VAPE: Venus Atmosphere Penetrative Explorer

Space mission design final report

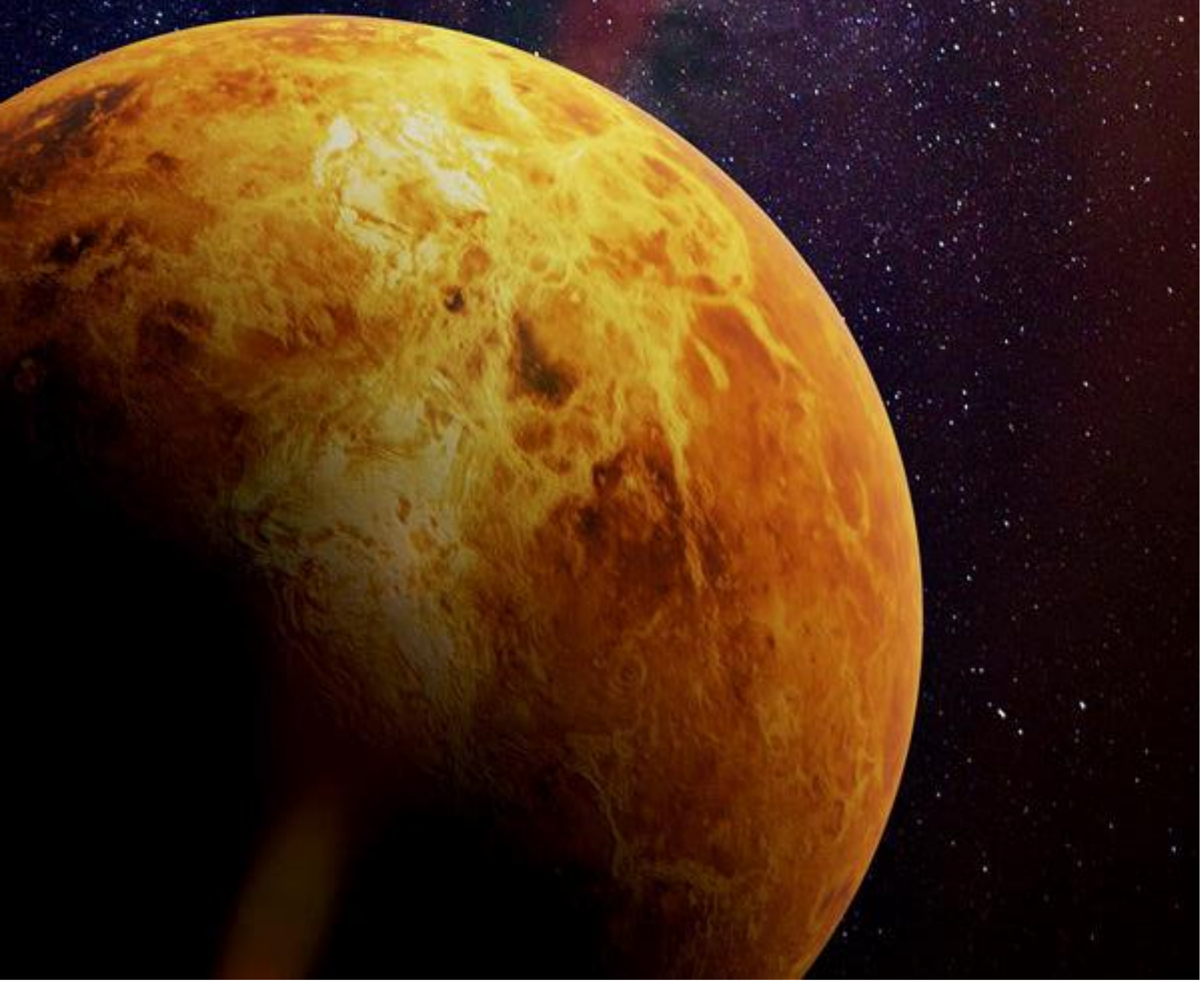

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Table 1 – Document description

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Applicable documents

ECSS-E-ST-10-02C | Space Engineering – Verification

ECSS-E-ST-10-03C | Space Engineering – Testing

ECSS-Q-ST-70-01C | Space product assurance – Cleanliness and contamination control

RNC-CNES-R-14-E-A | SECURITE DES SYSTEMES – Planetary protection requirements

Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies

Reference documents

Glaze, L. S., & Garvin, J. B. (2018). Exploring Venus: Never Give Up, Never Surrender. Greenbelt, MD: NASA. https://www.hou.usra.edu/meetings/lpsc2018/pdf/2024.pdf

Nikolov, N., & Zeller, K. (2017). New Insights on the Physical Nature of the Atmospheric Greenhouse Effect Deduced from an Empirical Planetary Temperature Model (2nd ed., Vol. 1, Research Article). Wellington, CO: Environment Pollution and Climate Change.

Enviropedia. (n.d.). Trace Gases. Retrieved January 17, 2019, from http://www.enviropedia.org.uk/Atmosphere/Trace_Gases.php

Andrew A. Lacis, James E. Hansen, Gary L. Russell, Valdar Oinas & Jeffrey Jonas (2013) The role of long-lived greenhouse gases as principal LW control knob that governs the global surface temperature for past and future climate change, Tellus B: Chemical and Physical Meteorology, 65:1, DOI: 10.3402/tellusb.v65i0.19734

Abbreviations

AR – Acceptance review

CDR – Critical design review

CSA – Canadian Space Agency

DLR – Downwelling Longwave Radiation

ECSS – European Cooperation for Space Standardisation

ECOS – European Space Operations Centre

ESA – European Space Agency

ESTRACK – European Space Tracking [network]

FL – Florida

GEO – Geosynchronous Equatorial Orbit

HTO – Hohmann Transfer Orbit

LEO – Low Earth Orbit

JAXA – Japanese Aerospace eXploration Agency

KSC – Kennedy Space Centre

KSP – Kerbal Space Program

LEO – Low Earth Orbit

LV – Launch Vehicle

MDR – Mission design review

MDS – Mission Design Solution

MECO – Main Engine Cut Off

NASA – National Aeronautics and Space Administration

NOSS – Naval Ocean Surveillance System

PDR – Preliminary design review

PPM – Parts per million

PRR – Preliminary requirements review

PSR – Pre-shipment review

SECO – Second Engine Cut Off

SOI – Sphere of Influence

SRB – Solid Rocket Booster

SRR – System requirement review

STK – Systems Tool Kit

TBC – To be confirmed

TBD – To be determined

TBW – To be written

USN – United States Navy

VAPE – Venus Atmospheric Penetrating Explorer

VST – Venus Solar Time

Table of Contents

Introduction

Our team has conceived a space mission to Venus. This document describes the nature of the mission. We present the mission objective, overview, and constraints. Which are followed by the mission requirements, phases, and orbital parameters. The results of our trade studies, the system block diagrams, engineering budgets, along with the work breakdown chart and schedule shall illustrate the scope of the mission that our team has envisioned.

Mission objective

The primary mission objective is, "to provide in situ measurements and gather scientific data on Venus by penetrating the atmosphere of the planet in order to investigate its greenhouse event and atmospheric composition." The goal of the mission is the collection of scientific information about the atmosphere of Venus. This was motivated by a desire to learn more about it and to expand the current understanding of the greenhouse effect. The this end several mission needs were created and are listed in the mission overview.

Mission overview

The mission needs are:

- To detect the presence of microbial life in potential algae plumes in clouds located at an altitude of 40 kilometres,
- To observe the seasonal variability of the atmospheric behaviour,
- To detect the presence of different greenhouse gases at different altitudes,
- To detect the presence of noble gases in the atmosphere,
- To analyse the chemical composition of the atmosphere at different altitudes,
- To determine the orbital trajectory from an Earth parking orbit to the chosen Venusian orbital parameters,

- To perform measurements of the downwelling longwave radiation (DLR).

Constraints to the mission

From the mission needs and objective listed, several important constraints emerge. To begin, the discovery of life on another planet would broaden our search. Currently, on exoplanets, microbial life in algae plumes is theorised to form at an altitude of 40 kilometres. This is the scope that the mission selected for this need. Then, the observation of seasonal variability means that the mission requires an extended presence on Venus. As such, it would need to last several years to obtain a relevant conclusion and to negate potential outliers in the data. Next, the greenhouse gases the mission aims to measure the concentrations of are carbon dioxide, nitrogen, carbon monoxide, and other minor molecules. Their concentrations shall be measured to an accuracy of $10\ ppm$ and at different altitudes between $30\ km$ and $50\ km$. Additionally, from prior missions, such as, sounding rockets, the Apollo programme, Huygens, Viking, Phoenix, and Venus express, mass spectrometers have gained an extensive flight heritage. Therefore, they shall be used as at least one of the techniques employed to detect noble gases in the atmosphere. Lastly, the Venusian downwelling longwave radiation shall be measured within the range of $0\ W\ m^{-2}$ to $20\ 000\ W\ m^{-2}$ and at an accuracy of $1.0\ W\ m^{-2}$. These values stem from the EPCC paper cited as a reference document for this report.

Mission requirements

This portion of the document presents preliminary design requirements for the mission design solution (MDS); which is divided into two parts, the spacecraft and the payload. The spacecraft MDS is the portion tasked with achieving the transport and delivery of the payload to the atmosphere of Venus. The payload MDS is the portion that shall operate in the Venusian atmosphere to perform the science phase of our mission.

From the preliminary mission description, we know that our project shall consist of a solution able to penetrate and navigate in the atmosphere of Venus. The MDS is also tasked with conducting chemical and thermal analyses. From the concept of operations, collected scientific data shall be published online. Our mission project has six different levels defined for the verification and testing procedures. These are,

- Component
    - When the design team receives a component. Ideally in pairs so that one can be put through test, the other, of the same batch is used in the assembly if the former passes.
- Subsystem assembly
    - When components are put together to form a nominally operating subsystem of either the spacecraft MDS or the payload MDS.
- Flat-sat
    - When subsystems are connected without the structure of the spacecraft or payload to perform software and interface verification.
- Spacecraft assembly
    - When subsystems are put together along with the associated structure to form the spacecraft MDS. Takes place in an appropriate facility for spacecraft assembly.
- Payload assembly
    - When subsystems are put together along with the associated structure to form the payload MDS. Takes place in an appropriate facility for spacecraft assembly.
- Full spacecraft integration
    - When spacecraft and payload MDSs are integrated. Occurs closest to launch, but before the mission leaves the assembly facilities, such that, changes can still be implemented.

Functional Requirements

VAPE-REQ-FUNC-0001						
Description	The mission shall sample the Venusian atmosphere during the science phase of the mission.			Time/Level of Verification	Component, and, Full spacecraft integration	
Comment				Nature of Verification	Test all components and later that completed MDS meets science objectives	
Rationale	Our mission goal is to provide scientific data about Venus's atmosphere.					
				Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Michael Tabascio	Last modified	13 FEB 2019	

VAPE-REQ-FUNC-0002						
Description	The selected launch vehicle shall bring the satellite to Venus during the launch and travel phase.			Time/Level of Verification	-	
Comment	The mission LV is TBD.			Nature of Verification	-	
Rationale	To reach our primary objective, travelling to Venus is necessary.					
				Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Michael Tabascio	Last modified	13 FEB 2019	

VAPE-REQ-FUNC-0003						
Description	The spacecraft MDS shall utilize an orbit around Venus for the duration of the science phase.			Time/Level of Verification	-	
Comment	Specific orbit parameters TBD by trade study.			Nature of Verification	-	
Rationale	An orbit allows us to provide complete coverage of the planet over a given time interval.					
				Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Michael Tabascio	Last modified	13 FEB 2019	

VAPE-REQ-FUNC-0004				
Description	The orbital parameters of the spacecraft MDS shall be determined by a trade study.	Time/Level of Verification	-	
Comment	Specific orbit parameters TBD by trade study. Connects back to requirement VAPE-REQ-FUNC-0003.	Nature of Verification	-	
Rationale	An orbit allows us to provide complete coverage of the planet over a given time interval.	Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Michael Tabascio	Last modified: 13 FEB 2019

VAPE-REQ-FUNC-0005				
Description	The orbital parameters of the spacecraft MDS shall allow the orbit to precess at TBD deg/day during the science phase.	Time/Level of Verification	-	
Comment	Connects back to requirement VAPE-REQ-FUNC-0003.	Nature of Verification	-	
Rationale	Precession of the orbit will allow us to cover the same location at different times during the science phase.	Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Michael Tabascio	Last modified: 13 FEB 2019

VAPE-REQ-FUNC-0006				
Description	The MDS shall transmit the collected data back to Earth during the science phase.	Time/Level of Verification	Flat-sat	
Comment		Nature of Verification	Test of communication subsystem data transmission	
Rationale	Our stakeholder need is the data that will be taken, so it will need to be sent back.	Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Michael Tabascio	Last modified: 13 FEB 2019

VAPE-REQ-FUNC-0007				
Description	The spacecraft MDS shall perform orbital manoeuvres necessary for the completion of the mission objectives.	Time/Level of Verification	Component, and, Full spacecraft integration	
Comment	ACDS used to acquire, control, and measure required attitude during all phases of the mission.	Nature of Verification	Verify that propulsion and ACDS parts and subsystems can fulfil requirement	
Rationale	Spacecraft MDS will need to perform burns and change its orbital parameters throughout the mission.	Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Yaseen Al-Taie	Last modified: 13 FEB 2019

VAPE-REQ-FUNC-0008				
Description	The MDS shall be able to orient itself using the star positions on the celestial sphere.	Time/Level of Verification	Full spacecraft integration	
Comment	Need a star tracker on the spacecraft MDS.	Nature of Verification	Test of ACDS subsystem operations.	
Rationale	Interfacing with a star map on board will allow the satellite to orient itself.	Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Michael Tabascio	Last modified: 13 FEB 2019

VAPE-REQ-FUNC-0009				
Description	The MDS shall be ready for a 2025 launch.	Time/Level of Verification	Throughout design phase	
Comment	The mission and probe design shall be compatible with a launch period duration.	Nature of Verification	Project managers and teams follow pre-arranged schedule.	
Rationale	Takes advantage of 2025 launch window to Venus in order to minimize delta-V required.	Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Jacob Samson	Last modified: 13 FEB 2019

VAPE-REQ-FUNC-0010				
Description	The payload MDS shall perform activities (TBW) at pressures between 0.858 and 1.04 ATM (TBC)	Time/Level of Verification	Full spacecraft integration
Comment	Pressure values may change with mission focus.	Nature of Verification	Environmental testing and cycling for operating ranges.
Rationale	These are typical maximum and minimum pressures believed to be found in the atmosphere of Venus.		
		Version	V-1.0
Written on	21 JAN 2019	Initial Author	Matthieu Durand	Last modified	13 FEB 2019

VAPE-REQ-FUNC-0011				
Description	The payload MDS shall gather atmospheric samples at a height where pressure is like Earth's.	Time/Level of Verification	Full spacecraft integration
Comment	Pressure should be about one (1) bar	Nature of Verification	Perform spacecraft testing in own atmosphere for verification
Rationale	We will need data collected from regions where microbial life has been theorized.		
		Version	V-1.0
Written on	05 FEB 2019	Initial Author	Jacob Samson	Last modified	13 FEB 2019

VAPE-REQ-FUNC-0020				
Description	The spacecraft and payload MDS shall survive the radiation environment of: • LEO • GEO • Interplanetary space • Venus orbit • Venus atmosphere	Time/Level of Verification	Component, and, Full spacecraft integration
Comment	Use models to predict Venus radiation environment.	Nature of Verification	Test all components and later that completed MDS is radiation hardened
Rationale	MDS needs to operate nominally in such environments to successfully complete the objective(s).		
		Version	V-1.0
Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	13 FEB 2019

VAPE-REQ-FUNC-0030				
Description	The payload MDS shall store science and housekeeping data when downlink to Earth is not possible.	Time/Level of Verification	Payload assembly	
Comment	Amount of data is TBD.	Nature of Verification	Testing of response to out of ordinary operating conditions.	
Rationale	Prevent loss of scientific and housekeeping telemetry. Payload shall determine when condition is true.			
		Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified: 13 FEB 2019

VAPE-REQ-FUNC-0040				
Description	The payload MDS shall save telemetry on-board using an on-board memory device in a continuous manner.	Time/Level of Verification	Flat-sat	
Comment	Total amount of data to store at one time is TBD.	Nature of Verification	Testing of software processes under nominal conditions.	
Rationale	Provides means of recording data prior to downlink and for housekeeping purposes.			
		Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified: 13 FEB 2019

VAPE-REQ-FUNC-0050				
Description	The payload MSD(s) shall survive in the atmosphere of Venus for a minimum of TBD unit of time (TBC).	Time/Level of Verification	Payload system assembly	
Comment	Base duration on technology level and scientific needs.	Nature of Verification	Environmental simulations	
Rationale	Allow reasonable time frame for measurements and observations to be made during the science phase.			
		Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified: 13 FEB 2019

VAPE-REQ-FUNC-0051				
Description	The science phase of the mission shall last for a minimum of one (1) Venus year.	Time/Level of Verification	Payload system assembly	
Comment		Nature of Verification	Environmental simulations	
Rationale	Interested in how regions of atmosphere change seasonally. So, need measurements for a least 1 cycle.	Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Michael Tabascio	Last modified: 13 FEB 2019

VAPE-REQ-FUNC-0060				
Description	The payload MDS shall survive in the Venusian atmosphere for at least 3 months.	Time/Level of Verification	Payload system assembly	
Comment	Base duration on technology level and scientific needs.	Nature of Verification	Environmental simulations	
Rationale	Allow for measurements and observations to be made during the decommissioning phase of the mission.	Version	V-1.1	
Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified: 03 APR 2019

VAPE-REQ-FUNC-0070				
Description	The payload MDS shall have an on-board instrument whose function is to measure DLR.	Time/Level of Verification	Component	
Comment	Units and precision of measurement are TBD. This instrument also allows temperature analysis.	Nature of Verification	Test instrument for desired properties.	
Rationale	Fulfil mission need and scientific objectives reported in mission statement and preliminary presentation.	Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified: 13 FEB 2019

VAPE-REQ-FUNC-0074				
Description	The payload MDS shall have on on-board infrared spectrometer instrument for thermal analysis.	Time/Level of Verification	Component	
Comment		Nature of Verification	Test instrument for desired properties.	
Rationale	IR data important for scientific analysis.	Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Jessie Atamanchuck	Last modified: 13 FEB 2019

VAPE-REQ-FUNC-0077				
Description	The payload MDS shall have on on-board mass spectrometer instrument.	Time/Level of Verification	Component	
Comment		Nature of Verification	Test instrument for desired properties.	
Rationale	To provide scientific data on chemical composition.	Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified: 13 FEB 2019

VAPE-REQ-FUNC-0075				
Description	The payload MDS shall have an on-board instrument whose function is to measure atmospheric pressure.	Time/Level of Verification	Component	
Comment	Precision of measurement TBB	Nature of Verification	Will expose designed system to volume with known pressure	
Rationale	Pressure data needed for scientific analysis.	Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Jessie Atamanchuck	Last modified: 13 FEB 2019

VAPE-REQ-FUNC-0080				
Description	The payload MDS shall have an on-board instrument whose function is to measure noble gas concentration.	Time/Level of Verification	Component
Comment	Precision of measurement in PPM are TBD.	Nature of Verification	Test instrument for desired properties.
Rationale	Fulfil mission need and scientific objectives reported in mission statement and preliminary presentation.	Version	V-1.0

Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	13 FEB 2019

VAPE-REQ-FUNC-0085				
Description	The probe shall collect Carbon Dioxide, Sulfuric Acid and Radiative balance (GHG) data up to ppm accuracy.	Time/Level of Verification	Component
Comment	Based on ISO 15859-12:2004 (Space systems--Fluid characteristics, sampling and test method) standard	Nature of Verification	Ensure sensors that are used can provide required accuracy through testing and verification
Rationale	To differentiate between normal and extreme amounts of concentration.	Version	V-1.0

Written on	05 FEB 2019	Initial Author	Yaseen Al-Taie	Last modified	13 FEB 2019

VAPE-REQ-FUNC-0090				
Description	The payload MDS shall have an on-board instrument to analyse the composition of the atmosphere.	Time/Level of Verification	Component
Comment	Nature of analysis and precision are TBD.	Nature of Verification	Test instrument for desired properties.
Rationale	Fulfil mission need and scientific objectives reported in mission statement and preliminary presentation.	Version	V-1.0

Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	13 FEB 2019

VAPE-REQ-FUNC-0095					
Description	The MDS shall measure concentration of CO_2, CH_4, H_2O in Venusian atmosphere.			Time/Level of Verification	Component
Comment				Nature of Verification	Expose system to volume with known concentration of gas
Rationale	Concentration data needed for scientific analysis				
				Version	V-1.0
Written on	05 FEB 2019	Initial Author	Jessie Atamanchuck	Last modified	13 FEB 2019

