Venus Probe Architecture

Robin Ripley
Goddard Space Flight Center
8800 Greenbelt Road
Greenbelt, MD 20770
Robin.A.Ripley@nasa.gov

Colby Goodloe
Goddard Space Flight Center
8800 Greenbelt Road
Greenbelt, MD 20770
Colby.S.Goodloe@nasa.gov

Abstract— **The Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) Descent Sphere (DS) is a probe designed to take measurements of the Venus atmosphere and take high resolution images of the Venus surface during a ~1 hour descent through the Venus atmosphere. This paper will discuss the design decisions made to ensure autonomous collection of scientific data in the midst of one of the harshest planetary environments in the solar system.**

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1. INTRODUCTION

The DAVINCI mission was selected in June 2021 as part of the NASA Discovery Program to explore Venus through remote sensing, in-situ chemistry measurements, and near-surface imaging[2]. The DAVINCI Descent Sphere (DS) is an evacuated spherical probe designed to enter the Venusian atmosphere and collect scientific data during an ~1 hour descent. The complete Probe Flight System (PFS) consists of the Descent Sphere (DS), and Entry System (ES) and the five scientific instruments the DS is designed to protect while still allowing them to take crucial scientific measurements [3]. See Figure 1 for how these elements fit together.

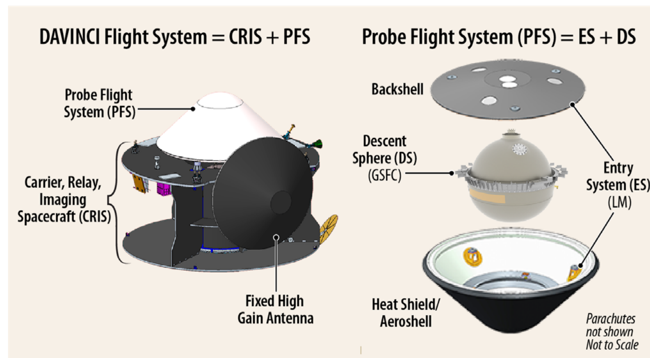

Figure 1. DAVINCI Flight System and Major Elements

Prior to Venus atmospheric insertion, the DS rides inside the ES which acts as a heat shield for the first part of the descent. The PFS is carried to Venus by the Carrier, Relay, and Imaging Spacecraft (CRIS), which is a spacecraft that will perform two fly-bys of Venus prior to releasing the PFS in preparation for final descent.

After separation from the CRIS, the PFS and then the stand-alone DS will communicate with the CRIS via an Adjustable Data Rate (ADR) S-band link. The DS will enter a hibernation state during the two-day coast from the point of separation from CRIS until just before reaching Venus Atmospheric Entry Interface (AEI). This low-power mode will save energy for the descent phase, when instruments will be turned on as they are needed throughout the descent. The ADR will be used to send data back to the CRIS at the highest feasible data rate based on current conditions. Figure 2 shows the nominal descent timeline, including key events throughout the descent.

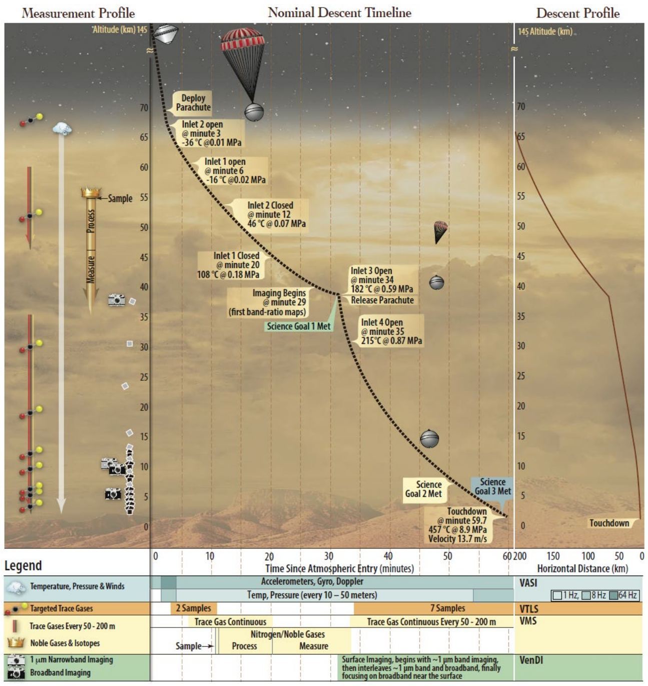

Figure 2. Nominal Descent Timeline [4]

