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The *Plume Chaser* mission: Two-spacecraft search for organics on the dwarf planet Ceres

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Abstract

We present a mission concept designed at NASA Ames Research Center for a two-probe mission to the dwarf planet Ceres, utilizing a set of small low-cost spacecraft. The primary spacecraft will carry both a mass and an infrared spectrometer to characterize water vapor detected to be emanating from Ceres. Shortly after its arrival a second identical spacecraft will impact Ceres to create an ejecta "plume" timed to enable a rendezvous and sampling by the primary spacecraft. This enables additional subsurface chemistry, volatile content and material characterization, and new science complementary to the *Dawn* spacecraft, the first to arrive at Ceres. Science requirements, candidate instruments, rendezvous trajectories, spacecraft design and comparison with *Dawn* science are detailed.
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1. Introduction

The Herschel Space Observatory recently detected the presence of water vapor in observations of Ceres, bringing it into the crosshairs of the search for the building blocks of life in the solar system. We present a mission concept designed at NASA Ames Research Center for a two-probe mission to the dwarf planet Ceres, utilizing a pair of small low-cost spacecraft. The primary spacecraft, *Plume Chaser*, will carry a mass spectrometer and an infrared spectrometer to characterize the vapor. Shortly after its arrival a second identical spacecraft, *Plume Maker*, will impact Ceres to create an ejecta "plume" timed to coincide with *Plume Chaser* flying through the ejecta. This enables additional subsurface chemistry, volatile content and material characterization, as well as new science complementary to that of the *Dawn* spacecraft.

The search for organics and the assessment of habitability form the core of the mission's objectives, making it a natural follow-on to *Dawn*. We demonstrate that a pair

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of spacecraft inside a cost cap of $200 M can fulfill these objectives. Science requirements, candidate instruments, rendezvous trajectories, spacecraft design and comparison with science from the *Dawn* spacecraft are detailed. The low cost of the design enables the exploration of multiple solar system bodies in a reasonable timeframe despite budgetary constraints. The volume of the spacecraft enables launch to Geostationary Transfer Orbit (GTO) as a secondary payload, providing multiple launch opportunities per year.

2. Science objectives

2.1. Motivation for Ceres exploration

One of the driving questions in Planetary Science is *how life emerged in our solar system*, and *on which bodies can life or traces of life be found*. The exploration of organics, search for habitability and characterization of the environments of our solar system form the overarching theme of the current Planetary Science Decadal Survey. This search is not restricted to planets and their moons (e.g. Europa, Enceladus) but also dwarf planets and asteroids, many of which could contain the "organic ingredients for life" (National Research Council, 2011, p.94).

The Hubble Space Telescope detected as many as eight dark regions on Ceres, possibly craters, releasing 10^{26} molecules (~6 kg) of material per second (Li et al., 2006). Near IR spectroscopy suggests that Ceres is mineralogically homogeneous (Carry et al., 2008), however, far IR spectroscopy conducted by the Herschel Space Observatory found water vapor in the vicinity of two mid-latitude dark regions (Küppers et al., 2014, 2013). Thermal models suggest that liquid water could exist just below the surface (McCord, 2005) despite a mean surface temperature of 160 ± 53 K (Briggs, 1973). It is likely that these regions are not craters but ruptures in the crust or even cryovolcanoes, through which water vapor and other volatiles are sublimating. These emanations present an extraordinary opportunity to sample the interior of Ceres and characterize the organic sub-surface chemistry. Results could provide valuable insights into the origin of biologically important molecules and possibly evidence for life.

Ceres is also interesting from a solar system formation standpoint. It has several properties that differentiate it from planetesimals (e.g. Lutetia), fragments of larger bodies (e.g. Gaspra) and shards (e.g. Itokawa). It has a differentiated structure, with an anhydrous silicate core and water-rich mantle (Carry et al., 2008; Castillo-Rogez and McCord, 2010; Castillo-Rogez, 2011; McCord, 2005). The relatively rare CM chondrites are thought to originate from it (Rivkin et al., 2006) and these contain chondrules, water, and organic compounds (Pizzarello et al., 2006). The C-chondrite composition of Ceres is puzzling, given the basaltic crust and metallic core of Vesta, another large asteroid in the belt. One possibility is that despite containing almost half the mass of the asteroid belt, Ceres may have accreted after bodies such as Vesta; if true, it likely contains fewer radiogenic elements such as ^{26}Al (Atreya et al., 1989). Though the Ceres origin of the C-chondrites is not certain (Milliken and Rivkin, 2009), the possibility makes Ceres a high priority exploration target. Spared from the effects of the Late Heavy Bombardment (LHB) and located in a region dynamically unfavorable for planet formation, Ceres is a unique laboratory for studying the raw materials of planet formation, and linking its formation to that of the asteroids and comets.

From the characterization of organic compounds to providing information about dwarf planet formation, the *Plume Chaser* mission to sample the Ceres water vapor will answer questions about the history of biologically important molecules and contribute to our understanding of how life originated in the solar system. Information collected will also identify the source of the vapor, which might be ice sublimation, water evaporation from a subsurface ocean, or even volatile loss from a cryovolcano. The mission also enables the technical development of a means for future exploration of plumes in the solar system such as those at the South Pole of Enceladus.

2.2. Plume Chaser as a follow-on to the Dawn mission

The *Dawn* spacecraft, which recently arrived at Ceres, carries a suite of instruments designed to explore the surface and immediate sub-surface. These include visible cameras for global mapping, a visible/near infrared (NIR) spectrometer for mineralogy, and a gamma-ray and neutron spectrometer for characterizing elemental abundances, particularly of Uranium, Thorium and Potassium (Russell et al., 2004). These techniques can detect water within a meter of the surface and identify its form as hydrated minerals or water ice. Morphology and distribution of craters or pits similar to those seen on Vesta (Bland, 2013; Denevi et al., 2012; McSween Jr et al., 2012) will indicate the amount of water on Ceres, as well as whether the water vapor originates from craters, volcanoes or crustal rifts. Though *Dawn* has experienced issues with reaction wheels (Polanskey et al., 2014; Rayman and Mase, 2010), its instruments remain proven with a successful year in orbit around Vesta (Rayman and Mase, 2014; Russell et al., 2013). In light of this, a relevant question to address is the added benefit that a follow-on mission to Ceres could provide.

