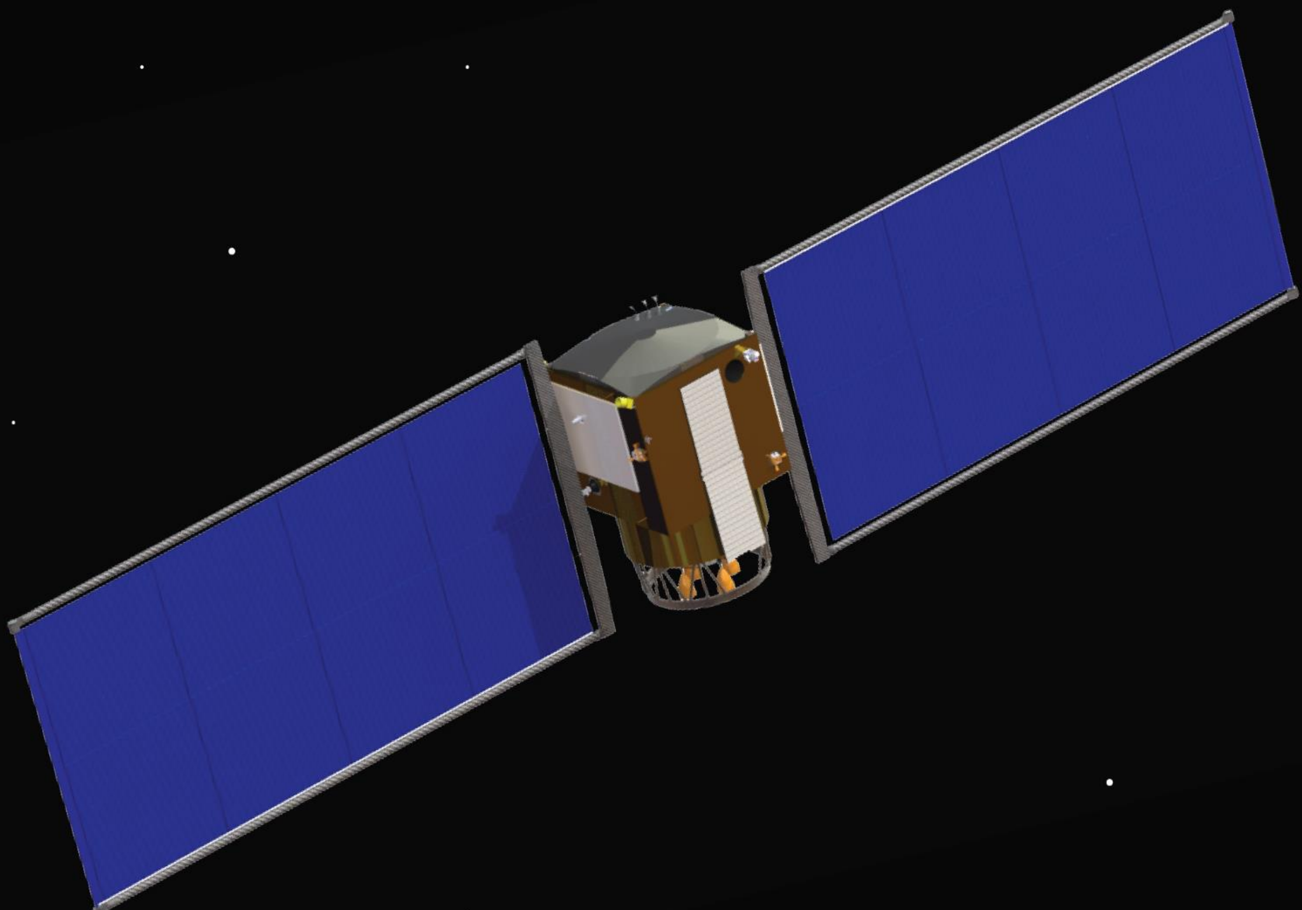
COSMIC Concept of Operations

Cal Poly Spacecraft Design 20-21



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1.0 Background

1.1 Mission Introduction

As Earth-based assets such as Pan-STARRS1 and Rubin Observatory's Large Synoptic Survey Telescope are detecting interstellar and near-parabolic objects, interests in better understanding the interstellar objects (ISOs) have led the National Aeronautics and Space Administration, the European Space Agency, and the Japan Aerospace Exploration Agency to solicit proposals for mission concepts focused on ISO identification. As a result, Celestial Object Sensing and Measuring Identification Campaign (COSMIC) was created to accomplish the three organizations' requests to characterize an ISO's composition, morphology, and angular momentum. COSMIC's mission is to provide space systems for interstellar exploration to further our understanding of the origins of our solar system through the study of these ISOs and Near-Parabolic Comets.

1.2 Mission Objectives

The mission objective requires an 80% likelihood of achieving the primary objectives and at least one secondary objective. Additionally, one ISO must be characterized within 20 years of the system readiness date of no later than 12/31/2030. The mission-level requirements were derived from the customer's solicitation and customer clarification. This section will cover COSMIC's interpretation and developments of the primary and secondary objectives proposed in the **Customer Solicitation**.

1.2.1 Primary Objectives

The **Customer Solicitation** requires the delivered system to characterize an ISO. For a system to characterize an ISO, it must conduct sciences focusing on composition, morphology, and angular momentum.

Composition:

- Collect visible imagery of 50% of the object's illuminated surface with a resolution of at least 5.0 meters per pixel
- Collect infrared imagery of 20% of the object's visible surface with a resolution of at least 10.0 meters per pixel

Morphology:

- Model 50% of the object's shape with an accuracy of +/- 10 meters
- Determine the object's mean dimensions within +/- 10 meters

Angular Momentum:

- Determine the object's spin axis within +/- 1.0 degree
- Determine the object's rotation rate within 1%

1.2.2 Secondary Objectives

In addition to the primary objectives, the **Customer Solicitation** provided a list of potential secondary objectives. The COSMIC team decided to pursue secondary objectives B.3, B.5, and two parts of B.1.

B.1 Advanced Object Definition:

- Not Pursued: Collect ultraviolet imagery of the object
- Perform active measurement of object shape and range via onboard Synthetic Aperture Radar (SAR)
- Calculate dielectric surface constant via returned SAR data

- Not Pursued: Measure dust flux and plasma properties of potential coma environment

B.3 Remote Observation Platform

- Perform one or multiple observation campaigns of heliocentric orbiting bodies

B.5 Exoplanet Platform

- Perform one or multiple exoplanet candidate follow-up campaigns

1.2.3 Object Parameters

This section outlines the identification parameters, orbital elements, and physical parameters of the desired ISO. The identification parameters and orbital elements help design a mission with an 80% likelihood of completion, as requested by the customer. The physical parameters help determine the necessary capabilities of the payload.

Identification Parameters:

- Object detected inbound at 3 AU
- One object is identified per Earth year

Orbital Elements:

- Eccentricity between 0.99 and 3.5
- Perihelion between 0.3 and 2 AU
- Inclination between 0 and 180 degrees
- Argument of Perihelion between 0 and 360 degrees

Physical Parameters:

- Albedo greater than 0.05
- Minimum mean dimension is between 1 km and 1.5 km

Detection Uncertainty:

- At detection epoch (inbound, heliocentric range of 3 AU), ephemeris accuracy is expected to be no better than +/-30k km, +/- 0.1 km/s, heliocentric, per axis

1.3 Mission Constraints

The **Customer Solicitation** also provides numerous constraints of the delivered system. These constraints are divided into two segments: launch and nuclear constraints.

Launch Constraints:

- No more than two launches
- Any US-based launch vehicle must be launched from VAFB, KSC, or MARS launch sites
- Any Japanese-based H-II launch vehicle variant must be launched from the Tanegashima launch site
- Any European-based Ariane or Vega launch vehicle variant must be launched from the Guiana Space Centre launch site
- All above cases must have been successfully launched or planned prior to the proposed system launch

Nuclear Constraints:

- Nuclear Thermal Propulsion Systems are not permitted
- Nuclear Power can be used, but it is greatly not preferred

1.4 Interstellar Object Coverage

The COSMIC system's performance is designed based on models that simulate 20-year missions, randomly generating ISOs in accordance with the solicitation's given range on orbital parameters. Each ISO over a 20-year mission is characterized by the required propellant mass needed to achieve intercept. The best-case ISOs are identified by the least amount of needed propellant mass. These masses are sorted and ranked, and a percentile of the set of ISOs is identified as the target ISO coverage. Considering the overall 80% mission success requirement, the COSMIC system must be capable of successfully conducting science on 87% of best-case ISOs from the set of 20-year missions. This modeling capability allows COSMIC to simulate an ISO on detection and estimate the required propellant mass needed to reach it successfully, allowing COSMIC to determine if the mission should attempt to reach a specific ISO.

In addition to this, the **Customer Solicitation** provided the COSMIC team with the option of whether the spacecraft will be preposition or ready-to-launch. A preposition spacecraft is one that would be launched into an orbit before an ISO is detected, while a ready-to-launch spacecraft would be launched once an ISO is detected and be sent directly to the ISO. After studying propulsion options, launch vehicles and dates, and ISO trajectories and speeds, COSMIC determined that two prepositioned spacecraft would provide the best system reliability due to scrubbed launches and the high amount of DV required to encounter an ISO.

The following pages contain two figures exemplifying the ISO coverage and modeling. **Figure 1. Mission ISO Analysis Model** shows the two COSMIC spacecraft in their preposition (PP) orbits and the possible encounter paths they could attempt. **Figure 2. ISO Trajectory Models** depicts six different trajectories for ISOs that were modeled using the same simulation. This figure shows the variability of ISOs with the same inputs.

