MAE 5160
Spacecraft Technology and Systems Architecture
Spring 2022

Venus Climate Orbiter and Autonomous Explorer

System Design Review
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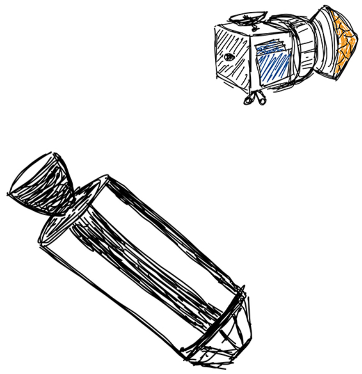
Subsystem Focus: EDL & Mobility

Contents

1.0 Mission Sequence of Events (Storyboard)



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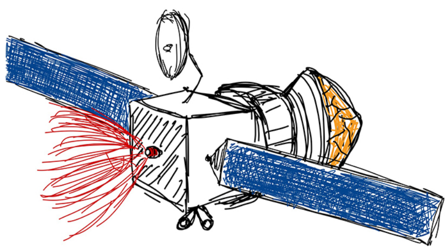
The launch vehicle upper stage will provide the necessary C3 of 10.4 km^2/s^2 to the spacecraft on a trajectory targeting Venus. Since Venus does not fall into the same level of planetary protection as Mars, the trajectory can be more direct than a Martian injection however the trajectory will still require correction. The launch vehicle will deploy the spacecraft in a passively safe configuration, in order to enable the next steps of the mission.

2

Once the spacecraft determines that it is at a safe distance from the upper stage of the launch vehicle, it will begin the deployment of its solar panels and high gain antenna. First the solar panels will deploy enabling the spacecraft to generate its own electrical power. Once the panels are latched and power is being generated, the high gain antenna will deploy into its cruise configuration to enable communications with Earth while in transit to Venus.



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During cruise, the spacecraft will perform number of corrective maneuvers to precisely target Venus and the intended orbit. The first correction maneuver will occur early into the cruise phase of flight with others occurring progressively later into the cruise. Depending on the exact orbit the spacecraft is delivered to by the launch vehicle some TCMs may not be necessary.

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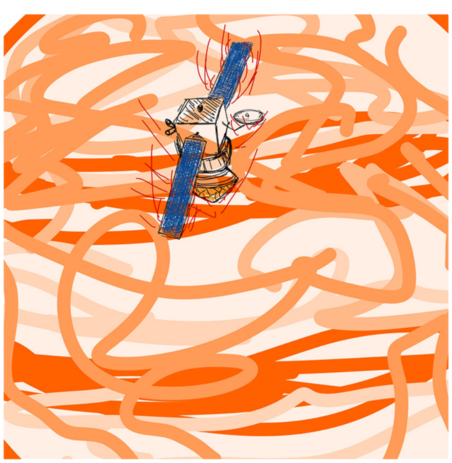
The spacecraft will perform a burn upon arrival to insert into a highly elliptical orbit above Venus. This will conclude the cruise phase of flight which is anticipated to last approximately 160 days. The orbit at capture will be an intermediary stage before aerobraking begins.



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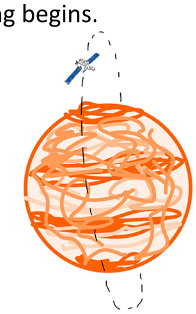
Aerobraking upon arrival to a planet is a technique that has been used a number of times by NASA missions to mars as a fuel saving method of changing the orbit of a spacecraft. The periapsis of the spacecraft orbit will be reduced to an aerobraking altitude, where it will reduce the apoapsis of its orbit while using small propulsive maneuvers to maintain aerobraking altitude. The altitude range for aerobraking is bracketed by the minimum effective density on the high end, and the maximum thermal loads on the low end.



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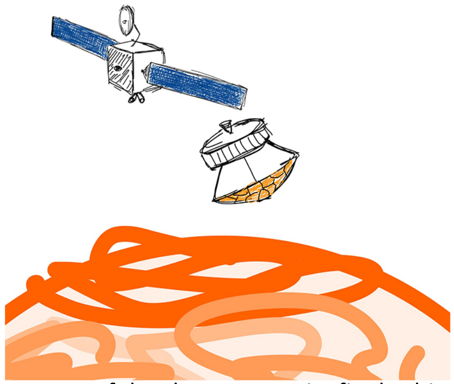
When the desired apoapsis is reached, the spacecraft will raise its periapsis out of the aerobraking envelope. The orbiter will then make final fine tuning adjustments to its orbit, placing it on its final trajectory; a polar orbit about Venus, enabling global observation and study of the surface.