VAPE-REQ-FUNC-0100					
Description	The payload MDS shall have an on-board instrument to capture optical images in a digital format.			Time/Level of Verification	Component
Comment	Placing, size, quality, and resolution of image TBD.			Nature of Verification	Test instrument for desired properties.
Rationale	Images from Venus useful to scientists and public interest in the mission.				
				Version	V-1.0
Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	13 FEB 2019

VAPE-REQ-FUNC-0110					
Description	System shall have ability to detect Venus			Time/Level of Verification	Full Spacecraft Integration
Comment				Nature of Verification	Will expose designed instrument to simulated Venus
Rationale	Needed for attitude determination when in orbit around Venus				
				Version	V-1.0
Written on	05 FEB 2019	Initial Author	Jessie Atamanchuck	Last modified	13 FEB 2019

VAPE-REQ-FUNC-0120	Description	The spacecraft and payload MDS shall be provided enough electrical power for all required activities, by the electrical power subsystem.	Time/Level of Verification	Flat-sat
	Comment	Exact amount of electrical power requires further design and research into the mission solution.	Nature of Verification	Test of power delivery to subsystems. Done in flat-sat configuration, and TVAC.
	Rationale	It is critical to the success of the mission that all subsystems be provided with the power then need.	Version	V-1.0

Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	13 FEB 2019

VAPE-REQ-FUNC-0151	Description	The satellite MDS shall provide its own power via the use of solar panels.	Time/Level of Verification	Full spacecraft integration
	Comment		Nature of Verification	Test solar panel and bus integration in terms of power provided to subsystems
	Rationale	Instruments need power to operate, not enough battery capacity to provide this without recharging.	Version	V-1.0

Written on	05 FEB 2019	Initial Author	Michael Tabascio	Last modified	13 FEB 2019

VAPE-REQ-FUNC-0130	Description	All MDS subsystem shall be provide with a suitable thermal environment, within a range (TBD) allowing for nominal spacecraft and payload operations.	Time/Level of Verification	Component and full assembly
	Comment	Suitable is vague, exact figure range will come later.	Nature of Verification	Components thermal testing and full spacecraft undergoes shake and bake procedure.
	Rationale	It is critical to the success of the mission that all subsystems be provided with the thermal environment required for nominal functions.	Version	V-1.0

Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	13 FEB 2019

VAPE-REQ-FUNC-0140	Description	The probe shall have the capability to enter and exit from all the functional modes and to emit in real time the current hardware and software status for diagnostic purposes.		Time/Level of Verification	
	Comment			Nature of Verification	
	Rationale	The telemetry shall provide unambiguous identification of the modes and mode transitions		Version	V-1.0
Written on	05 FEB 2019	Initial Author	Yaseen Al-Taie	Last modified	13 FEB 2019

Performance Requirements

VAPE-REQ-PERF-0010	Description	The payload MDS shall sample the atmosphere in the range of one (1) to ten (10) ATM.		Time/Level of Verification	Payload assembly
	Comment			Nature of Verification	Pressure (environmental) testing and verifications
	Rationale	This range allows us to look at different types of aerosols that have been confirmed in the Venus atmosphere and how the composition of the atmosphere changes with altitude.		Version	V-1.0
Written on	05 FEB 2019	Initial Author	Michal Tabascio	Last modified	13 FEB 2019

VAPE-REQ-PERF-0020	Description	The thermal on-board instruments shall collect atmospheric temperature levels to ± 0.5 K accuracy.		Time/Level of Verification	Component
	Comment	Based on ISO 11225:2012 (space environment--guide to reference and standard atmosphere models).		Nature of Verification	Ensure sensors that are used can provide required accuracy through testing and verification
	Rationale	To differentiate between normal and extreme temperature levels. Provides accuracy baseline for requirement VAPE-REQ-FUNC-0070.		Version	V-1.0
Written on	05 FEB 2019	Initial Author	Yaseen Al-Taie	Last modified	13 FEB 2019

VAPE-REQ-PERF-0030						
Description	The payload MDS shall regain attitude control within seven (7) seconds (TBC) after being struck by gust of winds reaching TBD km/h			Time/Level of Verification	Payload assembly	
Comment	High altitude winds may interfere with attitude.			Nature of Verification	Wind tunnel test using extreme air speeds typical to Venus.	
Rationale	Provide baseline for survivability to the physical hazards posed by the atmosphere of Venus.			Version	V-1.0	
Written on	21 JAN 2019	Initial Author	Matthieu Durand	Last modified	13 FEB 2019	

VAPE-REQ-PERF-0040						
Description	The payload MDS shall measure atmospheric pressure with an accuracy of 5% FS.			Time/Level of Verification	Component	
Comment	FS denotes full scale. This connect back to requirement VAPE-REQ-FUNC-0075			Nature of Verification	Test instrument for desired properties and accuracy.	
Rationale	This will ensure that the data recorded can be usefully analysed.			Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Jessie Atamanchuck	Last modified	13 FEB 2019	

VAPE-REQ-PERF-0050						
Description	The instrument in VAPE-FUNC-0110 shall operate nominally when in the 0-20 km part of the atmosphere.			Time/Level of Verification	Component	
Comment	Composition of deepest atmosphere is unknown.			Nature of Verification	TVAC and environment cycles to test nominal operating ranges.	
Rationale	Fulfil mission need and scientific objectives reported in mission statement and preliminary presentation.			Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	13 FEB 2019	

VAPE-REQ-PERF-0060			
Description	The spacecraft and payload MDS shall pass acoustic, shock, and sine vibrations tests.	Time/Level of Verification	Full spacecraft assembly
Comment	Use information from launch vehicle user manual.	Nature of Verification	Shake and bake testing using vibration table.
Rationale	The MDS needs to survive the launch environment as well as any accelerations during orbital manoeuvres.	Version	V-1.0

Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	13 FEB 2019

VAPE-REQ-PERF-0070			
Description	The spacecraft MDS shall be able to communication back to Earth with a bit rate of at least 60 Kb/s	Time/Level of Verification	Flat-sat
Comment		Nature of Verification	Test communication bands to ensure fast enough data rate
Rationale	The space craft must be able to receive and send telemetry and science data at a reasonable rate.	Version	V-1.0

Written on	05 FEB 2019	Initial Author	Jacob Samson	Last modified	13 FEB 2019

VAPE-REQ-PERF-0080			
Description	At launch, the MDS shall have a total mass equal to or less than five (5) metric tonne.	Time/Level of Verification	Full spacecraft assembly
Comment	This includes the launch vehicle adapter. Exact mass figure is to be refined throughout the design project.	Nature of Verification	Mass measurement of assemble spacecraft and payload.
Rationale	The current mass figure was selected according to the launch vehicle specifications and by viewing the launch mass of the planetary exploration missions.	Version	V-1.0

Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	13 FEB 2019

VAPE-REQ-PERF-0091				
Description	The payload MDS shall detect a minimum number density of 2×10^{19} particles per cm^3.	Time/Level of Verification	Component	
Comment		Nature of Verification	Test instrument for measurement limits in a controlled environment	
Rationale	The minimum number density for the upper limit of the range of the atmosphere we wish to sample.	Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Michael Tabascio	Last modified: 13 FEB 2019

VAPE-REQ-PERF-0092				
Description	The payload MDS shall detect a maximum number density of 1.5×10^{20} particles per cm^3.	Time/Level of Verification	Component	
Comment		Nature of Verification	Test instrument for measurement limits in a controlled environment	
Rationale	The maximum number density for the lower limit of the range of the atmosphere we wish to sample.	Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Michael Tabascio	Last modified: 13 FEB 2019

VAPE-REQ-PERF-0100				
Description	The probe shall differentiate between ±40 micrometre wavelengths when collecting Radiative balance data.	Time/Level of Verification	Component	
Comment	Based on ISO 17761:2015 (Space environment (natural and artificial) -- Model of high energy radiation at low altitudes (300 km to 600 km) standard.	Nature of Verification	Ensure sensors that are used can provide required accuracy through testing and verification	
Rationale	To differentiate among other parameters in Venus atmosphere. Provides accuracy baseline for requirement VAPE-REQ-FUNC-0071.	Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Yaseen Al-Taie	Last modified: 13 FEB 2019

Interface requirements

VAPE-REQ-INTE-0010					
Description	The spacecraft and payload MDS shall interface appropriately the selected communication network.			Time/Level of Verification	Full spacecraft assembly
Comment	Network in question TBD by trade study. The spacecraft must be compatible with pre-existing long-range communication networks.			Nature of Verification	Testing of communications with network regulations and protocols in anechoic chamber.
Rationale	Communicating with network will allow for easier data, GNC and TT&C between ground station and satellite.			Version	V-1.0
Written on	05 FEB 2019	Initial Author	Jessie Atamanchuck	Last modified	13 FEB 2019

VAPE-REQ-INTE-0011					
Description	The telemetry data shall be sent using the approved format for the selected communication protocol.			Time/Level of Verification	Full spacecraft integration
Comment	Communication protocol TBD.			Nature of Verification	Testing of communications with network regulations and protocols in anechoic chamber.
Rationale	The telemetry must be sent appropriately to function correctly with the bands and network selected.			Version	V-1.0
Written on	05 FEB 2019	Initial Author	Yaseen Al-Taie	Last modified	13 FEB 2019

VAPE-REQ-INTE-0012				
Description	The mission ground segment shall process and analyse the data upon its reception.	Time/Level of Verification	Full spacecraft integration	
Comment	Based on ISO 21076:2016 (Space data and information transfer systems -- Space communications cross support -- Architecture requirements document) standard.	Nature of Verification	Testing of interface between telemetry reception and ground station equipment/personnel.	
Rationale	Part of providing the data received to the scientist and other end users of the information.	Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Yaseen Al-Taie	Last modified 13 FEB 2019

VAPE-REQ-INTE-0013				
Description	The ground station shall be able to receive data on a 24/7 basis during the entire lifetime of the mission.	Time/Level of Verification	Full spacecraft integration	
Comment		Nature of Verification	Testing of interface between telemetry reception and ground station equipment/personnel.	
Rationale	The ground segment must always be able to receive data in case of an emergency.	Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Jacob Samson	Last modified 13 FEB 2019

VAPE-REQ-INTE-0014				
Description	The ground segment shall be able to send commands to the satellite.	Time/Level of Verification	Full spacecraft integration	
Comment		Nature of Verification	Testing of interface between transmission and ground station equipment/personnel.	
Rationale	The ground segment will need to be able to communicate with the satellite for various reasons.	Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Michael Tabascio	Last modified 13 FEB 2019

VAPE-REQ-INTE-0015					
Description	The MDS shall be able to receive commands from the ground station and apply then to the necessary subsystems with confirmation of completion sent back to the ground station.			Time/Level of Verification	Full spacecraft integration
Comment				Nature of Verification	Testing of interface between transmission and spacecraft autonomous operations.
Rationale	The satellite will need to work with the ground station to provide telemetry and telecommands and any changes to these received by the ground station will need to be understood and executed.			Version	V-1.0
Written on	05 FEB 2019	Initial Author	Michael Tabascio	Last modified	13 FEB 2019

VAPE-REQ-INTE-0016					
Description	When operating normally, the MDS shall transmit telemetry and receive commands to and from a dedicated ground stations located at TBD.			Time/Level of Verification	Full spacecraft assembly
Comment	This is where science phase team will operate from.			Nature of Verification	Run test and training procedure at ground station to verify and prepare for mission operations.
Rationale	Single ground station allows for smoother communication and operation between team dedicated to this mission phase. (Could also be a programmatic requirement)			Version	V-1.0
Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	13 FEB 2019

VAPE-REQ-INTE-0020					
Description	The MDS shall receive data from the instruments on a TBD basis.			Time/Level of Verification	Full spacecraft integration
Comment	Sampling of the atmosphere will need to be determined. Increasing our sample rate allows for more confidence in the data that is being received.			Nature of Verification	Testing of interfacing between the instruments and MDS bus.
Rationale	Sampling of the instrument readings determine data volume and required telemetry rate.			Version	V-1.0
Written on	05 FEB 2019	Initial Author	Michael Tabascio	Last modified	13 FEB 2019

VAPE-REQ-INTE-0030						
Description	The MDS shall be compatible for launch by the selected launch vehicle/provider.			Time/Level of Verification	Full spacecraft integration	
Comment	Ariane 5 flights have signed contracts until 2022. Arianespace provide reliable launch services and possesses launcher suitable for mission needs.			Nature of Verification	Shake and bake testing, check MDS dimensions.	
Rationale	Necessary for successful launch and compliance with the launch vehicle.			Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	13 FEB 2019	

VAPE-REQ-INTE-0031						
Description	The dimensions of the spacecraft MDS shall fit within the fairing of the launch selected in VAPE-INTE-0010.			Time/Level of Verification	Full spacecraft integration	
Comment	Fairing dimension TBD from launch vehicle manual.			Nature of Verification	Manual checking and measuring of dimension for validation.	
Rationale	To meet requirement, VAPE-INTE-0010 as the intended launch vehicle is an Ariane 6.			Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	13 FEB 2019	

VAPE-REQ-INTE-0040						
Description	The payload MDS shall be deployed into the atmosphere by the spacecraft MDS.			Time/Level of Verification	Full spacecraft assembly	
Comment				Nature of Verification	Test of separation processes and validation of simulated atmospheric insertion	
Rationale	The payload shall not be fitted with orbital manoeuvre capabilities; thus, it must be deposited into the atmosphere by the parent spacecraft.			Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	13 FEB 2019	

Regulatory requirements

VAPE-REQ-REGU-0010						
Description	The MDS shall adhere to all regulation set by Defence Production Act and Controlled Goods Regulations.			Time/Level of Verification	All phases	
Comment				Nature of Verification	Will cross-reference system with regulations.	
Rationale	Needed for system to be legal in Canadian domain.			Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Jessie Atamanchuck	Last modified	13 FEB 2019	

VAPE-REQ-REGU-0020						
Description	Spacecraft and all systems therein shall adhere to all regulations set by the launch provider.			Time/Level of Verification	All phases	
Comment				Nature of Verification	Will cross-reference system with regulations.	
Rationale	Needed for spacecraft to be accepted by provider.			Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Jessie Atamanchuck	Last modified	13 FEB 2019	

APE-REQ-REGU-0030						
Description	All design phases of the mission shall comply with RNC-CNES-R-14-E-A, section 6.5, on Planetary Protection Meetings and Reviews.			Time/Level of Verification	Pre-planning	
Comment	Decontamination, sterilization, and bio-cleaning are all aspects of the mission to consider attentively.			Nature of Verification	Validation of meetings planning by planetary biology expert.	
Rationale	The mission must respect Article IX of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies.			Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	13 FEB 2019	

VAPE-REQ-REGU-0040					
Description	Facilities used to assemble the MDS shall comply with standard ECSS-Q-ST-70-01C section 5.3.		Time/Level of Verification	Full spacecraft integration	
Comment	Specifically, sections, 5.3.1 on cleanrooms, 5.3.2 on vacuum facilities, and 5.3.3 on other facilities.		Nature of Verification	Examination of facilities by specialized inspector(s)	
Rationale	To prevent contamination of the MDS assembly by biological, chemical, and other contaminants.		Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	13 FEB 2019

VAPE-REQ-REGU-0050					
Description	Cleaning and decontamination activities of hardware and components shall be performed according to standard ECSS-Q-ST-70-01C.		Time/Level of Verification	Full spacecraft integration	
Comment	Specifically, section 5.4 on activity applies.		Nature of Verification	Examination of cleaning procedures by inspector(s)	
Rationale	To remove contamination of the MDS assembly by biological, chemical, and other contaminants.		Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	13 FEB 2019

VAPE-REQ-REGU-0060					
Description	During all phases, testing and verification of the MDS shall be performed according to standards ECSS-E-ST-10-03C section 5 and ECSS-E-ST-10-02C section 4-7.		Time/Level of Verification	Full spacecraft integration	
Comment	Additional sections from these standards are TBW.		Nature of Verification	Examination of verification and test procedures by inspector(s)	
Rationale	To provide standardized testing between different subsystems and systems teams for uniformity in the completion and publication of verifications.		Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	13 FEB 2019

VAPE-REQ-REGU-0070				
Description	The maximum amount of surface-level particulate contamination on the MDS shall be less than TBD.	Time/Level of Verification	Full spacecraft integration	
Comment	Requirement TBW to comply with an ECSS standard.	Nature of Verification	Sampling of MDS surface contamination by technicians.	
Rationale	To verify contamination level of the MDS assembly by biological, chemical, and other contaminants. Also, to comply to VAPE-REGU-0030 and Article XI.	Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified: 13 FEB 2019

VAPE-REQ-REGU-0080				
Description	The maximum amount of surface-level chemical contamination on the MDS shall be less than TBD.	Time/Level of Verification	Full spacecraft integration	
Comment	Requirement TBW to comply with an ECSS standard.	Nature of Verification	Sampling of MDS surface contamination by technicians.	
Rationale	To verify contamination level of the MDS assembly by biological, chemical, and other contaminants. Also, to comply to VAPE-REGU-0030 and Article XI.	Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified: 13 FEB 2019

VAPE-REQ-REGU-0090				
Description	The project shall be applicable to Risk assessment according to ECSS-Q-00A contributes to the overall project risk management process according to ECSS-M-00-03b (Launch site Safety Regulations).	Time/Level of Verification	Throughout design phase	
Comment		Nature of Verification	Verification of project management methods	
Rationale	Product assurance requirements provided by the Mission Product Assurance Requirements Document, to be issued in accordance to ECSSQ-00A shall apply.	Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Yaseen Al-Taie	Last modified: 13 FEB 2019

VAPE-REQ-REGU-0100					
Description	The probe shall adhere to IADC mitigation guidelines		Time/Level of Verification		
Comment	Design the mission to eliminate the possibility of leaving space debris by ensuring we have enough delta-V to de-orbit at the end of life.		Nature of Verification		
Rationale	We need to make sure our mission does not contribute to any space debris.		Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Jacob Samson	Last modified	13 FEB 2019

VAPE-REQ-REGU-0110					
Description	The launch vehicle orbital stages shall minimize the potential for break-ups during operational phases		Time/Level of Verification		
Comment	The space craft propulsion will have to be tested and orbit calculations performed to make sure we have enough delta-V.		Nature of Verification		
Rationale	The mission shall be designed to avoid failure modes which may lead to accidental break-ups. In cases where a condition leading to such a failure is detected, disposal and passivation measures shall be planned and executed to avoid break-ups.		Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Jacob Samson	Last modified	13 FEB 2019

VAPE-REQ-REGU-0120					
Description	The mission shall comply with outgassing standards.		Time/Level of Verification	Full system integration	
Comment			Nature of Verification	TVAC and vibration testing	
Rationale	Depending on which materials are selected, there are regulations on outgassing that must be met.		Version	V-1.0	
Written on	05 FEB 2019	Initial Author	Michael Tabascio	Last modified	13 FEB 2019

Programmatic requirements

<table>
<tr><td rowspan="4">VAPE-REQ-PROG-0010</td><td>Description</td><td>The mission shall be launched in the next TBD years.</td><td>Time/Level of Verification</td><td></td></tr>
<tr><td>Comment</td><td></td><td rowspan="2">Nature of Verification</td><td rowspan="2"></td></tr>
<tr><td rowspan="2">Rationale</td><td rowspan="2">Our mission deals with the effects of the accelerated greenhouse effect. For implementation to the current state of our effect, retrieval of this data should happen in a timeframe that is beneficial for us to look at the results to allow us to change our effect.</td></tr>
<tr><td>Version</td><td>V-1.0</td></tr>
<tr><td></td><td>Written on</td><td>05 FEB 2019</td><td>Initial Author</td><td>Michael Tabascio</td><td>Last modified</td><td>Written on</td></tr>
</table>

<table>
<tr><td rowspan="4">VAPE-REQ-PROG-0020</td><td>Description</td><td>The mission budget shall be of a sum of TBD CAN.</td><td>Time/Level of Verification</td><td></td></tr>
<tr><td>Comment</td><td>Looking at similar missions will allow to come up with a cost that will be comparable to the cost of our mission.</td><td rowspan="2">Nature of Verification</td><td rowspan="2"></td></tr>
<tr><td rowspan="2">Rationale</td><td rowspan="2">Need to set and meet budget constraints. Important for getting the project approved.</td></tr>
<tr><td>Version</td><td>V-1.0</td></tr>
<tr><td></td><td>Written on</td><td>05 FEB 2019</td><td>Initial Author</td><td>Michael Tabascio</td><td>Last modified</td><td>Written on</td></tr>
</table>

<table>
<tr><td>VAPE-REQ-PROG-030</td><td>Description</td><td>The mission phases shall be composed of:
• Launch
• Low Earth Orbit (LEO)
• Interplanetary hibernation
• Venus rendezvous
• Atmosphere penetration</td><td>Time/Level of Verification</td><td>Full spacecraft integration</td></tr>
</table>

		• Science phase • Decommission				
	Comment	These follow figure of mission profile		Nature of Verification	Verification of organisation schemes prior to launch.	
	Rationale	Dividing the mission into phases will help organise teams, activities, and procedures.				
				Version	V-1.0	
	Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	Written on

VAPE-REQ-PROG-040	Description	All scientific data received by the ground station shall be published on-line in raw form starting in LEO.		Time/Level of Verification	Flat-sat	
	Comment	Telemetry that constitutes scientific data is TBD.		Nature of Verification	Run test(s) of [semi-automated] process to publish telemetry	
	Rationale	Satisfy mission objective of “providing in situ measurements” and meet concept of operations outlined in Preliminary Mission Solution presentation.		Version	V-1.0	
	Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	Written on

VAPE-REQ-PROG-050	Description	The payload MDS shall operate using the local Venus solar time of the location in enters the atmosphere.		Time/Level of Verification	Flat-sat	
	Comment	This means a time conversion algorithm is needed.		Nature of Verification	Run test(s) of automated processes using VST.	
	Rationale	Allows for the synchronisation of science activities with the local position of the Sun on Venus.		Version	V-1.0	
	Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	Written on

Mission (space) phases

The VAPE mission is divided into four different phases. These are the parts of the mission that take place once the design solution is in space. The first is the **travel phase**. The spacecraft is launched in orbit about the Earth and placed into a Hohmann transfer trajectory to Venus. Next is the **deployment phase,** where the spacecraft shall enter a polar orbit around Venus and deploy its probe to descend into the atmosphere. This is followed by the **science phase.** During this part of the mission the probes and spacecraft will take a variety of measurements in the atmosphere. The last phase in the **communication phase** in which the probes transmit the scientific data that they gather from the Venusian atmosphere to the orbiter. In turn, the spacecraft relays it to Earth.