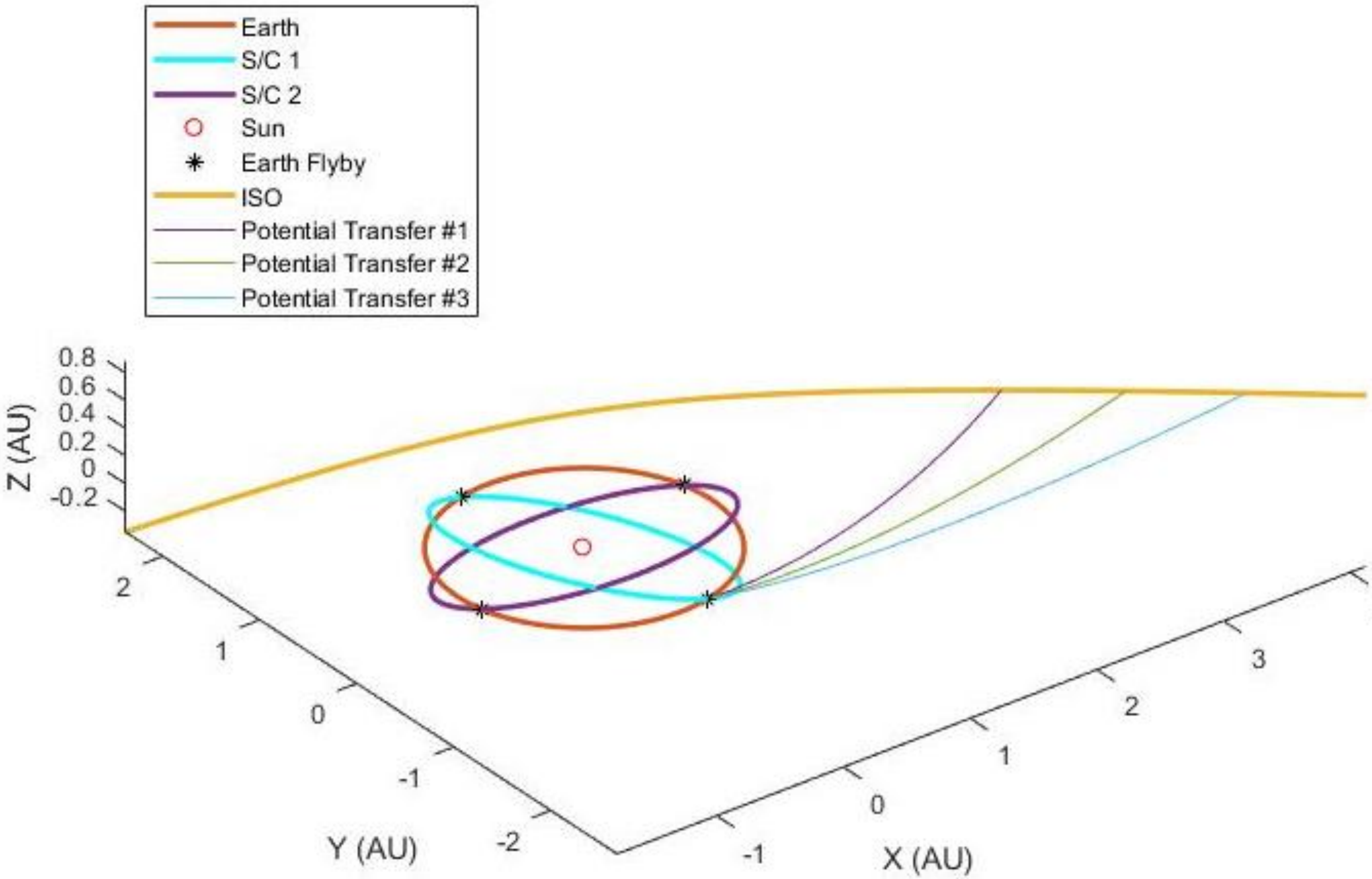

Figure 1. Mission ISO Analysis Model

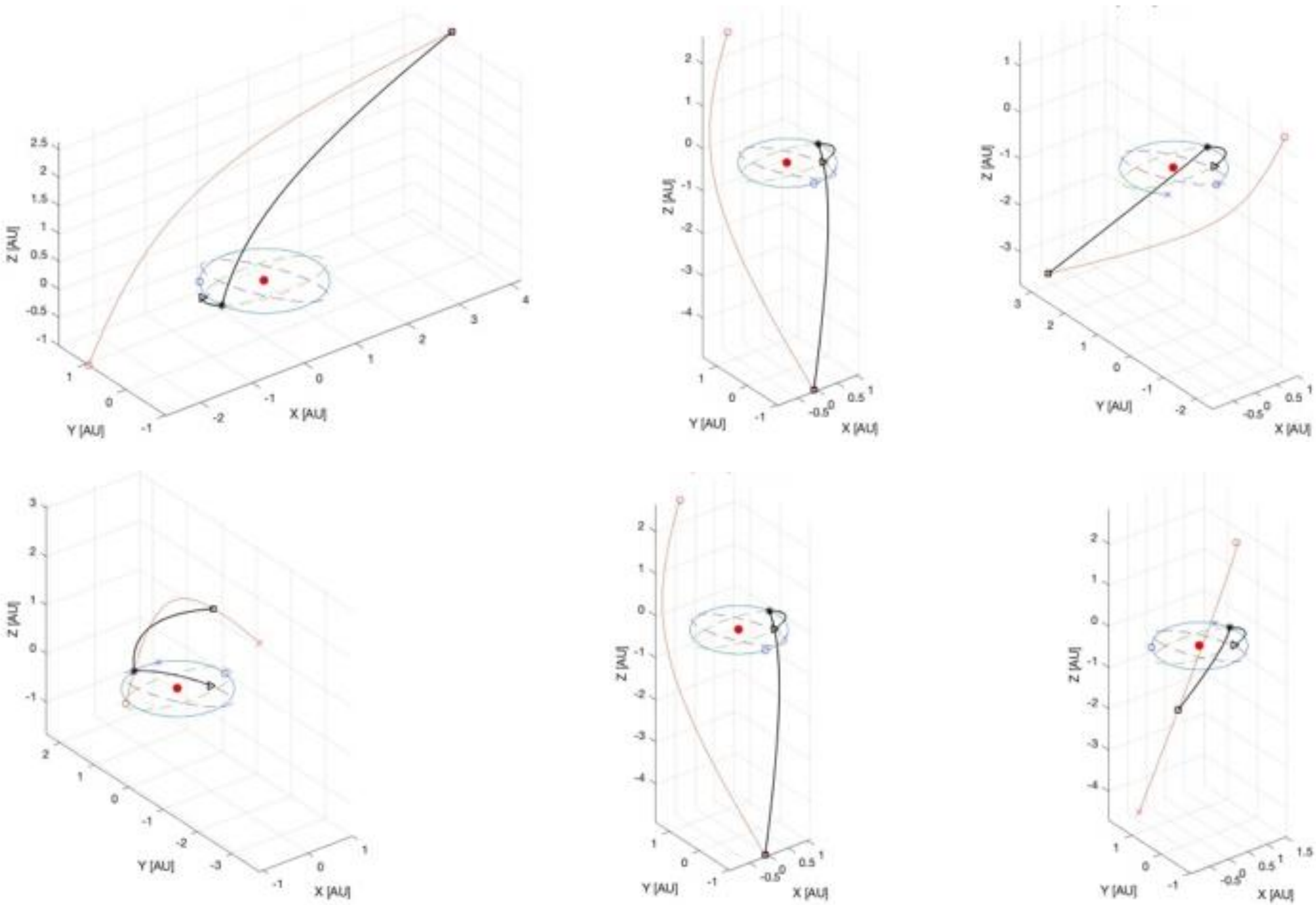

Figure 2. ISO Trajectory Models

1.5 System Descriptions

The COSMIC system consists of a contracted ground system (GS), two contracted SpaceX Falcon Heavy launch vehicles, the launch site at Cape Canaveral, and two spacecraft. The GS utilizes the spacecraft communications subsystem and C&DH subsystem to ensure the completion of the objectives described in **Section 1.2 Mission Objectives**. The two Falcon Heavy launch vehicles (LVs) will place the spacecraft into the desired prepositioned orbit. The two spacecraft will accomplish the secondary objectives outlined in **Section 1.2.2 Secondary Objectives** while in the preposition orbits waiting until ISO detection. After ISO detection (completed by a third party), only one spacecraft will travel to the ISO to accomplish the primary objectives and a secondary objective.

Figure 3. Product Breakdown Structure illustrates the current product breakdown structure for COSMIC. The flight system breakdown represents how each spacecraft is broken down. As shown above, each spacecraft features nine subsystems: payload, propulsion, power, communications, thermal, GNC, ADCS, structures, and C&DH. The PBS also includes the ground system (GS) and its subsystems: communications, software, and mission control.

- The payload subsystem holds the sensors and instrumentation needed to accomplish the science required for the mission objectives, including an infrared camera, a visible light camera, and a synthetic aperture radar system.
- The propulsion subsystem allows the spacecraft to insert into its preposition orbit, station keep while in its preposition orbit, and travel from its preposition orbit to the ISO.
- The power subsystem manages the power required to keep the spacecraft operational, including solar panels, batteries, and harnesses.
- The communications subsystem is the connection between GS and the spacecraft.
- The thermal subsystem helps regulate the spacecraft's temperature.
- The Guidance, Navigation, and Control subsystem guide the spacecraft to the ISO using Optical Navigation (OpNav) and Autonomous Optical Navigation (AON).
- The Attitude Determination and Control System subsystem maintains the spacecraft's pointing and attitude.
- The structures subsystem integrates all other subsystems in the spacecraft and features shielding to protect the spacecraft. It also contains mechanisms and deployable structures.
- The Command and Data Handling subsystem manages, stores, and downlinks the data and receives, processes, and operates any spacecraft command sent from GS.
- The GS science operations center will track the science requirements and data.
- The GS data storage and network subsystem will receive, process, and store the data collected.
- The GS mission control center communicates with the spacecraft, manages the mission and operations, and checks the spacecraft's health and status.

Figure 4. Rendering of Spacecraft depicts a preliminary rendering of the spacecraft with four key components labelled. **Figure 5. Side View of Spacecraft Body** and **Figure 6. Top View of Spacecraft Body** are two models of the spacecraft's interior featuring labels for the Level 4 flight system components called out in **Figure 3. Product Breakdown Structure**.