Dawn arrived in the vicinity of Ceres when the dwarf planet was close to aphelion. Maximum vapor activity has been observed at perihelion and therefore vapor emissions will be at their minimum during *Dawn*'s residence around Ceres (Rousselot et al., 2011). It is, however, possible that *Dawn* might be able to detect intermittent vapor release by catching ejecta on the horizon with the visible camera. If it can fly through one of these emanations after detecting it, *Dawn* might even be able to perform basic mineralogy on the ejecta using the visible/NIR spectrometer payload. However, a precise analysis of the solid and gaseous components of any ejecta emissions from the

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surface, the major window into the interior of Ceres, is something the spacecraft's instruments are not capable of. *Dawn* has no method for determining any information on the critical isotopic composition of the volatile components, which could provide insight into formation mechanisms of asteroids and comets, and the origin and history of biogenic elements. Questions such as the dust-to-water ratio of the ejecta, isotopic properties of the volatiles, and resulting implications will remain unanswered. A mass spectrometer is needed to capture and detect elemental and molecular species and spectrally analyze the constituents of the ejecta. The *Plume Chaser* spacecraft discussed in this paper will carry this important instrument.

Additionally, a controlled surface impact that can be observed will yield valuable information about Ceres' sub-surface chemistry and material strength. By imaging a location before and after impact, valuable information on the nature of the crust and its mechanical, chemical and geological properties can be obtained. This is information not available from a remote sensing approach. Collection of this data has many implications for constraining observations of other, similar dark objects such as comets and C-class asteroids. Furthermore, in the event that Ceres is not naturally emanating at the time of arrival, a controlled impact may allow sampling of the interior volatiles. Complementary observation of the impact by Earth-centered observatories such as Herschel and Hubble will also allow for calibrations that could aid future detections of similar events.*Dawn* was originally intended to carry a magnetometer, which was later descoped for budgetary reasons. Magnetometer payloads are relevant to an ejecta or plume centered mission concept; the Cassini magnetometer team were the first to report plumes on Enceladus (Dougherty et al., 2006; Leisner et al., 2006), inferred from water group ion cyclotron waves and later confirmed by the Cassini imaging system. Apart from measuring crustal magnetism, other interesting scientific questions include magnetic anomalies caused by thermal remnant magnetization (Hood and Schubert, 1980; Hood and Williams, 1989) and the detection of small-scale mini-magnetospheres, similar to those suggested to exist above certain lunar magnetic anomalies (Nayak et al., 2015, 2014). Miniaturized magnetometers have been developed to a high Technical Readiness Level (TRL) and proposed as payloads on lunar-bound small satellite missions (Garrick-Bethell et al., 2015a,b, 2013). Flight heritage for such an instrument would benefit a magnetometer payload on *Plume Chaser*, as well as future missions to Europa or Enceladus (Jonsson et al., 2015).

In addition to the significant scientific value of a follow-up mission to Ceres, there are budgetary and technology development benefits. The current exploration paradigm for planetary missions is one of multiple instruments and a budget in excess of a billion dollars (National Research Council, 2011, p. 242). The mission concept proposed here focuses on a different but complementary paradigm, dedicated to finding biologically important molecules by sending less complex and costly spacecraft to multiple destinations. For this reason, this work also details the compact spacecraft design (Section 4).

2.3. Science requirements

Table 1 summarizes the science objectives of the mission, listed in order of priority. Secondary objectives source from the decadal survey, ensuring good cross-correlation with data collected from *Dawn*.

To fulfill these objectives, a spacecraft carrying a three-instrument payload is proposed: a mass spectrometer, an infrared (IR) spectrometer, and a visual/near-IR camera. Future Phase A analysis will determine the feasibility of adding a magnetometer; this is not discussed further here. In addition to the science return of these instruments, responses from the three-axis stabilized attitude determination and control system (ADCS) can provide measurements of column density as it flies through the vapor ejecta.

2.3.1. Mass spectrometer

To fulfill the science requirements and maximize instrument return, a mass spectrometer optimized for high impact rates and a gas and plasma-rich background is desired. This instrument should be able to collect and analyze 10 nm–100 μm sized particles with mass spectra in the 1–2000 amu range. This makes it sensitive to water ice, minerals, metals, organic particles and mixtures of these components, optimal for detecting biologically important molecules. This wide range also permits characterization of the particle chemistry of individual ions like H+, C− and O−, as well as complex organics with heavier atomic masses.

An example of a suitable instrument is the Enceladus Icy Jets Analyzer (ENIJA), a reflection-based impact-ionization time-of-flight mass spectrometer developed by the University of Stuttgart for the detection of individual hypervelocity dust particulate impacts (Srama et al., 2015). Developed through miniaturization of flight-proven hardware from *Cassini* and *Stardust*, with a TRL of 4, the instrument has measurement modes for either cations or anions formed upon impact and can simultaneously determine the mass of detected grains. Further, it can capture and detect elemental and molecular species that might indicate a salty ocean source for the water vapor on Ceres, including Na, H_2O, H, C, O, $(H_2O)nNa+$, $(NaOH)nNa+$, $(NaCl)nNa+$ and $(Na_2CO_3)nNa+$ (Chester, 2000).

An important consideration for miniaturized spectrometers is the ionization speed. Collections by the spectrometer are produced by high-velocity impacts of individual particulate grains onto a metal target. To be ionized and measured, molecules must impact the detector at speeds typically in excess of $1\ \text{km s}^{-1}$. However, a stable repeating orbit for science collection will give *Plume Chaser* an orbital velocity in the 0.2–$0.3\ \text{km s}^{-1}$ range; in fact, the maximum achievable velocity from Ceres orbit is the escape

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Table 1
Science objectives.

Primary science objectives	
A.1	Search for evidence of organics in the Ceres vapor ejecta
A.2	Determine column water content and location of highest density
A.3	Determine elemental composition (C, H, O, N) of any carbon rich vapor particles
A.4	Characterize the particles in the ejecta for dissolved salts
Secondary science objectives	
B.1	Characterize the silicate dust in the plume and relate it to other solar system Objects, such as meteorites and comets
B.2	Characterize the mechanical, chemical and geological properties of the crust by Observing the impact site before and after impact
B.3	Look for surface compositional changes on the surface associated with venting; Characterize composition differences involving water or possible organics

velocity of 0.53 km s^{-1}. For this scenario, the natural ejection velocity of particles from the impact event can be leveraged for ionization. This velocity has been measured at 0.3–0.7 km s^{-1}; particles on ballistic trajectories are ejected with velocities exceeding 1 km s^{-1} (Küppers et al., 2014). If the miniaturized spectrometer is mounted on the nadir-facing surface at a 45° angle, combined with the velocity of the spacecraft, a large number of particles will impact the spectrometer with sufficient velocity for ionization at a measurement altitude of 200 km.