Delta-V calculations

As part of visualising the mission concept and different mission phases, the VAPE team simulated the launch and trajectory with two different software: STK and KSP. STK was used as an engineering tool to create the trajectory. STK is an astrodynamics simulation software that can render and solve for key parameters of interest. It was used to gather more precise delta-v figures for key mission events. KSP was used more qualitatively to assess the overall mission concept and to provide visually appealing renders of mission events.

To begin designing the delta-v budget, the VAPE team first calculated the necessary delta-v for the Earth-Venus HTO. The parameters needed as input were: semi-major axis of celestial bodies ($a_{\oplus}$, $a_{♀}$), radius of celestial bodies ($R_{\oplus}$, $R_{♀}$, $R_{\odot}$), mass of celestial bodies ($M_{\oplus}$, $M_{♀}$, $M_{\odot}$), standard gravitational parameters ($\mu_{\oplus}$, $\mu_{♀}$, $\mu_{\odot}$), orbital period of celestial bodies ($\tau_{\oplus}$, $\tau_{♀}$), orbital inclination of Venus ($i_{♀}$) and latitude of launch site (λ):

$$
\begin{aligned}
&a_{\oplus} = 1AU \\
&a_{♀} = 0.723332AU \\
&1AU = 149597870.70km \\
&R_{\odot} = 69570.00km \\
&R_{♀} = 6051.80km \\
&R_{\oplus} = 6378.14km \\
&M_{\odot} = 1.9885 \times 10^{30}kg \\
&M_{♀} = 4.8675 \times 10^{24}kg \\
&M_{\oplus} = 5.9723 \times 10^{24}kg \\
&\mu_{\odot} = 1.32712440018 \times 10^{11}km^3/s^2 \\
&\mu_{♀} = 324859.9000km^3/s^2 \\
&\mu_{\oplus} = 398600.4418km^3/s^2 \\
&\tau_{♀} = 224.701\ days \\
&\tau_{\oplus} = 365.250\ days \\
&i_{♀} = 3.39458^{\circ} \\
&\lambda = 28.5^{\circ}
\end{aligned}
$$

The first manoeuvre to be considered is a plane change. This is used to align VAPE's orbital plane with that of Venus:

$$let\ a_{LEO} = 6878.14km,$$

$$
\begin{aligned}
&v_{LEO} = \sqrt{\frac{\mu_{\oplus}}{a_{LEO}}} = \sqrt{\frac{398600.4418}{6878.14}} \\
&v_{LEO} = 7.61km/s
\end{aligned}
$$

$$
\begin{aligned}
&\Delta v_i = 2v_{LEO}sin(\frac{i_{♀}}{2}) = 2(7.61)sin(\frac{3.39458}{2}) \\
&\Delta v_i = 0.45km/s
\end{aligned}
$$

After aligning the orbit plane with Venus, VAPE now needs to escape Earth to start a Hohmann transfer:

$$v_{esc} = \sqrt{\frac{2\mu_\oplus}{a_{LEO}}} = \sqrt{\frac{2(398600.4418)}{3878.14}}$$
$$v_{esc} = 10.77 km/s$$

$$\Delta v_{esc} = v_{esc} - v_{LEO} = 10.77 - 7.61$$
$$\Delta v_{esc} = 3.16 km/s$$

After executing the Earth escape burn, VAPE will coast until out of the Earth's SOI.

$$r_{SOI\oplus} = a_\oplus \left(\frac{M_\oplus}{M_\odot}\right)^{\frac{2}{5}} = 149597870.70\left(\frac{5.9723\times10^{24}}{1.9885\times10^{30}}\right)^{\frac{2}{5}}$$
$$r_{SOI\oplus} = 924495.72 km$$

Once at this point, VAPE will begin burns to commence the Earth-Venus Hohmann transfer. The delta-v's are calculated below:

$$a_{HTO} = \frac{a_\oplus + a_♀}{2} = \frac{1AU + 0.723332AU}{2}$$
$$a_{HTO} = 128903398.85 km = 0.861666 AU$$

$$v_\oplus = \sqrt{\frac{\mu_\odot}{a_\oplus}} = \sqrt{\frac{1.32712440018\times10^{11}}{149597870.70}}$$
$$v_\oplus = 29.78 km/s$$

$$v_{HTO\oplus} = \sqrt{\mu_\odot\left(\frac{2}{a_\oplus} - \frac{1}{a_{HTO}}\right)} = \sqrt{1.32712440018\times10^{11}\left(\frac{2}{149597870.70} - \frac{1}{128903398.85}\right)}$$
$$v_{HTO\oplus} = 27.29 km/s$$

$$v_♀ = \sqrt{\frac{\mu_\odot}{a_♀}} = \sqrt{\frac{1.32712440018\times10^{11}}{149597870.70}}$$
$$v_♀ = 35.02 km/s$$

$$v_{HTO♀} = \sqrt{\mu_\odot\left(\frac{2}{a_♀} - \frac{1}{a_{HTO}}\right)} = \sqrt{1.32712440018\times10^{11}\left(\frac{2}{108208927.01} - \frac{1}{128903398.85}\right)}$$
$$v_{HTO♀} = 37.73 km/s$$

$$\Delta v_1 = v_{HTO\oplus} - v_{\oplus} = 27.29 - 29.78$$
$$\Delta v_2 = v_{♀} - v_{HTO\oplus} = 35.02 - 37.73$$

$$\Delta v_1 = -2.50 km/s$$
$$\Delta v_2 = -2.71 km/s$$

As seen, both burns required are negative. This means that VAPE will need will to provide these in the retrograde direction. This is because Venus is closer to the Sun, not further than Earth. An important parameter for mission planning would be the amount of time required to synchronise the Earth and Venus. Phasing of the two planets is very important. If the Hohmann transfer is completed without the planets having the correct phase, VAPE will arrive at Venus' orbit either before or after Venus does. For this reason, it is important to calculate the synchronisation time, $\tau_{syn\oplus♀}$.

$$\tau_{syn\oplus♀} = \frac{\tau_{\oplus}\tau_{♀}}{|\tau_{\oplus} - \tau_{♀}|} = \frac{365.25 \cdot 224.70}{|365.25 - 224.70|}$$
$$\tau_{syn\oplus♀} = 583.93\ days$$

This means that approximately every 584 days, Venus and the Earth are aligned for launch opportunities. Another key characteristic for launch would be the launch azimuth. As VAPE is launching from Cape Canaveral, FL the minimum inclination of our orbit will be 28.5833° (this is the latitude of the launch site). To launch into an orbit that takes the inclination of Venus (in regard to the ecliptic) into account would require the LV to point not completely East. The calculation for the launch azimuth is below:

$$cos i = cos\lambda sin A$$

$$i = Earth\ tilt + i_{♀} = 23.43 + 3.39$$
$$i = 26.82°$$

$$A = sin^{-1}\left(\frac{cos i}{cos\lambda}\right) = sin^{-1}\left(\frac{cos(26.82)}{cos(28.5833)}\right)$$
$$A = undef$$

We can see here that the launch azimuth is undefined. This is because the desired orbit inclination is below that of the launch minimum (that is the launch latitude). This means to change VAPE's inclination, a plane change manoeuvre will need to be performed at the ascending or descending node (points on the orbit plane that cross the equator). The figures calculated above serve as a starting point for creating the delta-v budget. To finalise it, these results were fed into STK. More accurate figures were obtained using STK's 'target sequence' tool. This is a numerical solver used to calculate parameters based on desired conditions. For more on the STK scenario, please read the Trajectory Design with STK/Astrogator section of the report. The computed values from STK would be more correct than what has been calculated above. This is because STK will take into consideration gravitational perturbations (such as J2 and J4), as well as nutation, precession and n-body physics.

Maneuvre	**Delta-v [km/s]**
First Hohmann Transfer Burn [Retrograde]	2.50
Second Hohmann Transfer Burn [Retrograde]	2.71
Venus Capture	12.28
Margin (25%)	4.37
Total	**21.86**

Table 3 – Delta-v budget summary

Mission Events

As mentioned earlier, to fully visualise key mission events, a software called KSP was used. Below are various images from KSP and explanations as to what event is being captured.

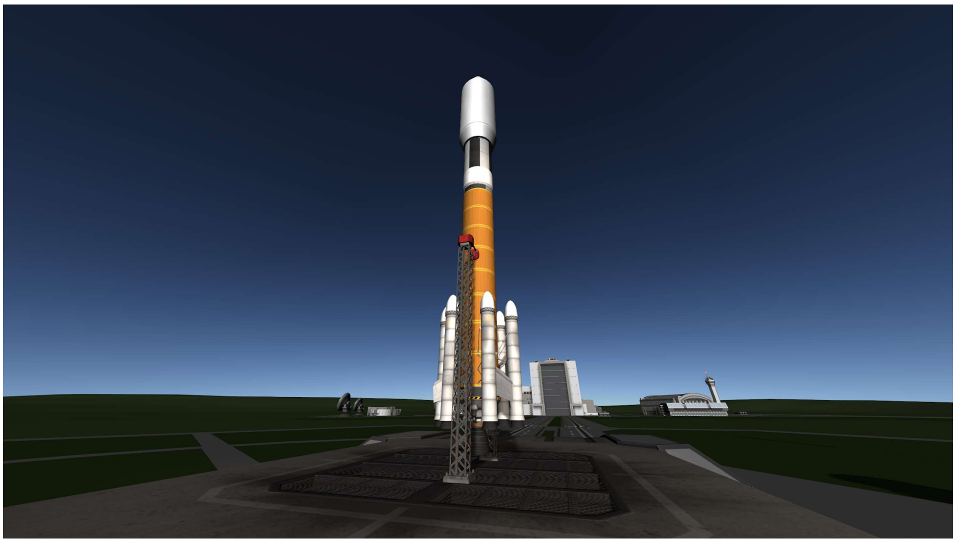


Figure 1 - Atlas V 551 at KSC launch pad

This image shows a mock Ares V 551 ready to launch at KSC. We can see the different sections of the LV that include the SRB’s, the main stage rocket engine and orange fuel tank, the second stage fairing with the upper Centaur stage and finally the payload fairing. Enclosed is the VAPE satellite with the daughter ships and all instruments on board.

Figure 2 - Atlas V 551 ascending over KSC

Figure 2 shows Ares V shortly after launch. The SRB and main core engine are operating in clear view while KSC begins to disappear in the background. If examined closely, we can begin to see the result of atmospheric forces on the fairing. The condensed air around the fairing indicates the LV going transonic.

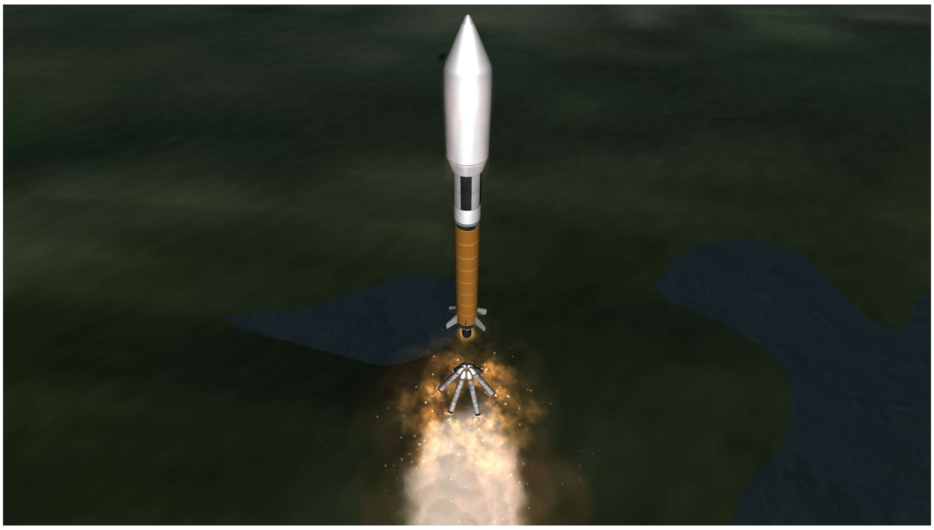


Figure 3 - Atlas V 551 booster separation

The figure above shows the first separation event. Here we can see the SRB's being jettisoned and falling back to Earth as debris. The difference in exhaust gasses can also be seen as now there is a clear difference in the liquid rocket engine and the SRB's.

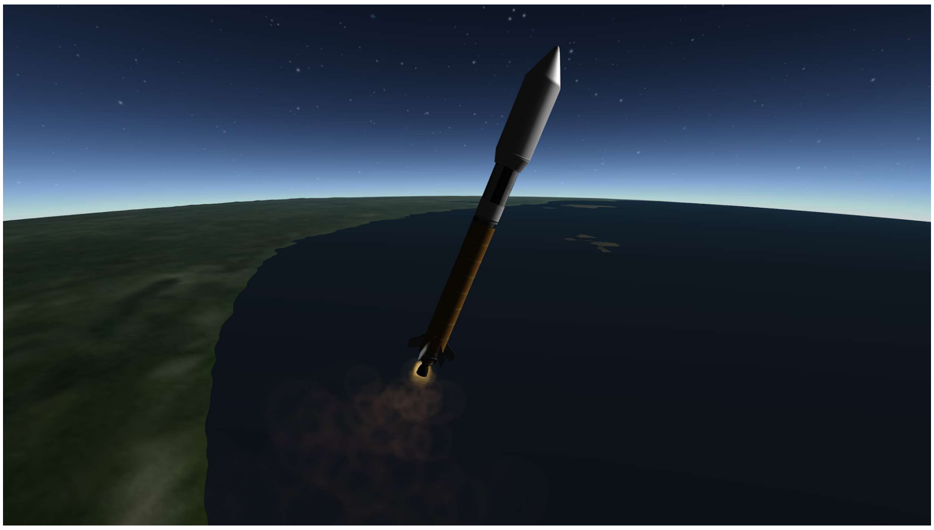


Figure 4 - Atlas V 551 executes a gravity roll

In figure 4 the LV is beginning its gravity roll. By pitching the vehicle, it will begin to gain horizontal velocity. This is crucial as to get into LEO, the vehicle will need to achieve a speed of 7.61km/s. Again, the plume of exhaust gasses is seen to be widening. This is due to a drop in atmospheric pressure allowing the hot gasses to spread more out of the engine bell.

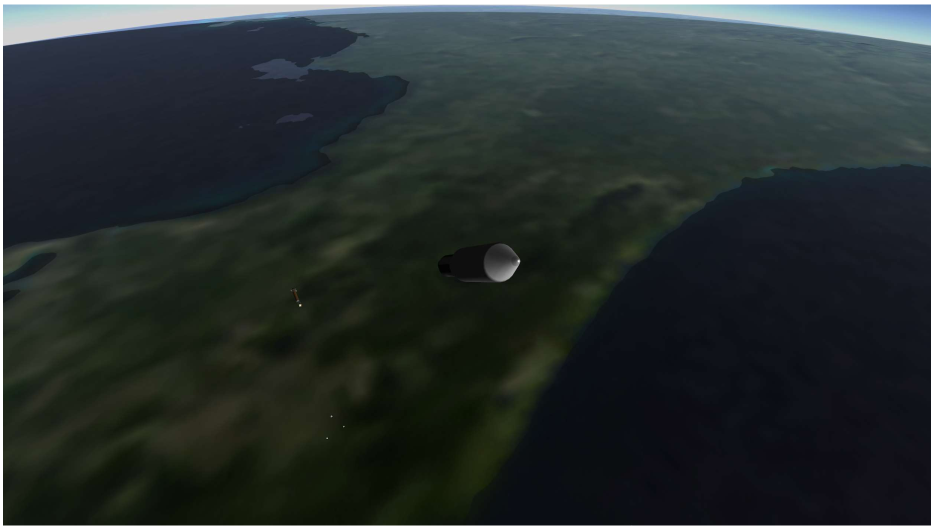


Figure 5 - MECO and main stage separation

Here, two events can be seen, MECO and main stage separation. In the distance, the main stage is seen falling back to Earth. We can also begin to make out the state of Florida with the Gulf of Mexico to the left and the Atlantic Ocean to the right.

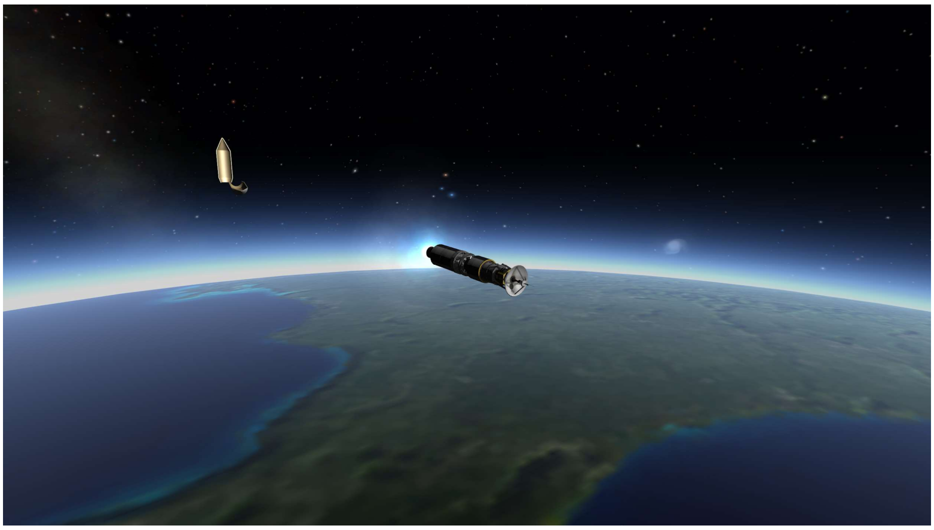


Figure 6 - Fairing separation and second stage ignition

Now past the Von Kármán Line, the payload fairing has been jettisoned. Most the atmosphere is now below the LV as indicated by the amount of atmospheric scattering visible and the blackness of outer space. The Centaur stage engine is still firing, adding more Δv to the spacecraft. We can see that the exhaust plume is now very wide and short lived. This is due to the pressure gradient between the exhaust gasses and the vacuum of space.

Figure 7 - VAPE in suborbital path above Earth

Now on a suborbital trajectory around Earth, SECO occurs. The LV will now use its attitude system to point in the correct direction for orbit circularisation. Once complete, the spacecraft will have a semi-major axis of 6878.14km.

