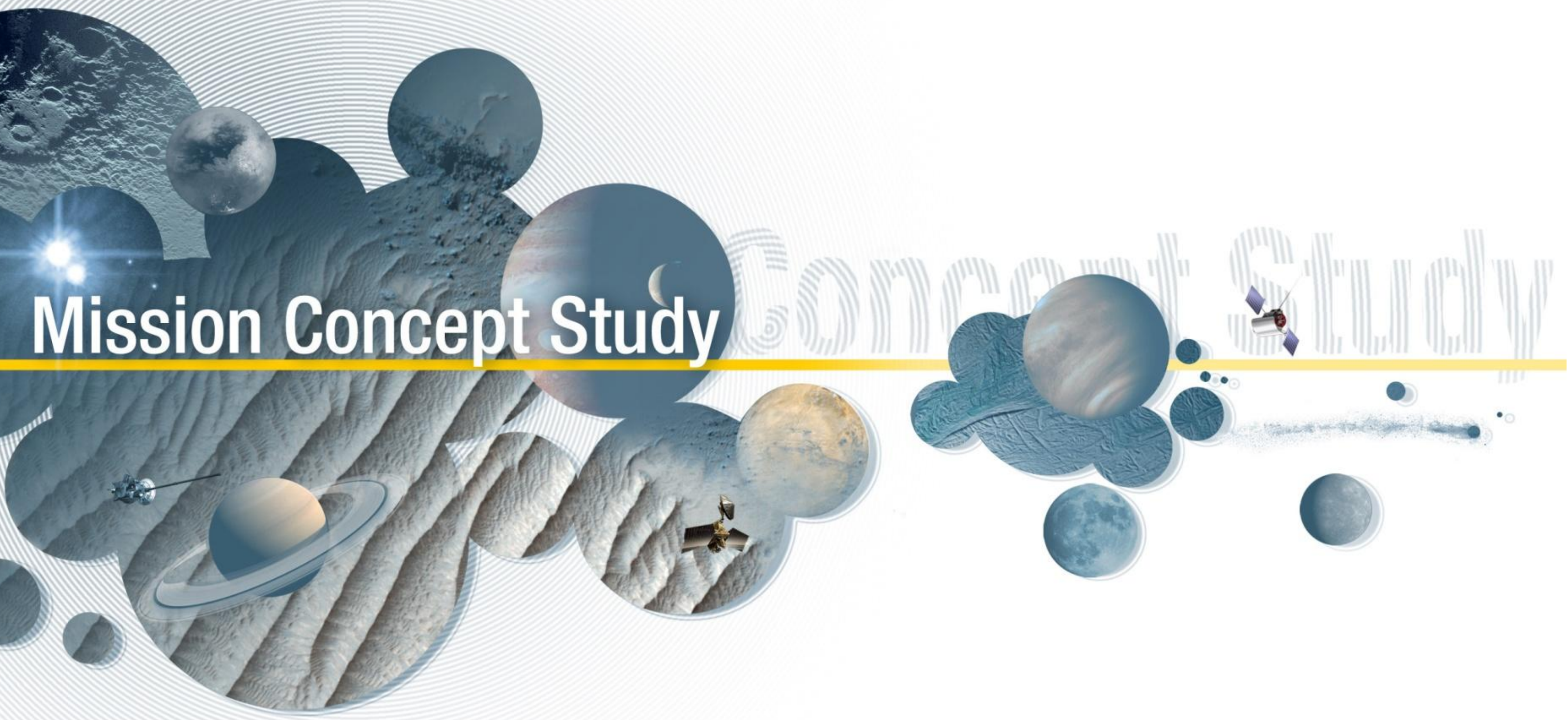
National Aeronautics and Space Administration



Comet Surface Sample Return (CSSR) Mission

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Planetary Science Decadal Survey

Mission Concept Study: Summary of Final Report

Appendices

A. Acronyms

Executive Summary

The National Academy of Science's Decadal Survey (*New Frontiers in the Solar System: An Integrated Exploration Strategy*, 2003) recommended that NASA develop a medium-class mission to return a comet surface sample to Earth for laboratory analysis. NASA tasked the Applied Physics Laboratory to refine the concepts described in the Decadal Survey. As stated in the task guidelines,

> The study results will include a pre-phase A fidelity plan to implement the mission concept, evaluating the cost, schedule and risk. A Science Definition Team (SDT) will be appointed by NASA Headquarters to work with mission designers and technologists. The study will take recent activities into account, assess opportunity and technological readiness, and provide estimated costs.

The study began in July 2007 with the identification of an SDT to guide the concept development. The SDT re-examined the scientific justification for a CSSR mission, explicitly considering the new knowledge gained during recent spacecraft missions to comets. The results from the Deep Impact mission in 2005, in combination with studies of fragmenting comets during the past two decades, strongly suggest that sampling the surface of a cometary nucleus should be much easier than previously thought. And the bounty of intriguing, new scientific results from the Stardust mission justifies taking the next logical step to a CSSR mission that would provide a more representative sample of cometary matter. In summary, the SDT reaffirms the Decadal Survey's statement that

> No other class of objects can tell us as much as samples from a selected surface site on the nucleus of a comet can about the origin of the solar system and the early history of water and biogenic elements and compounds. Only a returned sample will permit the necessary elemental, isotopic, organic, and mineralogical measurements to be performed.

The SDT found that a CSSR mission with a single, focused objective to return approximately 500 cc of material from the nucleus will provide a major scientific advancement and will fulfill the intent of the Decadal Survey's recommendation for a New Frontiers class mission. However, the mission must be designed to prevent aqueous alteration of the sample, which would jeopardize the fundamental scientific objectives.

With guidance from the SDT, the engineering team developed several CSSR mission concept options. The SDT determined that the return of a sample from *any* comet was of sufficient value to justify the mission and that the final choice of the target comet should be based on criteria that would reduce mission cost and risk. The initial review indicated that all potential targets are challenging from a mission design perspective. But some good candidates were identified, and we selected comet 67P/Churyumov-Gerasimenko [C-G] for this study, at least in part because the nucleus of this comet is expected to be well characterized by the Rosetta mission in the 2014 time frame, well in advance of the rendezvous and landing discussed here. The primary architecture of the mission is driven by the need to navigate in the vicinity of the comet, descend to the surface of the nucleus to acquire a sample, and return the sample to the Earth without altering the material. Our study found that two propulsion technology options are available to accomplish these objectives: a conventional chemical propulsion option and a solar electric propulsion (SEP) option, the latter of which has now been demonstrated by the DS1 and Dawn missions. Mission concepts were constructed around these two options.

The technologies for either mission option are sufficiently mature that the choice between them can be based on the difference in cost and risk.

Scientific Objectives

Science Questions and Objectives

The fundamental (Group 1) CSSR mission scientific objectives are as follows:

- Acquire and return to Earth for laboratory analysis a macroscopic (at least 500 cc) sample from the surface of the nucleus of any comet.
- Collect the sample using a “soft” technique that preserves complex organics.
- Do not allow aqueous alteration of the sample at any time.
- Characterize the region sampled on the surface of the nucleus to establish its context.
- Analyze the sample using state-of-the-art laboratory techniques to determine the nature and complexity of cometary matter, thereby providing fundamental advances in our understanding of the origin of the solar system and the contribution of comets to the volatile inventory of the Earth.

The baseline (Group 2) CSSR mission scientific objectives will also provide revolutionary advances in cometary science:

- Capture gases evolved from the sample, maintaining their elemental and molecular integrity, and use isotopic abundances of the gases to determine whether comets supplied much of the Earth’s volatile inventory, including water.
- Return material from a depth of at least 10 cm (at least 3 diurnal thermal skin depths), if the sampled region has shear strength no greater than 50 kPa, thereby probing compositional variation with depth below the surface.
- Determine whether the sample is from an active region of the nucleus because those areas may differ in composition from inactive areas.

