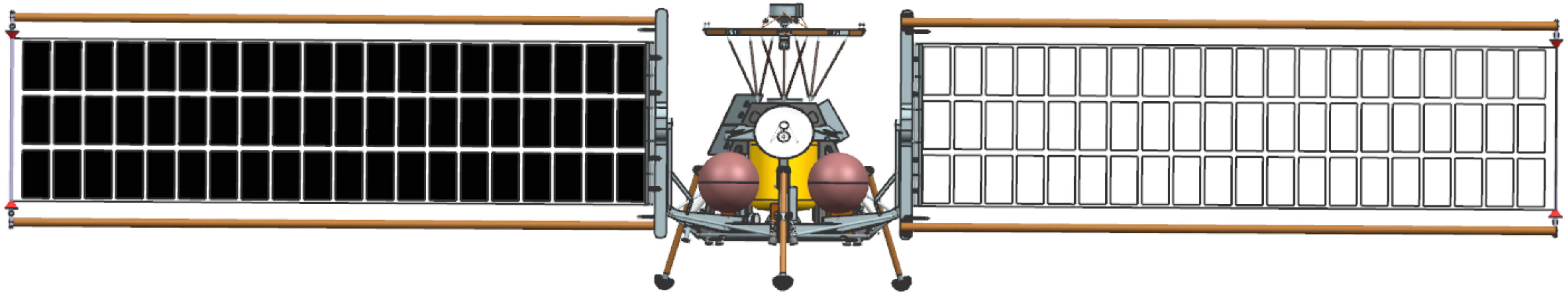


Configuration

Design Configuration Option 2

- Configuration Drawings – Deployed-Landed vertical

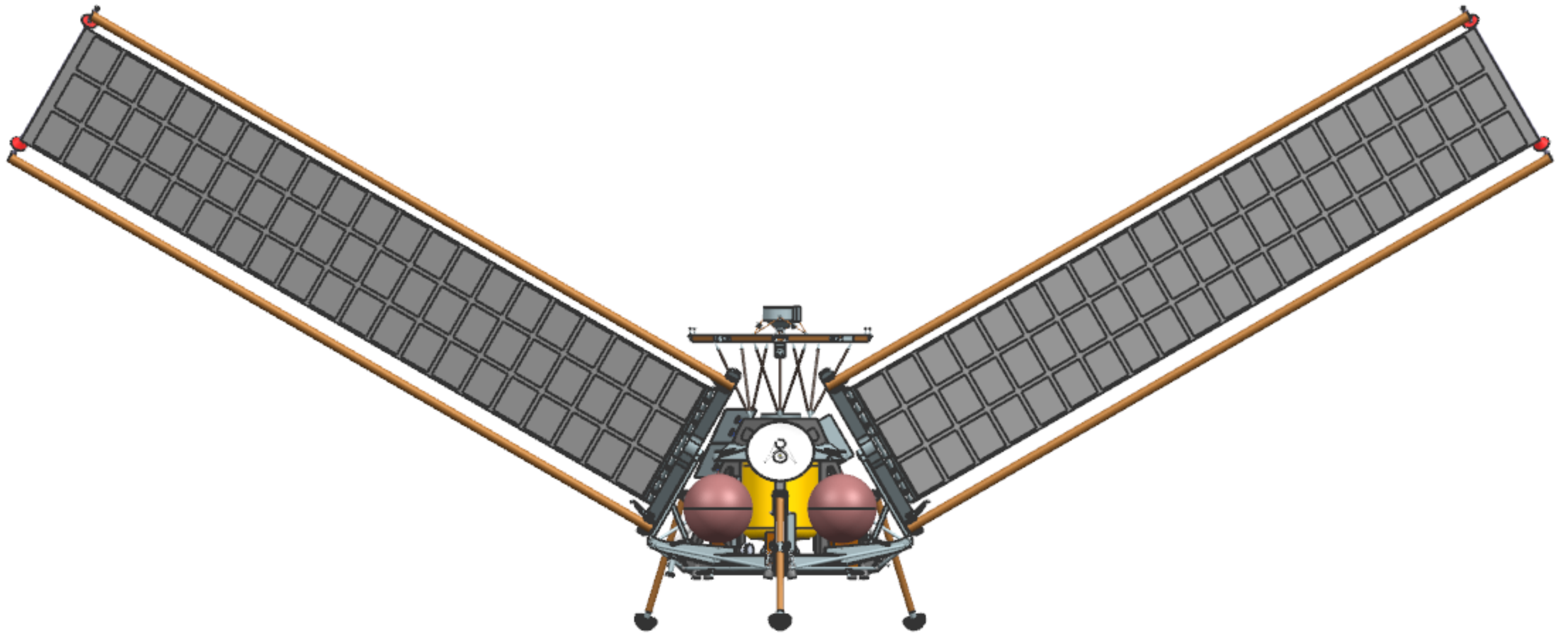


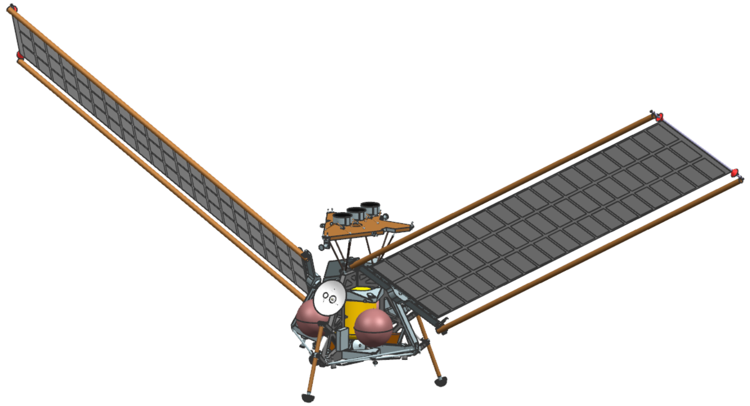


Configuration

Design Configuration Option 2

- Configuration Drawings – Deployed-Landed 45 Degree

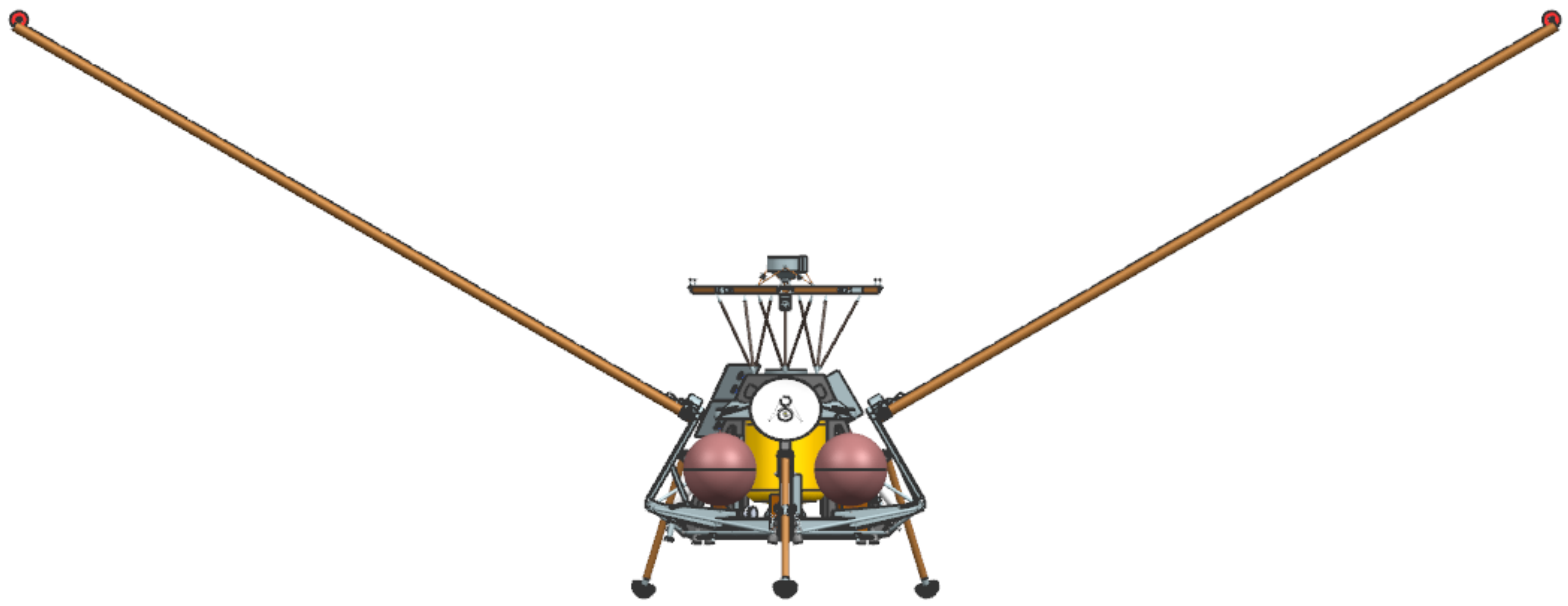


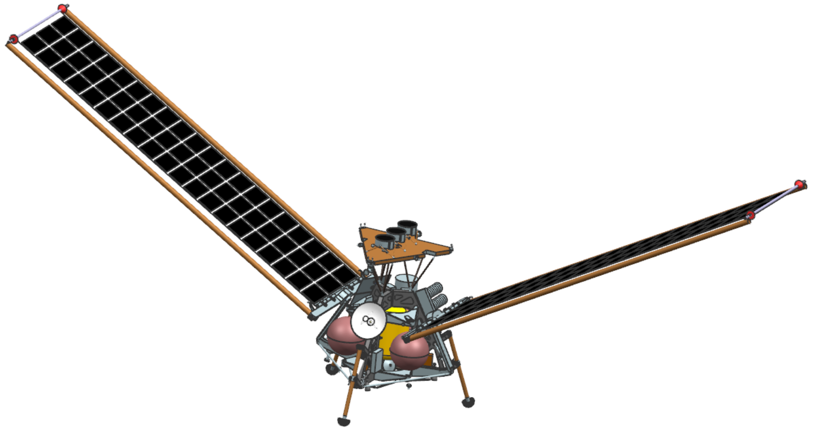


Configuration

Design Configuration Option 2

- Configuration Drawings – Deployed-Landed 90 Degree





Mechanical Report

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Mechanical

Design Requirements

- Mission: Ceres lander
- Launch Vehicle: Falcon 9 Heavy
- Stabilization: 3-Axis
- Payload:

Instrument Summary		
Name	Quantity	Mass
NAC	2	9.4 kg
PlanetVac and Tube closure system	1	38.0 kg
CIRS Micro-Raman	1	4.6 kg
EM Sounder	1	3.0 kg
Mini-TLS	1	2.3 kg
APXS	1	1.8 kg

Option 2

- Options
  - 1: Sample Return Lander (to be completed)
  - 2: Lander with hopping

Option 2

Mechanical

Design Assumptions

- Passed elements
  - Payload was passed from instrument chair. Assumed all sample acquisition and handling actuation was held under “PlanetVac” system
- No carried elements
- Customer MEL was provided, but only line item used was NEXT gimbal mass
- No mission heritage
- No non-standard materials
- Assume
  - Lander explores two locations on the surface
  - Lander uses all Xenon during trip to Ceres (minimizes landed mass)
  - Lander can support 62” launch vehicle adapter ring

Mechanical

Design

- Design
  - Spacecraft Bus: Base panel with truss structures for supporting EP system (provided by customer)
  - Power Source: ROSA solar arrays
  - Payload Support Structure: None

Mechanical

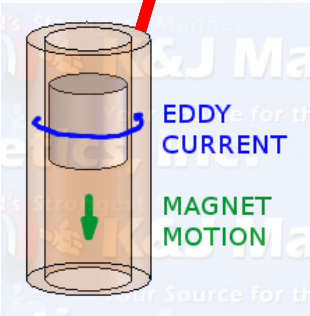
Design

- Mechanisms & Deployments
  - Power Deployments: 2 axis gimbal for Solar Array wings
  - Telecom Mechanisms: 2 DOF gimbal for HGA
  - Launch Vehicle Separation: Marmon Clamp
  - Propulsion: Three gimbaled EP thrusters (NEXT)
  - Landing Legs
    - Three landing legs
    - To support a “hop”, each leg requires “resettable” impact attenuation
    - Europa Lander leg was used as an analog for a non-passive landing leg design
    - A conservative mass estimate for the present Europa Lander leg design was scaled based on the landed weight of this mission vs. the landed weight of the Europa Lander
    - This resulted in a very coarse estimate of 28 kg per leg
    - Note that a more detailed structural dynamics model is needed here
      - This may remove the need for a more complex lander leg design by showing the primary structure has enough compliance and dampening to meet the requirements for a low gravity environment

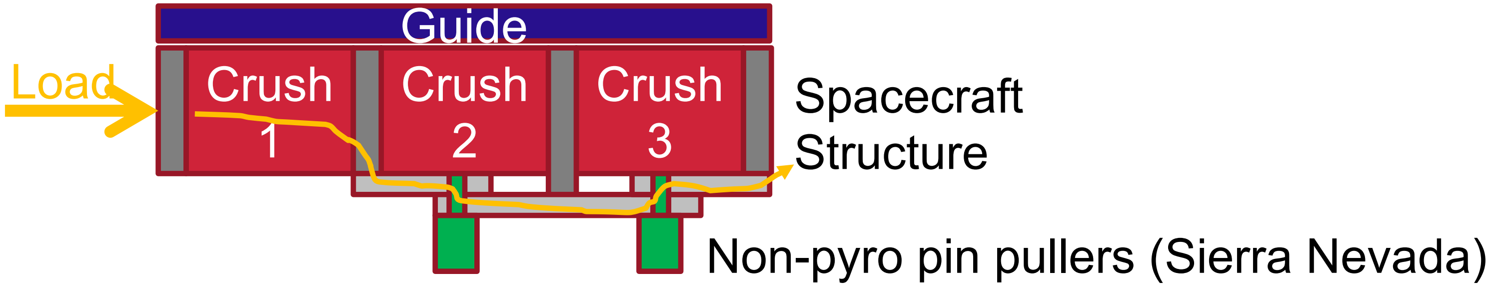
Mechanical

Design

- Mechanisms & Deployments
  - Landing Legs
    - One use (crushable) landing load attenuation is typically used
    - For this mission, legs must be able to attenuate multiple landing events in a row
    - Need dynamicist to perform analysis on landing event
    - Suggested leg concepts
      - Fixed landing legs with structural compliance/dampening – if landing speed is slow enough, this might suffice
      - Spring and friction based energy dampening - likely inconsistent
      - Spring and linear eddy current tube damper for landing legs (right) – fluid dampers are highly discouraged by Div 35 for any appreciable amount of time beyond launch
      - Shuntable crushable (below) – It might be possible to have a staged crushable with load shunts that enable you to “turn on” your next crushable. You will have non determinant leg lengths after your first landing



Previous brainstorming from Study 1754 describing a “resettable” landing leg.



Mechanical

Design Rationale

- Bus shape and design was provided by customer
  - Concept of bus appears feasible
  - Mass estimates provided by customer from bus were 2x-3x below Team X estimates
  - No structural analysis was performed to justify low numbers
  - Utilized Team X models
- Large solar arrays required for EP system
  - 2 axis gimbal allows for adjustment upwards to increase terrain clearance after landing
- PlanetVac styled sampling systems are affixed to the landing legs

Mechanical

Design

- Detailed Mass List
  - Customer MEL not used for mass estimates

Item	Type	Quantity	CBE	Contingency	CBE + Cont.
Primary Structure	Structure	1	311.7 kg	30%	405.2 kg
Secondary Structure	Structure	1	20.6 kg	30%	26.8 kg
Tertiary Structure	Structure	1	5.7 kg	30%	7.5 kg
Power Support Structure	Structure	1	0.0 kg	30%	0.0 kg
Power Mechanisms	Mechanism	1	8.4 kg	30%	10.9 kg
Telecom Support Structure	Structure	1	2.2 kg	30%	2.8 kg
Telecom Mechanisms	Mechanism	1	0.0 kg	30%	0.0 kg
Launch Vehicle Adapter - Struc	Structure	1	45.5 kg	30%	59.2 kg
Launch Vehicle Adapter - Mech	Mechanism	1	14.0 kg	30%	18.2 kg
Landing Gear	Mechanism	3	84.0 kg	30%	109.2 kg
Balance/Ballast	Structure	1	63.0 kg	30%	81.9 kg
Integration Hardware	Structure	1	23.7 kg	30%	30.8 kg
Lens dust covers	Mechanism	3	1.5 kg	30%	2.0 kg
NEXT Gimbal	Mechanism	3	17.2 kg	5%	18.1 kg
Harness	Cabling-Mfg	1	79.1 kg	30%	102.8 kg
Mechanical Total			**597.5 kg**	**29%**	**772.5 kg**
Harness Total			**79.1 kg**	**30%**	**102.8 kg**

Mechanical

Design

- Mass Drivers
  - The primary structure is the largest mass item at 405.2 kg
  - The landing gear and harness are the next two heaviest, at 109.2 kg and 102.8 kg, respectively
  - Note the large amount of balance mass
    - This is a landed spacecraft, so the location of the CM is important for stability during the landing event
    - This is a large spacecraft, so a lot of balance mass is needed to move the center of mass
    - Careful design and layout will minimize the need for balance mass, but this is likely a non-trivial challenge
    - A landing dynamics analysis could help reduce this, however the max elevation delta between any two legs was given as at least 1 m. This suggests a potential tip over problem may be lurking

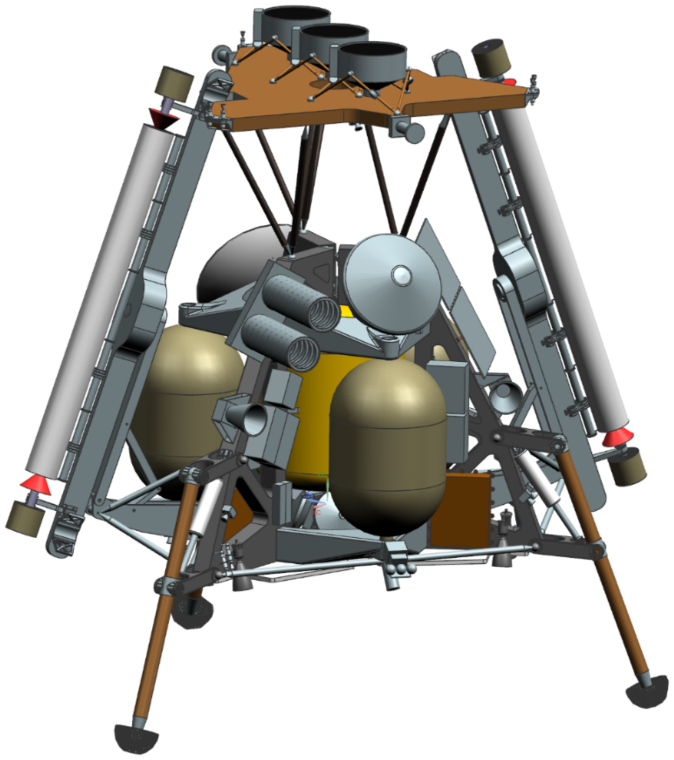
- Potential Mass Savings
  - A detailed structural analysis may show that this truss structure design is less massive than the Team X model predicts, however it will not likely reach the levels predicted by the customer

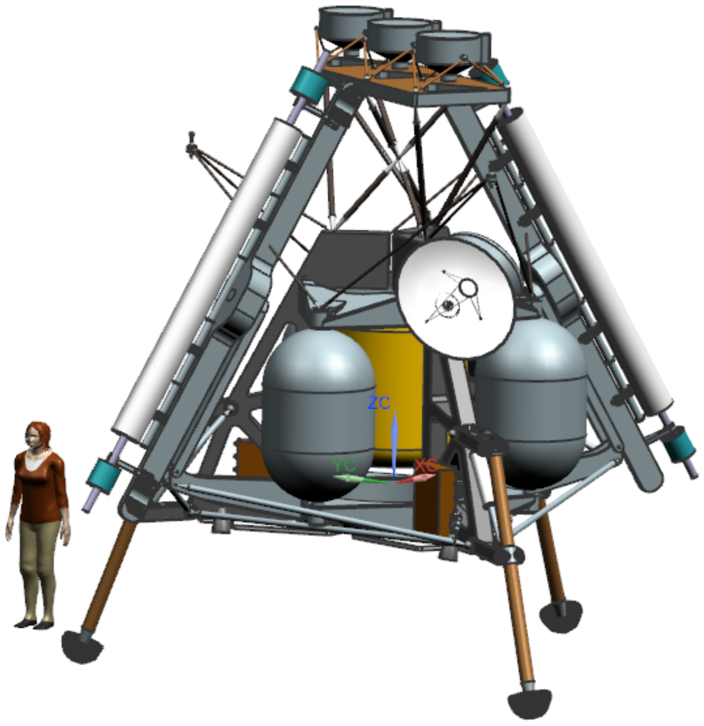
- Potential Mass Uppers
  - The landing leg design is one area of large uncertainty. While it is recognized that the gravity environment is very low, the mass of the spacecraft is very high. A structural dynamics and landing simulation is recommended to flesh out what is required for the spacecraft to Ceres interface.
  - The customer has assumed that the PlanetVac system is fixed to the landing legs. Note that most legs change height during the landing event (crushable, etc.), and it is likely that a “resettable” impact attenuation system may have additional variability built in. While some articulation is assumed to be within the sampling system, additional mechanisms may be required to bring the sampling system in contact with the surface.

Mechanical

Design

- Configuration Images – Stowed
  - Customer provided images – see configuration package for updated images

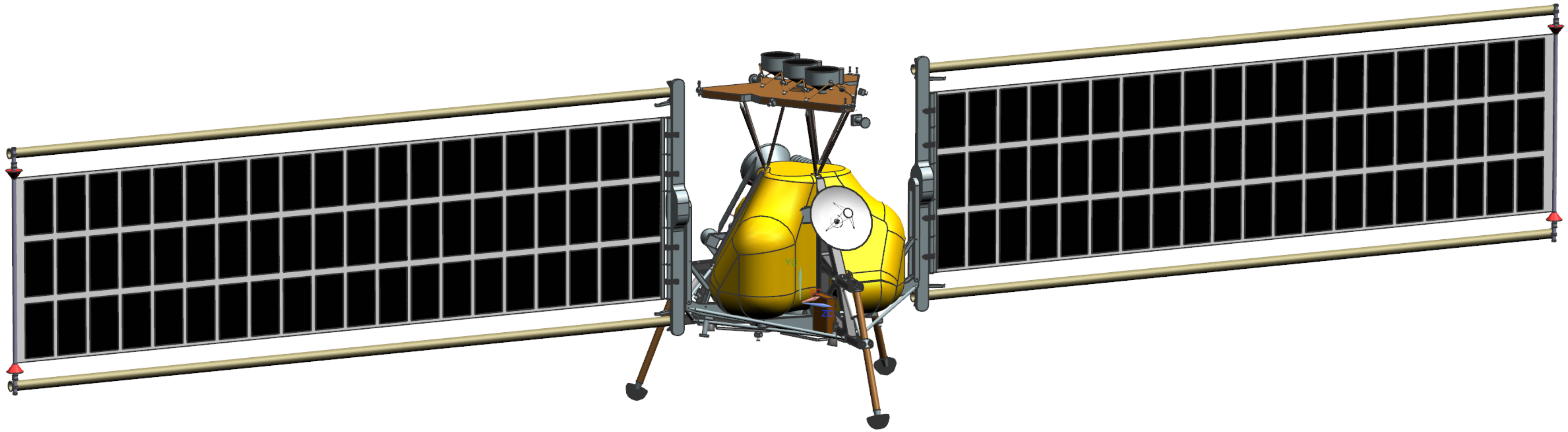




Mechanical

Design

- Configuration Images – Deployed
  - Customer provided images – see configuration package for updated images



Mechanical

Cost Assumptions

- PlanetVac system is included by the Instruments chair
- No customer provided costs for Mechanical
- A touchdown test was added to verify the lander’s ability to operate in a low gravity environment and hop from site to site utilizing non-passive landing legs
    - Estimated at $4.25M based on MSL touchdown test
    - Note that a significant dynamic gravity offload system will likely be required
- A DTM was assumed
- A cabling EM assembly was assumed

Mechanical

Cost Rationale

- Assuming NEXT thruster gimbal cost covered in Propulsion cost numbers
- Landing leg development costs from previous Ceres studies was used here
- Structural cost estimates are tied to the mass of the structure within the model. Heavier structures will cost more as a result.
- Contamination Control answers:

Inputs from User	
Category	Value
Contamination Sensitive	Yes
Extra Contamination Sensitive	Yes
Contamination Analysis	Yes
Complexity Upper	Yes
Analytical Chemistry Service	No

- Hardware Element Cost Table

Item	Type	Quantity	Base Cost	Spare Cost	Eng & Des	Dev Test	Hardware	Qual Test	NRE	RE	Labor	Procurement	Services	Total Cost
Primary Structure	Structure	1	$18.29 M	$0.00 M	$7.41 M	$5.02 M	$4.94 M	$0.91 M	$13.19 M	$5.85 M	$4.19 M	$10.28 M	$4.57 M	$19.03 M
Secondary Structure	Structure	1	$2.15 M	$0.00 M	$0.87 M	$0.59 M	$0.58 M	$0.11 M	$1.55 M	$0.69 M	$0.49 M	$1.21 M	$0.54 M	$2.23 M
Tertiary Structure	Structure	1	$0.11 M	$0.00 M	$0.05 M	$0.03 M	$0.03 M	$0.01 M	$0.08 M	$0.04 M	$0.03 M	$0.06 M	$0.03 M	$0.12 M
Power Support Structure	Structure	1	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M
Power Mechanisms	Mechanism	1	$5.20 M	$0.00 M	$2.11 M	$1.43 M	$1.40 M	$0.26 M	$3.75 M	$1.66 M	$1.30 M	$3.03 M	$1.08 M	$5.41 M
Telecom Support Structure	Structure	1	$1.03 M	$0.00 M	$0.42 M	$0.28 M	$0.28 M	$0.05 M	$0.74 M	$0.33 M	$0.24 M	$0.58 M	$0.26 M	$1.08 M
Telecom Mechanisms	Mechanism	1	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M
Launch Vehicle Adapter - Struc	Structure	1	$0.52 M	$0.00 M	$0.21 M	$0.14 M	$0.14 M	$0.03 M	$0.37 M	$0.17 M	$0.12 M	$0.29 M	$0.13 M	$0.54 M
Launch Vehicle Adapter - Mech	Mechanism	1	$0.41 M	$0.00 M	$0.17 M	$0.11 M	$0.11 M	$0.02 M	$0.30 M	$0.13 M	$0.10 M	$0.24 M	$0.09 M	$0.43 M
Landing Gear	Mechanism	3	$1.80 M	$0.00 M	$0.73 M	$0.49 M	$0.49 M	$0.09 M	$1.30 M	$0.58 M	$0.45 M	$1.05 M	$0.37 M	$1.87 M
Balance/Ballast	Structure	1	$0.14 M	$0.00 M	$0.06 M	$0.04 M	$0.04 M	$0.01 M	$0.10 M	$0.04 M	$0.03 M	$0.08 M	$0.03 M	$0.14 M
Integration Hardware	Structure	1	$0.14 M	$0.00 M	$0.06 M	$0.04 M	$0.04 M	$0.01 M	$0.10 M	$0.04 M	$0.03 M	$0.08 M	$0.03 M	$0.14 M
Lens dust covers	Mechanism	3	$0.50 M	$0.00 M	$0.20 M	$0.14 M	$0.14 M	$0.03 M	$0.36 M	$0.16 M	$0.12 M	$0.29 M	$0.10 M	$0.52 M
NEXT Gimbal	Mechanism	3	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M
Cabling: Management (PEM)	Cabling-Eng	1	$0.74 M	$0.00 M	$0.52 M	$0.07 M	$0.07 M	$0.07 M	$0.62 M	$0.15 M	$0.45 M	$0.12 M	$0.21 M	$0.78 M
Cabling: Engineering	Cabling-Eng	1	$1.27 M	$0.00 M	$0.89 M	$0.13 M	$0.13 M	$0.13 M	$1.07 M	$0.26 M	$0.77 M	$0.20 M	$0.36 M	$1.33 M
Cabling: Design	Cabling-Eng	1	$0.29 M	$0.00 M	$0.20 M	$0.03 M	$0.03 M	$0.03 M	$0.24 M	$0.06 M	$0.17 M	$0.04 M	$0.08 M	$0.30 M
Cabling: Parts	Cabling-Mfg	1	$0.68 M	$0.00 M	$0.10 M	$0.10 M	$0.37 M	$0.10 M	$0.28 M	$0.41 M	$0.06 M	$0.24 M	$0.40 M	$0.70 M
Cabling: Fab & Assy	Cabling-Mfg	1	$2.26 M	$0.00 M	$0.34 M	$0.34 M	$1.24 M	$0.34 M	$0.95 M	$1.38 M	$0.19 M	$0.81 M	$1.33 M	$2.33 M
Cabling: I&T	Cabling-Mfg	1	$1.58 M	$0.00 M	$0.24 M	$0.24 M	$0.87 M	$0.24 M	$0.66 M	$0.97 M	$0.13 M	$0.57 M	$0.93 M	$1.63 M
MSE: Mechanical PEM	Mech Sys-Labor	1	$2.90 M	$0.00 M	$2.32 M	$0.29 M	$0.00 M	$0.29 M	$2.44 M	$0.59 M	$2.15 M	$0.39 M	$0.48 M	$3.03 M
MSE: Administration	Mech Sys-Labor	1	$0.62 M	$0.00 M	$0.50 M	$0.06 M	$0.00 M	$0.06 M	$0.52 M	$0.13 M	$0.46 M	$0.08 M	$0.10 M	$0.65 M
MSE: Mech Chief Engineer	Mech Sys-Labor	1	$0.13 M	$0.00 M	$0.11 M	$0.01 M	$0.00 M	$0.01 M	$0.11 M	$0.03 M	$0.10 M	$0.02 M	$0.02 M	$0.14 M
MSE: Lead Designer	Mech Sys-Labor	1	$1.95 M	$0.00 M	$1.56 M	$0.19 M	$0.00 M	$0.19 M	$1.63 M	$0.40 M	$1.44 M	$0.26 M	$0.32 M	$2.03 M
MSE: Mass Properties Engineer	Mech Sys-Labor	1	$1.33 M	$0.00 M	$1.06 M	$0.13 M	$0.00 M	$0.13 M	$1.12 M	$0.27 M	$0.98 M	$0.18 M	$0.22 M	$1.39 M
MSE: Mech Systems Engineer	Mech Sys-Labor	1	$3.40 M	$0.00 M	$2.72 M	$0.34 M	$0.00 M	$0.34 M	$2.85 M	$0.69 M	$2.52 M	$0.46 M	$0.57 M	$3.55 M
MSE: Touchdown Test	Mech Sys-Test	1	$4.25 M	$0.00 M	$1.06 M	$1.70 M	$1.28 M	$0.21 M	$4.46 M	$0.00 M	$1.79 M	$1.12 M	$1.56 M	$4.46 M
Mechanical I&T	Structure	1	$3.20 M	$0.00 M	$1.29 M	$0.88 M	$0.86 M	$0.16 M	$2.30 M	$1.02 M	$0.73 M	$1.80 M	$0.80 M	$3.32 M
Mechanical GSE	Structure	1	$3.96 M	$0.00 M	$1.60 M	$1.09 M	$1.07 M	$0.20 M	$2.85 M	$1.26 M	$0.91 M	$2.22 M	$0.99 M	$4.12 M
Loads and Analysis	Lds & Dyn	1	$1.59 M	$0.00 M	$1.35 M	$0.16 M	$0.00 M	$0.08 M	$1.67 M	$0.00 M	$1.67 M	$0.00 M	$0.00 M	$1.67 M
Dynamic Environments	Lds & Dyn	1	$1.91 M	$0.00 M	$1.62 M	$0.19 M	$0.00 M	$0.10 M	$2.01 M	$0.00 M	$2.01 M	$0.00 M	$0.00 M	$2.01 M
Materials & Processes	Mat & Proc	1	$2.85 M	$0.00 M	$1.71 M	$0.57 M	$0.00 M	$0.57 M	$2.57 M	$0.29 M	$2.71 M	$0.14 M	$0.00 M	$2.85 M
Contamination Control	Cont Cntl	1	$1.62 M	$0.00 M	$1.62 M	$0.00 M	$0.00 M	$0.00 M	$1.36 M	$0.33 M	$1.51 M	$0.17 M	$0.00 M	$1.69 M
06.07 - Mechanical Subsystem			**$55.51 M**	**$0.00 M**	**$27.47 M**	**$13.36 M**	**$11.39 M**	**$3.29 M**	**$43.80 M**	**$14.07 M**	**$21.85 M**	**$23.72 M**	**$12.31 M**	**$57.88 M**
06.11 - Harness			**$6.81 M**	**$0.00 M**	**$2.29 M**	**$0.91 M**	**$2.71 M**	**$0.91 M**	**$3.83 M**	**$3.23 M**	**$1.76 M**	**$1.99 M**	**$3.30 M**	**$7.06 M**
06.13 - Materials & Processes			**$2.85 M**	**$0.00 M**	**$1.71 M**	**$0.57 M**	**$0.00 M**	**$0.57 M**	**$2.57 M**	**$0.29 M**	**$2.71 M**	**$0.14 M**	**$0.00 M**	**$2.85 M**
02.07 - Contamination Control			**$1.62 M**	**$0.00 M**	**$1.62 M**	**$0.00 M**	**$0.00 M**	**$0.00 M**	**$1.36 M**	**$0.33 M**	**$1.51 M**	**$0.17 M**	**$0.00 M**	**$1.69 M**