2.3.2. Infrared (IR) spectrometer

Good detection sensitivity for C–H and N–H bonds, which are indicative of hydrocarbons and other organics, is strongly desired for the mission's IR spectrometer. A primary science objective of the *Plume Chaser* mission is the detection and determination of the location of greatest vapor density (Table 1); this is possible by imaging H_2O emission lines at 1.89, 2, 2.7 and 3 μm wavelengths. Therefore the IR optical range must be at least 1.8–3 μm. The selected spectrometer should also be capable of measuring particle scattering in both emission and absorption modes, depending on the viewing angle, to yield more size and shape information on the ejected particles. Simulations of spectrometer observations are currently idealized; stray-light tolerances and sources of measurement error will be constrained during Phase A analysis.

An example of a capable instrument is an IR spectrometer being jointly developed by NASA Ames Research Center, Draper Laboratories and ThermoFisher Scientific. Currently at a TRL of 6, this actively cooled single-aperture spectrometer has dimensions of 0.8U for optics and 1U for electronics (where 1U denotes a volume of 1 L). The instrument has a programmable integration time between 500 μs and 5 s, consistent with expected observation durations, and an IR optical range of 1.6–3.4 μm and 0.15 μm resolution. This spectral band is sensitive to water in both gas and solid phases. The 1.89/2 μm bands are twice as sensitive as the shorter IR 1.38–1.5 μm bands, and the 2.7/3.0 μm bands are fifty times more sensitive. Further, the edge of the detection range, at 3.4 μm, allows good detection sensitivity for C–H and N–H bonds.

2.3.3. Visible wavelength camera

During the approach to Ceres, autonomous software that uses visual-based navigation techniques (Woffinden and Geller, 2007; Woffinden, 2008, 2004) will be used to guide the spacecraft into orbit, and subsequently toward ejecta emissions of interest. In addition to being part of the payload, the visible wavelength camera is therefore an integral part of the Guidance, Navigation and Control (GN&C) subsystem. Results from camera imagery taken concurrently with IR spectroscopy will improve guidance during subsequent passes, enabling the spacecraft to intersect the ejecta.

To allow ejecta column imagery and visual-based navigation, multiple cameras with a visible/near IR detection range are required, a minimum of two for *Plume Chaser* and one for *Plume Maker*. An example of a candidate instrument is the GomSpace NanoCam C1U visible wavelength camera, developed specifically for cubesatellites. It is currently at a mature TRL of 9, though additional testing will be needed for radiation shielding and applications beyond Low Earth Orbit (LEO). Its 3 MP CMOS sensor has 10-bit color and a 400–1000 nm capture spectrum. A 35 mm/*f*1.9 lens gives the camera a 9.22° field-of-view (FOV) and a resolution of <80 m per pixel from 650 km (GOMSpace, 2013), enabling it to fulfill all desired objectives. The placement of the cameras with respect to each other on *Plume Chaser* will be finalized with the Phase A design, and is currently baselined as to be on adjacent but perpendicular faces.

2.4. Development of mission objectives

To fulfill all science requirements, a two-spacecraft architecture with one orbiter (*Plume Chaser*) and one impactor (*Plume Maker*) is proposed. Both *Plume Chaser* and *Plume Maker* fall into the microsatellite category ($\leqslant$190 kg wet mass). At the time of this writing, the exact nature of the Ceres emanations is unknown. More information on the frequency and likelihood of vapor emanations will be available when *Dawn* has completed its exploration of Ceres; currently, there are three complementary possibilities that the proposed concept must be capable of performing within.

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1. *Vapor emanations from the surface of Ceres are common.* If true, all eight observed dark regions, and possibly others soon to be detected by *Dawn*, are capable of releasing ejecta containing water vapor. This raises the possibility of a permanent exosphere around Ceres, containing a varying but detectable density of molecules from beneath the surface. The spacecraft must be able to sample this tenuous exosphere. We refer to this as the **sniff** task. *Plume Chaser* must enter into low circular orbit (200 km) around Ceres and sample the exosphere both before and after the *Plume Maker* impact using the mass and IR spectrometers.
2. *Vapor emanations are not common on Ceres, but they are likely at perihelion.* If true, the trajectory must be designed to establish orbit around Ceres prior to perihelion. Given this condition, the spacecraft will likely encounter one or more vapor emanations from the surface. The lifetime of vapor molecules in the exosphere would be small; the spacecraft must be capable of lingering in orbit until outgassing is detected, then responsively maneuver to sample it. We refer to this as the **wait** task. Prepared with known locations from *Dawn*, the orbiter uses its visible camera payload to locate regions of naturally emanating vapor, then executes trajectories to fly through them and sample water vapor and organic content. *Plume Chaser* must arrive approximately 2–3 months prior to perihelion to collect data on the ramp-up of emissions and consistently revisit until approximately 1–2 months after perihelion. The impact by *Plume Maker* is timed to follow this collection period. Following the impact and subsequent observations, framing cameras should be present on-board to detect additional locations where vapor emanations are occurring. After initial reconnaissance *Plume Chaser* must maneuver into position to fly through as many of these locations as possible.
3. *Vapor emanations are rare on Ceres.* If true, Ceres water vapor detected by Herschel were a sporadic occurrence under extremely favorable conditions, and ejecta only emits from one or two locations on Ceres, likely the Piazzi region (21° latitude, 123° longitude) or Region A (23° latitude, 231° longitude) (Küppers et al., 2014, 2013). A trace exosphere or residue from prior outgassing may be beyond the detection limit of the instruments, and it is possible that no additional sublimation or eruptions could appear during residence around Ceres. *Plume Maker* will guarantee scientific return in this scenario. The impactor spacecraft must arrive at Ceres after the initial completion of the **wait** and **sniff** tasks and eject volatile material for *Plume Chaser* to fly through. We refer to the coordinated impact and emanated ejecta sampling as the **impact** task. Following impact observations, the orbiter returns to the **wait** and **sniff** tasks before departing Ceres for end of life (EOL).