The Descent Sphere (DS) is a 0.84 meter diameter titanium vessel and aero fairing designed to withstand 90 atmospheres of pressure, 450°C temperatures, and the sulfuric acid atmosphere of Venus[1]. The DS encapsulates and protects five scientific instruments from the harsh Venus environment: Venus Mass Spectrometer (VMS), Venus Tunable Laser Spectrometer (VTLS), Venus Atmospheric Structure Investigation (VASI), Venus fugacity of Oxygen (VfOx) sensor, and Venus Descent Imager (VenDI). The Descent Sphere supports the instruments with its own avionics bus and internal passive thermal system that place the instruments in a benign thermal environment, typical of a spacecraft bus.

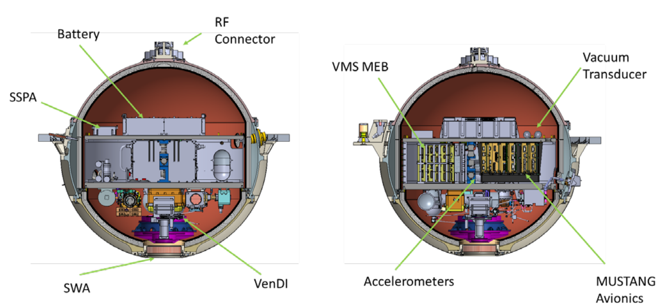

Figure 3. Descent Sphere Internal Layout

The DAVINCI DS is based on the Pioneer Venus probe that is designed to sample the Venusian atmosphere during a ~1 hour descent to the surface of Venus. The CRIS will fly by Venus twice over a two year period before releasing the PFS about two days prior to atmospheric insertion. During this two-day coast period, the DS must keep components inside the sphere warm enough to survive. The DS will warm up components to operational levels starting about 2 hours prior to entry. After Venus atmospheric entry, the DS must keep all components cool enough to operate prior to contact with the surface. All of this must be accomplished while also allowing various instrument to take science measurements throughout the descent.

The ES will separate from the DS after the PFS drops below Mach 0.9. After this separation, the bulk of science data acquisition can begin. This data must be transmitted to the CRIS prior to contact with the surface to be transmitted to Earth later.

Avionics

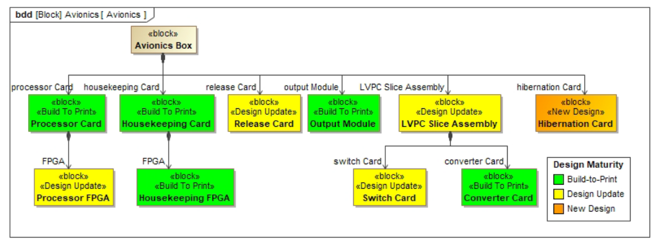

Figure 4. Avionics Block Definition Diagram

The DS Avionics is based on the MUSTANG avionics architecture which was developed at GSFC. It contains three build-to-print cards, two updated card designs, and one new card design.

Processor Card— The Processor Card is a standard Modular Unified Space Technology Avionics (MUSTANG) processor card with a Dual-Core LEON3FT SPARC V8 processor and an RT4G150 Field Programmable Gate Array (FPGA). The DS Flight Software (FSW) will run on the LEON3FT with supporting FPGA logic in the RTG4.

Housekeeping Card— The Housekeeping (HK) card interfaces with other Avionics cards and DS subsystems via discrete signals and SpaceWire links through front panel connectors. The HK card is responsible for monitoring both differential and single-ended telemetry signals throughout the DS such as thermal telemetry, single-ended or differential voltages, and internal housekeeping telemetry. Additionally, it serves as the master I2C controller for the Avionics.

Output Module (OM)— The OM card is commanded by the HK Card via the I2C interface on top panel connectors. The OM card receives low voltage power from the LVPC card through two separate top panel connectors, primary and redundant. The OM card receives primary bus power from DS 28 V power bus through a rear panel connector. The OM card is responsible for powering the RC card, VMS, VMS heaters, the Frontier Lite Radio Card, battery heaters, VenDI, and the SSPA via switched services.