Mechanical

Cost Table

- WBS Breakdown Cost Table

WBS Title	NRE	RE	Labor	Procurement	Services	Total Cost
06.07 - Mechanical Subsystem	**$43.80 M**	**$14.07 M**	**$21.85 M**	**$23.72 M**	**$12.31 M**	**$57.88 M**
06.07.01 - Mechanical Subsystem Management	$3.07 M	$0.75 M	$2.71 M	$0.50 M	$0.61 M	$3.82 M
06.07.02 - Mechanical Subsystem Engineering	$7.31 M	$0.69 M	$4.30 M	$1.58 M	$2.13 M	$8.01 M
06.07.03 - Loads & Dynamics Analysis	$3.68 M	$0.00 M	$3.68 M	$0.00 M	$0.00 M	$3.68 M
06.07.04 - Configuration & Mass Properties	$2.75 M	$0.67 M	$2.43 M	$0.44 M	$0.55 M	$3.42 M
06.07.05 - Structural Hardware	$16.13 M	$7.15 M	$5.12 M	$12.57 M	$5.59 M	$23.28 M
06.07.06 - Mechanisms	$5.71 M	$2.53 M	$1.98 M	$4.61 M	$1.65 M	$8.23 M
06.07.07 - Mechanical Subsystem EGSE	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M
06.07.08 - Mechanical Subsystem MGSE	$2.85 M	$1.26 M	$0.91 M	$2.22 M	$0.99 M	$4.12 M
06.07.09 - Mechanical Subsystem I&T	$2.30 M	$1.02 M	$0.73 M	$1.80 M	$0.80 M	$3.32 M
06.11 - Harness	**$3.83 M**	**$3.23 M**	**$1.76 M**	**$1.99 M**	**$3.30 M**	**$7.06 M**
06.11.01 - Harness Management	$0.62 M	$0.15 M	$0.45 M	$0.12 M	$0.21 M	$0.78 M
06.11.02 - Harness Engineering	$1.07 M	$0.26 M	$0.77 M	$0.20 M	$0.36 M	$1.33 M
06.11.03 - Harness Design	$0.24 M	$0.06 M	$0.17 M	$0.04 M	$0.08 M	$0.30 M
06.11.04 - Harness Parts	$0.28 M	$0.41 M	$0.06 M	$0.24 M	$0.40 M	$0.70 M
06.11.05 - Harness Fab & Assy	$0.95 M	$1.38 M	$0.19 M	$0.81 M	$1.33 M	$2.33 M
06.11.06 - Harness I&T	$0.66 M	$0.97 M	$0.13 M	$0.57 M	$0.93 M	$1.63 M
06.13 - Materials & Processes	**$2.57 M**	**$0.29 M**	**$2.71 M**	**$0.14 M**	**$0.00 M**	**$2.85 M**
02.07 - Contamination Control	**$1.36 M**	**$0.33 M**	**$1.51 M**	**$0.17 M**	**$0.00 M**	**$1.69 M**

Mechanical

Cost Table

- WBS Breakdown Cost Table by Phase

WBS Title	A	B	C1	C2	C3	D1	D2
06.07 - Mechanical Subsystem	**$1.16 M**	**$8.68 M**	**$14.47 M**	**$17.36 M**	**$8.68 M**	**$5.21 M**	**$2.32 M**
06.07.01 - Mechanical Subsystem Management	$0.08 M	$0.57 M	$0.95 M	$1.14 M	$0.57 M	$0.34 M	$0.15 M
06.07.02 - Mechanical Subsystem Engineering	$0.16 M	$1.20 M	$2.00 M	$2.40 M	$1.20 M	$0.72 M	$0.32 M
06.07.03 - Loads & Dynamics Analysis	$0.07 M	$0.55 M	$0.92 M	$1.10 M	$0.55 M	$0.33 M	$0.15 M
06.07.04 - Configuration & Mass Properties	$0.07 M	$0.51 M	$0.85 M	$1.03 M	$0.51 M	$0.31 M	$0.14 M
06.07.05 - Structural Hardware	$0.47 M	$3.49 M	$5.82 M	$6.98 M	$3.49 M	$2.10 M	$0.93 M
06.07.06 - Mechanisms	$0.16 M	$1.24 M	$2.06 M	$2.47 M	$1.24 M	$0.74 M	$0.33 M
06.07.07 - Mechanical Subsystem EGSE	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M	$0.00 M
06.07.08 - Mechanical Subsystem MGSE	$0.08 M	$0.62 M	$1.03 M	$1.24 M	$0.62 M	$0.37 M	$0.16 M
06.07.09 - Mechanical Subsystem I&T	$0.07 M	$0.50 M	$0.83 M	$1.00 M	$0.50 M	$0.30 M	$0.13 M
06.11 - Harness	**$0.14 M**	**$0.71 M**	**$1.06 M**	**$1.41 M**	**$1.76 M**	**$1.41 M**	**$0.56 M**
06.13 - Materials & Processes	**$0.50 M**	**$0.40 M**	**$0.53 M**	**$0.30 M**	**$0.24 M**	**$0.66 M**	**$0.22 M**
02.07 - Contamination Control	**$0.10 M**	**$0.38 M**	**$0.39 M**	**$0.22 M**	**$0.17 M**	**$0.32 M**	**$0.11 M**

Mechanical

Cost

- Cost Drivers
  - The largest cost is the primary structure (typical)
- Potential Cost Savings
  - The touchdown test cost could potentially be reduced if GSE surrogates for the hardware vs. a full DTM/EM can be utilized
- Potential Cost Uppers
  - If the fixed sampling system architecture does not work, additional mechanisms will need to be developed to bring the sampler to the surface (see potential mass uppers)
  - Assumed the NEXT Gimbal was included in the NEXT Thruster cost. If not, this may be an ~$3M upper.

ACS Report

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ACS

Design Requirements

- **NOTE: This report covers Option 2 (completed in Team X prior to Option 1)**
- Pointing:
  - Pointing knowledge : 0.3 mrad (0.017 deg)
  - Pointing control : 3.5 mrad (0.2 deg)
  - Pointing stability : 3 urad/150 ms
- Slewing / pointing directions:
  - Cruise: point SEP engines in direction of desired thrust, solar panels as close to sun as possible
  - Orbit: point to nadir (NAC)
  - DDL / hopping: descent engine in direction of desired thrust

ACS

Design Assumptions

- ACS subsystems identical for the two options studied
  - Option 1: Lander + Sample Return
  - Option 2: Lander + hop from outside to inside crater

ACS

Architecture

- Stabilization: 3-Axis
- Attitude Determination
  - Sun sensors, Star Trackers (2), IMUs (2)
  - LVS Camera (LCAM) for onboard terrain-relative navigation during descent and landing
  - Suite of cameras for use during the surface mission
- Attitude Control
  - Reaction wheels, SEP thrusters used for momentum unloading in cruise and in orbital phase (however S/C has RCS thrusters which could be used for unloading as well)
- Slewing

ACS

Design

List Edit	List Copy	Includes Elect?	Unit(s)	Mass Current Best Estimate (CBE) [kg]	Contingency %	Mass CBE + Contingency (kg)	Power [W] Max Possible	Launch	SEP Cruise @ Earth	SEP Cruise @ Ceres	Orbital Science	Cruise/Orbit Telecom	Landing or Hopping	Surface Ops - Sampling	Surface Ops - Science	Surface Ops - Night	TBD	TRL	Cost ($K)
Total			21	68.650	9%	74.802	500.9	41.6	107.6	107.6	73.9	73.9	58.4	48.7	41.2	0.0	0.0	5	
LVS LCAM	LVS LCAM	N	2	1.730	0%	1.730	16.8	0.0	0.0	0.0	0.0	0.0	16.8	0.0	0.0	0.0	0.0	8	2000
Surface Cameras	MSL / M2020 EECAM	Y	9	5.400	0%	5.400	22.5	0.0	0.0	0.0	0.0	0.0	0.0	15.0	7.5	0.0	0.0	9	1945
Sun Sensors	Adcole 2-Axis Coarse Sun Sensor, 1	N	2	0.260	10%	0.286	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		9	184
Star Trackers	Galileo AA-STR, 6	Y	2	5.260	10%	5.786	7.9	7.9	7.9	7.9	7.9	7.9	7.9					5	1321
IMUs	Honeywell MIMU, YG9666Hx, 0.005	Y	2	8.000	10%	8.800	33.7	33.7	33.7	33.7			33.7	33.7	33.7			9	842
RWAs	Honeywell,100	Y	4	48.000	10%	52.800	420.0		66.0	66.0	66.0	66.0						9	908
Gimbal Drive Electronic	MOOG 2-Channel Electronic Control Unit	Y	0	0.000	10%	0.000	0.0												

- Maintenance
  - Reaction wheel momentum unloading accomplished with SEP thrusters in cruise and in orbit

ACS

Cost Assumptions

Cost Parameter	Parameter Option
Include Phase D Costs	Yes
ADCS Heritage Factor	Similar w/ Minor Mods
Mission Class from Guidelines: B	B
S/C Performance Pointing Control & Stability	0.1 deg

Number of Pieces of ADCS Equipment	21
Number of Types of ADCS Equipment	6
Hardware Quantity Factor (for Engineering support sized with subsystem)	3.6

Optional ACS Control Functions

- [ ] Star Identification (not delivered with HW)
- [ ] Mars Pathfinder Style EDL
- [ ] Mars Exploration Rover Style EDL
- [ ] Mars Science Laboratory Style EDL
- [ ] Aero-manuevering During Entry
- [x] Pin-point Landing (~100 Meter Accuracy)
- [ ] Hazard Detection and Avoidance
- [ ] Terrestrial Planet Finder Class Formation Flying (3+ Spacecraft)
- [ ] 2 - Spacecraft Rendezvous
- [ ] Target - Relative Tracking (Small Body Target)
- [x] Small Body Landing
- [x] Small Body "Touch-and-Go" (Approach & Touch While Passing By)
- [ ] SMAP Style Dynamics and Control
- [ ] Extensive Field Testing

ACS

Cost

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		2,588	3,505	9,416	36,427	714	733	244	-	-	**53,627**
06.10.01 GN&C Subsystem Management		243	243	182	101	81	243	81			**1,175**
06.10.02 GN&C Subsystem Engineering		804	804	603	335	268	490	163			**3,466**
06.10.03 GN&C Sensors AND		-	917	7,475	35,535	-					**43,927**
06.10.04 GN&C Actuators AND											
06.10.05 GN&C I/F Electronics											
06.10.08 GN&C Control Analysis		1,541	1,541	1,156	456	365				-	**5,059**

Hardware Costs (with spares, EM's)

	Flight Models	#	Engineering Models	#	Qualification Units	#	Models for Current Study ($K)	H/W Engr Equip. Dev (Wm)	Flight Spares	#	Off-the-Shelf Cost ($K)	Cost for Flight Units	Cost for Spares	Cost for Qual Units	Cost for EM's	Development Type
LVS LCAM	4000	2	1600	1	0	0			0	0	2000	100%	100%	120%	80%	Out-of-House
Surface Cameras	17507	9	1556	1	0	0			0	0	1945	100%	100%	120%	80%	Out-of-House
Sun Sensors	368	2	147	1	0	0			0	0	184	100%	100%	120%	80%	Out-of-House
Star Trackers	2643	2	1057	1	0	0			0	0	1321	100%	100%	120%	80%	Out-of-House
IMUs	1685	2	674	1	0	0			0	0	842	100%	100%	120%	80%	Out-of-House
RWAs	3631	4	726	1	0	0			0	0	908	100%	100%	120%	80%	Out-of-House
Gimbal Drive Electronics		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
				0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
		0		0		0				0		100%	100%	120%	80%	Out-of-House
												100%	100%	120%	80%	Out-of-House
												100%	100%	120%	80%	Out-of-House
Subtotals in FY2025 $K	29833		5761		0		0	0	0							

ACS

Cost

- Cost Drivers
  - Large number of EECAM cameras (9).. Estimated cost = $5M (FY20$) for 3 cameras (equivalent to $1.7M FY20$ each).

- Potential Cost Savings
  - Average unit cost of 9 EECAMs probably is less than above (reasonable to assume some economy of scale). Potential savings guesstimate ~$2-3M?

- Potential Cost Uppers
  - Assumed “similar to minor mods”; however subsystem mods w.r.t. heritage could be “major” (~$6M “upper”)

Power Report

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Power

Design Requirements

- Mission:
  - Ceres lander at 2.8 AU

- Stabilization: 3-Axis during flight

- Option 1: Solar Electric Propulsion (SEP) to Ceres, orbit, land, in-situ science, sample collection, sample return to Earth
- Option 2: SEP to Ceres, orbit, land, in-situ science, “Hop” to another landing location, in-situ science, end

Power

Design Assumptions

- All options:
  - No SEP during eclipse because the battery DOES NOT support EP
  - Missed thrust analysis has been performed allowing 5% contingency on electric propulsion power estimates
  - Battery resides on the 32V bus not the 100V power bus provided for the SEP's power processing unit (PPU)
  - Ceres surface ops require deployed solar array for power
    - Deployed orientation would either flat and fixed or sun tracking
    - The array is so large that it would easily be able to support surface ops in the fixed orientation

Power

Summary – Option 2

Subsystem/Instrument	Mode #	1	2	3	4	5	6	7	8	9	10
		Power [W]									
OPTION 2	Mode Name	Launch	SEP Cruise @ Earth	SEP Cruise @ Ceres	Orbital Science	Cruise/Orbit Telecom	Landing or Hopping	Surface Ops - Sampling	Surface Ops - Science Day	Surface Ops - Night	TBD
ACS	W	42	108	108	74	74	58	49	41	0	0
C&DH	W	24	24	24	24	24	28	24	24	24	0
Instruments	W	0	0	0	2	0	0	165	86	0	0
Other Elements	W	0	0	0	0	0	0	0	0	0	0
Propulsion System 1	W	37	1	1	1	1	217	1	1	1	0
Propulsion System 2	W	0	14,480	2,000	0	0	0	0	0	0	0
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	10	10	10	10	205	205	205	205	10	0
Thermal	W	193	48	123	163	48	108	108	108	108	0
Power Subsystem	W	70	161	81	67	74	97	92	84	56	0
TOTALS		**375**	**14,831**	**2,345**	**341**	**425**	**713**	**643**	**548**	**198**	**0**
Systems Contingency	%	43%	43%	43%	43%	43%	43%	43%	43%	43%	43%
Calculated Contingency (Override)	%	43%	6%	11%	43%	43%	43%	43%	43%	43%	0%
Subsystem Contingency	W	**161**	**875**	**248**	**146**	**183**	**307**	**276**	**236**	**85**	**0**
Subsystems with Contingency	W	**536**	**15,706**	**2,594**	**487**	**608**	**1,020**	**919**	**784**	**283**	**0**
Distribution Losses	W	**11**	**314**	**52**	**10**	**12**	**20**	**18**	**16**	**6**	**0**
Total Subsystems	W	**546**	**16,020**	**2,646**	**497**	**620**	**1,040**	**938**	**800**	**289**	**0**
Systems with Contingency	W	536	16,430	2,702	487	608	1,012	909	770	274	0
Duration (published by Systems, **hours**)		4.0	24.0	24.0	2.3	8.0	1.0	1.0	4.5	4.5	0.0

Power

Design – **Array – Both Options**

- Array specified by the customer team based on the team's negotiation with DSS for the Roll Out Solar Array (ROSA)
  - $40M procurement from DSS, in FY 2025 $, including burdens
  - 225 kg in two ROSA wings
  - 27.5kW for two ROSA panels, at AM0
    - DSS based their test and have confidence in their estimates based on lunar lander project
  - 2 axis articulation

Mass - Total Array, override: 225kg total	**225.00 Kg**	112.5 kg/wing for 2 wings, 225kg total, as provided by the customer, passed through here	
Total Cell Area	**81.05 m^2**	**40.53 m^2**	Wing Cell Area
Total Array Area	**95.36 m^2**	**47.68 m^2**	Wing Array Area
# Wings	**2**	**0.85**	Packing Factor
Design Technology / Configuration	**Roll Out Solar Array (ROSA)**		**Note: ROSA mass based on Ultraflex mass calcs**

Power

Design – Array Design Parameters – Both Options

Main Selection Panel			
	User Input	Lookup Index	Legend
Articulation	Two Axis	5	Default
Configuration	Two Deployable Wings	4	Calculated or Linked
Technology	Roll Out Solar Array (ROSA)	4	Direct Entry
	User Input/Override	Used in Design Calcs	Pulldown
Nominal Array Voltage	100 volts	100 volts	Nominal Power Bus V
Solar W/m^2 @ 1 AU		1353 w/m^2	Baseline Incident W
EOM Nuclear Power (W)		0 watts	Addl Nuclear W
Manufacturing Loss Factors (0 = total loss, 1 = no loss)			
Mismatch & fabrication		0.98	Factor
Wiring loss		0.96	Factor
User Spec'd Mfg Factor 1		1.00	Factor
User Spec'd Mfg Factor 2		1.00	Factor
EOL / Sizing Power Mode Environmental Losses / Loss Factors (0 = total loss, 1 = no loss, >1 = gain)			
Nominal operating distance from sun		1353 w/m^2	Incident Power
Sun offset angle (from array surface normal)		1.00	Factor
Nominal cell operating temp. for Sizing Mode	28° C	28° C	Cell Operating Temp.
Shadowing factor		1.00	Factor
End of Life (EoL) Degradation Loss Factors (0=total loss, 1 = no loss)			
Ultraviolet degradation		0.98	Factor
Radiation degradation		0.96	Factor
Fatigue (thermal cycling)		0.98	Factor
Micrometeoroid loss		0.98	Factor

Power

Design – **Batteries – Both Options**

- Small cell Li-Ion 18650 (18mm diameter, 650mm height) batteries
- Driving power mode: Launch, allowing up to 70% depth of discharge (DOD)
- Battery mass based on Europa Clipper specific mass of 0.0068 kg/Wh
- One 126 Ah battery
- 60% DOD during the Launch phase

Power

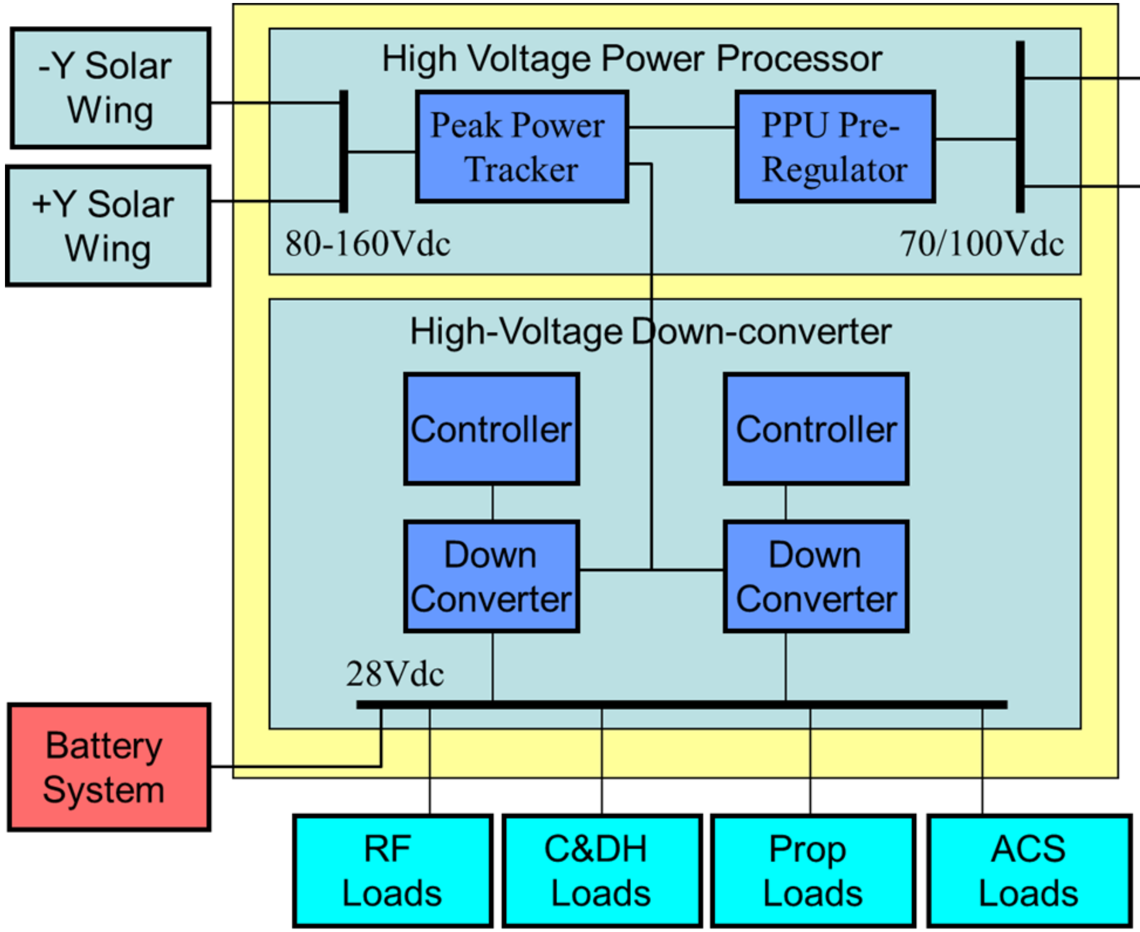
Design – **Electronics**

- Dawn inspired, but new design and build HVEA
- Reason for differences
  - Dawn HVEA interfaced to nickel hydrogen batteries, which are replaced by Li-Ion batteries
  - Dawn HVEA parts obsolescence requires redesign based on more contemporary catalog parts

					FMs	FSs				Protos					
Equipment Type or Level of Effort Cost Type Hover cursor here for details	Specific Equipment Type or Specific Level of Effort Hover cursor here for details	Design Level Hover cursor here for details	Board Name Alias Hover cursor here for details	Usage Information	FM Units	FS Units	FS Parts Kits	FS Units & Kits	FS Built Units	PT Units	EM Units	EM Sub Units Hover cursor here for details	EM Units	Total Units Cards Slices Assys Arrays RPSs Batts	Board Slice or Assy Level BTE Units
HV Down Converter	High Voltage Down Converter (aka High Voltage Electronics Assy (HVEA)	New assy	At best this has approximately the same functionality as Dawn		1		1	1	0	1			0	3	0
Next Gen Small Sat	Smallsat PCU	Heritage slice			4		2	2	0	4			0	10	0
EC Next Gen Load Switches	EC Next Gen Power Switch Slice - 32 H/L channels	Heritage slice	2 fault tolerant. 2 for load swtiching 1 for pyros		3		3	3	0	3			0	9	3
Diodes	Diodes Assembly	Heritage assy	Placholder for fuse assy		1			0	0	1			0	2	

Power

Block Diagram



Design Driver

•Fixed PPU Input Voltage

New Features

•SA Peak Power Tracker

•PPU Voltage Regulation

Retained

•High Voltage Down- converter

•28Vdc Battery Dominated Bus

Power

Design Rationale

- Array
  - Configuration, size and mass prescribed by the customer team
  - 100V
- Batteries
  - Sized for launch from T0 to array deployment
  - All other modes' energy requirements are less than launch
- Electronics
  - Design Drivers: provide high voltage power source for SEP system and down-convert to standard 28-32V bus for the rest of the spacecraft loads as most spacecraft equipment is designed for that voltage input

Power

Cost Assumptions – Both Options

- The following table enumerates the costed WBS and cost parameters that drove subsystem costing
  - Costed as Class B with heritage
  - Subsystem engineering includes subsystem management costs

Equipment Type or Level of Effort Cost Type Hover cursor here for details	Specific Equipment Type or Specific Level of Effort Hover cursor here for details	Design Level Hover cursor here for details	Board Name Alias Hover cursor here for details	Usage Information	FM Units	FS Units	FS Parts Kits	FS Units & Kits	FS Built Units	PT Units	EM Units	EM Sub Units Hover cursor here for details	EM Units	Total Units Cards Slices Assys Arrays RPSs Batts	Board Slice or Assy Level BTE Units	Assy or Subsys Level BTE Test Racks & Sims GSE Units
Level of Effort	Subsystem Engineering	Exotic	Includes subsystem management													
Solar Array	Solar Array	Novel	Deployable/retractable/redeployable ROSA 27.5kw for two ROSA panels at AM0		1			0	0				0	1		
Battery	Secondary Battery	Mod	Resides on low voltage bus.		1		1	1	0	1			0	3		
HV Down Converter	High Voltage Down Converter (aka High Voltage Electronics Assy (HVEA)	New assy	At best this has approximately the same functionality as Dawn		1		1	1	0	1			0	3	0	
Next Gen Small Sat	Smallsat PCU	Heritage slice			4		2	2	0	4			0	10	0	
EC Next Gen Load Switches	EC Next Gen Power Switch Slice - 32 H/L channels	Heritage slice	2 fault tolerant. 2 for load swtiching 1 for pyros		3		3	3	0	3			0	9	3	
Diodes	Diodes Assembly	Heritage assy	Placholder for fuse assy		1			0	0	1			0	2		
BTE / GSE / SSE	Power supply (simple array - RPS - battery sim)															1
BTE / GSE / SSE	Environmental Test Cycles															2
Level of Effort	Component BTE / GSE / SSE only															
Level of Effort	Component I&T only															

Power

Cost

- Both options are the same subsystem
- Any cost differences between the two would be due to programmatic differences, such as level of effort labor and different development schedules

Option 2 2025 $K	TOTAL COST Total	labor ($k)	Services ($k)	Procurements ($k)
Subsystem Management	**-**	-	-	-
System Engineering	**6,506**	6,506	-	-
Power Source - Solar Array	**40,247**	799	-	39,449
Power Source - RPS	**-**	-	-	-
Energy Storage - Rechargeable Secondary Battery	**1,733**	313	-	1,420
Energy Storage - Primary Battery	**-**	-	-	-
Energy Storage - Thermal Battery	**-**	-	-	-
Electronics	**16,333**	4,463	2,145	9,725
BTE / GSE / I and T	**5,886**	4,732	1,141	13
Total	**70,706**	**16,813**	**3,286**	**50,607**

Systems note: Option 1 cost table will be included after completion of the study

Power

Cost

- Cost Drivers
  - 27.5 kW Solar Array

- Potential Cost Savings
  - There may be a stronger heritage argument when small sat avionics comes on line, in which case there may "product lines" for the power converters as well as load switching and pyro driver electronics
  - The MAXAR/JPL avionics/power architecture for the Psyche mission, if still viable, may be a option as well

- Potential Cost Uppers
  - ~$30m without the solar array is in line with JPL power subsystem costs

Power

Risks

- Multiple solar array deploy / retract cycles: the failure of either action could jeopardize Ceres landing, hopping, and sample return

Propulsion Report

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Propulsion

Design Requirements

- Mission:
  - Mission to orbit and land on Main Asteroid Belt object Ceres
- Mission Design
  - Solar electric propulsion for outbound mission and Ceres proximity, with EP engines also used for momentum wheel unloads during cruise and proximity operations
  - Hydrazine monopropellant system for landing and hopping, along with three axis control during safe mode and occasional momentum wheel unloads
- ACS
  - Three axis control during safe mode, and occasional momentum wheel unloads
- Configuration
  - The Hydrazine landing system will utilize a modification of the MSL/M2020 skycrane MLE throttle valve on an Aerojet Rocketdyne MR-104 445 N class engines for landing and hopping

Propulsion

Design Assumptions

- Assume Electric Propulsion for Ceres cruise and proximity operations
- Assume large Hydrazine monoprop system for landing, and three axis control

Propulsion

Design

- Monoprop Hydrazine System Hardware – 150.9kg dry mass including 5% contingency
  - Six MR-104 445 N class Aerojet Rocketdyne main engines with throttle valves
  - Two redundant branches of twelve Aerojet MR-106 22N engines for RCS
  - Three PSI monolithic diaphragm titanium spheroid propellant tanks, 80263-201 measuring 1.02m radius x 1.01m height, and 34.5 kg each

- Electric Propulsion System Hardware – 275.3 kg dry mass including 5% contingency
  - Three NEXT Ion propulsion engines with PPUs and XFCs, and two DCIUs
  - One Keystone composite overwrapped Xenon tank, 1270000-1 measuring 1.16m radius x 1.12m height, and 90 kg

- Functionality
  - Chemical to perform landing and hopping, three axis ACS, and momentum wheel unloading
  - EP for Cruise to Ceres, proximity operations, and momentum wheel unloading

Propulsion

Design

- Monoprop Hydrazine – 800kg
  - Sized to a launch mass of 3900kg, 600 m/s delta-v, and a final mass of 2471 kg
- Electric Propulsion Xenon - 701 kg Xenon (includes 10% margin)
  - Sized to a launch mass of 3900kg, 7000 m/s delta-v, and a final mass of 2471 kg
- Delta-V Table