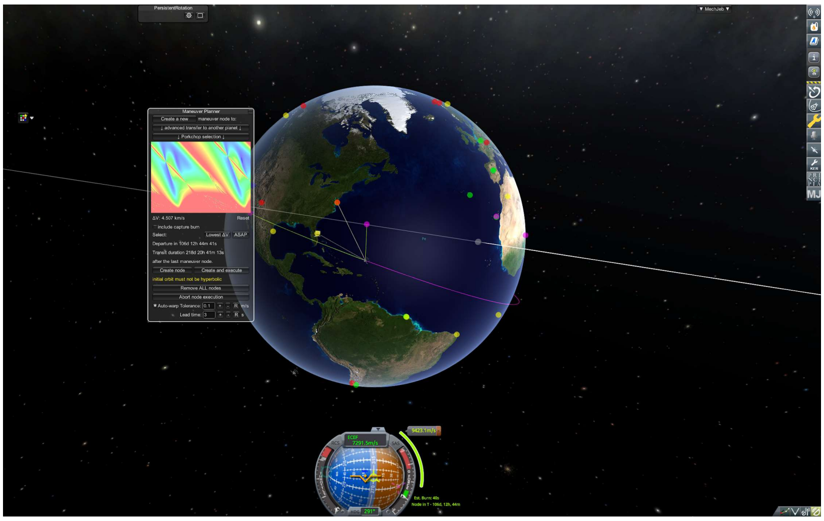


Figure 8 - VAPE in orbit with Porkchop Plot

Once in orbit, the Earth escape burn can be configured. In this image we can see a Porkchop Plot. On the x-axis is time (from present to launch time), on the y-axis is arrival time (increasing in value) and on the z-axis (indicated by colour) is the amount of Δv required. The colour scale is in such a way where hot colours are greater Δv and cool colours are lesser delta-v. The best trajectory would be closest to the left, closest to the bottom and dark blue in colour.

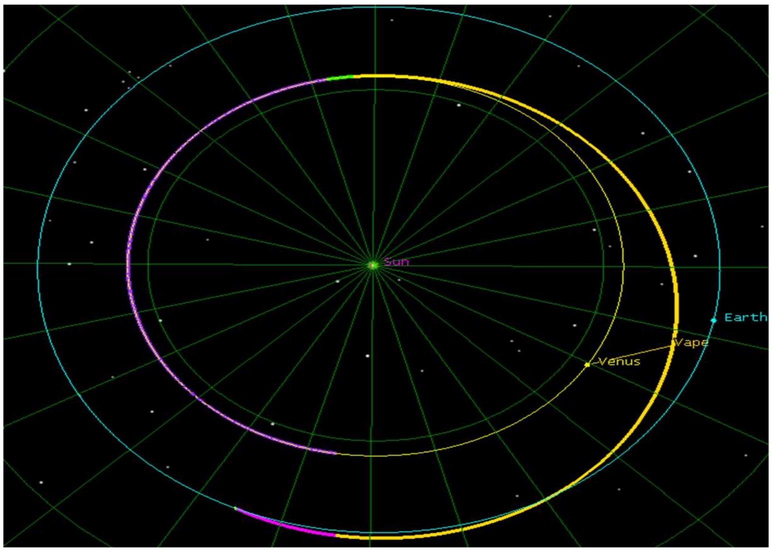


Figure 9 - STK view of solar system with VAPE's interplanetary trajectory

Once outside the Earth's SOI, the Centaur stage would execute the first HTO burn (Δv_1). Next the upper rocket stage separates and VAPE starts its interplanetary coat. The coast is seen in the image above and is indicated by a thick yellow line.

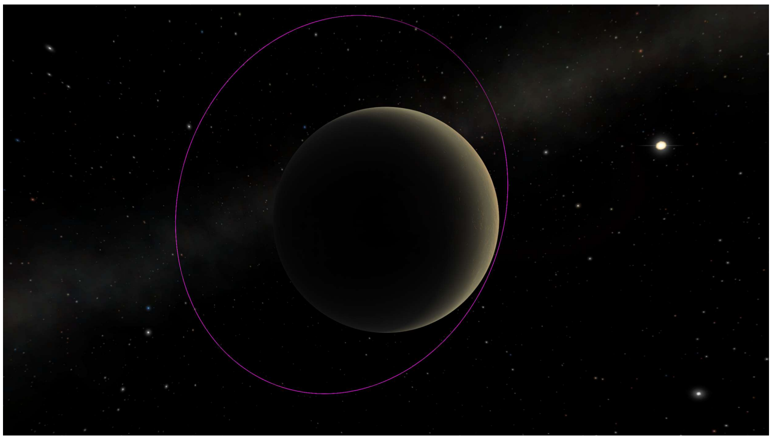


Figure 10 - View of VAPE's final orbit facing the Sun

Here we can see the final orbit of VAPE around Venus after Venusian capture. We can see that the orbit parameters match our desired with an inclination of ~89° and a semi-major axis around $10290.67\ km$.

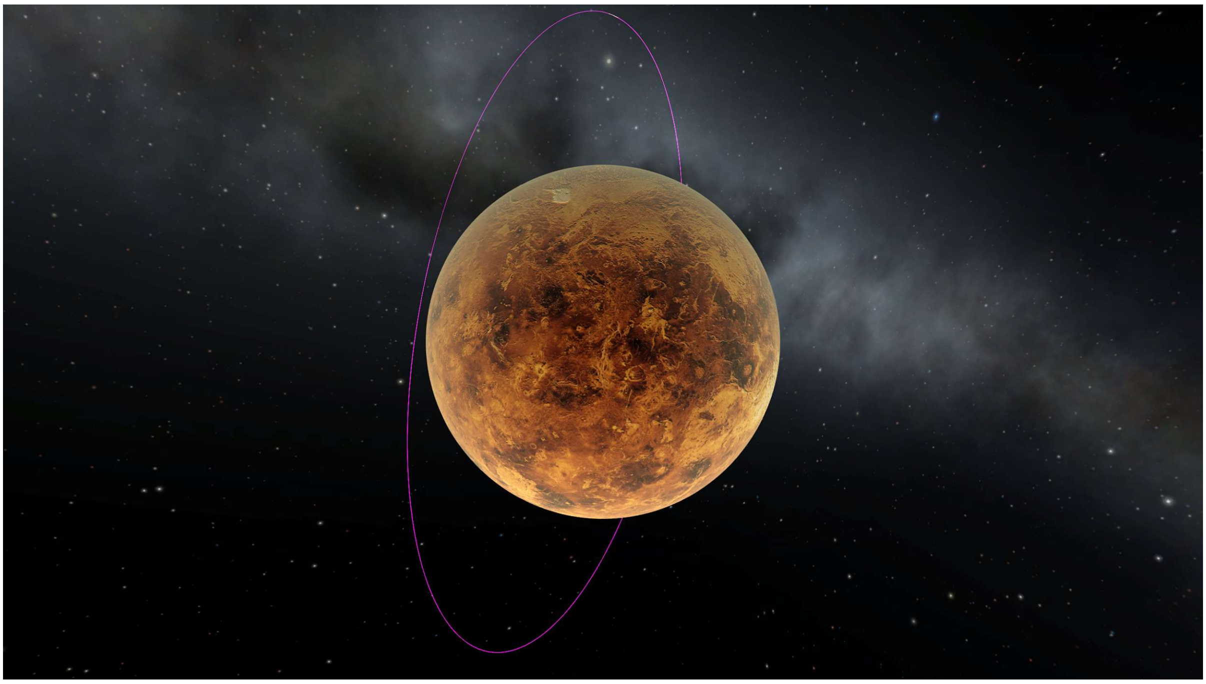


Figure 11 - View of VAPE's final orbital facing away from Sun

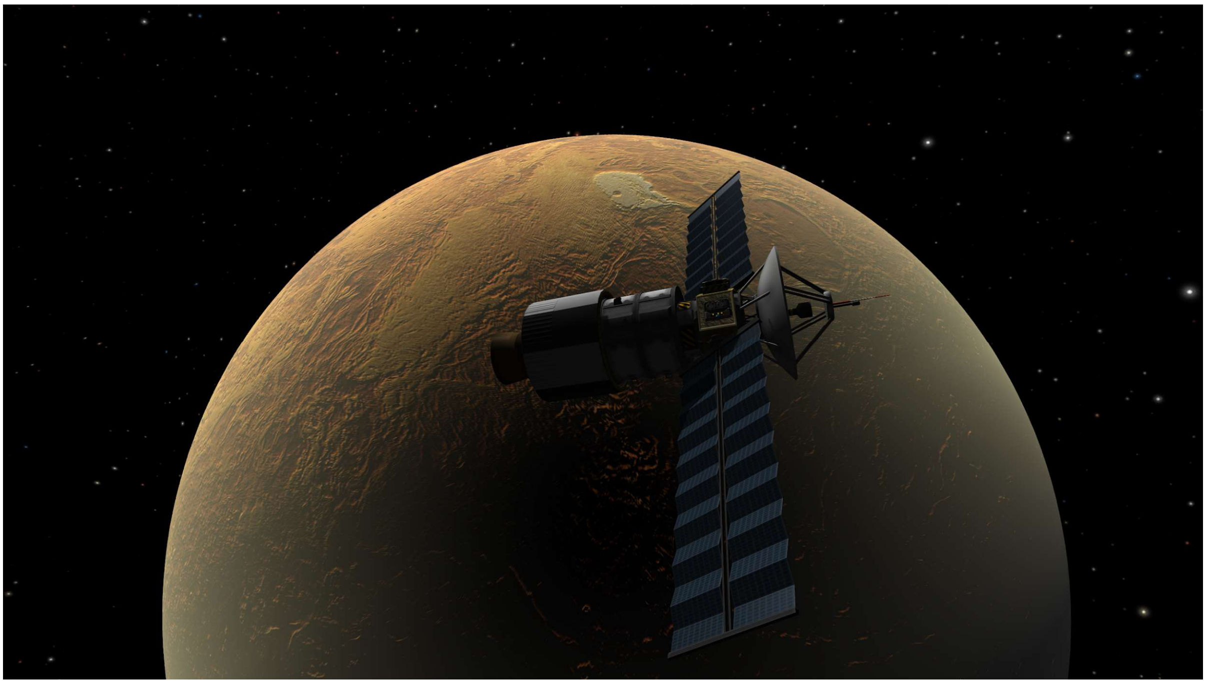


Figure 12 - VAPE in orbit around Venus

In the two images above, we can see the final VAPE orbit (away from Sun here) and a close-up of VAPE in orbit near the North pole of Venus. Below is another view with VAPE's position indicated as well as the periapsis and apoapsis.

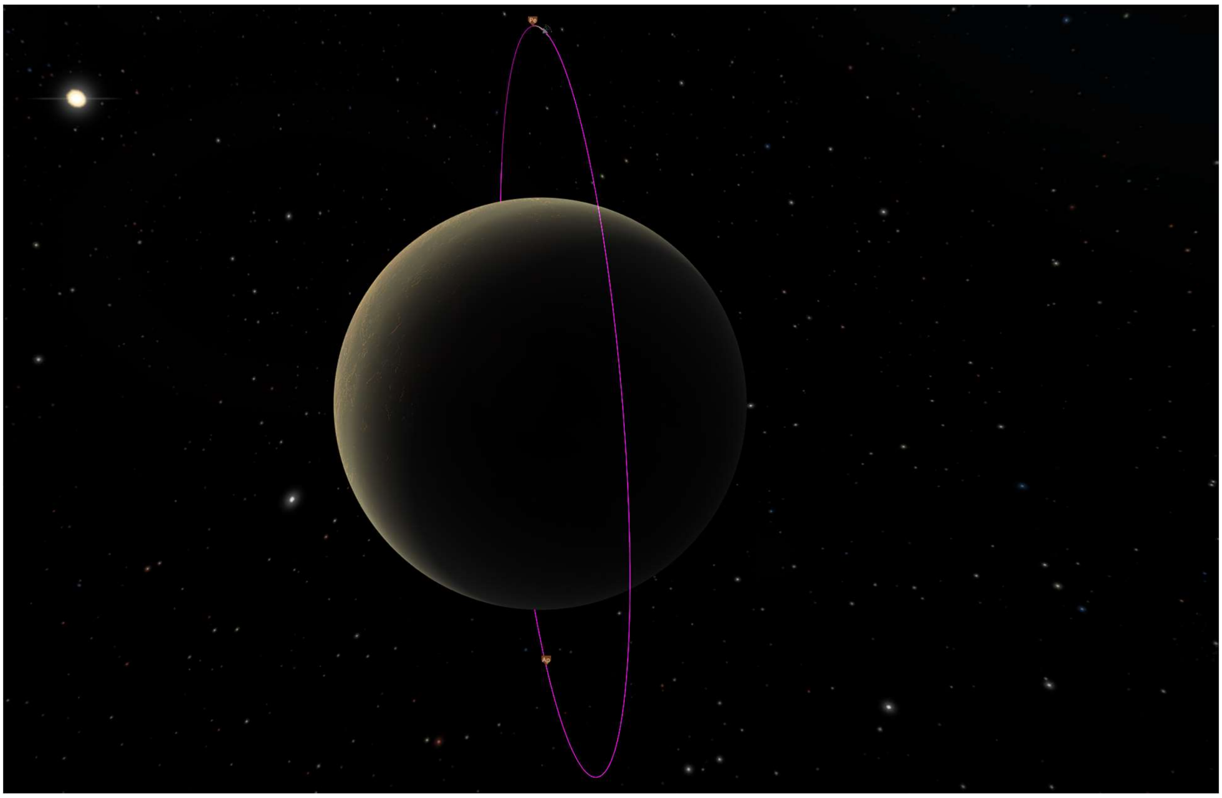


Figure 13 - VAPE’s final orbit with VAPE’s position, apoapsis and periapsis indicated

Trajectory design with STK/Astrogator

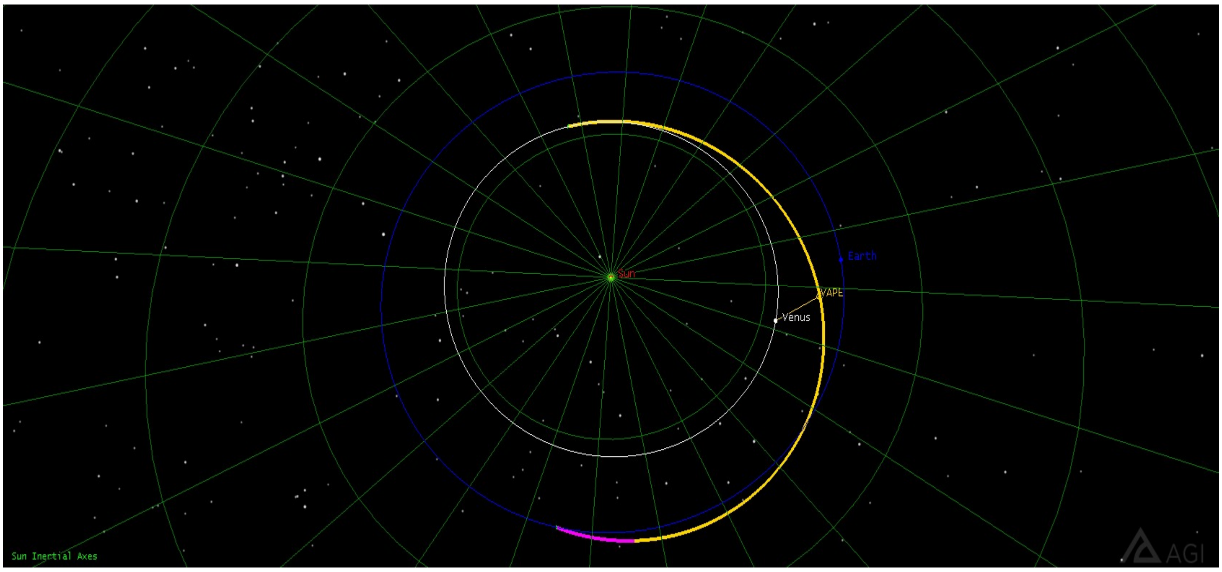


Figure 14 - Main graphics window in STK

In this mission, we will model a mission to Venus. Starting from the earth, we will:

- Use the target vector outgoing asymptote parameters to specify our outgoing state.
- Use a trajectory correction manoeuvre to target Venus approach.
- Coast to Venus periapsis
- Perform an impulsive Venus Orbit Insertion (VOI) manoeuvre.
- Circularize our orbit at 89 degrees.

In order to implement these procedures, we need to use a TCM manoeuvre in a mission control sequence, used multiple profiles to achieve our desired parameters, used constraints to help us target and created a trajectory that leaves the Earth enters heliocentric space, and then orbits Venus. For our mission we need to specify an appropriate time for the launch to make it to Venus's orbit. So, the time period for the mission should be, **25 Aug 2029 to 1 May 2030**.

Building the mission control sequences (MCS)

- Setting our satellite (VAPE) by using the propagator as an Astrogator, in order to let VAPE making the needed manoeuvres for the mission.
- To get to Venus, first we need to adjust our satellite parameters and the location of the launching (Latitude: 27.6648 degrees N, Longitude: 81.5158 degrees W).
- Taking in consideration our Epoch time which is: **25 Aug 2029**
- Adjust the Ascent type to Cubic motion.
- Adjust the burnout for the launch (time of flight, Azimuth, downrange distance and altitude) and (eccentricity and inclination with respect to Earth as a central body)
- Adjust the Fuel tank parameters so we can get out of earth orbit (tank pressure, tank volume, tank temperature, fuel density, fuel mass and maximum fuel mass), all these factors will help us to support our mission in the beginning

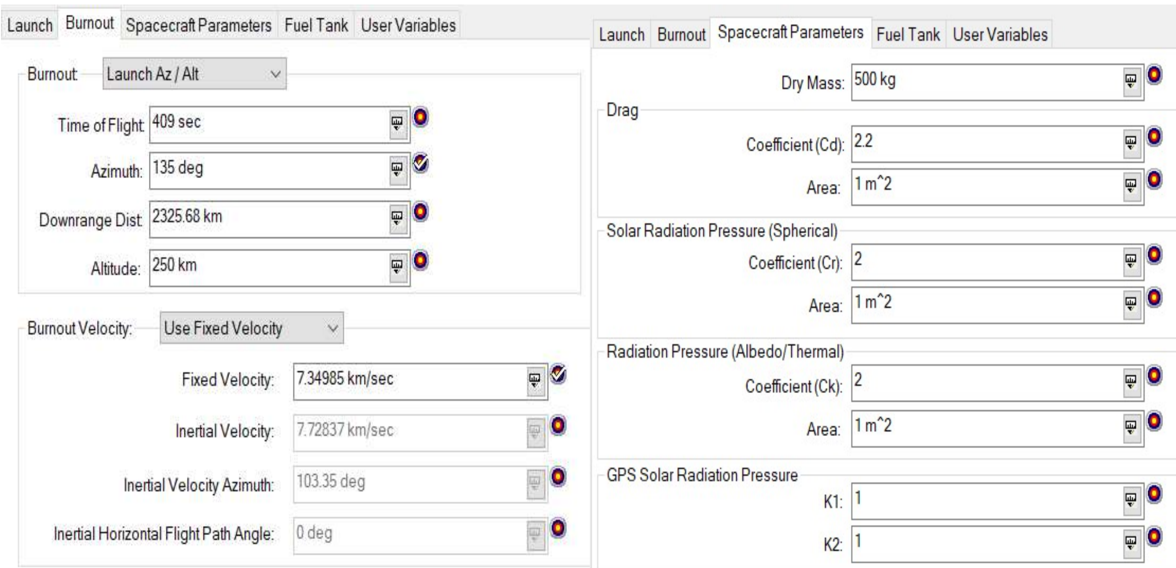


Figure 15 - Values for burnout and spacecraft parameters

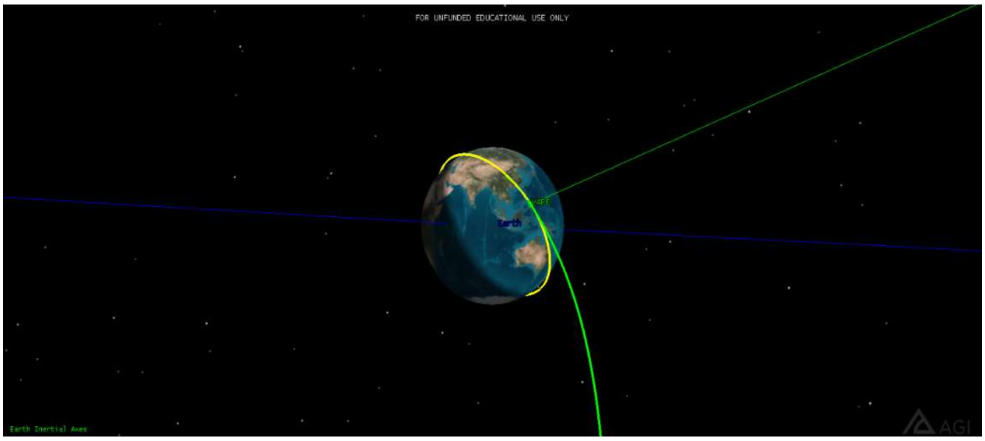


Figure 16 - VAPE trajectory

- As we see above, we have the main orbit around earth (yellow) and then do the push to get out of Earth orbit.
- We add the first manoeuvre (green) for our mission (TVI) with a Delta V magnitude of 3200 m/sec (along velocity vector)
- The manoeuvre has a specific parameter to do the Hohmann transfer orbit
    1. Target Vector: C3 Energy (central body: Earth)
    2. Target Vector: Outgoing Asymptote Dec (corrdSystem: Earth inertial)
    3. Target Vector: Outgoing Asymptote RA (corrdSystem: Earth inertial)
    4. Manoeuvre: Delta-V integrated along path.
    5. Our propagator is in the Earth full RFK
- Propagate to TCM1 (green line)
    1. Our propagator is in the Cislunar
    2. Target Vector: C3 Energy (central body: Earth)
    3. Target Vector: Outgoing Asymptote Dec (corrdSystem: Earth inertial)
    4. Target Vector: Outgoing Asymptote RA (corrdSystem: Earth inertial)
- Making our second Hohmann transfer orbit by using a new propagate (A new Heliocentric) with respect to the sun as a central body (purple line).