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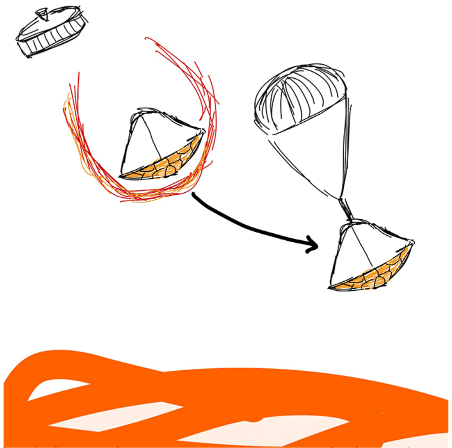
Once the spacecraft has been set on its final orbit, the orbiter and the ISX will detach. The location of separation will be chosen so that the ISX may enter Venus' atmosphere and target the site chosen for investigation. The propulsion module attached to its aeroshell will then fire its thrusters and place the ISX on its entry trajectory.



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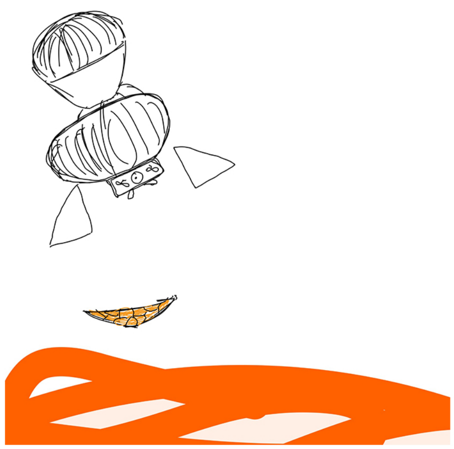
In order to safely deliver the ISX to its nominal altitude, it will be protected by a heat shield and backshell (forming an aerocapsule) much like the Mars Science Lab and Mars 2020 missions. The aerocapsule will protect the ISX through the hypersonic phase of descent. Once the capsule passes through the phase of significant heating, a supersonic parachute will deploy further slowing descent.



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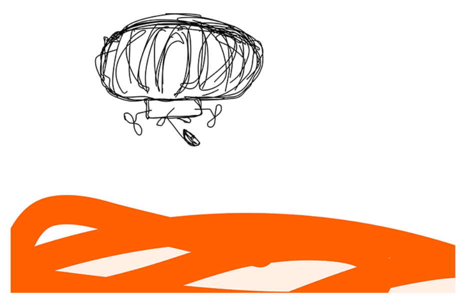
As the ISX nears its nominal altitude the heat shield and backshell will separate from the ISX and the balloon will begin to inflate. Unlike the MSL and Mars 2020 missions the parachute will not separate with the backshell. Once the balloon has reached higher pressure and speed of descent has slowed considerably, the parachute will be released and the balloons inflated to their final pressures.



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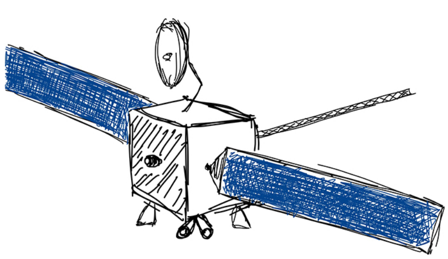
The deployed balloon is capable of passively maintaining altitude but not the position of the ISX. In order to maintain position, ISX will deploy its propellor systems and instruments from its packaged configuration into its operation configuration. After this series of deployments, ISX will be ready to begin its atmospheric investigations.



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After separation of the ISX from VCOAX, the orbiter can begin to configure itself for its scientific mission. The high gain antenna will be moved from its aerobraking configuration to its nominal operating configuration. Scientific instruments will deploy from their cruise configuration to their final intended positions.

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Once both the ISX and VCOAX orbiter have fully deployed, instruments will be calibrated. Once calibration is complete, both orbiter and in-situ explorer will be ready to begin their primary missions. The orbiter will take detailed scans of Venus and its atmosphere from its polar orbit, while the in-situ explorer will be able to sample the atmosphere directly and travel to points of interest.

2.0 Functional Baseline

Missions to Venus are rare. Throughout the space age there have been only 24 dedicated spacecraft sent to Earth's "twin", and only 6 when considering NASA missions. This as compared to Mars where there have been 23 successful missions operated by NASA alone. The opportunity to send a flagship class mission to Venus is rare, and success is of the utmost important. Because of this, the Venus Climate and Atmospheric Explorer [VCOAX] will rely heavily on flight heritage and proven deep space technologies to accomplish its mission.