Release Card— The Release Card (RC) provides 12 primary power outputs with resistive current limit. It is commanded by the HK Card via the I2C serial interface at the top panel connectors. The RC card receives low voltage power from the LVPC card through a top panel connector. The card receives protected primary bus power through back front panel connectors. The RC card is responsible for driving NSIs that trigger the parachute separation nuts and the ES thermal battery.

Linear Voltage Power Converter (LVPC)— The LVPC is a modified version of the LVPC developed for the MUSTANG Avionics or Instrument Electronics Architecture . The LVPC consists of 2 cards: the Converter Card and the Switch Card. The LVPC converts Bus power to +3.3 V, +5 V, and ±15 V and distributes these voltages to each of the internal Avionics components, switched low power to the accelerometer and VASI instrument, as well as switched primary power to the ES and Pressure Transducer with some spare services available. The LVPC is controlled by the housekeeping card via an I2C Bus.

The Switch Card will be updated to change some 3A services to 5A services for DAVINCI.

Hibernation Card— The Hibernation Card (HC) is a custom DAVINCI design that maintains time and a minimum of power during much of the coast phase of the mission. It is responsible for waking up the rest of the Avionics for regular comm checks and just before the final descent into the Venus atmosphere. The HC also monitors the separation signals and powers survival heaters.

Flight Software (FSW)

The DS flight software runs on the MUSTANG Processor Card's Dual-Core Leon3FT processor using RTEMS 5 as the operating system. The bootstrap software copies the flight software image from non-volatile memory into RAM and starts executing it. The Core Flight Executive (cFE) runs on top of RTEMS. Standard cFE reusable apps are included as well as custom apps for instrument interfaces and data prioritization.

Mechanical

The outer shell of the DS consists of two titanium hemispheres, a titanium mid-ring, an aeroshell consisting of spin-veins and drag plates, and a ring for mounting the DS to the ES. All components must be assembled such that the Venus atmosphere cannot leak in to the sphere, so metal seals are used at all external interfaces including ports and the interfaces between the mid-ring and each hemisphere.

Inside the sphere are two beryllium decks, a deck support structure, and a Multilayer Insulation (MLI) retainer to hold the blankets in place.

Power

The power subsystem consists of the rechargeable secondary battery and Descent Sphere Charge Card (DSCC).

Battery— The battery is a rechargeable Lithium-Ion battery with ~2400 Wh capacity. This is designed to meet the power needs of the DS coast and descent with sufficient margin.

DSCC— The DSCC is a responsible for charging the DS battery from CRIS bus power.

RF/Comm

The DS RF/Communications subsystem uses an APL supplied Frontier Lite radio card that is capable of adaptive data rate communication. This capability will maximize the amount of science data that the DS is able to uplink to the spacecraft.

Thermal

The DS thermal subsystem is critical to maintaining operational temperatures for all components within the sphere throughout the DAVINCI mission. Figure 5 shows the thermal subsystem components within the DS.

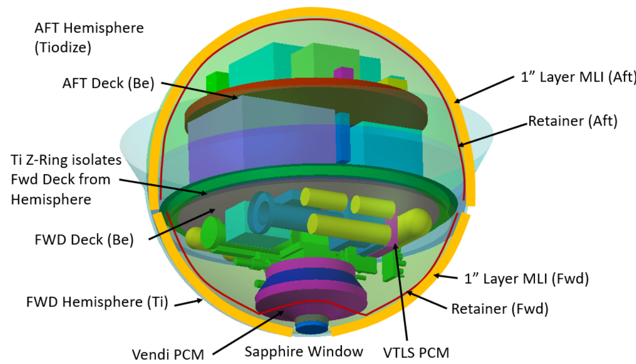

Figure 5. Thermal Subsystem Components

Beryllium Decks— Beryllium has a heat capacity four times larger than aluminum. The deck thickness is driven by thermal requirements to absorb heat.

High Temperature MLI— High temperature MLI lines the inside of the DS to insulate against the heat of the atmosphere. Additional layers of traditional MLI are attached to the high temperature MLI to form a 1-inch barrier between the titanium shell and the internal components. MLI provides better thermal isolation in a vacuum, contributing to the decision to maintain a vacuum inside the DS.

Heaters— One set of heaters inside the DS will be powered by the CRIS prior to PFS release. This pre-heats the inside of the sphere to ensure the internal components stay above survival limits for most of the coast without using the limited battery capacity inside the DS. On-board heaters to maintain survival temperatures can still be powered during coast, but pre-heating the DS prior to PFS separation will limit the amount of on-board power required to do this.