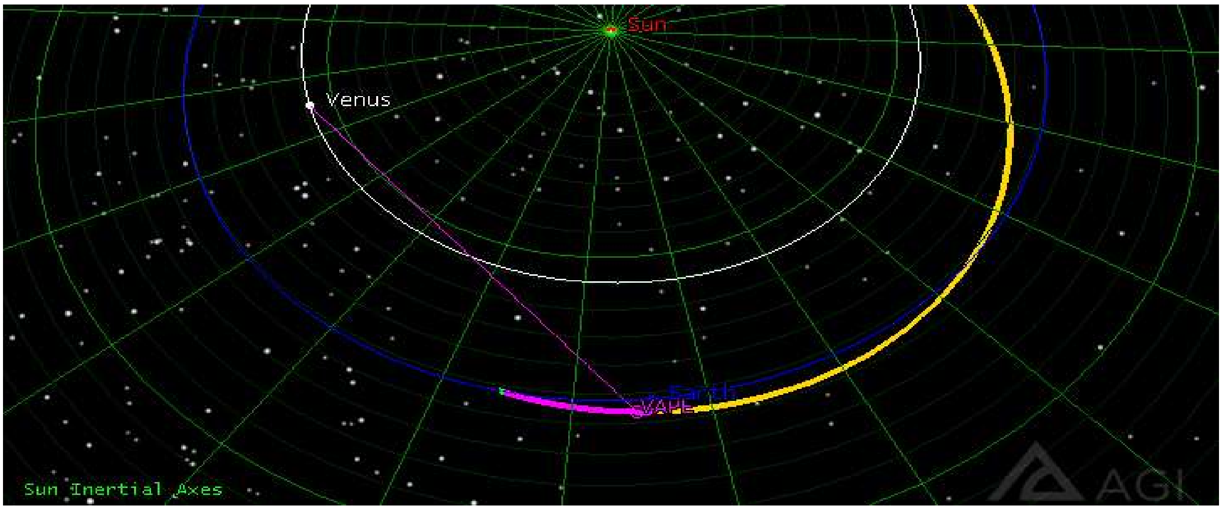


Figure 17 - Hohmann transfer orbit

- After this part, the VAPE needs to burn a lot of fuel to transfer from an orbit to another. In order to achieve that, a thrust vector is applied to the satellite (thrust axes with respect to VNC, sun)
- We are using VNC (sun) as the VAPE is in the middle of Earth and Venus. And taking the sun as a main centre body for VAPE.
- Delta-V is needed to do the transfer between orbits (manoeuvres)
- We constrain our mission when it reaches Venus, periapsis
- Periapsis is added to the new propagator (Heliocentric) as a stopping condition (central body: Venus) (yellow line)
- This is considered as the most important part of mission to let the VAPE goes along with Venus trajectory and this done by using specific conditions,
    1. B-Plane B and R vector dot product (target body: Venus)
    2. B-Plane B and T vector dot product (target body: Venus)
    3. Adjust the Epoch time to reach the right path on the right time
    4. Adjust the altitude above central body

5. Adjust the inclination and the declination of incoming aspides

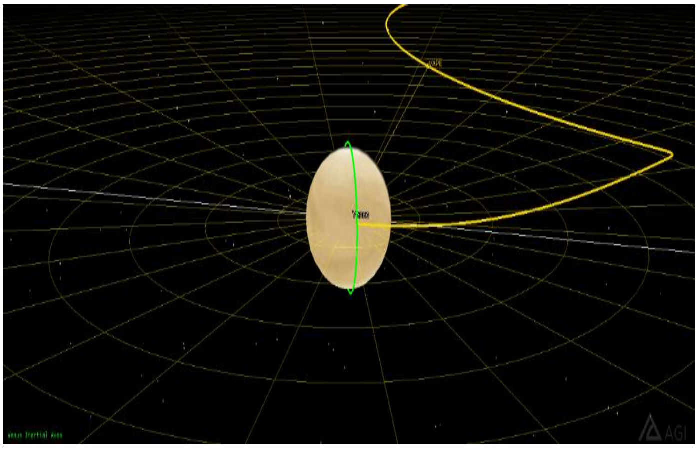


Figure 18 - Trajectory of VAPE approaching Venus

- In order to achieve all these steps above, we will apply some values to the MCS
- Get out of earth orbit and get into Venus orbit.

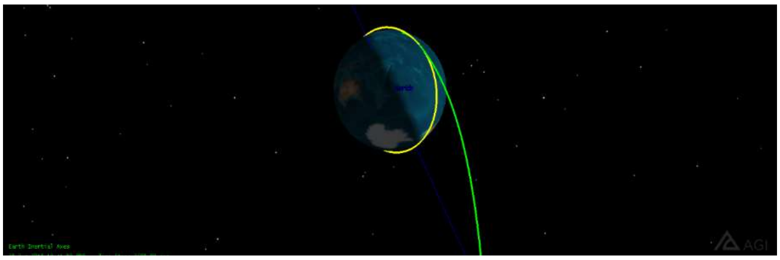


Figure 19 - Manoeuvre and following orbit propagation

1. Circularise

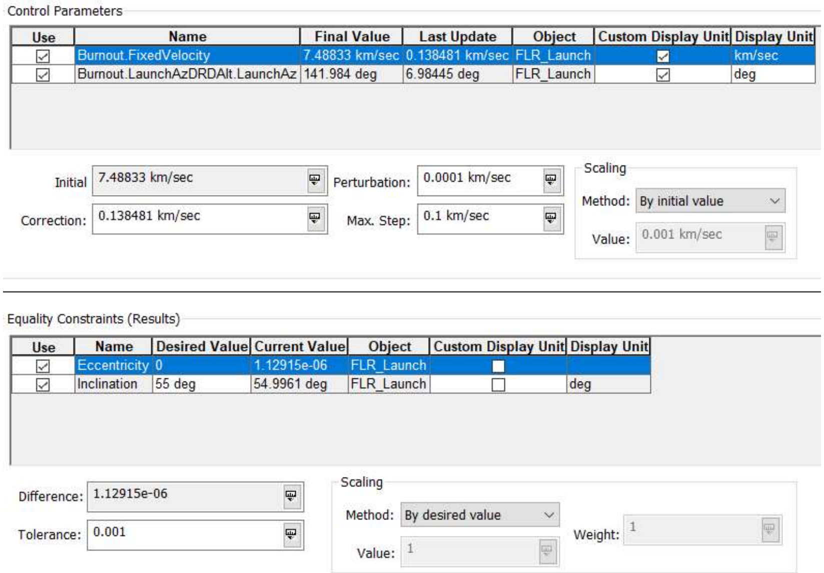


Figure 20 - Parameters for Earth-bound orbit

2. Launch coast burn

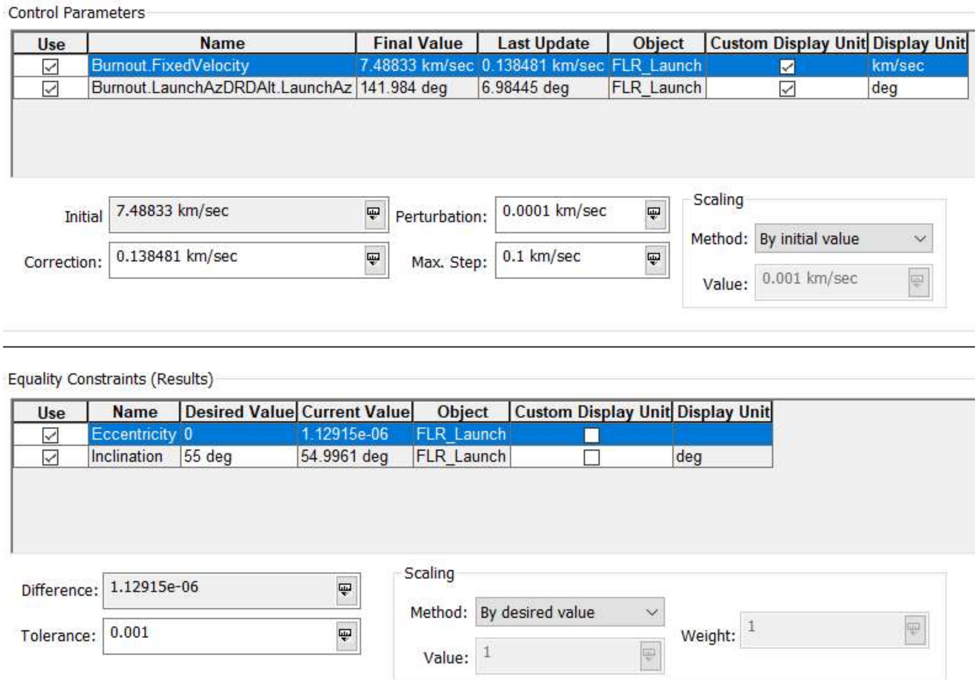


Figure 21 - Values for burnout and launch

3. C3 burn

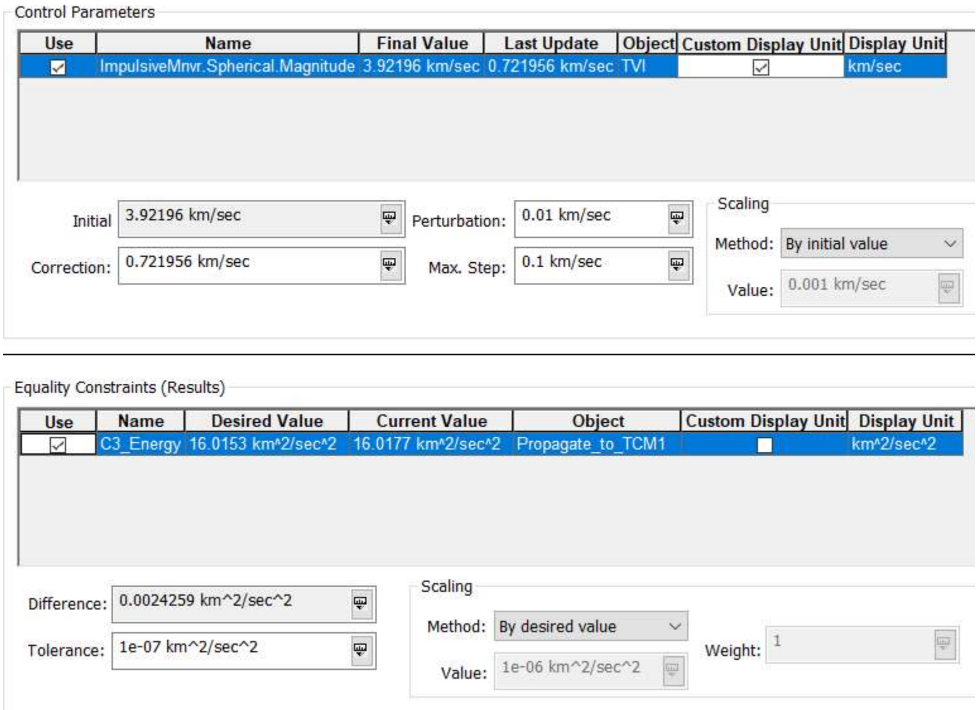


Figure 22 - Energy for push from Earth orbit

4. Time

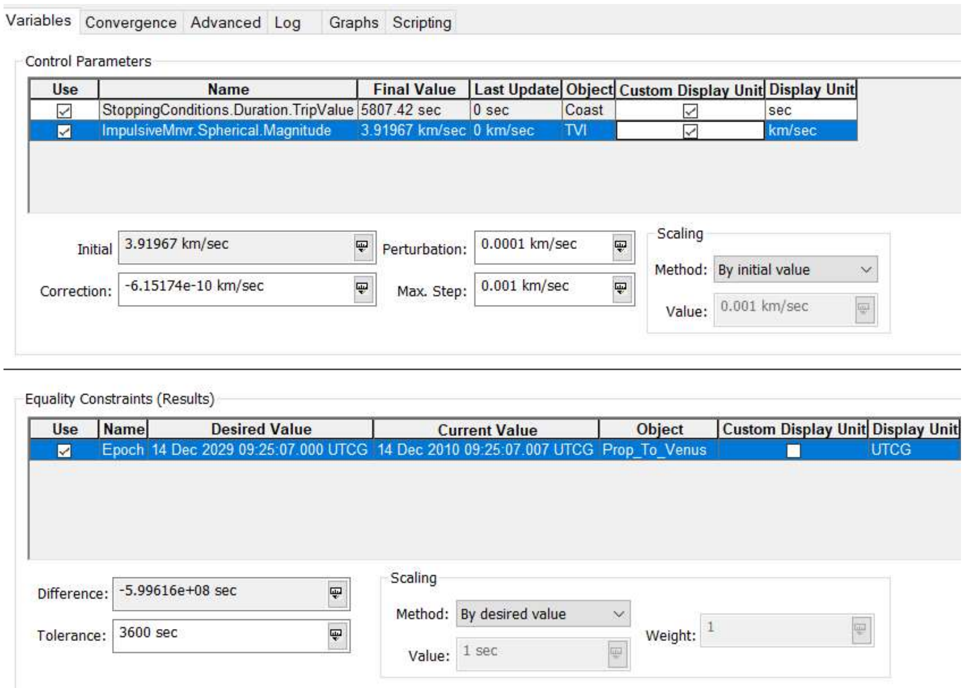


Figure 23 - Values for the time condition

5. B-plane

Now we have an impact trajectory, which is close, but we want to get to orbit. The best way to do that is target the B-plane. The B-plane is a planar coordinate system that allows targeting during a gravity assist or for planetary orbit insertion. It can be thought of as a target attached to the assisting body. If you have a trajectory that is close to the encounter planet, the B-plane gives you targets that behave very linearly, which is important with the differential corrector targeting scheme in Astrogator. [1]

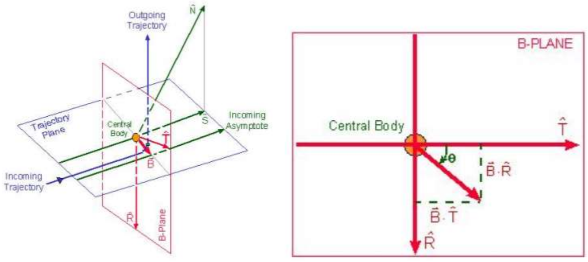


Figure 24 - B-plane method

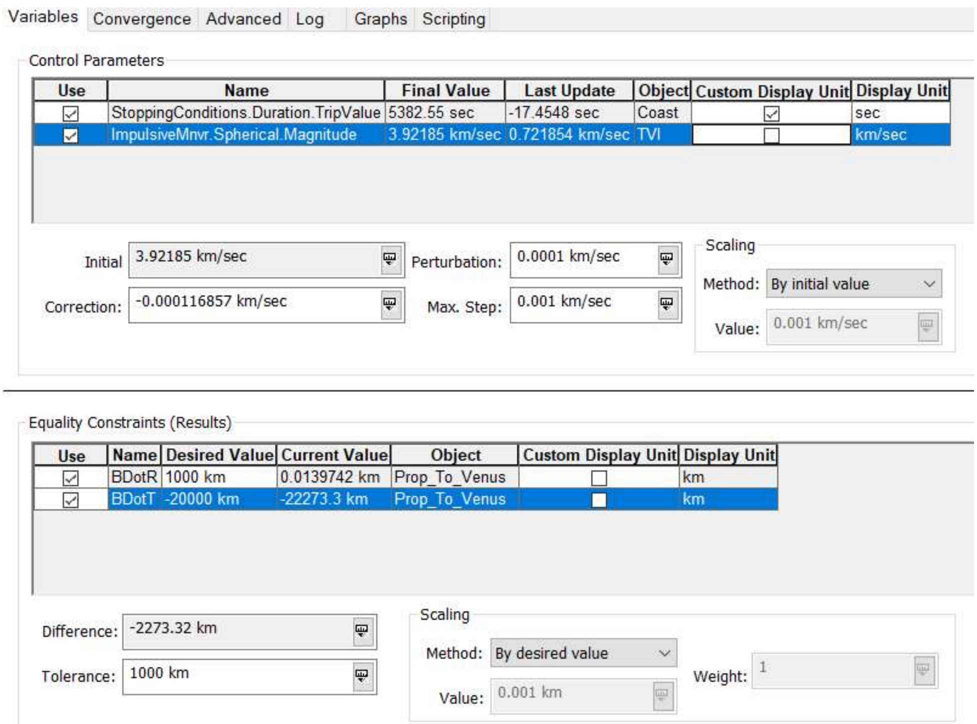


Figure 25 - Values for BDotR and BDotT

6. Altitude

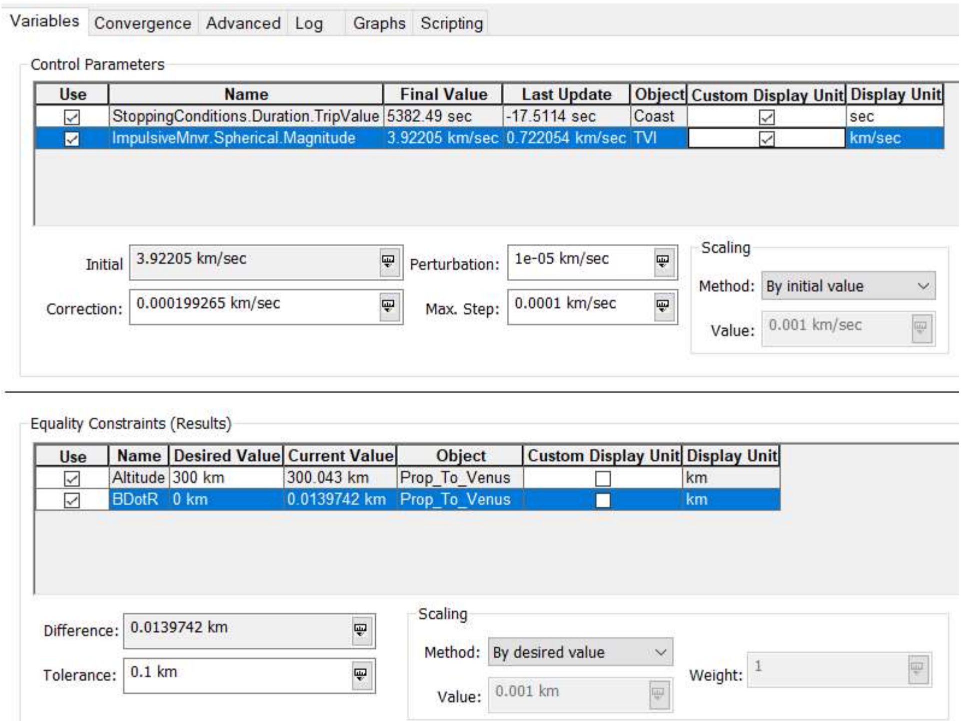


Figure 26 - Values for the altitude applied

Getting into Venus trajectory and insertion into Venus-bound orbit

In this part, we will need to capture the orbit of Venus and that is done by decreasing velocity towards X and Y directions

1. Thrust Axes, VNC(Venus).
2. Adjust the eccentricity
3. Slowdown the C3 energy
4. Slowdown the Delta-V
5. Match with Venus orbit period
6. Adjust the inclination to be 90 degrees
7. We constrain our mission when it reaches Venus, periapsis
8. Periapsis is added to the new propagator (Venus HPOP) as a stopping condition (central body: Venus) (Green line)