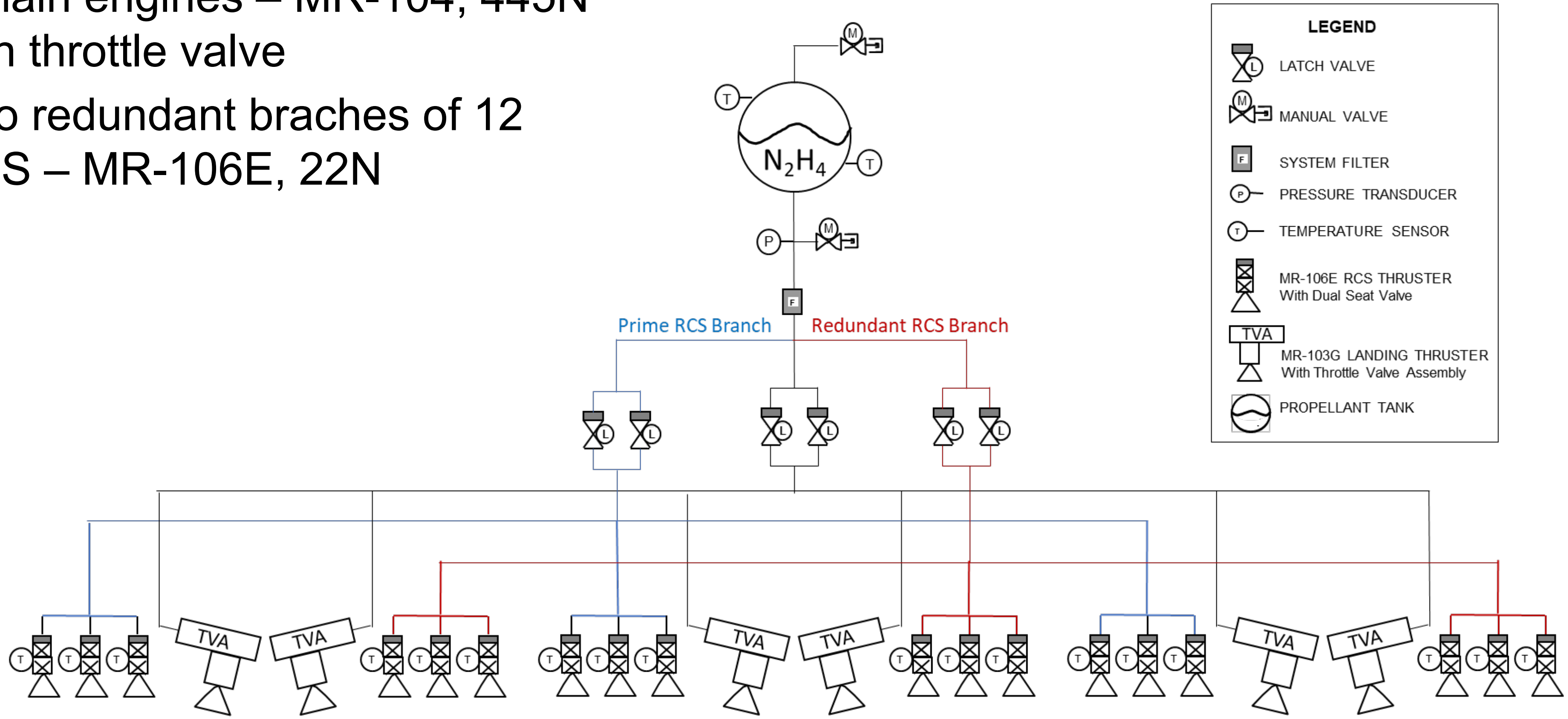
Mission Description	Maneuver Type		ADD, JET, ACS, or SEP	Delta V	Impulse	Engine Selection				Database Performance Data		
Event Name, Description	Assign Propellant To System:	Event Type	Mass (kg)	Delta V (m/s)	Impulse (N-sec)	Use engines on System #:	Pointing offset (deg)	Specific Engine from equipment list	# of Engines Firing	MR	Isp (s)	Thrust per Engine (N)
SEP Outbound	2	DV		7000		2		EP Main Engine	2	0	4155	0.235
Deobit, Descent and Landing	1	DV		401		1		Monoprop Main Engine	6	0	237	445
40 km Hop	1	DV		195		1		Monoprop Main Engine	6	0	237	445
Misc Delta-V, 600-(401+195)	1	DV		4		1		Monoprop Thrusters 1	2	0	235	22.25
ACS for Chem	1	ACS	15.00			1		Monoprop Thrusters 1	2	0	235	22.25

Propulsion

Block Diagram – Monoprop Hydrazine

Monoprop Hydrazine

- 6 main engines – MR-104, 445N with throttle valve
- Two redundant braches of 12 RCS – MR-106E, 22N

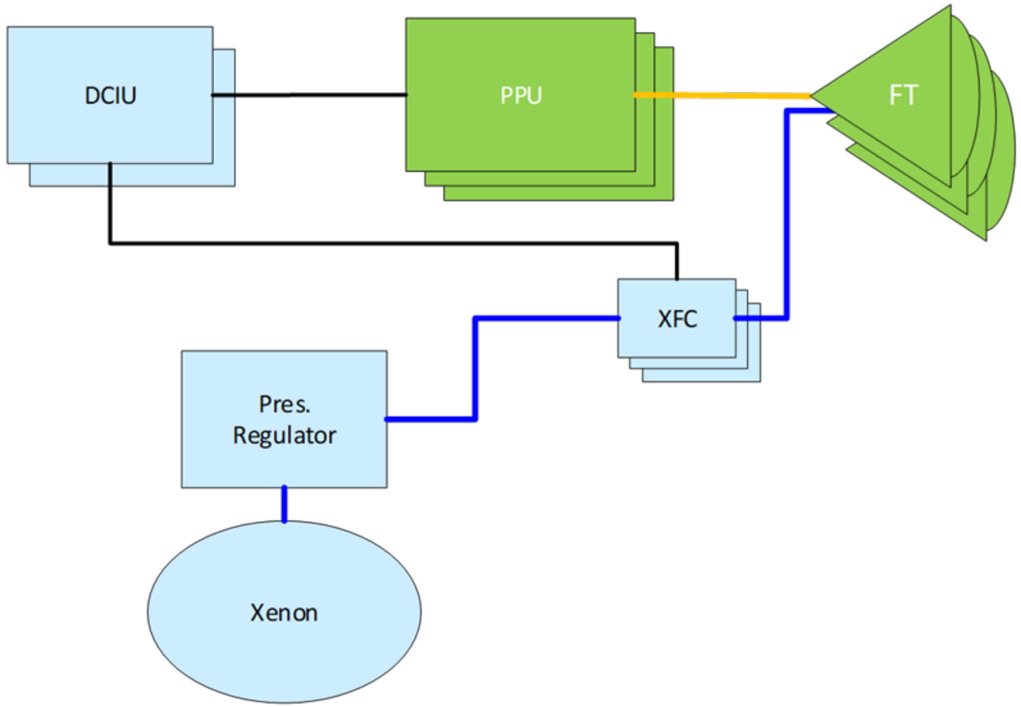


Propulsion

Block Diagram – Electric Propulsion

NEXT Ion Propulsion

- 2+1 system



Propulsion

Design Rationale

- An EP design for travel to Ceres is ideal due to the large delta-V requirement (7000 km/s)
- A chemical propulsion landing system is ideal for large delta-v maneuvers in a short timeframe, and the throttled valve compensates well for a soft landing in very low gravity

- Trades
  - No trades performed
  - A suggested trade that could be performed would be to look at a blowdown versus regulated system for the monoprop – often regulated systems are used on landers for higher fidelity control authority and higher specific impulse

Propulsion

Cost Assumptions

- The cost for the Electric Propulsion system is a direct pass through from GRC at $19.2M, and includes JPL's sub-contract burden
  - The Team X cost includes Xenon, and propellant loading
  - One FTE was added for all phase duration for JPL coordination with GRC
  - The GRC cost includes a development Xenon tank for the stretched Keystone design
- Did not include throttle valve development/adaptation cost – assumed tech ready by time of this mission
- Cost included full spares for Chemical system
- No other deviations from the Team X cost model were made

Propulsion

Cost

- Total cost for the both Ceres Propulsion systems is $50.3M
- Monopropellant Hydrazine system total cost: $26.8M
  - Non-recurring: $11.1M
  - Recurring: $15.7M
- Electric Propulsion system total cost: $23.5M
  - GRC non-recurring: $19.2M
  - Recurring: $4.3M

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	9	5	4	12	4	$k
.01 &.02 Management, Engineering, &	Engr Labor $	$1,803.9k	$1,803.9k	$1,352.9k	$751.6k	$601.3k	$1,803.9k	$601.3k	$8,719.0k
.03 Components Engr	Engr Labor $	$0.0k	$577.3k	$764.0k	$424.5k	$339.6k	$0.0k	$0.0k	$2,105.3k
.04 GSE	Engr Labor $	$0.0k	$0.0k	$0.0k	$288.2k	$288.2k	$0.0k	$0.0k	$576.4k
.05 I&T	Engr Labor $	$0.0k	$0.0k	$0.0k	$663.6k	$530.9k	$0.0k	$0.0k	$1,194.5k
.06 Prop loading & ATLO supt	Engr Labor $	$0.0k	$0.0k	$0.0k	$0.0k	$0.0k	$570.7k	$570.7k	$1,141.4k
.04 GSE	Service $	$0.0k	$0.0k	$0.0k	$345.9k	$345.9k	$0.0k	$0.0k	$691.8k
.05 I&T	Service $	$0.0k	$0.0k	$0.0k	$1,114.0k	$938.4k	$0.0k	$0.0k	$2,052.4k
.06 Prop loading & ATLO supt	Service $	$0.0k	$0.0k	$0.0k	$0.0k	$0.0k	$877.2k	$877.2k	$1,754.4k
Subtotal Labor and Services	Labor and Services $	**$1,803.9k**	**$2,381.2k**	**$2,117.0k**	**$3,587.9k**	**$3,044.2k**	**$3,251.8k**	**$2,049.2k**	**$18,235.2k**
.03 Components	Subcontract Procurement $		$5,647.5k	$8,195.0k	$8,195.0k	$8,195.0k		$1,826.5k	$32,058.9k
Non-Recurring	$k	$1,803.9k	$8,028.7k	$7,341.1k	$6,588.4k	$6,400.2k	$1,443.1k	$481.0k	$32,086.6k
Recurring	$k	$0.0k	$0.0k	$2,970.8k	$5,194.4k	$4,839.0k	$1,808.7k	$3,394.6k	$18,207.5k
Total	$k	**$1,803.9k**	**$8,028.7k**	**$10,311.9k**	**$11,782.8k**	**$11,239.2k**	**$3,251.8k**	**$3,875.6k**	**$50,294.1k**

Propulsion

Risks

- There is low cost risk to JPL for delivered systems such as the EP system from GRC, although there is schedule risk should the delivery be delayed or technical difficulties be discovered at GRC
- There is risk that the throttle valve development is not complete by the tech cutoff, which is mitigated to going to a pulsed landing model like Phoenix
- The Keystone stretched Xenon tank development is included in the GRC cost, but any development has schedule risk, which should be low in this case, and mitigated by changing to multiple smaller qualified tanks if necessary

Thermal Report

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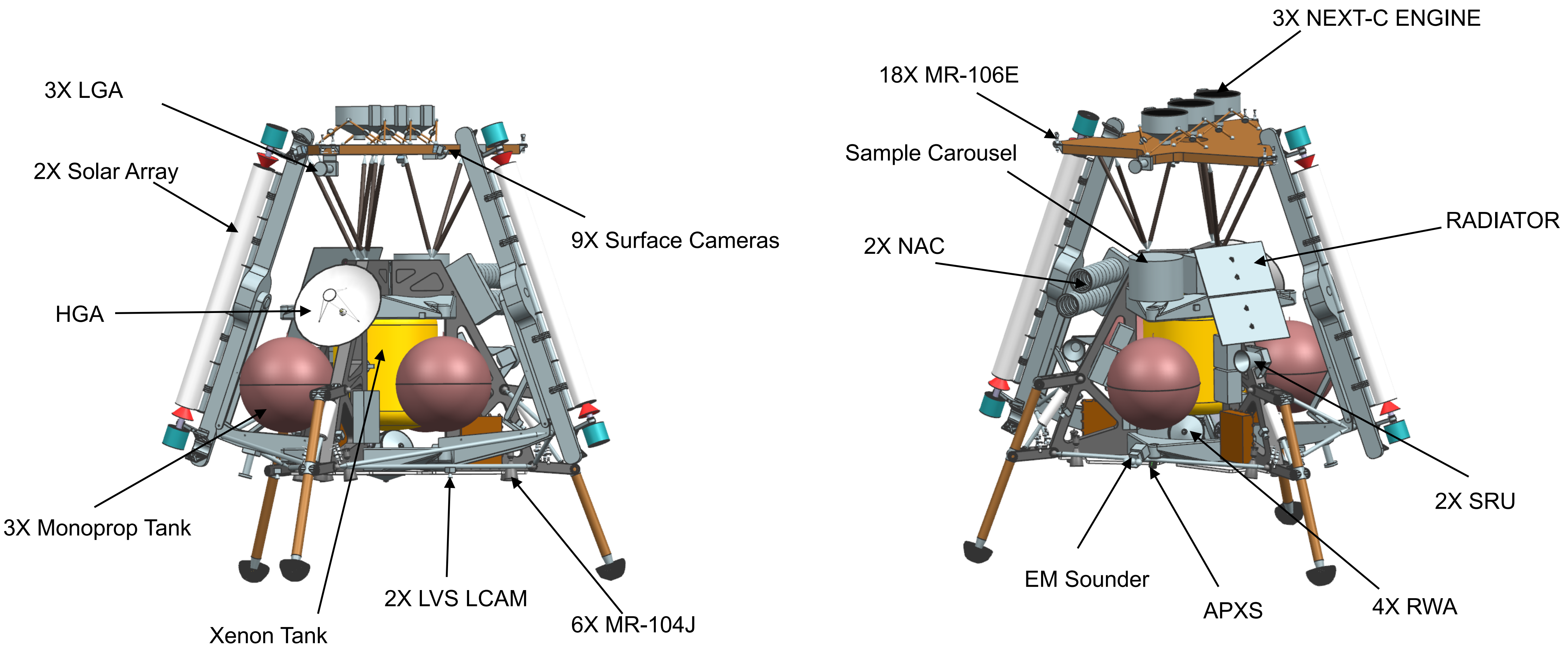
Thermal

Design Requirements—Option 2

- Mission:
  - Ceres Lander and Hop
  - SEP during Cruise and Ceres Orbit Raising/Adjustments
- Stabilization: 3-Axis
- Payload: Assumed to provide independent thermal control
- Other subsystem interfaces
  - Propulsion—Drives power dissipations due to SEP system
  - Power—Thermal is a driver on battery sizing

Design Configuration Option 2

- Configuration Drawings – Stowed



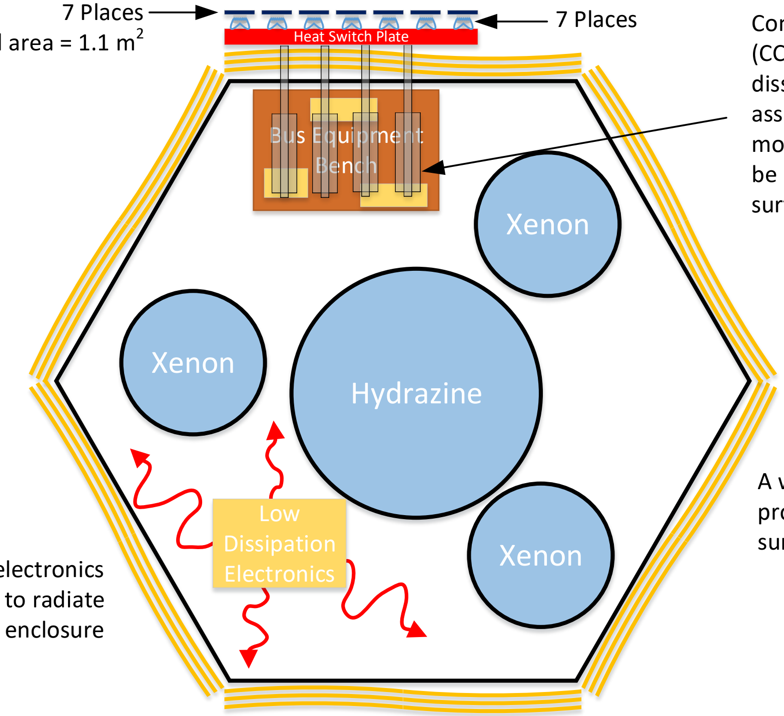
Thermal Architecture

Option 2

Avionics radiator located on North side of lander to minimize direct solar radiation (assuming 20° landing latitude)

Radiator Segments
7 Places
Total area = 1.1 m^2

Heat Switches
7 Places

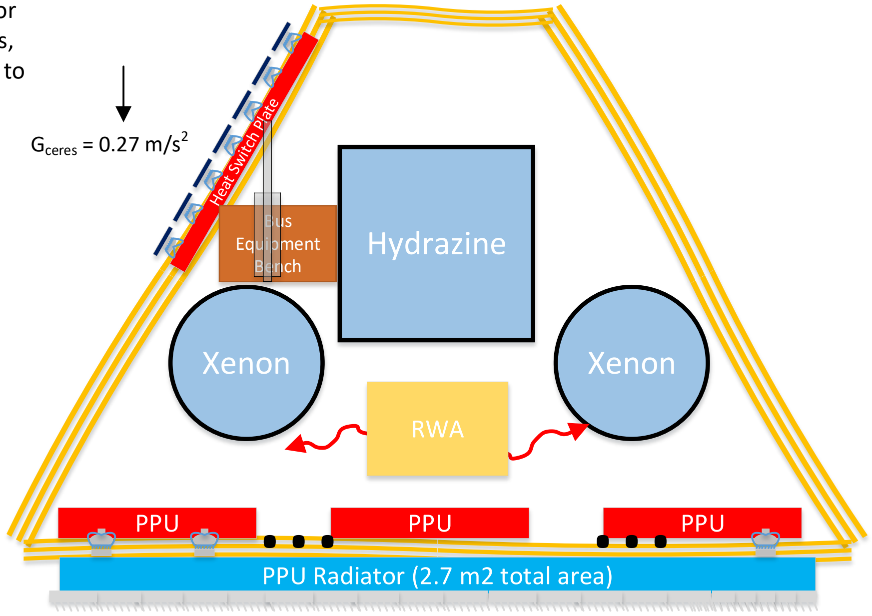


Constant conductance heat pipes (CCHPs) are used to couple the high dissipating avionics to the radiator assembly (radiator, heat switches, mounting plate). Note: radiator to be located at higher height from surface than the bus equipment

A wiffle-tree is used to provide regular, defined surfaces for MLI enclosure

Low dissipation electronics are allowed to radiate within the MLI enclosure

$G_{ceres} = 0.27\ m/s^2$



Either qty. 17 20-blade louver sets
—or—
18 heat switches are used for PPU radiator turn-down
(see trade analysis on next slide)

Thermal Design Guidelines

Radiator Sizing

- Dedicated PPU radiator
  - PPUs are 94% efficient, 14480 W x 94% = 870 W dissipation requires 2.7 m^2 radiator to maintain PPU below 50 °C
  - PPUs allowed to freeze after landing for Option 2
- Avionics radiator
  - Worst case load is 335 W, requires 1.1 m^2 area to maintain bus below 50 °C

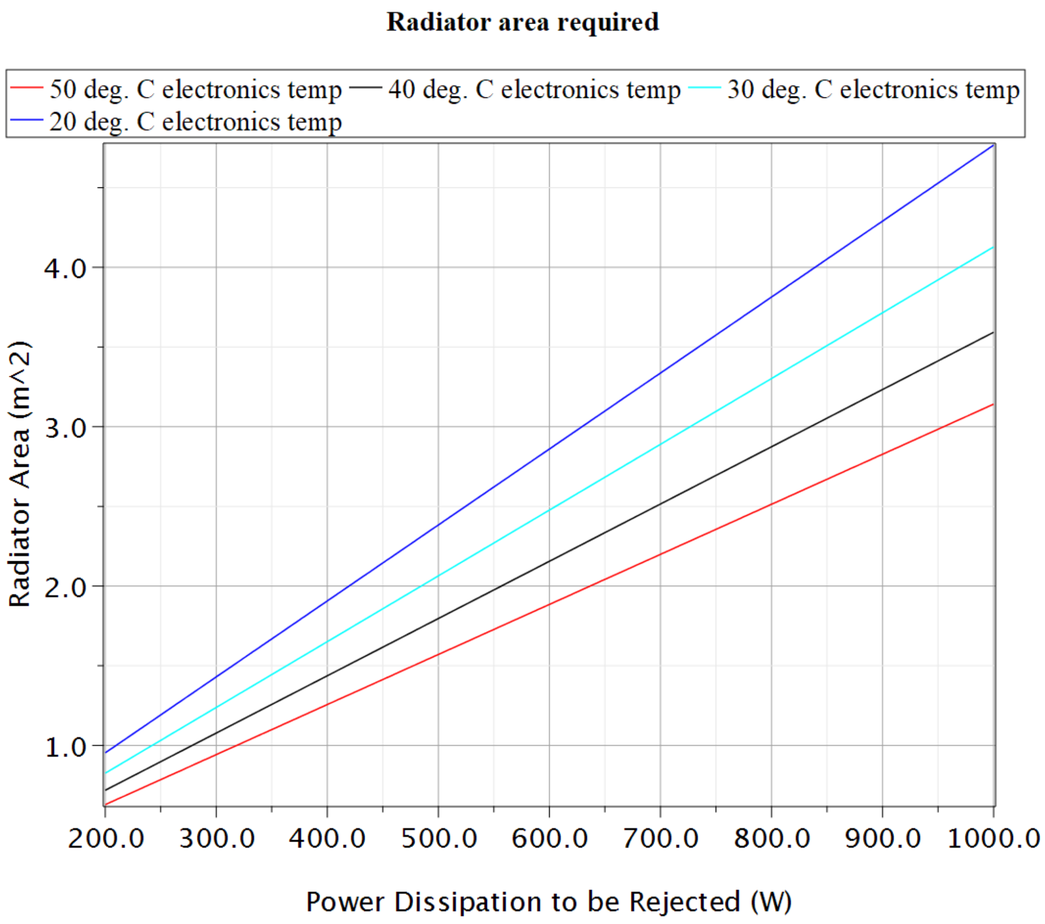
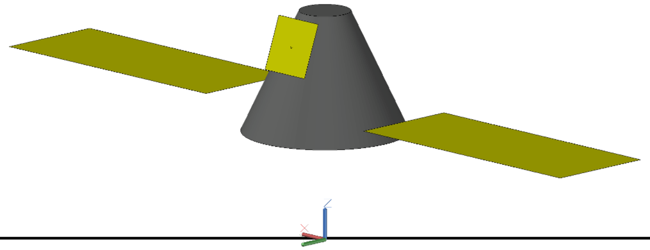


Figure 1. Radiator Area as a function of waste heat generation.

Thermal Design Guidelines

Heater Sizing During Cruise

- Heater power is driven by the need to maintain propellant temperatures above minimum allowable of 15 °C
- The plot to the right shows the amount of internal dissipation required to maintain temperatures. Heater power is the difference between these curves and non-PPU equipment dissipation
- Heater power is sensitive to effectiveness of MLI
- Note: the customer provided CAD showed MLI conformal to hardware elements, which resulted in irregular shapes, crevices. This is not recommended due to being less deterministic (solar trapping assessment); degraded performance due to abundance of seams (estar values can exceed 0.1); and increased area. Recommend that a wiffle-tree structure be used to give MLI a smooth, regular shape.



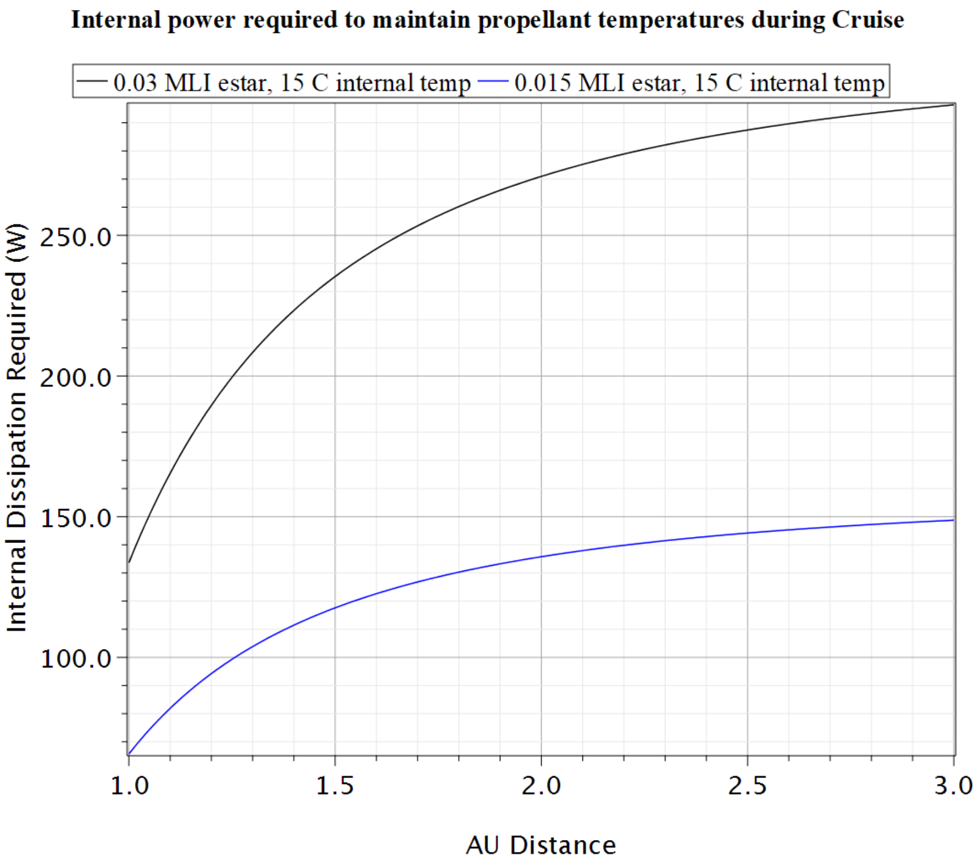
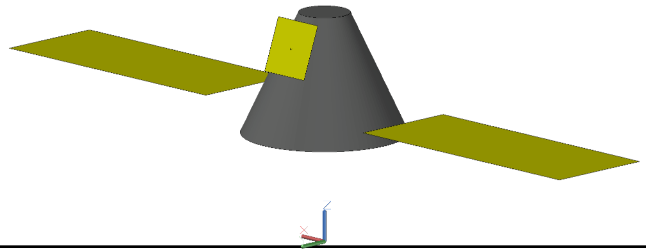


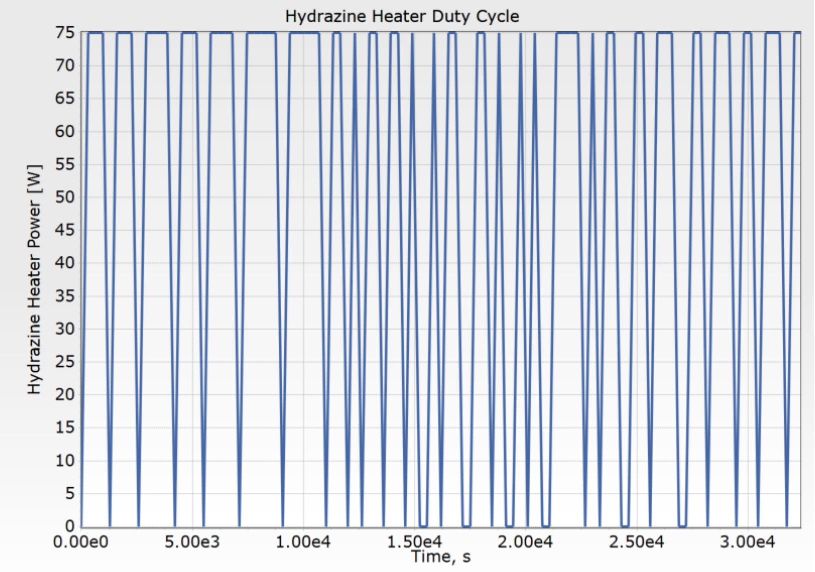
Figure 2. Internal power needed to maintain propellant temperatures.

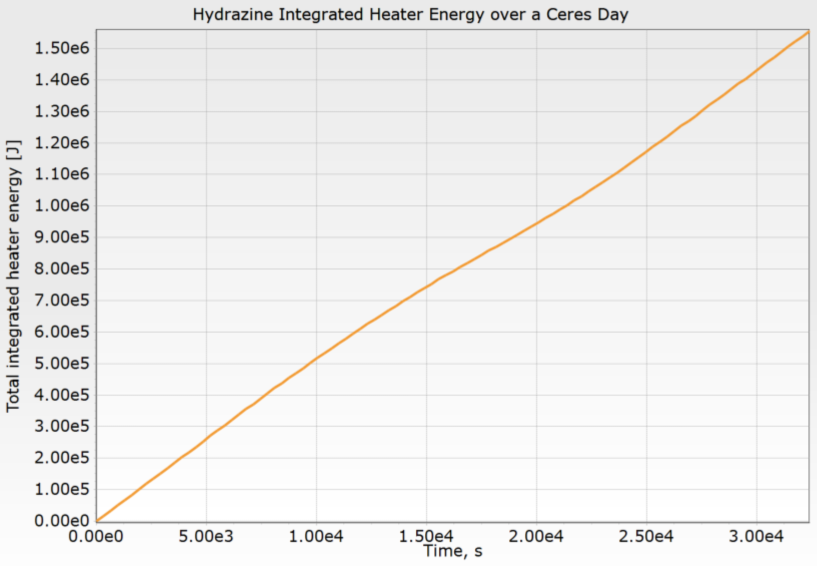
Thermal Design Guidelines

Heater Sizing During Surface Operations

- Heater power is driven by the need to maintain hydrazine and thruster valve temperatures above minimum allowable of 15 °C
- The plot to the right shows the duty cycle of a 75 W heater over a Ceres day (~ 9 Earth hrs). Total integrated energy over the Ceres day is ~ 450 W-hr (1.6 MJ)
- If thruster valves require ~ 2 W per valve. All 24 monoprop valve were assumed to be heated for a total of 48 W for the Team-X study.
- Heater power is sensitive to effectiveness of MLI
- Note: the customer provided CAD showed MLI conformal to hardware elements, which resulted in irregular shapes, crevices. This is not recommended due to being less deterministic (solar trapping assessment); degraded performance due to abundance of seams (estar values can exceed 0.1); and increased area. Recommend that a wiffle-tree structure be used to give MLI a smooth, regular shape.



