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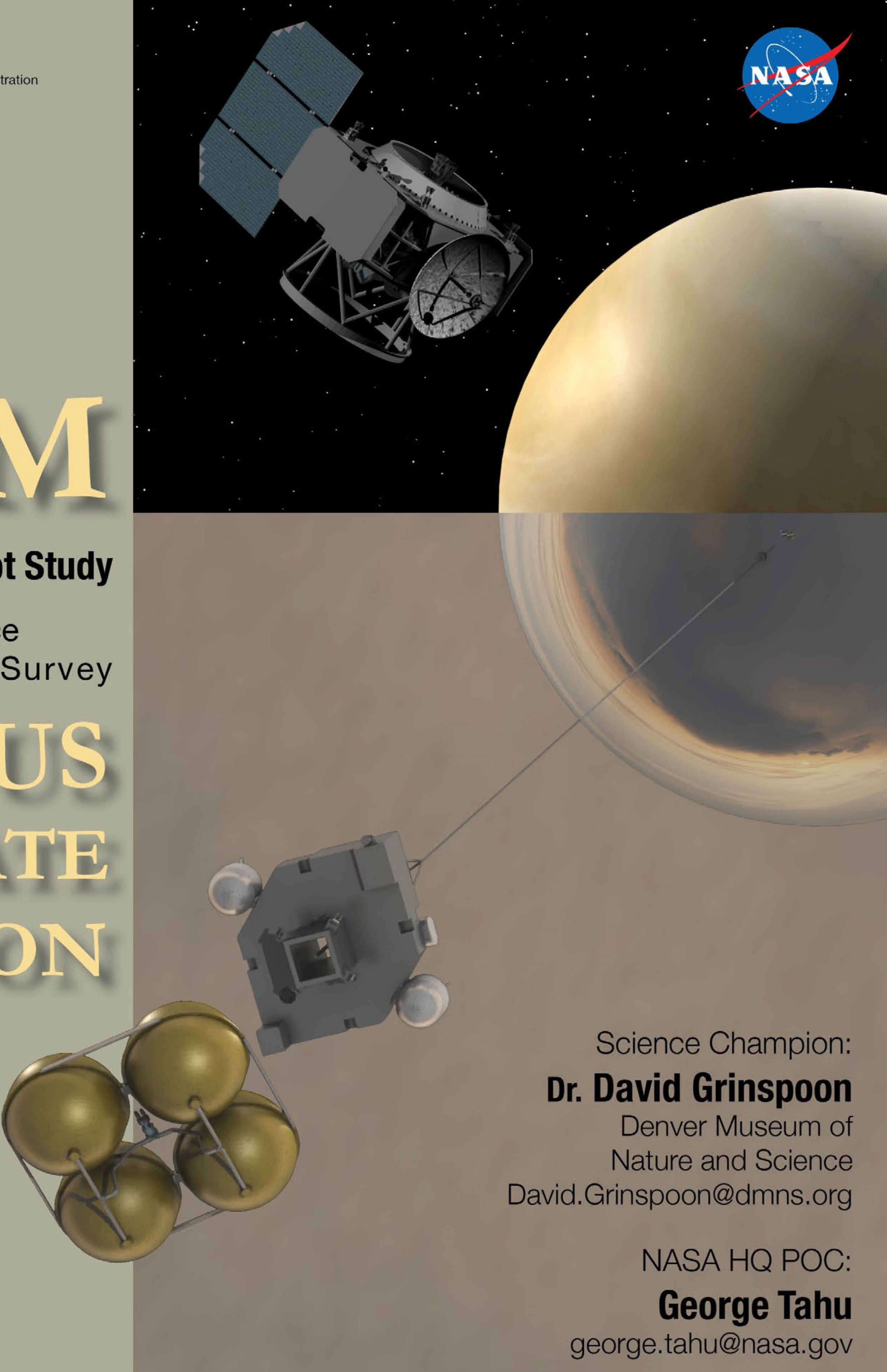


VCM

Mission Concept Study

Planetary Science
Decadal Survey

VENUS CLIMATE MISSION

Science Champion:
Dr. David Grinspoon
Denver Museum of
Nature and Science
David.Grinspoon@dmns.org

NASA HQ POC:
George Tahu
george.tahu@nasa.gov

June 2010

www.nasa.gov

Venus Climate Mission Study

Final Report

Presented to the Planetary Decadal Survey Steering Committee and the Inner Planets Panel

June 2010

David Grinspoon
Science Champion
Denver Museum of Nature & Science

Michael J. Amato
Planetary and Lunar Business Lead
NASA Goddard Space Flight Center

Michael L. Adams
Study Lead
NASA Goddard Space Flight Center

Tibor Balint
Study Lead
Jet Propulsion Laboratory

Venus Climate Mission

VCM

Planetary Science Decadal Survey
Mission Concept Study

VCM Science Objectives

- Characterize the strong CO_2 greenhouse atmosphere of Venus, including variability.
- Characterize the dynamics and variability of Venus's superrotating atmosphere.
- Characterize surface/atmosphere chemical exchange in the lower atmosphere.
- Search for atmospheric evidence of climate change on Venus.
- Determine the origin of Venus's atmosphere and the sources and sinks driving evolution of the atmosphere.
- Understand implications of Venus's climate evolution for the long-term fate of Earth.

Mission Concept Study Report to the NRC Decadal Survey Inner Planets Panel

June, 2010

Concept Maturity Level: 4

Cost Range: Low End Flagship

Launch Date: November 2, 2021

Science Campaign:

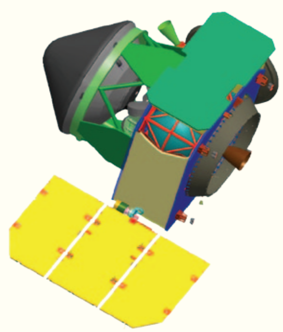
April 7, 2022 - April 28, 2022

Launch Mass: 3,948 kg

Launch Vehicle: Atlas V 551

VCM Science Payload

- Carrier Spacecraft
  - Venus Monitoring Camera Vis-IR
- Gondola/Balloon System
  - Neutral Mass Spectrometer (NMS)
  - Tunable Laser Spectrometer (TLS)
  - Atmospheric Structure Instrumentation (ASI)
  - Nephelometer
  - Net Flux Radiometer (NFR)
- Mini-Probe
  - NMS; NFR; ASI
- Drop Sondes,
  - ASI; NFR



Carrier Spacecraft

Function: Deliver and deploy Entry Flight System; orbit Venus as communication relay for Gondola/Balloon system

Power: 5 m^2 solar panels

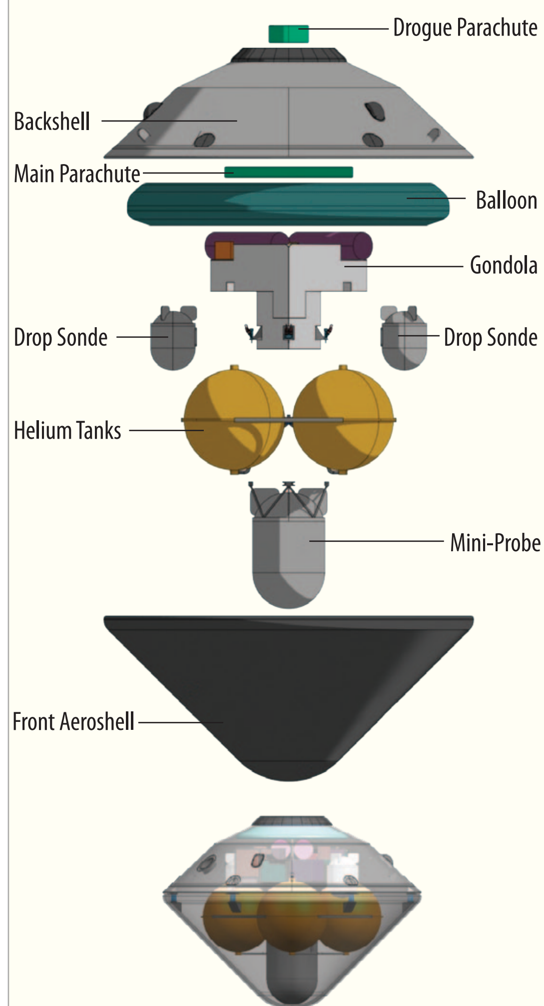
Attitude Control: 3-axis stabilized (Spin up for release of the EFS)

Telecom: 1.7m dia. HGA; two-way S-band comm. with gondola; two-way Ka-band comm. with Earth

Science Data Return: 14 Gb from Carrier Spacecraft Camera plus 142 Mb from Gondola/Balloon System; Mini-Probe and Drop Sondes

Entry Flight System

with Gondola/Balloon System, Mini-Probe and Drop Sondes



Mini-Probe

Function: 45 minute descent from 55.5 km to surface

Power: Distributed rechargeable Polymer Lithium-ion batteries

Telecom: 1 way S-band to gondola

Science Data Return: 5 Mb

Design: 44 cm dia., 66 cm tall titanium pressure vessel, passive thermal control

Drop Sondes (2)

Function: 45 minute descent from 55.5 km to surface

Power: Distributed rechargeable Polymer Lithium-ion batteries

Telecom: One-way S-band to gondola

Science Data Return: 1 Mb (each probe)

Design: 29 cm dia., 35 cm tall titanium pressure vessel, passive thermal control

Entry Flight System

Function: Deliver in situ elements through the atmosphere; carries the Gondola/Balloon System, Inflation System, Mini-Probe and two Drop Sondes

Power: Lithium-thionyl chloride (Li-$SOCl_2$) primary battery

Design: Carbon-Phenolic front shell, Phenolic Impregnated Carbon Ablator back shell, 45 deg cone angle (Pioneer-Venus heritage), 2 m diameter

Gondola/Balloon System

Function: 21 day science campaign at 55.5 km float altitude

Power: Lithium-thionyl chloride (Li-$SOCl_2$) primary battery

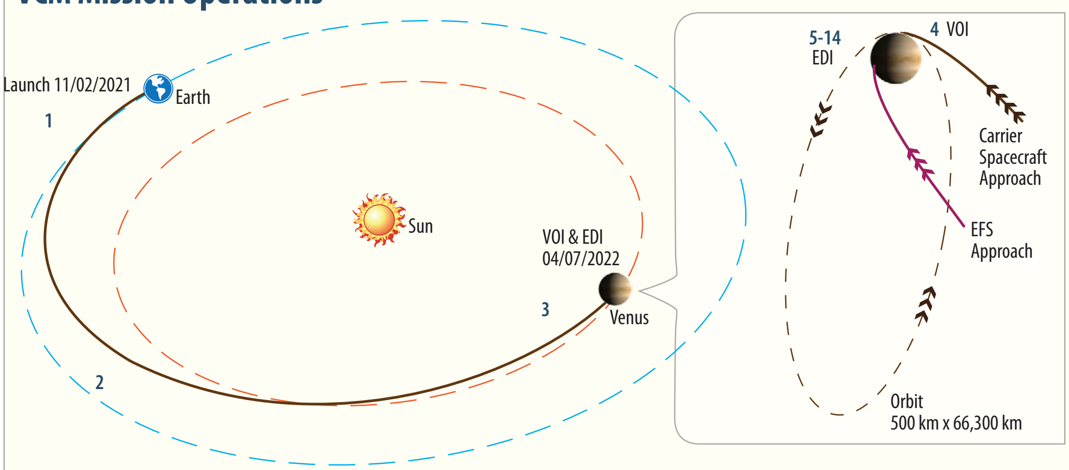
Telecom: Two way S-band (plus Doppler) to Carrier Spacecraft; one way S-band from Mini-Probe and Drop Sondes

Science Data Return: 135 Mb from Gondola science + 7 Mb from Probe & Sondes science

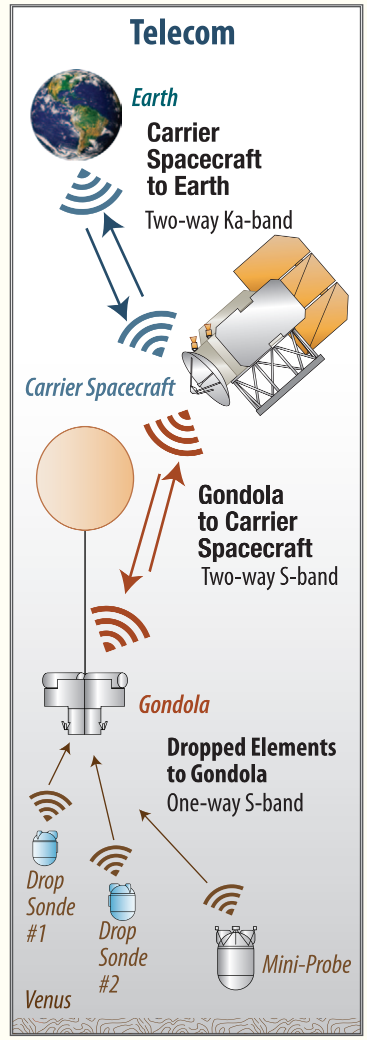
Balloon Design: 8.1 m diameter helium filled balloon; teflon coated for sulfuric acid resistance; Vectran fabric plus Mylar film construction; metalized for low solar heating

Inflation System Design: 4 x 0.5 m dia. titanium tanks; pipes; valves

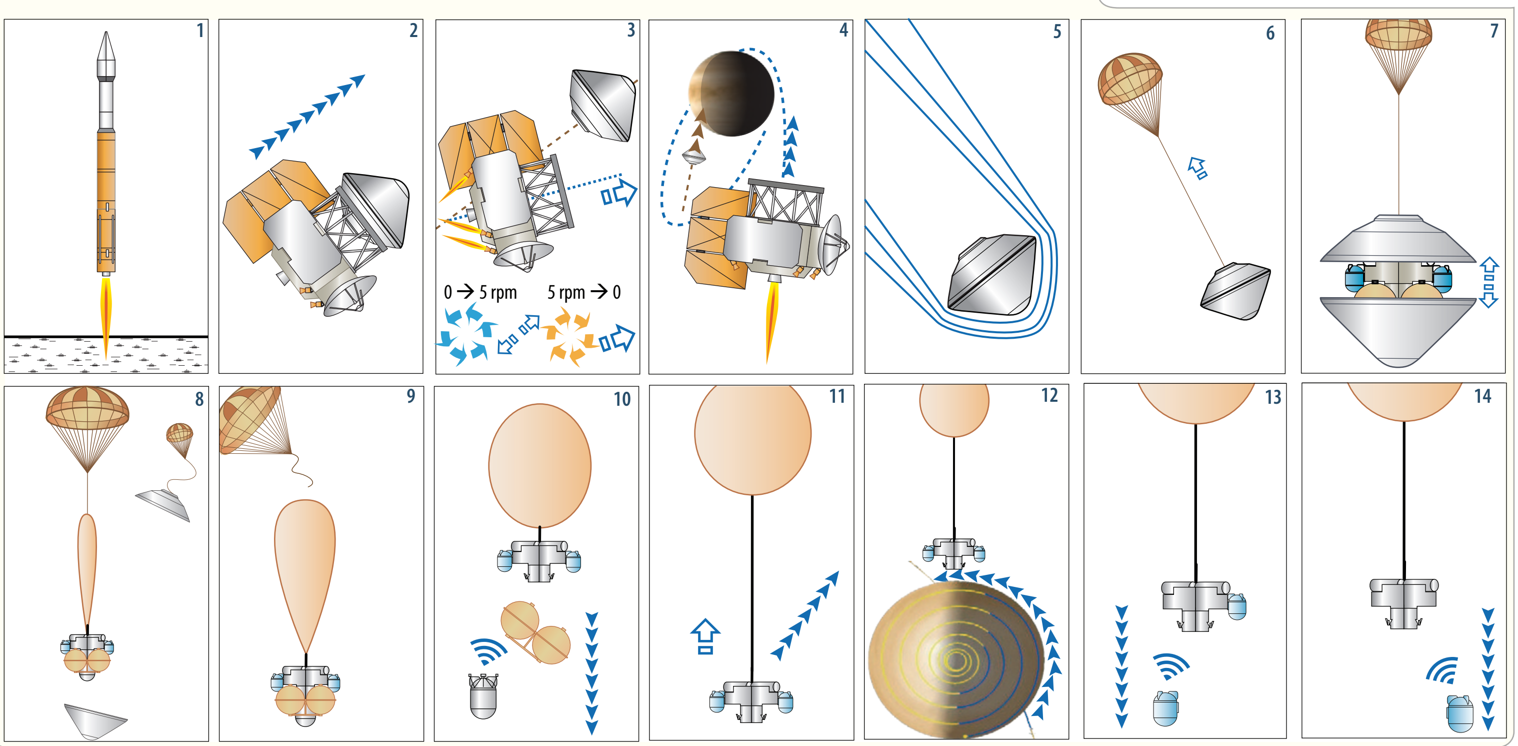
VCM Mission Operations



1. VCM launches in November 2021 on an Atlas V 551 L/V, with a C3 of 8.8 km²/sec², capable of delivering up to 5,141 kg of mass
2. Five month cruise to Venus
3. Ten days prior to Venus entry, the Entry Flight System (EFS) is released with 5 rpm from the Carrier Spacecraft, a day later the Carrier Spacecraft diverts for a Venus Orbit Insertion (VOI) approach
4. Carrier Spacecraft performs VOI and enters an elliptic orbit to provide telecom support to the in situ elements (Gondola, Mini-Probe, two Drop Sondes)
5. EFS reaches atmospheric entry interface at 175 km altitude, decelerates over a minute
6. Drogue parachute opens at subsonic speeds, further decelerates the EFS
7. Aeroshell separates
8. Back and front Aeroshell jettison and Balloon inflation begins
9. Main parachute jettisons
10. Balloon inflation is completed in 5 minutes; Helium inflation tanks are jettisoned and the Mini-Probe is released at 53 km (lowest altitude)
11. Balloon chord extends as the Balloon rises to a float altitude of 55.5 km
12. Balloon begins its 21-day science operation, spiraling toward pole multiple times
13. First Drop Sonde is deployed on command or at a predetermined time
14. Second Drop Sonde is deployed on command or at a predetermined time



Telecom strategies: The Probe and Sondes communicate data on S-band to the Gondola during their 45 min descent; the Gondola sends all science data to the Carrier Spacecraft; the Carrier Spacecraft relays all data (incl. Carrier Spacecraft camera) to Earth on Ka-band.



CONTENTS

EXECUTIVE SUMMARY

The National Research Council's 2010 Planetary Decadal Survey Inner Planets Panel commissioned the NASA Goddard Space Flight Center (GSFC) and the California Institute of Technology Jet Propulsion Laboratory (JPL) to perform a point design study, conducted under NASA Headquarters leadership. The charge is to mature a Venus mission concept capable of studying the Venus climate within a New Frontiers cost range. The NASA Ames Research Center also participated in this study, providing expertise in planetary atmospheric entry.

The Venus Climate Mission (VCM) undertakes a thorough examination of the radiation balance, atmospheric motions, cloud physics, and atmospheric chemistry and composition of Venus. VCM will be the first ever truly 3-dimensional (and to a large extent 4-dimensional, including many measurements of temporal changes) characterization of the Venus atmosphere. Additionally, VCM will collect elemental and isotopic measurements to reveal the origin and evolution of the atmosphere and the evolution of the extreme greenhouse climate. It will gather evidence for the existence, nature and timing of the suspected ancient radical global change from habitable, Earth-like conditions to the current hostile runaway greenhouse climate, with important implications for understanding climate stability and predicting the long term fate of Earth's climate under a future warming Sun.

Launched on an Atlas V 551 launch vehicle in 2021, a Carrier Spacecraft delivers an Entry Flight System (EFS) to Venus in 2022. The EFS carries a Gondola/Balloon System (with its inflation system), a Mini-Probe and two Drop Sondes. After release from the Carrier Spacecraft, the EFS enters the atmosphere, slows with the aid of a parachute, and inflates the balloon to begin its science campaign at an altitude of 55.5 km. Science measurements are conducted over a 21 day campaign as the Gondola/Balloon system circles Venus, drifting toward the South Pole. The Mini-Probe and two Drop Sondes are released from the Gondola/Balloon System during the campaign and descend through the atmosphere collecting data and transmitting this data back to the Gondola/Balloon system. The Gondola/Balloon system transmits data to the orbiting Carrier Spacecraft throughout the science mission and the Carrier Spacecraft in turn transmits this data to Earth.

The cost estimate for the baseline VCM implementation is $1,145 M to $1,577 M in FY15 dollars. This range covers Phase A through Phase E costs and includes a 50% margin and the Launch Vehicle. The assumption for a New Frontiers cost limit for this Decadal Survey Is $1.050 M which places VCM in the low end cost range of a Flagship mission. Additional engineering trades and technology advancements could allow a mission that has a high probability of fitting within a New Frontiers budget. The study utilizes high Technology Readiness Level (TRL) components to minimize both cost and risk. After completing this study, the VCM Concept Maturity Level (CML) is raised from 3 to 4.

1.0 SCIENTIFIC OBJECTIVES

1.1 Scientific Questions and Objectives

Background

Venus presents unique opportunities to study climate on a nearby, active planet that is both surprisingly like Earth and startlingly different. Venus is remarkably like Earth in terms of bulk properties such as size, mass and density. And yet its modern climate has evolved to a state which is dramatically divergent from that of Earth, with a surface temperature and pressure of 763 K and 92 bars, respectively.

Thus Venus presents a fascinating experimental laboratory for studying and modeling climate processes on an Earth-sized world with a strong atmospheric greenhouse and for exploring the role of heliocentric distance and other initial conditions in determining the outcome of climate evolution on an Earth-like planet. Previous spacecraft investigations of Venus, combined with ground based observations, have confirmed the existence of a dynamic, changeable atmosphere with a deep troposphere extending to an altitude of 65 km, a highly variable globally encompassing cloud deck extending from 48 to 70 km altitude, and a complex pattern of global circulation dominated by superrotating winds which circle the globe at a rate up to 60 times faster than the retrograde rotation of the solid planet, with the peak wind velocities at an altitude of 60 km. Other large scale features of the global circulation include Hadley cells in which air rises at low latitudes and travels poleward at high altitudes; and large, complex vortices at both poles where sinking air from the Hadley circulation intersects with the superrotation.

Attempts to model this global circulation using modified terrestrial General Circulation Models (GCMs) have been only partially successful. Such tests have the promise of not only increasing our understanding of the Venus atmosphere and its response to solar radiation, but improving our general knowledge of climate and global circulation on Earth-sized terrestrial planets, including Earth itself. They also serve as a "reality check" on the current generation of terrestrial GCMs and their ability to accurately model climate and circulation on radically altered versions of Earth's climate. In the framework of comparative planetology, climate models and GCMs in particular have taken on a vital role in understanding and predicting the role of anthropogenic forcing in Earth's climate, and separating human from natural influences. The potential role of new spacecraft observations of Venus in improving our ability to accurately model climate on moderately to severely perturbed variations of Earth's current climate is thus extremely valuable. Several efforts to model climate on Venus using terrestrial GCMs have reproduced the gross properties of the Venusian global circulation. These efforts have also revealed that various components of terrestrial GCMs are "hard coded" with empirically-derived assumptions that are at best only accurate for the current terrestrial climate. Many of these assumptions are hidden within complex "black boxes" of code that are not always obvious to the modelers using the code. Thus pushing the codes near to, or beyond, the breaking point by applying them toward the problem of Venus helps to improve the veracity and reliability of these models for terrestrial applications. Recent progress shows that different models can partially reproduce the superrotation with different starting assumptions. At this point our ability to greatly improve upon these efforts is hampered by the amount and quality of available data on the Venus atmosphere. In order to understand which model, and which assumptions are correct, improved in situ spacecraft observations are required.

Science Drivers

The key science driver for VCM is to answer many of the outstanding science questions that remain about the Venus climate system, thereby greatly improving our understanding of the current state and evolution of the strong CO_2 greenhouse climate and providing fundamental advances in our understanding of and ability to model climate and global change on Earth-like planets. The VCM seeks to resolve the major outstanding mysteries of the climate of Venus by undertaking a thorough examination of the atmosphere. In particular VCM will resolve current uncertainties in atmospheric motions, radiation balance, cloud composition and chemistry, while also making elemental and isotopic measurements that will reveal the origin and evolution of the atmosphere and the evolution of the extreme greenhouse climate.

The relationships and feedbacks between several of these parameters, such as cloud properties and radiation balance, are among the most vexing problems limiting our current ability to improve terrestrial GCMs and their forecasting ability. In addition, evidence will be gathered for the existence, nature and timing of the suspected ancient radical global change from habitable, Earth-like conditions to the current hostile runaway greenhouse climate, with important implications for understanding the stability of climate and our ability to predict and model climate change on Earth and extra solar terrestrial planets.