1.1 Propulsion

Hydrazine has been selected as optimal propellant for its propulsion. Hydrazine is stable over long durations and only requires a catalyst to produce thrust. For orbital insertion VCOAX will use 2 MOOG industries MONARC-445 together producing 890N of thrust, for smaller trajectory correction maneuvers, the spacecraft will be equipped with 4 MONARC-22-6 thrusters capable of producing 22-88 N of thrust. Hydrazine will be stored in a composite overwrapped pressure vessel (COPV), due to their lightweight nature. The estimated propulsion system mass including the COPV, Thrusters, and feed lines is 55 kg. Each MONARC-445 requires 58 W, and each MONARC-22-6 requires 30 W, resulting in a maximum power consumption of 120 W when all 4 MONARC-22-6 thrusters are firing. The ISX Propulsion ring will contain an additional fuel tank and 2 MONARC-22-6 thrusters for deorbiting the spacecraft.

1.2 Power

The total power requirement for the orbital segment of VCOAX is 900 W, including margin. Due to the high solar irradiance at Venus, this allows a relatively small set of solar wings. Using triple junction GaAs solar arrays, VCOAX would require only 5 square meters of solar array to fulfil its power needs. The ISX will also have a smaller GaAs array on board its carriage to charge its batteries while in passive sleep mode.

1.3 Structure

The orbiter spacecraft structure will be composed of aluminum honeycomb with composite face sheets. The bus dimensions will be a 2 m square made of the honeycomb structure. Attached to the front will be struts connected with explosive bolts to the ISX propulsion ring. A 2m diameter ring houses the deorbiting propulsion equipment and the ISX aeroshell. The aeroshell is much like the MSL and Mars 2020 aeroshell but scaled down to a maximum diameter of 3m. The total structural mass will be 650 kg. The ISX will be a 2m cylindrical carriage made of aluminum honeycomb and composite face sheet, with a mass of 50 kg.

1.4 Attitude Control and Navigation

The primary means of Attitude determination aboard VCOAX will be through the use of a COTS star tracker. These technologies are incredibly mature and provide a raw accuracy .1 arcsecond decreasing with every star they are tracking. Gyros will be used to interpolate spacecraft motion between star tracker scans. In order for the orbiter to take useable measurements, the pointing accuracy must be at least 4 milliarcseconds necessitating the use of 4 10 kg reaction wheels for attitude control each. The orbiter will also have a hydrazine RCS composed of 20 MONARC-1 thrusters with a total mass of 3.8 kg and each consuming 18 W of power.

1.5 Command and Data Handling

Venus lacks a protective magnetosphere to shield spacecraft from radiation making radiation hardness an even larger priority than for other missions. With that in mind, the BAE systems RAD5545 SpaceVPX Single-board computer is the optimal choice for the VCOAX flight computer, with a redundant backup computer. The hardware is specifically designed for the space environment and has flight heritage making it a good choice for this mission. SEAKR Engineering has been a NASA partner in high volume storage since its founding with significant expertise in the subject. VCOAX will make use of the Gen3 Flash Memory Card due to its 192Gbyte storage volume which is necessary to store both VCOAX data and ISX data. In total the CDH system will require 35 W per computer system, and 5 W for the Gen3 FMC.

1.6 Thermal

Venus experiences almost double the solar irradiance of Earth at an average of 2600 W/m^2. Additionally, the spacecraft will experience more heating during its aerobraking maneuvers, thus the thermal protection system must be designed with this peak case in mind. A white coating of Z93 will be applied to the backs of the solar panel wings. Additionally, the spacecraft will be insulated with MLI blankets to protect from the heat of aerobraking. The spacecraft will have a radiator for rejecting excess heat delivered to it through heat pipes.

The thermal problem for the ISX segment of the VCOAX mission is relatively straight forward. While Venus has a reputation for being incredibly hot, at the chosen operational altitude where the pressure is 1 bar, temperatures are on average 30°C well within the standard operating temperature of many COTS parts. Additionally due to the presence of an atmosphere, convective cooling is possible allowing conventional technologies like fins to be used in the management of the thermal environment.

1.7 Telemetry and Control

The Telemetry and Control subsystem on board the VCOAX orbiter segment will be required to serve two mission critical functions. The first is to communicate with the VCOAX ground segment on Earth through the Deep Space Network, receiving instructions and sending scientific and engineering data. VCOAX will operate a high-gain antenna in the K_a-band allowing it to transmit data on the order of ~2 Mbps. The orbiter will also have 2 low-gain omnidirectional X-band antennas for emergency communications. The T&C package will have an estimated mass of 35 kg and a power requirement of 110 W.