Science Traceability

Science Traceability Matrix

Science Objective	Measurement	Instruments	Functional Requirement
Floor Objective #1: Return a macroscopic (≥500 cc) sample from the surface of a comet to Earth with no aqueous alteration		(A) Sample Acquisition System (SAS) capture, maintain and hold sample (B) Temperature and pressure sensors together with Sample Monitor Cameras (SMCs) monitor sample during capture and return to Earth (C)Sample Return Vehicle (SRV) transports SAS and sample to Earth	Maintain the sample at ≤263 K (i.e., ≤−10°C) in order to prevent aqueous alteration and possibly retain some of the water ice in the sample
Floor Objective #2: Determine the geomorphological context of the sampled region	Global images of the comet nucleus	Geomorphology determined by suite of 3 cameras: (1) Narrow field-of-view, visible light camera (NFV) (2) Wide field-of-view, visible light camera (WFV) (3) Thermal infrared camera (IRC)	Image the entire sunlit nucleus at a resolution better than 1 m and perform visible characterization of the sampled region with a spatial resolution better than 1 cm
Floor Objective #3: Maintain samples in a curation facility without degradation for more than 2 years		NASA JSC’s existing Curation Facility, upgrading astromaterials analytical laboratories to handle frozen samples	
Baseline Objective #1: Capture gases evolved from the sample, maintaining their elemental and molecular integrity		Separate (flask) chamber incorporated in SAS	
Baseline Objective #2: Return material from a depth of at least 10 cm (≥3 diurnal thermal skin depths) if the sampled region has a shear strength no greater than		SAS drill & capture design	

High-Level Mission Concept

Overview

MISSION OVERVIEW

After the mission spacecraft travels to Comet 67P/C-G and collects images to characterize the comet's nucleus, a sample return vehicle (SRV) will return ≥500 cc of material to Earth for laboratory analysis. The payload will collect the samples using 4 drills. Samples will be maintained during the return trip at ≤ –10°C. After SRV recovery, the samples will be transferred to Johnson Space Center astromaterials analytical laboratories that will have been upgraded with capabilities to store, analyze and characterize frozen samples. The reliance on heritage spacecraft design wherever possible is intended to minimize risk. The following critical technologies will require development to Technology Readiness Level (TRL) 6:

- Ballistic-type sample return vehicle (SRV)
- UltraFlex solar array
- Sample Acquisition System (SAS)
- NASA's Evolutionary Xenon Thruster (NEXT)-based ion propulsion system
- Height and Motion System (H&MS)

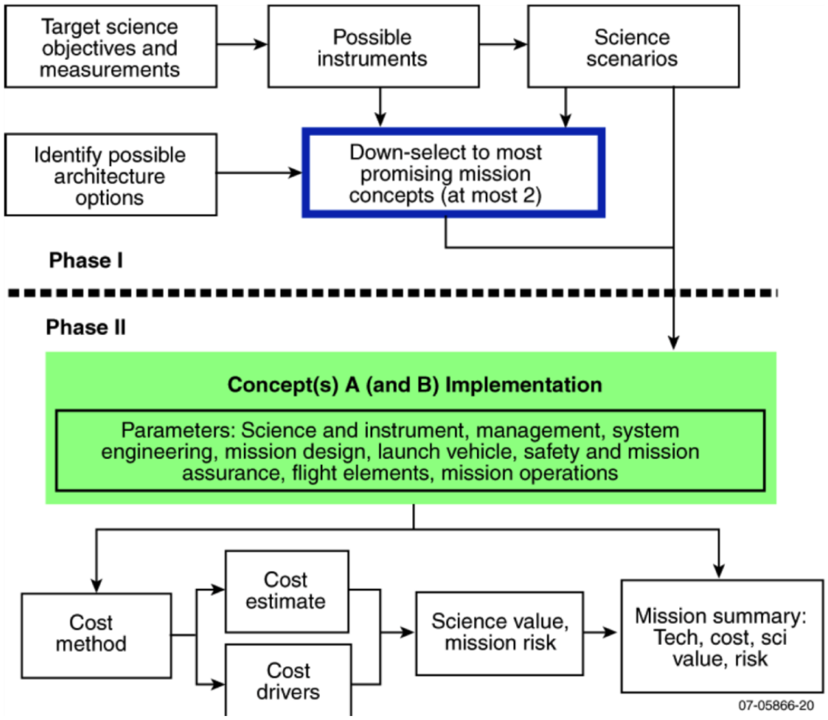
The two mission options are compatible with EELV-class launch vehicles as follows:

- Conventional chemical propulsion option: Atlas V 551 (3920 kg)
- Solar electric propulsion (SEP) option: Atlas V 521 (1865 kg)

The anticipated duration of Phases A–D for either option is 5 years. Phase E duration is 13–14 years, including a 2-year curation activity after return and recovery of the sample return vehicle, depending on the option.

Concept Maturity Level

The Comet Surface Sample Return (CSSR) Mission Study was conducted in two phases as shown in the figure below. During Phase I from July through October 2007, major trades affecting mission architectures were identified and evaluated. The two preferred design options were examined at a CML-4 level during Phase II which ran from November 2007 through March 2008.



Technology Maturity

Execution of the CSSR mission requires some system developments that were novel in 2007 for NASA space missions and lacked a history of development and qualification within the space community. Specific technology development tasks were recommended during the formulation phase of a CSSR mission. The four primary components of concern with TRL less than 6 are (1) the SAS, (2) the SRV, (3) the NEXT ion-propulsion engine and its ancillary equipment, and (4) the H&MS. The requirements and technology development plan for each component are described below.

<u>SAS</u>. The SAS must perform a number of separate individual mechanical operations that are all in series with one another. The concerns raised by these requirements are two:

1. The SAS must engage its sample gathering mechanism with the comet, collect the sample, transport the sample to the sample-holding canister cells in the SRV, seal the sample cells, seal the SRV door, and ensure that it does not interfere with the release of the SRV from the spacecraft at the time of reentry to Earth.
2. Because of the large range of uncertainty in the physical nature of the surface of the comet—with hypotheses ranging from a loose, unconsolidated material with a consistency of powder to a hard surface of solid ice--the sample mechanism must deal with these two extremes or anything in between, including a mix of ice and rock, and still reliably return a minimum amount of the sample.

Both concerns can be addressed by a technology maturation and risk reduction project that starts early in Phase A. This work will increase the system maturity to a level sufficient to pass review at the time of confirmation (i.e., bring the system to a TRL of 6 or better). Also, it will reduce the overall developmental risks to ensure that a fully qualified sample acquisition system is ready for the CSSR integration and test phase.

The following SAS-related development activities carried out during the first 23 months of the program will demonstrate that the sample acquisition devices (drills) can collect samples over the range of materials, temperatures, and dynamic loads that the system might experience during operation at the comet:

1. Construction of prototype sampling drills with candidate materials, coatings, and lubricants. The prototype drills will be subjected to a variety of tests with simulated comet surface materials over the full range of expected environmental conditions at the comet.
2. Construction of a prototype sampling mechanism, including the sample drills, prototype SRV interior layout with sample holding cells, and the SRV cover. Tests of this assembly will demonstrate that the samples from the drills can reliably be transferred to the sample cells in the SRV, the cells can be sealed, and the SRV cover assembly locked in place. These tests must also be done in the appropriate environment expected at the sampling site.

SRV Development. The CSSR sample return vehicle is a scaled version of the Mars Sample Return Earth Entry Vehicle (MSR EEV) that has been under development by LaRC since 1999, modified to accommodate the CSSE-specific requirements to receive the samples and to maintain thermal control. The MSR EEV design objective is a low-risk, robust, and simple operations approach to safely return samples to Earth. Its entry is completely ballistic, relying on no parachute or other deployments, which simplifies entry operations and reduces overall mission risk. The MSR EEV is passively stable in the forward orientation and passively unstable in the backward orientation, making it possible for the vehicle to orient itself to nose-forward under all separation and entry contingencies, including tumbles. CSSR intends to leverage heavily on the MSR EEV's technology development and key features.

Unlike the MSR EEV, the SRV's thermal design must keep the samples cold throughout the cruise phase of the return as well as reentry and landing. It must also collect volatiles that may evolve from the sample after capture and during the return to Earth.