Phase Change Material (PCM)— PCM will be installed around the VenDI camera to keep it from exceeding its operational limits. Since the camera is looking through a window that allows more transmission of heat from the outside than through the blankets, it has higher heat exposure than other components inside the DS.

2. Data Collection and Transmission

DAVINCI plans on collecting a large amount of scientific data critical to understanding the current composition and history of Venus. As such, it is necessary to collect and send that information in a way that maximizes science data return. Rather than transmit data directly to Earth, the DS will transmit data to CRIS during the descent. The CRIS will store the data and uplink it to Earth at a later date.

Data Collection on Sphere

Each of the on-board instruments collects data and sends it to the DS avionics asynchronously. This minimizes the back-and-forth communication generally required by polling. The DS then processes and prioritizes the data for uplink.

Data processing— the VASI instrument requires the DS to process its science data. All other instruments forward their science and health and status data with information about the type of data that allows the DS to prioritize it without needing to process it.

Data prioritization—The DS will collect more science data than can be transmitted back to CRIS, even under ideal conditions, so data prioritization is key. The priority algorithm is based on mission criticality, time since atmospheric entry, and current link rate.

Data critical to mission success is prioritized first. Data needed to meet threshold requirements is next followed by data need to meet baseline requirements. Any additional data that can be transmitted allows DS to meet requirements with margin.

The priority of certain measurements may change as the probe descends through the atmosphere. The link rate will also change (first increasing, then decreasing) throughout the descent. Early in the descent the link is slow enough that data must be stored and transmitted later. As the link improves, the backlog of data may be sent. As the link rate decreases again later in the descent, recent measurements need to be prioritized to ensure that near-surface measurements are transmitted back to the CRIS prior to contact with the surface.

Data allocation-- Each instrument is allocated a certain amount of data volume. This is relevant to the amount of data that can be stored on the DS and transmitted up to CRIS during the descent under ideal conditions. The link rate is expected to be large enough in the middle of the descent to transmit data backlog and re-transmit high-priority data.

Later in the descent, each instrument is allocated a certain data latency and data rate to ensure that data collected near the surface is transmitted back to CRIS in a timely manner.

Transmission to CRIS

A direct data link back to Earth would be prohibitively slow, so CRIS will be used as an intermediary in collecting data from the DS.

Adjustable Data Rate (ADR)—The link to CRIS will use an Adjustable Data Rate to change the uplink speed based on current conditions. An analysis was done to estimate how much data could be returned in a worst case (154 Mbits), most likely (636.2 Mbits), and best case scenario (1.2 Gbits) (see Figure 6).

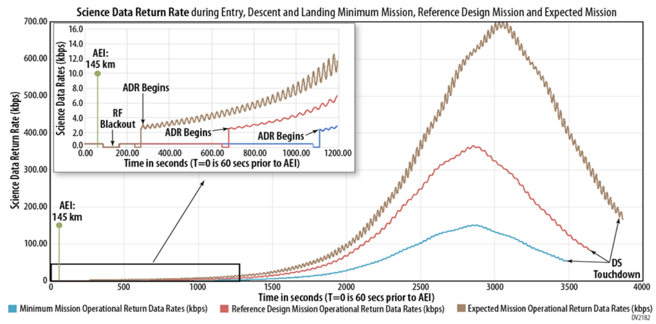

Figure 6. ADR Data Return Estimates

Fixed Rate Data Link— The communication system is also capable of fixed data rate of up to 500 Mbps. The communication system can enter this fixed data mode in case of a fault that results in the ADR not working as expected. The fixed-rate mode is also used to test the connection prior to entering ADR mode.

3. Balancing Power, Thermal, Mass, and Volume Constraints

For the DS, power, mass, and volume are all limited resources. To complete the mission, the probe must reach the surface 1) before any of the internal components overheat, 2) before running out of power, and 3) before CRIS passes over the horizon and out of communication. However, the DS needs to spend time in the atmosphere taking measurements, so it cannot descent too quickly. All of these constraints needed to be considered in the design of the DS.

Titanium Shell

The shell of the DS is made of titanium. Titanium is light yet strong, which is critical for surviving Venus' surface pressure. It is also resistant to sulfuric acid. However, the titanium is too thin to act as a thermal isolator, so blankets have to be placed inside the sphere to prevent heat from soaking through the shell and radiating directly into the interior. This protects the instruments inside long enough to reach the surface within operational temperature levels.