Mission Elements

Synergistic observations will be made with a Gondola/Balloon system that will be tracked for up to five circumnavigations of Venus and a Mini-Probe and two Drop Sondes deployed from the Gondola/Balloon system. A carrier spacecraft will serve as a communications relay while also providing context imaging for the in situ mission elements. This will be the first ever truly 3-dimensional (and to a large extent 4-dimensional, including many measurements of temporal changes) characterization of Venus's atmosphere. Gondola/Balloon system instruments will measure the atmospheric energy balance and sample the clouds and atmosphere. Tracking the Gondola/Balloon system for up to five circumnavigations will provide vital information on Venus's atmospheric circulation. Gondola/Balloon system tracking will allow for the first time measurements of winds at one altitude over several Venus rotations, covering the entire range of solar zenith angles, which are fundamental for understanding what drives the atmospheric superrotation. Previous investigations, including ESA's Venus Express (VEx), have shown the atmospheric and cloud properties to be highly variable both spatially and temporally. The two Drop Sondes will measure the pressure/temperature structure from the cloud base to the surface. The Drop Sondes are tracked by the Gondola/Balloon system to obtain deep atmosphere wind measurements. The dynamical measurements from the Mini-Probe and Drop Sondes can be combined with the Gondola/Balloon system dynamics to provide a very good 4-D picture of the atmosphere.

Simultaneous dynamical measurements from the Gondola/Balloon system and the Mini-Probe and Drop Sondes will allow, for the first time, concurrent measurements of vertical dynamics, cloud particle size and density, and cloud forming species over a wide range of longitudes, solar zenith angles, altitudes and times.

An important target here is measurement of the solar thermal tides, which are a prime candidate for the (still unknown) acceleration mechanism responsible for the atmospheric superrotation. In this proposed mechanism, longitudinal variations in solar radiation provide energy to a prograde (that is, in the direction of the planet's rotation) movement of air. The solar thermal tide hypothesis can only be tested by measuring winds at a near constant level in the atmosphere across the globe. Tracking the Gondola/Balloon system for several weeks will provide the necessary data to resolve between competing hypotheses for superrotation drivers.

In addition, tracking the Gondola/Balloon system motions as it circumnavigates the planet and drifts toward the pole will also allow measurement of numerous other dynamical phenomena such as meridional circulation, including the characterization of planetary waves and any Hadley cells that transport heat poleward from the equator.

Precise measurements of the atmospheric noble gas isotopes as measured in situ by a Neutral Mass Spectrometer (NMS) will reveal the early history of the atmosphere and also gather evidence for the existence, nature and timing of the suspected ancient radical global change from habitable, Earth-like conditions to the current hostile runaway greenhouse climate, with important implications for understanding climate stability and predicting the long term fate of Earth's climate under a future warming Sun. Light element isotopes will also be measured by the NMS for clues to the history of atmospheric escape, and the record of the transfer of volatiles between the atmosphere, surface and interior.

A key goal is the understanding of sulfur based chemistry and its role in producing and maintaining clouds, radiative balance, and climate. The intense, reactive chemistry that results in Venus's ubiquitous cloud cover is poorly understood. In particular, the composition of the mysterious UV absorber (presumably an allotrope of sulfur), the production and loss mechanisms for this absorber as well as the H_2SO_4 clouds, and the roles of CO and OCS in helping to catalyze the formation and destruction of these clouds are not known. In-situ measurements, by the NMS on both the Gondola/Balloon system and Mini-Probe, complemented by the Tunable Laser Spectrometer (TLS) on the Gondola/Balloon system, of the numerous key species involved in this chemistry over all times-of-day and a variety of latitudes and altitudes can help disentangle the roles of various photochemical and thermal reactions in controlling cloud formation/dissipation. This will enlighten us on how Venus's current cloudy climate is maintained, clarify the role of surface-atmosphere chemical interactions, and reveal how this climate may change with small variations in environmental factors.

The final piece of the climate puzzle is to provide boundary conditions for existing GCMs by quantifying the downwelling and upwelling radiation as a function of altitude and solar zenith angle. Again, the Gondola/Balloon system, Mini-Probe and Drop Sondes provide this key information in 4-D. All three drop packages will measure upwelling and downwelling radiation to help characterize the climate balance at a range of solar zenith angles.

The Mini-Probe, in addition to providing a third vertical trace of atmospheric structure, to insure wide coverage of longitude and solar zenith angle, will measure the vertical profiles of key trace gases in the lower atmosphere via an NMS. Measurements of lower atmosphere abundances from the Mini-Probe, in particular those of several sulfur species and water, will help elucidate the complex interactions between the surface, interior, and atmosphere, including whether outgassing is occurring at present and whether surface rocks are currently in equilibrium with volcanic gasses.

Table 1 shows the relationship between the major mission elements and critical measurement requirements.

1.2 Science Traceability

Table 2 traces the primary science objectives of the VCM study to the key measurements needed to address each. The third and fourth columns of Table 2 indicate nominal instrumentation that could satisfy the measurement requirements (see Section 3.1 for details) and functional or implementation needs.

Table 1: Critical Measurement Requirements Met by Each Element

Mission Element	Critical Measurement
Balloon	Full coverage of solar zenith altitudes and wide latitude coverage; sustained cloud measurements over several circumnavigations
Mini-Probe	Chemical measurements of lower atmosphere
Sondes	Lower atmosphere structure and radiation measurements at several solar zenith angles simultaneous with balloon measurements
Orbiter	Context imaging of upper and middle clouds for in situ elements

Table 2: Venus Climate Mission Science Traceability Matrix

Science Objective	Measurement	Instrument	Functional Requirement
Characterize the strong CO_2 greenhouse atmosphere of Venus, including variability.	Upward and Downward visible and IR fluxes, atmospheric composition, aerosol composition and size distribution.	ASI, Nephelometer, Radiometer, TLS	Three descent traces at varied longitude and solar zenith angles. Four complete gondola/balloon system circumnavigations of Venus.
Characterize the dynamics and variability of Venus' superrotating atmosphere	Cloud motions, global and local wind speeds at multiple altitudes, P, T, stability, radiation balance, thermal tides and turbulence.	VIS-IR Camera, Gondola/ balloon system tracking ASI, Accelerometer, Radiometer.	Three descent traces at varied longitude and solar zenith angles. Four complete gondola/balloon system circumnavigations of Venus.
Constrain surface/atmosphere chemical exchange in the lower atmosphere.	Measure stable isotopes and trace reactive gases with altitude.	NMS, TLS	One descent trace.
Search for atmospheric evidence climate change on Venus.	Stable isotopes and atmospheric composition.	NMS, TLS	In situ sampling of atmospheric gases and aerosols, descent trace.
Determine the origin of Venus' atmosphere and the sources and sinks driving evolution of the atmosphere.	Noble gases and isotopes. Stable isotopes.	NMS, TLS	In situ sampling.
Understand implications of Venus' climate evolution for the long-term fate of Earth.	Stable isotopes (D/H, S,O,N) rare gases and isotopes,	NMS, TLS	In situ sampling of atmosphere and cloud aerosols.

On the Gondola/Balloon system, science instrumentation measures reactive trace gases as well as stable and noble gas isotopes via the NMS and TLS. Aerosol size and column density are measured via a Nephelometer. An NFR measures upwelling and downwelling visible and infrared radiation. An Atmospheric Structure Instrumentation (ASI) measures pressure and temperature. In addition, Doppler/radio tracking of the vehicle by the carrier spacecraft as well as by Earth-based radio telescopes yields the Gondola/Balloon system's velocity in all three dimensions. The Doppler measurements are done through the telecom system of the Gondola/Balloon system and the carrier spacecraft and do not require a separate dedicated science instrument.

The two Drop Sondes and the Mini-Probe each measure atmospheric structure with ASI which is included on all four in situ platforms. The Drop Sondes and the Mini-Probe are tracked by the Gondola/Balloon system, to obtain deep atmosphere wind measurements. Deep atmosphere wind measurements are made by tracking the Drop Sondes and the Mini-Probe by the Gondola/Balloon system. In future concepts additional tracking could be done between the dropped elements and the carrier spacecraft, but that would require resources beyond the current VCM configuration. All three drop packages are equipped with NFRs to measure upwelling and downwelling radiation. The Mini-Probe also measures vertical distribution of key trace gases via an NMS.

The carrier spacecraft mostly serves as a communication relay but carries a Vis-IR camera to characterize the Gondola/Balloon system and drop package entry points and provide hemispheric and regional context for the Gondola/Balloon system measurements by imaging cloud properties at the time of its entry into the atmosphere.

2.0 HIGH-LEVEL MISSION CONCEPT

The VCM design achieves the science objectives by utilizing a gondola and balloon system measuring atmospheric conditions and by deploying a Mini-Probe and two Drop Sondes for vertical scale measurements. The mission is comprised of distinct systems. The Carrier Spacecraft delivers the EFS to Venus and acts as the communications relay system from Venus to Earth while in orbit around Venus, the EFS includes the Aeroshell, Gondola/Balloon System and Mini-Probe and the Gondola/Balloon System includes the gondola with instruments and avionics, the balloon inflation system, the balloon and the Drop Sondes. Launched on an Atlas V 551 in November 2021, the spacecraft begins a 5 month cruise to Venus (**Figure 1:** Heliocentric View of the Cruise Phase). Ten days prior to arrival at Venus, the EFS is released from the Carrier Spacecraft and begins its cruise to Venus atmosphere entry. One day after the EFS is released, the Carrier Spacecraft performs a divert maneuver to establish a track for Venus Orbit Insertion (VOI) and enters Venus orbit 9 days later. The Carrier Spacecraft perform the VOI maneuver 2 hours prior to EFS entry. At Venus, the EFS enters the atmosphere followed by Aeroshell jettison and parachute deployment. After slowing the Gondola/Balloon System, balloon inflation begins. During balloon inflation, the Mini-Probe is released. Following balloon inflation, the empty helium tanks are jettisoned and the Gondola/Balloon System rises to a 55.5 km nominal float altitude for scientific measurement. During the 21 day campaign, the Gondola/Balloon System circumnavigates the planet and spirals toward the South pole (**Figure 2:** View of Carrier Spacecraft and track of Gondola/Balloon) and the Drop Sondes are released. Release of the Drop Sondes is accomplished by an Earth uplink to the Gondola/Balloon System through the Carrier Spacecraft. EFS operations are shown in **Figure 3:** Entry, Descent and Inflation Sequence.

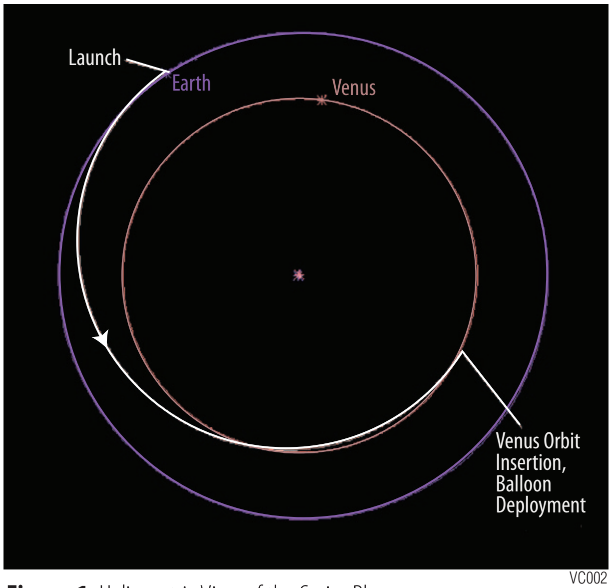


Figure 1: Heliocentric View of the Cruise Phase

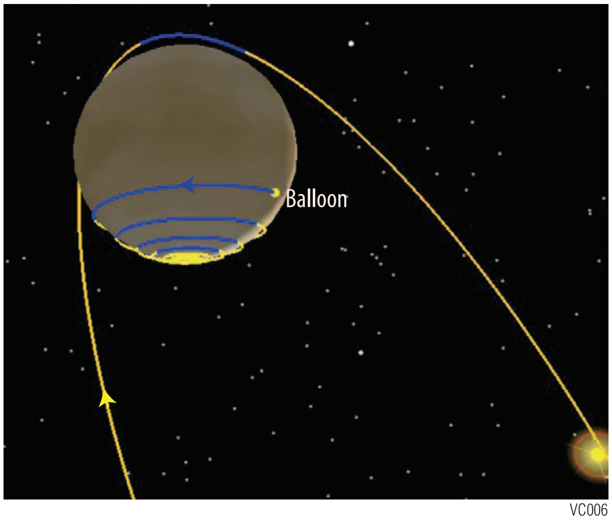


Figure 2: View of Carrier spacecraft and track of Gondola/Balloon, portions shown in blue are in Venus shadow

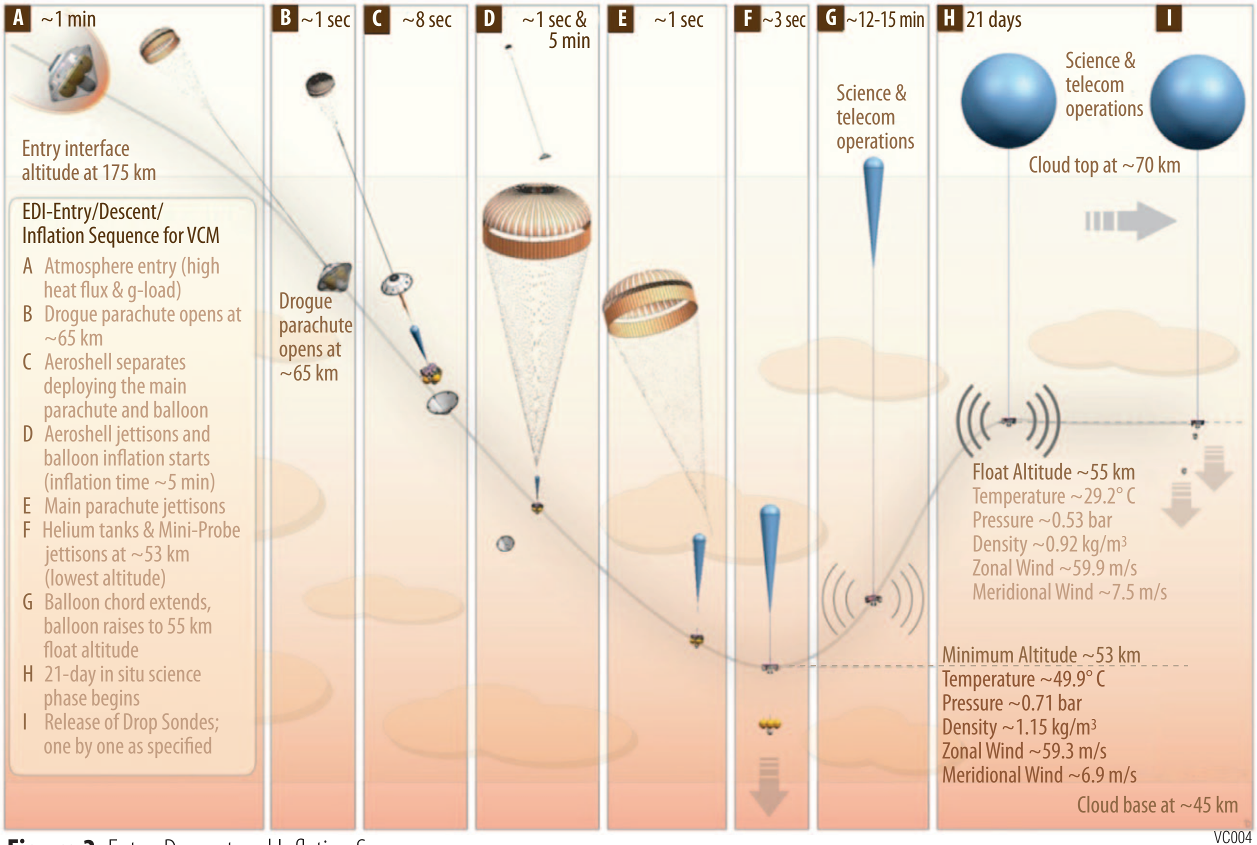


Figure 3: Entry, Descent and Inflation Sequence

After delivering and releasing the Gondola/Balloon System, the Carrier Spacecraft performs a VOI burn and enters into an elliptical orbit around Venus where it acts as the communication relay between the Gondola/Balloon System and earth. **Figure 4,** Arrival at Venus shows this sequence. In addition to communication relay, the Carrier Spacecraft also images regional content around the Gondola/Balloon System position in the Venus atmosphere using a Vis-IR camera.

The timeline of significant events for the November 2, 2021 launch trajectory is shown in **Table 3:** VCM Significant Events.

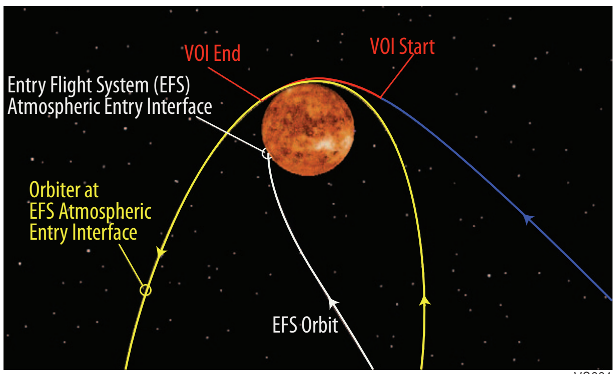


Figure 4: Arrival at Venus viewed from Sub-Solar Longitude

Table 3: VCM Significant Events

Event	Time
Launch Window Opens	10/23/2021
Launch	11/2/2021
Launch Window Closes	11/11/2021
Cruise Phase	11/2/2021 - 3/27/2022
EFS Release	3/28/2022
Carrier Spacecraft Divert Maneuver	3/29/2022
Carrier Spacecraft VOI	4/7/2022
EFS Atmospheric Entry (VOI plus 2 hours)	4/7/2022
Gondola/Balloon System Operations	4/7/2022 – 4/28/2022
End of Mission	5/6/2022

3.0 TECHNICAL OVERVIEW

3.1 Venus Climate Mission Instrument Payloads

Table 4 outlines the instruments installed on specific VCM platforms. It should be noted that although the instruments discussed in this section are all based on previously flown designs, in some instances adjustments are made to the heritage accommodation requirements (mass, power, volume). Minor changes to the instruments are intended to reflect an expected reduction in accommodation requirements by applying more recent technologies. It is acknowledged that these changes will require additional instrument development effort.

3.1.1 Carrier Spacecraft Instrument Payload: Venus Monitoring Camera

The sole instrument payload on the Carrier Spacecraft is the Venus Monitoring Camera (VMC, **Figure 5**). The VMC is designed to provide global imaging of Venus and takes images of Venus in four narrow band filters from UV to near-IR. The VMC tracks cloud motions at ~70 km altitude (cloud tops) and at ~50 km altitude (main cloud layer).

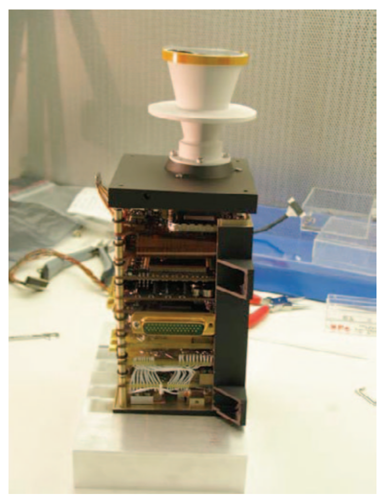


Figure 5: Venus Monitoring Camera (Venus Express)

Table 4: Instruments on VCM Atmospheric Platforms and Carrier Spacecraft

Platform	Venus Climate Mission Instruments					
	Atmosphere Structure Instrumentation (ASI)	Nephelometer	Tunable Laser Spectrometer (TLS)	Net Flux Radiometer	Neutral Mass Spectrometer	Venus Monitoring Camera (VMC)
Gondola/Balloon System	X	X	X	X	X	
Mini-Probe	X			X	X	
Sondes (2)	X			X		
VCM Carrier Spacecraft						X

3.1.2 Gondola/Balloon System and Probes (Mini-Probe and Drop Sonde) Instrument Payloads

Below is a brief description of each instrument that comprises the Gondola/Balloon System, Mini-Probe and sondes payloads. Although some instrument types are duplicated across all three platforms and are functionally equivalent, a different heritage may have been used due to environmental differences and measurement requirements, resulting in different resource requirements. Where different, this heritage is noted in the mass and power tables below.

3.1.2.1 Atmospheric Structure Instrumentation (ASI) package: comprised of sensors and electronics package to characterize gross atmospheric properties. The ASI consists of a temperature sensor, a pressure transducer, anemometer, and an accelerometer. On the two Drop Sondes and the Mini-Probe, the sensors are located on the outside of the vessel on a small boom.

3.1.2.2 Nephelometer: The Nephelometer experiment will provide information on the structure and particle size of the clouds of Venus. The Nephelometer will vertically locate and characterize the source of UV absorption in the vicinity of the instrument and help document the optical properties of the atmosphere. The Nephelometer (**Figure 6**) is comprised of a pulsed light source, a detector to measure scattered light, collimating and collecting optics, spectral filters, internal calibration systems, a window contamination monitor, "housekeeping" measurement systems and analog and digital electronics and power supplies.

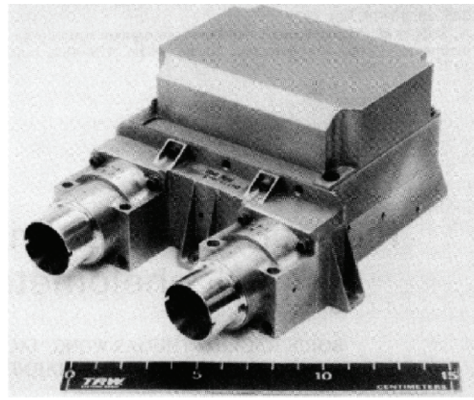


Figure 6: Nephelometer (Pioneer Venus)

3.1.2.3 Net Flux Radiometer: The net flux radiometer (**Figure 7**) will investigate the dynamic distribution of radiative balance which drives atmospheric circulation on Venus. The instrument uses an external sensor to measure the net flux of solar and planetary radiation during descent through the thick Venus atmosphere. The sensor, consisting of a high temperature flux plate detector and protective diamond windows, is designed to make accurate flux measurements while exposed to the severe Venus environment.

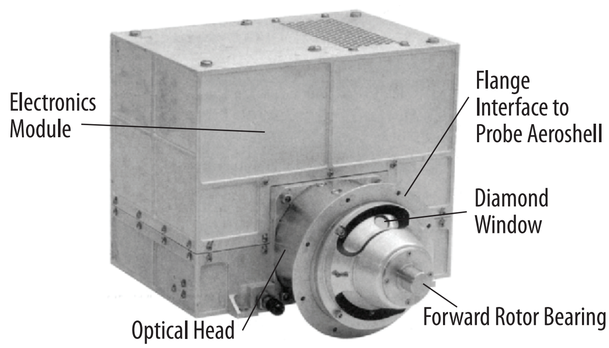


Figure 7: Net Flux Radiometer (Galileo Probe)

3.1.2.4 Tunable Laser Spectrometer (TLS): measures trace gases, including multiple isotopes of sulfur and hydrogen-bearing species. Utilizing extremely small tunable laser spectrometers with room temperature laser detector arrays in a Herriott cell configuration, TLS (**Figure 8**) provides multi-wavelength in situ measurements of the Venusian atmosphere. TLS and NMS together provide enhanced science return greater than the sum of their individual efforts.

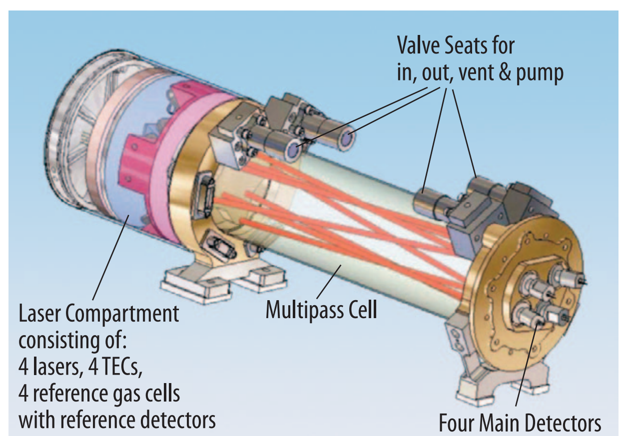


Figure 8: Tunable Laser Spectrometer (MSL) Net Flux Radiometer (Pioneer-Venus)

3.1.2.5 Neutral Mass Spectrometer (NMS): provides in situ measurement of noble gas isotopes and multiple trace gas mixing ratios. The NMS instrument consists of three modules: an ion source to convert gas phase sample molecules into ions; a mass analyzer, which applies electromagnetic fields to sort the ions by mass; and a detector, which measures the abundance of each ion present.