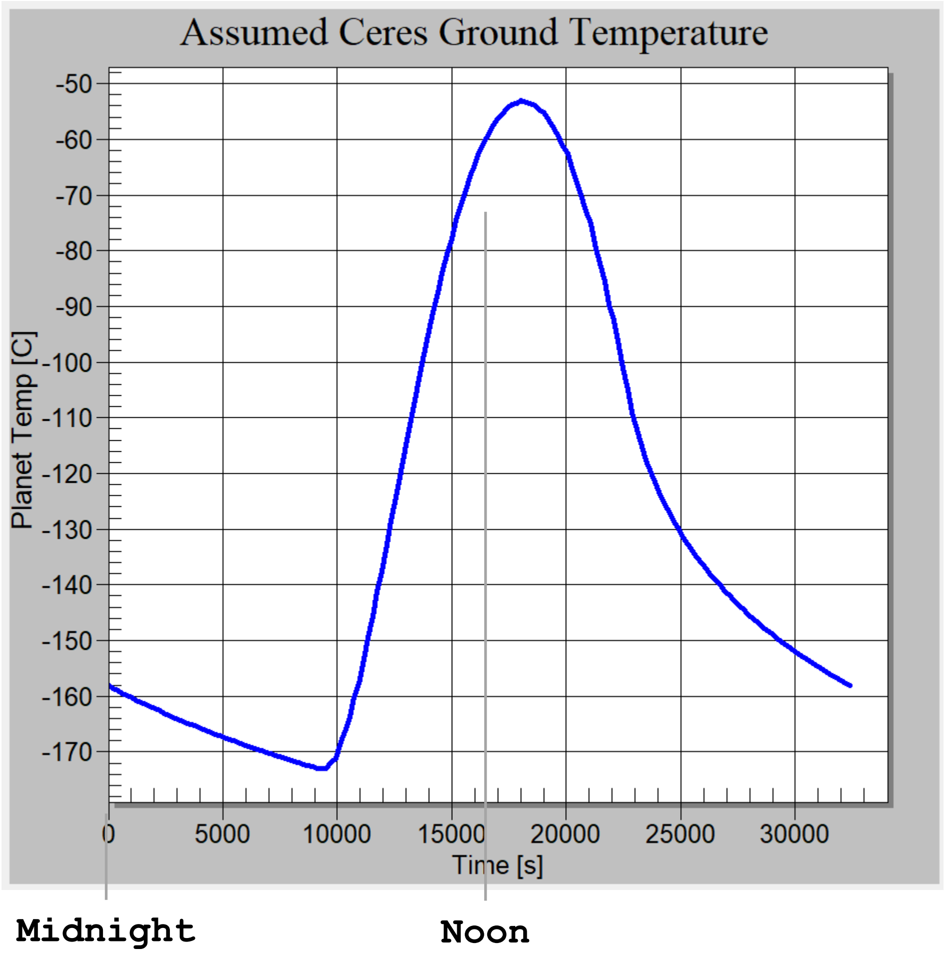




Thermal

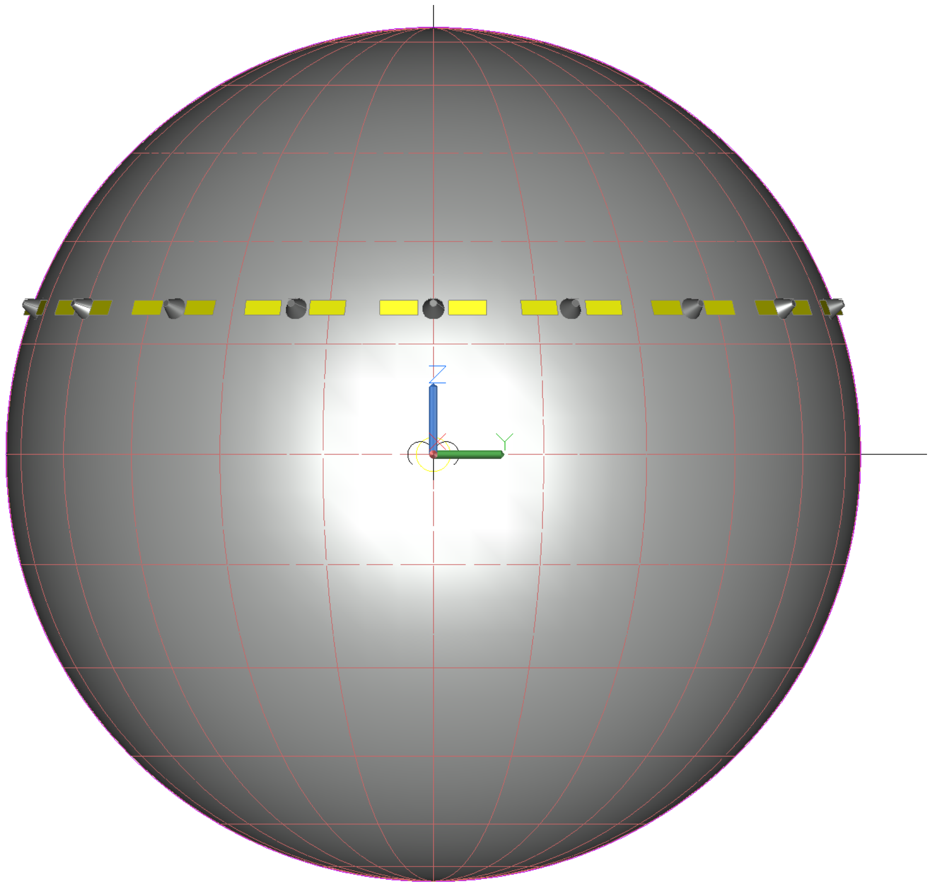
Environments

- Hot—1AU Cruise
  - 1400 W/m^2 solar insolation
- Cold—2.8 AU Cruise
  - 183 W/m^2 solar insolation
- Diurnal
  - Ceres assumed spherical, 470 km radius, 4° inclination of equator
  - Ceres day ~ 9 Earth hours
  - Landing site assumed as Vinalia (~ 20° latitude)
  - 183 W/m^2 solar insolation
  - 0.24 albedo / 0.95 ground IR emissivity assumed (salts?)
  - Surface temperature based on customer input of "200 K at noon; 160 K ave"

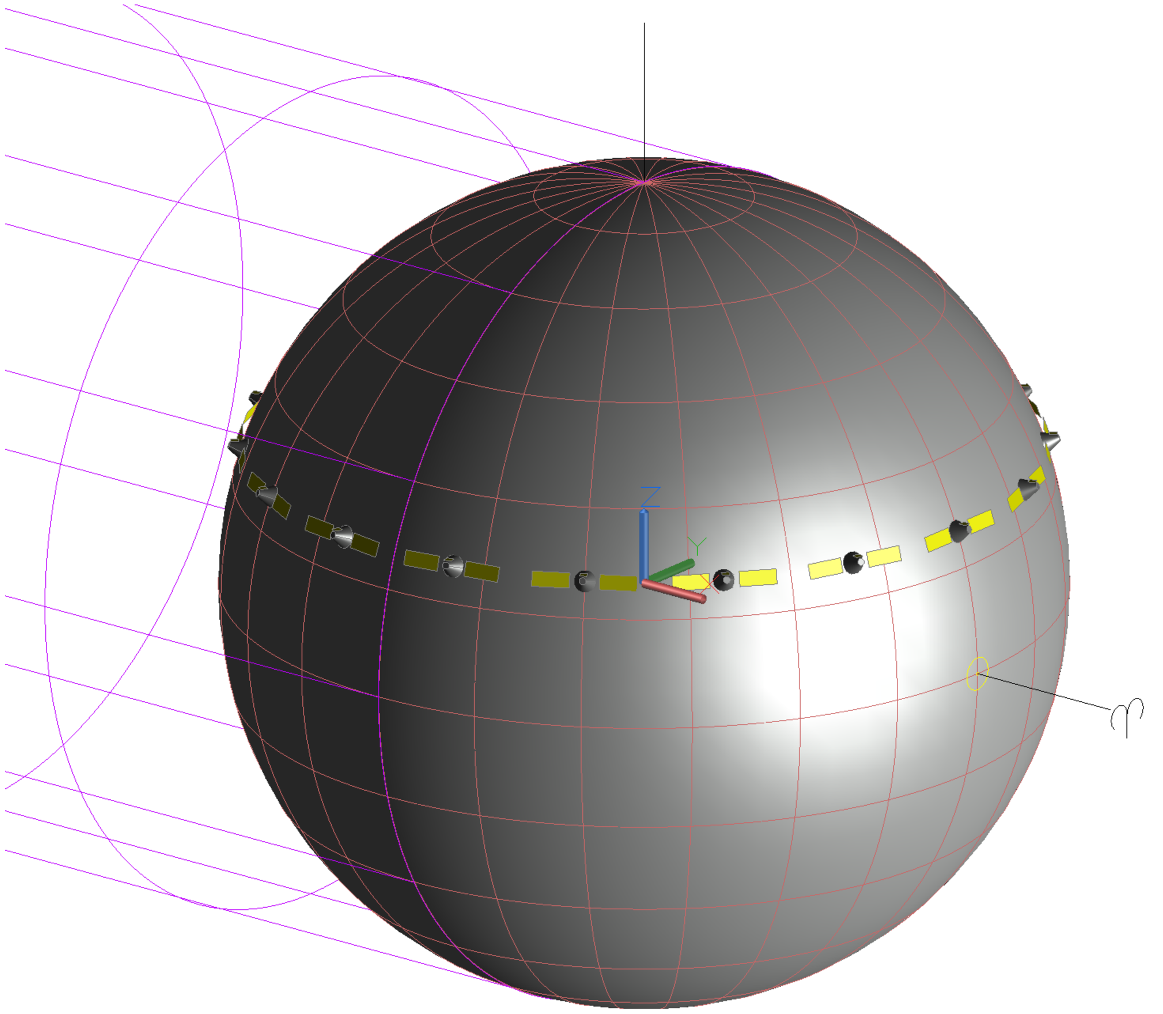


S/C on Ceres at various times of the day

Spacecraft not to scale



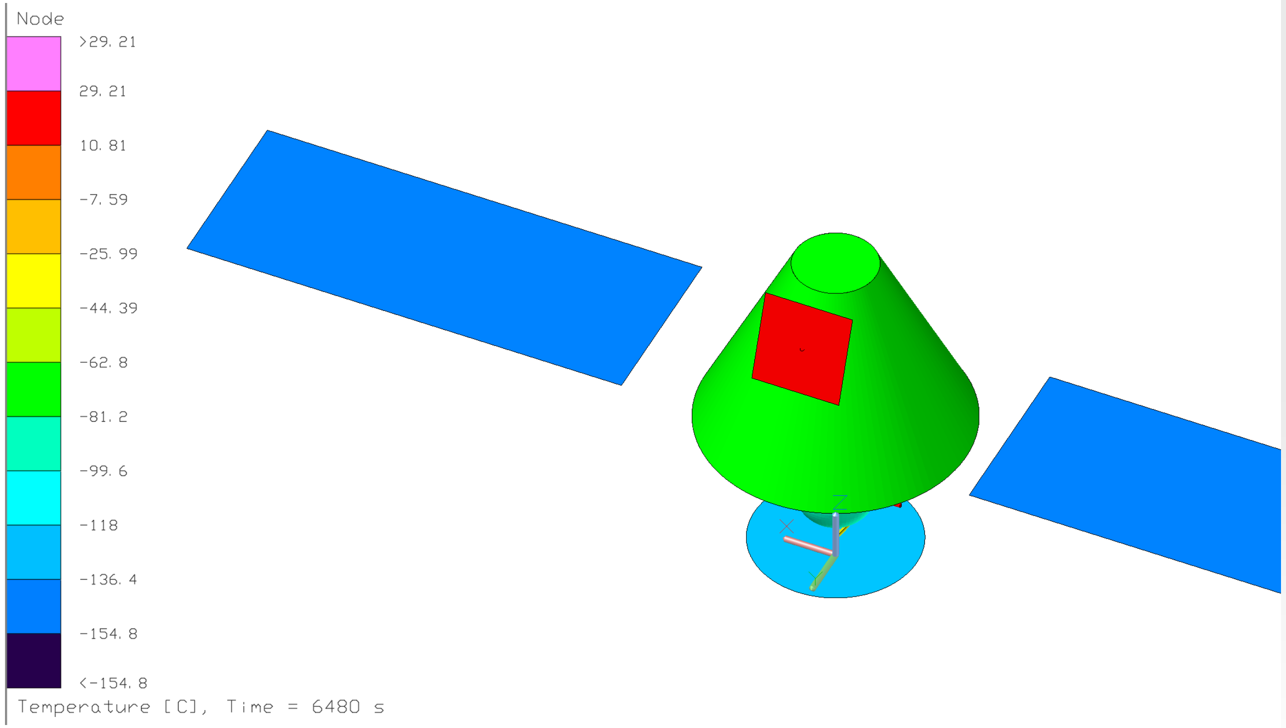
View from the Sun



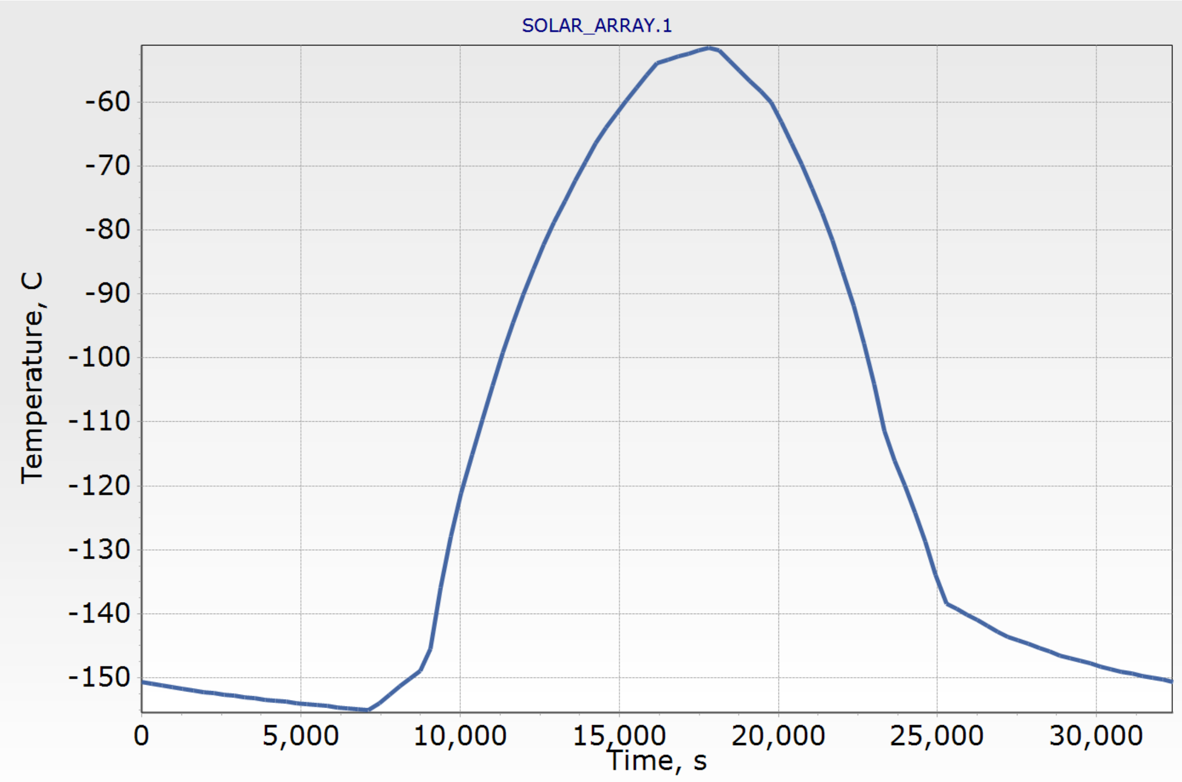
External Hardware on Ceres

Solar array temperature (as representative of external elements)

Diurnal temperature swings of external hardware can exceed Δ100 °C, which may drive hardware qualification



Shown above is the pre-dawn solar array temperature of -155 C (188 K)



Solar array temperature throughout the Ceres day

Thermal

Design Rationale for Option 2

- Heat switches have a much higher turn-down capability than louvers. To minimize energy while on the surface, heat switches are used for the avionics radiator.
- Because the PPU radiator is not required during the surface operations, its turn-down is not as critical and louvers can be used instead to help minimize replacement heater power needed during non-SEP operations for Cruise and orbit. But the low cost of heat switches may be preferred, despite their lower TRL (TRL 7). Cost comparison for PPU radiator turn-down device:
  - Louvers: $11.2M for qty. 17 20-blade louver sets
  - Heat Switches: $1.5M for qty. 18 (assumed for Team-X study)
- Flight rule imposed by Thermal: PPU and Avionics Radiators shall be precluded from direct solar loads for all periods other than while on the surface of Ceres.

Thermal

Summary—Option 2

- Power Thermal Summary Chart

	Suggested	Input/Override	Used
Thermal Design Inputs			
Thermally Controlled Mass	1921.2 kg		1921.2 kg
Spacecraft Dry Mass Density	200.0 kg/m3		200.0 kg/m3
Spacecraft Wet Mass Density	200.0 kg/m3		200.0 kg/m3
Thermal Power/Controlled Mass	0.05 W/kg	0.00 W/kg	0.00 W/kg
Conduction Ctrl Mass/Ctrlled Mass	0.001 kg/kg		0.001 kg/kg
Bus Geometry Approximation	Cube		Cube
Multi-Layer Insulation			
MLI Type	Interlayered		Interlayered
Number of Layers	20		20
Specific Mass	0.75 kg/m2		0.75 kg/m2
Specific Area	0.50 m2/blanket		0.50 m2/blanket
Propulsion Heater Power			
Tank Heaters	2.5 W		2.5 W
Line Heaters	0.5 W		0.5 W
Thermal Design Calculations			
Thermally Controlled Surface Area	27.1 m2		27.1 m2
Total Propulsion Tank Surface Area	27.9 m2		27.9 m2

Subsystems	Mass			Power Modes									
	CBE	Cont.	PBE	Launch 4.0 hr.	SEP Cruise @ Earth 24.0 hr.	SEP Cruise @ Ceres 24.0 hr.	Orbital Science 2.3 hr.	Cruise/Orbit Telecom 8.0 hr.	Landing or Hopping 1.0 hr.	Surface Ops - Sampling 1.0 hr.	Surface Ops - Science Day 4.5 hr.	Surface Ops - Night 4.5 hr.	TBD 0.0 hr.
Total Wet Stack (w/o Thermal)	3060.6 kg	13%	3468.1 kg	182.0 W	14783.3 W	2215.9 W	177.4 W	377.4 W	605.0 W	534.8 W	440.4 W	90.2 W	0.0 W
Carried Elements	0.0 kg	0%	0.0 kg										
Wet Element (w/o Thermal)	3060.6 kg	13%	3468.1 kg	182.0 W	14783.3 W	2215.9 W	177.4 W	377.4 W	605.0 W	534.8 W	440.4 W	90.2 W	0.0 W
Pressurant & Propellant	1502.0 kg	0%	1502.0 kg										
Dry Element (w/o Thermal)	1558.6 kg	26%	1966.1 kg	182.0 W	14783.3 W	2215.9 W	177.4 W	377.4 W	605.0 W	534.8 W	440.4 W	90.2 W	0.0 W
Instruments	68.5 kg	30%	89.1 kg	0.0 W	0.0 W	0.0 W	1.9 W	0.0 W	0.0 W	165.0 W	85.7 W	0.0 W	0.0 W
Other Payload	0.0 kg	0%	0.0 kg										
Dry Bus (w/o Thermal)	1490.1 kg	26%	1877.1 kg	182.0 W	14783.3 W	2215.9 W	175.5 W	377.4 W	605.0 W	369.8 W	354.7 W	90.2 W	0.0 W
ADC	68.7 kg	9%	74.8 kg	41.6 W	107.6 W	107.6 W	73.9 W	73.9 W	58.4 W	48.7 W	41.2 W	0.0 W	0.0 W
CDH	20.3 kg	19%	24.3 kg	23.6 W	23.6 W	23.6 W	23.6 W	23.6 W	27.5 W	23.6 W	23.6 W	23.6 W	0.0 W
Power	277.0 kg	29%	358.4 kg	70.2 W	161.5 W	74.1 W	67.4 W	74.3 W	97.5 W	91.8 W	84.2 W	55.9 W	0.0 W
Propulsion	405.2 kg	-64%	145.7 kg	36.7 W	14480.7 W	2000.7 W	0.7 W	0.7 W	216.7 W	0.7 W	0.7 W	0.7 W	0.0 W
Mechanical	689.1 kg	29%	891.5 kg	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Telecom	29.8 kg	18%	35.0 kg	10.0 W	10.0 W	10.0 W	10.0 W	205.0 W	205.0 W	205.0 W	205.0 W	10.0 W	0.0 W
Systems Contingency			347.3 kg										
Thermal	46.1 kg	28%	59.0 kg	192.7 W	48.0 W	122.7 W	163.1 W	48.0 W	108.0 W	108.0 W	108.0 W	108.0 W	0.0 W

	Power Modes									
Thermal Control System	**192.7 W**	**48.0 W**	**122.7 W**	**163.1 W**	**48.0 W**	**108.0 W**	**108.0 W**	**108.0 W**	**108.0 W**	**0.0 W**
Heaters										
Catalogue (Propellant Bay)	144.7 W	0.0 W	74.7 W	115.1 W	0.0 W	60.0 W	60.0 W	60.0 W	60.0 W	
Custom (Thruster Valve)	48.0 W	48.0 W	48.0 W	48.0 W	48.0 W	48.0 W	48.0 W	48.0 W	48.0 W	

Thermal

Cost—Option 2

Phase / Duration	System Res Total 58 mo.	A 12 mo.	B 12 mo.	C1 9 mo.	C2 5 mo.	C3 4 mo.	D1 12 mo.	D2 4 mo.	Thermal Control System Cost Total 58 mo.	NRE (A-C1) 33 mo.	RE (C2-D2) 25 mo.
06.08 Thermal Control System	10.3 WY	$314.1 K	$876.1 K	$1872.0 K	$5636.8 K	$791.0 K	$1134.0 K	$77.0 K	$10700.9 K	$3062.2 K	$7638.7 K
06.08.01 Mgmt and Sys. Eng.	0.9 WY	$50.8 K	$99.4 K	$158.4 K	$100.6 K	$109.0 K	$173.2 K	$11.5 K	$702.9 K	$308.6 K	$394.3 K
06.08.01.01 Management	0.9 WY	$50.8 K	$99.4 K	$158.4 K	$100.6 K	$109.0 K	$173.2 K	$11.5 K	$702.9 K	$308.6 K	$394.3 K
Management Support	0.9 WY	$29.5 K	$57.7 K	$92.0 K	$58.4 K	$63.3 K	$100.6 K	$6.7 K	$408.3 K	$179.2 K	$229.0 K
Secretary Support	0.0 WY	$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
Computer HW/SW Support	$294.7 K	$21.3 K	$41.7 K	$66.4 K	$42.2 K	$45.7 K	$72.6 K	$4.8 K	$294.7 K	$129.4 K	$165.3 K
06.08.01.02 System Engineering	0.0 WY	$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
Project Engineer	0.0 WY	$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
Lead Engineer (Engineering 4)	0.0 WY	$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
Sys Engineer (Engineering 3)	0.0 WY	$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
Sys Engineer (Engineering 1-2)	0.0 WY	$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
06.08.02 Analysis/Design	6.4 WY	$263.3 K	$776.8 K	$764.6 K	$299.4 K	$239.5 K	$369.4 K	$65.4 K	$2778.5 K	$1804.7 K	$973.7 K
Analysis Engineer (Engineering 4)	3.8 WY	$180.4 K	$403.2 K	$374.1 K	$207.8 K	$166.2 K	$196.3 K	$65.4 K	$1593.5 K	$957.7 K	$635.8 K
Analysis Engineer (Engineering 3)	1.6 WY	$0.0 K	$0.0 K	$247.3 K	$91.6 K	$73.3 K	$173.1 K	$0.0 K	$585.3 K	$247.3 K	$338.0 K
Analysis Engineer (Engineering 1-2)	1.1 WY	$82.9 K	$123.5 K	$143.3 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$349.7 K	$349.7 K	$0.0 K
Development Testing	$250.0 K	$0.0 K	$250.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$250.0 K	$250.0 K	$0.0 K
Planetary Protection	0.0 WY	$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
PP Lead Engineer	0.0 WY	$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
PP Analysis / Design	0.0 WY	$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
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	0.5 WY	$0.0 K	$0.0 K	$902.2 K	$4819.5 K	$158.1 K	$12.3 K	$0.0 K	$5892.1 K	$902.2 K	$4989.9 K
HW Support Engineer (Engineering 4	0.5 WY	$0.0 K	$0.0 K	$11.7 K	$90.9 K	$83.1 K	$12.3 K	$0.0 K	$198.0 K	$11.7 K	$186.3 K
HW Support Engineer (Engineering 3	0.0 WY	$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
HW Support Engineer (Engineering 1	0.0 WY	$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
Flight HW	$5394.1 K	$0.0 K	$0.0 K	$890.5 K	$4503.6 K	$0.0 K	$0.0 K	$0.0 K	$5394.1 K	$890.5 K	$4503.6 K
Flight HW Testing HW	$300.0 K	$0.0 K	$0.0 K	$0.0 K	$225.0 K	$75.0 K	$0.0 K	$0.0 K	$300.0 K	$0.0 K	$300.0 K
06.08.04 BCE/AHSE/GSE	0.8 WY	$0.0 K	$0.0 K	$35.1 K	$276.0 K	$79.0 K	$186.5 K	$0.0 K	$576.5 K	$35.1 K	$541.4 K
H/WTest Engineer (Engineering 4)	0.8 WY	$0.0 K	$0.0 K	$35.1 K	$26.0 K	$79.0 K	$186.5 K	$0.0 K	$326.5 K	$35.1 K	$291.4 K
H/WTest Engineer (Engineering 3)	0.0 WY	$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
H/WTest Engineer (Engineering 1-2)	0.0 WY	$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
BCE/AHSE/GSE	$250.0 K	$0.0 K	$0.0 K	$0.0 K	$250.0 K	$0.0 K	$0.0 K	$0.0 K	$250.0 K	$0.0 K	$250.0 K
06.08.05 Integration And Test	1.8 WY	$0.0 K	$0.0 K	$11.7 K	$141.3 K	$205.3 K	$392.6 K	$0.0 K	$751.0 K	$11.7 K	$739.3 K
Subsystem Integration and Test	0.5 WY	$0.0 K	$0.0 K	$11.7 K	$37.4 K	$80.7 K	$98.2 K	$0.0 K	$227.9 K	$11.7 K	$216.2 K
I&T Engineer (Engineering 4)	0.5 WY	$0.0 K	$0.0 K	$11.7 K	$26.0 K	$62.3 K	$98.2 K	$0.0 K	$198.2 K	$11.7 K	$186.5 K
I&T Engineer (Engineering 3)	0.1 WY	$0.0 K	$0.0 K	$0.0 K	$11.5 K	$18.3 K	$0.0 K	$0.0 K	$29.8 K	$0.0 K	$29.8 K
I&T Engineer (Engineering 1-2)	0.0 WY	$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
System Integration and Test	1.2 WY	$0.0 K	$0.0 K	$0.0 K	$103.9 K	$124.7 K	$294.5 K	$0.0 K	$523.1 K	$0.0 K	$523.1 K
I&T Engineer (Engineering 4)	1.2 WY	$0.0 K	$0.0 K	$0.0 K	$103.9 K	$124.7 K	$294.5 K	$0.0 K	$523.1 K	$0.0 K	$523.1 K
I&T Engineer (Engineering 3)	0.0 WY	$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
I&T Engineer (Engineering 1-2)	0.0 WY	$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
06.08.25 HRS	0.0 WY	$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
06.08.25.01 HRS labor	0.0 WY	$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
HRS Engineer Lead (Engineerin	0.0 WY	$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
HRS I&T Design/Fab (Engineerin	0.0 WY	$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
HRS Fab Engineer (Engineering	0.0 WY	$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
HRS analysis (Engineering 1-2)	0.0 WY	$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
06.08.25.02 HRS hardware	0.0 WY	$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	$0.0 K
HRS flight HW - pump ($M)	$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
HRS pump CTM (Engineering 3)	0.0 WY	$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	$0.0 K
HRS flight HW - electronics ($M)	$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
HRS electronics CTM (Engineeri	0.0 WY	$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	$0.0 K
HRS GSE cart ($M)	$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

Thermal

Option Comparison

Option	Mass (kg)	Cost ($M)	Radiator size (m^2)	Comments
1				
2	59 kg PBE	$10.7M	2.7 m^2 for PPU 1.1 m^2 for Bus	

CDS Report

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CDS

Design Requirements

- Mission:
  - Solar Electric propulsion to Ceres
  - Option 1:
    - Ceres Sample Return - travel to Ceres, orbit, land, return to Ceres orbit, then return sample to Earth
  - Option 2:
    - Land on Ceres, then hop to second site on surface of Ceres

- Data Volumes
  - 39 Gbits during orbital phase (~360 Earth days)
  - 4 Gbits during landed phase (3+ Earth days)

- Interfaces
  - Instruments, cameras, magnetometer, sample system, GNC devices
  - Gimbals (HGA, Solar Arrays, Ion engines, Monoprop system)
  - Lander Vision System

- Radiation
  - Radiation environment at Ceres is not problematic

CDS

Design Assumptions

- Customer arrived with multi-element Sphinx- and Sabertooth-based design, which includes the following elements:
  - Main compute element with redundant Sabertooth main processors, redundant GNC sensor processors, and single Fault Management Unit
  - Two motor control boxes
  - Two GNC actuator and camera interface processors
  - Sphinx-based Lander Vision System
- Heritage Assumptions
  - Sphinx is current SmallSat CDS system, in process of being certified for Class B missions
  - Sabertooth is next step along that design path, assuming it will be ready for use in the timeframe of this mission
  - Lander Vision System has heritage from Mars 2020, but the version for this study is based on a Sphinx processor, in a smaller form factor than the M2020 package
- Sphinx and Sabertooth hardware chosen for low mass and power consumption.
  - Sabertooth used where greater computing performance needed.