Beryllium Decks

The DS has two decks inside the sphere: the Forward Instrument Deck and the Aft Battery Deck. In order to absorb the head leaking into the sphere from outside during descent and absorb heat generated by the internal electronics, the decks use beryllium, which has a thermal capacity 4 times that of aluminum. This reduces the mass and volume of required of the decks.

Evacuated Sphere

The Pioneer Venus probe that the DS was based on was designed to hold a 1.1 atmosphere CO_2 environment. For this DS, this proved thermally challenging and also required additional mass and volume to maintain that environment. It was decided to make the internal environment a vacuum instead. This reduces heater power, reduces risks related to keeping parts of subsystems thermally isolated from one another, improves blanket efficiency, eliminates aeroacoustics effects of air bouncing around inside the sphere, and reduces the risk of running out of room inside the sphere for all necessary components. The trade off is that maintaining the vacuum inside the sphere is more challenging than maintaining the CO_2 atmosphere. Cleaning and bake-out processes for components inside the sphere are under development to minimize outgassing.

Power Management

The DS will coast toward Venus for two days after being released from the CRIS. The DS has no solar panels to recharge its battery, so several power management strategies are utilized to guarantee the battery will last until probe end of mission.

Battery—Although a primary battery was initially baselined, investigations into newer secondary battery technology showed that the probe could feasibly carry a secondary battery large enough to hold a charge from PFS release through probe end-of-mission.

The use of a secondary battery allows for more flight-like testing on the ground as a primary battery would have required testing with the battery out of the loop. Also, troubleshooting with the battery in the loop will be lower risk with a secondary battery. The battery can be charged until just before PFS release to maximize battery capacity for coast and descent.

Use of the secondary battery also reduces risks associated with accidental discharge which are particularly important once the sphere is integrated. De-integrating the sphere to replace the battery would be a large cost and schedule hit. Although the secondary battery has a lower energy density than the primary battery, it was determined to be worth the additional required mass to reduce there other risks.

Hibernation Mode—All battery implementations required that the DS be capable of entering a low-power mode, or "hibernation" state, during the coast phase. A hibernation card is being designed which will allow the DS to pull less than 2 W during much of coast phase. The hibernation card will be responsible for turning on power to the Avionics for communication checks during coast and one last time prior to entry, after which the Avionics will take over.

DSCC—The Descent Sphere Charge Card (DSCC) is responsible for charging the battery on the DS using the CRIS power bus and communicating with the hibernation card prior to separation. Though it is considered part of the DS system, due to mass/volume constraints within the DS, the DSCC is physically located inside the CRIS because it will only be needed when the PFS is attached to the CRIS.

The DS battery will be trickled charged through the cruise to Venus from Earth up until PFS release from the CRIS. Just prior to PFS release, the CRIS will power on the DS via the DSCC to prepare it for the autonomous phase of its mission. After PFS release, the DSCC function will no longer be necessary.

Sphere Volume

The size of the sphere is limited by both mass and thermal constraints. The greater the surface area, the faster it will heat up. A larger sphere is also more massive and may cause the heat shield to fail. Five instruments, a battery, the avionics, and several RF components must all fit within a sphere that is less than a meter in diameter. The size of the sphere was carefully considered based on multiple constraints including space required to fit all required components plus growth allowance, maximum heat load during entry (which is a function of the area of the heat shield vs mass), and the mass of the sphere itself. These are competing needs since increased volume would increase DS size and increase mass. But the heat shield can only accommodate so much mass before even the heat shield cannot protect the DS during entry.

Utilization of the space inside the sphere will be closely monitored throughout the design life of the mission to ensure that everything will fit and the sphere can be assembled without undue risk to neighboring components.

4. Sealing the Sphere

None of the instruments inside the sphere can operate in the Venus environment. They are designed to work in a more typical space environment of low pressure and temperatures above -30°C and below 50°C A pressurized environment above 1e-3 Torr would make it difficult to maintain different components at different temperatures due to convection, negatively impacting thermal performance. Additionally, MLI performs better at pressures below 1e-3 Torr. Therefore, making sure nothing gets into the DS (but does get into the appropriate instrument inlets) is key. Figure 7 shows external elements on the DS that must fit together and remain sealed against the external environment.