3.2 Flight System

3.2.1 Concept of Operations and Mission Design

3.2.1.1 Launch and Cruise to Venus

A 20-day Type II launch window in 2021 is analyzed for launch on an Atlas V 551. For the required C3 of 8.8 km^2/sec^2, the launch vehicle delivers up to 5,141 kg mass to Venus based on KSC ELV performance data. The VCM launch mass is 3,984 kg. The launch window meets the (EFS entry interface velocity constraints as well as the Gondola/Balloon System deployment latitude (20–30 degrees North or South latitude) and Gondola/Balloon System-Carrier Spacecraft communications constraints. **Table 5:** VCM 2021 Launch Window Parameters provides specific data parameters for the 2021 launch window. The middle of window trajectory (November 2, 2021 launch) used for detailed analysis is an integrated trajectory and includes Solar, Earth, Venus, Lunar, and planetary gravity, Solar radiation pressure, and Venus drag. The window open and close trajectories analyzed are also integrated trajectories. A delta-V budget including statistical and deterministic delta-Vs and margin is determined for the November 11, 2021 launch opportunity, the worst case across the 20 day launch window. This delta-V requirement is 1734 m/s. The mission is designed to this delta-V. Additional trajectory options can be investigated in more detail in the future, including identification of viable launch windows during the next launch opportunity in 2023. However, preliminary analysis of a 2023 launch trajectory indicates that the same mission design approach and constraints used for this study could be applied to a 2023 launch, although nominal Gondola/Balloon System deployment would occur at 30° North latitude for the 2023 launch trajectories.

Following launch and a 5 month cruise, the three-axis stabilized, bipropellant Carrier Spacecraft releases the EFS 10 days prior to Venus entry on the entry interface trajectory. Prior to EFS release, the Carrier Spacecraft spins up to 5 rpm to provide spin stability to the EFS during the 10 day coast. Following release, the Carrier Spacecraft spins down to 0 rpm and the EFS performs a status check, relays it to the Carrier Spacecraft and then powers down except for a reactivation timer. One day after EFS release the Carrier Spacecraft performs a divert maneuver to send it on a Venus Orbit Insertion (VOI) trajectory. At Venus, the VOI maneuver occurs 2 hours prior to EFS entry interface. The timer in the EFS powers up the system 1 hour prior to atmospheric entry.

3.2.1.2 Operations at Venus

Figure 4: Arrival at Venus viewed from the Sub-Solar Longitude is a Venus-centered view of the EFS entry interface and spacecraft VOI on April 7, 2022 for the November 2, 2021 launch case. Gondola/Balloon System deployment occurs ~3° downrange of the entry interface at 30° South latitude. The entire VOI maneuver is visible to Earth. The post-VOI orbit has a nominal period of 24 hours, nominal periapsis and apoapsis altitudes of 500 and 66,300 km, and nominal apoapsis latitude of 61.5° South, which ensures favorable geometry for Carrier Spacecraft-Gondola/Balloon System communications during the EFS entry interface and Gondola/Balloon System deployment and over the duration of the mission.

The Gondola/Balloon System is able to transmit data to the Carrier Spacecraft during all critical maneuvers including the descent, parachute deployment, extraction of the Gondola/Balloon System from the Aeroshell, and balloon inflation. **Figure 3** illustrates the Entry, Descent and Inflation (EDI) Sequence for the EFS and its payload.

The Mini-Probe is concurrently released from the Aeroshell with the Gondola/Balloon System. As it descends through the Venus atmosphere, the Mini-Probe transmits its data to the Gondola/Balloon System, where it is stored for later playback. The Gondola/Balloon System provides real time status data to the Carrier Spacecraft during this phase.

The Gondola/Balloon System drifts for three weeks, circumnavigating the planet every 4 or 5 days. The Gondola/Balloon System spirals towards the pole over this time (**Figure 9:** Gondola/Balloon Drift during Campaign). The total amount of power is a major constraint on all Gon-

Table 5: VCM 2021 Launch Window Parameters

Launch Date	Venus Arrival	C3 (km^2/s^2)	DLA (deg)	VHP at entry interface (km/s)	Divert ΔV (m/s)	VOI ΔV (finite, m/s)
10/23/2011	4/5/2022	7.987	-24.8	4.77	61.1	1568.9
11/2/2021	4/7/2022	7.933	-24.3	4.75	61.0	1563.0
11/11/2021	4/10/2022	8.642	-20.3	4.77	60.9	1572.9

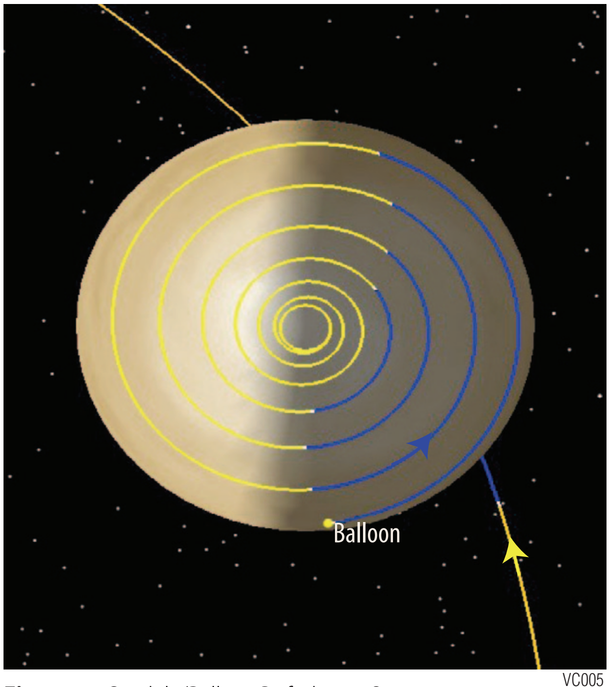


Figure 9: Gondola/Balloon Drift during Campaign

dola/Balloon System operations. The Gondola/Balloon System spends a significant amount of time in a low power mode to ensure that it will retain enough power to operate for the full 3-week duration. The operations will be preplanned, and updated during the mission to adjust the activities to account for the uncertain drift of the Gondola/Balloon System. The Gondola/Balloon System releases the two sondes at two distinct times in order for each sonde to sample environments at different latitudes and at varying times in the day/night cycle. The sondes, like the Mini-Probe, send data from their 45-minute descent in the Venusian atmosphere to the Gondola/Balloon System which will store the data and then send it to the Carrier Spacecraft at a later time. The mission ends 21 days after the start of Gondola/Balloon System operations when the system runs out of power.

The Carrier Spacecraft points its fixed HGA to the predicted location of the Gondola/Balloon System whenever it is visible. At scheduled times, the Carrier Spacecraft communicates to the Gondola/Balloon System. The Gondola/Balloon System responds in real time and transmits its stored data. The Carrier Spacecraft performs a search pattern if the Gondola/Balloon System does not respond. While receiving data from the Gondola/Balloon System the Carrier Spacecraft performs small cyclic perturbations (dithers) to find the direction of the strongest Gondola/Balloon System signal. This information, along with Doppler information, is down-linked to earth once per day when the Gondola/Balloon System is not in view of the Carrier Spacecraft. Based on this information and any Doppler measurement made by ground observatories, the operations and navigation teams on the ground update the predicted location of the Gondola/Balloon System and send new schedules for both the Carrier Spacecraft and the Gondola/Balloon System (via the Carrier Spacecraft).

The Carrier Spacecraft cloud monitoring camera is aligned with the HGA and takes data when the predicted location of the Gondola/Balloon System is in view. This data (approximately 700 Mbits per day) is down-linked to earth during the once per day contact. **Table 6** summarizes the data volumes and communications links.

3.2.2 Mission Communications

The VCM requires several distinct communication links between the various elements of the mission as illustrated in **Figure 10:** VCM Communication Links. These links include:

- Mini-Probe and Drop Sondes transmit to Gondola/Balloon System
- Gondola/Balloon System to Carrier Spacecraft two-way communications path
- Carrier Spacecraft to Earth two-way communications path

The VCM science instruments generate a modest amount of data during the 21-day mission. To support the relaying of data, the Carrier Spacecraft will alternate between communication with the Gondola/Balloon System and communicating with Earth. One or more contacts with the Gondola/Balloon System per day will occur; totaling,

Table 6: VCM Data Generation and Required Communications

Element	Data		Communications			
	Data Generation	Mission Total	Sessions	Session Duration (min)	Total Comm Time (min)	Data Rate (minimum)
Probe	5 Mb per 45 min descent	5 Mb	Continuous during descent	45	45	3.4 kbps
Sondes (2)	2 Mb per 45 min descent	2 Mb	Continuous during descent	45	45	0.3 kbps
Gondola/balloon system	6.5 Mb per day	135 Mb	As scheduled	5 to 90	90 per day	1.2 kbps
Carrier spacecraft	700 Mb per day in Venus orbit	14 Gb	As scheduled	210	210 per day	65 kbps

on average, 90 minutes per day. Communication with Earth will occur for extended periods ranging from 30 minutes to 3.5 hours per day depending upon data rate selection. The Carrier Spacecraft will also point toward the Gondola/Balloon System (for up to 19.5 hours per day) for conducting imaging of the atmosphere around the Gondola/Balloon System and receiving sinusoidal signals for Doppler measurements. Using this approach, the Gondola/Balloon System and Carrier Spacecraft ensure nearly daily delivery of data, and the required data rates are well within normal operating practices. A summary of the VCM communications link data is shown in **Table 7**.

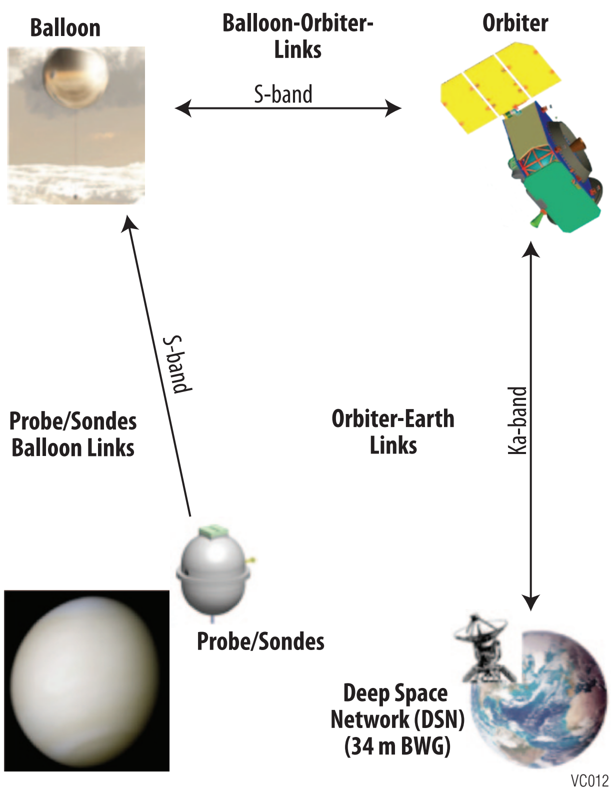


Figure 10: VCM Communication Links

3.2.3 Carrier Spacecraft Entry Flight System (EFS)

The Entry Flight System consists of the front and back aeroshells with structures and Thermal Protection System (TPS), a drogue parachute and a simple power system. The requirement for a battery in the EFS will be discussed in Section 3.2.3.4.7. The EFS carries a payload, consisting of the Gondola/Balloon System, its inflation system, the Mini-Probe, two Drop Sondes, and the main parachute. An exploded view of the EFS and its carried elements are shown in **Figure 11**. The mass breakdown of the main elements is given in **Table 8**.

3.2.3.1 Aeroshell

The EFS is composed of the Aeroshell, the TPS, parachute, deployment mechanisms, and cabling. The EFS provides aerodynamic drag during atmospheric entry and also protects the EFS and its payload from entry heating. The Aeroshell structure and TPS materials are designed to withstand the high deceleration loads (~160 g during entry for the current conditions).

Table 7: VCM Communication Links - Summary Data

	Probe/Sonde to Gondola/Balloon	Gondola/Balloon to Carrier Spacecraft	Carrier Spacecraft to Gondola/Balloon	Carrier Spacecraft to Earth	Earth to Carrier Spacecraft
Data	Science Data / Telemetry	Science Data / Telemetry	Command	Science Data / Telemetry	Command
Data Rate	5 kbps	1.2 kbps	1.2 kbps	70 kbps	1 kbps
Signal Frequency Band	S-Band	S-Band	S-Band	Ka-Band	Ka-Band
Transmit					
Power	1 W	5 W	5 W	50 W	
Antenna	Patch (>-2dBi)	Helix	1.7 m dish	1.7 m dish	34 m BWG
Effective Isotropic Radiated Power (EIRP)	-2.5 dBW	6 dBW	34 dBW	66 dBW	118 dBW
Range (max)	225 km	42,000 km	42,000 km	146 million km	146 million km
Receive System					
Antenna	Helix (1.0 dBi at max off-pointing)	1.7 m dish	Helix	34 m BWG	1.7 m dish
Margin	3.5 dB	3 dB	3 dB	>10 dB	>6 dB

Sensitivity studies were performed for the VCM mission parameters, based on scaled versions of the Pioneer-Venus Large Probe (PVLP). The current -19.0° Entry Flight Path Angle (EFPA), and entry velocity of 11.26 km/s results in lower g-loads and heating rates than those experienced by the PVLP, which in turn reduces structural mass of the Aeroshell, and lowers the qualifying requirements for the instruments as well. The lower total heat load impacts TPS sizing, resulting in a lighter heat shield.

The monocoque 2.0 m diameter, 45° sphere cone Aeroshell encapsulates the probe, supports launch and entry loads, and enables safe and reliable atmospheric entry of the EFS. The heat shield is a scaled version of PVLP (which had a diameter of 1.42 m), while the backshell is similar in shape to that of the Stardust backshell.

The structure underneath the heat shield is a 2-inch (5.08 cm) sandwich configuration with composite face sheets and aluminum honeycomb, providing mass savings over solid aluminum. The total mass of the Aeroshell is 253.7 kg (not including 30% margin). The mass breakdown is provided in **Table 9**.

The heat shield TPS consists of 0.65 inch (1.65 cm) tape wrapped and chopped molded carbon phenolic (TWCP and CMCP) onto the honeycomb structure. CMCP and TWCP are the only materials flight-qualified for the severe conditions of Venus entry. Peak stagnation heat flux (combined convective and radiative) on the heat shield is calculated to be 4.25 kW/cm^2. Both CMCP and TWCP were flown on the Pioneer-Venus and Galileo entry probes. Although heritage carbon phenolic (CP) production has been discontinued since the 1980s because the supplier ceased production of the rayon precursor material, NASA's Ames Research Center (ARC) has a

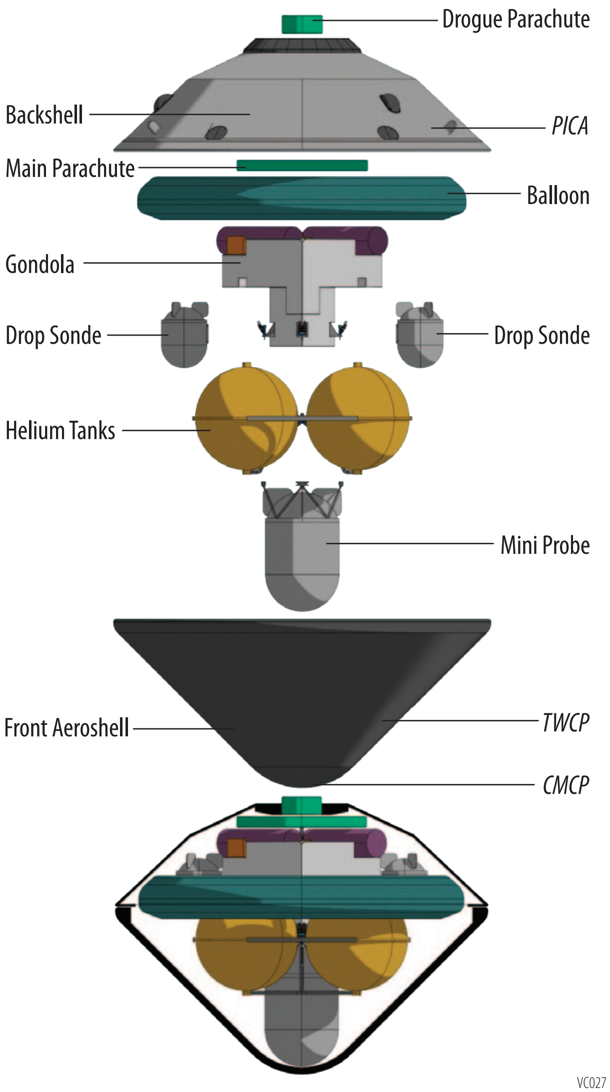


Figure 11: Exploded view of the EFS with its payload, including Gondola, Balloon, Inflation System, Mini-Probe and Drop Sondes (top). Packed configuration of the EFS (below)

Table 8: Mass Summary of the EFS and its carried elements

Entry Flight System Overall Mass Rollup	CBE Mass	Contin-gency	CBE+ Cont.
Aeroshell Mass	253.7	30%	329.8
Drop Sonde 1	12.4	30%	16.1
Drop Sonde 2	12.4	30%	16.1
Mini-Probe	38.4	30%	49.9
Aerostat (balloon and gondola)	196.7	30%	255.7
Inflation System and Helium	135.1	30%	175.7
Total	**648.7**		**843.3**

Table 9: Entry Flight System mass summary

Entry System (Aeroshell) Mass Summary	CBE Mass	Contin-gency	CBE+ Cont.
ACS	0.3	30%	0.4
Power (battery for 10-day cruise)	8.1	30%	10.6
Structures/Mechanisms	110.3	30%	143.4
Front Aeroshell	45.8	30%	59.5
Backshell	19.4	30%	25.2
Parachute	20.0	30%	26.0
S/C Side Adapter	7.6	30%	9.9
Cabling	17.5	30%	22.7
TPS (thermal protection system)	135.0	30%	175.5
Front Aeroshell	114.2	30%	148.5
Backshell	20.8	30%	27.0
Aeroshell Mass Total	**253.7**		**329.8**

sufficient supply of the original CP precursor to fabricate a VCM-sized probe and the associated test and evaluation billets. Even assuming that a PVLP-sized probe is launched to Venus prior to VCM, there is sufficient heritage rayon to construct the VCM Aeroshell. The descent, heat flux and g-load profiles as a function of time from atmospheric entry until the opening of the drogue parachute are shown in **Figure 12**.

Based on engineering estimates for the backshell environment, Phenolic Impregnated Carbon Ablator (PICA), a lightweight ablator, can be used as the back shell TPS material. The 1.25 cm thick PICA tiles (approximately 50) are bonded to the structure using 20 mil (0.5 mm) HT-424 adhesive, and the 80 mil (2 mm) gaps are filled with RTV-560 silicone encapsulating compound, using the same manufacturing techniques as used on the Mars Science Laboratory (MSL) entry system. PICA has flown on Stardust and has been extensively evaluated and characterized as a heat shield material for MSL and was a candidate heat shield for Orion.

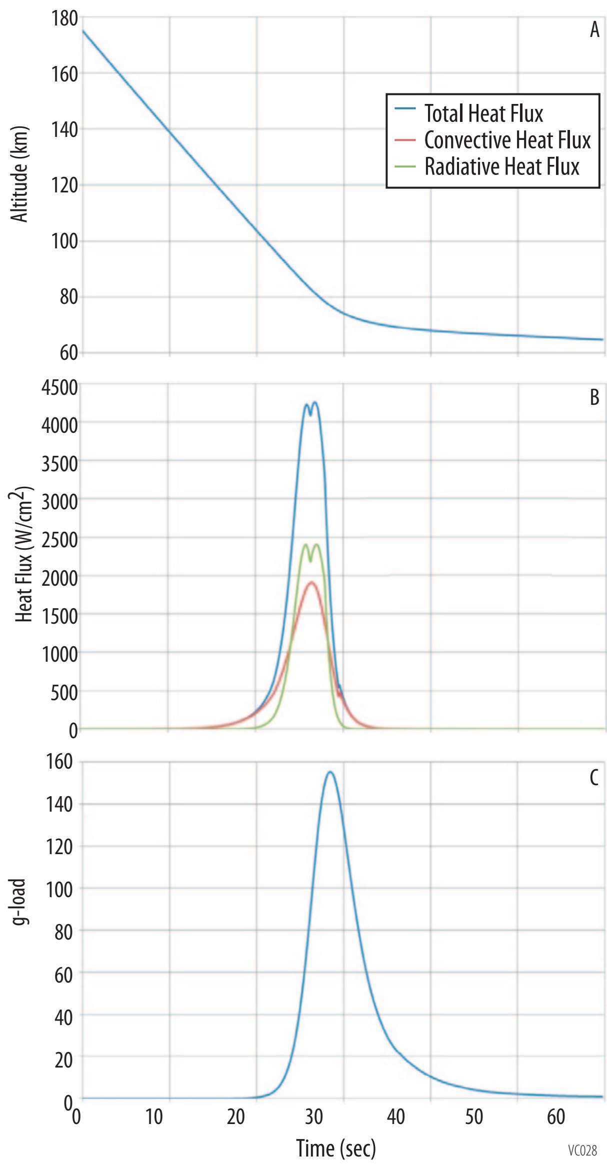


Figure 12: Analysis of the first minute of the atmospheric entry, showing; (A) descent profile, (B) entry heating profile, and (C) g-load profile

3.2.3.2 Entry Flight System (EFS) Attitude Control System

The EFS is released from the Carrier Spacecraft 10 days before atmospheric entry with a rotation of 5 RPM to provide stability during the silent cruise. Once the atmospheric interface is reached (assumed at an altitude of 175 km) the atmospheric drag rapidly decelerates the EFS. The Entry, Descent and Inflation (EDI) sequence is timer based and triggered by a redundant set of g-switches. The g-switch interfaces with the timer carried on the Gondola/Balloon System. The same timer activates pyros located on the EFS, used for drogue chute deployment, and Aeroshell separation before jettisoning the front and backshells.

3.2.3.3 Probe and Sonde Descent

The EFS carries a Mini-Probe, which is released during the EDI sequence, and two Drop Sondes, which are released during the 21 days of Gondola/Balloon System operation. The probe and sondes are designed to descend from the 55.5 km float altitude to the surface in 45 minutes, while performing descent science. These capsule shaped elements have masses and dimension of 49.9 kg (CBE+cont.) and 396×436 mm for the probe, and 16.1 kg (CBE-cont.) and 246×326 mm for the sondes. The aerodynamics calculations are based relevant drag coefficients for a similarly sized cylinder with blunt nose. The required 45 minutes descent can be achieved by adjusting the surface roughness of the probe and sondes to a drag coefficient (C_d) of ~1.1 (see **Figure 13.a**). As the probes descend to the surface the atmospheric density increases and gradually slows their terminal velocities. The velocity profiles are shown in **Figure 13.d**. The zonal and meridonal wind components drift the probes from the release points by 53–58 km, and 5.3–5.8 km, respectively (see **Figures 13.b and 13.c**). These descent profiles and drifts are accounted for while designing and sizing the telecom links between the probe, sondes and the Gondola/Balloon System riding the winds at 55.5 km altitude. The gondola's telecom system is discussed in Section 3.3.3.4.8.