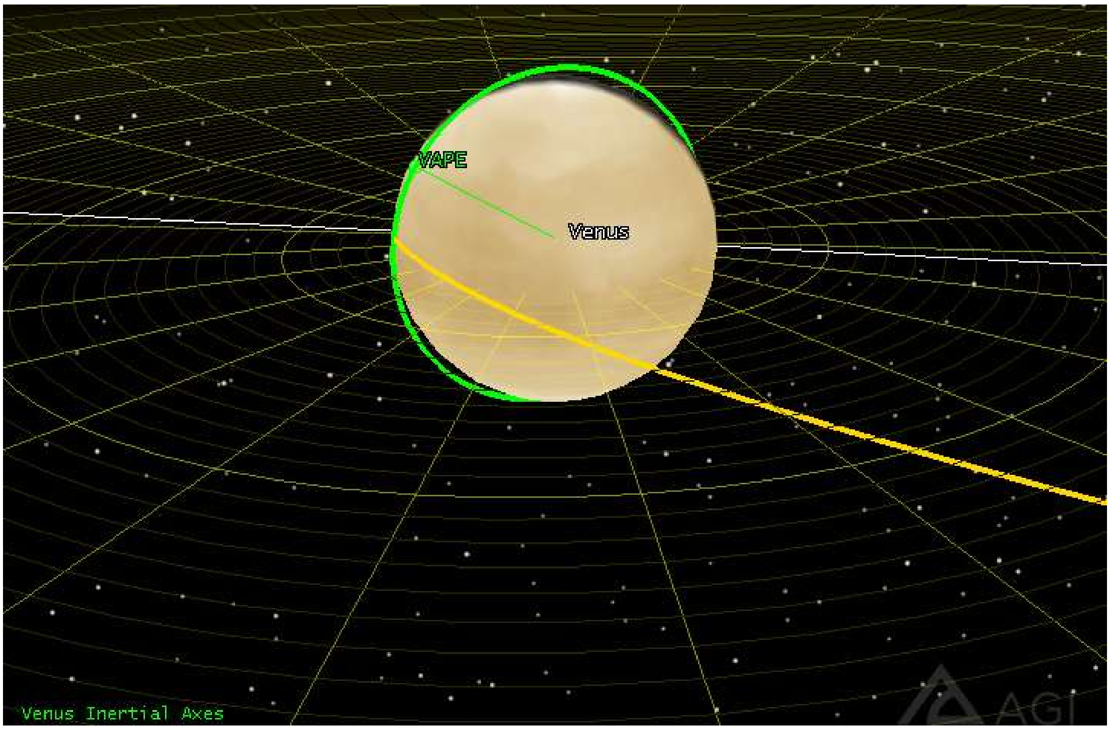


Figure 27 - Orbit about Venus

MCS Summary report

```
State Vector in Coordinate System: Venus Inertial

Parameter Set Type:  Cartesian
         X:    -4239.8700571479794235 km             Vx:        0.6453532485713076 km/sec
         Y:    -4656.1608119049069501 km             Vy:        0.6804734203972366 km/sec
         Z:      830.4079807152747890 km             Vz:        7.1104899362011960 km/sec

Parameter Set Type:  Keplerian
       sma:     6388.6431438031386278 km           RAAN:         227.6593474350365 deg
       ecc:        0.0057602499181513                 w:          7.51209111857262 deg
       inc:         89.84939027707686 deg            TA:     2.898596377980139e-07 deg

Parameter Set Type:  Spherical
 Right Asc:         227.6792078932488 deg     Horiz. FPA:     1.660096877099246e-09 deg
      Decl:         7.512065305463715 deg       Azimuth:        0.1519135462389714 deg
       |R|:     6351.8429626569477477 km            |V|:        7.1720702746227429 km/sec


Other Elliptic Orbit Parameters :
 Ecc. Anom:                         0 deg       Mean Anom:                         0 deg
 Long Peri:         235.1714385536091 deg        Arg. Lat:         7.512091408432258 deg
 True Long:         235.1714388434687 deg        Vert FPA:          89.9999999983399 deg
  Ang. Mom:         45555.86410154356 km^2/sec          p:     6388.4311655627043365 km
        C3:        -50.84938769730888 km^2/sec^2   Energy:        -25.42469384865444 km^2/sec^2
   Vel. RA:         46.51736815742902 deg       Vel. Decl:         82.48640761901046 deg
 Rad. Peri:     6351.8429626569486572 km        Vel. Peri:        7.1720702746227429 km/sec
  Rad. Apo:     6425.4433249493276890 km         Vel. Apo:         7.089917659790863 km/sec
 Mean Mot.:       0.06395240279196272 deg/sec
    Period:         5629.186461861028 sec          Period:         93.81977436435047 min
    Period:         1.563662906072508 hr           Period:       0.06515262108635449 day
             Time Past Periapsis:                            0 sec
        Time Past Ascending Node:           116.1201722387236 sec
   Beta Angle (Orbit plane to Sun):         -59.7816231344369 deg
Mean Sidereal Greenwich Hour Angle:           224.22286401021 deg

Planetodetic Parameters:
  Latitude:         7.512065305463715 deg
 Longitude:        -127.2037901064082 deg
  Altitude:      300.0429626569487027 km
Planetocentric Parameters:
  Latitude:         7.512065305463715 deg
 Longitude:        -127.2037901064082 deg
```

Figure 28 - Final stage parameters for VAPE [1/2]

```
Spacecraft Configuration:
      Drag Area:  1 m^2
       SRP Area:  1 m^2
       Dry Mass:  500 kg
      Fuel Mass:  500 kg
     Total Mass:  1000 kg
Area/Mass Ratio:  1e-09 km^2/kg
  Tank Pressure:  5000                        Pa
   Fuel Density:  1000                        kg/m^3
             Cr:  2.000000
             Cd:  2.200000
 Rad Press Area:  1 m^2
Rad Press Coeff:  2.000000


User-selected results:
    Eccentricity =        0.0057602499181513
    C3 Energy =      -50.8493876973088774 km^2/sec^2
    Venus Orbit Period =      5629.1864618610279649 sec
    DeltaV =       12.2796592371535223 km/sec
    Inclination =         89.84939027707686 deg
```

Figure 29 - Final stage parameters for VAPE [2/2/]

Global statistics	No.	Segment	Est./Act. Finite Burn Duration (sec)	Delta-V (m/sec)	Fuel Used (kg)
	1	Get to Venus. TVI	4332.667	3922.053569	736.349
	2	Get to Venus.TCM1	1342.34	423.23	120.52
	3	Capture sequence	5793.425	12279.659237	984.608
Total Est./Act. Finite Burn Duration (sec)			11468.432	16624.94281	
Total Delta-V (m/sec)				16624.94281	
Total Fuel Used					1841.477

Table 4 – Mission results for all manoeuvres

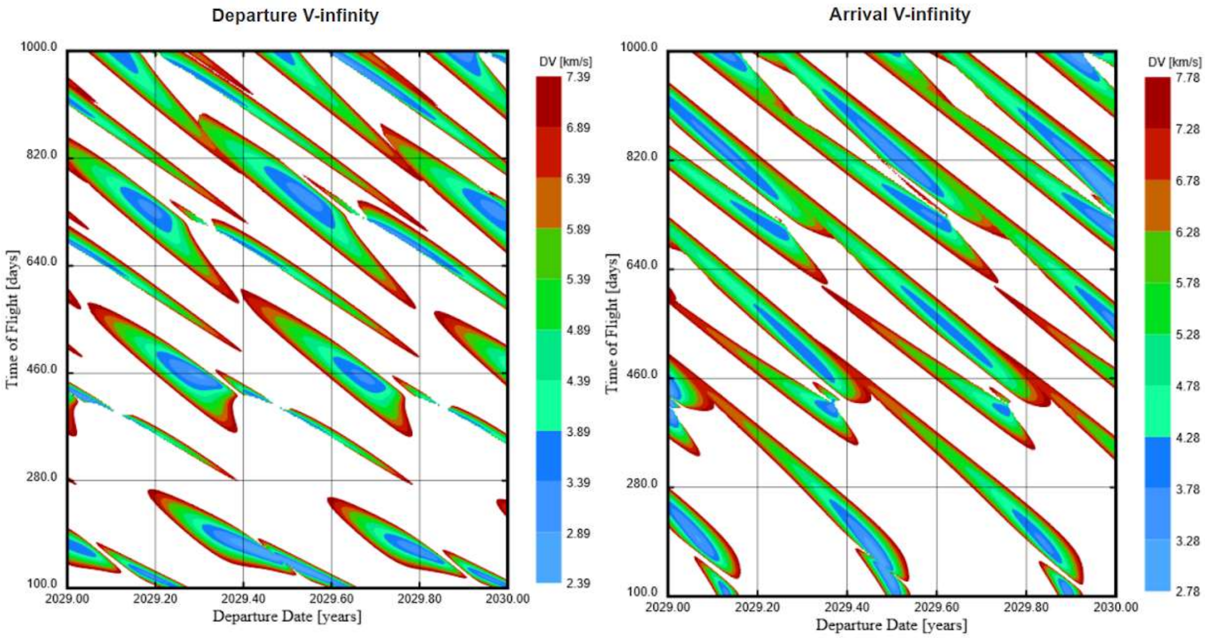


Figure 30 - Departure and arrival times for VAPE

Summarised trade studies

Orbital parameters trade study summary

The purpose of the study is to select an appropriate orbit for the satellite that is suitable for the mission targets or objectives. The study shall include a comparison between several orbits, and we would know the characterises variations of each orbit by doing an analytical solution to the access time, perturbations, radiation environment, power generation and coverage profiles. The final decision shall be proved or supported by some critical data obtained from STK and some calculations.

Constrains

Conjunction of the satellite with the ground station on Earth, Cover latitudes between 85 degrees north and 85 degrees south, the probe restricted to follow Magellan mission, Taking the cost in consideration regarding (material, manoeuvres, etc.…), Scheduling of the mission shall be under the observation as possible as we can. As we would like to reach Venus orbit in a point where the gravity underneath the satellite coverage is weak enough to let the probe orbiting Venus with less perturbations.

Trade study results

To send a spacecraft to an inner planet, such as Venus, the spacecraft is launched and accelerated in the direction opposite of Earth's revolution around the sun until it achieves a sun orbit with a perihelion equal to the orbit of the inner planet. It should be noted that the spacecraft continues to move in the same direction as Earth, only more slowly.

Low inclination orbits smaller range of latitudes make repeated observations over given area and covering around 40% of the planet. The most energy efficient orbit, that is one that requires the least amount of propellant, is low inclination orbit. Sun-synchronous orbit is a geocentric orbit that combines altitude and inclination in such a way that the satellite passes over any given point of the planet's surface at the same local solar time. Such an orbit can place a satellite in constant sunlight and is useful for imaging, spy, and weather. Polar orbit large range of latitudes, data resolution is higher, the circular orbit implies a constant satellite velocity and the near polar orbit allows to cover more than 85% of the planet. Polar orbit is useful for satellites that carry out mapping and surveillance operations because as the planet rotates the spacecraft has access t virtually every point on the planet's surface.

In terms of the access times between the ground stations and the satellite, both orbits (sun-synchronous and polar) provide frequent access times, however, the low inclination orbit provides low rate of access when comparing between the access times. For orbit perturbations, the sun-synchronous orbit is perturbed much less than the low inclination orbit when comparing values. But based on the calculations on STK, polar orbit has the lowest rate of perturbations. However, when comparing the environmental radiation, we figured out that the three orbits will faces almost the same amount of radiation, but the polar orbit is near to the polar of Venus (more radiations would be faced), the proton and electron fluxes on the spacecraft is higher when in a sun-synchronous orbit than when in low inclination orbit. This means that the spacecraft in a sun-synchronous orbit will require more shielding which can drive up the mission cost, same for polar orbit. Also, the power generation for a sun-synchronous orbit is higher than polar orbit and low inclination orbit and that because a sun-synchronous orbit makes the satellite solar panels facing the sun most of the time (more free power, less cost). Finally, the satellite coverage time above Venus for polar orbit is high as it passes over the required altitudes more often than the sun-synchronous orbit and low inclination orbit.

Launch vehicle trade study summary

The LV trade study for the VAPE Mission has several metrics. These are criteria that the chosen solutions will be graded against. They are characteristics that the LV should have to appeal to the mission needs. For this evaluation, they have been decided to be:

- Launch Capability
- Launch Efficiency
- Reliability
- Cost
- Interplanetary Flight Heritage
- In the table below is all the options considered and the scores from each of the metrics desired. For more detail on the LV trade study, please see the Appendix.

Metric	H-IIA	Soyuz-FG/Fregat	Atlas V	Falcon Heavy
Launch Capability (45%)	0.71	0.55	1.33	4.50
Launch Efficiency (20%)	1.87	1.14	2.00	2.00
Reliability (25%)	2.44	2.48	2.47	0.8
Cost (10%)	0.49	1.00	0.32	0.56
Interplanetary Flight Heritage	Yes	Yes	Yes	No
Total	5.51 (Yes)	5.17 (Yes)	**6.12 (**Yes**)**	7.86 (No)

Table 5 – Launch vehicle trade study results

In conclusion, this trade study dealt with the task of performing detailed analysis as to which capable LV to use for the VAPE Mission. This LV would be responsible for the launch event, insertion into a parking orbit, a plane change manoeuvre and the initial burn of a Hohmann transfer to set the spacecraft on a transfer orbit to Venus. Once at its destination, the VAPE satellite will employ its scientific instruments and daughter ships to gather in situ data on the Venusian atmospheric temperature, pressure, composition and the greenhouse effect. The LV's were graded on a basis of 0-10 points in each of the following metrics: launch capability, launch efficiency, reliability, cost and interplanetary flight heritage. With the respective weightings of 45%, 20%, 25% and 10%, the preferred solution was the Atlas V with a score of 61.2%.

Communications trade study summary

The two primary networks that will be considered are NASA's Deep Space Network (DSN) and ESA's ESTRACK. The two networks are very similar between each other. The DSN has 3 communications facilities that are spread out by 120° around the world. 1 in Goldstone California, 1 in Canberra Australia, and 1 in Madrid Spain. Each of these facilities contain 4 antenna dishes each ranging from 14-65m in diameter. These antennas use the Ka, S, and X bands for communication purposes. With all these Venus Atmosphere Penetrating Explorer (V.A.P.E) 6 antennas, the DSN has a service rate of 99% as one antenna in each location is always available for communication purposes. As proven by doing so, the antennas can receive signals as low as -160dBm (Voyager 1 and Voyager 2 for reference). In addition to distinguishing such low power, the antennas also communicate between 128kb/s and 4Mb/s. Unlike the DSN, ESTRACK has stations all over the world including Argentina, Australia, and multiple in Europe allowing for 360° of coverage. This system contains a total of 18 antennas which primarily use the X-bands for deep space communications but are able to use Ka and S bands with certain antennas. By the date of the launch, most of these antennas should be equipped with Ka and Ku band capabilities. Because the system contains so many spread out dishes, ESTRACK has a 99% service availability. Upon analysis of the trade spreadsheet it is visible that ESTRACK would be the more beneficial communication network. A cost of 5 has been given to both DSN and

ESTRACK as there is not an available price estimate for both in order to adequately compare the cost. ESTRACK is the beneficial network and will be chosen to be used as the ground station to communicate with the spacecraft at Venus.

Probe trade study summary

The probe is one of the most integral aspects of our mission as it is the means for completing all of the scientific measurements of the Venusian atmosphere. The probes primary mission goals are to measure seasonal variability of atmospheric behaviour and composition to improve our atmospheric models of Venus. The composition analysis includes measurements at different altitudes looking for the presence of different greenhouse gases, noble gases, and measurements of downwelling longwave radiation. The probes secondary mission goal is to detect the presence microbial life in potential algae plumes that form in areas with similar pressures and temperatures as here on earth.

From the decision matrix found in the appendix a balloon suspended large probe that would hold all of the mission essential instruments in one housing is the clear winner at 81% over the pico-cluster probe design at 61%. With this probe design we will be able to pressurize the balloon such that the probe floats at a desired height and we could let out some pressure to descend and take measurements lower in the atmosphere if needed so we can get full coverage of the measurements we need to take. The probe would be able to hold large instruments and would allow us to complete our secondary mission to look for microbial life. The probe would navigate the Venusian atmosphere through wind-based propulsion so we could theoretically float across large areas of the atmosphere and gather large samples of data. The lifespan could be very long which would allow us to measure seasonal variability. Since it will be only a single probe the cost will be feasible as well and the design will be simple with no extra moving parts.

Drone trade study summary

	Multi-rotor	Fixed-wing	Single-rotor	Fixed-wing hybrid	Weighting
Carriable mass	3	2	3	2	20
System mass	3	4	3	4	20
Technological maturity	2	4	3	0	15
Moving parts	3	3	4	3	10
Control + stability	4	2	2	3	15
Unit price [USD]	4	3	2	0	10
Top-flight time	1	3	1	3	5
Top-flight speed	2	3	4	3	5
Score	73,75	75	70	56,25	

Table 6 – Drone trade study results

From the full trade study presented in the appendix, we see that the multi-rotor drone type is the recommended alternative. The trade study table originally pointed towards the fixed-wing alternative, then, taking into consideration the take-off and landing method changed this outcome. However, it should be noted that the fixed-wing hybrid would have been a more serious candidate if the technology had been further developed.

Prior to performing the trade study, it was expected that the fixed-wing option would be the recommend alternative. It would have been followed by the multi-rotor and then the single-rotor. The hybrid was expected to be last. Once the trade study was completed, the first two options switched positions. In the case of the VAPE mission, we are not limited to transported only one type of drone. The multi-rotor is the recommended alternative and a plurality of them is expected to be see in the final concept. We must also keep in mind that due to the low battery life of many models the drones need to be fitted with a manner of safely recharging their battery. This would likely result in a future trade study on the selection of the drone model to transport to Venus. The main options to consider are a set of commercially available drones modified to fit our needs or a custom designed drone tailored specifically to meet the objectives of the mission.

Instrumentation trade study summary

Criteria	Mandatory (0,1)	Weight (%)	Grade	Option 1	Option 2	Option 3	Option 4
REQ-FUNC-0001	1	X	0 – 1	1	1	1	1
REQ-FUNC-0095	1	X	0 – 1	1	1	1	1
REQ-PERF-0010	1	X	0 – 1	1	1	1	1
REQ-PERF-0091	1	X	0 – 1	1	1	1	1
Measurement Effectiveness	0	10	0 – 3	1	3	2	3
Measurement Quality	0	20	0 – 3	3	3	2	2
Measurement Ability	0	25	0 – 3	2	1	1	3
Size	0	30	0 – 3	2	1	0	3
Cost	0	15	0 – 3	2	3	1	0
TOTAL		100		70	63	43	**78**

Table 7 – Instrumentation trade study results

From the full trade study in the appendix, the TDLAS appears to be the best option. However, it is only 8 higher than the mass spectrometer. This can be due to the weighting of the trade study, so a secondary decision matrix will be made for sensitivity testing. For the secondary matrix, more of an emphasis will be put on the measurements itself rather than the size of the probe. Figure 16 outlines the new decision matrix, where size was reduced from 30 to 25, cost was reduced from 15 to 10 and measurement effectiveness increased from 10 to 20. This now means that 65% of the weight is based off the characteristics of the instruments.

System block diagrams

The key aspect of our mission is how we get the data back from the probes and send it to Earth. As mentioned before, the probes will be powered by batteries due to the high optical depth that will be expected once the probes enter the atmosphere. The batteries will power the onboard computer, payload, pressure sensor and amplifier. Once the pressure sensor reads that were at ~1 ATM, the computer will tell the payload, which is most likely a TDLAS but select probes can have different instruments, to begin reading data. The data will be stored until the satellite is in range of the probe, which then it will be sent to the satellite. Since the probes are dropped into the atmosphere there is no need for attitude control, as that is part of the balloon or the drone, which is developed outside the scope of this mission. There is also no need for the probe to retrieve signals from the satellite, as well we want to keep the entire access link between the probe and the satellite to be sending data. The figure below outlines the system block for the probe.

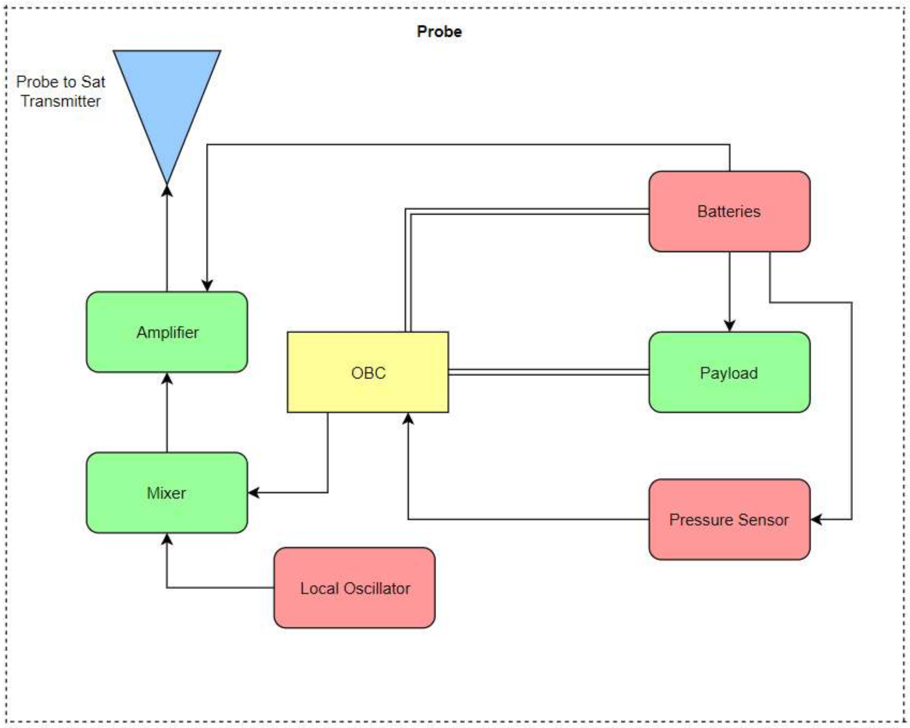


Figure 31 - System block diagram of the probe

The next unique area of our mission will be the communication system of the satellite. Since we are very close to the Sun, the obvious choice for generating excessive amount of power will be solar panels, so our power system will be standard for space missions. The same can be said out our attitude control, computer and thermal subsystems, which can have their system blocks found in Appendix A. The thermal subsystem may have more additions of coolers, but this is a redundant system within the system block already. The communication system however must be able to communicate and receive from Earth, as well as receive data from the probes. In total there will be three antennas onboard for these functions. The data received from the probes will be decoded and sent to the OBC. If the data cannot be relayed instantly to Earth, it will be stored and sent later. The satellite will receive telecommand from Earth, which will be sent to the OBC to be sent to the various subsystems. The OBC will also get telemetry to send back to Earth. Telemetry will be sent back in the same access time as the data if it is achievable. The figure below shows the system diagram for the communications subsystem.