In summary, the baseline mission design must be capable of performing all three tasks: **wait**, **sniff** and **impact**, and arrive at Ceres as close to perihelion as possible.

2.5. Observation window

When *Plume Maker* impacts the surface, *Plume Chaser* will fly through the ejecta, enabling the sub-surface science characterization goals of the mission. Determining the post-impact observation window is an important factor to enable this return. Fig. 1 shows the distribution of particles that will reach an orbital altitude of 200 km, plotted against time of flight (TOF) (after Melosh, 1989; Colaprete et al., 2012).

If *Plume Chaser* arrives at $t \leqslant 2$ min after impact (Fig. 1), a meaningful number of particles may not have reached the observation altitude. Further, particles with a velocity of $\leqslant$250 ms^{-1} do not make it to a 200 km altitude even after >10 min. Even when combined with a component of the spacecraft's velocity, these particles are at the edge of a miniaturized spectrometer's minimum required ionization speed. From Fig. 1 we observe that a majority of particles in the 750–1250 ms^{-1} range have crossed the 200 km observation altitude at $t \geqslant 6$ min after impact. Therefore, the window for *Plume Chaser* to rendezvous with the impact site at an orbital altitude of 200 km is between 2 and 6 min after impact. This will be the most stringent requirement driving further Phase A development. Earth occultations at the target Ceres orbit are expected, and will be deconflicted for rendezvous.

All three of *Plume Chaser*'s instruments will be located on the face opposite the propulsion system, allowing for the capture of imagery and particles as the spacecraft flies through the ejecta. The approach trajectory must keep the Sun behind the spacecraft to allow collection of spectral and visible backscatter from the vapor ejecta. After passing through, the spacecraft can rotate toward the anti-velocity vector to observe the Sun and collect transmission spectra. Simultaneous camera observations in backward and forward scatter will constrain grain sizes and concentrations. During additional orbits around Ceres, the spectrometer and camera can record spectral surface characteristics and high-resolution images that can complement and constrain *Dawn* observations, and help characterize potential future landing sites on Ceres.

The science traceability matrix, presented in Table 2, demonstrates how tentatively proposed candidate instruments might fulfill science objectives.

3. Spacecraft concept

This section details spacecraft design criteria that will enable a challenging mission of this nature. Pre-Phase A spacecraft requirements are discussed, and candidate components capable of fulfilling these requirements briefly detailed.

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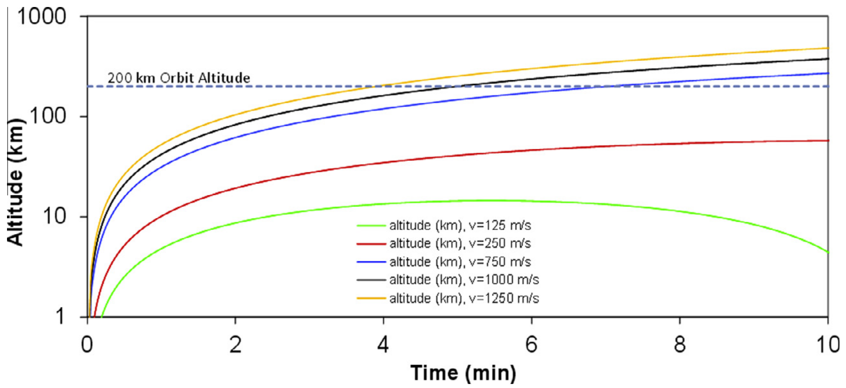

Fig. 1. Altitude versus time after impact: distribution of ejected particle velocities. Velocities are with reference to the Ceres surface. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

To meet the challenges of a low-cost small satellite mission, *Plume Chaser* is designed to fit within the ESPA Grande volume envelope (Maly et al., 2013) and is compatible with a 61 inch height Moog Engineering ESPA Grande ring adapter (Moog/CSA Engineering, 2012). *Plume Maker*'s avionics package, propellant tank and fuel mass are identical to that of *Plume Chaser*, though removal of the payload package reduces the dry mass and allows for additional propellant that can be used to increase the impact velocity. Fig. 2 shows the baseline design.

Both spacecraft must be able to sustain a high level of continuous power at increasing distance from the Sun while maintaining the capability for robust, responsive maneuvering and timely rendezvous with the ejecta. Power is supplied by solar arrays sized to the minimum solar intensity in Ceres orbit, calculated at 11.27% of the solar intensity at Earth (154 W/m^2). This results in an active solar panel area of 0.8 m^2 and solar array mass of 3.5 kg, of which 1 kg is the accompanying gimbal system. On departure from Low Earth Orbit (LEO), the spacecraft is expected to have 1 kW of power available. The low mass allows for margin to add additional panels should Phase A analysis determine the need for more power; for this analysis we specify that at least 200 W of power margin should be available to the bus at anytime during the mission, including at end of life (EOL).

In the target orbit, *Plume Chaser* is expected to experience solar eclipses; for the battery and electrical power system (EPS) on both spacecraft, a proven design with flight heritage is strongly preferred. In-house designs by NASA Ames can be tailored to the specific requirements of the mission. The EPS design is aimed at reuse of the heritage of the nanosat bus flown on GeneSat (Kitts et al., 2006), PharmaSat (Diaz-Aguado et al., 2009), Nanosail-D2 (Whorton et al., 2008), O/OREOS (Minelli et al., 2010), and SporeSat (Martinez et al., 2013). The Ames batteries are 0.5U in volume and 0.9 kg or less in mass each. Phase A design iterations on these systems will advance these designs to satisfy the demands of a propulsion system.

3.1. Attitude determination and control system (ADCS)

ADCS requirements are derived from performance data of previous interplanetary spacecraft that performed gravity-assist flyby maneuvers. Pointing requirements for the Cassini spacecraft during the Enceladus-5 flyby are used as a baseline to size the *Plume Chaser* ADCS (Goodson et al., 1998). The estimated worst-case external disturbance torque when flying through a plume was approximately 125 mN m at Enceladus (Sarani, 2010), well below *Plume Chaser*'s maximum angular momentum storage of 500 mN m per axis. In the Saturn system, Cassini required a pointing accuracy of $\geqslant 0.34°$ for flyby maneuvers.