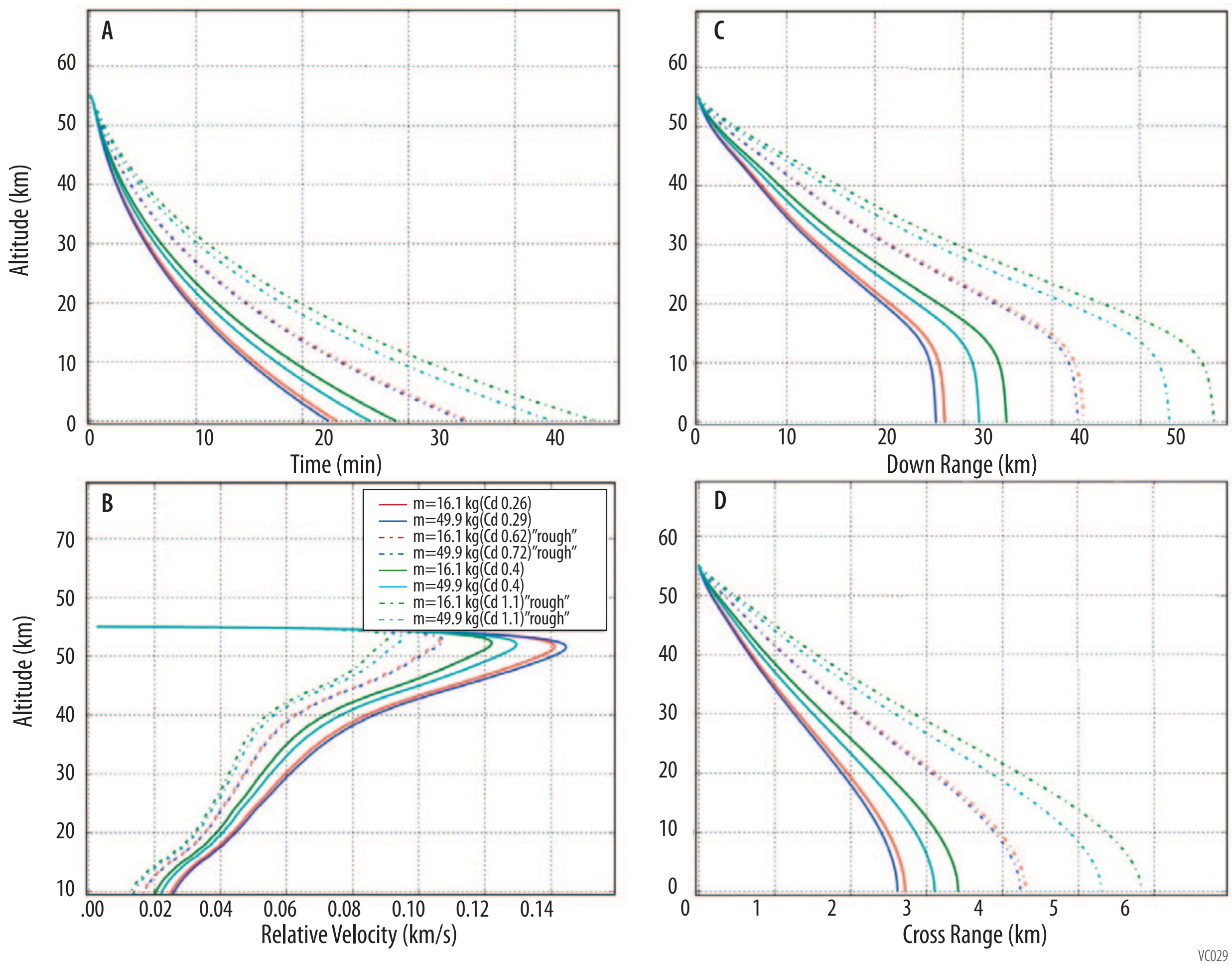


Figure 13: Probe and Sonde descent analysis: (A) descent time profile, (B) descent velocity profile, (C) down-range drift profile, (D) cross-range drift profile

3.2.3.4 Balloon, Gondola and Inflation System Design

This section discusses the balloon, gondola and inflation system designs. All of these elements are housed inside the EFS from launch until in situ deployment. The mass breakdown is given in **Table 10**.

3.2.3.4.1 Balloon Sizing

The VCM Gondola/Balloon System will fly for 21 days at an altitude of 55.5 km. It has a single string design based on the presumption that this short lifetime can be achieved with limited redundancy. The Gondola/Balloon System will take measurements of the Venusian atmosphere and clouds and relay the collected data to the Carrier Spacecraft. The 55.5 km flight altitude is suitable to meeting the science measurement objectives, while providing a moderate temperature environment (30° C) that allows for the use of existing balloon materials for construction (see Section 3.5). The Gondola/Balloon System is expected to drift

Table 10: Balloon, Gondola and Inflation System mass summary

Gondola/Balloon System and Inflation System Mass			
Gondola/Balloon System	**CBE Mass**	**Contin-gency**	**CBE+ Cont.**
Instruments	19.5	30%	25.4
Command & Data	6.9	30%	9.0
Power	27.6	30%	35.9
Structures & Mechanisms (incl. balloon)	110.4	30%	143.5
Cabling	25.6	30%	33.2
Telecom	5.5	30%	7.2
Thermal	1.1	30%	1.4
Gondola/Balloon System total	196.7		255.7
Inflation system and Helium	**CBE Mass**	**Contin-gency**	**CBE+ Cont.**
Inflation system	113.3	30%	147.3
Helium for balloon inflation	21.8	30%	28.3
Inflation system total	135.1		175.7

poleward due to the prevailing winds and could potentially reach the polar vortex by the end of the third week. This will provide substantial latitudinal coverage for the Gondola/Balloon System science investigations.

The balloon design is similar to the Venus Flagship Mission's balloons, but will use only one balloon due to cost constraints. However, the VCM balloon is larger than each of the VFM balloons in order to accommodate two Drop Sondes. (The Mini-Probe is deployed during the EDI sequence and not carried during the float phase.) The sondes and the probe designs are discussed in Section 3.4.

The balloon is a spherical super-pressure balloon filled with helium. This type of balloon is stable at altitude to atmospheric turbulence and diurnal solar flux variations without the need for active control through ballasting and gas venting. However, on the VCM Gondola/Balloon System the Drop Sondes act as ballasts when deployed. Consequently, the current design will include a pressure relief valve to maintain the Gondola/Balloon System at the design float altitude while maintaining the required pressure differential with the atmosphere.

The VCM has adopted the particular Venus balloon design recently developed by JPL, ILC Dover, and NASA Wallops Flight Facility [Hall et al., 2008, 2009], which is then suitably scaled up in size to accommodate the desired VCM suspended gondola mass. A prototype balloon is shown in **Figure 14**.

The VCM Gondola/Balloon System mass breakdown is shown **Table 8**. The two Drop Sondes are not listed in this table but are accounted for in the sizing of the balloon. The VCM requires an 8.1 m diameter balloon, as compared to the 5.5 m size prototyped by the JPL-led team. This almost 50% diameter increase results in a 50% increase in the predicted tensile stress on the balloon material, which is tolerable given the predicted structural safety margin of 3 for the existing prototype balloon. This gives confidence that the larger size required by the VCM balloon can be accommodated, although validation experiments will be required to confirm this. This type of superpressure balloon is considered to be a mature technology at TRL 6.

The Gondola/Balloon System is comprised of three elements: the balloon itself, the gondola that houses the scientific instruments with their support systems, and a 20 m long tether that structurally connects the balloon and gondola.

As seen in **Table 10**, the estimated total floating dry mass is 287.9 kg, including the two carried

Figure 14: Prototype Venus balloon [Hall et al., 2008]

Drop Sondes and 30% contingency on all elements. This dry mass can be suspended under an 8.1 m diameter balloon, which requires 21.8 kg of helium fill gas.

The balloon will be aerially deployed and inflated in the atmosphere after entry. This process is described in Section 3.3.1, and shown in **Figure 3**. The EDI sequence mimics that used by the Soviet Vega balloons in 1985. The sequence will be autonomous and ends when the discharged helium inflation tanks (and the Mini-Probe) are jettisoned and the fully inflated balloon starts floating.

3.2.3.4.2 Inflation System Sizing

The balloon is filled with helium, which is stored in multiple composite over-wrap high-pressure (10,000 psi) tanks during the cruise and inflation phases. The design is based on previous studies, including the Venus Flagship Mission study [Hall, Bullock et al., 2009]. The required 21.8 kg helium is stored in four 0.5 m diameter tanks, with pyro-activated valves to control the flow to the balloon. The tanks are connected through a common manifold, with diffusers to limit the flow rate to the balloon. The block diagram for the inflation system is shown in **Figure 15.**

During the 5 minutes inflation phase two nor-

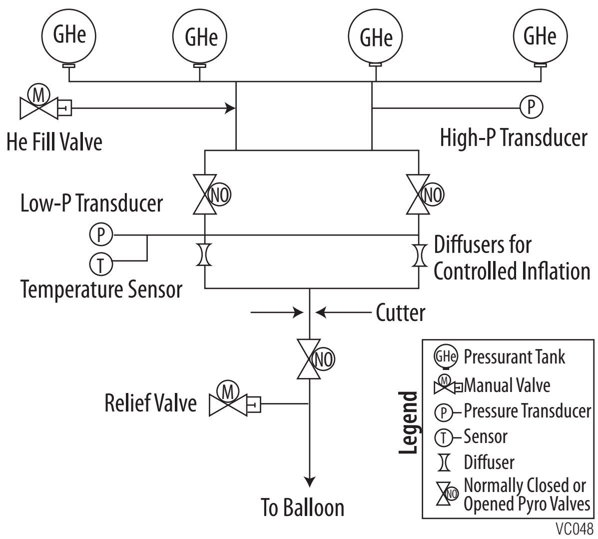


Figure 15: Schematics of the balloon inflation system

mally closed control valves open one after the other to maintain a constant flow rate as the pressure drops in the tanks. Once the helium is transferred to the balloon, a third valve at the end of the fill line closes and the line is cut, allowing the inflation system to be jettisoned.

3.2.3.4.3 Gondola Design

A CAD model of the gondola, with the inflation system, the Mini-Probe and the Drop Sondes is shown in **Figure 16**. Details on the various subsystems are provided below. The gondola dimensions are provided in **Figure 17.**

3.2.3.4.4 Attitude Control System (ACS) of Gondola/Balloon System

The Gondola/Balloon System is designed to operate at a float altitude of 55.5 km, driven by the winds. None of the instruments require special orientation. Consequently, the Gondola/Balloon System does not require an attitude control system. The ACS for the EFS is discussed in Section 3.3.3.2.

3.2.3.4.5 Command and Data System (CDS) of Gondola/Balloon System

The CDS is based on a single string design using the MSAP/MSL hardware, driven by the short 21 days mission duration. The Gondola/Balloon System is power limited, which requires powering off the CDS for periods of time. Functionality for timed or event driven commands is provided by an Event Timer Module (ETM), which can turn on and off the CDS, the instruments, collect science data and send collected data to the CDS. The ETM uses 2 Gbits of non-volatile memory, which can store the entire mission data set. When

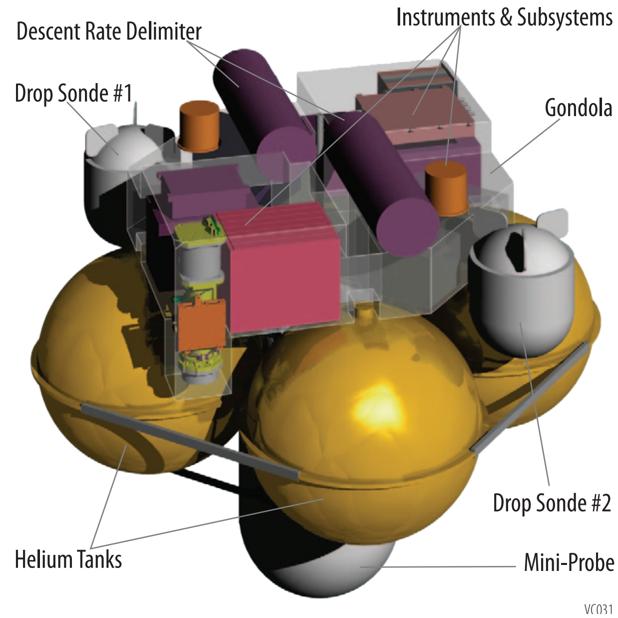


Figure 16: CAD model of the Gondola, Inflation System, Mini-Probe and Drop Sondes.

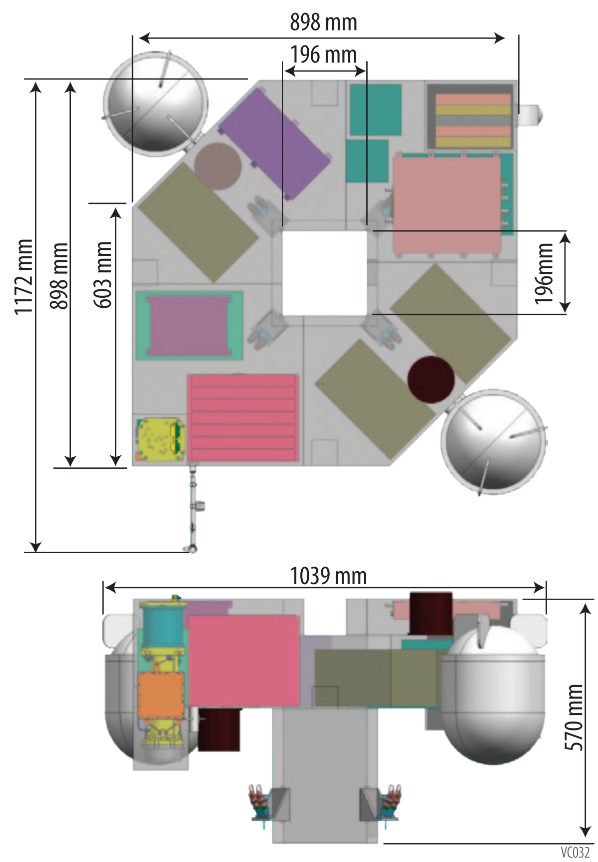


Figure 17: Gondola dimensions

the CDS is turned on to relay data to the Carrier Spacecraft, the ETM stored data is transferred to the CDS processor memory for transmission to the Carrier Spacecraft. Timed commands require pre-loaded time-command lists (updatable through the Carrier Spacecraft's C&DH system). While the current design is based on time driven commands only, future designs could add event driven functionality that initiates a time driven table of commands. Due to the short mission duration, the total ionizing dose (TID) radiation is low (~5.7 Krad, including RDF), therefore, the CDS does not require special design considerations. Two testbeds are considered adequate for the Gondola/Balloon System development, one for development and testing and one for software development. These are used through the development process, including system tests and ATLO. The CDS uses 4 W of power.

The total data volume transmitted from the Gondola/Balloon System to the Carrier Spacecraft is 142 Mbits. This includes 135 Mbits collected by the instruments on the Gondola/Balloon System; 5 Mbits by the Mini-Probe and 1 Mbit by each of the two Drop Sondes.

3.2.3.4.6 Software Design of Gondola/Balloon System, Mini-Probe and Sondes

The EFS and its carried in situ elements are assessed as an integrated entry system design.

The Gondola/Balloon System does not require altitude and attitude control, and only requires an extremely limited control for the inflation system's pressure relief valve. The operations are autonomous for both data collection and transmission, and only require some CDS software, mainly related to transmission timing. There is also a potential for receiving commands from the Carrier Spacecraft as discussed above.

The Mini-Probe and sondes are treated as firmware with a very simple automatic (hardware controlled) interface with the Gondola/Balloon System. The data management on the Gondola/Balloon System, in support of the probe and sondes is low, it requires that these deployed elements send data automatically to the Gondola/Balloon System on a pre-planned timing schedule. The Gondola/Balloon System would send a complete set of "canned data" to the Carrier Spacecraft for later transmission to Earth.

Due to the low data volume and sufficient data link capability, the CDS is designed to store the full set of science data onboard the Gondola/Balloon System. This data is not processed by the Gondola/Balloon System or the Carrier Spacecraft.

The Gondola/Balloon System software is designed to handle: thermal control, fault protection, power control, storage interface capabilities, deployment operations, and interfaces with instruments and data handling.

3.2.3.4.7 Power System of Entry Flight System and Gondola/Balloon System

The power system is designed with two Li-$SOCl_2$ primary batteries, one inside the EFS and another inside the Gondola/Balloon System.

The first battery inside the EFS is used to power standby operations and system checkups after EFS release from the carrier and before atmospheric entry, and during entry to provide EDI tones to confirm successful completion of the entry stages. This 60 A-hr Li-$SOCl_2$ battery, with a mass of 5.64 kg and energy storage capacity of 1730 W-hr, is attached to the EFS and jettisoned with it during the EDI phase. Consequently, the Gondola/Balloon System will not have to carry this additional mass during the in situ operations phase. The average power usage during this phase is 6.2 W. It should be also noted that during the 10 days silent cruise the EFS does not require dedicated power for thermal management, due to a design approach where the vehicle is warmed to 40° C before release from the carrier. This would provide sufficient thermal inertia for 16 days before the EFS would reach 0 degrees, which is 60% longer than the EFS's cruise time from release to Venus entry. Two power modes are identified for the EFS. Mode 1: in the pre-EDI phase the Gondola/Balloon System's CDS would draw 4 W of power for the event timer and 0.7 W for the power and telecom system. This would be a lower power, but continuous drain through the 10 days (240 hours). Mode 2: during EDI the power use is similar to Mode 1, but would include an additional 1.5 W for the ACS (g-switches). This higher power mode would be about 25 minutes, conservatively timed until the end of the EDI phase.

The second main battery on the Gondola/Balloon System is used from the balloon inflation phase (after successful entry) until the end of the mission. The battery is sized to support in situ operations through 21 days of various operating modes. This 90 A-hr battery has a storage capacity of 7780 W-hr, and a corresponding mass of 25.1 kg. With 2.5 kg of dual string power electronics and packaging and 30% margin, the power system mass on the Gondola/Balloon System is 35.9 kg. The battery's depth of discharge (DOD) is 94% at the end of the 21 days in situ mission. The Gondola/Balloon System's power modes include: Mode 1: inflation plus telecom between the Gondola/Balloon System and the descending probe or sondes. When the instruments are off, the power draw by the telecom system is 40 W. For 45 minutes (probe descent time) the power requirement is 64 W. Mode 2: is for science operations, where the power draw is 94.5 W for 1.77 hours/day throughout the 21 days. Mode 3: telecom mode with 99 W of power draw for 1.77 hours/day through 21 days. Mode 4: is during standby, where the system requires 4 W of power for the timer, while all subsystems are off. This is 21.86 hours per day for 21 days. Additional modes, not assessed for the baseline case, could include a Doppler mode for more frequent ranging between the Gondola/Balloon System and the Carrier Spacecraft (6 W) and a listening mode for the telecom beacon to refine the telecom window with the Carrier Spacecraft (8 W).

An alternate design with solar arrays and (rechargeable) secondary batteries was identified, but not studied in detail.

3.2.3.4.8 Gondola/Balloon Telecom System and Design

The Gondola/Balloon System's telecom system requirements are closely connected to the telecom design of the Carrier Spacecraft, the Mini-Probe and the two Drop Sondes. Between the Gondola/Balloon System and the Carrier Spacecraft the telecom system supports two-way S-band communications, designed for a distance up to 42,000 km. From the descending Probe/Sondes to the Gondola/Balloon System the communication is one-way S-band to the Gondola/Balloon System, supporting a maximum range of 220 km, with a 75° off-zenith angle.

The Gondola/Balloon System's telecom system must communicate 135 Mbits of science data collected by the Gondola/Balloon System, and relay an additional 5 Mbits from the Mini-Probe and 2 Mbits from the two Drop Sondes.

The Probe/Sondes telecom design supports a data rate up to 5 kbps, with 1 W (RF) power. The Probe/Sondes low gain antenna transmits nearly uniformly in the hemisphere above the Probe/Sonde with >-2 dBi gain out to the off-zenith direction of the anticipated maximum range of 220 km. The one way transmission from the Probe/Sondes to the Gondola/Balloon System is done autonomously (without a receiver on the Sonde). Further information on the dropped elements' telecom systems are given in Section 3.3.1.

The Gondola/Balloon System has two (switched) body fixed S-band low gain helix antennas, because they provide better coverage than patch antennas at the required 75° off pointing. The single string S-band CXS-610 transponder from L3 Communications would include a built in 5 W_{RF}/40.4 W_{DC} Solid State Power Amplifier (SSPA) and diplexer. The transponder needs to be modified for relay communications.

The telecom system is designed to operate for 31 hours during the 21 days in situ Gondola/Balloon operations, which translates to 1.3 kW-hr energy requirement (with 6% duty cycle) and a margin of 6.6 dB. This option provides the optimum energy use between (a) high data rates at high power for short burst or (b) lower data rates at lower power for longer durations. The other design driver was to maximize the link time for Doppler tracking; which in turn would provide valuable science data on atmospheric circulation and dynamics.

The current optimized design can provide a data rate of 1200 bps between the Gondola/Balloon System and the Carrier Spacecraft with a 1.7 m parabolic antenna. It was selected for providing acceptable energy consumption, threshold Doppler tracking duty cycle, and less modifications to existing hardware. (The link calculations also assumed a -1 dB loss from the Venusian atmosphere.)

The telecom system block diagram of the Gondola/Balloon System is shown in **Figure 18**.

Future improvements could include longer Doppler tracking than through the current relay times. A dedicated low-power instrument (estimated to be ~1 W_{RF} /23 W_{DC}) could provide tones for Doppler ranging, which may be more power-efficient than a modified telecom system. This, however, would still increase payload mass and power requirements, impacting the overall Gondola/Balloon System design.

3.2.3.4.9 Balloon/Gondola and Inflation System: Structures and Mechanisms

The Gondola/Balloon System structure consists of three main components: the balloon, the gondola, and the inflation system (see **Figure 11**).

The mass estimate for the Gondola/Balloon System structure and mechanisms is 50.9 kg, including 3.3 kg for fittings and 30% contingency.

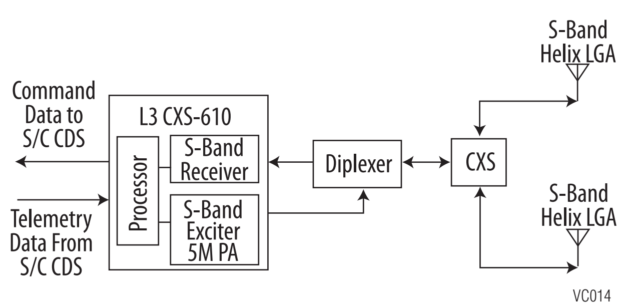


Figure 18: Gondola telecom system block diagram; two antennas supporting probe/sonde and orbiter

The balloon consists of a fabric-based laminate material and metal end fittings. The Gondola/ Balloon System structure consists of aluminum, titanium, and composite materials. The balloon material is a high-strength, sulfuric-acid-resistant laminate developed by JPL, ILC Dover, and NASA-Wallops [Hall et al., 2008]. **Figure 19** shows a schematic diagram of this material comprised of the following elements:

- An outer layer of 25 μm thick Teflon film for acid resistance.
- The inside surface of the Teflon is metallized with 30 nm of aluminum to provide a highly reflective surface for visible light, thereby minimizing the solar heating at Venus.
- The next layer in is a 25 μm thick metallized Mylar film for helium gas retention.
- The Mylar is, in turn, bonded to a Vectran fabric that provides the high strength needed to withstand the internal pressurization.
- Finally, the innermost layer is an aliphatic urethane coating that bonds to the Vectran fabric and provides a good surface on which to bond the internal gore-to-gore structural tape.

This laminate has an areal density of 173 g/m^2. Structural tapes are used on the inside and outside surfaces to connect the 16 flat gores into a nominally spherical shape. A second Teflon cover tape is laid down on top of the outside structural tape to provide the required sulfuric acid resistance. A sulfuric acid resistant adhesive developed by ILC Dover is used to bond this cover tape on to the Teflon surface of the gore, providing complete acid protection.

A CAD model of the gondola is presented in **Figure 16**. The gondola structure is a vented box built from aluminum struts and face sheets. The outer surfaces of the box are coated with Teflon to provide sulfuric acid resistance. Venting is accomplished through a 25 mm tube that contains a sulfuric acid filter. This allows ambient atmosphere to flow into and out of the gondola, thereby equalizing the pressure during altitude changes without bringing sulfuric acid droplets inside. Individual components inside the gondola are mounted on horizontal decks, as shown in **Figure 17.** The support structure is sized to accommodate the maximum entry deceleration load of 160 g plus margin.

During the initial deployment and inflation of the balloon, the gondola is mechanically connected to the helium tank support structure **(Figure 16)**. There is a 4 m long flexible hose connecting the helium tanks and gondola to the bottom of the balloon; therefore, during the inflation sequence, the balloon-to-tank separation distance will be less than 4 m. However, after inflation it is necessary to greatly increase the separation distance between the balloon and gondola because the metallized balloon will interfere with radio communications. Two descent rate limiter (DRL) mechanism are used, one for controlled deployment of the uninflated balloon and a second for the fully inflated balloon. These mechanisms unspool tethers at a speed of 0.2 m/s. The second DRL increases the (inflated) balloon-to-gondola separation distance from 4 m to 20 m in 80 seconds.