SRV technology risk can be significantly reduced by an early technology maturation project. Phase-A risk reduction activities will concentrate on proving both the basic design of the SRV and on the SRV interior's capabilities to accommodate and protect the samples. The design will be refined. and the appropriate thermal protection materials will be selected for the re-entry conditions of this mission. Interface issues between the spacecraft, sampler, and SRV will also be resolved during Phase A. Analyses will also be performed during Phase A to assess design robustness. If the analyses and MSR EEV data are insufficient, additional drop and impact tests will be performed during Phase B.

In addition to the above activities, mission engineers will conduct independent entry analyses using state-of-the-art, flight-validated codes (POST, LAURA, DPLR) to ensure an accurate end-to-end simulation of SRV entry, descent and landing. Entry simulations, ballistic range and wind tunnel testing, and computational fluid dynamics (CFD) analyses will evaluate trajectory, aerodynamic and aeroheating solutions through all flight regimes.

NEXT Propulsion System Development. NASA's Glenn Research Center (GRC) and its industrial partners have been developing the NEXT engine and ancillary devices required to produce a complete propulsion system within the In-Space Propulsion Technology (ISPT) project of the NASA Planetary Science Division. When the CSSR final report was published, key components remained to be developed, and significant challenges in such areas as thermal design remained. The NEXT program was planning complete technology development to TRL 6 during 2008, with major system integration test and multi-string testing planned for early 2008.

The thruster life capability required for the CSSR mission will not be demonstrated by test under 2010 or later. If thruster capability cannot be validated to the required level, mitigation strategies include incorporation of a second thruster operating serially with the first thruster (similar to the Dawn mission) and inclusion of a third thruster string. The latter would increase mission performance as well.

Ion propulsion system components must be developed and tested thoroughly prior to delivery. Additionally, the system will be tested as an integrate propulsion system prior to spacecraft I&T.

H&MS Development. The CSSR spacecraft can use its inertial guidance sensors and algorithms to orbit and approach the comet with high accuracy. However, the actual sampling interval requires precise control of the height and relative motion of the spacecraft at the comet surface. A number of individual components exist and have demonstrated the performance levels required for this portion of the mission. However, an integrated system of algorithms, sensors, actuators, and controls has not been demonstrated through a full simulation of sampling activity. Confidence in this functionality cannot be gained by testing this system piecemeal, meaning that a fully integrated test is needed. Since these tests can be complex to set up and run, an early technology maturation activity will be important to reduce the overall mission risk.

Key Trades

A number of trades were analyzed to ensure that mission objectives could be accomplished within the cost cap:

- Payload composition, including inclusion of non-sample-related instruments
- Number and depth of comet samples
- Temperature and pressure at which samples would be maintained
- Sampling mechanisms
- Possible comet targets
- Mission design, including time spent characterizing the target comet prior to sampling

For the SEP mission option, a key trade is solar array (input power) size versus number of operating thrusters. As the mission and science objectives are defined in detail, this trade can be performed to balance mission performance and cost. The selected 1+1 system is the NEXT system that minimizes cost. Adding a thruster string for a 2+1 system, permitting simultaneous operations of two thrusters, would provide for additional payload performance for increased propulsion subsystem cost. Array size can then be tailored to further balance performance against cost.

The SAS concept is one of many options. If uncertainty in surface properties can be reduces, the SAS may be simplified and other design options considered (e.g., “stick pads” that could pick up surface material).

The SRV trade between MSR-EEV and Stardust types depends on a detailed thermal analysis. If the existing Stardust design or its Genesis or Hyabusa derivatives can be shown to satisfy thermal and other requirements, cost and risk savings might accrue.

Further detailed analysis of the risks and benefits of inertial landing, could eliminate the requirement for a costly and risky Height and Motion System (H&MS).

Technical Overview

Payload: Optical Instruments Description

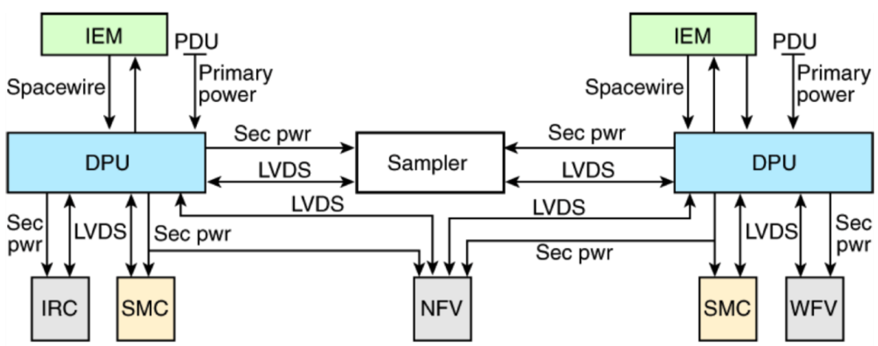
Intensive monitoring of the nucleus is required to create a detailed shape model, determine its rotational properties, map surface features, measure albedo variations, create a thermal map, and search for sources of activity. All of these tasks can be accomplished with only three instruments: a narrow field-of-view, visible light camera (NFV); a wide field-of-view, visible light camera (WFV); and a thermal infrared camera (IRC).

The CSSR sample acquisition system (SAS) is comprised of two pairs of drills, each pair containing one short and one long drill. During an acquisition sequence, both the short and long drills within a single pair turn slowly, moving material up the shaft while they penetrate the surface to a depth of 100 mm and 150 mm, respectively. Assuming each drill is filled to capacity, the sampling would yield 250 cc and 380 cc, respectively, of comet surface material and would provide the potential for measuring differences between the samples collected from the two depths. The second pair of drills provides redundancy in case the first pair fails, as well as an opportunity for collecting more samples if the original pair succeeds. A pair of sample microcams (SMC1 and SMC2) will be used for optical verification that the drilling operation collected the required volume of sample material.

The figure below lists the key instrument characteristics. The Long-Range Reconnaissance Imager (LORRI) on the New Horizons spacecraft [Cheng et al. 2007] was designed for a long-duration outer solar system mission, and the requirements are very similar to those of CSSR. The two primary imagers use LORRI focal plane units (FPUs), i.e., charge coupled device (CCD) detectors and their associated electronics boards. These can be built to print.

Sensor	FOV (deg)	Resolution (radians)	Dynamic Range	Mass (kg)	Size (cm)	Power (W)	Sens (Wm^{-2})
NFV	1.2	30×10^{-6}	10^3–10^6	2.5	10×10×25	2	8×10^{-15}
WFV	20	5×10^{-4}	10^3–10^6	2.0	8×10×20	2	2×10^{-15}
IRC	30	5×10^{-3}	10^2	2.5	10×10×15	5	ΔT=3 @ 170 K
SMC1	30	1×10^{-3}	10^3–10^4	1.5	10×10×15	5	2×10^{-14}
SMC2	30	1×10^{-3}	10^3–10^4	1.5	10×10×15	5	2×10^{-14}
Temp	2 + 2 Thermistors		16 b/s	0.1	1×1×1 ea	0.1	0.1 K
Press	2 + 2 MEMS		16 b/s	0.1	1×1×1 ea	0.1	0.01 bar
DPU1	Rate is per sensor		1.3 Mb/s (Data Rate)	2	30×30×51	13 (40 peak)	N/A
DPU2	Burst rate per image		1.3 Mb/s (Data Rate)	2	30×30×51	13 (40 peak)	N/A

The figure below shows the payload block diagram:



Instrument Table, NFV Instrument

Item	Value	Units
Type of instrument	Imager	
Optics design	Reflective Richey-Chretien design	
Detector type	CCD, New Horizions	
Size/dimensions (for each instrument)	10 cm x 10 cm by 25 cm	
Instrument mass contingency	NPIR	%
Instrument mass **with** contingency (CBE+Reserve)	2.5	Kg
Instrument average payload power contingency	NPIR	%
Instrument average payload power **with** contingency	2	W
Instrument average science data^ rate contingency	NPIR	%
Instrument average science data^ rate **with** contingency (inferred)	1300	kbps
Instrument Fields of View (if appropriate)	1.2	degrees
Pointing requirements (knowledge)	NPIR	degrees
Pointing requirements (control)	NPIR	degrees
Pointing requirements (stability)	NPIR	deg/sec