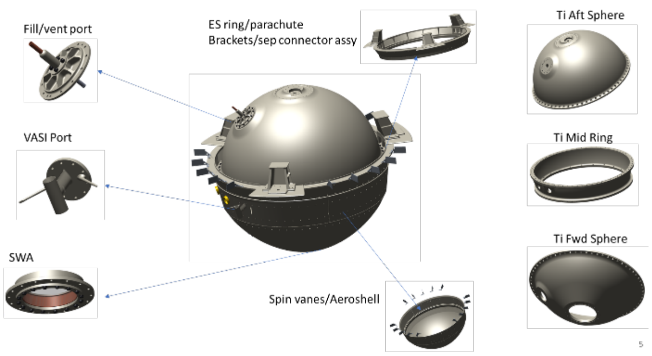

Figure 7. Descent Sphere and External Components

Penetrations

The are multiple penetrations into the shell of the DS and the blanket inside. Each penetration makes the sphere less thermally efficient, so it is important to make sure each one is essential and is properly sealed against leaks.

There are two connectors, a fill/vent port, an RF connector, the VASI port, the VMS port, and the Sapphire Window Assembly (SWA). Each one requires a different seal.

Main Seals

The two main seals are situated between the mid-ring and each of the hemispheres. They are 88 mm in diameter. This seal poses a particular challenge due to the need to maintain a certain level of flatness on the circular lay to guarantee a tight seal. Work is being done now to improve processes for milling the circular lay to the necessary specifications.

Outgassing

In order to maintain the vacuum environment inside the sphere, the outgassing potential of all components must be considered. If items inside the sphere outgas, pressure inside the sphere will build up to greater than acceptable levels.

To address this risk, several steps need to be taken:

Careful selection of materials—Early attention is being paid to material selection. By reducing the outgassing potential of components inside the sphere, the risk of internal pressure rise can be reduced.

Pretreat subcomponents—Prior to delivery to the sphere, components will be expected to be cleaned and/or baked out the burn off as many volatiles as possible prior to integration.

Pump down during ground testing—Once the sphere is sealed, the internal "atmosphere" will need to be pumped out. Any moisture and remaining volatiles will contribute to a rise in pressure over time, so the sphere will need to be pumped down more than once. Processes may need to be developed to pump down the sphere at high temperatures to speed up the process. Otherwise, it may be necessary to pump down on a semi-continuous basis until delivery to the spacecraft.

5. Instrument Accommodations

To collect the scientific data that this mission aspires to acquire, the DS must allow aspects of Venus to enter the sphere in a controlled manner so the instruments can take measurements. As such, there are several features of the sphere that accommodate the instruments' needs while still protecting the integrity of the sphere.

Sapphire Window Assembly (SWA)

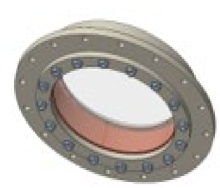

Figure 8. Sapphire Window Assembly

VenDI must be able to see out of the sphere to the surface of Venus during the descent, so there is an opening on the forward hemisphere to give VenDI a view. However, normal glass would readily melt in the heat of Venus, so sapphire is used as the outer window. Two additional windows are situated inside the sphere to block infrared and protect the camera from the heat.

Phase Change Material (PCM) for VenDI

In addition to the SWA, VenDI also needs accommodations to keep its temperature at operational levels. A PCM assembly will be installed around the camera to slow the rise in temperature throughout the descent.

VASI Port

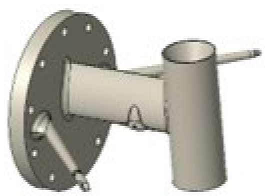

Figure 9. VASI Port

VASI collects temperature and pressure data during the entire descent. A one-piece titanium port will be 3D printed and mounted to the side of the sphere to take these measurements. 3D printing was chosen to reduce the number of connections and seals that would be required to assemble and mount the port.

VMS Port

The VMS and VTLS instruments will collect and measure atmospheric gases during the descent. The VMS and VTLS will be sealed prior to descent and opened via puncture valves once the instruments are ready to take measurements.

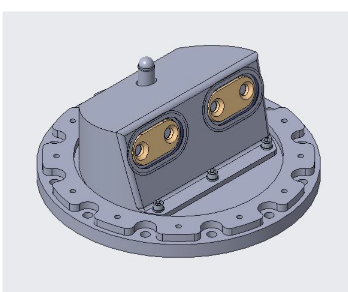

Figure 10. VMS Port

6. Single String with Select Redundancy

Due to the space limitations inside the sphere, the DS is only single string. However, there are select areas of redundancy or resilience to increase chance of mission success. This approach balances the need for reliability with mass, volume, and budget constraints of the mission.