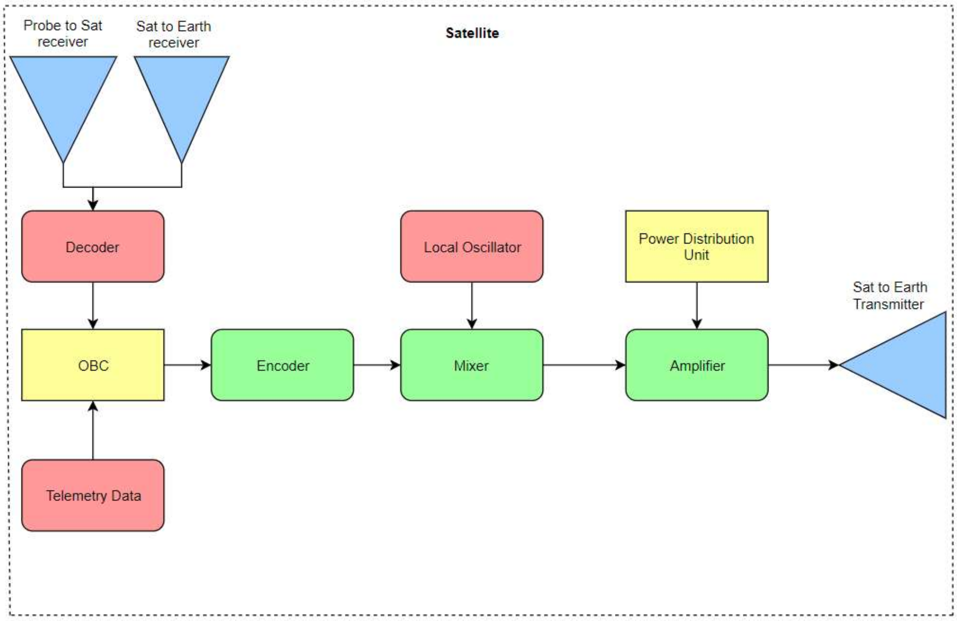


Figure 32 - System block diagram of the communication subsystem

Engineering budgets

Mass Budget

Our mission is highly based around the probe and the main structure will mostly serve as a communications link back to earth. We investigated 3 other probe-based space missions Cassini, Venera 5, and Vega 2. The Cassini space craft had a lot more instruments onboard but what we will be looking at is the mass of the Huygens lander. With the Huygens probe and adapter weighing in at $348\ kg$ and the dry space craft weighing in at $2068\ kg$ the Huygens consisted of 17% of the mass of the space craft, with propellant included it only represented 6% of the mass. The Cassini mission provides a good start for comparing our Venus missions mass budget (figure 33), but we will need a higher probe mass percentage on our mission as our main space craft will not include as much fuel or instruments as Cassini.

Table 2.4.4. Mass breakdown of the Cassini/Huygens spacecraft.

Orbiter (dry, inc. payload)	2068 kg
Probe (inc. 44 kg payload)	318 kg
Probe Support Equipment	30 kg
Launch adaptor	135 kg
Bipropellant	3000 kg
Monopropellant	132 kg
Launch mass	5683 kg

Figure 2.4.4. The Cassini/Huygens spacecraft and its principal features.

Figure 33 - Mass breakdown of the Cassini spacecraft

The Venera 5 and Venera 6 spacecraft were of identical design and launched 5 days apart in January 1969. The spacecraft were designed to make in-situ measurements as they descended through the Venusian atmosphere. Measurements included temperature, pressure, composition which are very similar goals of our mission. The total mass of Venera 5 was $1130\ kg$. The probe was spherical with a mass of $405\ kg$ and was designed for decelerations as high as 450g. Venera 5 and 6 were designed with smaller parachutes so it could dive deeper into the atmosphere (figure 34). This mission had a probe taking up 40% of the mass. This will be a similar mass budget as our mission as they share many similar traits and goals.

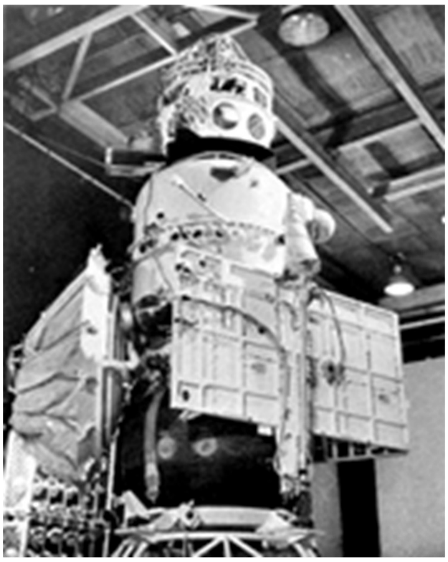


Figure 34 – Venera spacecraft

Vega 2 was a multi goal mission as the Venus lander was just stage 1 of the full mission to intercept Halley's comet but we will look at the mass and design of the probe. The total space craft had a mass of $4920\ kg$ with the probe/lander weighing $1500\ kg$ with a balloon suspended probe assembly with a mass of $21\ kg$ (Figure 35). The balloon probe was jettisoned from the lander at 61km of altitude. The balloon was inflated 100 seconds later at $54\ km$ and the parachute and inflation system were jettisoned. The mean stable height was 53.6 km, with a pressure of $535\ mbar$ and a temperature of $(35\text{–}\ 43\ °C)$ in the middle, most active layer of the Venus three-tiered cloud system. The probe did not have as many instruments as our mission so ours will be much heavier, but it provides a proof of concept of our probe design. In total the probe only accounted for .5% of the mass but the lander consisted of 30% of the total mass.


Figure 35 - Vega space craft and balloon probe

Our VAPE mission, based on the goals and masses of the other missions will have less mass then the others. This is because we have a single goal of dropping the probes and relaying communications. With the scope of our mission and the capability of our launch vehicle our total mass budget will be no greater than $3500\ kg$ see table below for breakdown. Our space craft will need a propulsion system in order to perform a capture burn at Venus. We are also dropping two probes, one balloon suspended and one fixed wing drone so both will count towards the payload mass. The main space craft will contain all the attitude control, thermal control and shielding for the probes journey to Venus as well as the main communications antennas for the transmissions to and from the probes and the Earth.

Subsystem	Mass (Kg)	Margin (%)	Total mass (Kg)
Power	150kg	20	180
Payload	500	15	575
Communications	100	10	110
Attitude control/ thrusters	300	10	330
Thermal control	50	10	55
Shielding	100	5	105
Harness (5%)	70	0	70
Structure (20%)	300	0	300

Total dry mass			**1725 Kg**
Additional System margin (25%)			430
propellant			1300
Total wet mass			**3456 Kg**

Table 8 – Estimated mass budget for the mission

Since we are still pre phase A on our mission design we have left large margins surrounded the subsystems that still have to be designed and finalized but our mission should stay under the $3500\ kg$ needed for our rocket.

Power Budget

The power budget represents the amount of power our satellite will need to successfully complete its mission. The mission gives us a polar orbit around Venus for the duration of the year. Being close to Venus gives us a great opportunity to utilize Solar cells for our main satellite. This will not be utilized for the probes that will be dropped in as there is a high optical depth in the Venusian atmosphere. Venus is an atmospheric distance of $0.72\ AU$ from the Sun. Using the solar constant calculation, we know that the solar constant is proportional to the distance squared. If we do the calculation for what the average solar constant would be on Venus, we see that we get a value of $2{,}636\ W/m2$, which is an increase of $\sim 51\%$. It shows that we will have little difficulty creating the necessary power for our mission. It can therefore be assumed that Solar Panels will be the primary source of renewable power onboard our satellite, with batteries being the main power source for the probes.

To estimate the amount of power that will be needed for the different subsystems, we will look at previous missions as an example. For this case we will only include interplanetary satellites for this comparison, as human missions or communication satellites may vary with the amount of power that will be used. A mission that will be looked at is Ulysses [1], which is an ESA mission to look at the Sun's polar region. Another ESA mission, Venus Express, will be extensively compared to for a few reasons. First, the Venus Express is an ESA mission to Venus from 2006 to 2014 [2]. The testing, development and integration time for the Venus Express was only 3 years. Because of little amount of time given, many components were taken from the Mars Express, which is another ESA mission, and changed to suite the environment and mission to Venus. Documentation provides what needed to be changed between the two missions and the justification behind it. This is a very useful tool for our estimation as it gives us insight in what will need to be changed from the typical interplanetary satellite to comply with the environment around Venus.

Figure 33 shows the typical power allocations for an interplanetary satellite. We can see that most of the power is allocated to communication and the payload. Most interplanetary mission have the payload as part of the satellite. This is where our design differs as we attach the main payloads on the balloons and probes that will be dropped into the Venusian atmosphere.

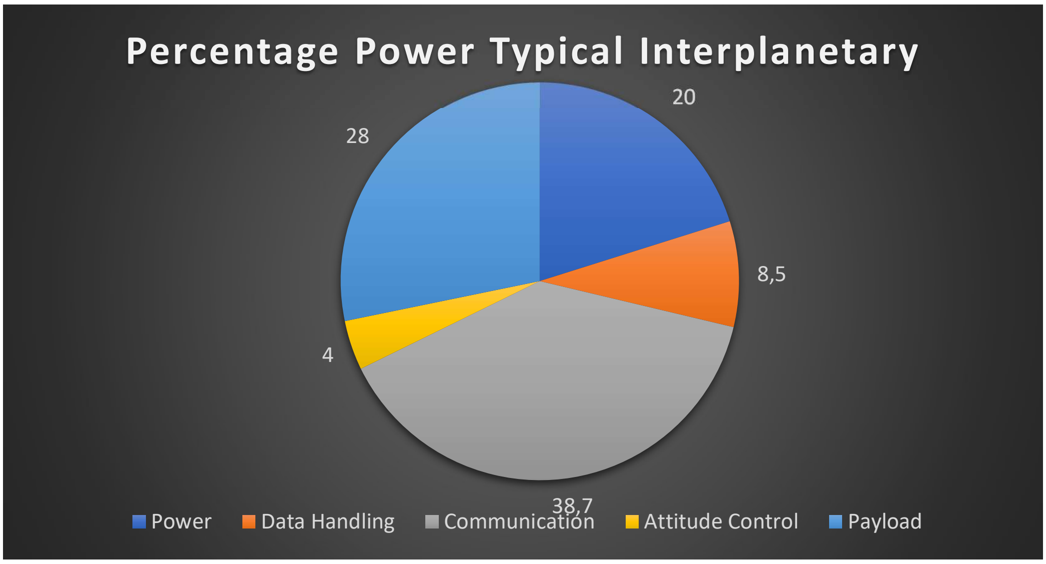


Figure 36 - Percentage of power driven by main subsystems for a typical interplanetary satellite

After reading the systems review for the Venus Express there were a few key requirements that would need to be addressed for the power budget. First off, the temperature fluctuations encountered at Venus are much greater than seen in orbit around Earth and Mars, for this reason there is extensive addition to the cooling system as the heating systems are considered because almost every mission is in shadow at some point. This means that power required for heating would almost be equal for the power required for cooling. A difference between the two could be seen in the Ulysses mission where 8.9 W was allocated for cooling and 24.9 W was allocated for heating. For our mission both would be allocated for 30 W after the addition of margin. A second consideration is the communication system that would need to be in place for our mission. We will be receiving and communicating to Earth throughout the mission, and this link is extremely crucial during the primary science phase of our mission. During this phase, telemetry and scientific data will be sent back to Earth. In turn, the scientific data must be retrieved from the balloons and probes in orbit. To keep this link between our satellite and Earth, a receive antenna primarily focused on retrieving data from the probes will be needed. This means that we will have 3 crucial communication links, whereas most missions only need 2 as the payloads that provide the data are most likely on the satellite. This means that the overall transmission and receiver power for our satellite will increase based on previous missions. Since the data will be stored and not relayed from the probes if Earth is not in view, our software required power will not be increased. Finally, since our payloads are not attached to our satellite, a secondary power budget will be created for the probes. This means that the only power drawn from the probes would be making sure the batteries are in nominal range before the probes are deployed, which decreases our payload allocated power.

Figure 34 shows the estimated percentage power for our mission and table 1 shows the breakdown for our power budget using a component by component estimate, with consideration for margin based on the phase of our mission. While the overall power for our satellite is very comparable to other interplanetary satellites, there is a significant decrease in the amount of payload power allocated. As mentioned above, this is because of the detachment of our payloads from our satellite.

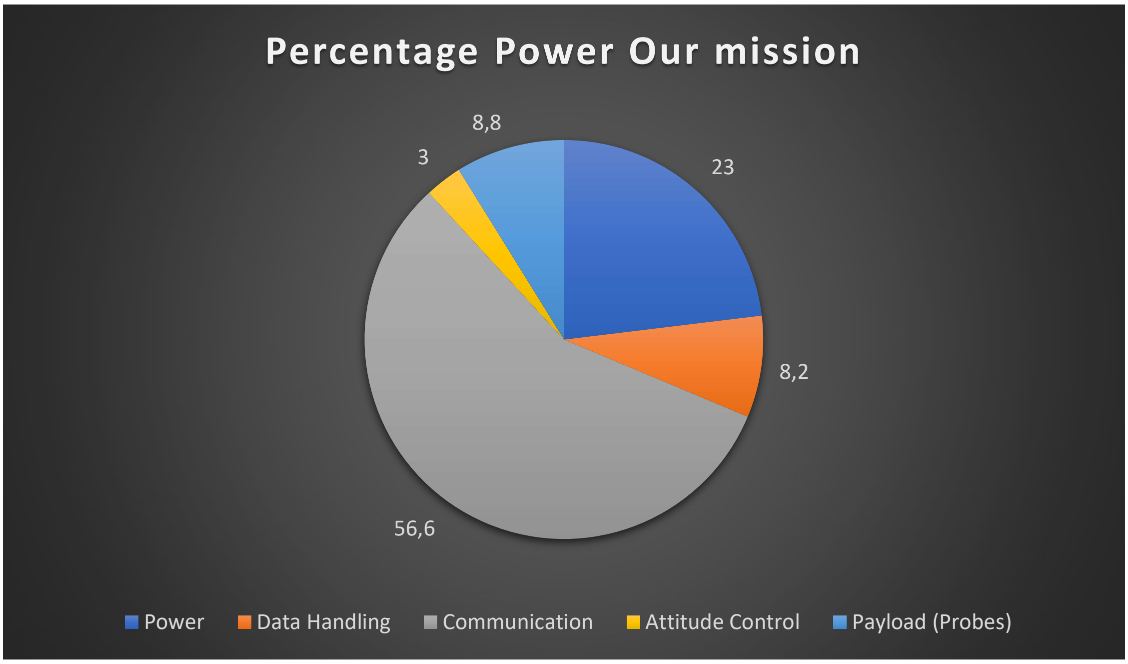


Figure 37 - Percentage of power driven by the main subsystems for VAPE

Power Subsystem	**Est. Power (W)**	**Margin (%)**	**Power (W)**
Hot Case Coolers	30	15%	34.5 W
Cold Case Heater	30	15%	34.5 W
Power Total			**69 W**
Data Handling Subsystem			
OBC	18	5%	19 W
Control Electronics	5	5%	5.5 W
Data Handling Total			**24.5 W**
Communication Subsystem			
Receiver from Earth	4	20%	5 W
Receiver from Probe	4	20%	5 W
Transmitter X - band	8	25%	10 W
Transmitting Amplifier	120	25%	150 W
Communication Total			**170 W**

Attitude Control Subsystem	Est. Power (W)	Margin (%)	Power (W)
Attitude Sensors	2	20%	2.5 W
Attitude Processing	2	20%	2.5 W
Attitude control electronics	4	20%	5 W
Attitude Control Total			**10 W**
Payload Subsystem			**Power (W)**
Battery for Probes	2	5%	2 W
Probe Regulator	3	10%	3.5 W
Optical Instruments	15	40%	21 W
Payload Total			**26.5 W**
Total Power			**300 W**

Table 9 – Estimated power budget for the spacecraft

To estimate for the probes, 3U CubeSat missions will be looked at. The reason for this is because they are similar in size, and much of the instruments and subsystems onboard a CubeSat are like those onboard the probes. A few things that can be omitted include an attitude control subsystem as the attitude control will be controlled by the balloon or drone and not by the probe. Also, the Satellite will not be sending commands to the probe, as the data will just be taken and then sent back. Therefore, a receiver is not needed on the probe. The CubeSats that will be compared to come from ELFIN, which is an Electron Losses and Field Investigation Nanosatellite developed by UCLA [3]. Figure 3 shows the percentage for the different elements on the probe and Table 2 shows the breakdown for the estimated power.

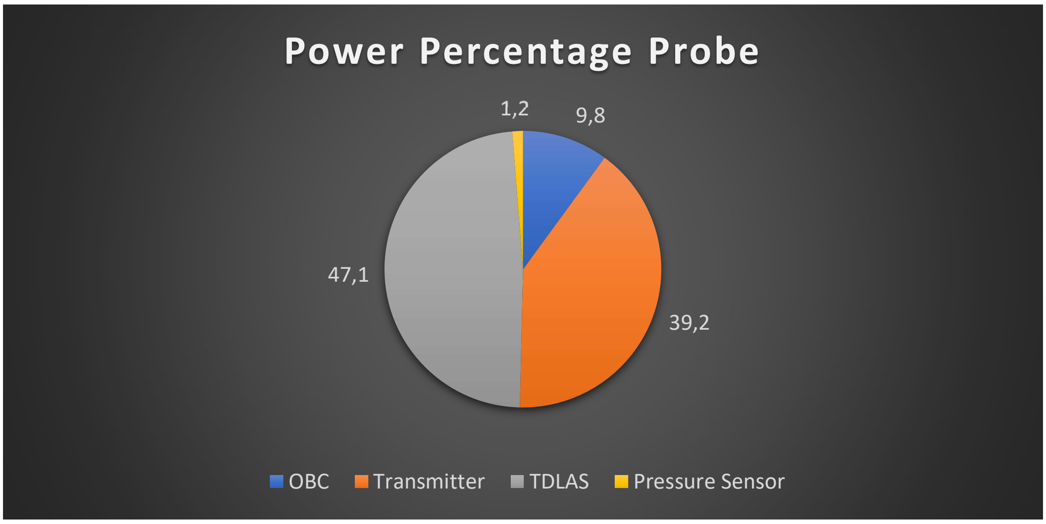


Figure 38 - Percentage of power for the Probes.

Probe	Est. Power (W)	Margin (%)	Power (W)
OBC	0.3	20%	0.5 W
Transmitter	1.5	10%	1.65 W
TDLAS	2	5%	2.1 W
Pressure Sensor	0.2	5%	0.2 W
Probe Total			4.45 W

Table 10 – Estimated power budget for the probes

Link Budget

The link budget for satellite communications is the accounting of all gains and losses of the entire communication system. This system includes the transmitter, the mediums (cables, atmosphere, free space) up until the receiving system of the desired target. The purpose of the link budget is to mathematically ensure whether it be the transmitter or the emitter that the signal to noise ratio is significantly strong enough to be detected and have an acceptable bit to error ratio. A link margin or safety factor tells us whether the system meets the requirements comfortably, marginally, or not at all. The link budget can help predict equipment weight, size, prime power requirements, and technical risk.

A few key things to consider for the calculation of the link budget are the basic parameters of the system we will be using. In our system we will be using a 35m transmitting and receiving antenna on Earth that has a system temperature of 20.2 Kelvin, an efficiency of 65%, a transmitting power of 20 kW and an estimated line loss of 4dB. We will also be primarily using the X-band as the transmitting and receiving band. For transmissions we will be using between 7.9 – 8.395 GHz as the uplink frequency and 7.250-7.745 GHz as the downlink frequency. The satellite will contain a Gaussian antenna with a 2.2 m diameter, an efficiency of 55% and a transmitting power of 150 W. These will be the fixed components to perform the calculations required.