Candidate systems to fulfill these requirements include the RWp-500 reaction wheels from Blue Canyon Technologies and an accompanying nano-star tracker (Blue Canyon Technologies, 2013; Greenbaum et al., 2014) for attitude control. The issue of restricted star fields at low Ceres altitude, and possible need for additional ADCS sensors, will be addressed during our Phase A design iteration. For reaction wheel de-saturation, candidate ADCS systems include the Busek µPPT-1 Micro Propellant Attitude Control System (MPACS) cluster (Mueller et al., 2008), which hosts pulsed plasma thrusters with flight heritage from FalconSat-3 (Hruby, 2003). Nanosatellite specific models to manage disturbance torques (e.g. Franquiz et al., 2014) can be applied to test the spacecraft's ability to meet all objectives, including the ability to maintain sufficient pointing for telecommunications; the details of that subsystem are discussed in Section 3.3.

3.2. Propulsion module

The spacecraft design includes a 3D printed titanium tank that doubles as propellant storage and radiation shielding, dramatically reducing structural mass and required shielding. The tank also contains the main avionics/payload module, which adds modularity and aids Assembly, Integration and Testing (AI&T). All payload

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Table 2
Science traceability matrix.

Science objectives	Capable Instrument	Instrument functional Requirements	Mission functional Requirements
A.1 Search for evidence of organics in the Ceres vapor	Mass spectrometer IR spectrometer	Physical capture and detection of elemental and molecular compounds	Fly through Ceres plume at closest approach altitude of 200 km Align instruments with velocity vector Collect up to 40 s of data from instruments
A.2 Determine column water	Mass spectrometer	– Same as A.1	
Content of the ejecta and Location of highest density	IR spectrometer NanoCam; S/C ADCS	– Spectral analysis of H_2O emission Lines at 1.89, 2, 2.27 and 3 um wavelengths	
A.3 Determine elemental composition of carbon rich particles in the vapor ejecta	Mass spectrometer IR spectrometer	Collect and compositionally analyze 10 nm to 100 um sized particles with mass spectra in the 1–2000 amu range	
A.4 Characterize ejecta particles for dissolved salts	Mass spectrometer IR spectrometer	Same as A.3	
B.1 Characterize the silicate dust in the vapor, relate it to other solar system objects	Mass spectrometer IR spectrometer	Same as A.1	No additional requirements
B.2 Characterize mechanical, chemical and geological properties of the crust by observing the impact site before and after impact	NanoCam IR Spectrometer	– 400–1000 nm spectrum – 35 mm/f 1.9 lens, 9.22 deg FOV – Resolution of <80 m per pixel	Point spacecraft camera at surface before and/or after flyby
B.3 Characterize surface compositional changes associated with ejecta release	IR Spectrometer	Spectral analysis of H_2O emission lines at 1.89, 2, 2.27 and 3 um wavelengths	No additional requirements

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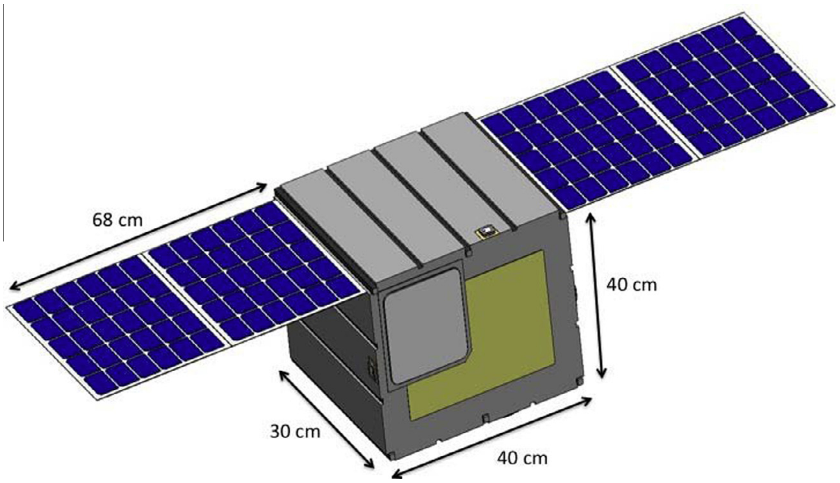

Fig. 2. Baseline design for *Plume Chaser* and *Plume Maker.*

instruments are located on the opposite end from the thruster to reduce interference. Desired power and thrust requirements for a propulsion module are 1200 s of specific impulse, power of 175 W, and an efficiency of at least 0.6 for a 120 kg propellant mass, resulting in 17.8 mN of thrust. The module should preferably be optimized for small satellite propulsion and be capable of firing for long periods of time (see Fig. 3).

A candidate system is the University of Michigan's CubeSat Ambipolar Thruster (CAT) engine (Sheehan et al., 2014). Planned spaceflight testing in 2015 will raise this system's TRL to 8 (Kolosa et al., 2014). It fits in one CubeSat form factor (1U) and the propellant tanks accommodate 25 kg of iodine propellant for every 5U. Various propellants are viable, although iodine is preferred for high efficiency (>60%) and molecular density (5 g/cm^3). The CAT engine can operate on 3–300 W of power and be fired continuously for weeks at a time. With a single gimbaled thruster, an efficiency factor of 0.6 and specific impulse of 1200 s, this engine would be able to meet all operational requirements, however for redundancy, two thrusters are planned on both spacecraft. Details on the plasma acceleration mechanisms within the engine are in the literature (Longmier, 2014).

3.3. Telecommunications

Technical challenges arise with regard to the feasibility of telecommunications for a small satellite at Ceres. By extrapolating assumptions from analysis of telecommunications with CubeSats in the Martian system (Babuscia et al., 2014) and assuming the use of two-arrayed 34-meter Deep Space Network (DSN) dishes and the Opportunistic Multiple Antenna per spacecraft scenario (Abraham and MacNeal, 2014; Abraham et al., 2015; Lluch and Golkar, 2014), we conclude that communication to Ceres orbit is feasible with an onboard antenna capable of transmitting at 20 dBi gain. However, most CubeSat systems at a TRL of 9 use simple low gain antennas (max 6 dBi) and operate in the UHF or S-Band with no navigation capability.