Instrument Table, WFV Instrument

Item	Value	Units
Type of instrument	Imager	
Optics Design	Refractive, radiation tolerant glass optics	
Size/dimensions (for each instrument)	8cm x 10cm x 20cm	
Instrument mass contingency	NPIR	%
Instrument mass **with** contingency (CBE+Reserve)	2.0	Kg
Instrument average payload power contingency	NPIR	%
Instrument average payload power **with** contingency	2	W
Instrument average science data^ rate contingency	NPIR	%
Instrument average science data^ rate **with** contingency (inferred)	1300	kbps
Instrument Fields of View (if appropriate)	20	degrees
Pointing requirements (knowledge)	NPIR	degrees
Pointing requirements (control)	NPIR	degrees
Pointing requirements (stability)	NPIR	deg/sec

Instrument Table, IRC Instrument

Item	Value	Units
Type of instrument	Infrared imager	
Type of sensor	160 x 120 pixel micro-bolometer array	
Size/dimensions (for each instrument)	10cm x 10cm x 15cm	
Instrument mass contingency	NPIR	%
Instrument mass **with** contingency (CBE+Reserve)	2.5	Kg
Instrument average payload power contingency	NPIR	%
Instrument average payload power **with** contingency	5	W
Instrument average science data^ rate contingency	NPIR	%
Instrument average science data^ rate **with** contingency	NPIR	kbps
Instrument Fields of View (if appropriate)	30	degrees
Pointing requirements (knowledge)	NPIR	degrees
Pointing requirements (control)	NPIR	degrees
Pointing requirements (stability)	NPIR	deg/sec

Sensor	FOV (deg)	Resolution (radians)	Dynamic Range	Mass (kg)	Size (cm)	Power (W)	Sens (Wm^{-2})
NFV	1.2	30×10^{-6}	10^3–10^6	2.5	10×10×25	2	8×10^{-15}
WFV	20	5×10^{-4}	10^3–10^6	2.0	8×10×20	2	2×10^{-15}
IRC	30	5×10^{-3}	10^2	2.5	10×10×15	5	ΔT=3 @ 170 K
SMC1	30	1×10^{-3}	10^3–10^4	1.5	10×10×15	5	2×10^{-14}
SMC2	30	1×10^{-3}	10^3–10^4	1.5	10×10×15	5	2×10^{-14}
Temp	2 + 2 Thermistors		16 b/s	0.1	1×1×1 ea	0.1	0.1 K
Press	2 + 2 MEMS		16 b/s	0.1	1×1×1 ea	0.1	0.01 bar
DPU1	Rate is per sensor		1.3 Mb/s (Data Rate)	2	30×30×51	13 (40 peak)	N/A
DPU2	Burst rate per image		1.3 Mb/s (Data Rate)	2	30×30×51	13 (40 peak)	N/A

*CBE = Current Best Estimate.

^Instrument data rate defined as science data rate prior to on-board processing

Please note that the SMC1, SMC2, and the temperature and pressure assemblies are engineering components that support payload operations and environment but are not full level science instruments.

Payload: Sample Acquisition System

The SAS must be capable of extracting a sample from a comet whose surface strength properties can vary by 6 orders of magnitude from several tens of pascals for unconsolidated ice crystals to tens of megapascals for water or carbon dioxide crystalline ice. The consequence may be sacrificing collection optimization at the extremes for a more reliable capability throughout the entire range. This section describes the trade study results and presents a solution capable of collecting a surface sample from a comet regardless of the surface that is encountered.

The SAS operates a pair of Ø63.5-mm drills simultaneously that are designed to penetrate the surface to a depth of 100 mm and 150 mm, respectively. Assuming each drill is filled to capacity, the sampling would yield 250 cc and 380 cc, respectively, of comet surface material and the potential for a stratigraphic difference between the 100-mm and 150-mm sampling depth. The SAS has a primary and an identical secondary pair of drills should a second sampling attempt be desired. The SRV contains four sample receptacles that are capable of receiving and returning to Earth the primary and secondary, just the primary, or just the secondary set of drilled comet surface samples.

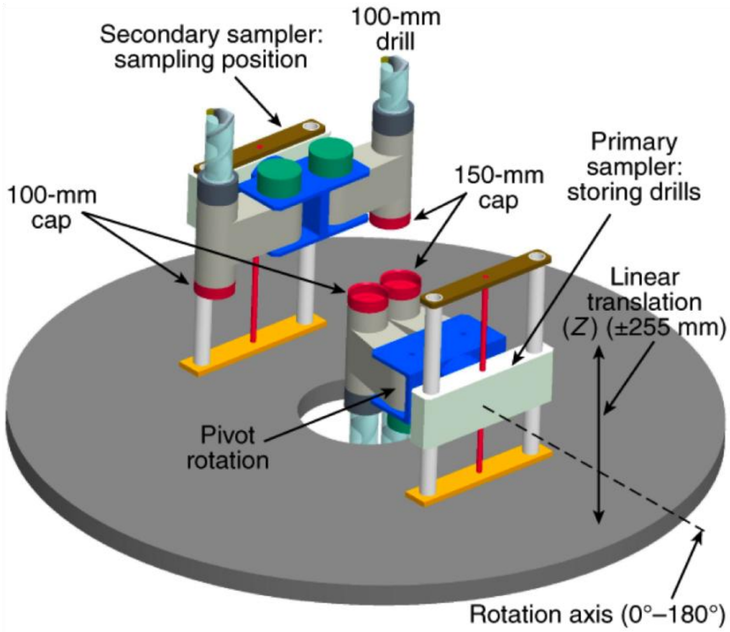


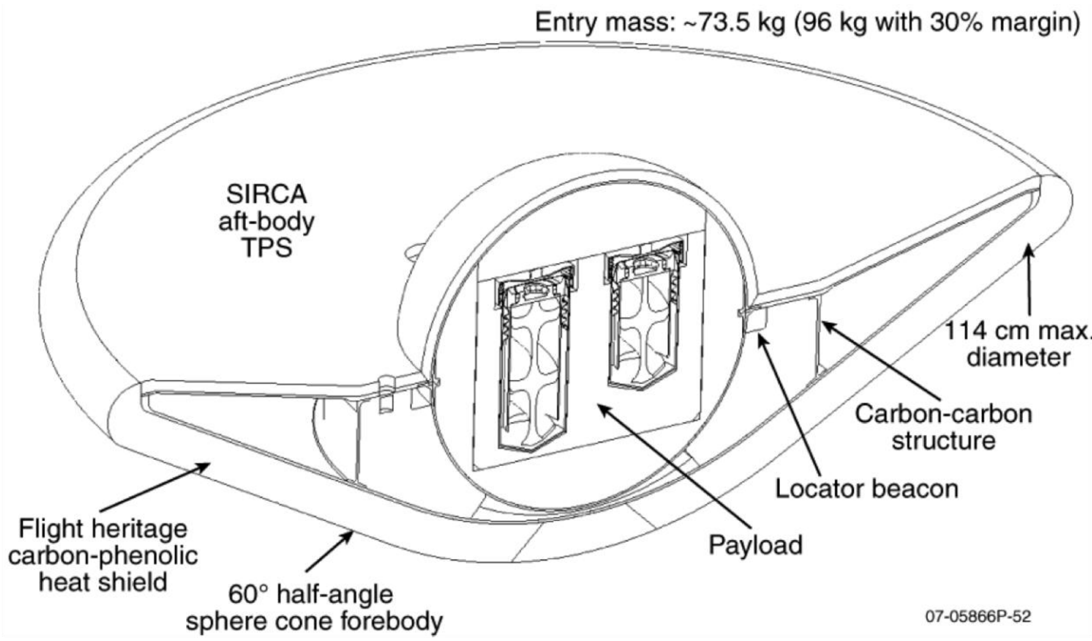
Figure X-X. The SAS is fully redundant and uses a single mechanism for acquisition and stowage.