The design includes a number of mechanisms and deployments, such as: drogue chute deployment, heat shield and backshell separation, main chute deployment then separation, DRLs, probe and sonde separation mechanisms, and inflation system separation mechanism.

3.2.3.4.10 Thermal System of the Entry Flight System

The thermal design addresses four key mission phases for the EFS:

a. 150 days of interplanetary cruise – During the interplanetary cruise phase the payload inside the EFS is kept above survival temperature using heaters, powered by the Carrier Spacecraft's power system
b. 10 days of silent cruise – Before release from the Carrier Spacecraft, the EFS is warmed up to 40° C. It would take 16 days to cool down to 0° C, which provides sufficient thermal inertia during the 10 days cruise of the EFS before atmospheric

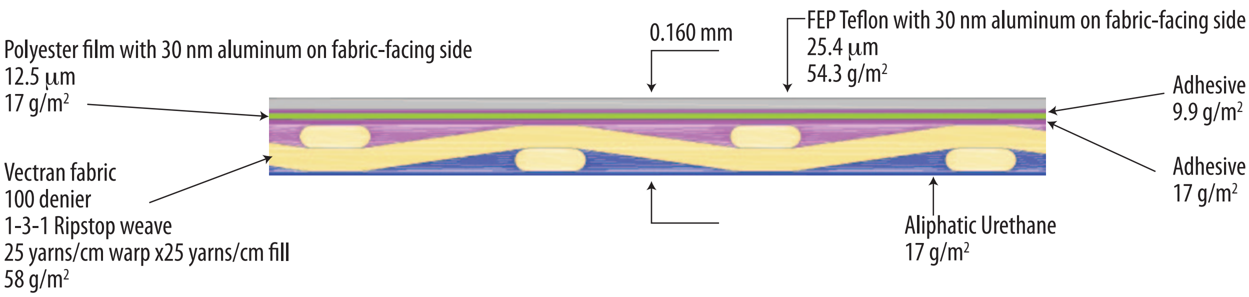


Figure 19: Balloon laminate material.

entry, removing the requirement for heater operations

c. EDI phase, for ~25–35 minutes – During the brief atmospheric entry phase the TPS and Aeroshell structure protect the payload from overheating

d. 21 day in situ operations phase – While floating at a design altitude of 55.5 km, the Gondola/Balloon System experiences terrestrial-like temperature and pressure conditions, 30° C and 0.5 atm, respectively

Consequently, the gondola design does not require thermal control, heaters or radiators; however, it does include multi layer insulation (MLI) to reduce temperature transients while the float altitude fluctuates within a few kilometers.

3.3 Mini-Probe and Drop Sondes

The Mini-Probe and Drop Sondes (**Figures 20 and 21**) are attached to the Gondola/Balloon System and released into the Venus atmosphere during the mission campaign. The Mini-Probe is released from the Gondola/Balloon System during balloon inflation and drops to the surface over 45 minutes. The two Drop Sondes are released on command by the Gondola/Balloon System and descend to the surface over 45 minutes. Data from the Mini-Probe and Drop Sondes are transmitted to the Gondola/Balloon System where it is stored for future relay to the Carrier Spacecraft. The Mini-Probe and Drop Sondes are designed to survive until impact with the surface but are not required to operate after impact. For this study, the Mini-Probe and Drop Sondes have not been optimized for mass or volume. Further design efforts will reduce the size and mass of these units, resulting in a more efficient Gondola/Balloon System design. **Table 11** provides an overview of each system.

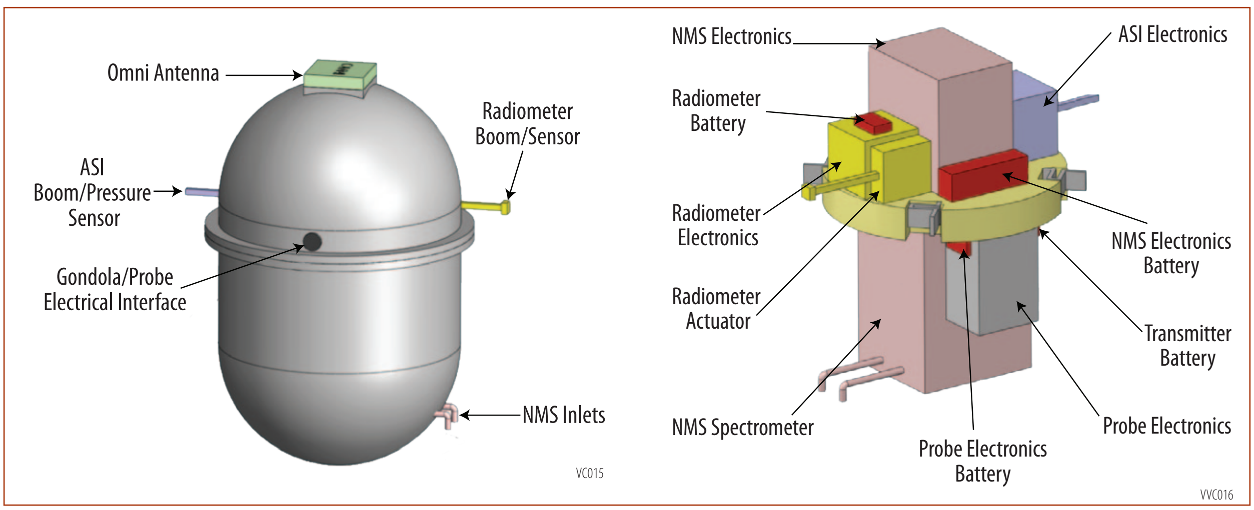


Figure 20: Mini-Probe with internal components

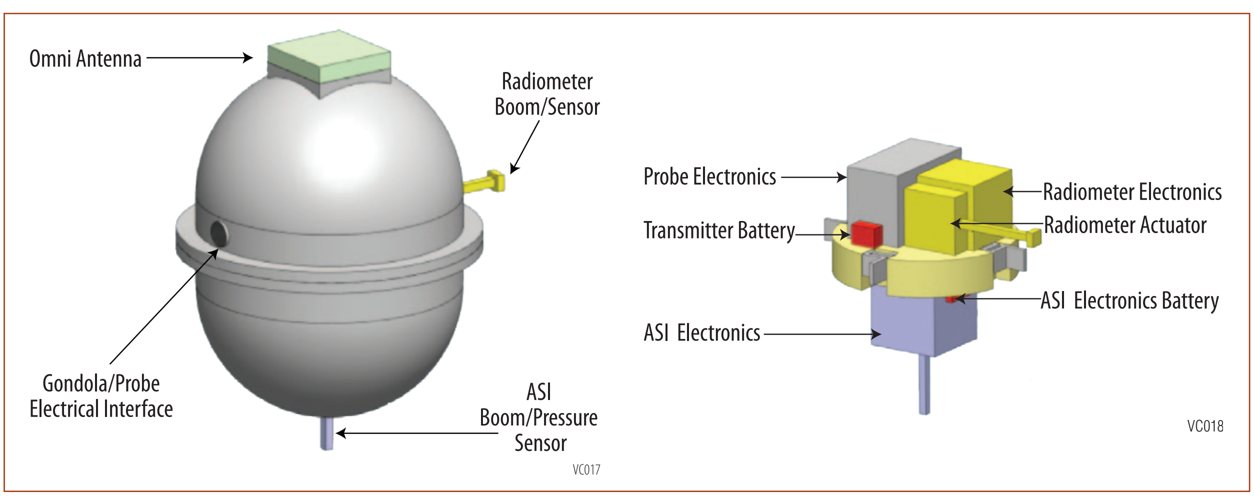


Figure 21: Drop Sonde with internal components

Table 11: Mini-Probe and Drop Sonde Overview

	Mini-Probe	Drop Sonde (2)
Payload	ASI, NFR, NMS	ASI, NFR
Mass	38.4 kg	12.4 kg each
Volume	44 cm dia., 66 cm tall	29 cm dia., 35 cm tall
Power	66 W peak, 51 W avg	16 W
Data Rate	3.4 kbps	0.3 kbps

3.3.1 Design of Mini-Probe and Drop Sondes

The Mini-Probe and Drop Sondes are titanium pressure vessels containing instruments and supporting avionics to power the instruments and transmit data during descent. The instruments and supporting avionics are mounted on an aluminum honeycomb deck in the pressure vessel. A common avionics system for the Mini-Probe and Drop Sondes contains an instrument control board for instrument readout and time stamping along with the S-Band transmitter. The control board also buffers data prior to transmission. The communication system consists of communication and data formatting processing on the instrument control board along with an integrated S-Band transmitter board and an S-Band patch antenna. Prior to release, the Probe and the Sondes utilize a direct wire line connection to the Gondola/Balloon System to permit interrogation and status reporting. The patch antenna radiates energy directly above the Mini-Probe/sondes, but due to its broad-beam characteristics the signal will also propagate out to 75º off-zenith to transmit to the Gondola/Balloon System at the end of the 45 minute drop. Power to the Mini-Probe and sondes is accomplished with a distributed system utilizing a power converter during the cruise phase and secondary (rechargeable) batteries after release from the Carrier Spacecraft. During the cruise phase, components of both the Mini-Probe and the sondes receive power from the Carrier Spacecraft through a direct wire power converter. The power converter also conditions the secondary batteries up to the point of EFS release. Once released from the Carrier Spacecraft, each component is powered by a dedicated battery. The secondary batteries have a self discharge rate of 2% per year and are sized to a maximum depth of discharge of 70% to allow for contingency power growth.

Thermal control for the Mini-Probe and Sondes is accomplished with thermal blankets and phase change material (PCM). The thermal design keeps the internal pressure vessel temperature below +60° C during descent. MLI blankets cover the interior pressure vessel wall. The pressure vessel is pressurized to 1.1 earth atmospheres to reduce thermal gradients. Thermal conduction from the pressure vessel to the mounting deck is minimized to reduce Venus environment heating. PCM is embedded in the aluminum honeycomb deck to absorb Venus environment heat during the descent. Approximately 1 kg of PCM is needed for the Mini-Probe and approximately 0.75 kg of PCM is needed for the sonde to maintain operating temperature in the pressure vessel.

3.3.2 Carrier Spacecraft

3.3.2.1 Carrier Spacecraft Mechanical System

The VCM Carrier Spacecraft (**Figure 22**) mechanical system consists of the following elements: a main truss structure/propellant module, an EFS support structure, 2.3 m^2 radiator, avionics mod-

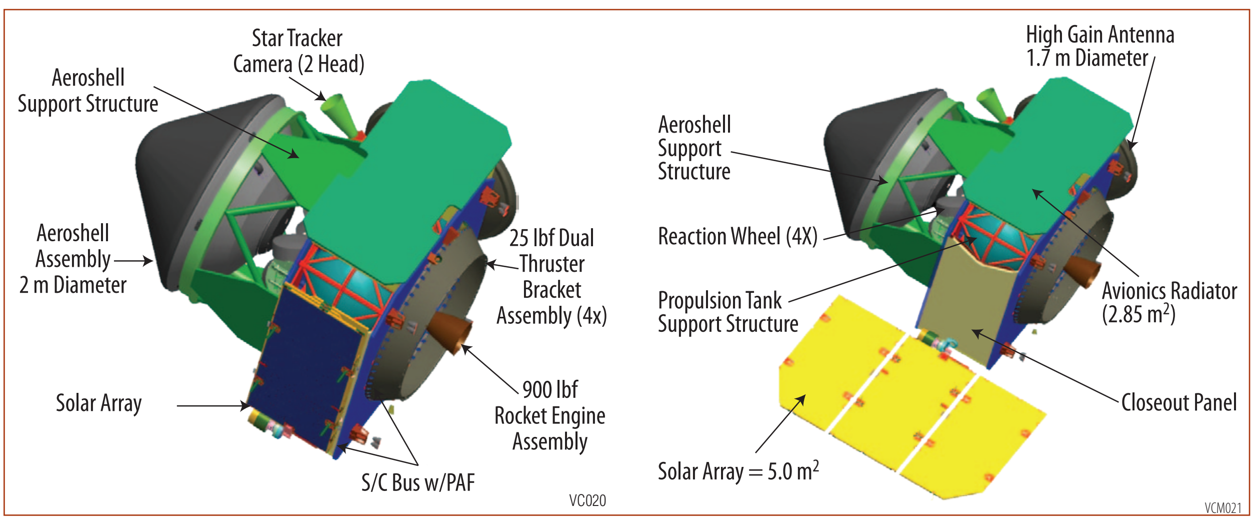


Figure 22: VCM Carrier Spacecraft (Solar Array Stowed and Deployed Configurations)

ule, 1.70 m high gain antenna and a 5 m^2 solar array (single axis).

Design Description: The design objective for VCM Carrier Spacecraft is to develop a mass efficient, low risk structure with heritage from previous space missions. The assumptions for the mechanical design of the Carrier Spacecraft are that the Carrier Spacecraft fit in an Atlas V 551 with a 5 m short fairing, utilize the D1666/C29 Payload Attach Fitting (PAF) with its associated separation system, and carry 1446.7 kg of propellant.

Light Weight, Low Cost, Modular Structural Elements: The primary objective of the VCM structural design is to create a robust, easy to manufacture, light weight modular structure with flexibility for Integration and Test. The primary structure consists of eight Tank Truss modules. Tank Truss modules can be constructed from composite materials with titanium end fittings or from welded Aluminum alloy extrusions. The details of the truss structure are shown in **Figure 23.**

Basic elements of the structural design are repeated in spacecraft. This modularity is exhibited in several different design components in the spacecraft, For example, the construction of the upper deck, lower deck, inner backbone panel and outer backbone panel are all made of the same aluminum honeycomb sandwich panel with composite or aluminum face sheets. The tank truss hemisphere and payload support structure are made of the same structural element, either a 0.1" thick composite or a 0.13" aluminum alloy tubing with four sandwich panels. The payload adapter cone is aluminum alloy

The objectives for the structural design of the Carrier Spacecraft are to minimize schedule, cost and risks. The design is finalized after carefully consideration of the issues of hardware testing, verification, heritage of flight components and the use of ground support equipment. Whenever possible the VCM Carrier Spacecraft structure utilizes designs and components with extensive heritage from previous planetary missions.

3.3.2.2 Carrier Spacecraft Thermal System

Environmental Loads: As the spacecraft travels on its trajectory from Earth to Venus, it temporarily passes inside Venus's orbit around the Sun, reaching a perihelion distance of approximately 105 million km (solar flux of 2,932 W/m^2). This is the hottest environment experienced by the solar array during the mission. Once the spacecraft has entered into orbit around Venus, the spacecraft receives environmental heat loads from three major sources: heat emitted directly from the planet itself (155 W/m^2), the solar load reflected off the cloud layer (Venus albedo = 0.8), as well as a direct solar load from the Sun (2,759 W/m^2). Of these three sources, direct solar heating is the main driver for the thermal design. The solar flux at Venus is approximately double the amount experienced near Earth, due to Venus's closer proximity to the Sun.

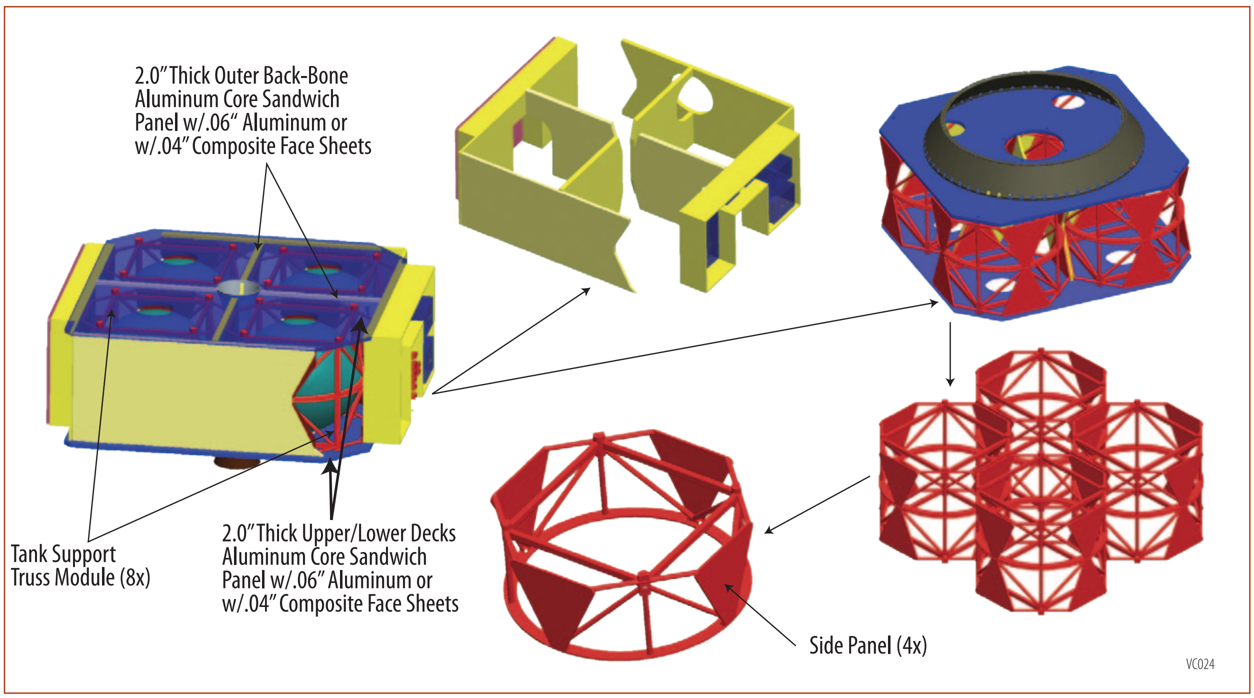


Figure 23: VCM Carrier Spacecraft Truss Structure (Outer Back-Bone Panels not shown for clarity)

Spacecraft Orbit: The spacecraft's orbit around Venus is highly elliptical, with a perigee of 500 km and apogee of 66,300 km. Because of it's highly eccentric orbit, the spacecraft travels quickly through perigee. As a result, the spacecraft spends very little time in eclipse during each orbit. Specifically, the spacecraft spends approximately 15 to 33 minutes in eclipse during each 24 hour orbital period. During the first orbit around Venus, the eclipse time is 15 minutes. This value grows progressively larger with each orbit as the mission progresses. Venus's shadow shifts slowly during its orbit around the Sun, changing the thermal environment and spacecraft's view to the Sun slightly as it does so. Images of the spacecraft's initial and final orbits are provided in **Figures 24 and 25.**

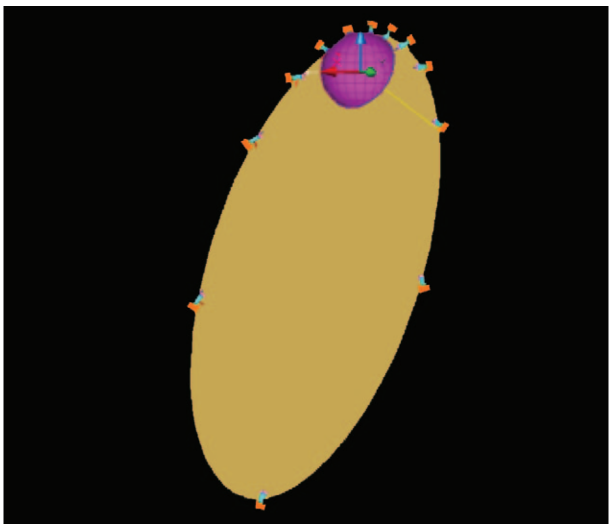


Figure 24: Venus orbit, beginning of mission. +Z Nadir, view shown from Sun, spacecraft displayed at 12 positions in orbit

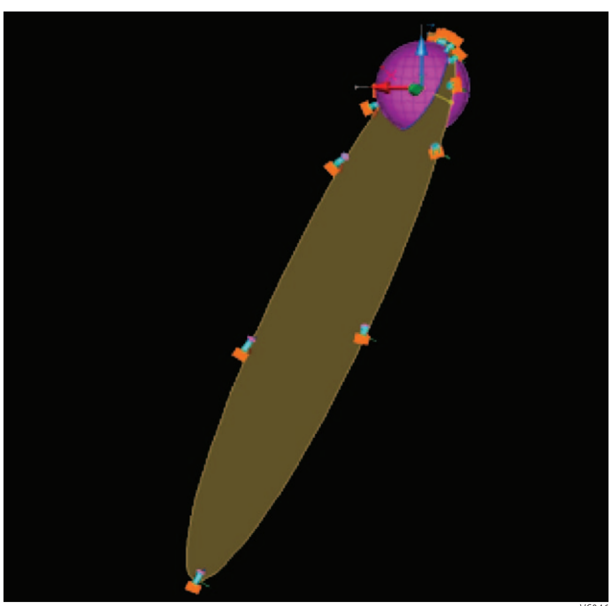


Figure 25: Venus orbit, end of mission. +Z Nadir, view shown from Sun, spacecraft displayed at 12 positions in orbit

Spacecraft Orientation: The orbiter's orientation is driven by the requirements for communication both to the Gondola/Balloon System and to the Earth. The communication dish, which is located on the +Z side of the spacecraft (**Figure 26**), is pointed towards Venus throughout most of the orbit in order to track the Gondola/Balloon System. However, for a portion of every orbit, the spacecraft rotates and points the +Z side (dish) towards Earth for data transfer. The spacecraft has the freedom to spin about its +Z axis, which enables it to maximize the solar array's view to the Sun, while still meeting these two pointing requirements (+Z nadir to Venus, and +Z towards Earth). In the thermal model, this is achieved by defining a tracker to rotate the spacecraft about the +Z axis, with the goal of maximizing the –Y side's view to the Sun in order to shade the radiator. In addition to spacecraft spin about the Z axis, the solar array itself is allowed to gimbal 180 degrees about the X axis, to further increase the view of the array to the Sun. The trackers which are used to define spacecraft spin and solar array gimbal are shown in **Figure 26.**

Material and Coatings: Multi-Layer Insulation (MLI) blanketing will be used on the exte-

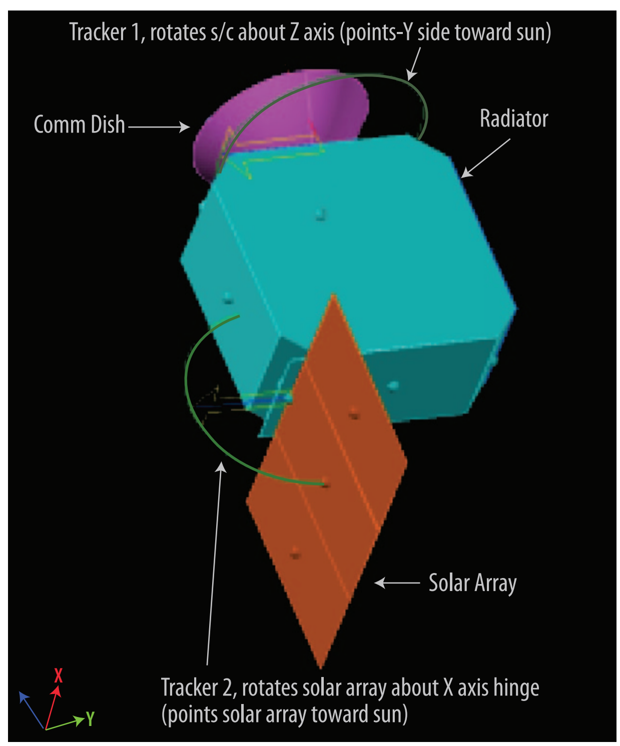


Figure 26: Thermal model of VCM spacecraft, trackers shown

rior surfaces of the spacecraft. Germanium Black Kapton (GBK) is selected as the outer layer of the MLI to minimize electric charge buildup. GBK is used on all sides of the spacecraft bus, with the exception of the -Y side (Sun-side). When this side was modeled with an outer layer of GBK, temperatures reached 150° C. Temperatures this high will approach the maximum temperatures allowed for the adhesives which are often used on MLI. To mitigate this, the outer layer of the MLI blanket on this side only is coated with silver Teflon, which has a much lower solar absorptivity than GBK, and will reduce the temperature on this surface to 21° C. In addition, high temperature blankets (titanium/epoxy-glass) are located at the main engine and at the 12 thrusters. The location of these high temperature blankets is shown in **Figure 27**.