G-Trigger Back-up Timer

The DS has no direct way of knowing how far above the surface of Venus it is. Instead, the DS has an accelerometer which will be used to detect atmospheric entry. This g-trigger will set off the descent sequence which will determine what modes the instruments need to be in as the DS approaches the surface. Altitude, and therefore instrument mode, is estimated based on time since g-trigger. As such, it is essential that this sequence start with a few seconds of AEI. A timer in the avionics counts down until estimated AEI to serve as a back-up for the g-trigger function in case it does not work. This functional redundancy is crucial for proper execution of the descent sequence.

Redundant Pyros

Pyros are used both to separate the heat shield from the DS and to separate the parachute from the DS. If the DS fails to separate from the heatshield, only acceleration and gyro data can be taken, which will result in mission failure. If the parachute does not separate properly, the DS may not reach the lower atmosphere before losing contact with the CRIS. Due to the criticality of this functionality, primary and redundant pyros are used to release both the heat shield and the parachute.

Data Redundancy and Retransmission

The instruments in the DS acquire more samples than are necessary to meet requirements. Additionally, critical and high priority data like noble gas data and ESI data is transmitted multiple times to ensure receipt. This combination of redundancy increases the likelihood that enough measurements will be received to meet science objectives.

7. Summary

Studying the Venus atmosphere while passing through it poses a unique engineering challenge. Various competing needs and design constraints were considered in the design of the DS. The wide temperature and pressure range from the cold vacuum of space to the 90 atms, 460°C environment of the surface of Venus drove much of the thermal and mechanical design. A desire to maximize data return drove both the use of ADR and the need for autonomous operation of the probe during descent since it would not be communicating directly to Earth. And space limitations within the sphere drove the need for a single string system with limited redundancy.

Appendix

A. Acronyms

ADR – Adaptive Data Rate

AEI – Atmospheric Entry Interface
APL – Applied Physics Laboratory
CRIS - Carrier, Relay, and Imaging Spacecraft
DAVINCI - Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging
DS – Descent Sphere
DSCC – Descent Sphere Charge Card
ES – Entry System
FPGA – Field Programmable Gate Array
FSW – Flight Software
GSFC – Goddard Space Flight Center
HC – Hibernation Card
HK – Housekeeping Card
LM – Lockheed Martin
LVPC – Low Voltage Power Converter
MLI – Multilayer Insulation
MUSTANG – Modular Unified Space Technology Avionics for Next Generation
NASA – National Aeronautics and Space Administration
OM – Output Module
PCM – Phase-Change Material
PFS – Probe Flight System
RF – Radio Frequency
SSPA – Solid State Power Amplifier
SWA – Sapphire Window Assembly
VASI - Venus Atmospheric Structure Investigation
VenDI - Venus Descent Imager
VfOx - Venus fugacity of Oxygen
VMS – Venus Mass Spectrometer
VTLS – Venus Tuneable Laser Spectrometer

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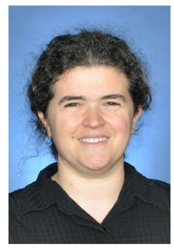
BIOGRAPHY



Robin Ripley *started working for NASA as a contractor for Orbital Sciences Corporation in 2005, then joined NASA as a full-time employee in 2008. She spent 12 years in 587 supporting various versions of SpaceCube. She has experience with embedded software, FPGA design, board level testing, box integration and test, payload integration and test, environmental testing, and mission support. In the past few years, she has transitioned to systems engineering, including work on SmallSats and instrument platforms for airless bodies. She currently works on DAVINCI as the Deputy Systems Engineer for the Descent Sphere. Her BSEE is from Virginia Polytechnic Institute and State University and her MSEE is from Johns Hopkins University.*

Colby Goodloe *received a B.S. and M.S. in Electrical Engineering from University of Maryland in 2005 and 2008, respectively. He has worked for NASA Goddard Space Flight Center since 2002 and is the Descent Sphere Lead Engineer. Previously he was the Lead Spacecraft Engineer for Lucy and Project V&V engineer for OSIRIS-REx. He also worked on electronics for GNC components and instruments for several successful missions including SDO, GPM, FASTSAT, MMS, and 7-SEAS BASELInE and others still in development including ICESAT-2 and LCRD.*