The samplers are composed of a drill that rotates inside a thin tube. The cut/extracted material will be captured inside the tube until it is compacted to capacity. The stage to which the drills are attached is designed to limit the maximum force placed on the drills to prevent them from stalling or any mechanism from being damaged during the sampling impact. In addition, the entire SAS is isolated from the spacecraft via shock mounts to prevent a hard strike from transferring loads into the spacecraft. After sample collection, the drill head retreats, rotates 180°, and places the drills and samples in the SRV. After releasing the drills, the drill head moves away from the SRV, rotates back 180°, and then seals each drill/sample with a hermetically sealed cap.
The SAS is then ready to be jettisoned or to attempt a second sampling using the second drill pair.

Payload: Sample Return Vehicle

The SRV design is based on the concept developed for the Mars Sample Return Earth Entry Vehicle (MSR EEV). This architecture is focused on a low-risk, robust, and simple operations approach to safely return samples to Earth. The same approach is applied here to CSSR to provide a low-cost, highly reliable solution that leverages heavily on the technology development experience of MSR. The SRV is a scaled version of the MSR EEV (Fig. 4.2.3-1). The entry is completely ballistic, relying on no parachute or other deployments prior to impact at the landing site. This provides a very robust design, which greatly simplifies the entry operations, thus reducing overall risk. The SRV is passively stable in the forward orientation and passively unstable in the backward orientation. This unique approach makes it possible to ensure the vehicle can self-orient to nose-forward under all separation or entry contingencies, including tumbles. Additional risk mitigation features include:

• Proven flight-heritage components for critical subsystems
• Flight-proven, aerodynamically stable 60º half-angle sphere cone forebody similar to that used for Genesis and Stardust capsules
• An integrally hinged lid to ensure that the sealing surfaces are accurately mated
• Fully redundant sets of lid locking pins
• Redundant battery-powered beacons to locate the SRV if radar tracking fails



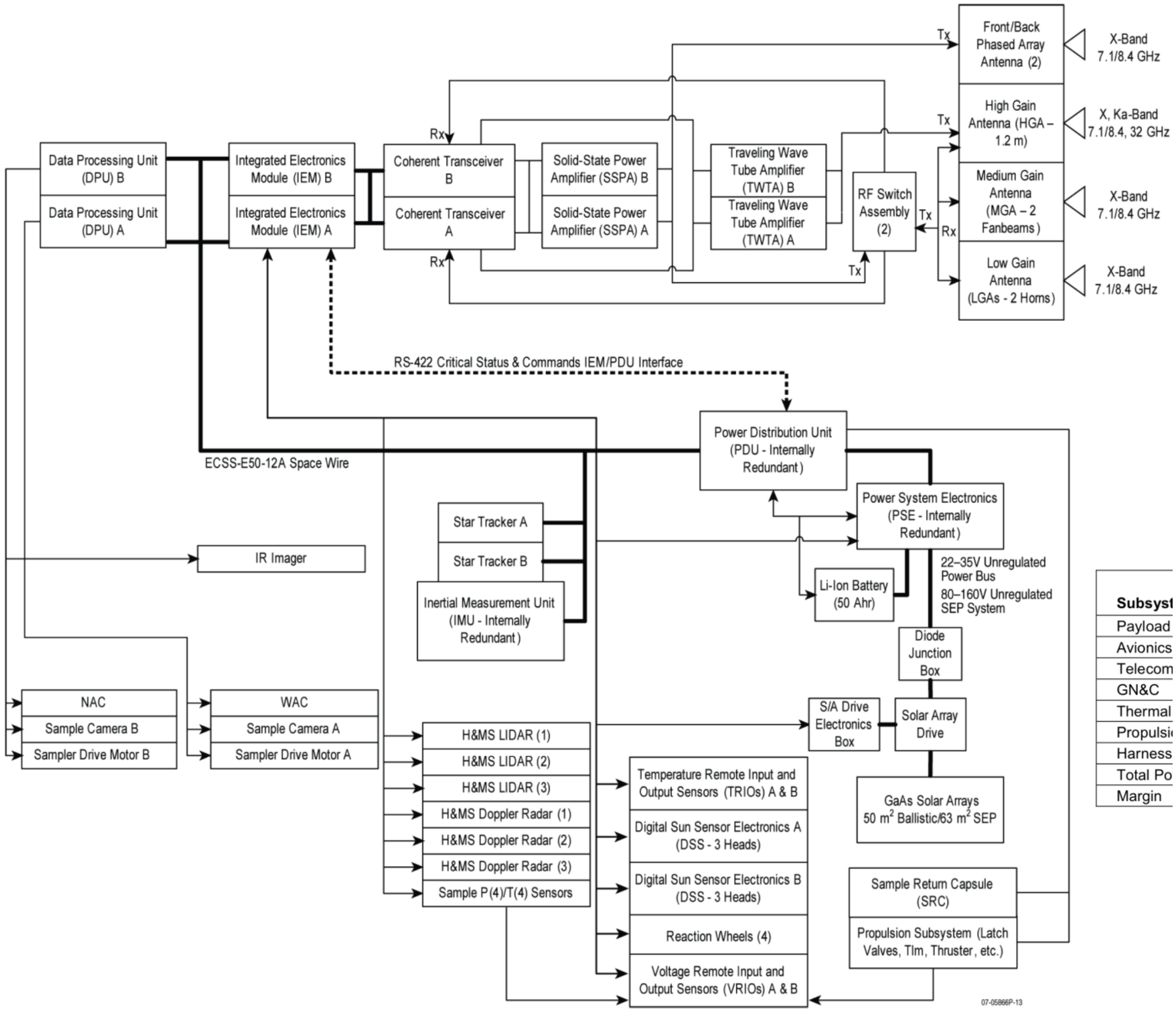
Instrument Table, Sample Return Vehicle

Item	Value	Units
Type of instrument	Sample Return Vehicle	
Size/dimensions (for each instrument)	1.1 diameter	meters
Instrument mass **without** contingency (CBE*)	73.5	Kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	96	Kg
Instrument average payload power **with** contingency	N/A	W
Instrument average science data^ rate **with** contingency	N/A	kbps
Instrument Fields of View (if appropriate)	N/A	degrees
Pointing requirements (knowledge)	N/A	degrees
Pointing requirements (control)	N/A	degrees
Pointing requirements (stability)	N/A	deg/sec

Flight System

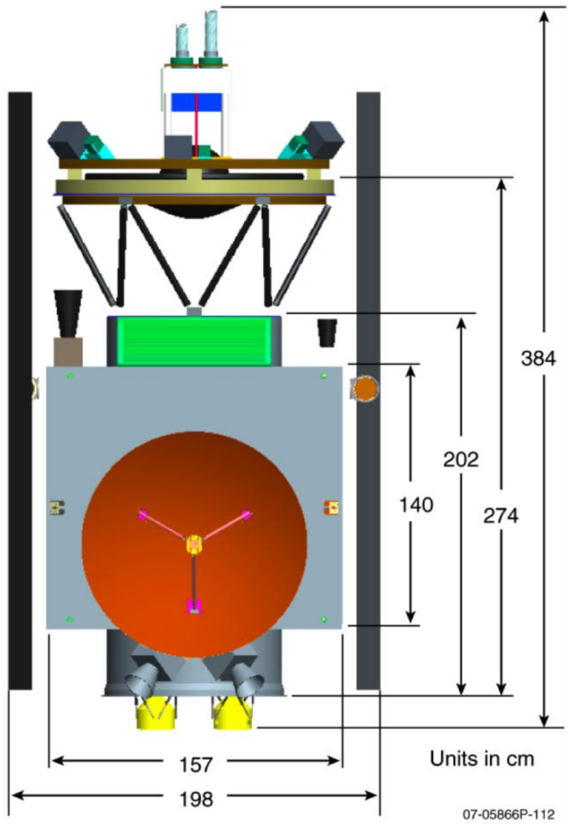
CSSR has a single flight system – a spacecraft probe. Discussion of the flight system design and development approach is included within the following sections. The manufacturer and flight heritage information provided assumes that the spacecraft is being built today. The technology readiness level (TRL) for each component is estimated based on current technology. All components are considered TRL greater than 6 except for the SAS, SRV, height and motion subsystem (H&MS), and the NEXT system as there are no additional exotic requirements and existing representative heritage components for each subsystem.