The second is to serve as a communication relay between Earth and the ISX vehicle. ISX will carry a high data rate UHF antenna (up to 12 Mbps) for communication with the orbiter. The orbiter in turn will carry a UHF package to allow it to receive data from ISX and relay instructions back to it. Under normal operation, ISX will relay data to the obiter via UHF, which can then be sent to the ground via the DSN using the Orbiters much more powerful communication links. The UHF antenna system has a mass of 3 kg and a 65 W maximum power requirement.

1.8 Payload

1.8.1 Orbiter

The VCOAX orbiter segment will contain several instruments for studying the climate and atmosphere of Venus. The orbiter will carry the Orbiting Planet Atmospheric Lidar (OPAL) instrument which will allow the orbiter to conduct measurements of winds, atmospheric density, temperature, and aerosols and construct a global map of Venus' atmosphere between 50-120 km above the operating region of the ISX. VCOAX will also have cameras capable of imaging Venus in high resolution at a variety of light bands from IR to UV. The position in a polar orbit will allow complete coverage of the planet. The LIDAR will operate with a power of ~500 W and a mass of ~500 kg. The cameras will consume 2-5 W of power with a mass of .5 kg.

1.8.2 In-Situ Explorer

The In-Situ Explorer will carry an atmospheric measurement package (AMP) comprised of thermometers, pressure transducers, barometric pressure sensors and wind velocity measurement devices. The AMP will be based on radiosonde devices used on terrestrial weather balloons. The AMP will have a mass of .5 kg and a power consumption of 2-5 W. It will also carry a tunable laser spectrometer for measuring for trace gasses in the Venusian atmosphere which will consume 30 W of power with a mass of 3 kg. The last instrument carried by the ISX will be a surface imaging camera following the Tow-Body concept proposed by Kevin Baines at JPL with a mass of 7.5 kg using rechargeable batteries that will be charged during ISX passive sleep mode.

1.9 Entry Descent and Landing

For Entry Descent and Landing the ISX will follow much of the same path as the two most recent mars missions. The vehicle will be protected by an aeroshell comprised of a Backshell and heatshield. The heatshield will be composed of a Phenolic Impregnated Carbon Ablator that was used on MSL and Mars 2020 as well as on the Stardust mission. PICA has significant flight heritage and is a proven TPS material. There is further discussion in the Long-Lead items section about further work necessary to verify PICA for this application, but it has a few advantages over other possible TPS materials such as a woven TPS. Woven TPS has not been adequately tested and is much too risky for use on a flagship class mission. The Backshell will use the same SLA-561V cork ablator TPS material which is also a heritage material.

Once the aeroshell has slowed from hypersonic to supersonic entry, a supersonic parachute will be deployed, and the Backshell and heatshield detached. The Backshell will separate in two pieces unlike the MSL and Mars 2020 because the parachute must remain attached. Once the Backshell has separated, the ISX balloon will begin to be inflated from its helium tanks to the appropriate pressure to maintain buoyancy at an altitude where the pressure is 1 bar. Once the balloon is inflated the parachute will be cut.

1.10 Mobility

The ISX is more than a balloon, it also has the ability to navigate much like a quadcopter. Once safely floating in the atmosphere, booms will deploy from the carriage section of the ISX with electric motors attached. These motors and attached propellors will have gimbals allowing them to rotate and control lateral flight in any direction. Additionally, the ISX can control the pressure of its balloon to allow it to increase and decrease its altitude to both dip into the cloud layer and rise above any weather it may encounter. Because the propellors are not necessary to keep the ISX aloft, they can be significantly lighter and less power hungry than would be necessary if the balloon was not there. They will be connected to a rechargeable battery system allowing them to operate in any weather condition, or when the sun is not shining.

3.0 Risk Assessment

The aerobraking maneuver presents several significant risks that must be retired in the next phases of design. While this is a technique that has been used on several Mars missions and by the Magellan spacecraft at Venus during its extended mission, VCOAX will be a more challenging problem. Unlike Magellan, VCOAX will not already be in a relatively low orbit about Venus, and unlike the Mars missions, VCOAX will be entering a denser atmosphere leading to higher heating.