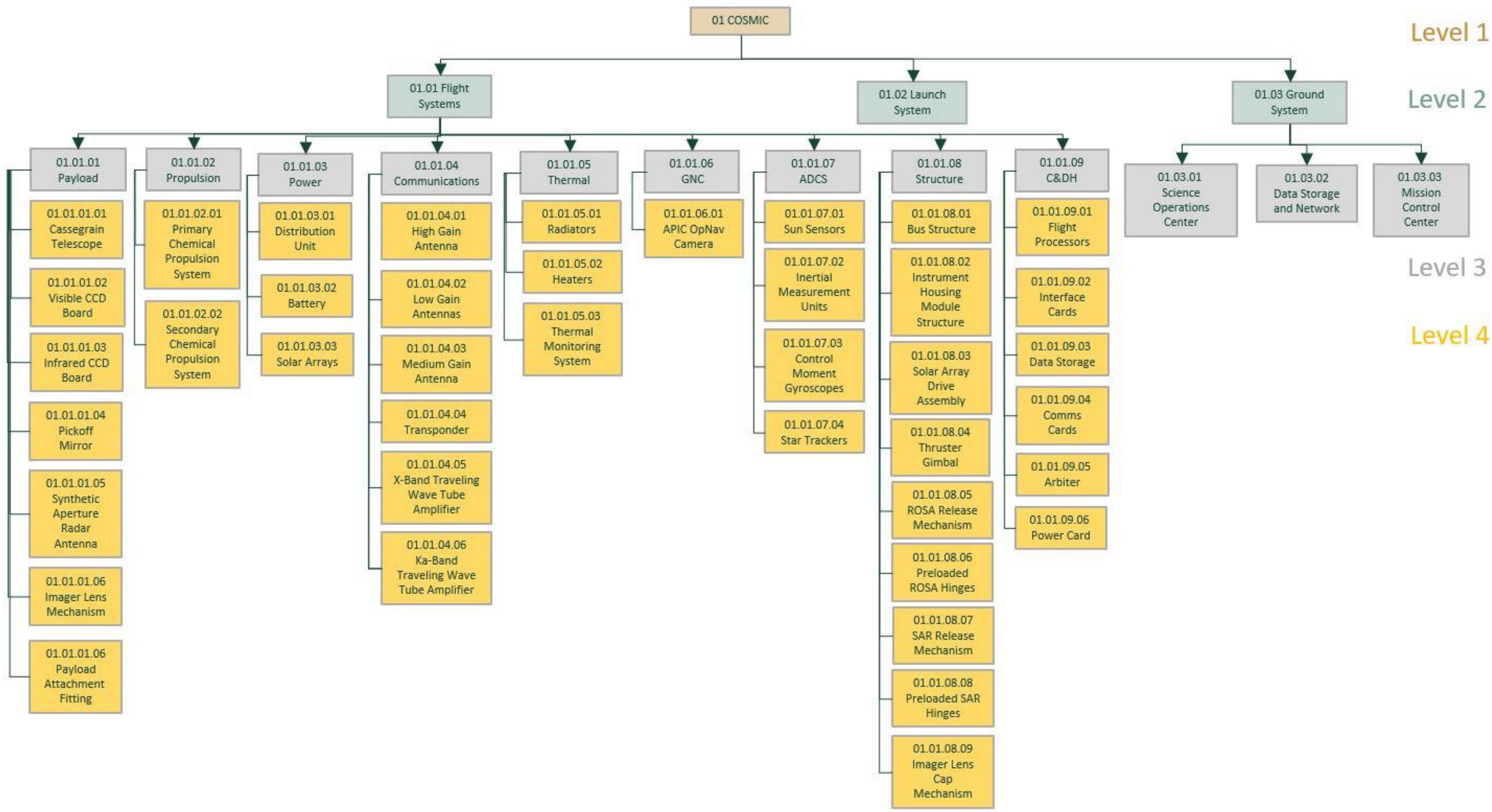

Figure 3. Product Breakdown Structure

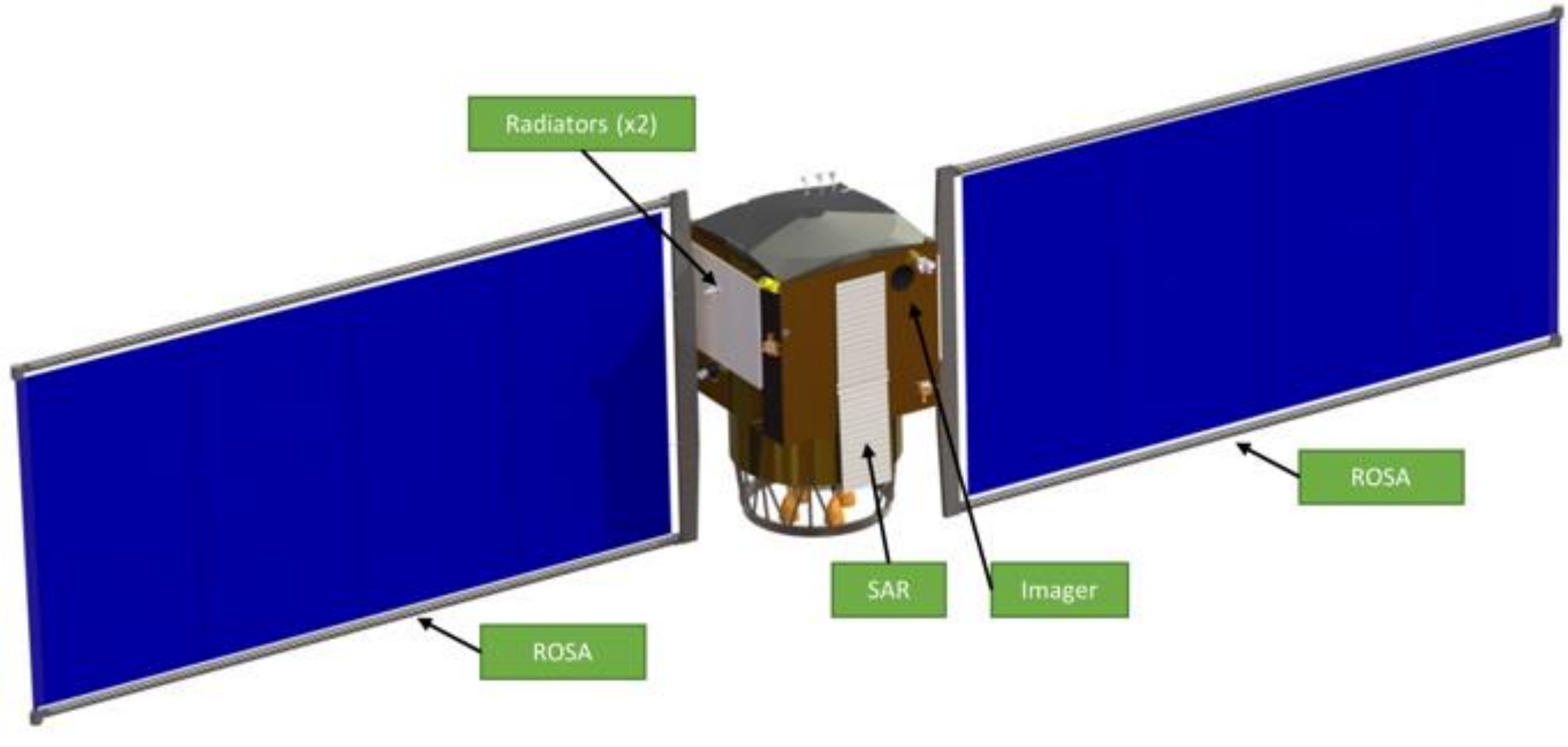

Figure 4. Rendering of Spacecraft

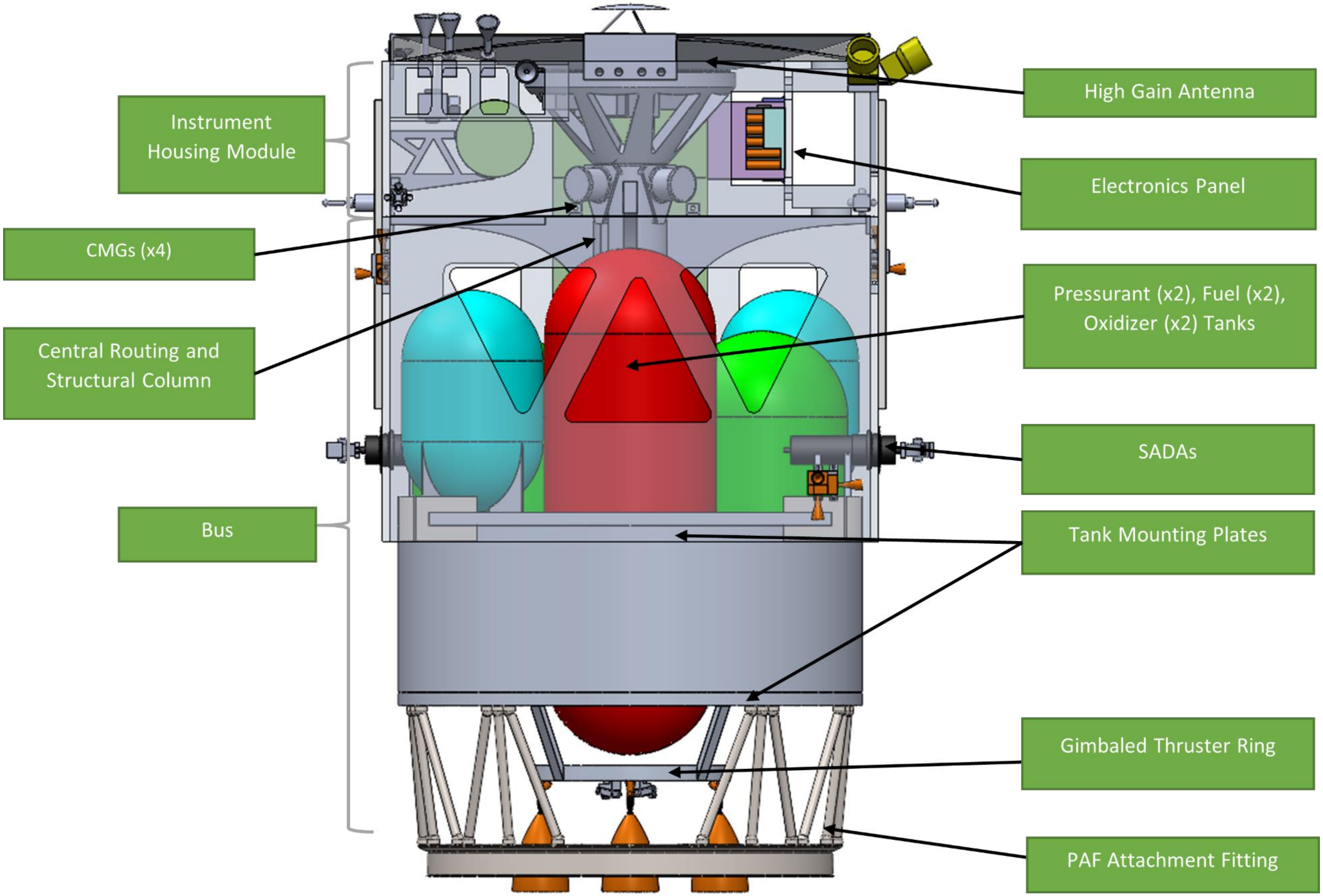

Figure 5. Side View of Spacecraft Body

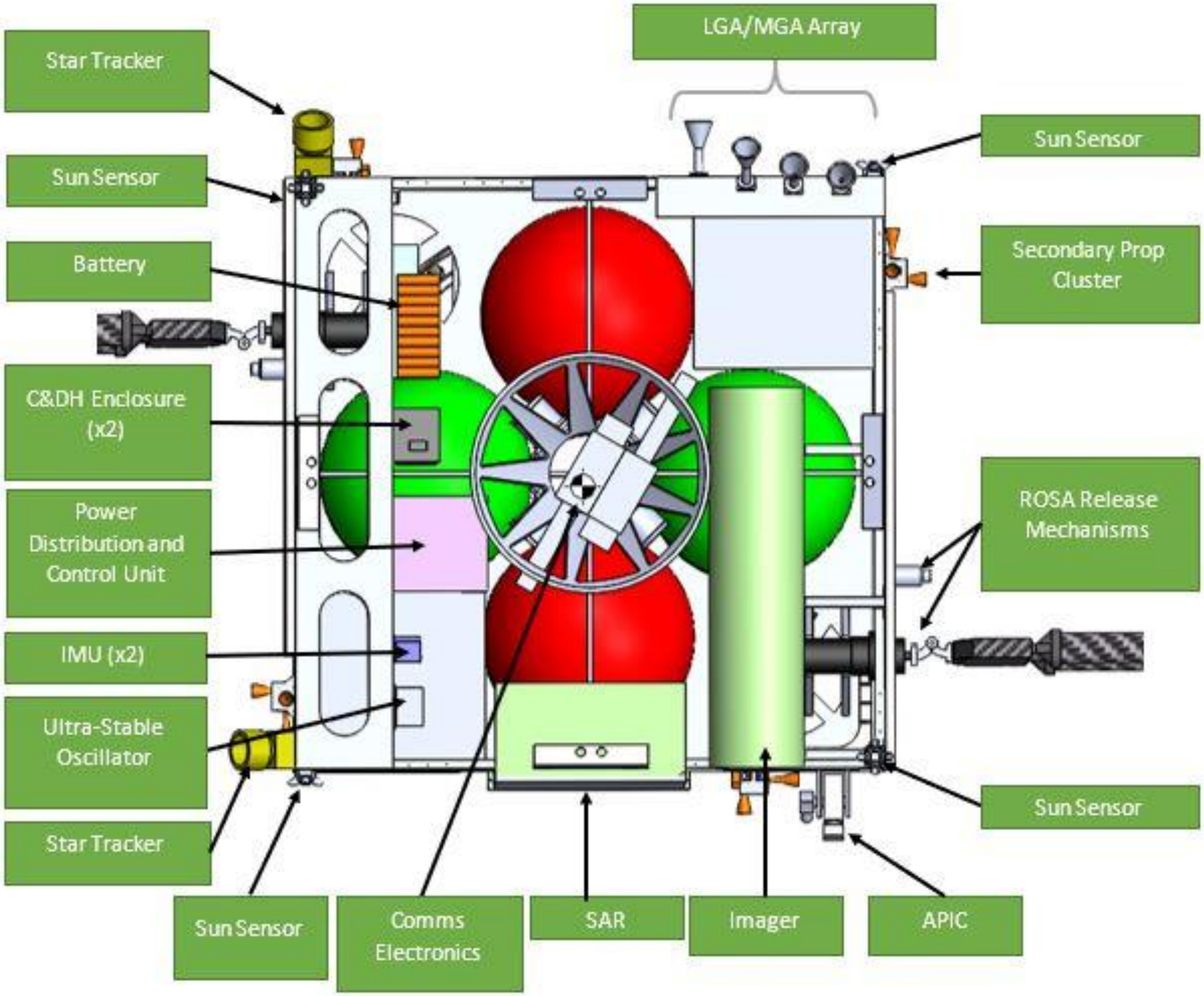

Figure 6. Top View of Spacecraft Body

1.6 Reference Documents

COSMIC Requirements:

- This document contains all the program requirements through primary and secondary objectives to Level 4.
- The requirements correlate with the Concept of Operations and help define how the mission was designed.