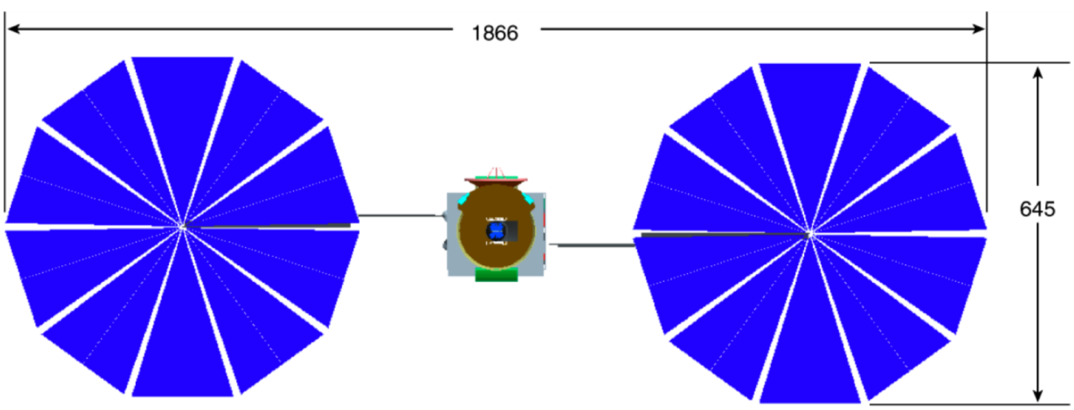
Flight System Block Diagram



Flight System Element Mass and Power Table

		Average Power		
	CBE (kg)	Cruise (W)	Orbit (W)	Sampling (W)
Payload	127	1	21	13
Structures & Mechanisms	236	N/A	N/A	N/A
Thermal Control	98	152	123	138
Propulsion (Dry Mass)	167	2	2	2
Attitude Control (GN&C)	52	85	85	121
Telecommunications	38	68	187	68
Harness	27	6	7	6
Avionics and Power	227	74	74	67
Total Flight Element Dry Bus Mass	972	N/A	N/A	N/A





Flight System Element Characteristics Table

Flight System Element Parameters (as appropriate)	Value/ Summary, units
General	
Design Life, years	12 years
Structure	
Structures material (aluminum, exotic, composite, etc.)	Aluminum, Al honeycomb
Number of articulated structures	2 (solar arrays)
Number of deployed structures	2 (solar arrays)
Aeroshell diameter, m	1.1 meters

Thermal Control	
Type of thermal control used	Passive, includes heat pipes, louvers, MLI
Propulsion	
Estimated delta-V budget, m/s	11.5 km/s (NEXT), 73 m/s (ACS-blowdown)
Propulsion type(s) and associated propellant(s)/oxidizer(s)	NEXT Ion Propulsion, Hydrazine Propulsion
Number of thrusters and tanks	1 Tank/2 Engines (NEXT), 1 Tank/18 Thrusters (ACS)
Specific impulse of each propulsion mode, seconds	4170 (NEXT),
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	NPIR – reaction wheel based
Attitude knowledge limit, degrees	NPIR – star tracker based
Agility requirements (maneuvers, scanning, etc.)	NPIR
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	Solar arrays, 2-axis gimbals
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	IMU(s)(2) Star tracker(s) Sun sensors Lidars Doppler radars
Command & Data Handling	
Flight Element housekeeping data rate, kbps	NPIR
Data storage capacity, Gbits	16 Gbits
Maximum storage record rate, kbps	1500 (inferred)
Maximum storage playback rate, kbps	NPIR
Power	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	Deployed, Ultraflex (ATK)
Array size, meters x meters	63 square meters
Solar cell type (Si, GaAs, Multi-junction GaAs, concentrators)	GaAs
Expected power generation at Beginning of Life (BOL) and End of Life (EOL), watts	17.4 kW (BOL – at 1 AU); EOL not provided
On-orbit average power consumption, watts	500 W (at comet)
Battery type (NiCd, NiH, Li-ion)	Li-Ion
Battery storage capacity, amp-hours	50 Amp Hours

Subsystem: NEXT Ion Propulsion System

The NEXT ion propulsion system will provide the primary propulsion to propel the spacecraft to the destination comet and return the spacecraft to Earth vicinity for sample delivery. The total ΔV provided by the ion propulsion system is approximately 11.5 km/s. The study team has defined a two-string system, referred to as a 1+1 system, in which the primary string provides all the propulsion and the second string provides block redundancy. This block diagram for this 1+1 ion propulsion system is shown in Fig. 4.4.2.1-1, the components of which are described in more detail below. The NEXT thruster has a maximum input power of approximately 6.9 kW. As the spacecraft travels farther from the Sun, solar array power drops off. The NEXT system throttles as the power drops below 6.9 kW.

Concept of Operations and Mission Design

The CSSR mission is divided between: Cruise to comet, Comet Operations (orbit and sample acquisition, and Earth return. A top-level summary of the mission design is shown below. Section 4.5 of the Concept Study report provides an excellent description of the mission concept of operations of the different mission phases.

MISSION DESIGN TABLE
Include separate Tables where appropriate for landers/orbiters.

Parameter	Value	Units
Orbit Parameters (apogee, perigee, inclination, etc.)	Planetary Trajectory	
Mission Lifetime	12	years
Maximum Eclipse Period	N/A	
Launch Site	KSC	
Total Flight System Dry Mass **with** contingency (includes instruments/payload)	972	kg
Propellant Mass **with** contingency (15%)	468	kg
Launch Adapter Mass **with** contingency		N/A
Total Launch Mass	1440	kg
Launch Vehicle	Atlas V 521	
Launch Vehicle Lift Capability	1865	kg
Launch Vehicle Mass Margin	425	kg
Launch Vehicle Mass Margin (%)	30	%

Mission Operations and Ground Data Systems Table

Downlink Information	Cruise	Comet Orbit Ops	Surface Activities
Number of Contacts per Week	See Table Below		
Number of Weeks for Mission Phase, weeks	See Table Below		
Downlink Frequency Band, GHz	X-band, Ka-band		
Telemetry Data Rate(s), kbps	NPIR	NPIR	NPIR
Transmitting Antenna Type(s) and Gain(s), DBi	1.2m HGA dish, Phased Array, LGA		
Transmitter peak power, Watts	35		
Downlink Receiving Antenna Gain, DBi	NPIR	NPIR	NPIR
Transmitting Power Amplifier Output, Watts	35 Watts		
Total Daily Data Volume, (MB/day)	Minimal	750 Mb/day	<750 Mb/day
Uplink Information			
Number of Uplinks per Day	See Table Below		
Uplink Frequency Band, GHz	X-band		
Telecommand Data Rate, kbps	1 kbps		
Receiving Antenna Type(s) and Gain(s), DBi	1.2m HGA, LGA		

Mission Phase	Period (days)	Days from Launch	DSN Contact
Early Operations	L to L+6 L+7 to L+20 L+21 to L+60	0–6 7–20 21–60	Continuous 8 h/d 2×8 h/wk
Cruise to DSM1	L+61 to DSM1–11	61–394	Beacon hibernation mode† One checkout every 6 months‡
DSM1	DSM1–10 to DSM1–1 DSM1–1 to DSM1+1 DSM1+1 to DSM1+30	395–404 404–406 406–435	2×8 h/wk Continuous 2x8 h/wk
Cruise to Earth Swingby	DSM1+31 to E–61	436–626	Beacon hibernation mode One checkout every 6 months
Earth Swingby	E–60 to E–11 E–10 to E–2 E–2 to E+2 E+2 to E+40	627–676 677–685 685–689 689–727	3×8 h/wk 8 h/d Continuous 3×8 h/wk
Cruise to DSM2	E+41 to DSM2–11	728–1730	Beacon hibernation mode One checkout every 6 months
DSM2	DSM2–10 to DSM2–1 DSM2–1 to DSM2+1 DSM2+1 to DSM2+30	1731–1740 1740–1742 1742–1771	2×8 h/wk Continuous 2x8 h/wk
Cruise to C-G	DSM2+31 to C-G–61	1772–2414	Beacon hibernation mode One checkout every 6 months
C-G Arrival	A–60 to A–21 A–20 to A–8 A–7 to A	2415–2454 2455–2467 2468–2475	3×8 h/wk 8 h/d Continuous
C-G Operations	A to A+10 A+11 to A+180 3 Landings, L–2 to L+2 A+181 to Departure –5	2475–2485 2486–2655 3–4 d periods TBD between 2595 & 2655 2656–3240	Continuous 3x8 h/wk (but each month, 1 wk 8 h/d & 2 d continuous) Continuous 3x8 h/wk less than 3 AU; 8h/wk more than 3 AU from Sun
C-G Departure	D–5d to D–1d D–1d to D+1d D+1d to D+30d	3240–3244 3244–3246 3246–3275	8h/d Continuous 3x8 h/wk
Cruise to Earth Return	D+31 to R–61	3276–4634	Beacon hibernation mode One checkout every 6 months
Earth Return	R–60 to R–11 R–10 to R–5 R–4 to R+2 R+2 to R+20	4635–4684 4685–4690 4691–4697 4697–4715	3×8 h/wk 8 h/d Continuous 3×8 h/wk