Recent developments point in the right direction, such as the DSN compatible X-band Iris CubeSat transponder (Duncan and Smith, 2014). We anticipate that the navigation capability of Iris and $\geqslant 0.34°$ pointing accuracy (Section 3.1) will allow all mission objectives to be met. Alternately, multiple antenna solutions could meet mission needs; a patch antenna array capable of 20 dBi gain with a mass of $\leqslant 0.5$ kg can close the link at Ceres range. Inflatable

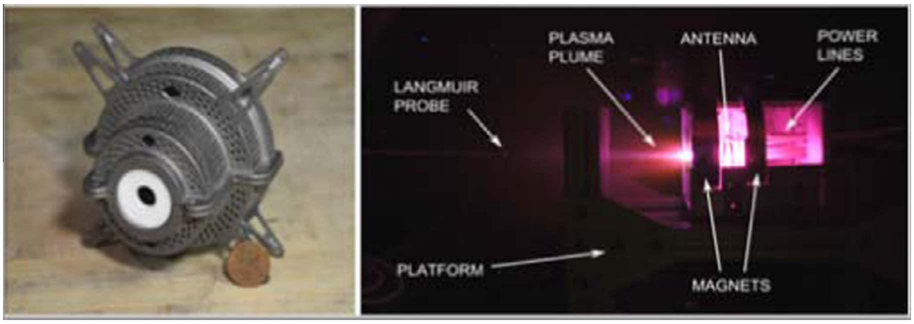

Fig. 3. Cubesat Ambipolar Thruster (CAT) engine (Aether Industries).

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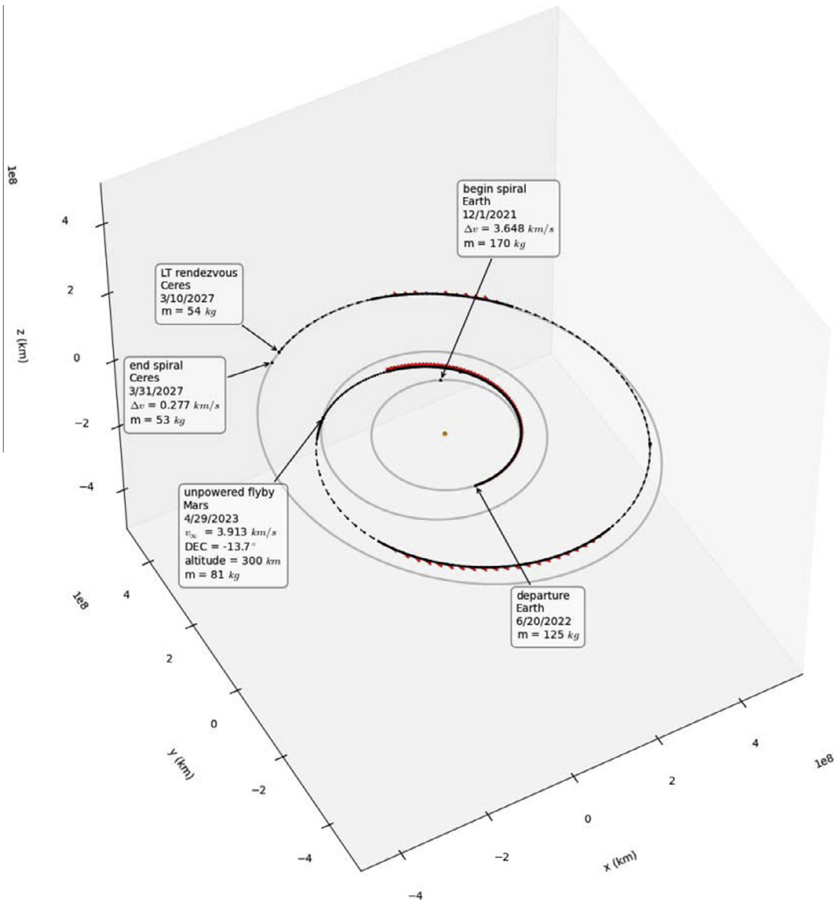

Fig. 4. Interplanetary trajectory for *Plume Chaser*.

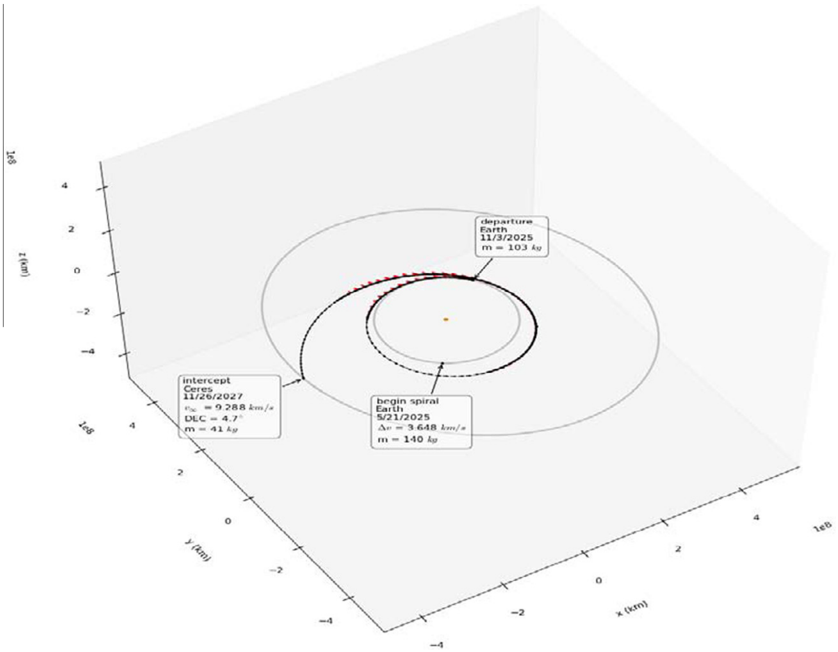

Fig. 5. Interplanetary trajectory for *Plume Maker*.

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antennas being developed at the Jet Propulsion Laboratory (JPL) offer a promising 30 dB gain with a 2 m parabolic dish for a stowed volume ⩽2U and a total mass ⩽2 kg (Ravichandran and Thanga, 2014). Therefore, there are multiple candidate solutions to close a link budget for the proposed mission. Details on instrument-specific data volumes and an initial link budget with assumptions are provided in the Appendix; to download the full buffer of expected science data, an estimated 6.2 h of DSN time will be required. The assumptions made for this initial analysis (Appendix), together with engineering and telemetry data volumes, will be matured further during Phase A design.