COSMIC Work Breakdown Structure:

- This document outlines the organizational structure of the COSMIC team and includes insight on the product breakdown for the system.
- The Concept of Operations will detail operations of the system and subsystems explained in the WBS and PBS.

Customer Solicitation:

- This document is the request for proposal from the customer outlining mission objectives and constraints.
- The solicitation provides the baseline for the mission design and what the mission needs to complete.

SpaceX Falcon User's Guide:

- This document is the user guide put out by SpaceX for their Falcon launch vehicles.
- The user guide helps layout requirements for the Falcon Heavy Expendable and assisted COSMIC in designing the spacecraft.

2.0 Concept of Operations

2.1 Overview of Concept of Operations

The Concept of Operations details the COSMIC mission from prelaunch preparation to the spacecraft decommission and includes an overview of the mission concept and corresponding infographic. Also, the Concept of Operations explains what the flight system and the GS will do during each mission phase. There are eight separate COSMIC phases, including a preliminary phase (Phase 0: Prelaunch) for launch preparation.

- Phase 1: Launch is the phase in which each spacecraft is launched, separated, and detumbled.
- Phase 2: Preposition Orbit Insertion is when the spacecraft uses gravity assists to emplace the spacecraft into their preposition orbit.
- Phase 3: Secondary Science Conduction is when the spacecraft is in its preposition orbit, conducting secondary science.
- Phase 4: Navigation to Interstellar Object is when the encounter spacecraft (ES) travels from the preposition orbit to the ISO.
- Phase 5: Interstellar Object Flyby is the encounter phase where the encounter spacecraft will fly by the ISO and complete primary objectives and two parts of secondary objective B.1 Advanced Object Definition.
- Phase 6: Data Downlink is when the encounter spacecraft will downlink the collected data back to Earth.
- Phase 7: Decommission is the decommissioning process of spacecraft.

Figure 7. Concept of Operations Infographic is a detailed infographic that displays and explains the concept of operations. This figure outlines what happens in each phase of the mission, along with graphical explanations. Additionally, there is an infographic for Phase 1 and 2, Phase 3, and Phase 5 to increase visual understanding of more complex phases. These three infographics will help visualize the phases after explaining what happens during them.

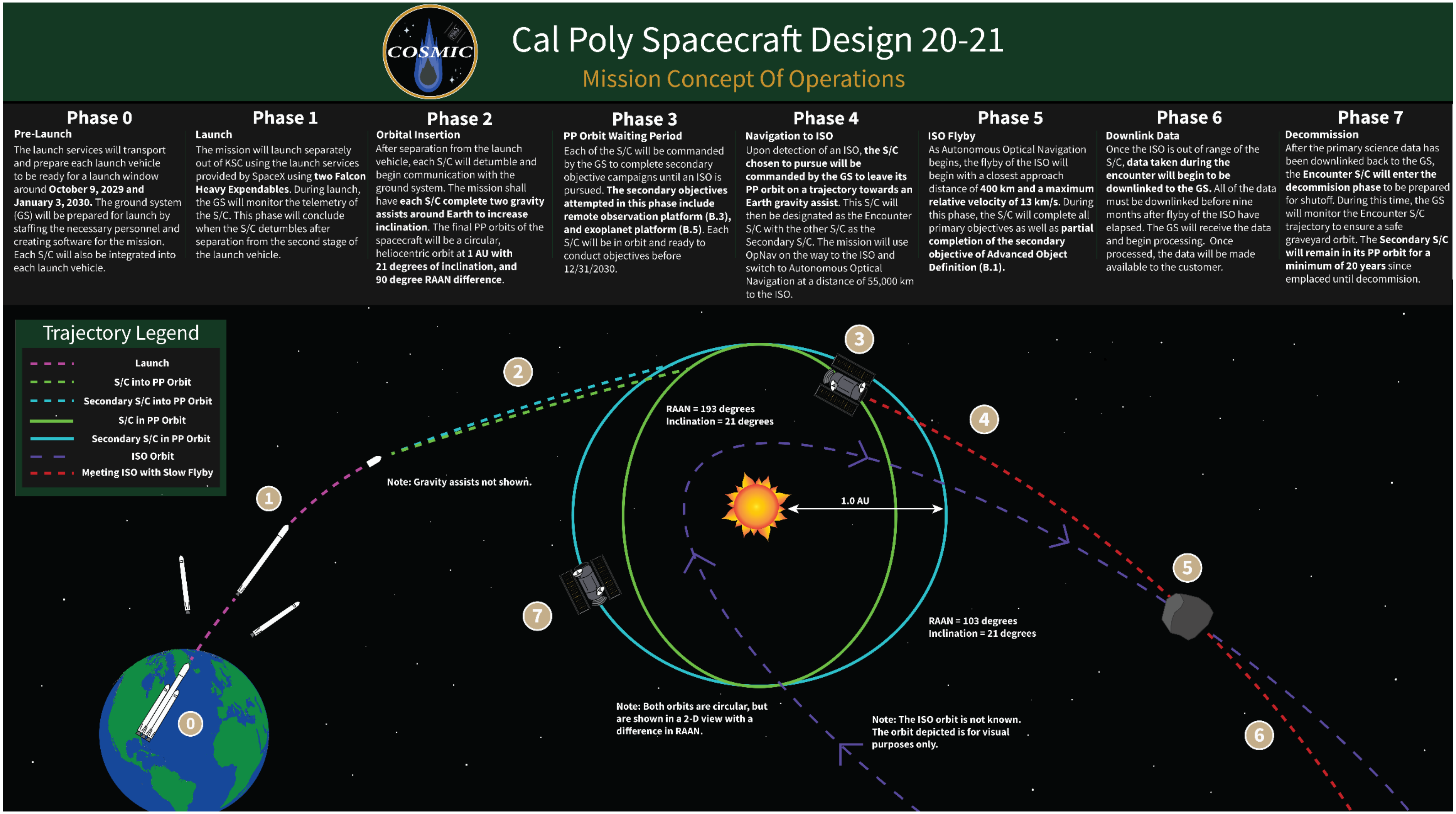

Figure 7. Concept of Operations Infographic

2.2 Mission Phases

Throughout the mission lifetime, the spacecraft will move through the phases listed in chronological order unless indicated otherwise. Although the spacecraft are identical, the timeline for each spacecraft during phases 1 and 2 will not be the same due to a difference in launch dates but will take the same amount of time.

2.2.0 Phase 0: Prelaunch

The overall mission starts with Phase 0: Prelaunch. Before this phase occurs, the spacecraft will be constructed and verified using the **COSMIC Requirements**. Once the spacecraft have finished production, integration, and testing, the spacecraft will be stored in the production facility until the scheduled time. The spacecraft will then be transported from COSMIC's construction and test facility to the Kennedy Space Center launch site. The Falcon Heavy Expendable currently only launches from Launch Pad 39-A. Once arrived, the spacecraft will be received and prepped for fueling using a third-party vendor. After fueling has finished, the spacecraft will be transported to the SpaceX Payload Processing Facility (PPF). The integration and test team will conduct a full checkout of each spacecraft before integration to the launch vehicle. After this checkout for the spacecraft's health and functionality is completed, the spacecraft will be integrated into the launch vehicle by SpaceX. One spacecraft will be ready to launch by October 9, 2029 (labeled Spacecraft A) with a window of plus or minus one week, and another spacecraft will be prepared to launch by January 3, 2030 (labeled Spacecraft B) with a window of plus or minus one week. As a result, the GS will be equipped with the necessary personnel, communication network, and software for launch. Once the payloads and launch vehicles are verified for launch, the mission will move into the next phase.

This phase will be conducted through the launch services of SpaceX using the Falcon Heavy Expendable. The launch site will be secured and scheduled two years before launch.

Time Completed	Event in Phase 0: Prelaunch
November 2021	Spacecraft A Production Begins
January 2022	Spacecraft B Production Begins
January 2025	Spacecraft A Integration Begins
April 2025	Spacecraft B Integration Begins
August 2028	Spacecraft A Finishes Integration
November 2028	Spacecraft B Finishes Integration
Fall 2029	Spacecraft A is transported to the launch site.
Two months prior to Launch Date	Spacecraft A Launch Vehicle Integration Begins
October 9, 2029, with a window of plus or minus one week	Spacecraft A Launch Date
Two months prior to Launch Date	Spacecraft B is transported to the launch site
Before Fall 2029	Spacecraft B Launch Vehicle Integration Begins
January 3, 2030, with a window of plus or minus one week	Spacecraft B Launch Date

Table 1. Timeline Breakdown of Phase 0: Prelaunch

2.2.1 Phase 1: Launch

After **Phase 0: Prelaunch**, the launches of both spacecraft will occur. As mentioned previously, SpaceX's Falcon Heavy Expendable will be used to launch the first spacecraft on October 9, 2029 (with a window of plus or minus one week), and the second spacecraft on January 3, 2030 (with a window of plus or minus one week). The launch for each spacecraft will follow the process outlined in **Section 2.2.1.1**.

2.2.1.1 Spacecraft Launch Process

Prior to launch, the thermal subsystem will be powered on to maintain connection and provide the spacecraft status during prelaunch and launch. The power subsystem will also be switched on to provide battery power to the thermal subsystem. Also, the spacecraft will be thermally controlled by SpaceX's pad air conditioning while awaiting launch. To meet SpaceX requirements (as directed by the **SpaceX Falcon User's Guide**) and minimize spacecraft battery power consumption, no other subsystems will be powered on until spacecraft separation from the Falcon Heavy. The spacecraft will be linked to the second stage of the Falcon Heavy using a provided standard electrical interface. While it is attached to the launch vehicle, the spacecraft's communication subsystem will be powered off, and all telemetry and health data will be provided through the Falcon Heavy's second stage with the catenary umbilical quick disconnect. After launch, the spacecraft will arrive at its first predetermined orbit and separate from the second stage of the Falcon Heavy while it is in its "stowed" configuration.