There are a number of thermal risks that are thus associated with the aerobraking maneuver. First is to the solar wings which will be deployed and will experience heating due to their large surface area. Failure of the solar wings due to this heating or due to any stress due to drag is unacceptable and would result in significant setbacks if not total mission failure. Similarly, the high gain antenna faces the same risks, and its failure could once again result in a total mission failure.

The balloon deployment and parachute release sequence of the ISX entry and descent system is the least well investigated part of entry. While the entry heating is also an inherent risk, it is a problem that has been tackled before. The primary risk with the ISX is that it will never land, it must enter and descend to a nominal altitude and the begin to hover there using its balloon. The parachute must be able to slow the descent of the ISX enough while the balloon is inflating to make this happen. Both the systems are mounted to the ISX on the top and must not interfere with the operation of one another, otherwise the ISX will likely fail to maintain its altitude and fall below a safe pressure zone resulting in a failure of the mission. The parachute must also not be allowed to deflate and fall onto the balloon or the ISX service platform. If this happens it could obscure instruments or solar panels rendering the ISX useless. Further design work is necessary to mitigate the risks of this entry scheme.

There is also a serious scheduling risk associated with missing a launch on December 10th, 2032. A small delay in launch is permissible up to January 11th, 2033, with only a slight (~.31 km/s) increase in delta V. However, missing that 1 month launch window to Venus will result in a 1.5-year delay until June 2034. Not only will missing the launch window force the program to wait a significant amount of time until it can attempt a launch, but also a built-in increase to the injection delta V. The December 2032 launch window represents the minimum delta V transfers between 2028 and 2040. Missing the December 2032 window could potentially force a change in launch vehicles or launch vehicle configuration for the mission which would be prohibitively expensive.

4.0 Long-Lead Items

The heat shield of the ISX vehicle will be made of Phenolic Impregnated Carbon Ablator (PICA), a material with significant flight heritage starting with the Stardust sample return mission and including both the Mars Science Lab and Mars 2020 missions. There are several unsolved challenges with using PICA on this mission which will need to be solved before flight. To date, PICA has been flown in both Earth's and Mars' atmosphere which are composed of mostly inert gasses, and while Venus' atmosphere contains mostly CO2, corrosive gasses are present in a much higher proportion. It will be critical to test PICA in a simulated Venus atmosphere to ensure that performance of the ablative material is not significantly impacted. This additional verification will contribute to the lead time of the Heat Shield. Additionally, PICA is a very difficult material to make, with only two manufacturers in the world capable of producing it. PICA-X, developed as a NASA spinoff by SpaceX is faster to produce and cheaper however, it has not been made available outside of the SpaceX's own projects. The only commercially available form of PICA is manufactured by Fiber Materials Inc. in Biddeford Maine.

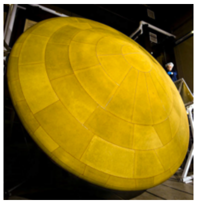

Figure 1 MSL PICA Heatshield (NASA.gov)

The ISX Balloon will be another long lead time item due to the novel nature of the platform. Much like the PICA heatshield, the balloon will need to be able to withstand the corrosive atmosphere of Venus. The balloon will likely spend much more time in contact with corrosive gasses, so this is of the utmost importance. The second challenge is that the balloon must allow the ISX to remain aloft for the required 90-day duration of the mission. To make the ISX successful, it will draw on NASA expertise in long duration stratospheric balloon flight such as the Super-TIGER long duration balloon experiment. That balloon was manufactured by Raven Aerostar, a frequent NASA contractor for atmospheric balloons. This contractor has expertise in both free flying balloons and stratospheric airships making them an attractive partner for this challenge. Lockheed Martin also has some experience with stratospheric airships making them another potential collaborator.

Figure 2 NASA Super-TIGER Balloon in Antarctica (NASA.gov)

Make Buy tradeoffs needing resolution:

- ISX scientific instruments
    - The ISX will be operating in an environment that is hostile to most commercial off the shelf equipment. Requirement SYS1.16 states that the ISX must be able to sample and analyze the atmosphere, meaning that some instruments will necessarily have to be exposed to the elements. It is still unclear whether it is better to purchase and ruggedize existing hardware or design from the ground up instruments capable of achieving mission goals within the hostile environment.
- ISX Propellor system
    - There is the potential to use COTS electric motors and propellors for the ISX, with the addition of shielding from the corrosive environment. This could potentially simplify the mobility system and allow the use of very well-developed motors. However, COTS motors may require more power, or be more powerful than is strictly necessary for the ISX mission goals. A custom designed system could be tailored to fit the available power on the vehicle and dialed in to the specific performance needs of the mission.