CDS

Design

- Hardware
  - Compute Element
    - Dual-redundant Sabertooth processors
    - Dual-redundant GNC Sensor processors
    - Single fault tolerant Fault Management Unit
  - Motor Controllers (2)
    - Sphinx processor
    - Motor drivers (3 each)
  - REU Processors (2)
    - Sphinx processor
    - Camera Interface
    - GNC Actuator processor
  - Power Conversion handled separately in each box

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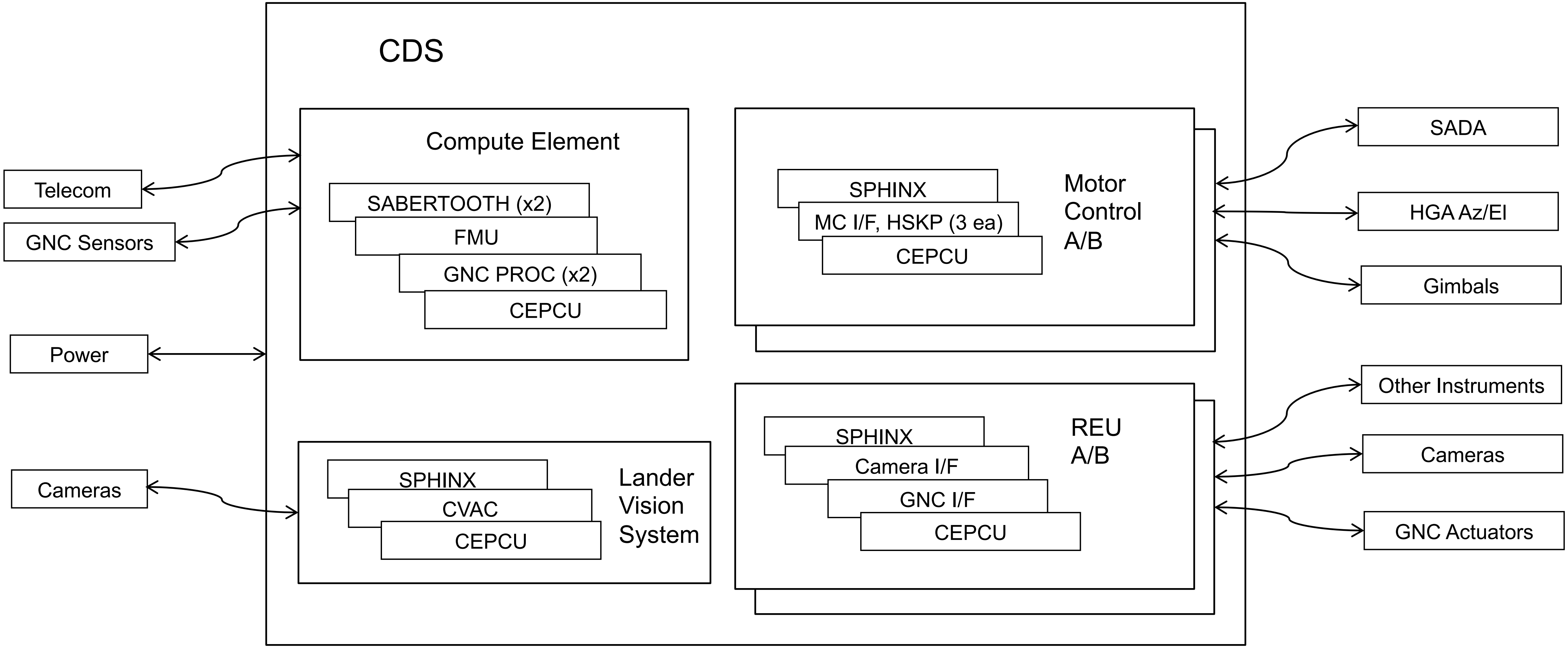
Block Diagram



CDS

Design Rationale

- Customer supplied multi-element Avionics Subsystem design
  - Based on Sphinx and Sabertooth Avionics processors
  - Low mass, low power, high performance

CDS

Data Story

- Typical Data Rate at Ceres ~70 kbits/sec

- Orbital Operations:
  - 39 Gbits generated over ~360 Earth days
  - Will take ~154 hours to downlink
  - One hour of downlink every other Earth day is sufficient for science data

- Surface operations
  - 4 Gbits generated
  - Will take ~16 hours to downlink
  - Assume ~4 hours downlink per Cerean day
  - Will take ~4 Cerean days to downlink surface data
    - Surface operations on Ceres are planned for at least 9 Cerean days
  - Amount of data generated on surface for two options not significantly different

CDS

Cost Assumptions

- In-house build
- Hardware complement
  - 2 FM, 1 Spare FM
  - 2 EM, 2 Prototype
    - 2 Testbeds
  - One set of BTE, 2 sets of GSE, 4 WSTS

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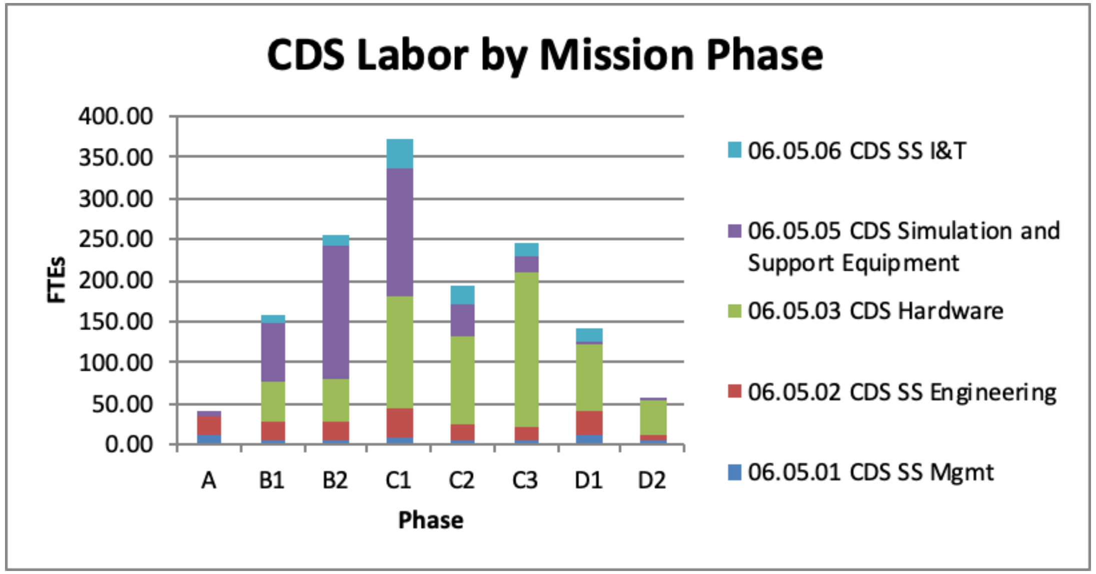
Cost

- 1^{ST} Unit Cost : $66.5M
- Nth Unit Cost: $40.3M



Task ID	2326 Ceres Pre-Decadal	A	B	C1	C2	C3	D1	D2	E	F	Total
06.05	Total Cost (K$)	1485.6	20887.0	20067.7	6989.4	10228.1	4978.2	1903.3	0.0	0.0	66539.4
	Labor Total (FTE)	42.00	420.95	380.07	199.35	250.33	146.74	53.81	0.00	0.00	124.44
06.05.01	Subtotal Cost - Subsystem Management	424.5	424.5	318.3	176.9	141.5	424.5	141.5	0.0	0.0	2051.5
	Labor (FTE)	12.00	12.00	9.00	5.00	4.00	12.00	4.00	0.00	0.00	4.83
06.05.02	Subtotal Cost - Subsystem Engineering	848.9	1273.4	955.0	530.6	424.5	848.9	283.0	0.0	0.0	5164.2
	Labor (FTE)	24.00	42.00	36.00	20.00	16.00	30.00	8.00	0.00	0.00	14.67
.06.05.03	Subtotal Cost - C&DH Hardware	0.0	8995.9	10478.4	3918.4	8383.8	3093.5	1448.5	0.0	0.0	36318.5
	Labor (FTE)	0.00	106.76	138.85	107.35	188.07	84.89	39.63	0.00	0.00	57.21
06.05.05	Subtotal Cost - Simulation & Support Equipment (SSE)	212.2	9344.4	7042.5	1479.3	641.7	80.8	30.3	0.0	0.0	18831.4
	Labor (FTE)	6.00	233.16	155.73	38.57	18.14	2.29	0.86	0.00	0.00	37.90
06.05.06	Subtotal Cost - I & T	0.0	848.9	1273.4	884.3	636.7	530.6	0.0	0.0	0.0	4173.8
	Labor (FTE)	0.00	24.00	36.00	25.00	18.00	15.00	0.00	0.00	0.00	9.83

CDS

Cost Discussion

- Cost Drivers
  - n/a
- Potential Cost Savings
  - Demoting flight spare to parts rather than an assembled subsystem could save $4.2M
  - Descoping to a single testbed could save $11.2M
- Potential Cost Uppers
  - Adding a third testbed to support testing could cost $11.2M

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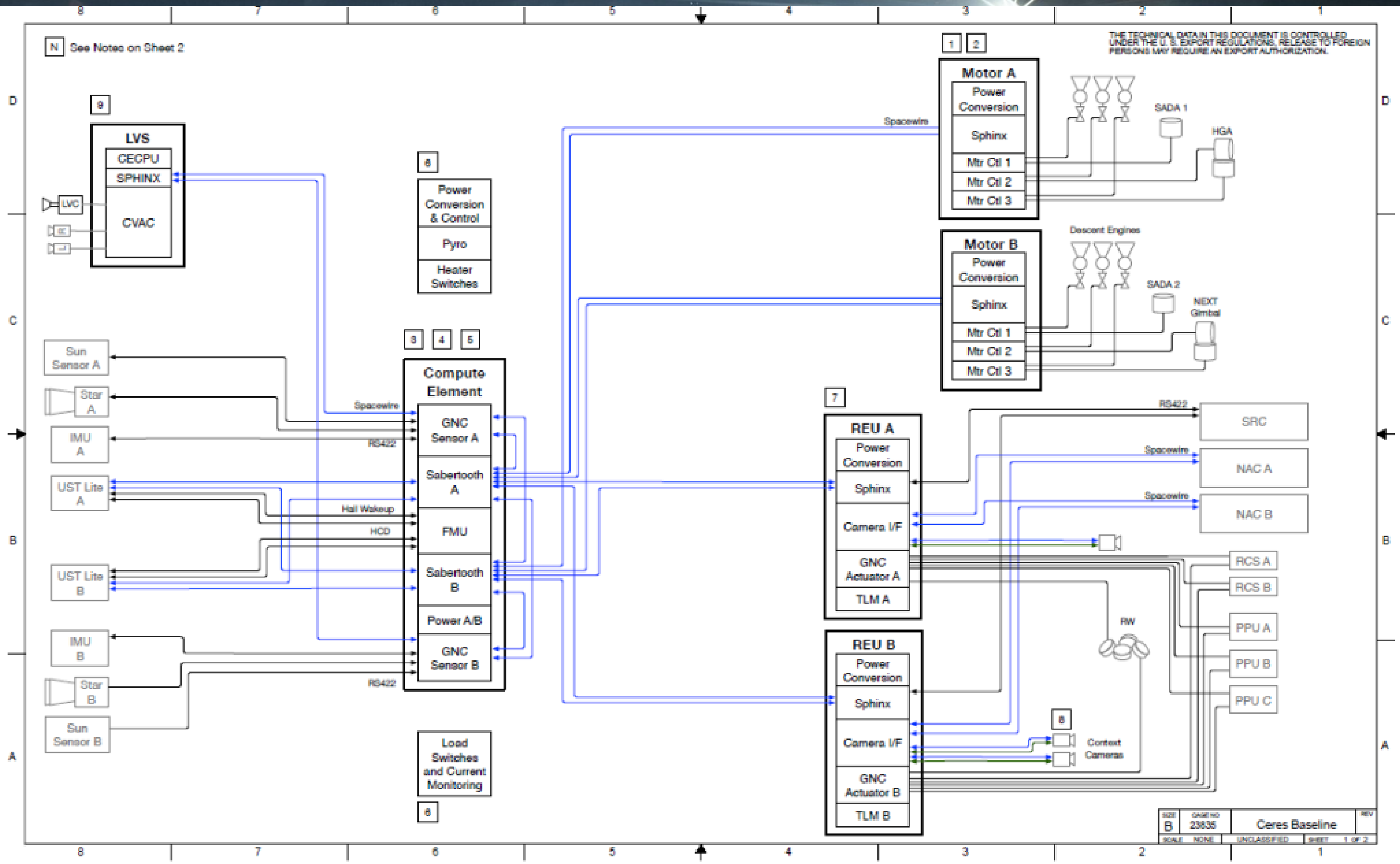
Risks

- Future heritage assumed
  - Sphinx Class B certification assumed
  - Sabertooth availability assumed

CDS

Additional Comments

- Block diagram from customer input package



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Additional Comments

- Block diagram from customer input package

THE TECHNICAL DATA IN THIS DOCUMENT IS CONTROLLED UNDER THE U. S. EXPORT REGULATIONS. RELEASE TO FOREIGN PERSONS MAY REQUIRE AN EXPORT AUTHORIZATION.

Table 1

UNIT	BOARD	OUTPUT 1	OUTPUT 2	OUTPUT 3
A	MOTOR 1	DESCENT ENGINE 1A	SADA 1	SPARE
A	MOTOR 2	DESCENT ENGINE 2A	HIGH GAIN ANTENNA AZ	SPARE
A	MOTOR 3	DESCENT ENGINE 3A	HIGH GAIN ANTENNA EL	SPARE
B	MOTOR 1	DESCENT ENGINE 1B	SADA 2	SPARE
B	MOTOR 2	DESCENT ENGINE 2B	NEXT GIMBAL AXIS 1	SPARE
B	MOTOR 3	DESCENT ENGINE 3B	NEXT GIMBAL AXIS 2	SPARE

NOT DRAWN TO SCALE

* New board design, based on previous reference bus

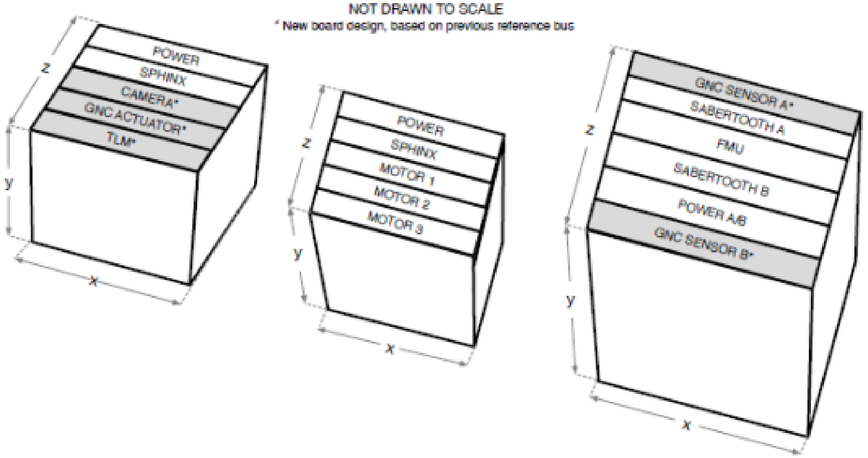

Table 2

Unit	Quantity	x (mm)	y (mm)	Z (mm)	Mass (kg)	Peak (W)	Avg (W)
Sabertooth	1	120	130	140	6	13	7
REU	2	100	100	134	2	11	5
Motor	2	100	100	133	3	12	6

Notes:

1. Assumes one set of three descent engines is required for landing and no simultaneous control of SADA or gimbals.
2. Each motor board has three outputs, one can be used at a time. Input 28V is controlled on the board by switch and fuse.
3. FMU should be hooked up to PMBus and 28V and eliminate Power A/V card (future work).
4. GNC SENSOR A and B boards should each have 28V and PMBus so that they can both be powered independently.
5. IMUs, Star Trackers and Sun Sensors are redundant but each processor can communicate with both GNC SENSOR boards allowing dual IMU or Star Tracker data operations.
6. Load switching should be performed at the load in new designs wherever possible per 346. In some cases it may be necessary to have a switch unit for equipment that is already qualified and can not be redesigned.
7. REU implements a camera interface similar to NVMCAM, a GNC ACTUATOR board for reaction wheel, PPU and RCS thruster control and a TLM board for collecting analog and status telemetry.
8. Context cameras are not redundant.
9. Enhanced LVS uses stereo cameras. This is an assumed hardware configuration but there is on-going work to identify the best LVS hardware configuration for descent and landing.

SIZE	CAGE NO		REV
B	23835	Intrepid Baseline	
SCALE NONE	UNCLASSIFIED	SHEET 1 OF 2	

Telecom Reports

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Telecom

Design Requirements – Both Options

- General Telecom Requirements
  - Support a two-way link with Earth through all mission phases (sample return, EDL, orbital, etc.)
- Downlink/Return Requirements
  - N/A
- Uplink/Forward Requirements
  - Support an uplink of 2 kbps
- Link Quality Requirements
  - BER of 1E-05 for CMD links
  - FER of 1E-04 for TLM links
  - Minimum 3 dB margin on all DTE links
- Specific Requirements from Customer
  - Design given by customer
  - Fully redundant

Telecom

Design Assumptions – Both Options

- Operational Assumptions
  - S/C goes through orbital phases and landed, sample return phases
  - S/C has a gimbaled 1.5m X-band HGA to ensure communication during landed phase
- Antenna Assumptions
  - HGA is gimbaled and will be pointed within 0.25 degrees
  - Three LGAs will be positioned with one on each side of the S/C
- Ground Station Assumptions
  - 34m BWG DSN ground stations with 20 kW transmitters
- Coding Assumptions
  - Assumed Turbo 1/6 for high data rate (70kbps) downlink
- Link Assumptions
  - -2 dB loss from Venus atmosphere
- Hardware Availability/Capability Assumptions
  - UST-Lite used, which is in line with a 2030 launch and where technology will be at that time
  - TWTA EQM required to re-qual to necessary shock and random vibration loads for EDL
- **NOTE: Both options are identical for the Telecom subsystem. Everything presented here applies to both options**

Telecom

Design – Both Options

- Overall system description
  - For all options, telecom is a fully redundant X-band system
- Hardware Includes:
  - One 1.5m X-band 2-Axis Gimbaled HGA
  - Three X-band low gain antennas
  - Two X-band UST-Lite Transponders
    - Next-generation design in-line with 2030 launch
    - Low mass and power ideal for this application
  - Two 100W X-band TWTAs
    - EQM required for re-qual for telecom during EDL shock and vibration loads
  - Waveguide transfer switches and coax cabling
- Estimated total mass of 29.8kg (CBE, 35kg MEV)

Telecom

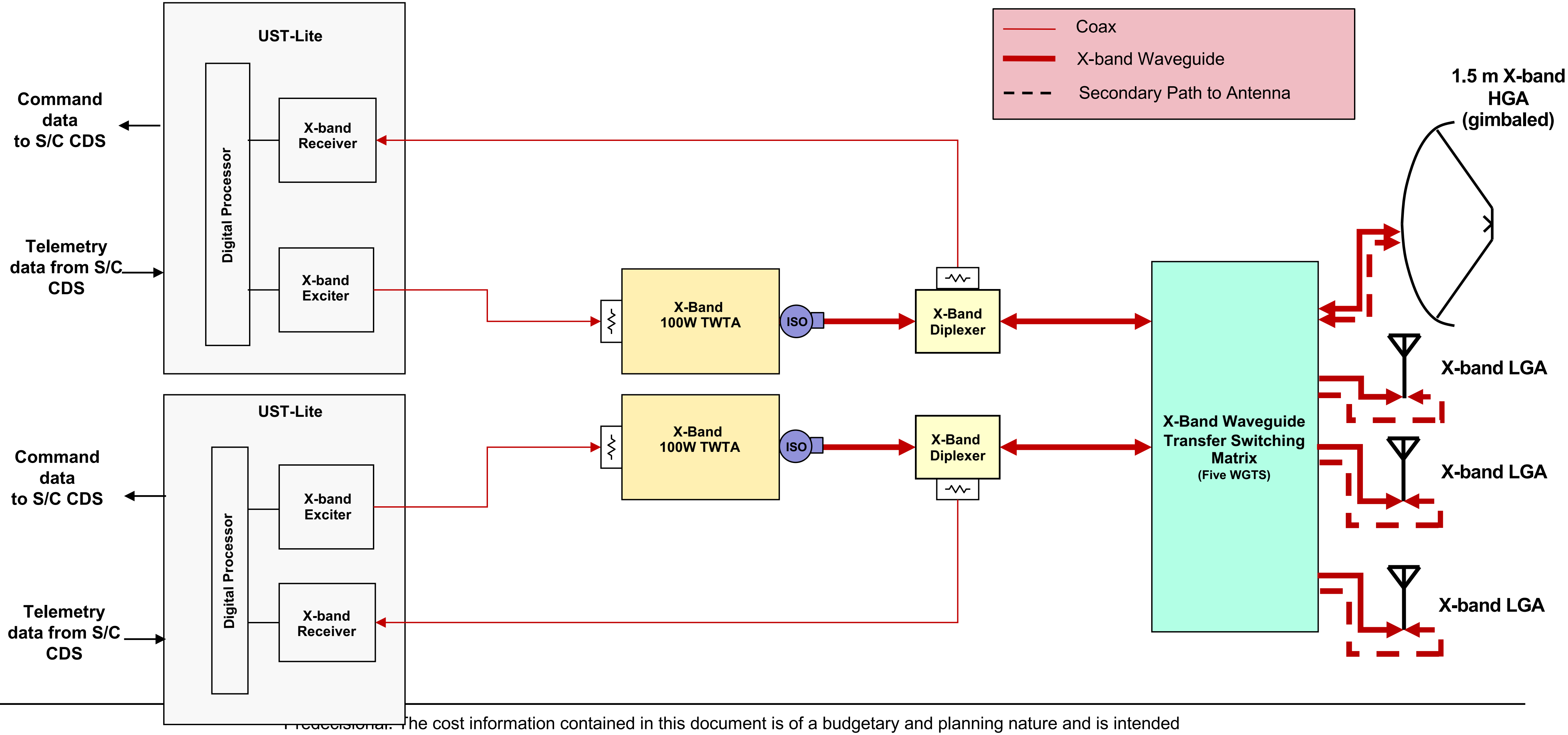
Design Rationale – Both Options

- Rationale for Frequencies
  - X-band appropriate for this deep-space application and availability of DSN ground station and ground station compatibility
- Rationale for Hardware
  - UST-Lite used for it’s very low mass and power (1kg, 15W full duplex)
- Link Capabilities and Sizing:
  - Downlink:
    - 70kbps downlink at 3.92AU (max Earth-Ceres distance) to a 34m DSN station using HGA
    - Will get 10bps downlink out to 3.3 AU through the LGA during safe mode if the spacecraft can point relatively well during safe mode
      - Could consider a MGA for safe mode, depending on pointing constraints during safe mode
  - Uplink:
    - 2kbps through the HGA during all mission phases
    - A minimum of 31.25bps through the LGA during safe mode at max range

Link Description:	HGA Downlink	LGA Downlink (Safe Mode)	HGA Uplink	LGA Uplink
Data Rate	70kbps	10bps	2 kbps	31.25bps
TRX Antenna	1.5m HGA	LGA, 9dBi gain	34m DSN	34m DSN
TRX Power (RF)	100W	100W	20kW	20kW
Range	3.92AU	3.3AU	3.92AU	3.92AU
RCV Antenna	34m DSN	34m DSN	HGA	LGA
Coding	Turbo 1/6	Turbo 1/6	Uncoded	Uncoded
Margin	3.0 dB	3.0 dB	$\geq$11 dB	3.0 dB

Telecom

Block Diagram – Both Options



Telecom

Cost – Both Options

- Costing Assumptions
  - Includes $1M for TWTA EQM and re-qual effort
  - Single Spares (except for HGA reflector)
  - Costs and mass for antenna gimbal carried by mechanical chair
  - Costs for telecom support to ATLO carried by systems chair
- Option 2 cost
  - NRE: $25.2M RE: $11.1M Total: $36.3M

Systems note: Option 1 cost tables will be provided after completion of the study

	Phase A	Phase B	Phase C			Phase D		
			Subsystem Design	Subsystem Fabrication	Subsystem I&T	System Level IA&T	Launch Operations	Total
WBS	12.0 months	12.0 months	9.0 months	5.0 months	4.0 months	12.0 months	4.0 months	$36,345
6.06 Telecom Subsystem	**$381**	**$12,286**	**$15,774**	**$3,388**	**$3,014**	**$1,296**	**$205**	**$36,345**
06.06.01 Telecom Management	**$211**	**$498**	**$450**	**$239**	**$253**	**$326**	**$145**	**$2,123**
06.06.02 Telecom System Engineering	**$170**	**$424**	**$318**	**$323**	**$258**	**$424**	**$57**	**$1,974**
06.06.03 Radios	**$0**	**$6,412**	**$5,016**	**$407**	**$254**	**$9**	**$3**	**$12,102**
06.06.04 Power Amplifiers	**$0**	**$2,163**	**$3,344**	**$338**	**$14**	**$0**	**$0**	**$5,859**
06.06.05 Antennas	**$0**	**$2,357**	**$3,383**	**$1,358**	**$1,674**	**$0**	**$0**	**$8,771**
06.06.06 Optical Comm Assembly	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
06.06.08 Microwave Components	**$0**	**$0**	**$1,830**	**$212**	**$0**	**$0**	**$0**	**$2,042**
06.06.09 RFS I&T	**$0**	**$432**	**$1,433**	**$511**	**$561**	**$537**	**$0**	**$3,474**
***06.06.10 Telecom Support to ATLO**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**

Telecom

Risks

- Moderately low telecom risk mission
  - Only risk is in operating TWTA during EDL
    - MSL 100W TWTA on Descent Stage tripped off during EDL, due to random vibe and shock or pressure gradients
    - As Ceres has a much more benign gravity, this problem should be far less severe on Ceres
    - **$1M for EQM and re-qual to Ceres landing shock and vibe loads is accounted for in cost estimate, which comes from RFIs with TWTA vendor for doing this work for M2020 (never pursued)**
    - **Perceived as moderately low-risk, and work will be done early to mitigate this risk**

Ground Systems Report

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Ground Systems

Design Requirements

- Mission:
  - Ceres Exploration
  - SEP cruise to Ceres, circular orbit to landing and option for sample return
- Data Volumes
  - Orbiter/sample return option has 39 Gb during orbit, 6 Gb on surface
  - Orbiter/lander option 39 Gb during orbit, 4 Gb on surface
- 2 Options
  - Sample return
  - Lander mission with 1 hop

Ground Systems

Design Assumptions

- Ground system is based on a mission specific implementation of the standard JPL mission operations and ground data systems
- Surface Ops mostly preprogrammed with no planned tactical operations,

- Phase E Activity Description – Option 1
  - Launch and check-out
  - SEP Cruise with Mars Gravity Assist to Ceres
  - Ceres Approach
  - Approach science
  - Orbit Science + landing site selection
  - Landing activities
    - Prep for landing
    - Landing
    - Surface deployments
    - Science observations
    - Option 1 sample collection
    - Launch
  - SEP Return to Earth cruise
  - Sample delivery to UTTR
  - End of Flight Ops

- Phase E Activity Description – Option 2
  - Launch and check-out
  - SEP Cruise with Mars Gravity Assist to Ceres
  - Ceres Approach
  - Approach science
  - Orbit Science + landing site selection
  - Landing activities
    - Prep for landing
    - Landing
    - Surface deployments
    - Science observations
    - Prep for Hop
    - Hop
    - Redeployments
    - Science Observations
  - End of Flight Ops

Ground Systems

Design

- Ground Network
  - DSN 34m BWG Subnet, all communications via X-band
  - At max range average data rate 75Kb/s
  - Data rate and tracking plan more than adequate for basic mission needs

Option 1 DSN Profile

	Support Period		Antenna	Service	Hours per	No. Tracks	No. Weeks
	No	Name	Size	Year	Track	per Week	Required
	(#)	(description)	(meters)	(year)	(hours)	(# tracks)	(# weeks)
Phase D	1	Launch & Early Ops	34BWG	2030	8	21.0	2.0
Phase D	2	Check out and first maneuver	34BWG	2030	8	14.0	2.0
Phase E	3	Crusie to MGA	34BWG	2030	8	1.0	28.0
Phase E	4	MGS coverage	34BWG	2030	8	14.0	4.0
Phase E	5	Cruise to Ceres	34BWG	2030	8	1.0	296.0
Phase E	6	Ceres Orbital Ops part 1	34BWG	2030	8	7.0	75.0
Phase E	7	Ceres Surface Ops	34BWG	2030	8	21.0	1.0
Phase E	8	Ceres orbital Ops part 2	34BWG	2030	8	7.0	2.0
Phase E	9	Cruise to Earth - 3 momths	34BWG	2030	8	1.0	274.0
Phase E	10	Cruise to Sample Return endgame	34BWG	2030	8	3.0	13.0
Phase E	11	Earth End Game	34BWG	2030	8	21.0	4.0

Option 2 DSN Profile

	Support Period		Antenna	Service	Hours per	No. Tracks	No. Weeks
	No	Name	Size	Year	Track	per Week	Required
	(#)	(description)	(meters)	(year)	(hours)	(# tracks)	(# weeks)
Phase D	1	Launch & Early Ops	34BWG	2030	8	21.0	2.0
Phase D	2	Check out and first maneuver	34BWG	2030	8	14.0	2.0
Phase E	3	Crusie to MGA	34BWG	2030	8	1.0	28.0
Phase E	4	MGS coverage	34BWG	2030	8	14.0	4.0
Phase E	5	Cruise to Ceres	34BWG	2030	8	1.0	276.0
Phase E	6	Ceres Orbital Ops part 1	34BWG	2030	8	7.0	75.0
Phase E	7	Ceres Surface Ops	34BWG	2030	8	7.0	9.0

Ground Systems

Cost Assumptions – Option 1

- Mission is Sample return from Ceres
- Has 3 instrument types, or which one type is a series of engineering cameras. Radio science uses the telecom system and not considered a separate instrument
- Selected One of a kind science operation for this mission, surface portion is not tactical nor is it routine. The orbital operations would be routine complex.

Systems note: Option 1 design will be provided after completion of the study

Ground Systems

Cost Assumptions – Option 2

- Mission is Lander on Ceres
- Has 6 instrument types, or which one type is a series of engineering cameras. Radio science uses the telecom system and not considered a separate instrument
- Selected One of a kind science operation for this mission, surface portion is not tactical nor is it routine. The orbital operations would be routine complex.

Number of Commandable Spacecraft	1
Type of Spacecraft	Lander
Domain	Deep Space
Number of Instruments	6
Nature of Science Operations	One of a kind
Number of Partners	1
Number of Foreign Partners	0
Lowest Experience of Partners	Significant
S/C Builder	JPL
S/C Operator	JPL
Science Operations	JPL
Launch Date	12/20/2030
Phase E LOE Distribution	Duration (Months)
Heavy Support	12
Moderate Support	78
Light Support	0
Phase E Total	90
	Duration (Months)
Science Ops	22
Non-Science Ops	68

Ground Systems

Cost

- $M BY2025
  - Does not include MD/Nav related costs found in WBS 07/09, these are reported in MD/Nav section and summed together in the Cost section.

Option 2			
$M BY 2025	Total Dev	Total Ops	Total A-F
07 MOS	$ 27.87	$ 92.43	$ 120.30
09 GDS	$ 28.82	$ 23.33	$ 52.15
09A Flt Sys GDS	**$ 24.96**	**$ 15.25**	**$ 40.21**
09B SDS/IDS	**$ 3.85**	**$ 8.08**	**$ 11.94**

Systems note: Option 1 costs will be provided after completion of the study

Software Report

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Software

Design Requirements

- Mission:
  - Ceres Lander
  - Includes an orbital science phase and a landing/surface science phase
  - Option 1
    - Surface phase includes a Return to Orbit
    - There is a Return to Earth phase after the surface science phase
    - There is additional hardware for an earth return capsule
  - Option 2
    - Surface phase includes a “hop” maneuver into a crater

- Data
  - Filesystem, data products, parameters, data compression
  - Total expected data volume ~43GB

- Instrument
  - Sphinx/Sabertooth reference hardware for instruments – 1553/RS422/LVDS
  - 6 instruments total (NAC, EM Sounder, EECAM, APXS, MiniTLS, IR Spectrometer)

- Team Graphical Distribution
  - Assume JPL co-located development

Software

Design Assumptions – Option 2

- Assume a product line for the Sphinx/Sabertooth CDH, with major mods for GNC (EDL and hop) and engineering applications (for surface sample acquisition) and minor mods for payload accommodation.
- FSW Infrastructure – **Complex** – MSL analogous
- Fault and Behavior Autonomy – **Complex** – Cross-strapping, dual-string RCE, warm monitoring, and autonomous fault recovery
- Lander – **Complex** – Analogous to Phoenix lander, plus added complexity for “hop”
- Mechanisms: Solar array stow and redeploy, sample carousel, sample acquisition
- Attitude control – **High** – Dawn analogous
- Articulated pointing: solar panel arm (x2), solar panel rotate (x2), HGA gimbal, NEXT thruster gimbal
- Thrust vector control – **Medium** – Dawn analogous
- Space navigation – **High** – Asteroid intercept mission
- EDL Type – Precision – MSL/M2020 analogous (see note about VCE FSW on slide 5)
- Data Management complexity – **High** – Dawn analogous
- Thermal control, Telecom, and Power subsystems – **Medium** – Dawn analogous

Software

Design Rationale

- The CDH was specified by the customer. JPL has made spacecraft with similar architectures before, so we can assume a high level of inheritance for some areas.
- EDL/GNC are the biggest drivers, but no area dominates this design. This is a complex flight software across several dimensions.
- Trades
  - None

Software

Cost Assumptions

- JPL heritage is assumed for this cost estimate
  - Level: Product line with major modifications

- This cost estimate includes a second software product, distinct from RCE software: VCE software.