An optical solar reflector (OSR), located on the +Y side (space-side) is used as the spacecraft's main radiator. OSRs are selected over white paint due to their lower solar absorptance value (an important consideration when operating close to the Sun). The battery as well as the electronic boxes with high power dissipations are mounted directly to this radiator. The boxes with lower power dissipations are located on the opposite side of the spacecraft (-Y, Sun-side), in order to balance inertial forces. Dual bore heat pipes transfer heat from the -Y electronics around to the radiator on the +Y side. A diagram of this is shown in **Figure 27**. The anti-Sun side of the solar array is coated with NS43C white paint, in order to radiate heat. A solar cell efficiency of 20% is assumed, which results in optical properties for the solar cells of alpha = 0.72 and emissivity = 0.77.

Temperature Results: The temperature limits for electronic boxes are assumed to be 30° C and 5° C, for the hot case and cold case, respectively. A temperature gradient of 15° C is assumed between boxes and the OSR radiator (conservative). Given this, the temperature requirements placed on the radiator are 15° C and -10° C, for the hot and cold cases, respectively. The total heat dissipated from electronics in the hot case is 419 W, which results in an OSR radiator size of 2.3 m². For hot case calculations, maximum values are assumed for solar flux and albedo at Venus.

During the cold case, the electronics dissipate 284 W. In order to keep the spacecraft above the cold limit, a total of 505 W of heat needs to be applied to the spacecraft. Subtracting the heat supplied by electronics, a resulting value of 221 W of heater power is applied to the radiator during the cold case.

The hot temperature limit for the solar array is 135° C, based on solar array requirements developed for the Lunar Reconnaissance Orbiter (LRO). Four bounding conditions are modeled for VCM to evaluate solar array temperatures. The first and second are Venus-pointing and Earth-pointing at the beginning of the three-week mission. The third and fourth are Venus-pointing and Earth-pointing at the end of the mission. Of these four scenarios, the highest solar array temperature predicted is 121° C. This leaves sufficient margin to the 135° C hot limit. The temperature profile for this case is shown in **Figure 28**. The perihelion case is considered as well, in the form of a hand calculation. If the solar array is facing full Sun at perihelion, the temperature limit is not exceeded as long as the array is positioned between 74° and 180° away from the spacecraft bus panel to which it is mounted. If the solar array is at an acute angle to the bus that is smaller than 74°, the back side of the solar array is occluded by the bus and does not have enough view to space to dissipate the amount of heat necessary to meet the temperature requirement.

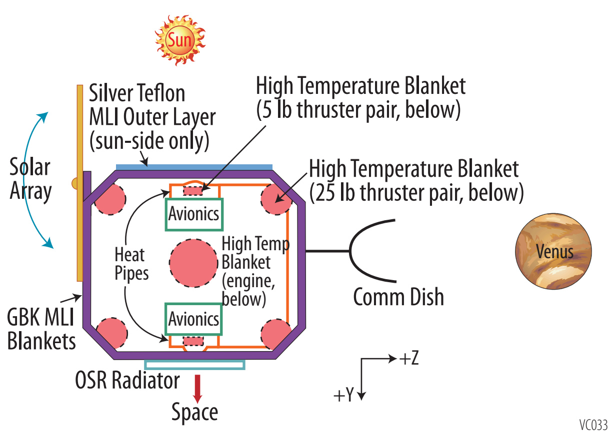


Figure 27: Sketch of thermal design components

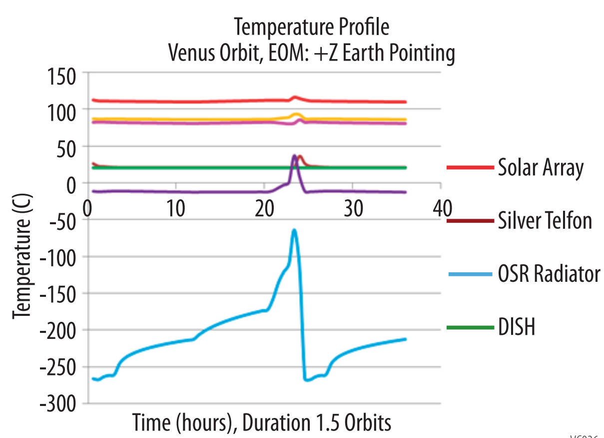


Figure 28: Temperature results for hot solar array case (121° C). Spikes in chart correspond to eclipse.

3.3.2.3 Carrier Spacecraft Communications System

The Carrier Spacecraft communication sub-system provides store and forward relay services for the Gondola/Balloon System and Probe/Sondes science data and provides reliable command and telemetry links to the Earth. The communication sub-system, as delineated in **Table 12:** VCM Carrier Spacecraft Communication Sub-Systems Parameters and illustrated in **Figure 29**: Carrier Spacecraft Communication Sub-System, consists of an S-Band transceiver chain and a Ka-Band transponder chain both utilizing a dual S/Ka-Band 1.7 m high gain antenna. The Carrier Spacecraft S-Band chain supports a two-way link for reliably transferring the Gondola/Balloon System data at 1.2 kbps, sending commands, and measuring Doppler for Gondola/Balloon System tracking. The Ka-Band transponder chain supports a two-way link to Earth via the Deep Space Network 34 m stations. Nominal uplink and downlink operations utilize the 1.7 m high-gain antenna to support downlinks of 70 kbps (or higher) and uplinks of 1 kbps. For contingency operations, the Ka-Band signals can be switched through two low gain antennas that provide a wide field of view (>70 degrees each). Although general operations do not require a 50 W Traveling Wave Tube Amplifier (TWTA) (a 1 W amplifier would be sufficient), the VCM system design uses a 50 W TWTA to support contingency op-

Table 12: VCM Carrier Spacecraft Communication Sub-Systems Parameters

Item	Units per Element	Unit Size (cm x cm x cm)	Unit Mass (kg)	Unit Power (W)
Ka-Band Transponder	1	18 x 17 x 11	3.2	15.8
Ka-Band TWTA (50 W output)	1		5.0	100.0
Diplexer	2		0.25	-
Switch	1		0.2	-
Hybrid	1		0.2	-
Multipliers/Downconverters	2		0.2	-
RF connectors & cabling	1		4.0	-
S-Band Transceiver	1	20 x 14 x 8	2.5	25.0
S-Band Solid State Power Amplifier (5 W output)	1		2.5	15.0
Ka-Band Low Gain Antenna	2		1.0	-
Dual-band (S/Ka-Band) Dish	1	1.7 m diameter	15.0	-
Total Carrier Spacecraft: Communications			34	155.8

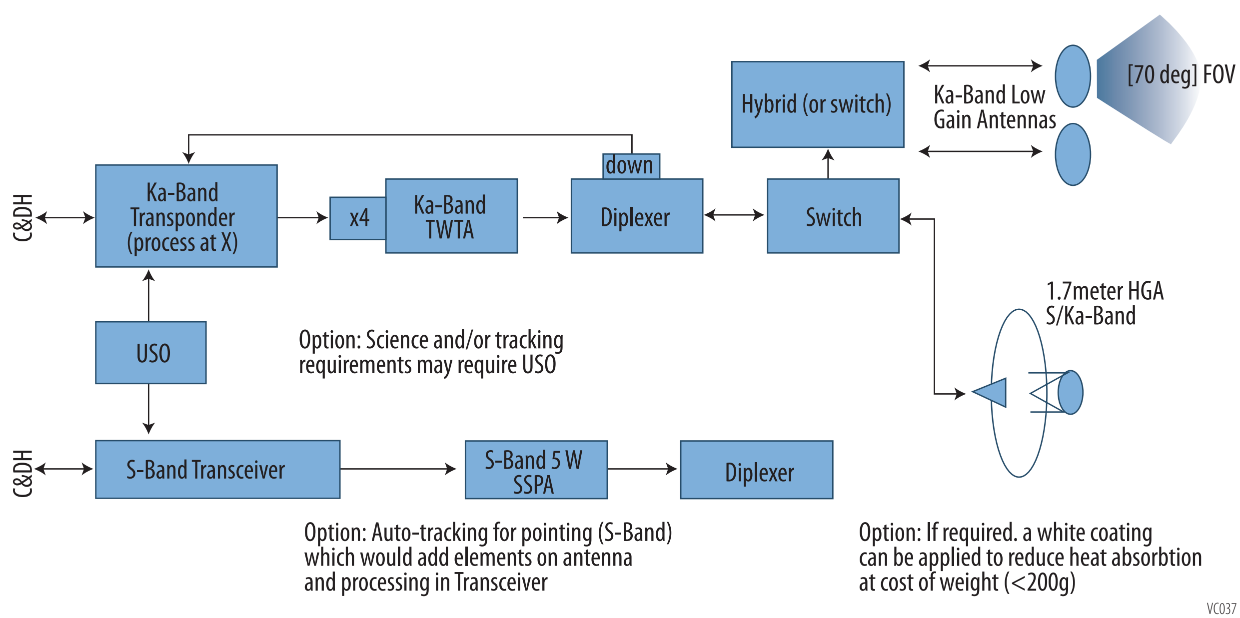


Figure 29: Carrier Spacecraft Communication Sub-System

erations through the low-gain antennas.

VCM is following the assumptions for DSN availability stated in NASA's "Groundrules for Mission Concept Studies in Support of Planetary Decadal Survey," Rev, 2, Nov, 2009. This document states missions should baseline Ka-Band for science return. The communications sub-system strives for the simplest design possible and avoids the use of multiple high-gain antennas or developing a tri-band antenna. The VCM design assumes all Ka-Band operations for uplink, downlink, and contingency communications with Earth. This design requires the DSN to support this all Ka-Band approach. However, operations using X-Band for uplink, downlink, and contingency also satisfy the mission requirements.

3.3.2.4 Spacecraft Propulsion

The initial area of focus for the Carrier Spacecraft propulsion system entails sizing the propulsion system's main engine. Because of the orbital scenario selected, the mission requires a large amount of thrust during the VOI burn. It is required that the VOI be completed within a 30 minute time span in order to minimize the non-impulsive velocity change time and optimize the probability that the burn can be accomplished while the spacecraft is in contact with the Earth. This keeps the operation similar to other planetary orbit insertions. The calculations for this orbit insertion burn result in a thrust of 400 lbf. A search of existing hypergolic bipropellant apogee engines (looking at Aerojet, AMPAC, and EADS) indicated that qualified engines were either in a 100–150 lbf class range or in a 700–1000 lbf class range. In order to aid a more conservative thermal design, the decision was made to avoid using multiple 100–150 lbf engines. Multiple engines nested together need extensive thermal and plume analysis in order to ensure that engines work effectively together. Thus, it was determined that the single 700–1000 lbf engine be used with its thrust being set by adjusting the feed pressure appropriately.

Based on the main engine to be used for VOI, attitude control thrusters are selected. After reviewing previous mission such as SDO and LRO, conservative values for thrust vector misalignment and center of mass location error are 1° and 2 cm, respectively. Using an initial assumption of a 4 meter spacecraft diameter and thus a 2 meter moment arm, it is determined that approximately 15 lbf-ft of torque is required to offset the worst case torque due to location and misalignment errors. A fully redundant set of eight (8) 25 lbf thrusters are chosen to provide this torque for attitude correction during VOI main engine firing.

ACS analysis determined that an angular velocity of 5 rpm is needed for probe release. A set of four coupled, 5 lbf ACS thrusters are included in order to support the spin-up and spin-down modes as well as other attitude fine tuning maneuvers.

The main engine is located colinear with the spacecraft's theoretical center of mass in the thrust axis. The eight (8) 25 lbf thrusters are paired into four clusters and are located on the +/- Z side of the spacecraft's bottom (-X) deck. The thrusters are placed at 10° cant angles toward the opposing side of the spacecraft. The thruster placement and cant angle ensures maximum moment arm length and 3 axis control of the spacecraft while minimizing cosine losses. The four 5 lbf thrusters are paired into two clusters located on the +/- Y side of the bottom deck of the spacecraft. Each set is oriented in a horizontal bow tie fashion with a 45° cant out from the +/- Z axis. This orientation provides the necessary spin up/spin down control without overheating the radiator or other spacecraft components while firing. All Carrier Spacecraft maneuvers for this mission are shown in **Table 13 and Table 14**. **Table 13** is the Pre EFS release maneuvers and **Table 14** is the post EFS release maneuvers.

Propellant tanks are sized based on the required volume of 37,500 in^3 of Nitrogen Tetroxide (NTO) and another 37,500 in^3 of Monomethylhydrazine (MMH). The pressurant tank are sized on a 200 psia engine inlet pressure, a Beginning of Life (BOL) pressurant temperate of 0° C – 10° C, and an End of Life (EOL) temperature of 40° C – 50° C. From existing PSI pressurant tank designs, either one 23.6" ID, 7,100 in^3 volume pressurant tank or two 16" OD x 26" long, 4,105 in^3 volume pressurant tanks are sufficient. Both options remained under the Maximum Expected Operating Temperature (MEOP) of the pressurant tank at BOL while providing the engines the necessary inlet pressure throughout the mission duration.

The propulsion system block diagram is shown in **Figure 30** and propulsion component masses are shown in **Table 15**.

3.3.2.5 Carrier Spacecraft Attitude Control System

The Attitude Control System (ACS) is based on a standard three axis stabilized system which is capable of managing a 5 RPM spin rate for probe release. Post launch vehicle separation, the ACS reduces the tip-off rates and maintains a power positive attitude. During the cruise phase, the ACS points the spacecraft fixed high gain antenna toward Earth while commanding the solar array

Table 13: Pre EFS Release Maneuver Profile and Propellant Usage

Maneuver	Delta V (m/s)	Isp (s)	Delta V/Isp (m/s^2)	M_b (kg)	M_w (kg)
At LV Release	n/a	n/a	n/a	n/a	4356.3
Earth Venus TCM's (25# thruster)	32.0	280	0.114	50.47	4305.8
Orbit Divert Maneuver (25#)	64.0	280	0.229	99.20	4206.6
Margin (25#)	50.0	280	0.179	75.91	4130.7
Momentum Management (25#)	2.0	280	0.007	3.01	4127.7
Spin-Up (5# thruster)	1.0	300	0.003	1.40	4126.3
Total	**149.0**		**0.532**	**228.59**	

M_b = mass of propellant burned for maneuver M_w = wet-mass of the spacecraft after the burn

Table 14: Post EFS Release Maneuver Profile and Propellant Usage

Maneuver	Delta V (m/s)	Isp (s)	Delta V/Isp (m/s^2)	M_b (kg)	M_w (kg)
At Probe Release	n/a	n/a	n/a	n/a	2651.3
Spin-Down (5# thruster)	1.0	300	0.003	0.90	2650.4
Venus Capture (900# engine)	1641.0	290	5.659	1162.02	1488.4
VOI Correction (25# thruster)	21.0	280	0.075	11.34	1477.1
Momentum Management (25#)	0.1	280	0.000	0.05	1477.0
Total	**1662.1**		**5.737**	**1174.32**	

M_b = mass of propellant burned for maneuver M_w = wet-mass of the spacecraft after the burn

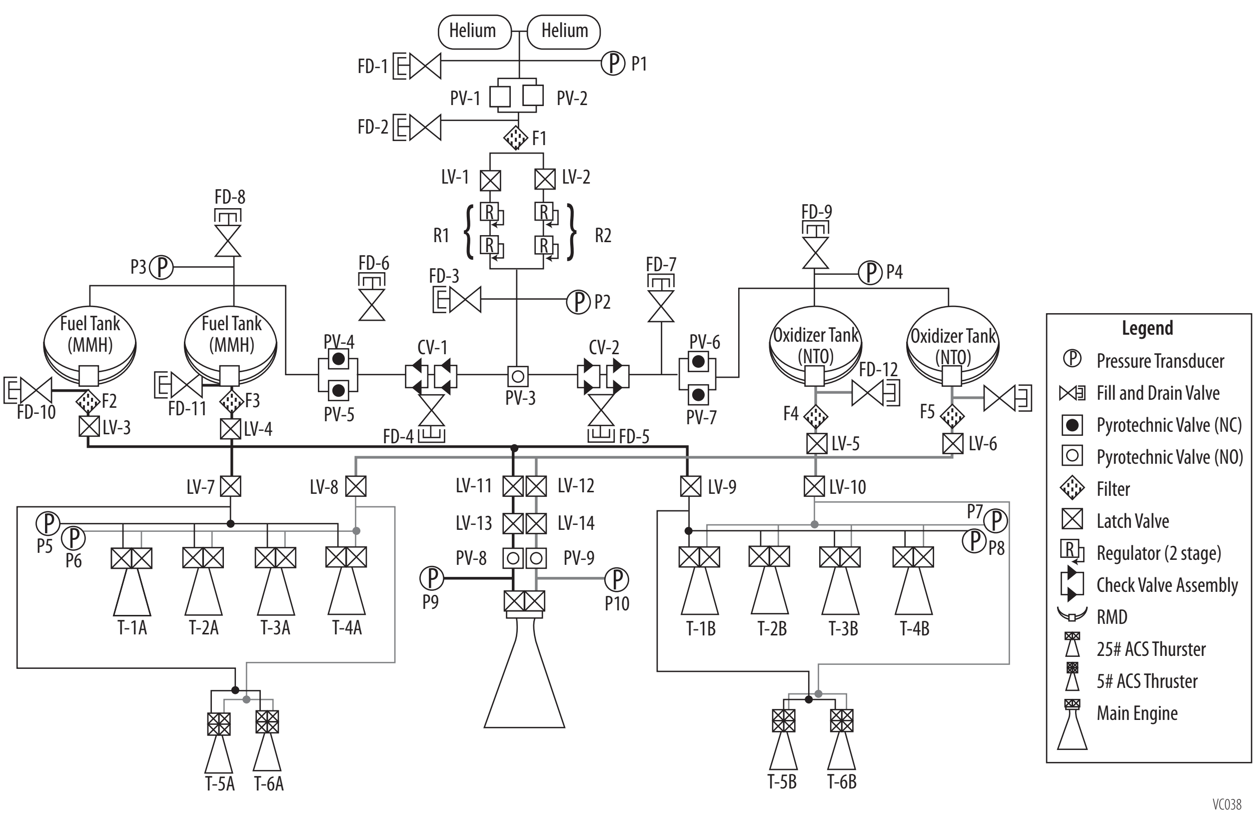


Figure 30: VCM Bipropellant Fluid Schematic

Table 15: VCM Propulsion Module Dry Mass

Component	Mass/Unit (kg/unit)	#	Mass (kg)	Status	Notes
NTO Oxidizer Tank	17.12	2	34.24	ETU	PSI 80440-1
MMH Fuel Tank	17.12	2	34.24	ETU	PSI 80440-1
Helium Tanks	10.00	2	20.00	ETU	PSI 80402-1
Main Engine (900 lbf)	6.80	1	6.80	ETU	Aerojet R-40B
ACS Thrusters (25 lbf)	1.59	8	12.72	ETU	Aerojet R-1E
ACS Thrusters (5 lbf)	0.65	4	2.60	ETU	AMPAC-ISP 5 lbf
Pressure Transducers	0.27	10	2.69	ETU	Paine
HP Latch Valvues	0.34	2	0.68	ETU	Vacco V1E10763
LP Latch Valves	0.75	10	7.48	ETU	Vacco V1D10392-01
Fill and Drain	0.05	13	0.65	ETU	Marotta Proposal
Gas System Filters	0.11	1	0.11	Est	Vacco F1D10286-01 (reduced to 1 per simplification)
Propellant Filters	0.91	4	3.64	ETU	Vacco F1D10559-01
Check Valves	0.14	4	0.54	ETU	Vacco V1D10495-01
Pressure Regulators	1.10	2	2.20	ETU	m-SPACE proposal
Plumbing Lines	0.09	80	7.06	Est	ESTIMATE (Using 0.0882 kg/m titanium tubing 3/8x0.028)
Thermal Hardware	0.40	80	35.00	Est	ESTIMATE (Using MAP thermal tubing mass of 0.4 kg/m)
NC Pyro Valves	0.11	6	0.66	ETU	CONAX 1832-207
NO Pyro Valve (ME)	0.16	2	0.32	ETU	CONAX 1801-102
No Pyro Valve (3-way)	0.20	2	0.39	ETU	CONAX 1801-103
Fasteners	0.02	212	3.99	Est	18.8 g for bolt + nut + 2 washers. No tank fasteners.
Total Dry Mass			**176.00**		

gimbal to optimize solar array power. The optimum angle to point the antenna is found by performing a raster scan toward Earth. This pointing profile uses the antenna in a closed loop manner to optimize the receiving power. For the probe release, the ACS targets the probe toward Venus, and imparts a 5 RPM spin rate about the probe and carrier spin axes using momentum wheels. After probe release, the wheels despin the carrier. The residual momentum in the wheels is unloaded using thrusters. The VOI maneuver requires a 900 lb main engine thruster. To maintain control, 25 lb thrusters are off-modulated. General orbit and momentum maintenance during the cruise phase and in Venus orbit is controlled using the 5 lb thrusters for finer resolution.

ACS Modes: Mission Mode directs the spacecraft toward reference targets including the Sun, Earth and Venus during cruise and science operations. Orbit Control Mode performs delta-V maneuvers using 25 lb or 5 lb thrusters depending on the pointing resolution required. The Momentum Management Mode uses 5 lb thrusters to establish a commanded angular momentum vector. Sun acquisition mode is the first mode entered after launch vehicle separation to maintain a power and thermally safe three axis stabilized attitude. Safe mode uses a reduced sensor set to direct a selected body axis toward the Sun, and establishes a slow constant spin rate for communication.

ACS Hardware: Two star tracker heads with a common electronics box combined with two 3-axis ring-laser gyros provide sufficient attitude determination accuracy and redundancy for mission mode. Attitude control is also maintained by propagating the ring-laser gyros during Orbit Control and Momentum Management Modes.

The four, less accurate, single axis MEMS gyros and 16 Course Sun Sensors (CSSs) track the Sun and spacecraft body rates for the Sun Acquisition and Safe Modes. There are four 75 Nms reaction wheels mounted in a pyramid configuration for storing momentum and performing a 180 degree slew in under 10 minutes. The 25 lb thrusters, mounted parallel to the main engine with a cant angle for three axis control, are primarily used in the orbit control mode.

3.3.2.6 Carrier Spacecraft Avionics (C&DH)

The Carrier Spacecraft avionics consists of the Command and Data Handling (C&DH), the Power System Electronics (PSE), the Attitude Control Electronics (ACE), and the Ka-band Transponder and the S-band transceiver. The LRO C&DH is the basis for the VCM Carrier Spacecraft avionics. The box consists of many of same boards as the LRO design such as the powers supply card, the S-band and Ka-band telecom cards, the single board computer (SBC), the housekeeping I/O card, the data storage board (DSB), and the multifunction analog card (MAC). The VCM avionics has added a gimbal control card that was not part of the LRO design. All commands and telemetry go through the internal RAD750 processor on the SBC. All commands and telemetry are sent to the ground via the Ka-band transponder and the Ka-band communication card in the C&DH. It is in the C&DH that all commands are verified and forwarded to the appropriate subsystems. The C&DH also digitizes all analog telemetry and temperatures and transmits the information in the housekeeping telemetry at a rate of 3 kbps. The C&DH uses a standard 1553 communication bus to communicate with other Carrier Spacecraft avionics boxes and an RS-422 bus through an umbilical interface to communicate with the EFS. The RS-422 link supports ground operations and operation of the Gondola/Balloon System electronics during the cruise phase for aliveness tests and state of health information of the system. The C&DH contains 100 Gbits of solid state data storage, which is enough memory to store all of the science data taken during the 21 day Gondola/Balloon System mission.

The SDO heritage ACE box interfaces with all the attitude control subsystem components and the propulsion hardware. Using internal software, the box controls the attitude of the spacecraft during the cruise to Venus and performs the VOI maneuver. During the mission phase, the ACE uses feedback from the communication subsystem to maintain pointing of the fixed high gain antenna to the Gondola/Balloon System to receive science data over the S-band communication link. The ACE then commands the Carrier Spacecraft to point the fixed high gain antenna to Earth for transmission of science data using the Ka-band communication link.

The LRO heritage PSE box is responsible for energy balance, distribution of power to all Carrier Spacecraft avionics boxes and switching of power to the heater services. The modular design of the PSE output modules allows for the addition of a low voltage power card to condition the Mini-Probe and Drop Sondes batteries prior to EFS release.

Figure 31: Carrier Spacecraft Avionics Block Diagram shows the avionics system.