2.2.1.2 Detumble Operations

After separation from the launch vehicle, the spacecraft will be powered only through batteries until the ROSAs are deployed. The spacecraft will then enter System Fault Protocol as outlined in **Section 4.1**. Once the rate nulling has been achieved and communication with ground system has been established, the ROSAs will begin deployment. First, the non-explosive actuators will release the ROSAs at their fixed points of contact with the bus of the spacecraft. Next, the pre-loaded hinges attached to the Solar Array Drive mechanisms rotate the ROSAs out 90 degrees. Then the ROSAs "roll out" to their final deployed configuration. After the ROSAs have been deployed, they will be commanded to rotate via the solar array drive assemblies towards the Sun. The lens cap on the primary telescope will then be actuated to a non-obstructive position, and the spacecraft will be powered through the ROSAs.

2.2.1.3 Ground System Operations During Launch

During launch, all communication with the GS will operate through the LV. Once the spacecraft is deployed, there may be a loss of contact with the spacecraft until it can communicate with NASA's Deep Space Network (DSN). The spacecraft will then communicate with the GS using the DSN with an uplink and downlink frequency in X-Band while using the high gain antenna (HGA).

2.2.2 Phase 2: Preposition Orbital Insertion

Once Spacecraft A has completed the detumble operations outlined in **Section 2.2.1.2**, Phase 2: Preposition Orbital Insertion will begin. The initial orbit of Spacecraft A will be heliocentric at 1 AU with a 2.5-degree inclination, a right ascension of the ascending node (RAAN) of 193 degrees, and an argument of periapsis of 270 degrees. The spacecraft will start with an inclination of 2.5-degrees through each launch achieving a C3 of 2 km/s. Over the next year, the GS will command Spacecraft A to complete two gravity assists around Earth to increase inclination. The gravity assists will occur every six months per spacecraft. Spacecraft B will follow the same procedure, but with an argument of periapsis of 0 degrees and a RAAN of 103 degrees. In their final prepositioned orbits, both spacecraft will be at an inclination of 21 degrees. Both spacecraft will also be emplaced in their final orbits before 2031.

Spacecraft	Semi-Major Axis (AU)	Start Inclination (Degrees)	End Inclination (Degrees)	Eccentricity	RAAN (Degrees)	Argument of Periapsis (Degrees)
First Launch	1	2.5	21	0.0167	193	270
Second Launch	1	2.5	21	0.0167	103	0

***Table* 2. Orbital Parameters of Each Spacecraft**

2.2.2.1 Gravity Assists to Prepositioned Orbit

The mission will have each spacecraft complete two gravity assists around Earth on the way to the final prepositioned orbits to increase inclination to 21 degrees. The gravity assists are bounded at a minimum altitude of 1000 km. Currently, the gravity assists and orbital trajectory to the final prepositioned orbits is not modeled. It is assumed that the gravity assists will achieve the desired Classical Orbital Elements (COEs) for each spacecraft. Moving forward, this orbital trajectory and gravity assists will be studied and modeled.

2.2.2.2 Ground System Interactions During Orbital Insertion

Throughout emplacement, each spacecraft's ADCS will point the HGA to Earth to communicate using the DSN once a week for 4-8 hours per each communication. During this time, each spacecraft's position will be determined and confirmed using radiometric tracking techniques. A health status will also be downlinked to GS for analysis. If attitude adjustments are necessary, the GS will send commands back to the spacecraft to make corrections.

Throughout Phase 2: Preposition Orbital Insertion, the customer will have the option to complete the secondary science objectives of B.3 Remote Observation Platform and B.5 Exoplanet Platform. Observation campaigns performed during this phase will also allow for calibration of the telescope before the final prepositioned orbit. Phase 2: Preposition Orbital Insertion will conclude once Spacecraft B has been emplaced into its final prepositioned orbit.

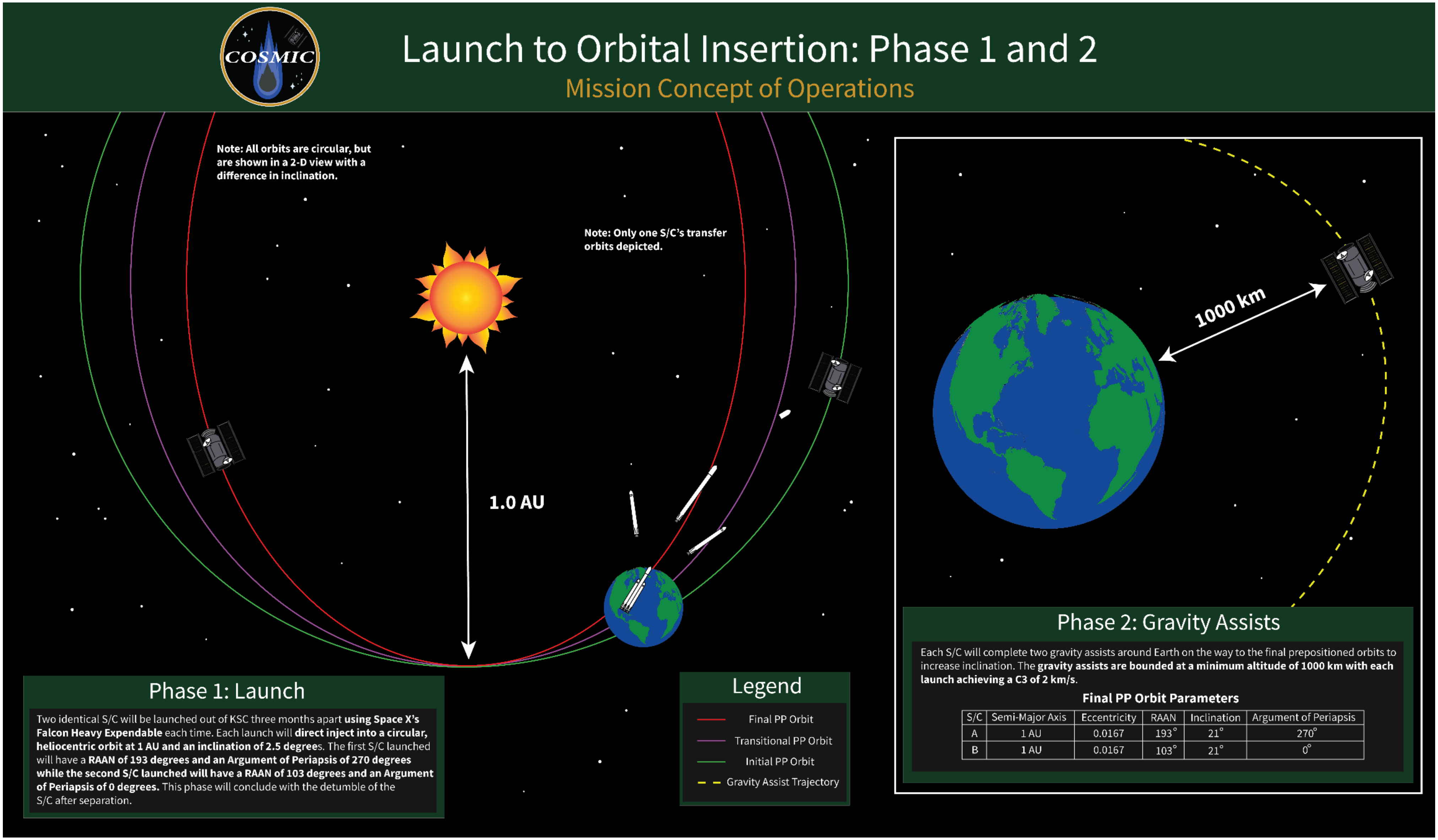

Figure 8. Orbital Insertion Infographic

2.2.3 Phase 3: Prepositioned Orbit Waiting Period

Once the spacecraft are in their prepositioned orbits, there will be a waiting period until an ISO is chosen. During this time, each spacecraft will be commanded by the GS to conduct secondary objectives B.3 Remote Observation Platform and B.5 Exoplanet Platform. This phase will begin and end at different times for each spacecraft due to their different launch dates. Once a candidate ISO is selected, the Secondary Spacecraft (SES) will continue observations while the Encounter Spacecraft completes Phases 4 through 6. Each spacecraft will be designed to last in the prepositioned orbit for a minimum of 20 years due to **Customer Solicitation**.

2.2.3.1 Completing B.3 Remote Observation Platform

To meet B.3 Remote Observation Platform, the spacecraft will observe objects for 2-4 weeks at a time. These will be follow-up observations on known near-Earth objects and will alternate with B.5 Exoplanet Platform campaigns outlined in **Section 2.2.3.2**. Images will be acquired with the primary telescope so that the target is observable with an SNR greater than or equal to 2.5, based on near-earth objects or heliocentric orbiting bodies. These observations will provide further knowledge of the targets to the scientific community, potentially used to derive spin rates, or see how their orbits change over time.

2.2.3.2 Completing B.5 Exoplanet Platform

To complete B.5 Exoplanet Platform, each spacecraft will perform follow-up science on known exoplanets for 2-4 weeks at a time, acquiring images every 30 minutes to build light curves that will be analyzed on the ground to look for exoplanet transits. Targets will be selected based on known exoplanets with an apparent magnitude of their stars brighter than Magnitude 14.43 to ensure the transits are observable. This follow-up science will provide greater knowledge of these exoplanets and their orbital characteristics.

2.2.3.3 Station Keeping

Station keeping while in the prepositioned orbit is necessary to correct the perturbing effects of SRP and maintain the opportunities for Earth gravity assists provided by the nominal spacecraft orbit. The station keeping maneuvers are designed for DV minimization with the routine, weekly DSN communication schedule: The spacecraft will spend one week on-orbit. It will then perform a chemical propulsion burn to start a three-week transfer back to the nominal orbit. When the spacecraft arrives back on the nominal orbit at the end of the transfer, it will perform a second burn to end the transfer. The spacecraft will conduct this 4-week station keeping cycle for the entirety of its time in the prepositioned orbit. It will require 45 m/s of DV to maintain this station keeping scheme for one spacecraft for 20 years.

2.2.3.4 Ground System Interactions

Each spacecraft will continue to communicate with the DSN once a week for 4-8 hours per each communication. During this time, each spacecraft's position will be determined and confirmed using radiometric techniques, and an overall health check of the spacecraft will be completed. Furthermore, the customer will have the option to pursue either a remote observation campaign or an exoplanet platform campaign with each spacecraft. Once the customer chooses a campaign to pursue, the GS will prepare a set of commands for the spacecraft to be uplinked. During the weekly scheduled communication time with the spacecraft, the GS will uplink these commands. Once the spacecraft has finished the selected campaign, the data will be downlinked to the GS using Ka-Band to be processed and stored. After this, the data will be made available to the customer.