- TeamX has costed VCE software before, and I reused that estimate
  - Estimated 70K lines of code
    - M2020 VCE FSW 93K LOC * 0.75
  - Assume M2020 heritage with major modifications
  - M2020 VCE FSW costs:
    - $7.4M
    - 17.2 WY
  - Approximate cost for VCE software on this spacecraft: $3.2M
  - Note: This $3.2M does not include GNC algorithm development or FPGA development effort – GNC is bookkept elsewhere in this estimate while FPGA would be bookkept in VCE hardware

Software

Cost – Option 2

- NRE: $41.5mm
- RE: $2.2mm
- Total: $43.7mm

WBS	Title	Cost ($M) Phase A	PMSR-PDR Phase B	PDR-ARR Phase C	ARR-Launch Phase D	Total $M
06.12.01	Flight Software Management	$ 0.3	$ 1.1	$ 1.7	$ 1.3	**$ 4.4**
06.12.02	Flt SW System Engineering	$ 0.2	$ 1.4	$ 3.0	$ 1.3	**$ 5.8**
06.12.03	C&DH	$ -	$ 0.3	$ 2.9	$ 0.7	**$ 3.9**
06.12.04	GN&C FSW	$ -	$ -	$ 4.9	$ 2.4	**$ 7.2**
06.12.05	Engineering Applications FSW	$ -	$ -	$ 2.0	$ 0.4	**$ 2.4**
06.12.06	Payload Accommodation FSW	$ -	$ -	$ 1.3	$ 0.8	**$ 2.0**
06.12.07	System Services	$ -	$ -	$ 0.3	$ 0.2	**$ 0.5**
06.12.08	Flt SW Development Testbed	$ -	$ -	$ 1.3	$ 0.5	**$ 1.8**
06.12.09	Flt SW - Integration and Test	$ -	$ -	$ 7.7	$ 3.8	**$ 11.6**
Total Cost of Labor		**0.4**	**$ 2.7**	**$ 25.0**	**$ 11.3**	**$ 39.5**
06.12.01	Development Infrastructure Procurements	$ 0.0	$ 0.1	$ 0.9	$ 0.4	**$ 1.5**
06.12.01	Travel	$ -	$ -	$ -	$ -	**$ -**
06.12.01	Development Infrastructure Support	$ -	$ 0.3	$ 1.6	$ 0.7	**$ 2.7**
	Total Cost (including Procurements, etc.)	**$ 0.5**	**$ 3.2**	**$ 27.5**	**$ 12.5**	**$ 43.7**
Percent by Phase		1%	7%	63%	29%	

Software

Cost

- Cost Drivers
  - The VCE code is included in this development, as well as the RCE code.

- Potential Cost Savings
  - I might have overestimated
    - The complexity of the sample acquisition mechanism
    - The complexity of space navigation for intercepting the asteroid

- Potential Cost Uppers
  - I may have overestimated:
    - The level of inheritance that can be assumed for this hardware
  - The estimate assumes a high level of developer experience with the inherited software

Software

Risks

- Current phase C duration is a little shorter than our tool estimates
  - Plan for phase C is 18 months
  - Our tool projects 22 months

- Inheritance is always tricky. There's always risk that the inherited software might not map neatly into new requirements. I've tried to account for that in the most obvious places (GNC, VCE FSW), but inheritance inherently involves uncertainty.

Software

Option Comparison

Option	Cost ($M)	Complexity	Functionality	Comments
2	$43.7	Complex	No sample return Added “hop” Additional instruments	

Planetary Protection Report

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Planetary Protection

Mission Category and Justification

- Option 1
  - This is a Category V mission according to the official NASA Planetary Protection guidelines, "NPR 8020.12D Planetary Protection Provisions for Robotic Extraterrestrial Missions." Category V includes all sample return mission from any solar system body.
    - Outbound: This mission must meet the requirements of a Category III mission.
    - Inbound: This mission must meet the requirements of a Category 5-Unrestricted mission.

- Option 2
  - Outbound: 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).
  - Inbound: N/A

Planetary Protection

Requirements

- Documentation:
  - Request for Planetary Protection Mission Categorization
  - Planetary Protection 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
  - *Note: Subsidiary Plans should not be required for this mission*

Planetary Protection

Requirements (cont'd)

- 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

Planetary Protection

Requirements (cont'd)

- Mars Impact Avoidance:
  - Probability of impact of Mars by the launch vehicle (or any stage thereof) shall not exceed 10^{-4} for 50 years following launch
  - 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

Planetary Protection

Requirements (cont'd)

- Mars Impact Avoidance (cont'd):
  - If probability of Mars impact exceeds requirement then (cont'd):
    - Biological Contamination Control:
      - Bioassays to establish the microbial bioburden levels
      - Independent verification bioassays by NASA Planetary Protection Officer
  - *Note: it will be assumed that the Ceres mission will meet the Mars probability of impact requirement*

- Spacecraft assembled in Class 100,000 / ISO Class 8 (or better) clean facilities, with appropriate controls and procedures

Planetary Protection

Requirements (cont'd)

- Project shall demonstrate a probability of less than 10^{-4} that one or more Earth micro-organisms might survive to contaminate an ocean or other liquid water body on Ceres
  - The calculation of this probability shall include a conservative estimate of poorly known parameters, and address the following factors, at a minimum:
    a. Bioburden at launch
    b. Cruise survival for contaminating organisms
    c. Organism survival in the radiation environment adjacent to the target
    d. Probability of encountering/landing on the target, including spacecraft reliability
    e. Probability of surviving landing/impact on the target
    f. Mechanisms and timescales of transport to the subsurface
    g. Organism survival and proliferation before, during, and after subsurface transfer

- Option 1:
  - No additional requirements on the sample handling hardware and the earth return portion of the mission

Planetary Protection

Implementing Procedures

- 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 accidental impact of Mars due to Failure during the cruise phase
  - Flight System microbial burden estimation at launch
  - Final disposition of all hardware
  - Probability that a spacecraft failure prevents a soft landing on Ceres
  - Option 1: Probability of accidental impact of Mars due to Failure during Earth return
- Spacecraft assembly performed in Class 100,000 / ISO Class 8 (or better) clean facilities, with appropriate controls and procedures

Planetary Protection

Subsystem Design Requirements

- Launch vehicle trajectory must be biased to meet Mars probability of impact requirement
- Flight System trajectory must be biased to meet Mars probability of impact requirement

Planetary Protection

Assumptions

- The Ceres asteroid will be re-categorized to a PP Category II* body
- Mission will meet both Mars probability of impact requirements and Ceres probability of contamination requirement by analysis
  - No cleaning and/or microbial reduction of flight system or launch vehicle hardware will be required
  - No bioassay sampling of flight system or launch vehicle hardware will be required
- No cleaning/microbial reduction or bioassay sampling of sample-handling hardware will be required
- The planned final disposition of the Lander will be acceptable to the NASA PP Officer

Planetary Protection

Cost Assumptions / Rationale

- The Ceres asteroid will be re-categorized to a PP Category II* body
- This Cost includes the following:
  - All PP documentation and review support:
  - Required analyses

Planetary Protection

Cost – Option 2

	FTE (yrs)	Cost (FY25 M$)
Development Phase	**1.23**	**0.53**
Operations Phase	**0.33**	**0.14**
TOTAL	**1.56**	**0.67**

Planetary Protection

Risks

- Mars probability of impact requirements may not be met, requiring cleaning/microbial reduction, bioassay sampling, and additional analyses
- Ceres probability of contamination requirement may not be met, requiring cleaning/microbial reduction, bioassay sampling, and additional analyses
- Stringent biological cleanliness requirements may be placed on the sample handling hardware, requiring cleaning/microbial reduction, bioassay sampling, and a biobarrier

Planetary Protection

Option Comparison

- Difference in options from a Planetary Protection perspective is that Option 1 includes a sample return and Option 2 does not

SVIT Report

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- This report only addresses Option 2: Lander with no sample return

SVIT

V&V Summary

- Key Aspects of Verification of the Ceres Pre-Decadal system
  - 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 L3 verification activities
  - System test bed will be used for ALL MST/ORTs
  - System test bed will be used for ALL off-nominal scenarios
  - Ops products

SVIT

V&V Statement of Work

- Project V&V ensures verification events are defined and completed.
  - Project V&V Plan
    - Defines the process for V&V
  - Requirements Validation
    - Reviews that requirements are well-written, linked and verifiable
  - TAYF (test as you fly) Exceptions List
    - Identify test that deviate from use in flight
  - ITL (incompressible test list)
    - Identify which test must be completed before launch
  - Verification Activity Matrix (VAM)
    - Reporting V&V progress to project management
  - Verification Activity Buy off
    - Ensures that verification activities have been completed, reported and have met the test objective
  - CoFR (confirmation of flight readiness) support
    - Presents all verification evidence to project prior to launch

SVIT

V&V Cost

- Cost for V&V is $1.9M

Project Verification & Validation Cost By Phase								
Phase	**A**	**B**	**C1**	**C2**	**C3**	**D1**	**D2**	**Total Cost**
Duration	12 mo.	12 mo.	9 mo.	5 mo.	4 mo.	12 mo.	4 mo.	58 mo.
Total	**$0.0 K**	**$132.6 K**	**$212.2 K**	**$312.3 K**	**$249.9 K**	**$749.6 K**	**$249.9 K**	**$1906.5 K**
Lead	$0.0 K	$132.6 K	$212.2 K	$176.9 K	$141.5 K	$424.5 K	$141.5 K	$1229.1 K
Deputy	$0.0 K	$0.0 K	$0.0 K	$135.5 K	$108.4 K	$325.1 K	$108.4 K	$677.3 K

SVIT

System Testbed Summary

- The Ceres Pre-Decadel project will develop 2 test beds in order 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

SVIT

System Testbed Statement of Work

- Generate testing/GSE/capability requirements
- Assemble/configure/maintain test bed equipment
- Test bed certification
- Write test bed operational procedures/scripts/user manuals
- Write V&V procedures
- Execute V&V procedures
- Produce V&V procedure reports
- Trouble shooting / problem retest

SVIT

System Testbed Cost

- Cost for Testbeds is $9M

Testbed Cost by Phase								
Phase	A	B	C1	C2	C3	D1	D2	Total
Duration	12 mo.	12 mo.	9 mo.	5 mo.	4 mo.	12 mo.	4 mo.	58 mo.
Total	$0.0 K	$278.2 K	$1460.3 K	$1597.6 K	$1278.0 K	$3834.1 K	$564.7 K	$9012.9 K
General	$0.0 K	$278.2 K	$576.5 K	$450.0 K	$360.0 K	$1080.0 K	$360.0 K	$3104.8 K
PEM	$0.0 K	$172.1 K	$258.2 K	$143.4 K	$114.8 K	$344.3 K	$114.8 K	$1147.6 K
Lead TB Eng	$0.0 K	$106.1 K	$318.3 K	$176.9 K	$141.5 K	$424.5 K	$141.5 K	$1308.7 K
Maintenance	$0.0 K	$0.0 K	$0.0 K	$129.7 K	$103.8 K	$311.3 K	$103.8 K	$648.5 K
Set-up	$0.0 K	$0.0 K	$865.4 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$865.4 K
Set-up 3	$0.0 K	$0.0 K	$463.1 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$463.1 K
Set-up 1-2	$0.0 K	$0.0 K	$402.3 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$402.3 K
Testbed Ops	$0.0 K	$0.0 K	$0.0 K	$1117.0 K	$893.6 K	$2680.8 K	$180.2 K	$4871.6 K
System Events 3	$0.0 K	$0.0 K	$0.0 K	$237.6 K	$190.1 K	$570.2 K	$0.0 K	$997.9 K
System Events 1-2	$0.0 K	$0.0 K	$0.0 K	$206.4 K	$165.1 K	$495.4 K	$0.0 K	$867.0 K
CDH 3	$0.0 K	$0.0 K	$0.0 K	$26.7 K	$21.4 K	$64.1 K	$0.0 K	$112.3 K
CDH 1-2	$0.0 K	$0.0 K	$0.0 K	$23.2 K	$18.6 K	$55.7 K	$0.0 K	$97.5 K
GNC	$0.0 K	$0.0 K	$0.0 K	$141.5 K	$113.2 K	$339.6 K	$0.0 K	$594.2 K
Power 3	$0.0 K	$0.0 K	$0.0 K	$31.2 K	$24.9 K	$74.8 K	$0.0 K	$131.0 K
Power 1-2	$0.0 K	$0.0 K	$0.0 K	$27.1 K	$21.7 K	$65.0 K	$0.0 K	$113.8 K
Telecom 3	$0.0 K	$0.0 K	$0.0 K	$20.8 K	$16.6 K	$49.9 K	$0.0 K	$87.3 K
Telecom 1-2	$0.0 K	$0.0 K	$0.0 K	$18.1 K	$14.4 K	$43.3 K	$0.0 K	$75.9 K
Payload	$0.0 K	$0.0 K	$0.0 K	$159.2 K	$127.3 K	$382.0 K	$0.0 K	$668.5 K
FSW 3	$0.0 K	$0.0 K	$0.0 K	$84.2 K	$67.4 K	$202.1 K	$67.4 K	$421.0 K
FSW 1-2	$0.0 K	$0.0 K	$0.0 K	$73.2 K	$58.5 K	$175.6 K	$58.5 K	$365.8 K
Fault Protection	$0.0 K	$0.0 K	$0.0 K	$67.9 K	$54.3 K	$163.0 K	$54.3 K	$339.6 K
Services (Burdened)	$0.0 K	$0.0 K	$18.3 K	$30.6 K	$24.4 K	$73.3 K	$24.4 K	$171.1 K
Cleanroom	$0.0 K	$0.0 K	$5.2 K	$8.7 K	$7.0 K	$21.0 K	$7.0 K	$48.9 K
Loanpool	$0.0 K	$0.0 K	$10.5 K	$17.5 K	$14.0 K	$41.9 K	$14.0 K	$97.8 K
Training/Certification	$0.0 K	$0.0 K	$2.6 K	$4.4 K	$3.5 K	$10.5 K	$3.5 K	$24.4 K

SVIT

System I&T Summary

- The Ceres Pre-Decadal system will be assembled, and tested at JPL. Instrument deliveries are assumed as JPL deliverables.
- Key Assumptions
  - JPL build
  - JPL environmental test lab
  - All MGSE and EGSE are delivered to ATLO by sub-systems

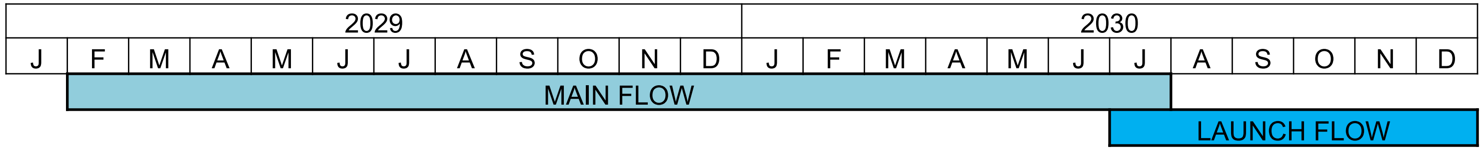
SVIT

System I&T Statement of Work

- Manage the assembly, test, and launch operations of the flight system.
  - Assemble flight system
  - Execute environmental testing program
  - Interface verification and subsystem-to-subsystem functional testing
  - System verification
  - Launch activities

SVIT

Combined System I&T and Launch Flow



SVIT

System I&T Cost

- Cost for SI&T is $31M

	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.	9 mo.	5 mo.	4 mo.	12 mo.	4 mo.	12 mo.	12 mo.	9 mo.	5 mo.	4 mo.	12 mo.	4 mo.	58 mo.
1st Unit Cost	**0.0 FTE**	**0.3 FTE**	**4.8 FTE**	**4.8 FTE**	**11.6 FTE**	**32.7 FTE**	**32.7 FTE**	**$0 K**	**$132 K**	**$1791 K**	**$995 K**	**$1904 K**	**$21367 K**	**$4829 K**	**$31017 K**
10.01 ATLO Management	0.0 FTE	0.3 FTE	1.3 FTE	1.3 FTE	2.0 FTE	3.9 FTE	3.9 FTE	$0.0 K	$131.6 K	$523.6 K	$290.9 K	$399.7 K	$2073.2 K	$691.1 K	$4110.2 K
ATLO Management (Phase B-D)	0.0 FTE	0.3 FTE	1.0 FTE	1.0 FTE	1.0 FTE	1.3 FTE	1.3 FTE	$0.0 K	$131.6 K	$394.9 K	$219.4 K	$175.5 K	$678.6 K	$226.2 K	$1826.3 K
Documentarian	0.0 FTE	0.0 FTE	0.3 FTE	0.3 FTE	1.0 FTE	1.3 FTE	1.3 FTE	$0.0 K	$0.0 K	$125.2 K	$69.6 K	$222.6 K	$860.6 K	$286.9 K	$1564.9 K
System Administrator	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	1.3 FTE	1.3 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$529.4 K	$176.5 K	$705.9 K
Doc Services			3.5 $K	1.9 $K	1.5 $K	4.6 $K	1.5 $K	$0.0 K	$0.0 K	$3.5 K	$1.9 K	$1.5 K	$4.6 K	$1.5 K	$13.1 K
10.02 ATLO System Engineering	0.0 FTE	0.0 FTE	2.0 FTE	2.0 FTE	2.0 FTE	2.3 FTE	2.3 FTE	$0.0 K	$0.0 K	$789.9 K	$438.8 K	$351.1 K	$1205.2 K	$401.7 K	$3186.7 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	$394.9 K	$219.4 K	$175.5 K	$526.6 K	$175.5 K	$1492.0 K
Electrical Lead	0.0 FTE	0.0 FTE	1.0 FTE	1.0 FTE	1.0 FTE	1.3 FTE	1.3 FTE	$0.0 K	$0.0 K	$394.9 K	$219.4 K	$175.5 K	$678.6 K	$226.2 K	$1694.7 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	$547.8 K	$182.6 K	$730.4 K
Facility/Cleanroom						547.8 $K	182.6 $K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$547.8 K	$182.6 K	$730.4 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	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
Subsystem Support	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
10.07 Instrument and Payload Support	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	2.6 FTE	2.6 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$1093.9 K	$364.6 K	$1458.6 K
Instrument Support	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	2.6 FTE	2.6 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$1093.9 K	$364.6 K	$1458.6 K
10.08 Flight and Payload System I&T	0.0 FTE	0.0 FTE	1.5 FTE	1.5 FTE	5.8 FTE	21.9 FTE	21.9 FTE	$0.0 K	$0.0 K	$477.5 K	$265.3 K	$885.5 K	$9258.7 K	$2900.8 K	$13787.8 K
Test Conductor	0.0 FTE	0.0 FTE	1.0 FTE	1.0 FTE	1.0 FTE	1.3 FTE	1.3 FTE	$0.0 K	$0.0 K	$318.3 K	$176.9 K	$141.5 K	$547.0 K	$182.3 K	$1366.0 K
Command	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.3 FTE	1.3 FTE	1.3 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$35.4 K	$547.0 K	$182.3 K	$764.7 K
Flight Software	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.3 FTE	1.3 FTE	1.3 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$35.4 K	$547.0 K	$182.3 K	$764.7 K
Mechanical Engineer	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	0.8 FTE	1.9 FTE	1.9 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$106.1 K	$820.5 K	$273.5 K	$1200.1 K
Electrical Engineer	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	1.2 FTE	1.5 FTE	1.5 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$169.8 K	$656.4 K	$218.8 K	$1044.9 K
Electrical Technician	0.0 FTE	0.0 FTE	0.0 FTE	0.0 FTE	1.8 FTE	2.3 FTE	2.3 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$326.6 K	$1262.7 K	$420.9 K	$2010.2 K
System Engineer	0.0 FTE	0.0 FTE	0.5 FTE	0.5 FTE	0.5 FTE	0.6 FTE	0.6 FTE	$0.0 K	$0.0 K	$159.2 K	$88.4 K	$70.7 K	$273.5 K	$91.2 K	$683.0 K
Mechanical Tech Services						11.6 FTE	11.6 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$4048.5 K	$1349.5 K	$5398.0 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	1.9 FTE	1.9 FTE	1.9 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$268.1 K	$1062.8 K	$268.1 K	$1599.1 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	1.9 FTE	1.9 FTE	1.9 FTE	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$268.1 K	$804.4 K	$268.1 K	$1340.7 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	$2161.6 K	$19.8 K	$2181.4 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	$59.5 K	$19.8 K	$79.3 K
Travel and Lodging						2102.1 $K		$0.0 K	$0.0 K	$0.0 K	$0.0 K	$0.0 K	$2102.1 K	$0.0 K	$2102.1 K

Cost Report

(2326)

Ceres Pre-Decadal 2020-03
Option 1 (Partial) and Option 2

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Status: Ready
(as of 5/21/2020)

Cost

Disclaimer

The costs presented in this 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.

Cost

Cost Requirements

- Constant/Real Year Dollars: FY$2025 by WBS element
- Cost Target: $1.1B (FY$2025)
  - Estimates are generated using the current JPL Institutional Cost Models (ICM) with 2025 rates and factors for the JPL effort
  - Pass thru values obtained from the customer include a 17.5% burden (JPL)
  - Subsystem reports include estimates in FY$2025
- Cost estimates are lifecycle costs provided at WBS levels 2 and 3
- Assume Out-House development for Spacecraft using a Product Line development
- There is no cost included for de-orbit activities
- Launch Vehicle cost is excluded
- Launch date is 12/20/2030
  - Based on a schedule provided in Customer briefing package

Cost

Cost Assumptions

- Fiscal Year: FY$2025
- Mission Class: B
- Mission duration:
  - Option 2 – 7.5 years of operations, plus 4 months for Phase F
- Cost Category: Large

- Wrap Factors
  - Mission Assurance (Less Reserves)
    - Development 3.0%
    - Operations 0.9%
  - E&PO – no cost is included
  - Reserves (Not calculated on Tracking costs)
    - Phases A-D 50%
    - Phases E-F 25%

Cost

Cost Assumptions – Schedule

- Development schedule, **58 months**, assumes significant flight system heritage consistent with a December 2030 launch date
- Mission Operations duration
  - Option 2 – **94 months**, includes a 4 month Phase F

Phase	Option 2
Phase A	**12 mo.**
Phase B	**12 mo.**
Phase C	**18 mo.**
Design	9 mo.
Fabrication	5 mo.
Subsystem I&T	4 mo.
Phase D	**16 mo.**
System I&T	12 mo.
Launch Operations	4 mo.
Phase E	**90 mo.**
Phase F	**4 mo.**

Cost

Basis of Estimate (1 of 5)

WBS #	Title	Description	Estimating Method
01.0	Program Management	The business and administrative planning, organizing, directing, coordinating, controlling, and approval processes used to accomplish overall Project objectives that are not associated with specific hardware (HW) or software (SW) elements.	Wrap factor from JPL ICM
02.0	Project Systems Engineering	The technical and management efforts of directing and controlling an integrated engineering effort for the project. Includes the effort to define the Project space-ground system, conducting trade studies; the integrated planning and control of the technical program efforts of design engineering, specialty engineering, and integrated test planning; the effort to transform Project objectives into a description of system requirements and a preferred system configuration; the technical oversight and control effort for planning, monitoring measuring, evaluating, directing, and replanning the management of the technical program. Documentation products include Level 2 Project Requirements; Design Report; Interface Control Documents (ICDs); CADRe; Project Verification and Validation (V&V) Plan; Information & Configuration Management Plan; Project Software Management Plan; Project Risk Management Plan; Planetary Protection Plan; Contamination Control Plan; and several launch services deliverables. Excludes any design engineering costs (which are in elements 06 and 07).	Wrap factor from JPL ICM
03.0	Mission Assurance	The technical and management efforts of directing and controlling the Safety & Mission Assurance Elements of the project. Includes design, development, review, and verification of practices and procedures intended to assure that the delivered Spacecraft System and Instruments/payloads meet performance requirements and function for their intended lifetimes. Excludes Mission and Product Assurance efforts at partners/ subcontractors other than a review/oversight function, and the direct costs of environmental testing.	Wrap factor from JPL ICM

Cost

Basis of Estimate (2 of 5)

WBS #	Title	Description	Estimating Method
04.0	Science	The technical and management efforts of directing and controlling the Science investigation aspects of the project. Includes the efforts associated with defining the science requirements; ensuring the integration of the science requirements with the Instruments, Payloads, Flight and Ground Systems; providing the algorithms and software for science data processing and analyses; science data analysis and archiving. Products include the Level 2 Science Requirements; Science Management Plan; Science Data Management & Archive Plan; and MOU with science data archive provider. Technology: The technical and management efforts of directing and controlling the Technology Demonstration aspects of the project. Includes the efforts associated with defining the technology demonstration requirements, integrating those requirements with the other project systems, and the team(s) associated with planning and analyzing the results of the technology payload demonstration(s). Excludes hardware and software for on-board science Instruments / Payloads and technology demonstration payloads.	Provided by customer - grass roots estimated based on experience
05.0	Payload System	The equipment provided for special purposes in addition to the normal equipment integral to the spacecraft. Includes experimental, scientific data gathering, and technology demonstration equipment placed on board the flight system.	Estimated by Payload Chair running the JPL ICM

Cost

Basis of Estimate (3 of 5)

WBS #	Title	Description	Estimating Method
06.0	Flight System Management	The Spacecraft System serves as the platform for carrying payload, instruments and other mission-oriented equipment in space to the mission destination(s) to achieve the mission objectives. May be a single module Spacecraft System; or multiple modules that comprise the Spacecraft System such as cruise stage, orbiter, lander, or rover. Each module of the Spacecraft System includes subsystems such as: power, C&DH, telecom, mechanical, thermal, propulsion, GN&C, harness and flight software. Includes all design, development, production, assembly, and test efforts to deliver the completed Spacecraft System for integration with the Payload, Launch Vehicle, MOS and GDS Systems. NOTE: The term Flight = SC + Payload and either 'SC' or 'S/C' is used as an acronym for spacecraft. Documentation products include the S/C System Implementation Plan; S/C Operating Scenarios; Level 3 S/C System Requirements; S/C System Design; various software documents; S/C System Block Dictionary; Flight Rules & Constraints; Command and telemetry dictionaries; and other documents listed in elements below. Does not include support to the Project level I&T activity (ATLO). Note that Payload/Instrument only projects are not required to use this element of the standard WBS Template.	Estimated by Subsystems Chairs running their respective JPL ICMs

Cost

Basis of Estimate (4 of 5)

WBS #	Title	Description	Estimating Method
07.0	Mission Opera-tions	The Mission Operations System (MOS) is the ground-based system required to conduct project mission operations and consists of the following key components: a) Human resources: Trained and certified personnel b) Processes and Procedures: Documented, tested procedures to ensure that operations are conducted in a reliable, consistent and controlled manner c) Facilities: Offices, conference rooms, operations areas, testbeds and other space to house the personnel and perform the operations d) Hardware: Ground-based communications and computing hardware and associated documentation required to perform mission operations e) Software: Ground-based software and associated documentation required to perform mission operations f) Networks: Ground-based networks utilized during mission operations g) Tracking stations of the Deep Space Network and NEN/SN Note that some of these components are developed and maintained under WBS Element 09, Ground Data System.	Estimated by MOS/ GDS Chair running the JPL ICM
08.0	Launch Vehicle	The primary means for providing initial thrust to place the flight system directly into its operational environment or on a trajectory towards its intended target. Includes launch Vehicle; associated launch services.	Not included
09.0	GDS	The grouping of the Flight Engineering Ground Data System (GDS) and the Science Data System accounts under a single roll-up account.	Same as 07.0
10.0	ATLO	The human resources, equipment, data, services, and facilities required to assemble, integrate, test, and deliver the Integrated Spacecraft, Payload, Launch Vehicle, MOS and GDS systems that meet Project requirements. Includes mechanical and electrical assembly; functional testing; performance testing and environmental testing; transportation/logistics; Launch Site support.	Estimated by SVIT Chair

Cost

Basis of Estimate (5 of 5)

WBS #	Title	Description	Estimating Method
11.0	Education and Public Out-reach	Provide for the Education and Public Outreach (EPO) responsibilities of JPL's missions, projects, and programs in alignment with NASA's Strategic plan for Education. Includes management and coordinated activities, formal education, informal education, public outreach, media support, and web site development.	Not included in estimate
12.0	Mission and Navigation Design	Mission Design: Manage and develop the project mission and navigation designs. Includes all mission analysis; mission engineering; and navigation design. Also includes management of Mission Design schedules, cost and performance, liaison with all elements of the project, and support of Project design teams and reviews.	Estimate provided by Navigation Chair running the JPL ICM
-	Re-serves	Project reserves	% provided by customer

Cost

Option 2 – Total Cost

COST SUMMARY (FY2025 $M)	Generate ProPricer Input	Team X Estimate CBE	Team X Estimate PBE
Project Cost		**$1000.7 M**	**$1445.3 M**
Launch Vehicle		**$0.0 M**	**$0.0 M**
Project Cost (w/o LV)		**$1000.7 M**	**$1445.3 M**
Development Cost		**$789.1 M**	**$1183.2 M**
Phase A		$7.9 M	$11.8 M
Phase B		$71.0 M	$106.5 M
Phase C/D		$710.2 M	$1064.9 M
Operations Cost		**$211.7 M**	**$262.1 M**

Cost

Option 2 – Cost A-D

WBS Elements	NRE	RE	1st Unit
Project Cost (excluding Launch Vehicle)	$1038.1 M	$407.2 M	$1445.3 M
Development Cost (Phases A - D)	$776.2 M	$407.0 M	$1183.2 M
01.0 Project Management	$16.9 M		$16.9 M
1.01 Project Management	$8.1 M		$8.1 M
1.02 Business Management	$7.4 M		$7.4 M
1.04 Project Reviews	$1.3 M		$1.3 M
1.06 Launch Approval	$0.1 M		$0.1 M
02.0 Project Systems Engineering	$17.8 M	$0.6 M	$18.4 M
2.01 Project Systems Engineering	$5.4 M		$5.4 M
2.02 Project SW Systems Engineering	$3.5 M		$3.5 M
2.03 EEIS	$0.6 M		$0.6 M
2.04 Information System Management	$1.8 M		$1.8 M
2.05 Configuration Management	$1.6 M		$1.6 M
2.06 Planetary Protection	$0.3 M	$0.3 M	$0.5 M
2.07 Contamination Control	$1.4 M	$0.3 M	$1.7 M
2.09 Launch System Engineering	$1.0 M		$1.0 M
2.10 Project V&V	$1.9 M		$1.9 M
2.11 Risk Management	$0.4 M		$0.4 M
03.0 Mission Assurance	$19.9 M	$10.5 M	$30.4 M
04.0 Science	$25.4 M		$25.4 M
04.01, 04.02, & 04.03 Science Teams	$25.4 M		$25.4 M
05.0 Payload System	$91.6 M	$64.0 M	$155.5 M
5.01 Payload Management	$6.3 M		$6.3 M
5.02 Payload Engineering	$6.2 M		$6.2 M
Instruments	$79.0 M	$64.0 M	$143.0 M
NAC	$9.3 M	$13.5 M	$22.7 M
PlanetVac and Tube closure system	$23.6 M	$17.1 M	$40.7 M
CIRS Micro-Raman	$22.6 M	$16.4 M	$39.0 M
EM Sounder	$5.2 M	$3.8 M	$9.0 M
Mini-TLS	$13.7 M	$9.9 M	$23.6 M
APXS	$4.6 M	$3.4 M	$8.0 M

WBS Elements	NRE	RE	1st Unit
06.0 Flight System	$250.1 M	$191.7 M	$441.8 M
6.01 Flight System Management	$12.2 M		$12.2 M
6.02 Flight System Systems Engineering	$23.7 M		$23.7 M
6.03 Product Assurance (included in 3.0)			$0.0 M
Spacecraft	$207.4 M	$189.5 M	$396.9 M
6.04 Power	$14.8 M	$55.9 M	$70.7 M
6.05 C&DH	$26.2 M	$40.3 M	$66.5 M
6.06 Telecom	$25.2 M	$11.1 M	$36.3 M
6.07 Structures (includes Mech. I&T)	$43.8 M	$14.1 M	$57.9 M
6.08 Thermal	$3.1 M	$7.6 M	$10.7 M
6.09 Propulsion	$30.3 M	$17.2 M	$47.5 M
6.10 ACS	$16.2 M	$37.4 M	$53.6 M
6.11 Harness	$3.8 M	$3.2 M	$7.1 M
6.12 S/C Software	$41.5 M	$2.2 M	$43.7 M
6.13 Materials and Processes	$2.6 M	$0.3 M	$2.9 M
6.14 Spacecraft Testbeds	$6.8 M	$2.3 M	$9.0 M
07.0 Mission Operations Preparation	$30.2 M		$30.2 M
7.0 MOS Teams	$27.9 M		$27.9 M
7.03 Tracking (Launch Ops.)	$0.7 M		$0.7 M
7.06 Navigation Operations Team	$1.6 M		$1.6 M
7.07.03 Mission Planning Team	$0.0 M		$0.0 M
09.0 Ground Data Systems	$29.4 M		$29.4 M
9.0A Ground Data System	$25.0 M		$25.0 M
9.0B Science Data System Development	$3.9 M		$3.9 M
9A.03.07 Navigation H/W & S/W Development	$0.6 M		$0.6 M
10.0 ATLO	$26.4 M	$4.6 M	$31.0 M
11.0 Education and Public Outreach	$0.0 M	$0.0 M	$0.0 M
12.0 Mission and Navigation Design	$10.1 M		$10.1 M
12.01 Mission Design	$1.5 M		$1.5 M
12.02 Mission Analysis	$3.5 M		$3.5 M
12.03 Mission Engineering	$1.6 M		$1.6 M
12.04 Navigation Design	$3.5 M		$3.5 M
Development Reserves	$258.5 M	$135.7 M	$394.2 M