3.3.2.7 Carrier Spacecraft Power System

The VCM Power System provides power to all observatory loads throughout all phases of the mission. It consists of three components: Solar Array (SA), Battery, and PSE. The 5 m^2 solar array produces 1000 W (at Earth) of electrical power. This power is conditioned by the PSE and distributed to the spacecraft and payload systems in a voltage range of 24–35 V_{DC}. The PSE is designed with a throughput capability of 823 W orbit average. It can provide up to 12 un-switched power services to critical subsystems like C&DH, ACS, Propulsion, Communications and survival heaters that must be active throughout the mission. An additional 48 switched power services are available for other spacecraft systems and instruments as required for the science phase of the mission. All switched services have re-settable over current protection and current monitoring capability. The PSE accepts commands from the C&DH as well as provides telemetry to the C&DH through the 1553 bus interface. The PSE also controls the charging of the 60AH lithium ion battery which provides all spacecraft power during non-sun periods. The PSE unit described here is based on the LRO version and can be optimized for mass, power, and capability based on specific VCM requirements. The power system is made up of components and circuits that have flown on many missions and is very low risk and at a high TRL.

3.4 VCM Mass and Power

The VCM total mass is 3889.9 kg which includes propellant of 1446.7 kg (including margin). **Table 16:** Overall Launch Mass details the VCM system mass developed for this concept. **Table 17** provides details of power requirements for the VCM system.

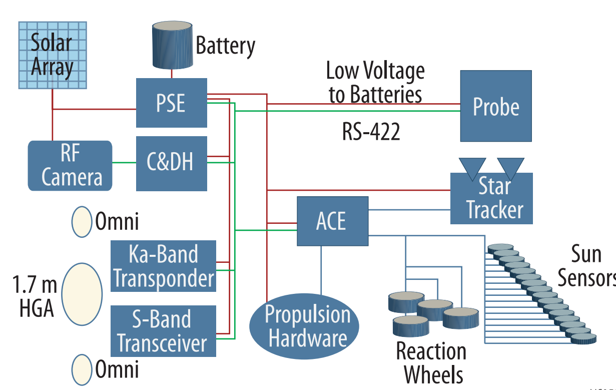


Figure 31: Carrier Spacecraft Avionics Block Diagram

Table 16: Overall Launch Mass

Item	CBE (kg)	Margin (%)	Mass w/Margin (kg)
Aeroshell			
ACS	0.3	30%	0.4
Power (battery for 10-day cruise)	8.1	30%	10.6
Structures/mechanisms	110.3	30%	143.4
Front aeroshell	45.8	30%	59.5
Backshell	19.4	30%	25.2
Parachute	20.0	30%	26.0
S/C side adapter	7.6	30%	9.9
Cabling	17.5	30%	22.7
TPS (thermal protection system)	135.0	30%	175.5
Front aeroshell	114.2	30%	148.5
Backshell	20.8	30%	27.0
Aeroshell Total	253.7		329.8
Mini-Probe and Drop Sondes			
Mini probe	38.4	30%	49.9
Drop sonde 1	12.4	30%	16.1
Drop sonde 2	12.4	30%	16.1
Mini-Probe and Drop Sondes Total	63.2		82.2
Gondola/Balloon System			
Instruments	19.5	30%	25.4
Command & Data	6.9	30%	9.0
Power	27.6	30%	35.9
Structures & Mechanisms (incl. balloon)	110.4	30%	143.5
Cabling	25.6	30%	33.2
Telecom	5.5	30%	7.2
Thermal	1.1	30%	1.4
Gondola/Balloon System Total	196.7		255.7
Inflation System & Helium			
Inflation system	113.3	30%	147.3
Helium for balloon inflation	21.8	30%	28.3
Inflation System and Helium Total	135.1		175.7
Carrier Spacecraft			
Probe Separation System	30.0	30%	39.0
VIS IR Camera	2.0	30%	2.6
Science Payload Accommodation	2.5	30%	3.2
S/C Mechanical, Structural and Gimbal, array substrate	652.2	30%	847.9
GN&C	48.0	30%	62.4
Propulsion Hardware	176.0	30%	228.8
Thermal (MLI, Heaters, Tstats)	57.0	30%	74.1
Power (Solar Arrays, Battery, PSE)	104.0	30%	135.2
Harness, Fastners, Brackets, Misc	90.0	30%	117.0
RF Comm	34.0	30%	44.2
Avionics (ACE, C&DH)	35.0	30%	45.5
Carrier Spacecraft Total	1230.7		1599.8
VCM (S/C + Probe) Dry Mass	1879.4		2443.2
Propellant Mass	1432.4	1%	1446.7
VCM Wet Mass (without Launch Adapter)	3311.8		3889.9
Launch Adapter			94.0
VCM Wet Mass (with Launch Adapter)			3983.9
Atlas V 551 Throw Mass, C3 = 8.8			5141.0
LV Margin			1157.1
LV Margin (%)			22.5

Table 17: Spacecraft Average Power (Watts)

	Launch	Cruise	Probe Release	Probe Cruise	VOI	Venus Orbit	Balloon Ops	Probe Science	Earth Comm	Sizing w 30% contingency
Totals	**207**	**479**	**481**	**382**	**657**	**405**	**405**	**404**	**492.5**	**854.1**
Instruments										
VIS IR Camera		0.75				7.5	7.5	7.5	7.5	
Probe Testing (10% Duty Cycle)		13.74								
Probe Thermal		70								
Probe Battery Conditioning		5								
S/C Components										
C&DH	87	87	87	87	87	87	87	87	87	
ACE	27	27	27	27	27	27	27	27	27	
Power	43	43	43	43	43	43	43	43	43	
Comm System	38	46	141	38	141	53	53	53	141	
Propulsion	10	10	11	10	187	10	10	10	10	
ACS Components	2	62	62	62	62	62	62	62	62	
Array Motor	0	5	0	5	0	5	5	5	5	
Thermal	0	110	110	110	110	110	110	110	110	
Totals	**207**	**479.49**	**481**	**382**	**657**	**404.5**	**404.5**	**404.5**	**492.5**	

3.5 Ground Systems

The ground data system is shown in **Figure 32.** VCM uses a Ka-band downlink to a DSN 34-meter ground station for science data relay and full duplex contingency communications (through two low gain antennas). Although Ka-band components such as low gain antennas do not exist today, they are expected to be available well before VCM PDR. If they are not, a hybrid X/Ka band system or a solely X-band system is feasible.

VCM does not require the use of the 70-meter antennas and uses only one ground station at a time, with the exception of infrequent Delta Doppler One-way Ranging support to refine the navigation.

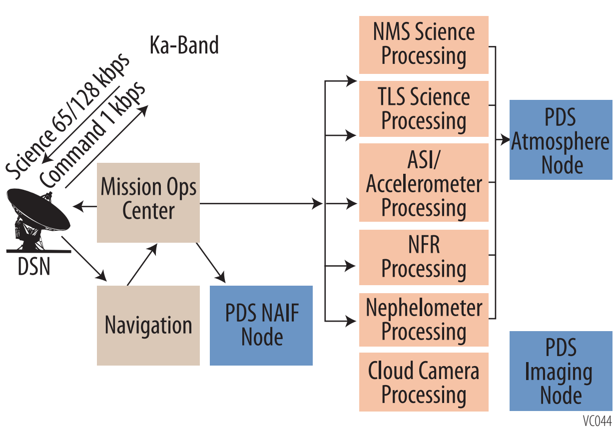


Figure 32: Ground Data System

The Navigation function is responsible for determining the trajectory of the spacecraft and planning maneuvers. The Mission Operations Center (MOC) is responsible for Carrier Spacecraft and Gondola/Balloon System operations and monitoring the sonde and probe operations.

The instrument teams process the science data and deliver the science data products to the Planetary Data System within 6 months of the end of mission operations.

3.6 Key Trades

3.6.1 Propulsion Trade

An initial propulsion module trade study was performed for the VCM comparing a monopropellant versus bipropellant system. Although the monopropellant system has the inherent advantage of a simpler design and lower cost, the larger fuel fraction associated with the monopropellant system drove the design to selecting the higher efficiency bipropellant propulsion system. The nearly 800 kg propellant mass difference can be seen in the propellant budget trades between the two systems (**Tables 18 and 19**).

3.6.2 Mechanical System Trades

A trade study to optimize the mechanical layout for the Carrier Spacecraft was performed. Since the propulsion system is the main driver for the Carrier Spacecraft's mass and volume, the mechanical and structures trades included three configurations of the orbital bus structure to best accommodate the propulsion system. The first, Concept 1, stacked the eight propulsion tanks on a cone. Concept 2 stacked the eight tanks without a mounting cone. Concept 3 assembled the eight tanks in a horizontal truss structure. Concept 3 was selected because it optimized the overall height, minimized the structural mass, and provided a better configuration in terms of CG both with the EFS attached (during interplanetary cruise) and without the EFS while operating as an Carrier Spacecraft around Venus. **Figure 33** shows these concepts.

Table 18: Trade Study Results Monopropellant System

Monopropellant System	
Fuel (N_2H_4) Burn Pre-Probe Release	334.3656 kg
Fuel Burn Post-Probe Release	1834.94 kg
Total Fuel Burned	2169.306 kg
Fuel Residual Percentage	2.0 %
Fuel Residual (Unusable)	43.4 kg
Total Fuel Required	**2212.7 kg**
N_2H_4 Volume	134421.9 in³
Fuel Ullage Percentage	1 %
Fuel Ullage Volume	1344.219 in³
Required Fuel Tank Volume	**135766.1 in³**
N_2H_4 Density: 1.0045 g/cm³ = 0.0164608058 kg/in³	

Table 19: Trade Study Results Bipropellant System

Bipropellant System	
Fuel (MMH) Burn Pre-Probe Release	86.78824 kg
Fuel Burn Post-Probe Release	443.1379 kg
Total Fuel Burned	529.9262 kg
Fuel Residual Percentage	2.0 %
Fuel Residual (Unusable)	10.6 kg
Total Fuel Required	**540.5 kg**
MMH Volume	37482.77 kg
Fuel Ullage Percentage	1 %
Fuel Ullage Volume	374.8277 kg
Required Fuel Tank Volume	**37857.6 in³**
MHH Density: 0.88 g/cm³ = 0.0144206163 kg/in³	
Ox (NTO) Burn Pre-Probe Release	143.2006 kg
Ox (NTO) Burn Post-Probe Release	731.1776 kg
Total Ox Burned	874.3782 kg
Ox Residual Percentage	2.0 %
Ox Residual (Unusable)	17.5 kg
Total Ox Required	891.9 kg
Ox Volume	37534.47 kg
Ox Ullage Percentage	1 %
Ox Ullage Volume	375.3447 in³
Required Ox Tank Volume	37909.82 in³
NTO Density: 1.45 g/cm³ = 0.0237612428 kg/in³	
Total Propellant Mass Required	**1432.4 kg**

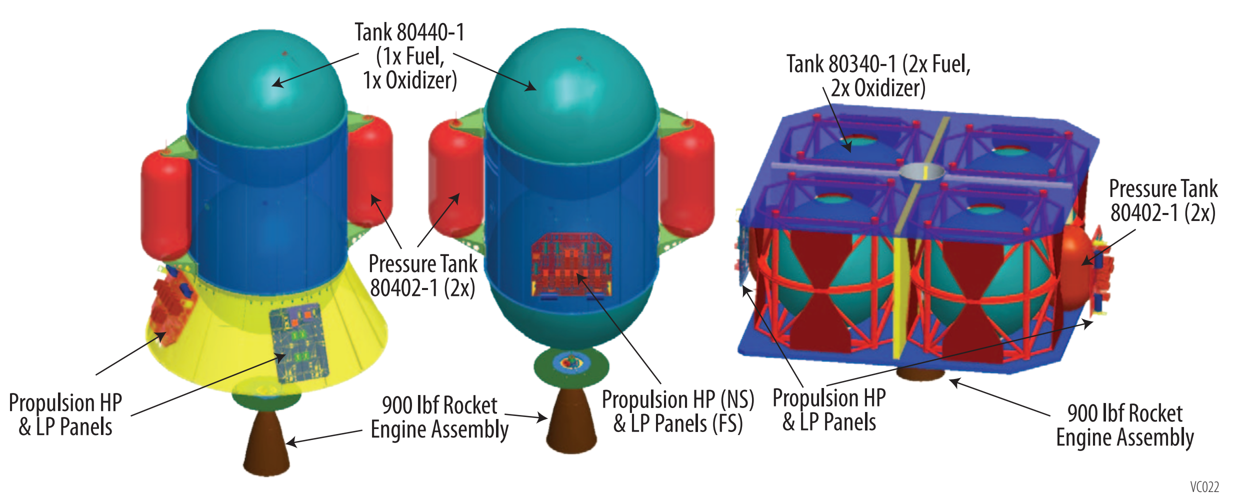


Figure 33: VCM Carrier spacecraft Propulsion Configuration Concepts

3.7 Risk List

Risks identified during the VCM study are listed below. Proposed mitigation of these risks is also presented. **Figure 34** summarizes the risks.

1. VCM contains four distinct flight elements (Gondola/Balloon System, Carrier Spacecraft, Mini-Probe and Drop Sondes). Integrating these four elements together will be challenging. There is a risk that integration problems will occur that affect the launch schedule and the cost of the mission. This risk is mitigated with project schedule margin (8 months), project budget reserve (50%).
2. Packaging a large NMS into the Mini-Probe is challenging when considering the thermal and structural loading issues of launch, Venus atmospheric entry and descent through the atmosphere. There is a risk of Mini-Probe failure during these events. This risk is mitigated by implementing a technology development program to design a robust Mini-Probe.
3. The mission contains multiple critical separation events. Before releasing the EFS, the Carrier Spacecraft spins up. The EFS separates from the Carrier Spacecraft. The EDI sequence is performed. The Gondola/Balloon System releases the Mini-Probe and the two Drop Sondes. If any of these events fail, the mission science is compromised. This risk is mitigated through a rigorous test program.
4. The communication links for the mission are critical. The Mini-Probe and Drop Sondes transmit data to the Gondola/Balloon System. The Gondola/Balloon System and Carrier Spacecraft communicate with each other. The Carrier Spacecraft communicates with Earth. Any failure in this system will compromise mission science. This risk is mitigated through a rigorous test program or by increasing redundancy.
5. The timer board is a new device on the CDS. Since there is a limited experience base in using this board, the implementation may be more complex than anticipated. This risk is mitigated by early design and rigorous testing.

3.8 Technology Maturity

Most of the systems discussed in this concept are at a mid to high TRL (6 to 9). No additional technology maturity is need for these systems. Mini-Probe and Drop Sondes subsystems range from TRL 3 to 5. The technology development effort to raise the TRL for both systems to 6 is described in Section 4.2. Additionally, balloon inflation system testing and balloon testing is currently on-going. These systems will be at TRL 6 for the start of Phase B.

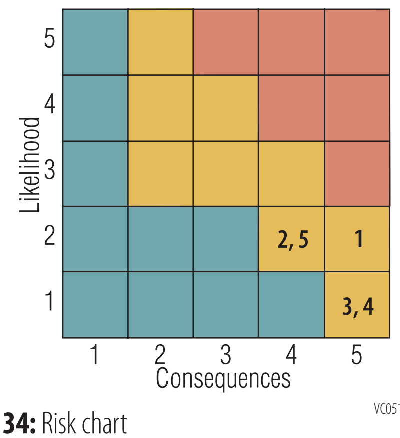


Figure 34: Risk chart

4.0 DEVELOPMENT SCHEDULE AND SCHEDULE CONSTRAINTS

4.1 High-Level Mission Schedule

Figure 35: VCM Schedule provides a high-level mission schedule. Phase A includes development effort for the pressure vessel. This effort is discussed in the technology development section. Other mission systems are mature enough to not need additional development prior to Phase B. The Phase B duration is approximately 18 months and includes the Preliminary Design Review and Critical Design Review. Phase C runs for 12 months and concludes with all the mission system elements fabricated, tested and ready for mission integration. Phase D last approximately 32 months and includes mission integration and test and launch site activities. Phase E begins with mission launch on November 2, 2021 and mission activities at Venus occurring in April and May of 2022. **Table 20**: Key Phase Durations details specific mission durations. The mission, as outlined in this concept, does not represent a high development risk mission.

4.2 Technology Development Plan

The technology development for this mission is the packaging of the Mini-Probe and Drop Sondes. This development will take place during Phase A. The main purpose of the development effort will be to design efficient packaging methods to minimize volume, power and mass for the two systems. Design requirements will be driven by the thermal and structural loads acting on these systems during launch, Venus atmospheric entry and descent through the atmosphere. A rigorous test program will be instituted to verify the packaging designs are capable of performing successfully at Venus.

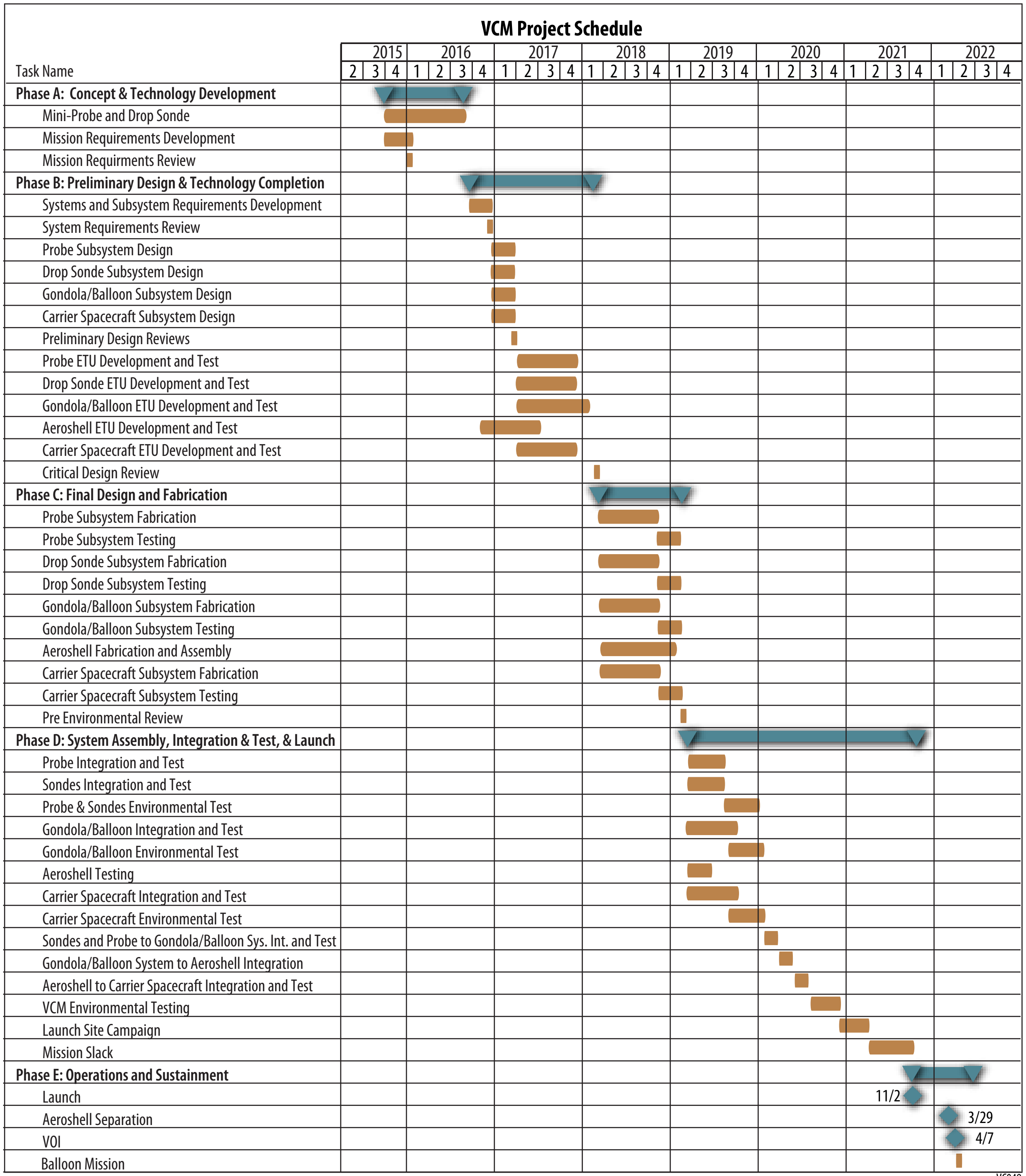


Figure 35: Venus Climate Mission Schedule

Table 20: Key Phase Durations for VCM

Project Phase	Duration (Months)
Phase A – Conceptual Design	11
Phase B – Preliminary Design	18
Phase C – Detailed Design	12
Phase D – Integration & Test	32
Phase E – Primary Mission Operations	6
Phase F – Extended Mission Operations	
Start of Phase B to PDR	8
Start of Phase B to CDR	18
Start of Phase B to Delivery of Instruments (assume all instrument delivered 2/2019)	30
Start of Phase B to Delivery of Flight Elements (assume all flight elements delivered 2/2019)	30
System Level Integration & Test	11
Project Total Funded Schedule Reserve	8
Total Development Time Phase B - D	62

5.0 MISSION LIFE-CYCLE COST

5.1 Costing Methodology and Basis of Estimate

Costing methodology for the VCM study is based on a combination of cost modeling and historic cost wrap factors (to account for program support, mission operations, ground systems, etc.). The two cost models used are Price H and NASA Instrument Cost Model (NICM). Price H parametric model cost estimates are driven by preliminary Master Equipment Lists (MELs). MEL item masses, type of materials, TRLs, and complexity are inputs to this model. NICM estimates instrument cost using various instrument parameters. These estimates are combined with mission-level cost wrap factors to derive an initial estimated mission cost. A reserve of 50% on Phases A-D and 25% on Phase E is added to the total estimated mission cost. The 50% reserve equates to an approximate 70% confidence level in the cost certainty in conventional cost risk analysis. No reserve is added to the Launch Vehicle. All costs are in Fiscal Year (FY) 2015 dollars. No grassroots estimates are developed for the study.

5.2 Cost Estimate

Based on the Price H and NICM results, the team estimated, at 70% confidence level, a VCM mission concept Phase A to Phase E total cost of $1,145 M to $1,577 M including launch vehicle and 50% margin. This cost range is at the low end of a flagship mission. The major technology development cost for this mission is the packaging design for the Mini-Probe and Drop Sondes and is described in Section 4.2. The mission cost estimate includes $10 M to advance this technology. **Table 21:** VCM Cost Funding Profile details the cost estimate for this study.

6.0 CONCLUSIONS

Over the past 40 years more than 40 spacecraft have been launched to explore Venus with flybys, orbiters and in situ probes, balloons and landers. While the understanding of our sister planet has increased significantly, there are still many questions remaining about the Venus climate system. It has become clear that, as on Earth, climate on Venus is a result of dynamic processes involving many nonlinear feedbacks. Therefore, studying the climate of Venus, including its strong greenhouse effect, can help us to understand the climate evolution of Earth and Earth-like planets.

The Venus Climate Mission (VCM) concept is designed around this climate theme, to answer remaining science questions by resolving uncertainties in atmospheric motions, radiation balance, cloud composition and chemistry, while also making elemental and isotopic measurements that reveal the origin and evolution of the atmosphere and the evolution of the extreme greenhouse climate.

The VCM is conceived as a multi-element architecture, with a Carrier/Orbiter Spacecraft and an EFS to deliver a Gondola/Balloon System, a Mini-Probe and two Drop Sondes to Venus. The Gondola/Balloon System builds on previous Venus balloon missions (Vega), design heritage (e.g., Venus Flagship Mission Study) and past and present development and test projects (e.g., JPL, CNES) to accomplish the science goals. The instruments for the various mission elements were selected to address the science goals and objectives of the VCM. Specifically, the Gondola/Balloon System includes a Neutral Mass Spectrometer (NMS), a Tunable Laser Spectrometer (TLS), Atmospheric Structure Instrumentation (ASI), a Nephelometer, and an Net Flux Radiometer (NFR) to collect data at an altitude of 55.5 km through multiple circumnavigations from mid-latitude towards the polar vortex to answer the Venus climate questions. The Mini-Probe with an NMS, ASI and NFR, and the two identical Drop Sondes with ASI and NFR measure vertical profiles from the balloon's float altitude to the surface to compliment the Gondola/Balloon System science measurements.