3.4. Trajectory design

Separating from a launch vehicle on its way to Geostationary Orbit (GEO) is an opportunity for total fuel (ΔV) and time-of-flight (TOF) savings. Since *Plume Chaser* and *Plume Maker* fall into the microsatellite category, they may be mounted either vertically or cantilevered, increasing the number of launch opportunities as a secondary payload. Specific interplanetary rideshare launch scenarios will be assessed in the Phase A stage of the mission design; in this work, trajectory design begins in a Geostationary Transfer Orbit (GTO) for both spacecraft.

Plume Chaser targets an arrival into a 200 km science orbit around Ceres between 1–4 months prior to the July 2027 Ceres perihelion. Other trajectory constraints include the use of solar electric propulsion, a maximum TOF of 5 years, an initial wet mass of between 140–200 kg and at least 200 W of power margin available. A propellant-power trade study found a relatively large window in January 2022 that meets these constraints. A finer search then targeted the maximization of available propellant after orbit insertion at Ceres.

For a departure epoch of 1 Dec 2021 with an initial wet mass of 170 kg and initial power of 1 kW, the baseline trajectory (Fig. 4) delivers 52.73 kg of mass to Ceres in 4.8 years (31 Mar 2027). After orbit insertion, 2.36 km s^{-1} of ΔV is available for science and EOL operations. The trajectory is detailed by orbit leg in Table 3. Due to the low gravity, stationkeeping consumes minimal fuel, leaving a 43 kg dry mass and 1.75 km s^{-1} of ΔV at the end of the 12-month nominal mission lifespan, enough to enable an extended mission.

The *Plume Chaser* trajectory utilizes a Mars Gravity Assist (MGA) to reach Ceres (Table 3). Since most of the vapor activity is centered on the mid-latitudes (Küppers et al., 2014, 2013), the target science orbit has an inclination of 21–25° to allow for maximum dwell time over these

Table 3
ΔV, propellant mass and duration for each trajectory leg for *Plume Chaser*.

Segment	Delta-V (km/s)	Propellant mass (kg)	Start date	End date	TOF (days)
GTO to Earth escape	3.65	45.32	12/1/2021	6/20/2022	201
Earth escape to MGA	5.11	43.97	6/20/2022	4/29/2023	313
MGA to Ceres SOI	4.73	26.73	4/29/2023	3/10/2027	1411
Science orbit insertion	0.28	1.25	3/10/2027	3/31/2027	21
Ceres science orbit	0.3	1.33	3/31/2027	3/31/2028	365
End of life	0.3	1.29	3/31/2028	4/21/2029	21
Total	14.37	119.89	Total TOF		6.4 years

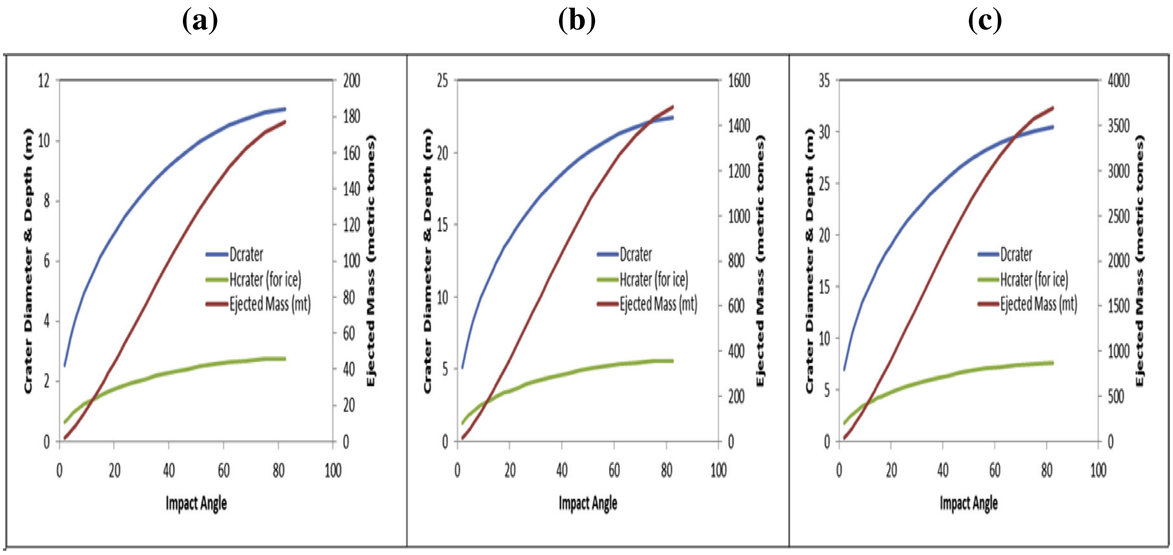

Fig. 6. Depth-diameter curves vs. impact angle for impact velocities of (a) 1 km s^{-1}, (b) 5 km s^{-1}, (c) 10 km s^{-1}. Diameter of the crater (D_{crater}, blue line), ejected mass in megatons (red line) and depth of the crater for an icy surface (H_{crater}, green line) are shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

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Table 4
ΔV, propellant mass and duration for each trajectory leg for *Plume Maker*.

Segment	Delta-V (km/s)	Propellant mass (kg)	Start date	End date	TOF (days)
GTO to Earth escape	3.65	37.32	5/21/2025	11/3/2025	166
Earth escape to *Ceres impact*	10.82	61.77	11/3/2025	11/26/2027	753
Total	14.47	99.09	Total TOF		2.5 years

Table 5
High energy Impact trajectory trade space with power at Beginning of Life (BOL), TOF, departure and arrival epochs, impact mass and impact energy shown.

Departure date	Mass (kg)	Power BOL (W)	TOF (year)	Arrival date	Impact speed (km/s)	Impact mass (kg)	Impact energy (MJ)
5/1/2025	180	1000	1.9	10/9/2027	11.1	44.5	2748.3
5/1/2025	170	1000	1.9	10/9/2027	11	43.6	2661.5
5/21/2025	170	1000	1.8	10/8/2027	10.5	43.6	2424.4
5/31/2025	180	1000	1.8	10/9/2027	10.3	44.5	2358.4
5/21/2025	160	1000	1.9	10/8/2027	10.3	42.7	2259.6
6/10/2025	180	1000	1.7	10/9/2027	10	44.5	2248.4

regions. Observations from *Dawn* will help narrow the focus of future design iterations. Fuel will be held in reserve to execute a hyperbolic escape trajectory should planetary protection concerns arise.