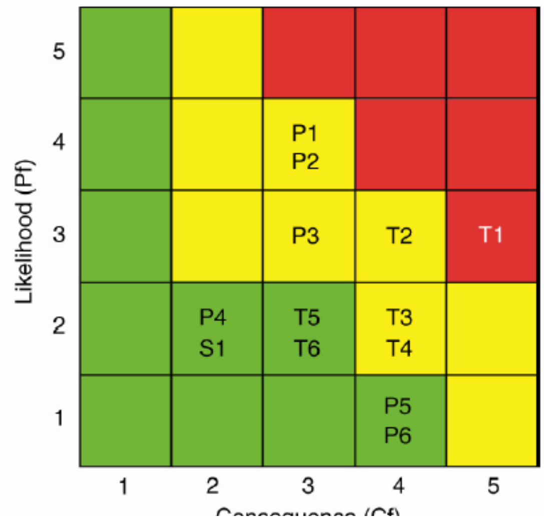
† Beacon hibernation mode is 1×1.5 h/wk (carrier only). 07-05866P–104

‡ Checkout is 20 d operations, 2×8 h/wk, every 6 months.

Risk List

The top 5 technical risks to be managed for successful execution of a CSSR mission (the project in the terminology of the risk assessment) are given below along with recommended plans for their mitigation; programmatic and schedule risk are not addressed. The primary theme of the technical risks for a CSSR mission during this assessment is technology maturity. A 5x5 matrix is also provided.

Risk	Description	Cf		Lf		R	Mitigation
T1	If the project cannot demonstrate that the sampler system can operate with low risk at the comet by confirmation, the project cannot proceed.	High	5	Moderate	3	15	A robust risk reduction program as described in Section 4.8 of this study is designed to provide the necessary demonstration by confirmation.
T2	If the sampling technique heats the sample above −10°C, important science data would be lost.	High	4	Moderate	3	12	The sample acquisition system risk reduction program will demonstrate that a sample can be collected over the range of potential sample material strengths while experiencing the dynamic forces of the spacecraft and sample acquisition mechanism without experiencing temperature excursions above −10°C. This will be demonstrated before the confirmation review.
T3	If the sample experiences temperature excursions during recovery in excess of −10°C, important science data would be lost.	High	4	Low	2	8	The project will monitor the thermal design progress to ensure that sufficient resources are available to ensure temperature margins sufficient to keep the sample below −10°C.
T4	The possibility of failures of critical components due to the duration of the flight mission.	High	4	Low	2	8	Redundancy of critical elements has been included in the baseline design. Additional analysis will be performed in Phase A to determine if additional redundancies are
T5	If the CEV wing development should not raise the maturity of the design to TRL 6 or above prior to the CSSR confirmation, the project would be required to apply resources for a demonstration test.	Moderate	3	Low	2	6	The project will monitor the CEV progress and determine if a CSSR-funded test would be required. The determination would be made at the time of the concept review to determine the impact on reserves.



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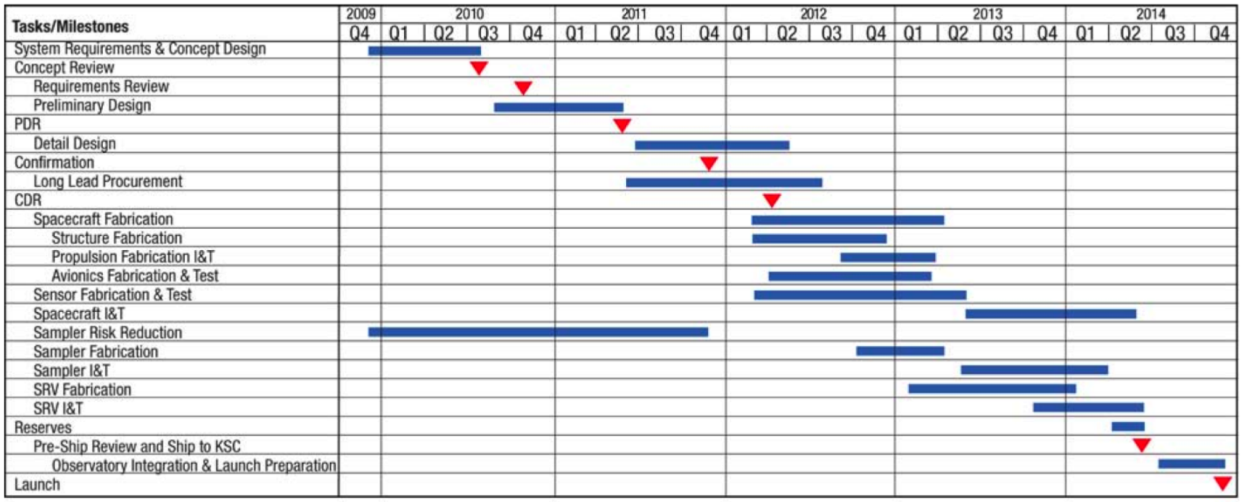
Development Schedule and Schedule Constraints

High-Level Mission Schedule

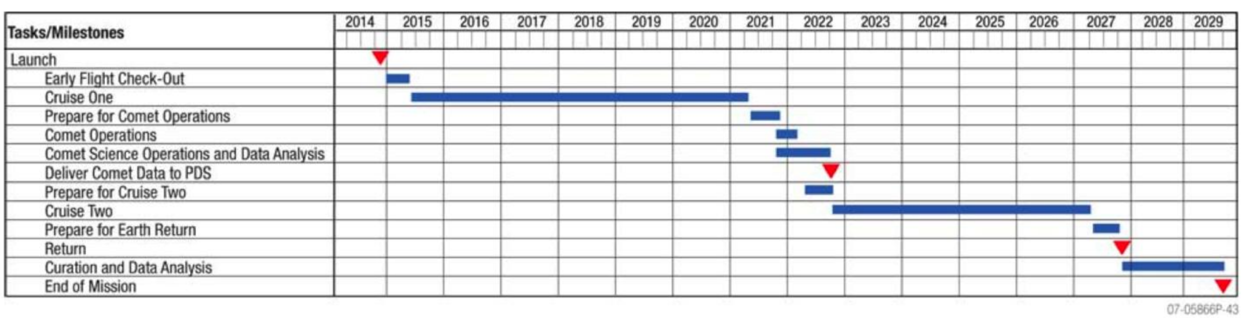
KDPs	Ballistic Mission
Phase A begins	Jan-10
Concept Review	Aug-10
PDR	May-11
NAR	Jul-11
Confirmation	Nov-11
CDR	Apr-12
Launch	Dec-14

The Phase A-D schedule for both the ballistic and SEP options is shown below.



The mission development plan is to design, fabricate, and test the three observatory elements (spacecraft, sampler, and SRV) separately and integrate them at the launch site. This approach is motivated by the general principle of discovering any system weakness in test at the earliest practicable time. Thus the risk of delaying the testing of the other two elements should the third experience a problem in earlier testing is reduced. In addition, this approach reduces the number of environmental tests in series.