Cost

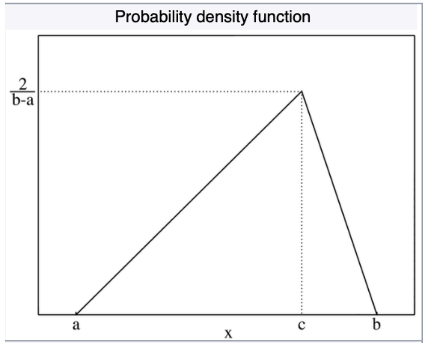
Option 2 – Cost E-F

WBS Elements	NRE	RE	1st Unit
Operations Cost (Phases E - F)	$261.9 M	$0.1 M	$262.1 M
01.0 Project Management	$9.9 M		$9.9 M
1.01 Project Management	$6.6 M		$6.6 M
1.02 Business Management	$2.9 M		$2.9 M
1.04 Project Reviews	$0.3 M		$0.3 M
1.06 Launch Approval	$0.0 M		$0.0 M
02.0 Project Systems Engineering	$0.0 M	$0.1 M	$0.1 M
2.06 Planetary Protection	$0.0 M	$0.1 M	$0.1 M
Element 01	$0.0 M	$0.1 M	$0.1 M
03.0 Mission Assurance	$2.3 M	$0.0 M	$2.3 M
04.0 Science	$59.4 M		$59.4 M
4.02 Science Team	$59.4 M		$59.4 M
06.0 Flight System	$0.0 M		$0.0 M
6.02 Flight System Systems Engineering	$0.0 M		$0.0 M
07.0 Mission Operations	$116.3 M		$116.3 M
7.0 MOS Teams	$92.4 M		$92.4 M
7.03 Tracking	$10.1 M		$10.1 M
7.06 Navigation Operations Team	$12.8 M		$12.8 M
7.07.03 Mission Planning Team	$1.0 M		$1.0 M
09.0 Ground Data Systems	$23.7 M		$23.7 M
9.0A GDS Teams	$15.3 M		$15.3 M
9.0B Science Data System Ops	$8.1 M		$8.1 M
9A.03.07 Navigation HW and SW Dev	$0.3 M		$0.3 M
11.0 Education and Public Outreach	$0.0 M	$0.0 M	$0.0 M
12.0 Mission and Navigation Design	$0.0 M		$0.0 M
12.01 Mission Design	$0.0 M		$0.0 M
12.02 Mission Analysis	$0.0 M		$0.0 M
12.04 Navigation Design	$0.0 M		$0.0 M
Operations Reserves	$50.4 M	$0.0 M	$50.4 M
8.0 Launch Vehicle	$0.0 M		$0.0 M
Launch Vehicle and Processing	$0.0 M		$0.0 M
Nuclear Payload Support	$0.0 M		$0.0 M

Cost

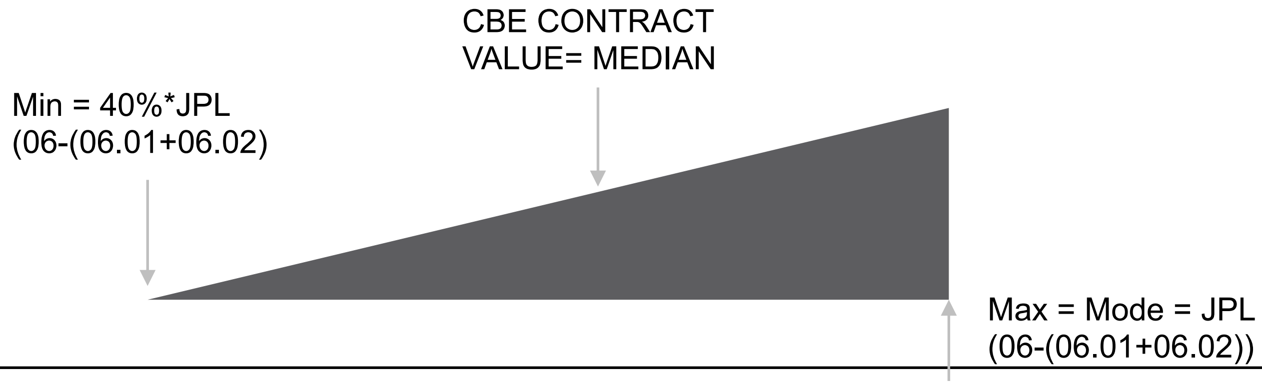
Option 2 - Approach Cost Uncertainty Analysis – Monte Carlo

- A triangular distribution was applied to the lander costs to simulate the uncertainty between the cost model and estimated to be industry's RE costs.
- Team-X has a percentage rule of thumb of 60%:40% split for NRE:RE
- If a commercial contractor was 100% efficient with NRE, then the best estimated cost of doing business out-of-house would be estimated to be 40% of JPL ICM output (applied in this analysis as min value)
- Min = 40%*JPL ICM (06-(06.01+06.02)+17.5% burden); Max = Mode = JPL ICM (06-(06.01+06.02) +17.5% burden)



Median $\quad a + \sqrt{\frac{(b-a)(c-a)}{2}} \quad \text{for } c \geq \frac{a+b}{2},$

a=min
b=max
c=mode



Cost

Option 2 - Uncertainty Analysis Results

Current modeled ICM for Spacecraft in WBS 6.04 only

Approach	Min	Mode	Max	50-th percentile cost	50th-% tile without burden
Min=40% JPL ICM and Max=Mode=JPL ICM JPL ICM = Lander System Only + 17.5% Procurement Burden	$ 187	$ 389	$ 389	$330	$281

Statistics	Values
Mean	321.539
Median	329.716
Variance	2281.801
Standard Deviation	47.768
Coefficient of Variation	0.149
Min	188.895
Max	389.030
Range	200.135
Standard Error	1.511

Percentiles	Values
10%	$251
20%	$277
30%	$297
40%	$315
50%	$330
60%	$343
70%	$356
80%	$368
90%	$379
100%	$389

Cost

Option 2 – Comparison with updated analysis to 6.04 Lander to overall total

Adjusted Cost = cost update with simulated output using spacecraft 50th-%tile cost output
Non-Adjusted Cost = ICM output with no adjustment

Overall change is ~8% total with (~$108M)

COST SUMMARY (FY2025 $M)	Generate ProPricer Input	Adjusted Cost	Non Adjusted Cost	Delta
		PBE	PBE	
Project Cost		**$1337.6 M**	**$1445.3 M**	8%
Launch Vehicle		**$0.0 M**	**$0.0 M**	
Project Cost (w/o LV)		**$1337.6 M**	**$1445.3 M**	8%
Development Cost		**$1075.6 M**	**$1183.2 M**	10%
Phase A		$10.8 M	$11.8 M	10%
Phase B		$96.8 M	$106.5 M	10%
Phase C/D		$968.0 M	$1064.9 M	10%
Operations Cost		**$262.1 M**	**$262.1 M**	

Cost

Option 2 – Comparison with updated analysis to 6.04 Lander to overall total (cont'd)

WBS Elements	Adjusted Cost	Non Adjusted Cost	Delta
Project Cost (excluding Launch Vehicle)	$1337.6 M	$1445.3 M	8%
Development Cost (Phases A - D)	$1075.6 M	$1183.2 M	10%
01.0 Project Management	$16.9 M	$16.9 M	
1.01 Project Management	$8.1 M	$8.1 M	
1.02 Business Management	$7.4 M	$7.4 M	
1.04 Project Reviews	$1.3 M	$1.3 M	
1.06 Launch Approval	$0.1 M	$0.1 M	
02.0 Project Systems Engineering	$18.4 M	$18.4 M	
2.01 Project Systems Engineering	$5.4 M	$5.4 M	
2.02 Project SW Systems Engineering	$3.5 M	$3.5 M	
2.03 EEIS	$0.6 M	$0.6 M	
2.04 Information System Management	$1.8 M	$1.8 M	
2.05 Configuration Management	$1.6 M	$1.6 M	
2.06 Planetary Protection	$0.5 M	$0.5 M	
2.07 Contamination Control	$1.7 M	$1.7 M	
2.09 Launch System Engineering	$1.0 M	$1.0 M	
2.10 Project V&V	$1.9 M	$1.9 M	
2.11 Risk Management	$0.4 M	$0.4 M	
03.0 Mission Assurance	$27.8 M	$30.4 M	9%
04.0 Science	$25.4 M	$25.4 M	
04.01, 04.02, & 04.03 Science Teams	$25.4 M	$25.4 M	
05.0 Payload System	$155.5 M	$155.5 M	
5.01 Payload Management	$6.3 M	$6.3 M	
5.02 Payload Engineering	$6.2 M	$6.2 M	
Instruments	$143.0 M	$143.0 M	
NAC	$22.7 M	$22.7 M	
PlanetVac and Tube closure system	$40.7 M	$40.7 M	
CIRS Micro-Raman	$39.0 M	$39.0 M	
EM Sounder	$9.0 M	$9.0 M	
Mini-TLS	$23.6 M	$23.6 M	
APXS	$8.0 M	$8.0 M	

WBS Elements	Adjusted Cost	Non Adjusted Cost	Delta
06.0 Flight System	$372.7 M	$441.8 M	19%
6.01 Flight System Management	$12.2 M	$12.2 M	
6.02 Flight System Systems Engineering	$23.7 M	$23.7 M	
6.03 Product Assurance (included in 3.0)	$0.0 M	$0.0 M	
Spacecraft	$330.0 M	$396.9 M	20%
6.04 Power	$0.0 M	$70.7 M	
6.05 C&DH	$0.0 M	$66.5 M	
6.06 Telecom	$0.0 M	$36.3 M	
6.07 Structures (includes Mech. I&T)	$0.0 M	$57.9 M	
6.08 Thermal	$0.0 M	$10.7 M	
6.09 Propulsion	$0.0 M	$47.5 M	
6.10 ACS	$0.0 M	$53.6 M	
6.11 Harness	$0.0 M	$7.1 M	
6.12 S/C Software	$0.0 M	$43.7 M	
6.13 Materials and Processes	$0.0 M	$2.9 M	
6.14 Spacecraft Testbeds	$6.8 M	$9.0 M	33%
07.0 Mission Operations Preparation	$30.2 M	$30.2 M	
7.0 MOS Teams	$27.9 M	$27.9 M	
7.03 Tracking (Launch Ops.)	$0.7 M	$0.7 M	
7.06 Navigation Operations Team	$1.6 M	$1.6 M	
7.07.03 Mission Planning Team	$0.0 M	$0.0 M	
09.0 Ground Data Systems	$29.4 M	$29.4 M	
9.0A Ground Data System	$25.0 M	$25.0 M	
9.0B Science Data System Development	$3.9 M	$3.9 M	
9A.03.07 Navigation H/W & S/W Development	$0.6 M	$0.6 M	
10.0 ATLO	$31.0 M	$31.0 M	
11.0 Education and Public Outreach	$0.0 M	$0.0 M	
12.0 Mission and Navigation Design	$10.1 M	$10.1 M	
12.01 Mission Design	$1.5 M	$1.5 M	
12.02 Mission Analysis	$3.5 M	$3.5 M	
12.03 Mission Engineering	$1.6 M	$1.6 M	
12.04 Navigation Design	$3.5 M	$3.5 M	
Development Reserves	$358.3 M	$394.2 M	10%

WBS Elements	Adjusted Cost	Non Adjusted Cost
Operations Cost (Phases E - F)	$262.1 M	$262.1 M
01.0 Project Management	$9.9 M	$9.9 M
1.01 Project Management	$6.6 M	$6.6 M
1.02 Business Management	$2.9 M	$2.9 M
1.04 Project Reviews	$0.3 M	$0.3 M
1.06 Launch Approval	$0.0 M	$0.0 M
02.0 Project Systems Engineering	$0.1 M	$0.1 M
2.06 Planetary Protection	$0.1 M	$0.1 M
Element 01	$0.1 M	$0.1 M
03.0 Mission Assurance	$2.3 M	$2.3 M
04.0 Science	$59.4 M	$59.4 M
4.02 Science Team	$59.4 M	$59.4 M
06.0 Flight System	$0.0 M	$0.0 M
6.02 Flight System Systems Engineering	$0.0 M	$0.0 M
07.0 Mission Operations	$116.3 M	$116.3 M
7.0 MOS Teams	$92.4 M	$92.4 M
7.03 Tracking	$10.1 M	$10.1 M
7.06 Navigation Operations Team	$12.8 M	$12.8 M
7.07.03 Mission Planning Team	$1.0 M	$1.0 M
09.0 Ground Data Systems	$23.7 M	$23.7 M
9.0A GDS Teams	$15.3 M	$15.3 M
9.0B Science Data System Ops	$8.1 M	$8.1 M
9A.03.07 Navigation HW and SW Dev	$0.3 M	$0.3 M
11.0 Education and Public Outreach	$0.0 M	$0.0 M
12.0 Mission and Navigation Design	$0.0 M	$0.0 M
12.01 Mission Design	$0.0 M	$0.0 M
12.02 Mission Analysis	$0.0 M	$0.0 M
12.04 Navigation Design	$0.0 M	$0.0 M
Operations Reserves	$50.4 M	$50.4 M
8.0 Launch Vehicle	$0.0 M	$0.0 M
Launch Vehicle and Processing	$0.0 M	$0.0 M
Nuclear Payload Support	$0.0 M	$0.0 M

Cost

Option 2 – References to other actual historic lander missions

Analogy comparison to actual historic mission landers (note that these landers has significant heritage)

Mission and Milestone, Cost in FY 25$M

Mission, Spacecraft cost only (no 6.01 and 6.02)	PDR	LRD	Cost growth from LRD to CSR/PMSR	
Phoenix*	$308	$321	59%	Significant heritage, Descope saved cost from CDR to SIR
Insight	$279	$341	42%	Descope saved costs from Post SIR to LRD

* $125M contribution (GFE from MPL) was accounted for in this estimate

Cost

Cost Rationale

- Cost Drivers
  - Large (27.5 kW) Solar Array mass
  - Primary structure mass
  - Number and unit cost of EECAM cameras being used
  - Software – complex software, using product line, but have major modifications

Cost

Cost Potentials

- Potential Cost Savings
  - Availability of product line Power subsystem components
  - Truss structure may be overestimated, mechanical recommends performing a detailed structural analysis
  - De-scoping to a single testbed for CDS
  - Potential quantity discount for the number of EECAM cameras being purchased

- Potential Cost Uppers
  - Landing legs design is uncertain, mechanical recommends performing a structural dynamics and landing simulation
  - Increasing to a third testbed for CDS
  - ACS heritage costed at “similar to minor mods”, could be “major”
  - Sample Handling System cost still needs to be included and may be more complicated than expected

Cost

Risks

- Software complexity and the amount of modification being made to the product line code
- Three of the six science instruments are new

APPENDIX C SPECIAL TECHNICAL ANALYSES

APPENDIX C.1 LANDING SITES IN VINALIA FACULAE – STATE OF KNOWLEDGE

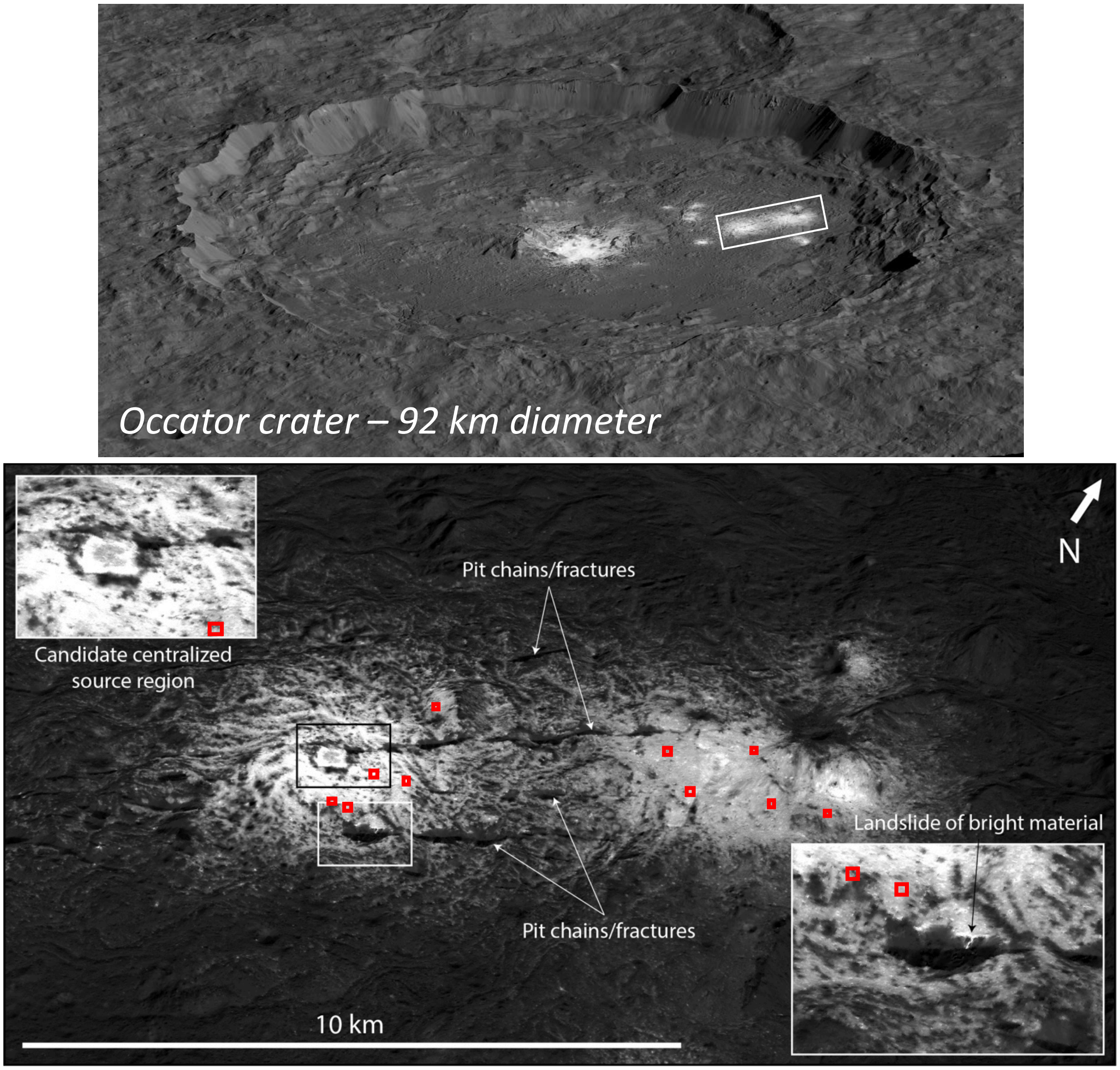


Figure C-1. Examples of 100 m diameter safe landing sites, based on Dawn XM2 imaging.

Accessible Landing Sites

Examples of landing/sampling sites that may be accessible, based on results from the Dawn second extended mission (~5 m/px) are shown in **Figure C-1**. In order to identify potential landing/sampling sites, the first priority is spacecraft safely. Slopes >15° and hazards would all pose a threat to a safe and stable landing and to successful operations and sample collection. Using the highest resolution Dawn shape model of Occator (horizontal resolution of ∼32 m/px and an intrinsic height accuracy of ∼1.5 (Jaumann et al. 2017)), we find that the majority (>90%) of Vinalia Faculae have slopes of <15°. We also identify hazards, such as fractures, pits and boulders in the Dawn XM2 images (~5 m/px). However, there are numerous smooth patches in which no such hazards are visible. Precision landing would be needed to avoid these hazards (i.e., landing within a ~20-m-diameter area), which is enabled by technologies such as hazard avoidance and terrain relative navigation (e.g., Johnson et al. 2007).

The second priority is the scientifically compelling nature of potential landing/sampling sites. As discussed in Section 1, Vinalia Faculae is a highly compelling target because it contains high concentrations of minerals thought to be derived from the deep brine reservoir (Raponi et al. 2019). Moreover, Vinalia Faculae is made up of relatively thin deposits (no more than ~2–3 m thick on average) that lie diffusely on top of the dark material that is found throughout Occator crater (Scully et al. 2020 and references therein). Thus, it would be possible to sample both bright faculae material and dark material at Vinalia Faculae.

Using the aforementioned Dawn data, we have identified ten 100-m-diameter safe landing/sampling sites in Vinalia Faculae. Many more (tens to hundreds) 100-m-diameter potential sites exist. Higher resolution camera and topographic data would be needed to confirm that the slopes in these potential landing/sampling sites are <15° degrees on a lander scale (i.e., on the scale of a few meters or less), and that hazards are not present at scales smaller than can be resolved in the XM2 data. Such higher resolution data would be obtained during the 275 km and 28 km altitude orbits discussed above. However, our preliminary analysis indicates that safe and scientifically compelling landing sites do exist in Vinalia Faculae (see Scully et al., submitted for additional information, available upon request).

Material Properties

The material in Vinalia Faculae has been recently emplaced, probably less than 2 My (Nathues et al. 2020). Geomorphology shows that the evaporite was displayed as a spray via ballistic flight around one structure identified a vent (**Figure C-1**) (Ruesch et al. 2019b). Material exposed that way is expected to be in the form of loose grains, which is consistent with the grain size estimated by Raponi et al. (2019). PlanetVac for Ceres would also include a drill bit, derived from the DragonFly mission, to break up surface material as a backup in case the material is stronger than expected. Since the material was recently exposed, it has been subjected to little space weathering and micrometeorite contamination. Hence, there is no requirement to sample below the surface to access fresh material.

APPENDIX C.2 PLANETARY PROTECTION WORKING GROUP PAPER

See attached paper.

Planetary Protection Requirements for Future Exploration of Ceres State of Understanding after the Dawn Mission, as of August 2020

Report Author: Julie Castillo-Rogez[1], Lynnae Quick[2], Marc Neveu[2,3], Jennifer Scully[1], Thomas Nordheim[1], Carol Raymond[1], Marc Rayman[1], Brian Clement[1]

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In preparation for submission to *Astrobiology*

Abstract
Here we review the state of understanding of Ceres as it relates to planetary protection policy for future missions to the dwarf planet. The Dawn mission found Ceres to be an intriguing target, with evidence for the presence of regional, possibly extensive liquid at depth, and local expressions of recent and potentially ongoing activity. The Dawn mission also found evidence for a high abundance of carbon in the regolith, interpreted as a mix of carbonates and amorphous carbon, as well as locally high concentrations of organic matter. However, it is unlikely that organic matter would be of biological origin based on our understanding of this small body. This review yields several findings: (a) Ceres shows no geological evidence for conduits from the surface to the interior; transport can only be by unidirectional upwelling of material from the deep interior to the surface, so forward contamination of deep liquid reservoir(s) is not an issue anywhere on Ceres; (b) a sample return should be considered unrestricted for the majority of Ceres' surface except in regions near vents where evaporites have been recently exposed as these may contain organic matter from a deep brine reservoir.

1. Introduction

The Dawn mission revealed Ceres to be a target of astrobiological interest (Castillo-Rogez et al. 2020). Ceres' surface looks globally homogeneous but locally shows evidence for a few atypical features with respect to the average Ceres' surface, specifically recent endogenic activity (Ahuna Mons, Occator faculae), sites rich in organic matter (Ernutet crater), and sites rich in carbonates and other salts (e.g. Haulani Crater). As Ceres is an ocean world (Castillo-Rogez 2020) and a tempting target for follow-on exploration (Shi et al. 2019; Castillo-Rogez et al. 2020b), we assess potential drivers of planetary protection requirements for future missions. This paper builds on an assessment of the end of mission plan for the Dawn spacecraft, which summarized the conclusions of the Dawn project on Ceres' biological potential and habitability (Raymond, Rayman, Castillo-Rogez, available upon request), based on the analysis of data obtained by June 2018, and augments it with all results available as of July 2020. Potential landing areas of scientific interest are addressed in Section 2. Implications of current understanding and uncertainties on planetary protection requirements are covered in Section 3. As per the current COSPAR policy, a future in situ mission to Ceres would qualify as Category II – noting that a Mars flyby for gravity assist would levy more stringent requirement on the whole mission, making it Category III. The categorization may be further elevated depending on landing site. A sample return mission from geologically old regions of Ceres' surface should be considered unrestricted as the total ionization dose (TID) estimate would be well in excess of the dose considered for sterilization (Section 4). However, a mission returning samples from material recently exposed on Ceres' surface may lead to more stringent requirements (i.e., restricted sample return).

This work also offers an opportunity to discuss planetary protection for future dwarf planet exploration, because dwarf planets are a newly explored class of objects that display evidence for geological activity. Both Ceres and Pluto are highlighted in the report from the Committee for Astrobiology and Planetary Science (*NAS* 2017), and NASA is funding concept studies for the follow-on exploration of these objects (e.g., Castillo-Rogez et al. 2020b; Howett et al. 2020) for consideration by the Planetary Science Decadal Survey 2023-2032.

2. Ceres' Astrobiological Significance

Ceres' astrobiological potential derives from its history as an ocean world. Its surface displays signatures of carbonates and other salts (*De Sanctis et al.* 2018) delivered in the form of evaporites, excavations by small impacts, or emplacement onto the surface via an endogenic mechanism (*Carrozzo et al.* 2018). Organics found on Ceres' surface are matched by the near-infrared spectra of insoluble organic material found in carbonaceous chondrites (*Kaplan et al.* 2018), which is consistent with Ceres' relationship to C-type asteroids and carbonaceous chondrites (*McSween et al.* 2018) but requires some enrichment mechanism that is not understood at this time. A full review of Ceres' astrobiological significance can be found in *Castillo-Rogez et al.* (2020). Since the publication of *Castillo-Rogez et al.* (2020), additional evidence for the recent occurrence of liquid below Occator Crater and potentially the whole Hanami Planum region has been reinforced by gravity observations returned in Dawn's second extended mission (*Raymond et al.* 2020).

Ceres is likely substantially too small for it to have been host to an independent origin of life (e.g., *Russell and Nitschke* 2017), but additional astrobiological interest stems from Ceres' potential habitability. This is an important factor in considering the hypothesis that life could have traveled through space (panspermia, e.g., Worth et al. 2013) and is directly relevant to the question of planetary protection.

Ceres is a heat-starved body with only long-lived radioisotopes as a long-term heat source (*Castillo-Rogez and McCord* 2010). In that regard, its study is relevant to other icy bodies with little or no tidal heating at present, like Pluto and Callisto (*Castillo-Rogez* 2020). Yet, the origin of the cryovolcanic activity observed in a few locations on Ceres is missing a definitive explanation. *Castillo-Rogez et al.* (2019) and *Hesse and Castillo-Rogez* (2019) proposed that a high abundance of clathrate hydrates in Ceres' crust slow down heat loss. A similar explanation has been offered for the preservation of a suspected ocean in Pluto (*Kamata et al.* 2019).

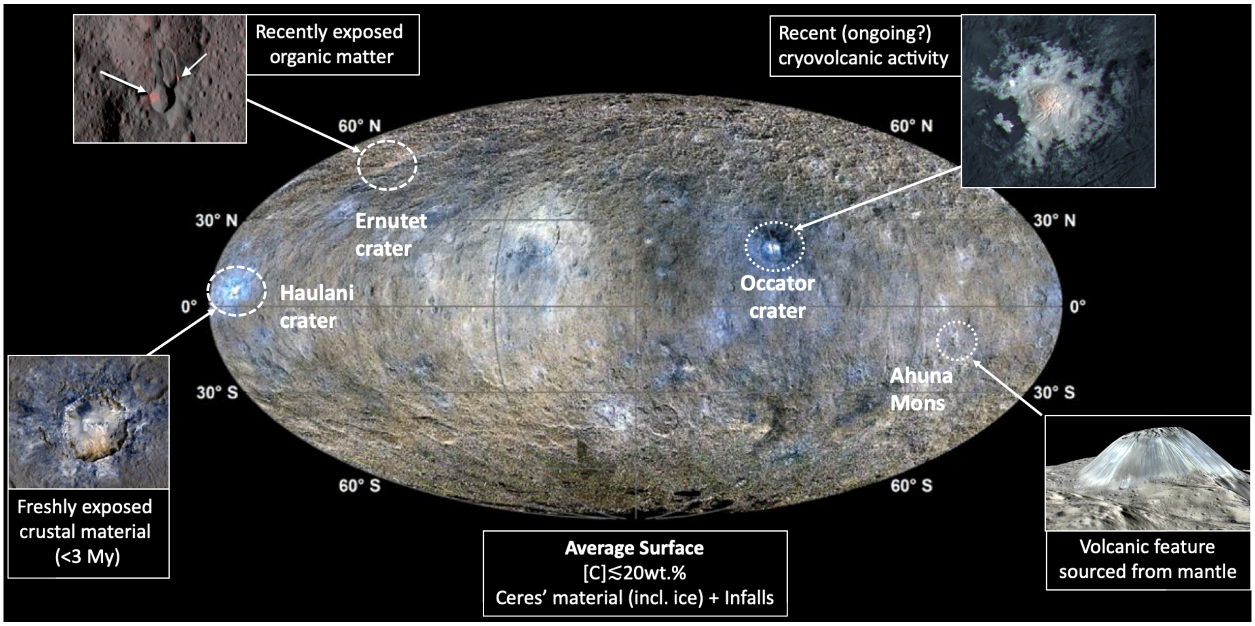

Figure 1. Ceres' surface is globally homogeneous except for a few landmarks where a high abundance of organic matter and pervasively aqueously altered materials have been found. Activity at Occator crater started ~20 My ago and may be ongoing. Organics exposed at Ernutet crater had to be exposed <10 My ago in order to preserve their infrared signature. These regions are likely candidates for in situ surface exploration and/or sample return. The faculae in Occator crater correspond to an area about 0.1% of Ceres' surface.

Surface Age: Most of Ceres' surface is old: model ages derived from crater counts indicate that the majority of Ceres' surface is greater than a few hundred million of years old, and > 1 Gy for a large fraction of the surface (*Mest et al.* 2017, 2018), except for regions that fall into the most recent chronostratigraphic period, called the Azaccan period. The latter consists of craters with a fresh morphology such as Occator crater (*Mest et al.* 2017). Most of the recent craters (e.g., Haulani crater) do not show any evidence for active flow of material on the crater floors; rather, material flow can be explained by mass wasting processes.

Evidence for Deep Liquid: Dawn's data show geological evidence for the presence of a small fraction of brines (>~5 vol.%) below a 35 to 55 km thick crust (*Ermakov et al.* 2017; *Fu et al.* 2017). These brines are the likely source of Ahuna Mons (*Ruesch et al.* 2019), an isolated ~4 km tall mountain, and contribute to the long-term activity in Occator's faculae (*Quick et al.* 2019; *Raymond et al.* 2020) (see map in Figure 1). Ahuna Mons displays 5-10 vol.% sodium carbonate (*Zambon et al.* 2017), which suggests its source is alkaline with a temperature of >250 K (*Castillo-Rogez et al.* 2019). The rich sodium carbonate in Occator's faculae, which may be in part sourced from the deep brine reservoir, supports this inference (*Raymond et al.* 2020). Gravity data indicate that that brine layer is at least 35 km deep (*Ruesch et al.* 2019; *Raymond et al.* 2020).