Plume Maker's trajectory design faces different challenges. This spacecraft must arrive at Ceres with sufficient mass and velocity to excavate a crater no less than 10 m wide and 3 m deep. Fig. 6 presents the crater depth-diameter curves for a 40 kg impactor with an impact velocity of 1 km s^{-1}, 5 km s^{-1} and 10 km s^{-1}. The impact angle bounds the trade space for the design of the trajectory from Earth.

Similar requirements of 50 W of power to the bus at all times and a maximum TOF of 5 years are levied, with the additional constraint to arrive 3–5 months after the July 2027 perihelion. This allows *Plume Chaser* time to conduct the **sniff** and **wait** mission sets; a thorough operational understanding of the spacecraft during this time will help ensure rendezvous within the 2–6 min post-impact observation window. Additionally, for planetary protection, a hypervelocity impact must vaporize the impactor and kill any microbes that may have accompanied the spacecraft from its origin (NASA, 2005). A lower limit of 3 km s^{-1} has been proposed to fulfill this requirement (Air Force Institute of Technology, 1991; Glasstone and Dolan, 1977); therefore *Plume Maker* must arrive at Ceres with at least this velocity in the local frame.

We performed a trajectory trade study seeking to maximize impact energy and minimize time of flight. Assuming a co-manifested launch with *Plume Chaser* for cost reasons, *Plume Maker* will remain in GTO until departure on a direct intersection path with Ceres. However, since it is possible that a launch opportunity closer to the departure date may be attainable, this pre-Phase A analysis does not consider GTO station-keeping costs. For a GTO departure epoch of 21 May 2025 with an initial wet mass of 140 kg and initial power of 1 kW, the baseline trajectory delivers 40.9 kg of impact mass to Ceres in 2.1 years, with an impact date of 26 Nov 2027. As designed, this trajectory creates an impact velocity of 9.3 km s^{-1} (Table 4, Fig. 5), generating an impact energy of 1.76 GigaJoules (GJ).

It has been proposed that the ice on Ceres may be unstable on the surface and down to a depth of a few tens of meters below a regolith layer (Castillo-Rogez and McCord, 2010). The baseline impact trajectory (Fig. 5) is very likely to exceed the minimum required crater and excavate material from beneath regolith tens of meters deep. However, if greater velocities are deemed necessary, the trajectory design space does include the potential for impact energies as high as 2.75 GJ and velocities up to 11.1 km s^{-1} (Table 5). Flexibility in the trajectory trade space is also important should issues with lost thrust due to safe mode entry arise for either spacecraft during flight, as was the case for *Dawn* (Rayman and Mase, 2014).

4. Conclusions

The *Plume Chaser* – *Plume Maker* mission concept presents a low-cost architecture to explore the dwarf planet Ceres, investigate the content of water vapor detected around its surface and characterize possible biologically important molecules. Results are applicable to open questions regarding the formation of the asteroid belt, origin of volatiles and the future habitability of Ceres. While *Dawn* will characterize surface features on Ceres in 2015, *Plume Maker* and *Plume Chaser* would be the first spacecraft to sample emanated water vapor ejecta, and create an impact cavity that facilitates study of sub-surface chemistry and interior composition.

Several details remain in flux or undetermined at this stage in the design, and will be rigorously addressed during future Phase A design iterations. These include assumptions made regarding telecommunications, detailed simulations to constrain *Plume Chaser*'s spiral into low-altitude Ceres orbit, effects of stray light on spectrometers and sizing of the solar arrays to ensure comfortable power

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margins. While the primary goals of this mission are scientific, secondary goals of opportunity include the validation of critical technologies for use on a small-satellite platform, including cubesat-based propulsion engines, miniaturized spectrometers and modular 3D-printed titanium propellant tanks. Rough order of magnitude (ROM) estimated mission costs developed using a "bottom-up" approach, based on NASA Ames Research Center's small satellite experience, put the total mission cost inside a horizon of \$200 M, including development, integration, launch and operations. This cost figure results in an annual investment level of less than \$30 M and is Discovery Class in funding profile, which bears particular relevance to the future of low-cost, repeatable solar system exploration.

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Appendix A. *Technical specifications*

Table 6
Telecommunications: downlink and uplink budget, with assumptions.

		Downlink	Assumptions	Uplink	Assumptions
Tx power	dBW	10	Aerospace corporation power amplifier	42.4	17.4 kW
Waveguide loss	dBW	−0.5		−0.5	
Antenna gain	dB	20		72.41	70 m DSS
EIRP		29.5		114.3	
Frequency, GHz		8.4		7.1	
Rx ant. gain	dB	73.87	70 m DSS	20	
Path loss	dB	−283.3		−281.8	
Data rate	bps	600	Min telemetry data rate 62.5 bps	1000	Min command data rate 1000 bps
Pointing loss	dB	−2.1		−2.1	
System noise temp	K	25.58		340	
Eb/No received	dB	4.7		23.6	
Eb/No required	dB	1.8	LPDC coding	9.6	Uncoded
Margin		2.9		14	

Table 7
Pre-phase a mass, volume and power budget.

Subsystem	Description	Volume (U)	Mass (kg)	Average power (W)	TRL
Payload	See Sectoin 2.3	8.3	3.7	−12	–
Propulsion (engine)	CubeSat Ambipolar thruster (CAT)	1	1	−175	4
Propellant tank	3D printed titanium tank	24	11.5	0	4
Propellant	Iodine	24	90.7	0	3
Power generation	Solar arrays	1.4	4.5	1000	1
ADCS/GNC	BCT wheels and star-tracker, Busek uPPT thruster	4	5	−20	7
EPS-C&DH	Space micro proton lite 200 k and Ames EPS board	0.5	0.5	−1.8	7
Radio	IRIS DSN compatible transponder	0.5	0.5	−15	2

Table 8
Science instrument mass and power budget.

Payload description	Data volume (kb)	Volume (U)	Mass (kg)	Average power (W)	TRL
ENIJA	72	6	2.2	6	4
Ames-draper IR spectrometer	48	1.8	1.3	2	4
NanoCam C1U visual camera	13,200	0.5	0.2	4	9

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