This mission concept study successfully demonstrates the feasibility of a scientifically viable mission to explore the climate of Venus using exist-

Table 21: VCM Cost Funding Profile

Item	FY16	FY17	FY18	FY19	FY20	FY21	FY22	Total ($M Real Yr.)	Total ($M FY15)
Phase A Concept Study	3.59							3.59	3.50
Technology Development	10.27							10.27	10.00
Mission PM/SE/MA	21.10	21.67	22.25	22.86	23.47	24.11	12.67	148.13	133.40
Instrument PM/SE/MA	2.88	5.90	6.10	5.00	3.20	1.31		24.39	22.20
Atmospheric Structure Instrumentation (Qty 4)	2.10	4.33	4.44	2.28				13.15	12.40
Radiometer (Qty 4)	2.50	5.12	5.30	2.71				15.63	14.60
Neutral Mass Spectrometer (Qty 2)	6.32	12.98	13.33	6.85				39.48	36.90
Nephelometer	0.26	0.53	0.54	0.28				1.61	1.50
Tunable Laser Spectrometer	1.78	3.66	3.76	1.93				11.13	10.40
Venus Monitoring Camera	0.63	1.30	1.33	0.68				3.94	3.70
Carrier Spacecraft	11.83	54.69	56.17	57.68	39.54			219.91	201.60
Gondola/Balloon System	11.34	52.41	53.83	55.28	37.89			210.74	193.20
Aeroshell		17.34	17.82	13.74				48.90	45.20
Mini-Probe	6.29	21.53	22.12	20.46				70.40	65.30
Drop Sonde (Qty 2)	1.64	5.60	5.76	5.33				18.33	17.00
MSI&T 2					14.53	14.91		29.44	25.40
Pre-launch Science	3.78	5.55	5.70	6.45	6.62	6.80	1.27	36.18	32.64
Ground Data System Dev	4.74	4.87	5.00	5.14	5.28	2.71		27.75	25.40
Total Dev. w/o Reserves	91.06	217.48	223.45	206.67	130.54	49.84	13.94	932.97	854.34
Development Reserves (50%)	45.53	108.74	111.73	103.33	65.27	24.92	6.97	466.49	427.17
Total A-D Development Cost	136.59	326.22	335.18	310.00	195.80	74.76	20.91	1399.46	1281.51
Launch services		42.83	42.83	42.83	42.83	42.83	42.83	257.00	257.00
Phase E Science							9.84	9.84	8.16
Other Phase E Cost - Mission Operations							23.03	23.03	19.10
Phase E Reserves							5.79	5.79	4.80
Education/Outreach		1.13	1.16	1.19	1.22	1.26	1.29	7.25	6.40
Total Cost	**136.59**	**370.19**	**379.17**	**354.03**	**239.86**	**118.85**	**103.69**	**1702.38**	**1576.97**

ing technologies and flight heritage from previous missions for the science payload and for the various mission elements. It should be noted, however, that many elements of this mission concept study have not been optimized, which likely results in an oversizing of various instruments and mission elements. Future studies and mission proposals could benefit from continuing development of instruments and Venus related technologies. Such development could increase the overall science returns and improve confidence in the cost estimates.

For the current VCM concept, the estimated cost is in the low range of a flagship mission ($1,145 M to $1,577 M, FY15 dollars). While technology maturation of some systems is needed, no high-risk elements have been identified.

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Michael Adams, Study Lead
Michael Amato, New Business Manager
Nerses Armani, Mechanical
Charles Baker, Systems
Heather Bradshaw, Thermal
Kara Chaprnka, Costing
John Galloway, Instruments
Lori Glaze, Science
William Horne, Communications
Carol Ladd, Report Production
William Lawson, Costing
David Mangus, ACS
Greg Marr, Flight Dynamics
Robin Mauk, Systems
Richard Mills, Electrical Systems
Tom Spitzer, Power
Scott Starin, ACS
Barbara Talbott, Report Graphics
Steven Tompkins, Mission Operations and Ground System
Sanjay Verma, Costing
Carl Wales, Systems
Graham Webster, Propulsion

JPL
Tibor Balint, Study Lead
Harry Balian, Software
Deberati Chattopadhyay, Risk
Loucas Christodoulou, Propulsion/Inflation
Douglas Equils, Ground Systems
Dwight Geer, CDS
Jeff Hall, Balloon Design and Sizing Support
Casey Heeg, Systems
Jennifer Herman, Power
Scott Howe, Configuration
Viktor Kerzhanovich, Balloon Design and Sizing Support
Ryan Lim, ACS
Michael Mercury, Deputy Systems
Robert Miyake, Thermal
Jeffrey Parker, Mission Design
Jamie Piacentine, Configuration
Michael Pugh, Telecom
Leigh Rosenberg, Costing
Brian Schratz, Telecom
Partha Shakkottai, Thermal

Evgeniy Sklyanskiy , EDI/Probe Descent
William Smythe, Science Operations
Matthew Spaulding, Mechanical
Paul Stella, Power
Marc Walch, Instruments
Keith Warfield, Facilitator

NASA/ARC
Ethiraj Venkatapathy, Aeroshell Chief Technologist
Gary Allen, Systems Analyst
Ken Hamm, Structural Analyst
Todd White, Aeroshell Engineer

APPENDIX A - ACRONYM LIST

ACS ....Attitude Control Subsystem
ACE....................Attitude Control Electronics
ATLO ....Assembly, Test and Launch Operations
ARC....................Ames Research Center
ASI......................Atmospheric Structure Instrumentation
BOL....................Beginning of Life
C.........................Celsius
C&DH...............Command and Data Handling
CAD ....Computer-aided Design
CBE....................Current Best Estimate
CDS....................Command and Data System
CG......................Center of Gravity
CMCP................Chopped Molded Carbon Phenolic
CML...................Concept Maturity Level
CNES ....Centre National d'Études Spatiales
CO ....Carbon Monoxide
CO^2 ....Carbon Dioxide
CP ....Carbon Phenolic
CSS.....................Course Sun Sensors
dB ....Decibel (gain)
dBi ....Decibel (isotropic gain)
Delta-V ....Change in Velocity
DLA....................Declination of Launch Asymptote
DOD ....Depth of Discharge
DRL....................Descent Rate Limiter
DSB ....Data Storage Board
DSN ....Deep Space Network
EDI.....................Entry, Descent and Inflation
EFPA ....Entry Flight Path Angle
EFS ....Entry Flight System
EOL....................End of Life
ETM...................Event Timer Module
FY ....Fiscal Year
GaAs ....Gallium Arsenide
Gb, Gbits ....Gigabits
GBK ....Germanium Black Kapton
GCM ....General Circulation Model
GHz....................Gigahertz
GSFC..................Goddard Space Flight Center
H2SO4 ....Sulfuric Acid
HGA...................High Gain Antenna
IR........................Infrared
JPL......................Jet Propulsion Laboratory
K.........................Kelvin
kbps ....Kilobits Per Second

kg........................Kilogram
kW.......................KiloWatt
lbf ....Pounds (force)
Li ....Lithium
Li-$SOCl_2$............Lithium-thionyl Chloride
LRO....................Lunar Reconnaissance Orbiter
MAC...................Multifunction Analog Card
Mb, Mbits...........Megabits
MEL ....Master Equipment Lists
MEOP ....Maximum Expected Operating Temperature
MEV...................Maximum Expected Value
MLI ....Multi Layer Insulation
MOC..................Mission Operations Center
MPL-MET ....Mars Polar Lander
MMH.................Monomethylhydrazine
MSL....................Mars Science Laboratory
NICM ....NASA Instrument Cost Model
NFR....................Net Flux Radiometer
NiCd...................Nickel Cadmium
NiH ....Nickel metal Hydride
NMS...................Neutral Mass Spectrometer
NTO...................Nitrogen Tetroxide
OCS....................Carbonyl Sulfide
OSR....................Optical Solar Reflector
PAF.....................Payload Attach Fitting
PCM...................Phase Change Material
PDR....................Preliminary Design Review
PICA...................Phenolic Impregnated Carbon Ablator
PSE.....................Power System Electronics
PV.......................Pioneer-Venus
PVLP ....Pioneer-Venus Large Probe
RF.......................Radio Frequency
RPM ....Revolutions Per Minute
S/A, SA ....Solar Array
SBC ....Single Board Computer
SDO ....Solar Dynamics Observatory
Si.........................Silicon
SSPA ....Solid State Power Amplifier
TID ....Total Ionizing Dose
TLS.....................Tunable Laser Spectrometer
TPS.....................Thermal Protection System
TRL ....Technology Readiness Level
TWCP ....Tape Wrapped Carbon Phenolic
TWTA................Traveling-Wave Tube Amplifiers
UV......................Ultraviolet
VCM ....Venus Climate Mission

VDC...................Voltage Direct Current
VEx.....................Venus Express
VFM...................Venus Flagship Mission
VHP ....Arrival Velocity
Vis-IR ....Visual Infrared
VMC ....Venus Monitoring Camera
VOI ....Venus Orbit Insertion
W.........................Watts
Xe ....Xenon

APPENDIX B - REQUIRED TABLES

1. Instrument Tables

The following seven tables present data for the VCM Instruments. These instruments are: Venus Monitoring Camera (VMC), Section 3.1.1; Atmospheric Structure Instrumentation (ASI), Section 3.1.2.1; Nephelometer, Section 3.1.2.2; Net Flux Radiometer (NFR-PV), Section 3.1.2.3; Net Flux Radiometer (NFR-Galileo), Section 3.1.2.3; Tunable Laser Spectrometer (TLS), Section 3.1.2.4; and Neutral Mass Spectrometer (NMS), Section 3.1.2.5.

Item	Value	Units
VMC: Camera/Imager		
1 CCD, 4 bandpasses from UV to near-IR		
Size/dimensions	Optics: 3 x 3 x 3 Elec: 12 x 8.4 x 8.4	cm^3
Instrument mass without contingency (CBE)	1.8	kg
Instrument mass contingency	30	%
Instrument mass with contingency (CBE+Reserve)	2.34	kg
Instrument average payload power without contingency	5.2	W
Instrument average payload power contingency	30	%
Instrument average payload power with contingency	6.76	W
Instrument average science data rate without contingency	10	kbps
Instrument average science data rate contingency	0	%
Instrument average science data rate with contingency	10	kbps
Instrument Fields of View (if appropriate)	17.5	degrees
Pointing requirements (knowledge)	-	degrees
Pointing requirements (control)	-	degrees
Pointing requirements (stability)	-	deg/sec

Item	Value	Units
ASI: Temperature/Pressure/Motion		
Number of channels		
Size/dimensions (for each instrument)	Elec: 10 x 10 x 10 Sensors: varies	cm^3
Instrument mass without contingency (CBE)	2.1	kg
Instrument mass contingency	30	%
Instrument mass with contingency (CBE+Reserve)	2.73	kg
Instrument average payload power without contingency	3.2	W
Instrument average payload power contingency	30	%
Instrument average payload power with contingency	4.16	W
Instrument average science data rate without contingency	0.25	kbps
Instrument average science data rate contingency	0	%
Instrument average science data rate with contingency	0.25	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

Item	Value	Units
Nephelometer: Particulate Measurement		
Number of channels		
Size/dimensions (for each instrument)	Not available	cm^3
Instrument mass without contingency (CBE)	0.5	kg
Instrument mass contingency	30	%
Instrument mass with contingency (CBE+Reserve)	0.65	kg
Instrument average payload power without contingency	1.2	W
Instrument average payload power contingency	30	%
Instrument average payload power with contingency	1.56	W
Instrument average science data rate without contingency	0.32	kbps
Instrument average science data rate contingency	0	%
Instrument average science data rate with contingency	0.32	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

Item	Value	Units
NFR (PV): Radiometer		
Number of channels		
Size/dimensions (for each instrument)	Sense: 3 x 8 x 8 Elec: 9 x 9 x 9	cm^3
Instrument mass without contingency (CBE)	1.1	kg
Instrument mass contingency	30	%
Instrument mass with contingency (CBE+Reserve)	1.43	kg
Instrument average payload power without contingency	4.6	W
Instrument average payload power contingency	30	%
Instrument average payload power with contingency	5.98	W
Instrument average science data rate without contingency	0.032	kbps
Instrument average science data rate contingency	0	%
Instrument average science data rate with contingency	0.032	kbps
Instrument Fields of View (if appropriate)	~120 (nadir) ~120 (zenith)	degrees
Pointing requirements (knowledge)	n/a	degrees
Pointing requirements (control)	n/a	degrees
Pointing requirements (stability)	n/a	deg/sec

Item	Value	Units
NFR (Galileo): Radiometer		
Number of channels		
Size/dimensions (for each instrument)	Sense: 8.5x8x10.5 Elec.: 13x19.5x16	cm^3
Instrument mass without contingency (CBE)	2.3	kg
Instrument mass contingency	30	%
Instrument mass with contingency (CBE+Reserve)	2.99	kg
Instrument average payload power without contingency	5.0	W
Instrument average payload power contingency	30	%
Instrument average payload power with contingency	6.5	W
Instrument average science data rate without contingency	0.5	kbps
Instrument average science data rate contingency	0	%
Instrument average science data rate with contingency	0.5	kbps
Instrument Fields of View (if appropriate)	~120 (nadir) ~120 (zenith)	degrees
Pointing requirements (knowledge)	n/a	degrees
Pointing requirements (control)	n/a	degrees
Pointing requirements (stability)	n/a	deg/sec

Item	Value	Units
TLS: Laser Absorption Spectroscopy		
Number of channels	4	
Size/dimensions (for each instrument)	Not available	cm^3
Instrument mass without contingency (CBE)	3.7	kg
Instrument mass contingency	30	%
Instrument mass with contingency (CBE+Reserve)	4.81	kg
Instrument average payload power without contingency	10	W
Instrument average payload power contingency	30	%
Instrument average payload power with contingency	13	W
Instrument average science data rate without contingency	0.5	kbps
Instrument average science data rate contingency	0	%
Instrument average science data rate with contingency	0.5	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

Item	Value	Units
NMS: Mass Spectrometer		
Number of channels		
Size/dimensions (for each instrument)	Sense: 26 x 16 x 18 Elec: 12.5 x 18 x 17	cm^3
Instrument mass without contingency (CBE)	14.7	kg
Instrument mass contingency	30	%
Instrument mass with contingency (CBE+Reserve)	19.1	kg
Instrument average payload power without contingency	35	W
Instrument average payload power contingency	30	%
Instrument average payload power with contingency	45.5	W
Instrument average science data rate without contingency	3.1	kbps
Instrument average science data rate contingency	0	%
Instrument average science data rate with contingency	3.1	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

2. Payload Mass and Power Tables

The following four tables present mass and power data for each flight element instrument suite. The four flight elements are the Gondola/Balloon System, the Carrier Spacecraft, the Mini-Probe and the Drop Sonde.

Gondola/Balloon System Payload Mass and Power Table

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Atm. Structure Investigation (MPL-MET)	2	30	2.6	3	30	3.9
Nephelometer	0.5	30	0.65	1.2	30	1.56
Neutral Mass Spectrometer	11	30	14.3	40	30	52
Tunable Laser Spectrometer	3.7	30	4.81	10	30	13
Net Flux Radiometer (Galileo)	2.3	30	2.99	5	30	6.5
Total Payload Mass	**19.5**	**30**	**25.35**	**59.2**	**30**	**76.96**

Carrier Spacecraft Mass and Power Table

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Structures & Mechanisms	776.7	30	1009.7			
Thermal Control	57	30	74.1	110	30	143
Propulsion (Dry Mass)	176	30	228.8	10	30	13
GN&C	48	30	62.4	109	30	141.7
Avionics (C&DH, ACE)	35	30	45.5	87	30	113
RF Comm	34	30	44.2	53	30	69
Power (S/A, Battery, PSE)	104	30	135.2	48	30	62.4
Total Flight Element Dry Bus Mass	**1230.7**		**1599.9**	**417**		**542.1**

Mini-Probe Payload Mass and Power Table

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Atm Structure Investigation (Flagship)	2.1	30	2.73	3.2	30	4.16
Neutral Mass Spectrometer	14.7	30	19.11	35.0	30	45.50
Net Flux Radiometer (PV)	1.1	30	1.43	4.6	30	5.98
Total Payload Mass	**17.9**	**30**	**23.27**	**42.8**	**30**	**55.64**

Drop Sonde Payload Mass and Power Table

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Atm Structure Investigation (Flagship)	2.1	30	2.73	3.2	30	4.16
Net Flux Radiometer (PV)	1.1	30	1.43	4.6	30	5.98
Total Payload Mass	**3.2**	**30**	**4.16**	**7.8**	**30**	**10.14**

3. Flight System Element Mass and Power Tables

The following two tables present the mass and power data for the Entry Flight System and the Carrier Spacecraft flight elements.

Entry Flight System Mass and Power Table

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Aeroshell	253.7	30	329.8	*		
Mini-Probe	38.4	30	49.9	51	30	52.3
Drop Sondes (2)	24.8	30	32.2	32	30	41.6
Gondola Instruments	19.5	30	25.4	59.2	30	77.0
Command & Data	6.9	30	9.0	*		
Power	27.6	30	35.9	*		
Structures & Mechanisms (inc. Balloon)	110.4	30	143.5			
Cabling	25.6	30	33.2			
Telecom	5.5	30	7.2	*		
Thermal	1.1	30	1.4			
Inflation System	113.3	30	147.3	*		
Helium	21.8	30	28.3			
Total Flight Element Dry Bus Mass	**648.6**		**843.1**			

*- Power modes vary significantly for the EFS. Section 3.2.3.4.7 details the power system

Carrier Spacecraft Mass and Power Table

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Structures & Mechanisms	776.7	30	1009.7			
Thermal Control	57	30	74.1	110	30	143
Propulsion (Dry Mass)	176	30	228.8	10	30	13
GN&C	48	30	62.4	109	30	141.7
Avionics (C&DH, ACE)	35	30	45.5	87	30	113
RF Comm	34	30	44.2	53	30	69
Power (S/A, Battery, PSE)	104	30	135.2	48	30	62.4
Total Flight Element Dry Bus Mass	**1230.7**		**1599.9**	**417**		**542.1**

4. Flight System Element Characteristic Table

Flight System Element Parameters (as appropriate)	Value/ Summary, units
General	
Design Life, months	6
Structure	
Structures material (aluminum, exotic, composite, etc.)	Aluminium, Aluminium honeycomb, Titanium, Composite
Number of articulated structures	1
Number of deployed structures (S/A, EFS, mini-probe, balloon, inflation system, sondes x 2)	7
Aeroshell diameter, m	2
Thermal Control	
Type of thermal control used	Radiator (2.3 m^2)
Propulsion	
Estimated delta-V budget, m/s	1734 m/s
Propulsion type(s) and associated propellant(s)/oxidizer(s)	MMH / NTO
Number of thrusters and tanks	13 / 4
Specific impulse of each propulsion mode, seconds	293 (900# thruster) , 290 (25# thruster)
Attitude Control	
Control method (3-axis, spinner, grav-gradient, etc.).	3-axis
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Earth pointing during cruise
Agility requirements (maneuvers, scanning, etc.)	180 degree slew in 10 minutes, 5 rpm spin (for probe release)
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	1
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	75 Nms reaction wheels
Command & Data Handling	
Flight Element housekeeping data rate, kbps	3
Data storage capacity, Mbits	1,000
Maximum storage record rate, kbps	65
Maximum storage playback rate, kbps	65
Power	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	Rigid, deployed, articulated (one axis)
Array size, square meters	5
Solar cell type (Si, GaAs, Multi-junction GaAs, concentrators)	GaAs
Expected power generation at Beginning of Life (BOL) and End of Life (EOL), Watts	1000 (BOL) , 1000 (EOL)
On-orbit average power consumption, watts	823
Battery type (NiCd, NiH, Li-ion)	LiH
Battery storage capacity, amp-hours	60

5. Mission Design Table, VCM

Parameter	Value	Units
Orbit Parameters (apogee, perigee, inclination, etc.)	66,200x500; 62.2	Km, deg.
Mission Lifetime (Carrier Spacecraft operations)	6	months
Mission Lifetime (Mini-Probe and Drop Sondes operations)	50	min
Mission Lifetime (Gondola/Balloon System operations)	21	days
Maximum Eclipse Period (at Venus)	33	min
Launch Site	KSC	
Total Flight Element #1 Mass with contingency (includes instruments)	843.3	kg
Carrier Spacecraft Mass with contingency (includes instruments)	1599.8	kg
Propellant Mass without contingency	1432.4	kg
Propellant contingency	1	%
Propellant Mass with contingency	1446.7	kg
Launch Adapter Mass with contingency	94	kg
Total Launch Mass (including Launch Adapter)	3983.8	kg
Launch Vehicle (Option 5)	Atlas V 551	
Launch Vehicle Lift Capability	5430	kg
Launch Vehicle Mass Margin	1446.2	kg
Launch Vehicle Mass Margin (%)	26.6	%

6. Mission Operations and Ground Data Systems Table

Down link Information	Mission Phase 1 Launch & Cruise	Mission Phase 2 Release & VOI	Mission Phase 3 Orbiting Venus
Number of Contacts per Week	7	7	7
Number of Weeks for Mission Phase, weeks	19	1.3	3
Downlink Frequency Band, GHz	Ka	Ka	Ka
Telemetry Data Rate(s), kbps	65	65	65
Transmitting Antenna Type(s) and Gain(s), dBi	1.7 m HGA dish, 52.5	1.7 m HGA dish, 52.5	1.7 m HGA dish, 52.5
Transmitter peak power, Watts	50	50	50
Downlink Receiving Antenna Gain, dBi	79	79	79
Transmitting Power Amplifier Output, Watts	50	50	50
Total Daily Data Volume, (MB/day)	87.5	87.5	87.5
Uplink Information			
Number of Uplinks per Day	1	1	1
Uplink Frequency Band, GHz	Ka	Ka	Ka
Telecommand Data Rate, kbps	1	1	1
Receiving Antenna Type(s) and Gain(s), dBi	52.5	52.5	52.5

7. Key Phase Duration Table

Project Phase	Duration (Months)
Phase A – Conceptual Design	11
Phase B – Preliminary Design	18
Phase C – Detailed Design	12
Phase D – Integration & Test	32
Phase E – Primary Mission Operations	6
Phase F – Extended Mission Operations	
Start of Phase B to PDR	8
Start of Phase B to CDR	18
Start of Phase B to Delivery of Instruments (assume all instrument delivered 2/2019)	30
Start of Phase B to Delivery of Flight Elements (assume all flight elements delivered 2/2019)	30
System Level Integration & Test	11
Project Total Funded Schedule Reserve	8
Total Development Time Phase B - D	62

8. Total Mission Cost Funding Profile Template

Item	FY16	FY17	FY18	FY19	FY20	FY21	FY22	Total ($M Real Yr.)	Total ($M FY15)
Phase A Concept Study	3.59							3.59	3.50
Technology Development	10.27							10.27	10.00
Mission PM/SE/MA	21.10	21.67	22.25	22.86	23.47	24.11	12.67	148.13	133.40
Instrument PM/SE/MA	2.88	5.90	6.10	5.00	3.20	1.31		24.39	22.20
Atmospheric Structure Instrumentation (Qty 4)	2.10	4.33	4.44	2.28				13.15	12.40
Radiometer (Qty 4)	2.50	5.12	5.30	2.71				15.63	14.60
Neutral Mass Spectrometer (Qty 2)	6.32	12.98	13.33	6.85				39.48	36.90
Nephelometer	0.26	0.53	0.54	0.28				1.61	1.50
Tunable Laser Spectrometer	1.78	3.66	3.76	1.93				11.13	10.40
Venus Monitoring Camera	0.63	1.30	1.33	0.68				3.94	3.70
Carrier Spacecraft	11.83	54.69	56.17	57.68	39.54			219.91	201.60
Gondola/Balloon System	11.34	52.41	53.83	55.28	37.89			210.74	193.20
Aeroshell		17.34	17.82	13.74				48.90	45.20
Mini-Probe	6.29	21.53	22.12	20.46				70.40	65.30
Drop Sonde (Qty 2)	1.64	5.60	5.76	5.33				18.33	17.00
MSI&T 2					14.53	14.91		29.44	25.40
Pre-launch Science	3.78	5.55	5.70	6.45	6.62	6.80	1.27	36.18	32.64
Ground Data System Dev	4.74	4.87	5.00	5.14	5.28	2.71		27.75	25.40
Total Dev. w/o Reserves	91.06	217.48	223.45	206.67	130.54	49.84	13.94	932.97	854.34
Development Reserves (50%)	45.53	108.74	111.73	103.33	65.27	24.92	6.97	466.49	427.17
Total A-D Development Cost	136.59	326.22	335.18	310.00	195.80	74.76	20.91	1399.46	1281.51
Launch services		42.83	42.83	42.83	42.83	42.83	42.83	257.00	257.00
Phase E Science							9.84	9.84	8.16
Other Phase E Cost - Mission Operations							23.03	23.03	19.10
Phase E Reserves							5.79	5.79	4.80
Education/Outreach		1.13	1.16	1.19	1.22	1.26	1.29	7.25	6.40
Total Cost	136.59	370.19	379.17	354.03	239.86	118.85	103.69	1702.38	1576.97

APPENDIX C - REFERENCES

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