Interior-Surface Communication: Ahuna Mons and Occator Crater offer the only evidence of Ceres geologically recent activity. Ahuna Mons is a volcanic feature emplaced ~50 to 240 My ago (*Ruesch et al.* 2016). Available evidence for Ahuna Mons points to a passively constructed feature that formed from one-way upwelling: either as a diapir or from compression of the deep brine layer (*Neveu et al.* 2015; *Ruesch et al.* 2016, 2019). Smaller montes (tholi) are observed on all terrains (*Sori et al.* 2018), but there is no evidence that the surrounding surface relaxed due to a thermal anomaly, which one would expect if these features were the product of convective upwelling. Instead, they might be due to the passive reorganization of material following impacts, with which these tholi are frequently associated (*Bland et al.* 2019).

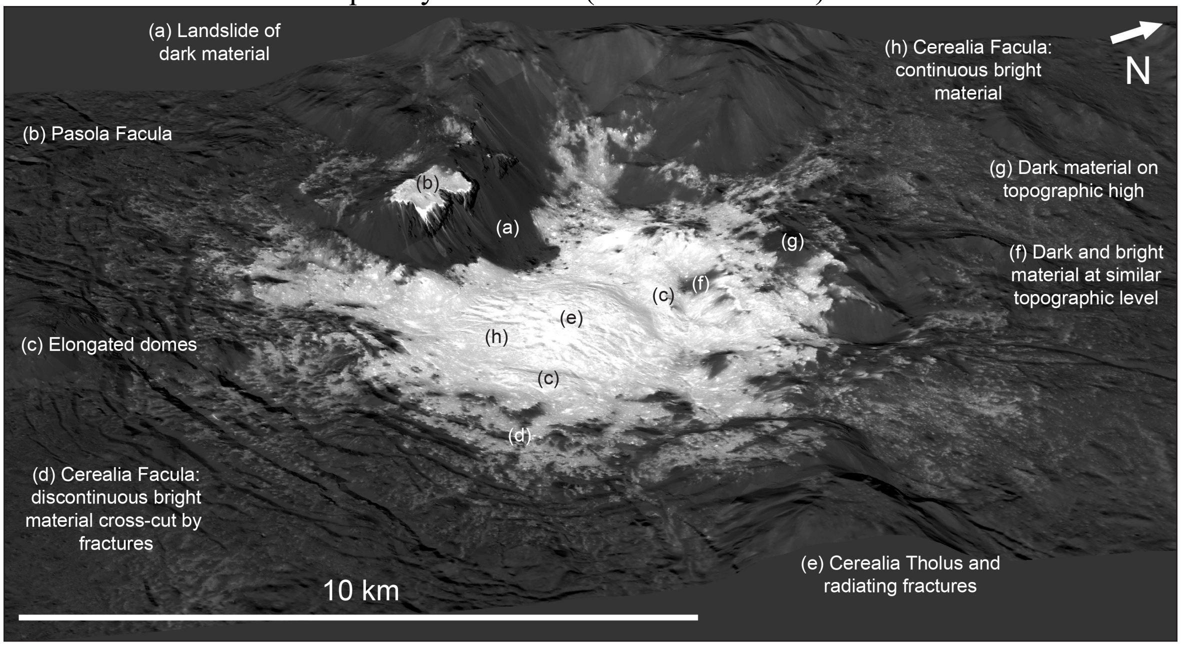

Figure 2a. Side view of the faculae in the center of Occator Crater. Cerealia Facula (the main bright deposit) is about 10 km across and coats the majority of the central pit. Pasola Facula is a smaller bright deposit located on a ledge above the central pit. Cerealia Facula is cross-cut by fractures at its edges and on Cerealia Tholus (the central dome). The other bright deposits in Occator Crater, the Vinalia Faculae, , located ~ x km to the east, also formed recently (<10 My ago) and both Cerealia Tholus and Vinalia Faculae may be active at present. (Credit: Scully et al. 2020).

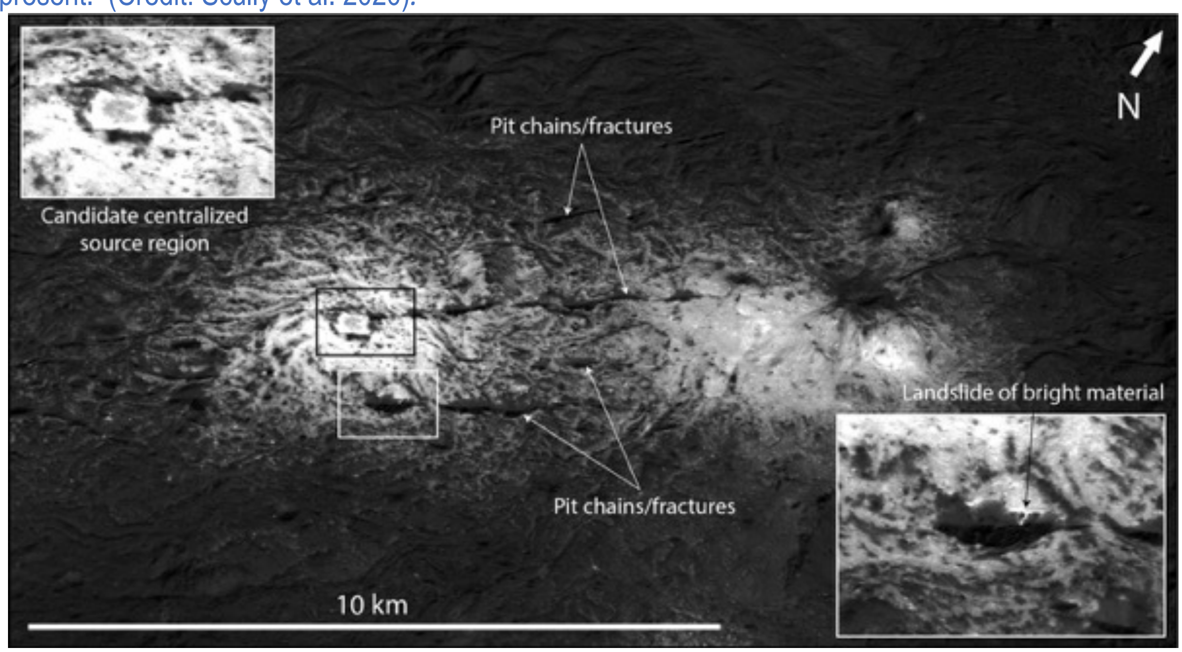

Figure 2b. Side view of the main Vinalia Faculae. Inset images show a landslide of bright material cascading into a pit chain, and the candidate centralized source region. The four main pit chains/fractures that cross-cut Vinalia Faculae are indicated. The base mosaic (D. P. O'Brien) has 5x vertical exaggeration and to make the perspective view we referenced the base mosaic to DLR LAMO DTM. (Credit: Scully et al. 2020).

Another remarkable feature, the faculae (bright deposits) in Occator Crater also display evidence for recent, and potentially even ongoing, activity (*Nathues et al.* 2017, 2020; *Quick et al.*, 2019; *Scully et al.* 2018, 2019; *Raymond et al.* 2020; *De Sanctis et al.* 2020) (Figure 2). At least early in their history, the activity that emplaced the faculae was driven by the heat produced upon impact, which led to the formation of a central, shallow impact melt reservoir that delivered brines/salts to the crater floor (*Bowling et al.* 2019; *Raymond et al.* 2020). If the only source of faculae-forming-brines was the shallow impact melt reservoir, volume changes as a result of freezing could lead to the extrusion of material, resulting in later additions of bright salts to the faculae. However, with some faculae-forming activity as recent as a few My ago, almost 20 My after the formation of Occator (*Nathues et al.*, 2020; *Neesemann et al.*, 2019), the source of the faculae cannot be a shallow impact melt reservoir alone (*Hesse and Castillo-Rogez*, 2019). Instead, it is likely that fractures created by the impact accessed the deeper brine reservoir, which directly formed the Vinalia Faculae in the eastern crater floor, and refreshed the Cerealia-Facula-forming brines in the impact melt reservoir (*Quick et al.* 2019; *Raymond et al.* 2020; *Scully et al.,* 2020). Crater-based ages uncertainties are at least 2 My, so it is not possible to discard the possibility that activity could be ongoing both at Cerealia and Vinalia Faculae (Neesemann et al. 2019). More robust evidence for ongoing material exposure is in the form of hydrated salt (hydrohalite, $NaCl.2H_2O$) found at the top of Cerealia Tholus, the dome in the center of Cerealia Facula (*De Sanctis et al.* 2020). Hydrated salts are not stable in vacuum at the temperature on Ceres' surface and dehydrate over a short timescale (months or years, *Bu et al.* 2017). This indicates that part of the material of Cerealia Tholus is currently being emplaced. Hydrohalite was not observed at the Vinalia Faculae, but its presence within the ~10 m pixels of Dawn infrared spectra cannot be ruled out. Here, again, the consensus interpretation for the source of activity is relief of the pressurized, gas-rich brine with the introduction of fractures by the crater-forming impact (*Quick et al.* 2019; *Raymond et al.* 2020). *Quick et al.* (2019) showed that a small amount (<1 to a few %) of gas is sufficient to drive brine upwelling to the surface.

We note that the Vinalia Faculae may have been emplaced during multiple events. Although the lack of clearly observable flow-fronts makes it difficult to prove this with certainty, if cryovolcanic eruption events on Ceres are similar to volcanic eruptive events on Earth, it is unlikely that all material was extruded at once with no further activitiy occurring. In addition, crater counts from[Nathues et al., (2020) suggest that Cerealia Facula was emplaced during mutlple eruptive events, which futher suggests that the Vinalaia Faculae were formed as a result of mutilple eruptions.

3. Implications for Planetary Protection Requirements

We assess the planetary protection assessment criteria defined for in situ missions to and samples returned from small bodies by COSPAR (Kminek et al. 2017), see also NASA NID 8020.109A "Planetary Protection Provisions for Robotic Extraterrestrial Missions."

3.1 Forward Contamination and Access to Deep Liquid Reservoirs

We distinguish between forward contamination (i.e., bio-molecules and organic compounds that could lead to biosignature false positives) alone versus forward contamination and microbial propagation on Ceres. The former pertains to the objectives of specific concepts that may involve a variety of implementation strategies. The latter point is the focus of this paper. Current practice in planetary protection is to consider temperatures ≤240K and/or water activity ≤0.6 inhibitory to all biological activity (specifically, enzymatic). If conditions on and inside Ceres meet either of these conditions, the energy required to live in a brine (e.g., by production of compatible solutes or maintenance of cytoplasm) might be limiting and, over the period of biological exploration (1000 years), forward contaminants could not propagate significantly. However, in the case of Ceres, we cannot rule out more favorable conditions for life to thrive. Specifically, the mineralogy found at Occator crater indicates a source temperature of ~245K (*Raymond et al.* 2020) and the high salt concentration suggests water activity > 0.6 (based on models by *Castillo-Rogez et al.* 2018).

The criterion for Planetary Protection Category II (NPR 8020.12D) of a proposed orbital or landed mission is that it presents "only a remote chance that contamination by a spacecraft could compromise future investigations." The driving requirement for forward contamination planetary protection is limiting to 10^{-4} the probability of introducing a viable Earth microbe into a potential habitat on a time scale shorter than 1000 yrs (*National Research Council* 2012; *Kminek et al.* 2017). This was agreed to by NASA as part of a Europa Clipper workshop in November 2018 and has yet to be codified in an NPR or NID (Briant Clement, personal communication).

Conduits of material deposited on the surface of an icy body into a potential habitat could take multiple forms: via fractures, in regions subject to volcanic activity, or in ice-rich regions that might produce liquid upon impact by meteoroids or spacecraft. Based on the prospect of abundant ice and possible liquid in the pre-Dawn literature, the Dawn mission was subject to planetary protection considerations for the end of its mission, which led to assessing the impact probability over a 50-yr period based on knowledge gained from the mission prior to June 2018, even though a stable orbit was not required. Analyses showed that starting from Dawn's final elliptical orbit, the spacecraft would not impact in 20 years and would have < 1% probability of impact within 50 years, with a chance << 0.01% of crashing into the Cerealia Facula (*Grebow et al.* 2018).

Available evidence indicates that subsolidus convection in Ceres' crust, which could transport material from the surface to the interior, is precluded by the crust's strength (*Bland et al.* 2016). In addition, transport from the surface to the deep brine layer is not supported by convection modeling (*Formisano et al.* 2020), which highlighted the lack of a driving force with the heat flow of <3 mW/m^2 expected within Ceres (*Castillo-Rogez et al.* 2019). This low heat flow is consistent with Ceres' surface being older than 100 My overall. Furthermore, there is no evidence for downward transfer of material at any place on Ceres (e.g., there are no confirmed thrust faults). The only region where the question of material transfer is warranted is at the Occator faculae.

Occator crater is the only region where liquid may be present in the shallow subsurface, based on surface dating and composition (*Nathues et al.* 2020; *De Sanctis et al.* 2020). As noted in the previous section, following the analysis of the high-resolution data obtained during the last phase of the Dawn mission, we can address whether material transfer happens in two directions, resulting in material from the surface reaching the deep brine layer on a short timescale. Compositional mapping of Cerealia Facula indicates that the dome has been extruding material (*De Sanctis et al.* 2020) via extensional faults (Nathues et al. 2020) with no geomorphological evidence for downward material withdrawal. The depth of the large fractures found in this region is unknown but they could connect to a broad network that could plausibly tap into the deeper brine reservoir (*Buzckowski et al.* 2019; *Quick et al.* 2019; *Raymond et al.* 2020; *Scully et al.* 2020). *Quick et al.* (2019) suggest that depending on the size of the deep brine reservoir, from which a substantial portion of Occator's bright materials may be sourced, excess pressures caused by the freezing of this reservoir could drive the faculae-forming brines to to the surface in as little as 3.5 Myr and as long as 1.7 Gyr. Owing to the intensely pressurized state of the brine reservoir, the movement of material in fractures that link this deep brine reservoir to the surface may be characterized by one-way transport of fluids for a significant amount of time. As such, it is unlikely that any terrestrial microbes that would be deposited into these fractures at surface vents would reach the deep brine reservoir while fluids are actively being erupted onto the surface. Conversely, microbes are more likely to be entrained in the brine flow and deposited back onto the surface in this scenario. In addition, similar to the case of terrestrial magmatic systems, fractures that transport brines to the surface may cool and crystallize into tabular intrusions once brine transport and surface eruptions end. Transport of microbes to the deep brine layer in inactive, solidified fractures is also improbable. Overall, the preponderance of our understanding of Ceres indicates that a surface mission would qualify as Category II. (Of course, other mission considerations, such as a Mars flyby, would motivate a higher category.)

3.2 Backward Contamination and Sample Return

Samples returned from almost any place on Ceres would contain organic matter. The region of Ernutet crater (Figure 1) is of particular interest because of the high concentration of organics identified there (*De Sanctis et al.* 2019) although their origin, whether exogenic or endogenic, is debated (*Pieters et al.* 2018). The current thinking is that a fraction of organic matter found on Ceres could have formed in situ, either in an early ocean or in a porous rocky mantle convecting over billions of years (*De Sanctis et al.* 2019; *Travis et al.* 2018). However, it is likely that Ceres' deep interior now lacks redox gradients and instead has reached chemical equilibrium as a consequence of long-lived water-rock interaction (*Vance et al.* 2016). In the course of Ceres' history, large impacts could have introduced "fresh" material into the system, as ice-rich bodies tend to retain a large fraction of the impactor material, thus creating transient redox gradients (*Bowling et al.* 2019; *Castillo-Rogez et al.* 2020). However, organic matter found in abundance on the surface shows a low abundance of oxygen functions (<30%, *De Sanctis et al.* 2019), which is consistent with an origin predominantly in a reducing environment.

The question then is whether a sample return from Ceres would be unrestricted as in the cases of the OSIRIS-REx and Hayabusa2 sample return missions. We follow the list of questions from COSPAR regarding whether a sample return mission is classified "Restricted Earth return" (*Kminek et al.* 2017; see section 5.5.2.1 of NID 8020.109A; see Table 1). The state of knowledge or lack thereof summarized in Table 1 indicates the answer to this question hangs in our understanding of the total radiation accumulated as sterilization equivalence. Nordheim et al. (in prep.) have estimated from computer modeling the deposited radiation dose from the charged particle environment at the surface of Ceres accumulated as a function of time and depth for materials encompassing the range of composition relevant to Ceres' average surface and faculae salts. At depths of ~cm to meters, the charged particle radiation dose is dominated by galactic cosmic rays. They show that it would take slightly less than 1 Myr to reach a dose of 2.5 Mrad TID in the first 10 cm below the surface, which we take as a threshold for the sterilization of lifeforms based on the state of the literature (*Musilova et al.* 2015, Figure 6).

Hence, the majority of Ceres' surface material (exposed for >> 100 My) has long reached the TID threshold for the sterilization of lifeforms, with TID on the order of tens to hundreds of Mrad. and would warrant unrestricted sample return. However, a sample return from the average surface is of lesser interest, due in part to the strong possibility that Ceres' regolith contains a large fraction, up to 70vol.%, of infall material (i.e., exogenic contaminants) (Marchi et al. 2018). Furthermore, the evaporites recently exposed in Occator are considered of much greater value for understanding the evolution of ocean worlds. Recently published mission concepts have been focusing on returning samples from the Occator faculae (e.g., *Burbine and Greenwood* 2020; *Shi et al.* 2019; Kissick et al. 2020; *Castillo-Rogez et al.* 2020c). Since the facula material is expected to have been exposed less than 2±2 My ago (Neesemann et al. 2019), it may not have yet been exposed to sterilizing levels of radiation. Hence, a sample return from these regions would be classified as "Restricted Earth Return."

Table 1. Assessment of the questions for the Categorization of Sample Return Missions from Small Solar System Bodies based on the COSPAR Planetary Protection Policy.

Questions	State of knowledge / Gaps
1 - Does the preponderance of scientific evidence indicate that there was never liquid water in or on the target body?	NO – Ceres has likely had liquid water throughout its history
2 - Does the preponderance of scientific evidence indicate that metabolically useful energy sources were never present?	NO – Ammonium, carbonate, and (likely) organic compounds are found throughout the surface, and there is organic material concentrated locally
3 - Does the preponderance of scientific evidence indicate that there was never sufficient organic matter (or CO_2 or carbonates and an appropriate source of reducing equivalents) in or on the target body to support life?	NO – There is pervasive evidence for carbonates, high carbon abundance in the regolith, and mineralogy formed under high partial pressure of hydrogen
4 - Does the preponderance of scientific evidence indicate that subsequent to the disappearance of liquid water, the target body has been subjected to extreme temperatures (i.e., >160ºC)?	No – There is no such evidence, and Ceres still contains liquid water (below ~40 km thick icy crust)
5 - Does the preponderance of scientific evidence indicate that there is or was sufficient radiation for biological sterilization of terrestrial life forms?	Yes – 99% of the surface has been exposed to sterilizing levels of radiation for >> 100 My No for Occator faculae, which have been exposed for <20 My, some areas <2 My ago
6 - Does the preponderance of scientific evidence indicate that there has been a natural influx to Earth, e.g., via meteorites, of material equivalent to a sample returned from the target body?	Unknown – No confirmed meteorite from Ceres has been found, which may be due to its icy surface (Rivkin et al. 2014). Dust influx cannot be ruled out.

4. Summary of Findings

Overall, Ceres' surface is heavily cratered, with no evidence of recent resurfacing or of geomorphologic features created by global-scale endogenic forces over all of its surface except faculae inside Occator crater. At these faculae or elsewhere, Ceres also shows no geological evidence for currently open conduits to a putative deep brine region. Observations suggest that the process driving the emplacement of material in Occator crater is unidirectional. Hence, the finding from this study is that a future orbital and/or landed mission at Ceres is determined to be Category II with no risk of forward contamination or microbial propagation in the brine reservoir. Furthermore, material returned from any location of Ceres' surface except for the Occator faculae would have been exposed to solar wind and galactic cosmic ray exposure for periods of time much longer than the 1 My at which a TID of 2.5 Mrad is reached, and therefore would have experienced sterilizing levels of radiation. A mission returning samples from these areas is determined to be classified as “Unrestricted Earth Return.”

Exposure of material from a deep brine reservoir at the Occator faculae may be ongoing, considering the large uncertainties of crater-based dating and the occurrence of hydrated salts with short surface lifetime found at least in Cerealia Tholus. In the absence of understanding of the extent of prebiotic chemistry in Ceres’ long-lived ocean, return to Earth of organic matter that may be trapped in salt grains could raise a back planetary protection concern. Hence, a sample return from the Occator faculae is determined to be classified as “Restricted Earth Return.” Additional knowledge gained by a future mission prior to sampling could help resolve the emplacement history of materials across the faculae and potentially identify regions that have been exposed to radiations for >1 My.

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APPENDIX D ADDITIONAL INFORMATION ON TECHNOLOGIES AND TECHNIQUES

Hirshorn and Jefferies (2106) provide an approach for evaluating whether a component or subsystem is a New Technology, and Engineering Development, or Heritage. An item is considered to be standard engineering development if its "*Performance or function well accepted (not new or novel), but needs engineering development for a specific mission*." Hirshorn and Jefferies provide a flow chart to determine which of the three buckets (new technology, engineering, or heritage) an item falls into.

For the retractable/redeployable solar array, the Hirshorn and Jefferies flow chart is given in Fig. **D-1**. The purple line indicates the flow through this chart as follows beginning from "Start:"

1. "Performance or function new or novel?" No, a retractable/redeployable ROSA solar array has been demonstrated in flight on the ISS.
2. "Performance or function demonstrated operationally?" No, the ROSA test on the ISS was a demonstration not an operation use.
3. "Performance or function bounded by demonstration?" Yes, the retraction and redeployment was demonstrated three times in flight and many times on the ground.
4. "Form and fit bounded by demonstrated capability? Yes, the ROSA solar arrays required for the Ceres sample return mission are of a similar size to those tested on the ground.
5. "Environments bounded by demonstrated capability?" No, the environments required for a Ceres sample return mission are significantly different from ground tests and the ISS demonstration. Specifically, the ROSA for Ceres must have the capability to be retracted after being deployed for approximately six years in space. It must also function properly in the dust environment on the surface of Ceres. This difference in environments puts the retractable/redeployable solar array in the New Technology category even though it has been demonstrated in flight.

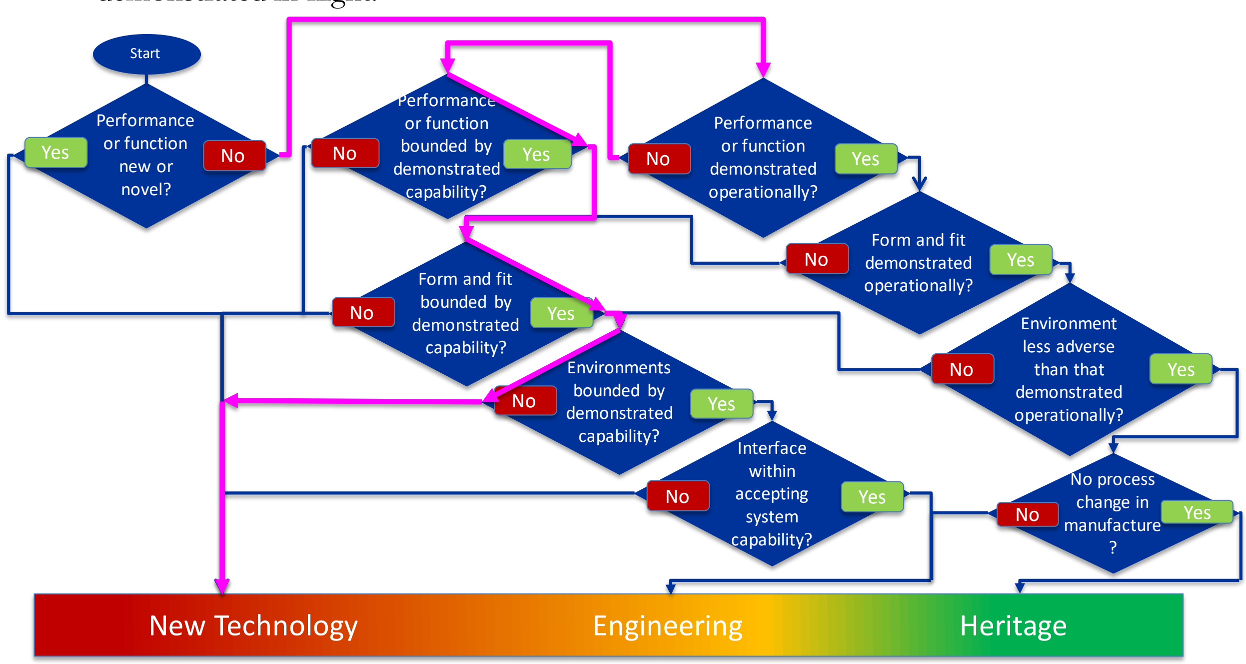

Figure D-1. Technology assessment flow chart (purple line) indicates that the restorable/redeployable ROSA solar array is a New Technology.

Similar flow charts are given for the sample acquisition system (**Fig. D-2**) and the sample transfer system (**Fig. D-3**). The sample acquisition system is based on the PlanetVac pneumatic sampling technology developed for JAXA's MMX mission that will return samples from Phobos. The questions in the flow chart in **Fig. D-2** indicate that standard engineering is required to adapt the MMX PlanetVac system for use in the Ceres sample return mission.

1. "Performance or function new or novel?" No, the PlanetVac system is being developed for the MMX mission. A similar system with an integral drill is being developed for NASA's Dragonfly mission.
2. "Performance or function demonstrated operationally?" No, the PlanetVac system has not yet been used operationally.
3. "Performance or function bounded by demonstration?" Yes, extensive ground testing and low-gravity testing has been performed on the PlanetVac system.
4. "Form and fit bounded by demonstrated capability? Yes, the form and fit of the MMX PlanetVac bound what is needed for the Ceres sample return mission.
5. "Environments bounded by demonstrated capability?" Yes, the environmental tests of the PlanetVac system bound the expected environments for the Ceres sample return mission.

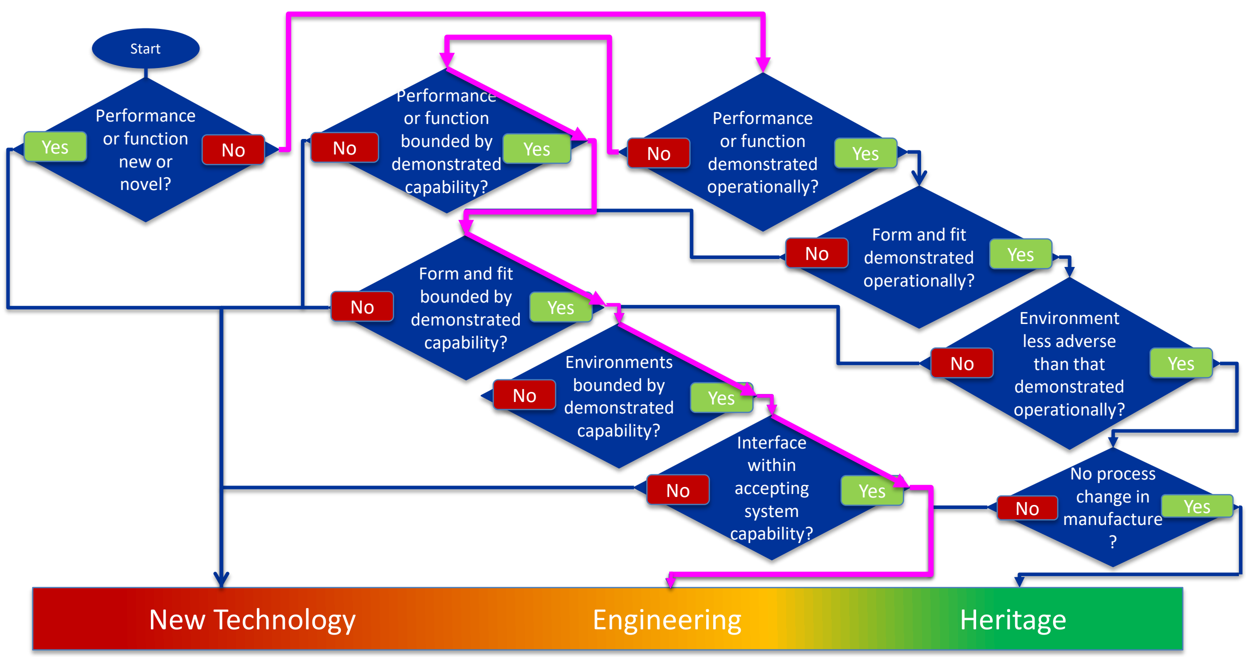

Figure D-2. Technology assessment flow chart (purple line) indicates that the sample acquisition system based on a derivative of the system developed for the MMX mission is standard Engineering.

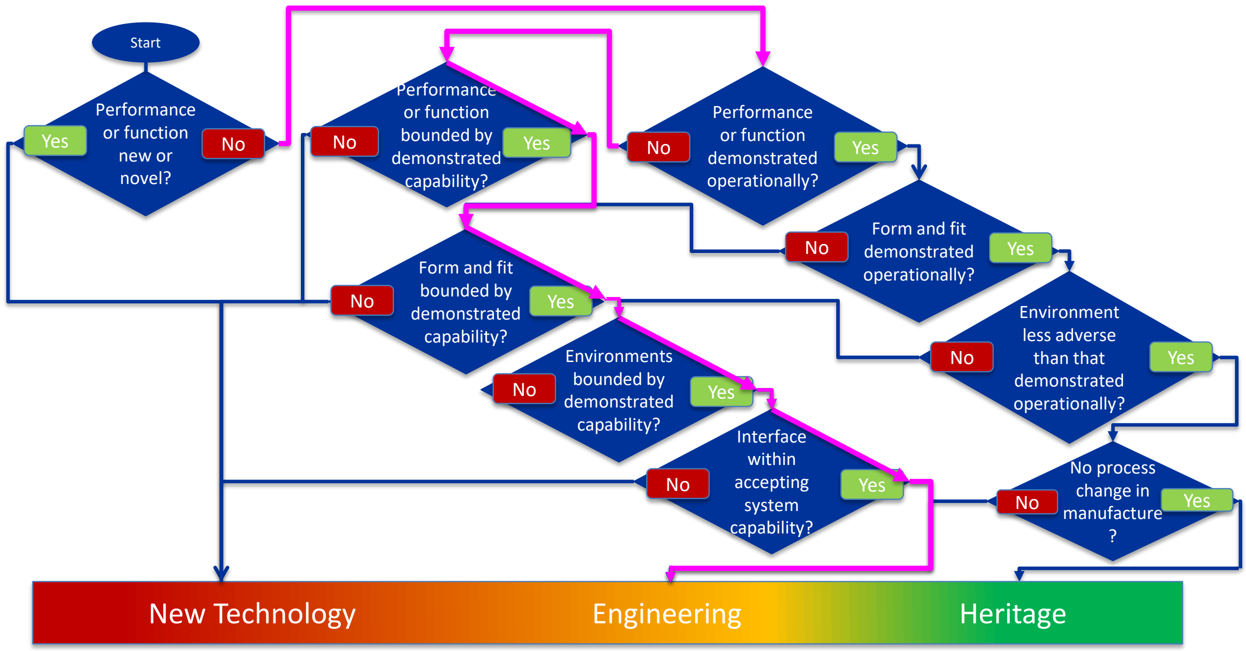

Figure D-3. Technology assessment flow chart (purple line) indicates that the system to transfer the samples into the SRC is standard Engineering.

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