The Phase-E schedule for the mission is shown below.



Key Phase Duration Table

Project Phase	Duration (Months)
Phase A – Conceptual Design	9 months
Phase B – Preliminary Design	14 months
Phase C – Detailed Design	11 months
Phase D – Integration & Test	28 months
Phase E – Primary Mission Operations	165 months
Phase F – Extended Mission Operations	N/A
Start of Phase B (Sept10) to PDR (May11)	9 months
Start of Phase B (Sept10) to CDR (April12)	20 months
Start of Phase B (Sept10) to Instrument Deliveries (March14)	42 months
Start of Phase B (Sept10) to Sampler Delivery (June14)	45 months
Start of Phase B to Delivery of Sample Return Vehicle (June14)	45 months
System Level Integration & Test	6 months
Project Total Funded Schedule Reserve	~3 months
Total Development Time Phase B – D (Dec14)	52 months

Launch Window and Backup Mission Opportunities

The table below lists the launch C3 and deterministic ΔV values for each day of the launch window of the baseline mission. This launch window is 20 days. Both the highest C3, 26.6 km2/s2, and highest total deterministic post-launch ΔV, 2785 m/s, occur on the first day of the window, December 22, 2014. The C3 would be higher for a launch on the 21st day, January 11, 2015, so that and later dates are excluded.

Date, 2014/2015	C_3 (km^2/s^2)	Total ΔV (m/s)	DSM-1 (m/s)	DSM-2 (m/s)	C-G Rendezvous ΔV (m/s)	C-G Depart ΔV (m/s)
Dec. 21*	26.794	2785.2	649	771.8	612.9	751.5
Dec. 22	26.56	2784.5	649.2	774.2	609.6	751.5
Dec. 23	26.35	2783.9	649.3	777	606.1	751.5
Dec. 24	26.164	2783.2	649.2	780	602.5	751.5
Dec. 26	25.863	2782.1	648.6	787.1	594.9	751.5
Dec. 28	25.656	2781.0	647.3	795.7	586.5	751.5
Dec. 30	25.543	2779.9	645.4	805.8	577.2	751.5
Jan. 1	25.521	2779.0	642.8	817.8	566.9	751.5
Jan. 3	25.588	2778.3	639.6	831.9	555.3	751.5
Jan. 5	25.744	2777.7	635.7	848.4	542.1	751.5
Jan. 7	25.985	2777.6	631.2	867.8	527.1	751.5
Jan. 9	26.307	2777.8	626	890.5	509.8	751.5
Jan. 10	26.498	2778.1	623.2	903.3	500.1	751.5
Jan. 11*	26.708	2778.6	620.2	917.3	489.6	751.5

* Date excluded from the planned 20-day launch window.

If for any reason the C-G baseline is missed, there is another opportunity 5 months later with slightly better performance (lower launch C_3 and lower total post-launch ⊗V) allowing the same architecture to be used for both windows. The backup trajectory to Wirtanen also launches from the ETR on an Atlas 541. The trajectory has no deterministic DSMs; rather, it uses two swingbys of Venus and one of the Earth to reduce the launch C_3 to reach the comet.

APPENDIX A. ACRONYMS AND ABBREVIATIONS

ACS	Attitude Control System
ADC	attitude determination and control
ATLO	Assembly, Test, and Launch Operations
AU	Astronomical Unit
BOL	beginning of life
C_3	launch energy
CCD	charge coupled device
CC&DH	command, control, and data handling
CCSDS	Consultative Committee for Space Data Systems
C&DH	command and data handling
CDR	Concept Design Review
CEV	Crew Exploration Vehicle
CFD	computational fluid dynamics
CFDP	CCSDS File Delivery Protocol
cFE	Core Flight Executive
CG	center of gravity
C-G	Churyumov-Gerasimenko
CGS	Common Ground Software
CMOS	complementary metal oxide semiconductor
COTS	commercial off-the-shelf
CPT	comprehensive performance test
CSCI	computer software configuration item
CSSR	Comet Surface Sample Return
D/A	digital-to-analog
DCIU	digital control interface unit
DEM	digital elevation map
D/H	deuterium to hydrogen
DI	Deep Impact
ΔDOR	Delta-Differential One-way Range
DPU	Data Processing Unit
DS-1	Deep Space One
DSM	Deep Space Maneuver
DSN	Deep Space Network
DSS	Digital Sun Sensor
EELV	evolved expendable launch vehicle
EEV	Earth Entry Vehicle
EM	Engineering Model
EMI/EMC	electromagnetic interference/electromagnetic capability
ESD	electrostatic discharge
ETR	Eastern Test Range
FMEA/FTA	failure mode effects analysis/fault tree analysis
FOV	field of view
FPM	fault protection module
FPU	focal plane units

GEMS	glass with embedded metal and sulfide
GSFC	Goddard Space Flight Center
GN&C	guidance, navigation, and control
GRC	John H. Glenn Research Center
HGA	high gain antenna
H&MS	height and motion subsystem
HPA	high-pressure assembly low-pressure assembly
IAU	International Astronomical Union
IDP	interplanetary dust particle
IEM	integrated electronics module
I/F	interface
IMU	Inertial Measurement Unit
IOM	insoluble organic matter
IRC	infrared camera
ISM	interstellar medium
ISPT	In-Space Propulsion Technology
I&T	integration and testing
JFC	Jupiter Family Comet
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KDP	key decision point
KSC	Kennedy Space Center
LaRC	Langley Research Center
Lat/Lon/Alt	latitude/longitude/altitude
LED	light emitting diode
LGA	low gain antenna
LILT	low-intensity, low-temperature
LORRI	Long-Range Reconnaissance Imager
LPA	low-pressure assembly
LRC	Langley Research Center
LWS	Living With a Star
MEMS	micro-electro-mechanical system
MGA	medium gain antenna
MLI	multi-layer insulation
MOC	Mission Operations Center
MO&DA	Mission Operations and Data Analysis [use this one]
MODA	Mission Operations and Data Analysis
MOSFET	metal-oxide semiconductor field effect transistor
MP	main processor
MRO	Mars Reconnaissance Orbiter
MSR	Mars Sample Return
NAC	Narrow Angle Camera
N/A	Not Applicable
NAFCOM	NASA-Air Force Cost Model
NAR	Non-Advocate Review
NEXT	NASA's Evolutionary Xenon Thruster

NICM	NASA Instrument Cost Model
NF	New Frontiers
NFV	narrow field visible
NPA	non-principal axis
NPIR	Not Provided In Report
NRC	National Research Council
NSTAR	NASA Solar Electric Propulsion Technology Application Readiness
PDR	Preliminary Design Review
PDS	Planetary Data System
PDU	power distribution unit
PFCV	Proportional Flow Control Valve
PM	Prototype Model
PMD	propellant management device
PPT	peak power tracker
PPU	power processing unit
PSE	power system electronics
PTP	Programmable Telemetry Processor
PWM	pulse width modulation
RIO	remote input/output
RTG	Radioisotope Thermoelectric Generator
S/A	solar array
SAS	sample acquisition system
SDT	Science Definition Team
SEP	solar electric propulsion
SMC	sample monitoring camera
SMOW	standard mean ocean water
SOC	Science Operations Center
SRC	Sample Return Capsule
SRV	sample return vehicle
SSPA	solid-state power amplifier
SSR	solid-state recorder
STOL	System Test and Operations Language
TBTK	TestBed ToolKit
T&C	telemetry and command
TCM	trajectory correction maneuver
TEC	thermal electric cooler
TEM	transmission electron microscopy
TLM	telemetry
TRIO	temperature remote input and output
TRL	technology readiness level
TRN	Terrain Recognition Navigation
TPS	thermal protection system
TWTA	traveling wave tube amplifier
UTTR	Utah Test and Training Range
∆VEGA	∆V-Earth Gravity Assist
VLBI	Very Long Baseline Interferometry

VRIO	voltage remote input and output
WAC	Wide Angle Camera
WBS	work breakdown structure
WFV	wide field visible
XANES	X-ray Absorption Near Edge Structure