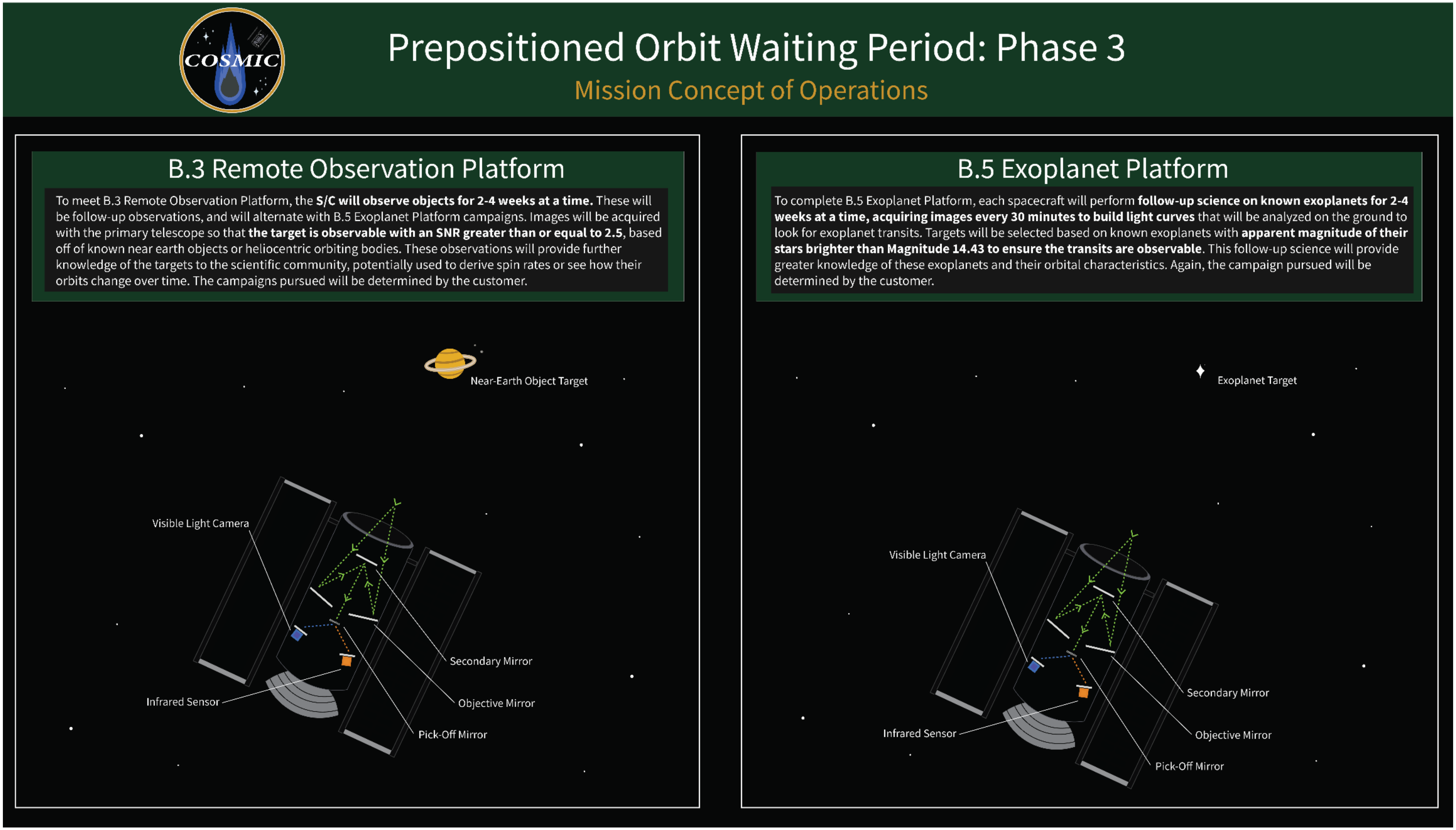

Figure 9. Secondary Science Infographic

2.2.4 Phase 4: Navigation to Interstellar Object

Once an interstellar object is identified, the COSMIC team will analyze orbital parameters and required delta-V for each spacecraft to reach it. After a waiting period of at least three days, the GS will command the spacecraft with a higher likelihood of completing the primary objectives (renamed the Encounter Spacecraft (ES)) to leave its prepositioned orbit and begin its third gravity assist around Earth. In some cases, the ES might have to leave its prepositioned orbit earlier or much later than these three days to use the necessary gravity assist. From here, the ES will travel to the ISO while being guided by the GS and optical navigation until it is 55000 km from the ISO. Once the ISO resolves as larger than one pixel in the APIC, the ES will be guided using autonomous optical navigation (AON). This marks the end of Phase 4, and the mission will move into **Phase 5: Interstellar Object Flyby**.

The spacecraft that remained in its prepositioned orbit is renamed the Secondary Spacecraft and will continue to complete secondary science until it is moved into **Phase 7: Decommission**.

2.2.4.1 Qualifications for Interstellar Object and Choosing Encounter Spacecraft

After an interstellar object has been detected, the trajectory will be analyzed using the process described in **Section 1.4 Interstellar Object Coverage** by the GS. The GS will then determine if either spacecraft can successfully encounter the ISO. If neither can, the ISO is deemed impossible to encounter and ignored by the COSMIC team. If only one spacecraft can, that spacecraft is selected for ISO encounter and will be ordered by the GS to leave its PP orbit. If both spacecraft can, the GS will analyze which spacecraft would require the least amount of change in velocity (DV) and that spacecraft will be selected for ISO encounter.

2.2.4.2 Exiting Preposition Orbit and Third Gravity Assist

Once an interstellar object has been chosen for encounter and the spacecraft with the best chance of encounter has been selected, the GS will command the ES to use a small magnitude burn (roughly 200 m/s) to leave its PP orbit. Based on the necessary gravity assist, the GS will later command the ES to conduct an additional small magnitude burn to begin this gravity assist. The gravity assist will be bounded at the closest approach of 1000 km and will last between 43 and 48 hours. The relative speed to the Earth will be between 10 to 16 km/s. This gravity assist will lower the DV required for ISO encounter.

2.2.4.3 Travelling to Interstellar Object

The ES will be guided to the ISO by the GS and using the primary telescope to perform optical navigation. The ES will continue like this until the APIC navigation camera can resolve the ISO as larger than one pixel on its CMOS board (assumed to be at 55000 km away from the ISO). The GS will order the ES to switch between pointing at the ISO with the primary telescope and pointing at Earth with the HGA for communication. Once it is in range of the ISO, the Encounter Spacecraft will be commanded by the GS to conduct a high magnitude burn (up to 4.1 km/s) to assist in the ISO flyby occurring in **Phase 5: Interstellar Object Flyby**.

After the GS switches the ES to AON, the propulsion subsystem will be turned off, and no further burns will be conducted to reduce image blur and light contamination while collecting data. **Figure 10. Burn Order Model** depicts a simulation of what the three burns in this phase might look like when pursuing one of the modeled ISOs from the case studies in **Section 1.4 Interstellar Object Coverage**.

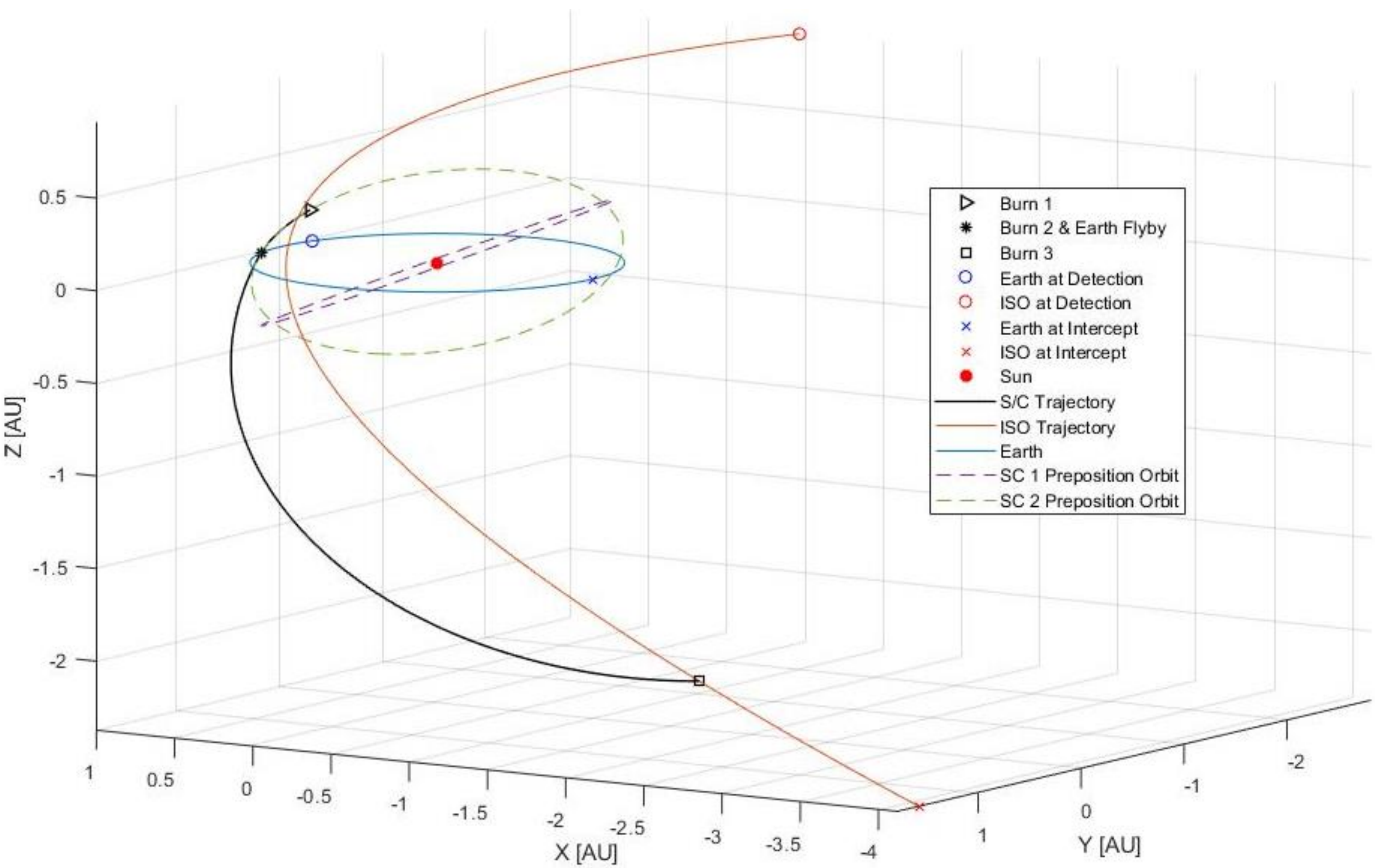

Figure 10. Burn Order Model

2.2.4.4 Ground System Interactions and Encounter Spacecraft Operations

During the OpNav segment, the HGA will be pointed towards Earth to communicate with the GS when it needs to send or receive data. While during travel, the primary telescope will be pointed at the ISO, and the propulsion subsystem will be pointed in the perpendicular direction.

Major Event	Encounter Spacecraft Operations	Ground System Interactions
ISO Detection and Selection	ES waits in its PP orbit for an ISO to be selected.	After an ISO is detected by a third-party, the orbital data and trajectory are provided to GS. The GS team will verify that this is a desirable ISO.
End of ISO Waiting Period	ES receives ISO data and prepares for the third GA.	Three days after ISO selection, GS will communicate to ES to tell it the ISO has been selected and where it is.
Beginning of Third Gravity Assist	ES uses a burn to leave its PP orbit and a second burn to begin its third GA.	ES Leaves PP Orbit and Begins Third Earth Gravity Assist.
End of Third Gravity Assist	ES finishes the third GA.	GS updates ES on its location.
End of ISO Travel	ES uses a high magnitude burn to put it on a trajectory towards the ISO.	GS updates ES on ISO location and trajectory.
ES is 55,000 km Away from ISO	ES begins using autonomous optical navigation.	GS stops communicating with ES until the completion of the flyby.

Table 3. Event Breakdown of Phase 4: Navigation to Interstellar Object

2.2.5 Phase 5: Interstellar Object Flyby

During this phase, all primary objectives will be completed, including a portion of the secondary objective of B.1 Advanced Object Definition. The ES will begin Autonomous Optical Navigation (AON) at 55000 km away from the ISO on the inbound trajectory. At this time, the spacecraft will be automated until the end of primary science conduction. Therefore, communication with GS will cease. At 4000 km away from the ISO, the infrared (IR) sensor will begin taking images of the ISO surface. At 2000 km away, the telescope will switch to visible images. The spacecraft will move at a maximum relative velocity with the ISO of 13 km/s and slew with the ISO at an acceleration rate of 0.0393 rad/s^2. Once the ES is 800 km away from the ISO, SAR will begin taking snapshots of the surface every three degrees of angle between the ISO and spacecraft. The closest approach will be 400 km. When the spacecraft is 800 km away from the ISO on the outbound trajectory, SAR will stop taking data. The telescope will switch back to IR imaging at 2000 km, and all primary science will conclude at 4000 km away from the ISO on the outbound trajectory. The total amount of time for the telescope to collect data is 11 minutes and 14 seconds with a 3 minute and 30-second margin.

Timeline	Event in Phase 5: Primary Science Conduction
T – 5 min 25 sec +/- 53 sec	IR imaging begins, primary science conduction begins
T – 2 min 35 sec +/- 32 sec	IR imaging stops, visible imaging begins
T – 1 min 1 sec +/- 21 sec	SAR begins, visible imaging continues
T – 0 sec	Closest Approach Distance
T + 1 min 1 sec +/- 21 sec	SAR ends, visible imaging continues
T + 2 min 35 sec +/- 32 sec	Visible imaging stops, IR imaging begins
T + 5 min 25 sec +/- 53 sec	IR imaging stops, primary science conduction ends

Table 4. Timeline Breakdown of Phase 5: Interstellar Object Flyby

Parameter	Range
Maximum Encounter Spacecraft Relative Velocity to ISO	13 km/s
Distance from ISO AON Begins	55000 km
Primary Telescope Begins Taking IR Images	4000 km away from ISO on inbound trajectory
Primary Telescope Begins Taking Visible Images	2000 km away from ISO on inbound trajectory
SAR Begins	800 km away from ISO on inbound trajectory
Closest Approach Distance	400 km
SAR Ends	800 km away from ISO on outbound trajectory
Primary Telescope Stops Taking Visible Images	2000 km away from ISO on outbound trajectory
Primary Telescope Stops Taking IR Images	4000 km away from ISO on outbound trajectory
Encounter Duration	11 min and 14 sec +/- 3 min and 30 sec
Maximum Distance from Sun at Closest Approach	5 AU
Number of SAR bursts	41
Maximum Slew Acceleration Rate	0.0393 rad/s^2
Total Amount of Data Taken	469 MB

Table 5. Parameters of Phase 5: Interstellar Object Flyby

2.2.5.1 Using Autonomous Optical Navigation on the Inbound Trajectory
After the ISO resolves larger than one pixel in the APIC imager, AON will begin. The ES will autonomously process the images produced by the APIC camera as it images at 15-second intervals. These processed images will be used to produce an orbital determination update to the ISO's relative ephemeris once every minute. The updated ISO ephemeris will guide the ES's pointing throughout the encounter.

2.2.5.2 Slewing the Encounter Spacecraft
During this phase, the ES will slew with the primary telescope boresight to the ISO. This will be completed using the onboard Control Moment Gyroscopes (CMGs). The maximum slew acceleration rate using the parameters contained in **Table 5. Parameters of Phase 5: Interstellar Object Flyby** will be 0.0393 rad/s^2.

2.2.5.3 Primary Telescope and SAR
The primary telescope will be of a Cassegrain design with a field-of-view (FOV) of 0.55 degrees. The telescope will contain an infrared and visible imager along with a pick-off mirror. The pick-off mirror will allow the telescope to switch between infrared and visible images. Along with the primary telescope, SAR will be used to take snapshots of the ISO surface around every 3 degrees between the ISO and ES for a total of 41 times between distance ranges of 800 km inbound and 800 km outbound. The SAR will be deployed at the start of AON.

2.2.5.4 Completing Composition Objective
To complete the composition primary objective, the spacecraft will use the infrared sensor and visible light imager. The data will then be sent to GS during **Phase 6: Data Downlink** for processing.

2.2.5.5 Completing Morphology Objective
To complete the morphology primary objective, visible and IR images will be used to create an outline of the ISO. From here, SAR will be used to construct a topography of the surface of the ISO. The images and topography data will be sent to the GS to be processed further to create a full-shape model.

2.2.5.6 Completing Angular Momentum Objective
The spacecraft will use the infrared, visible sensor, and SAR to complete the angular momentum primary objective. Some of the infrared images will be taken during optical navigation. Once the images and data are taken and sent back to GS, they will be processed to meet the requirement for spin axis and rotation rate of the ISO. This objective will also use the time tags kept by the onboard clock and the spacecraft position at the time of each data capture.

2.2.5.7 Completing Partial B.1 Advanced Object Definition
To complete the partial secondary objective of B.1 Advanced Object Definition, the telescope will take visible and IR images of the ISO. Finally, SAR will be used to provide the dielectric constant of the ISO and an advanced shape model. The ES will not complete science on the dust flux of the ISO or the plasma environment of the potential coma. This is because the added instruments that would be vital to conducting the science add unnecessary mass to our system. The mass that would be added would limit the propulsion system on the spacecraft.

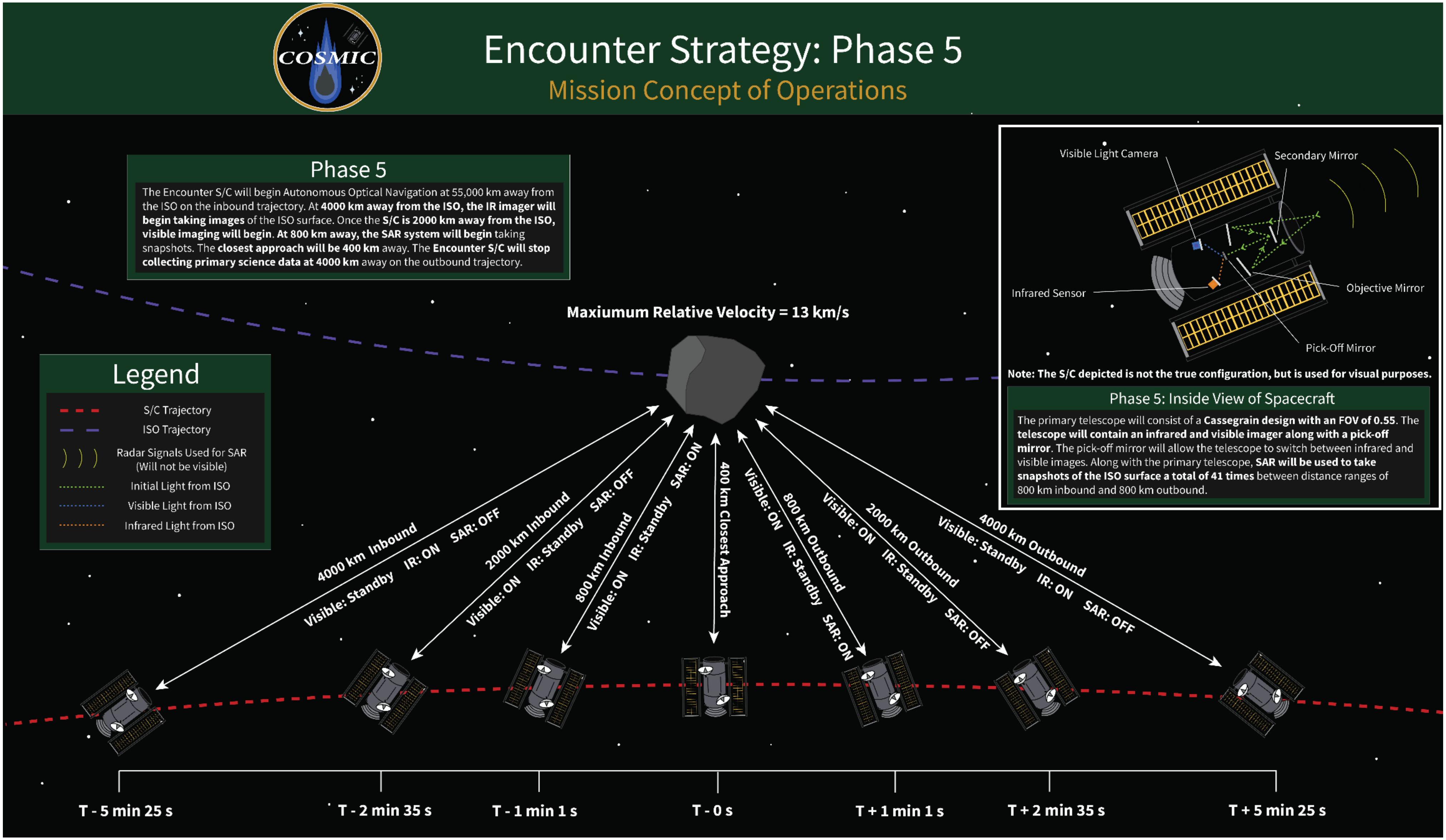

Figure 11. ISO Encounter Infographic

2.2.6 Phase 6: Data Downlink

Phase 6: Data Downlink will be entirely devoted to primary science data downlinking. The GS will set the ES to focus power on the telecom and C&DH subsystems in order to maximize the downlink data rate. The GS will command the ES to focus on gathering power through its solar arrays and maintaining attitude control for the next downlink session between downlinking sessions. Should additional downlinking time become available, the GS will be able to have the ES immediately resume downlinking data as it constantly pings Earth during this phase. Should data be corrupted in transmission, the telecom turbocode encoding scheme and onboard memory addresses will allow replay of any and all data as requested by the GS. Once all information has been downlinked, the GS will manually command the spacecraft to move into **Phase 7: Decommission**.

2.2.7 Phase 7: Decommission

After the data is downlinked to the COSMIC GS, the mission can move into Phase 7: Decommission. During this phase, the mission will be closed out, and each spacecraft will be decommissioned.

2.2.7.1 Encounter Spacecraft Decommission Plan

After the Encounter Spacecraft has completed its data downlink, the customer can either choose to attempt one of the extended mission scenarios outlined in **Section 3** or move directly into decommission. Since the ES will be in deep space and in a heliocentric orbit (could also be a hyperbolic trajectory), the GS will decommission the ES following the decommission process outlined below in **Section 2.2.7.3**.

2.2.7.2 Secondary Spacecraft Decommission Plan

If the customer decides to pursue one of the extended mission scenarios outlined in **Section 3**, the Secondary Spacecraft will follow the same decommission plan as the Encounter Spacecraft (outlined in **Section 2.2.7.1**). However, if the Secondary Spacecraft stays in its preposition orbit for 20 years, its telemetry and health data will be analyzed and presented to the customer. If the SES is in good condition, the customer then can either outsource the spacecraft or begin the decommission process outlined in **Section 2.2.7.3**. If the SES is not in good condition, it will begin the decommission process. Additionally, if at any point before the 20-year timespan is up the SES is in bad condition, it will begin the decommission process.

2.2.7.3 Decommission Process

Once one of the spacecraft is deemed ready for decommission, the GS will verify that it has received all collected data from the spacecraft, and it is in a safe graveyard orbit. The GS will then transmit the following decommission orders to the spacecraft in one package, then command it to run the orders.

Order	Decommission Activity
1	Dump remaining propellant from tanks and lines.
2	Vent pressurant from tanks and chambers to safe levels.
3	Turn off payload and science instrumentation.
4	Turn off ADCS and GNC equipment.
5	Turn off radiators and additional thermal equipment.
6	Turn off communications equipment.
7	Discharge batteries and power subsystem.
8	Turn off solar arrays.

Table 6. Decommission Activities

2.2.7.4 Mission Close-Out

After the spacecraft have downlinked their data, this data can then be processed and provided to the customer. This step can happen before or after each spacecraft has been decommissioned, based on customer preference. Once all of the data is provided to the customer, and both spacecraft have been decommissioned, the COSMIC mission has been completed and will be closed out.

3.0 Extended Mission Scenarios

Since the ISO trajectory will remain unknown until the mission is conducted, two scenarios for the Encounter Spacecraft and one scenario for the Secondary Spacecraft could extend the mission. Each of these extended mission concepts would need to be approved by the customer since they are outside the scope of the **Customer Solicitation** and mission objectives. The extended missions would provide additional science that would further the goals of the mission. Additionally, these provide the customer with the possibility to use the spacecraft to complete science for third parties requesting similar science.

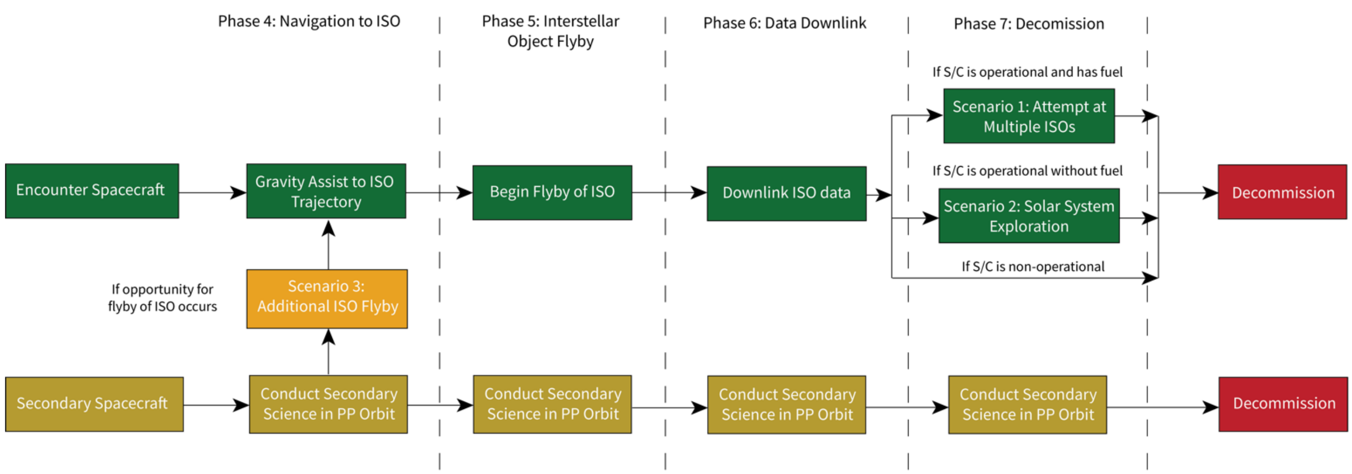

Figure 12. Flowchart of Extended Mission Scenarios

3.1 Scenario 1: Attempt at Additional ISO

In the event the Encounter Spacecraft is left with fuel for its propulsion systems and is operational at over 5 AU, the Encounter Spacecraft will wait for an opportunity to flyby a different ISO to collect more data. At this range, the Encounter Spacecraft will have less power, and therefore the data collected will be determined based on the potential power supply of the spacecraft and the power draw of the instruments. This scenario assumes power, communication, and propulsion limits have not been reached, and the scenario will continue until those conditions are met. Once the Encounter Spacecraft limits are reached, the spacecraft will move into decommission, as outlined in **Phase 7: Decommission**.

3.2 Scenario 2: Solar System Exploration

If the Encounter Spacecraft is operational at over 5 AU and has no fuel left, the Encounter Spacecraft will pivot its mission to solar system exploration. After **Phase 6: Data Downlink,** the spacecraft will likely be on a trajectory towards deep in our solar system. During this time, the Encounter Spacecraft will take images and gather data on planets and objects within the solar system. Once again, this scenario assumes power and communication limits have not been reached. As the limits are reached, the spacecraft will move into decommission, as outlined in **Phase 7: Decommission**.

3.3 Scenario 3: Secondary ISO Encounter

Should the opportunity to flyby an additional ISO present itself, the Secondary Spacecraft will move into **Phase 4: Navigation to Interstellar Object**, where it will move through the rest of the mission until decommissioned or the previously extended mission scenarios. This will provide the customer with an additional opportunity at an ISO encounter with a separate data set. The likelihood that this scenario could happen would be 40%.

4.0 Spacecraft Fault and Recovery Methods

4.1 System Fault Protocol

The spacecraft will enter system fault mode under the conditions in the Fault Mode Causes table. Once the spacecraft enters the system fault mode, all the components will enter their power on/off configuration, other than the solar array drives, which will remain on. The IMUs will determine any angular velocity to the spacecraft and nullify it using the secondary thrusters. Once stabilized, the system will check that the solar arrays are deployed, where if the solar arrays are not deployed, they will be triggered to do so and set as deployed. The solar arrays should only be deployed once following separation. Using the sun sensors, the spacecraft will locate the Sun, and point the solar arrays at the Sun. The spacecraft will then position the HGA face to be sun pointing. Once the solar arrays and HGA face are Sun pointing, the solar array drives will lock. The communication system will toggle from the HGA to the communication antenna for the current phase. The communication antenna will be defined by the GS during normal communications, to be updated based on the relative location of the Earth to the spacecraft for the current phase. The fault system will use either medium gain antennas (MGAs) or low gain antennas (LGAs). The spacecraft will begin transmitting that it has entered the system fault protection mode with a system-wide health check data package with a value from every health sensor, which requires 812 bytes of data. Using the secondary thrusters, the spacecraft will rotate about the Sun pointing vector (through the HGA boresight) at 3 deg/min or one full rotation in 2 hours, which will give multiple passes during the 4-8 hour scheduled period with the DSN. This rotation rate will give a capable communication period of 26 minutes during the prepositioned orbit using the LGA, a 10-minute minimum at 2AU using MGAs, a 20-minute minimum at 4AU using MGAs, and a 44-minute minimum at 7AU using MGAs. Given these communication periods, the spacecraft will be able to transmit the data package multiple times completely. Once in this configuration, the spacecraft will await commands from the ground system. The spacecraft will be thermally stable, power positive, and communications capabilities while in the system fault mode.

Fault Mode Causes
C&DH does not receive confirmation that a mission-critical command was performed
C&DH does not receive confirmation on any attitude commands
C&DH does not receive confirmation on any positioning commands
C&DH reboots for any unexpected reason
For power cycle issues
If a health sensor is outside of survival range
Following separation from the launch vehicle

Table 7. Fault Mode Causes

Subsystem	Components	Power	Function		
			Preposition	1AU to 2AU	2AU to 6AU
Payload	SAR	OFF	Inactive during system fault protection mode		
	Imager	OFF	Inactive during system fault protection mode		
	Health sensor	ON	Reporting health data		
Propulsion	Primary props	OFF	Inactive during system fault protection mode		
	Secondary thrusters	ON	Will perform attitude control		
	Plumbing & valves	ON	Will be performing nominally		
	Propellant	ON	Will be performing nominally		
	Health sensor	ON	Reporting health data		
Power	ROSA panels	ON	Will provide power to the system		
	Battery	ON	Will provide power to the system initially in the case that the solar panels are not sun-facing to start		
	Health sensor	ON	Reporting health data		
Thermal	Electrical resistance heater	ON	Will keep the system thermal stable		
	Health sensor	ON	Reporting health data		
Comms	HGA	N/A	Inactive during system fault protection mode		
	MGAs	N/A	Inactive during preposition	Inactive from 1AU to 2 AU	Will perform comms functions
	LGAs	N/A	Will perform comms functions	Will perform comms functions	Inactive from 2AU to 6 AU
	Deep Space Transponders	ON	Will be performing nominally		
	Travelling Wave Tube Amplifiers (Ka)	OFF	Inactive during system fault protection mode		
	Travelling Wave Tube Amplifiers (X)	ON	Will be performing nominally		
	Ultra-Stable Oscillator	ON	Will be performing nominally		
	Health sensor	ON	Reporting health data		
GNC	APIC	OFF	Inactive during system fault protection mode		
	Health sensor	ON	Reporting health data		
Structures	Solar Array Drive Assemblies	ON/OFF	Will rotate the solar arrays to be Sun facing, then lock once the HGA face and solar arrays are Sun-facing		
	Health sensors	ON	Reporting health data		
ADCS	CMGs	ON	In quasi-static mode		
	Star trackers	ON	Will be performing nominally		
	Coarse sun sensors	ON	Will be used to determining the location of Sun		
	IMUs	ON	Will be performing nominally		
	Health sensors		Reporting health data		
C&DH	Combined enclosure	ON	Will be performing nominally		
	Health sensor	ON	Reporting health data		

Table 8. Fault System Configuration

4.2 Standby

The standby phase is activated when GS deems it necessary because a change in the mission is required. Most of the spacecraft subsystems remain active until it is given instructions from GS to continue the mission.

Subsystem	Activity
Payload	Off
Propulsion	Off
Power	On
Communications	On
Thermal	On
GNC	On
ADCS	On
Structure	On
C&DH	On, will await commands from GS

Table 9. Standby Activities

Appendix A: Acronyms/Abbreviations and Definitions

Acronym	Definition
ADCS	Attitude Determination and Control Subsystem
AON	Autonomous Optical Navigation
AU	Astronomical Unit
C&DH	Command and Data Handling
CMG	Control Moment Gyroscope
COSMIC	Celestial Object Sensing and Measuring Identification Campaign
DSN	Deep Space Network
DV	Change in velocity required to achieve a maneuver
ES	Encounter Spacecraft
FOV	Field of View
GNC	Guidance, Navigation, and Control
GS	Ground System
HGA	High Gain Antenna
IMU	Inertial Measurement Unit
IR	Infrared
ISO	Interstellar Object
km	Kilometer
LGA	Low Gain Antenna
LV	Launch Vehicle
PP	Prepositioned
RAAN	Right Ascension of the Ascending Node
ROSA	Roll Out Solar Array
SAR	Synthetic Aperture Radar
S/C	Spacecraft
SES	Secondary Spacecraft
TBD	To Be Determined
TBC	To Be Confirmed