Decibels

The decibel is the expression of the ratio between two signals. In this case, the signals defined by the decibel are primarily power levels. The decibel uses logarithm of the ratios rather than the arithmetic ratio. By using the logarithmic ratios, we are able to simplify the equations with addition and subtraction rather than having them more complex with multiplication and division. The units that will be used to specify will vary between dB, dBW, and dBi. dB is the standard ratio, dBW is the power ratio where the power is in watts, and dBi will represent the gain relative to isotropic. Gain relative to isotropic means the gain relative to an isotropic radiator which radiates power equally in all directions (spherical).

Effective Isotropic Radiated Power (EIRP)

EIRP is the standardized definition of directional radio frequency emitted by a radio transmitter. It can also be defined by the total power radiated by a half-wave dipole antenna to give the same radiation intensity as the actual source at a distant receiver in the direction of the antenna's strongest beam. It is not possible for an antenna to radiate this way; therefore, the isotropic radiator is purely hypothetical. Even though the radiator is hypothetical, this method allows us to compare various antennas where 100% would mean that the antenna radiates all the power that is provided.

Transmission Losses

The EIRP can be considered as the power input to one end of the system (transmission link), and then it is required to find the power at the other end. Some losses are constant while others vary with time of year and weather. Rainfall is one weather effect that must be strongly taken into consideration. The constant losses can be determined and always used while the variable losses should be determined from statistical data and extrapolated for the time that will be used. The primary losses we encounter (assuming no cloud coverage or precipitation) are coverage loss, fade allowance, and the free space loss; which is the largest loss in the entire budget.

Free Space Loss

When transmitting signals, there is always a separation distance. This distance between the antennas causes a decrease in electric field strength which in turn decreases the signal strength. It is a loss that considered the fact that all the radiated power is not focused directly onto the receiving satellite.

Signal-to-Noise Ratio (SNR)

The SNR is the ratio of the strength of the received signal to that of interference. It compares the level of our desired signal to the level of background noise. A signal with an SNR greater than 0 dB indicates more signal than noise.

Bit Error Rate (BER)

The BER is the number of bit errors per unit of time. This is one way of measuring the performance of a digital system as a function of the energy/bit to noise-power density. For typical transmission systems, the BER lies in the range of 10^{-3} to 10^{-9}. For our mission we have determined that an appropriate bit error rate would be 10^{-4} therefore for every 100,000 or more bits of data we send, there should only be 1 incorrect bit. This error can be improved by the encoding techniques that are used. More advanced techniques are able to detect and automatically correct these errors.

Transmitter and Receiver Antenna Gains

The antenna parameter that relates the power output or input to that of an isotropic radiator as a geometric ratio is the antenna directivity or directive gain. The importance of using highly directional antennas is that they provide signal power gain. These gains are key performance numbers which take into account the antenna's directivity and efficiency. The gain also describes how well the antenna converts power into the desired radio waves headed in a specific direction.

Uplink from 35m ESTRACK Antenna

Uplink Frequency:	7.9-8.395 GHz
Diameter of Antenna:	35 m
Beamwidth:	0.065 deg
Gain:	66.5 dBi
Transmit Power:	20 kW
Backoff and Line Loss:	-4 dB
EIRP:	135.5 dBW
Propagation Range:	200,000,000 km
Free Space Loss:	-189.2 dB
Atmospheric Loss:	-10 dB
Net Path Loss:	-199.2 dB
Satellite Noise Temperature:	23.4 dB-K
Satellite Gain:	20.8 dBi
Satellite G/T:	7.11 dB/K
Received Carrier Power:	-34.9 dB-Hz
Carrier to Noise Ratio:	133.9 dB
Available Eb/No Ratio:	76.5 dB
Link Margin:	6.5 dB

Table 11 – Uplink calculations

Downlink to 35m ESTRACK Antenna

Uplink Frequency:	7.250-7.745 GHz
Satellite Transmit Power:	150 W
Antenna Efficiency:	65%
Backoff and Line loss:	-5 dB
Antenna Gain:	36.03 dBi
EIRP:	83.26 dBW
Propagation Range:	200,000,000 km
Free Space Loss:	-188.4 dB
Atmospheric Loss:	-7 dB
Net Loss:	-195.4 dB
Satellite Antenna Diameter:	2.2m
Antenna Beamwidth:	2.84 deg
Antenna Gain:	65.6 dB
Line Loss:	-2 dB
Received Carrier Power:	-36.11 dB-Hz
Carrier to Noise Ratio:	159.3 dB
Available Eb/No Ratio:	101.9 dB
Link Margin:	31.9 dB

Table 12 – Downlink calculations

By examining our link margins, we come to a conclusion that the link will be complete, and we should not encounter any unforeseen issues with the communications aspect.

Data Budget

The data volume budget is required to ensure that we will be able to transmit all acquired data within our possible communication windows. Our transmission times are once a day for 21,600s. Assuming a transmission rate of 720 kb/sec we are able to transmit 2,026,440 bits of data per orbit. When analysing the amount of data, the balloon and drone will transmit to the main satellite, we determine that the balloon will transmit about 4800 bits/sec for about 2800 seconds during the orbit access times for a total of 13,440,000 bits of data. The probe will transmit 2700 bits/sec for 2800 seconds for a total of 7,560,000 bits of data. In addition to these values we will also have some housekeeping to be done at 70bits/sec for a total of 196,000 bits. All this data comes to a total of 21,019,600 bits of data per orbit.

In order to transmit all that data within the transmission period, the data will require to be significantly compressed. These compressions are what cause the BER, but with higher standards we should be able to remain within our margin for BER. We estimate the balloon and drone data to be compressed 11x and the housekeeping data to be compressed 14x for a total data amount of 1,923,091. This value is less than the amount we are able to transmit per orbit so we will be able to transmit all data.

Cost Budget

After analysing the costs other mission to Venus conducted by the ESA, NASA and RosCosmos. The average mission costs 300-600 million USD in today's dollars. Some mission costs were higher, but they included secondary missions for the space craft to travel to comets or other planets. The cost breakdown for our mission starts with the highest priced items, the probes and the launch vehicle. Since we are sending two probes to another planet that will need many expensive instruments and extensive testing the probes will cost roughly 80 million to build with a 20% margin it could be as high as almost 100 million. The launch vehicle we chose has a set price of 158 million USD, we had to choose this more expensive launch vehicle as our total space craft has a high mass of $3500\ kg$.

Breaking down the other costs of the mission we will start with the power system, this 15 million includes the batteries for the main space craft as well as the batteries for the probes. It also includes the cost for the solar panels needed for the orbiting communications space craft we left a margin of 10% as this cost shouldn't fluctuate greatly. The communications system is projected to cost 30 million again with a 10% margin, this cost includes the antennas needed for Venus to earth communications as well as the antennas needed for communications between the probes and the orbiter through Venus's dense atmosphere. The thermal control system will cost roughly 5 million and this will include all the mylar and insulation needed around the space craft and probes to keep them safe during the journey to Venus.

Looking into cost of the structure it will be 20 million with a 10% margin this will include all the material to build the space craft bus and probe structures. Then assembly and testing of all of the components is projected to cost roughly 50 million with around 15% margins which could bring the cost up to 56 million, This will include all of the man hours needed to physically build the space craft as well as the cost of the TVAC chamber testing and Vibration testing of the completed space craft. Finally, the cost of the ground station will only be 4 million and this mainly just includes the man hours for the people that will be running the ground stations as this will most likely be a government mission the larger already set up networks of communications would be available to us.

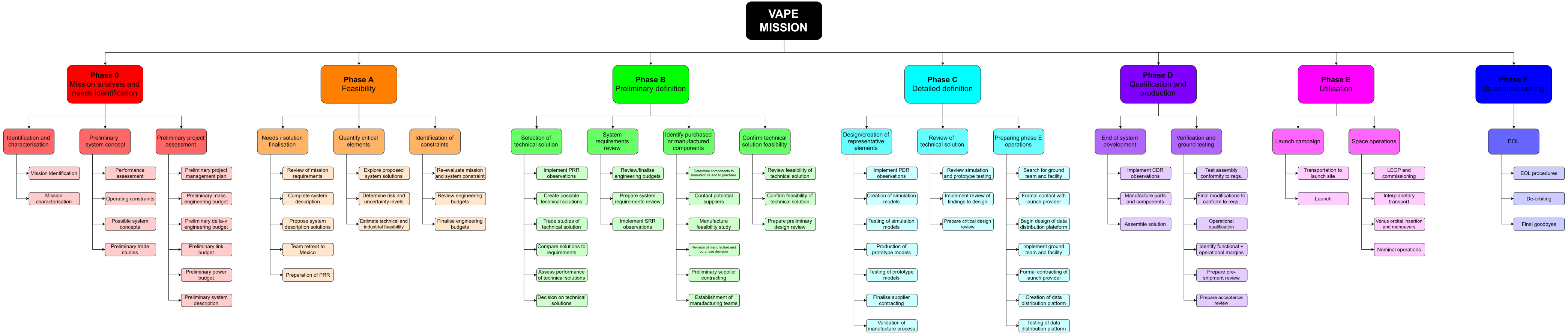
Subsystem	Cost (Millions USD)	Margin (%)	Total Cost (Million USD)
Power	15	10	17.25
Payload	80	20	96
Communications	30	10	33
Thermal control	5	15	5.75
Structure	20	10	22
Assembly	30	15	34.5
Launch Vehicle	158	0	158
Ground Station	4	10	4.4
Testing	20	10	22
Total cost			**400**

Table 13 – Cost breakdown for VAPE mission in USD millions

Mission work breakdown and scheduling

To obtain a work breakdown and schedule for the mission, it was divided into phases. These follow the ESA space mission phases 0 – F. Each phase was further discretised into 1 – 4 subphases (categories). Lists of tasks were drawn for each category that outline the main jobs that shall be completed. This allowed us to design a work breakdown diagram which is shown on the next page. From the lists, a spreadsheet schedule was composed using the estimated duration of each work package. In the spreadsheet, each task is assigned a number, a key team or members, a duration, a nominal start date, and a nominal stop date. The charts are shown after the work breakdown diagram. Using the schedules, we designed several Gantt charts. One portrays the timeline of the mission and the others that of each individual phase. Note that, the earlier phases are better known to the concepts team and as such contain more detailed work packages. The phases further in time shall be editing and appended extensively as the mission progresses.

Work breakdown diagram


VAPE MISSION
Phase 0 Mission analysis and needs identification
Identification and characterisation
Mission identification
Mission characterisation
Preliminary system concept
Performance assessment
Operating constraints
Possible system concepts
Preliminary trade studies
Preliminary project assessment
Preliminary project management plan
Preliminary mass engineering budget
Preliminary delta-v engineering budget
Preliminary link budget
Preliminary power budget
Preliminary system description
Phase A Feasibility
Needs / solution finalisation
Review of mission requirements
Complete system description
Propose system description solutions
Team retreat to Mexico
Preperation of PRR
Quantify critical elements
Explore proposed system solutions
Determine risk and uncertainty levels
Estimate technical and industrial feasibility
Identification of constraints
Re-evaluate mission and system constraint
Review engineering budgets
Finalise engineering budgets
Phase B Preliminary definition
Selection of technical solution
Implement PRR observations
Create possible technical solutions
Trade studies of technical solution
Compare solutions to requirements
Assess performance of technical solutions
Decision on technical solutions
System requirements review
Review/finalise engineering budgets
Prepare system requirements review
Implement SRR observations
Identify purchased or manufactured components
Determine components to manufacture and to purchase
Contact potential suppliers
Manufacture feasibility study
Revision of manufacture and purchase decision
Preliminary supplier contracting
Establishment of manufacturing teams
Confirm technical solution feasibility
Review feasibility of technical solution
Confirm feasibility of technical solution
Prepare preliminary design review
Phase C Detailed definition
Design/creation of representative elements
Implement PDR observations
Creation of simulation models
Testing of simulation models
Production of prototype models
Testing of prototype models
Finalise supplier contracting
Validation of manufacture process
Review of technical solution
Review simulation and prototype testing
Implement review of findings to design
Prepare critical design review
Preparing phase E operations
Search for ground team and facility
Formal contact with launch provider
Begin design of data distribution plateform
Implement ground team and facility
Formal contracting of launch provider
Creation of data distribution platform
Testing of data distribution platform
Phase D Qualification and production
End of system development
Implement CDR observations
Manufacture parts and components
Assemble solution
Verification and ground testing
Test assembly conformity to reqs.
Final modifications to conform to reqs.
Operational qualification
Identify functional + operational margins
Prepare pre-shipment review
Prepare acceptance review
Phase E Utilisation
Launch campaign
Transportation to launch site
Launch
Space operations
LEOP and commissioning
Interplanetary transport
Venus orbital insertion and manuevers
Nominal operations
Phase F De-commissioning
EOL
EOL procedures
De-orbiting
Final goodbyes

Work package spreadsheets by phase

Title	Number	Key people/teams	Time	Nominal start	Nominal stop	Category
Mission identification	10	VAPE Concepts Team	1 week	10/01/2019	17/01/2019	Identification and characterisation
Mission characterisation	20	VAPE Concepts Team	1 week	17/01/2019	24/01/2019	
Expected performance assessment	30	VAPE Concepts Team	3 weeks	17/01/2019	07/02/2019	Preliminary system concept
Determine operating constraints	40	VAPE Concepts Team	2 weeks	24/01/2019	07/02/2019	
Identify possible system concepts	50	VAPE Concepts Team	1 week	17/01/2019	24/01/2019	
Performance of preliminary trade studies	60	VAPE Concepts Team	2 weeks 5d	07/02/2019	26/02/2019	
Preliminary project management plan	70	VAPE Concepts Team	2 weeks	14/03/2019	28/03/2019	Preliminary project assessment
Preliminary mass engineering budget	80	Jacob Samson	2 weeks 5d	14/03/2019	02/04/2019	
Preliminary delta-v engineering budget	90	Jessie Atanmanchuk and Yaseen Al-taie	2 weeks 5d	14/03/2019	02/04/2019	
Preliminary link engineering budget	100	Konrad Kaczor	2 weeks 5d	14/03/2019	02/04/2019	
Preliminary power engineering budget	110	Michael Tabascio	2 weeks 5d	14/03/2019	02/04/2019	
Preliminary system description	120	Michael Tabascio	2 weeks 5d	14/03/2019	02/04/2019	

Table 14 – Work packages for phase 0

Title	Number	Key people/teams	Time	Nominal start	Nominal stop	Category
Review of mission requirements	140	VAPE Concepts Team	4 weeks	06/05/2019	03/06/2019	Needs and solution finalisation
Complete system description	150	VAPE Concepts Team	8 weeks	03/06/2019	29/07/2019	
Propose system description solutions	160	VAPE Concepts Team	5 weeks	29/07/2019	02/09/2019	
Team retreat to Mexico	170	VAPE Concepts Team	1 week	12/08/2019	19/08/2019	
Preparation of PRR	231	VAPE Concepts Team	3 weeks	02/12/2019	23/12/2019	

Explore proposed system description solutions	180	VAPE Concepts Team	4 weeks	02/09/2019	30/09/2019	Quantify critical elements
Determine uncertainty and risk levels for system	190	VAPE Concepts Team	3 weeks	30/09/2019	21/10/2019	
Estimate technical and industrial feasibility	200	VAPE Concepts Team + consulting experts	4 weeks	14/10/2019	11/11/2019	
Re-evaluate missions and system constraints	210	VAPE Concepts Team	2 weeks	11/11/2019	25/11/2019	Identification of constraints
Review of engineering budgets	220	VAPE Concepts Team	2 weeks	18/11/2019	02/12/2019	
Finalise engineering budgets	230	VAPE Concepts Team	4 weeks	18/11/2019	16/12/2019	

Table 15 – Work packages for phase A

Title	Number	Key people/teams	Time	Nominal start	Nominal stop	Category
Implement PRR observations	240	VAPE Concepts Team	12 weeks	16/12/2019	09/03/2020	Selection of technical solution
Create technical solutions	250	VAPE Concepts Team	16 weeks	09/03/2020	29/06/2020	
Trade studies of technical solutions	260	VAPE Concepts Team	12 weeks	29/06/2020	21/09/2020	
Compare technical solution to requirements	280	VAPE Concepts Team	4 weeks	21/09/2020	19/10/2020	
Assess performance of technical solutions	290	VAPE Concepts Team	4 weeks	19/10/2020	16/11/2020	
Decision on technical solutions	270	VAPE Concepts Team	2 weeks	16/11/2020	30/11/2020	
Review and finalise new engineering budgets and schedules	300	VAPE Concepts Team	8 weeks	23/11/2020	18/01/2021	SSR
Prepare SRR	301	VAPE Concepts Team	3 weeks	28/12/2020	18/01/2021	
Implement SRR observations	310	VAPE Concepts Team	12 weeks	18/01/2021	12/04/2021	
Determine components to manufacture and to purchase	320	VAPE Concepts Team	4 weeks	12/04/2021	10/05/2021	Identification of manufactured and purchased components
Contact potential suppliers	330	Legal team	2 weeks	10/05/2021	24/05/2021	
Manufacture feasibility study	340	Manufacturing team	2 weeks	10/05/2021	24/05/2021	

Revision of manufacture and purchase decisions	350	Manufacturing team	2 weeks	24/05/2021	07/06/2021	
Preliminary supplier contracting	360	Legal team	2 weeks	07/06/2021	21/06/2021	
Establishement of manufacturing teams	370	Manufacturing team	2 weeks	07/06/2021	21/06/2021	
Review feasibility of technical solution	380	VAPE Concepts Team	2 weeks	21/06/2021	05/07/2021	Confirm feasibility of technical/recommended solution
Confirm feasibility of technical solution	390	VAPE Concepts Team	2 weeks	05/07/2021	19/07/2021	
Prepare PDR	400	VAPE Concepts Team	2 weeks	19/07/2021	02/08/2021	

Table 16 – Work packages for phase B

Title	Number	Key people/teams	Time	Nominal start	Nominal stop	Category
Implement PDR observations	410	VAPE Concepts Team	3 months	02/08/2021	11/10/2021	Design and creation of the representative elements
Creation of simulation models	420	VAPE Design Team	6 months	11/10/2021	21/03/2022	
Testing of simulation models	430	VAPE Design Team	3 months	14/02/2022	09/05/2022	
Production of prototype models	440	VAPE Design Team	1 year	13/04/2022	17/04/2023	
Testing of prototype models	450	VAPE Design Team	6 months	16/01/2023	17/07/2023	
Finalise supplier contracting	460	Legal team	3 months	11/10/2021	10/01/2022	
Validation of manufacturing process	470	Manufacturing team	3 months	11/10/2021	10/01/2022	
Review of simulation and prototype testing	455	VAPE Design Team	3 months	17/07/2023	16/10/2023	Review of technical solution
Implement review findings to design	456	VAPE Design Team	6 months	16/10/2023	15/04/2024	
Preparation of CDR	457	VAPE Concepts Team	3 months	15/04/2024	05/08/2024	
Begin search for ground operation team and facilities	480	VAPE Concepts Team	3 months	06/12/2021	07/03/2022	Preparation of phase E operations
Begin formal contact with launch provider	490	Legal team	3 months	07/02/2022	09/05/2022	
Begin design of data distribution platform	500	VAPE Design Team	3 months	04/04/2022	08/07/2022	

Implementation of ground team and facilities	510	Ground team	6 months	06/06/2022	09/12/2022	
Formal contracting of launch provider	520	Legal team	6 months	10/10/2022	10/04/2022	
Creation of data distribution plateform	530	Ground team	1 year	10/10/2022	16/10/2022	
Testing of data distribution plateform	540	Ground team	3 months	19/09/2022	16/12/2022	

Table 17 – Work packages for phase C

Title	Number	Key people/teams	Time	Nominal start	Nominal stop	Category
Implement CDR observations	560	VAPE Design Team	3 months	12/08/2024	11/11/2024	End of system development
Manufacturing of parts and components	565	Manufacturing team	1.5 years	11/11/2024	18/05/2026	
Assembly of solution from part and components	570	VAPE Assembly Team	1.5 years	18/05/2025	09/11/2026	
Testing conformity of assembly to requirements	580	VAPE Assembly Team	1.5 years	10/11/2025	17/05/2027	Ground testing and verification
Modifications to conform to requirements	590	VAPE Design Team	6 months	17/05/2027	16/11/2027	
Operation qualification	600	Ground/Design Teams	4 months	16/11/2027	14/03/2028	
Identification of functional and operational margins	610	Assembly/Design Teams	3 months	15/11/2027	14/02/2028	
Preparation of PSR	620	Design/Concept Teams	1 month	15/11/2027	13/12/2027	
Preparation of AR	630	Design/Concept Teams	1 month	11/01/2027	14/02/2028	

Table 18 – Work packages for phase D

Title	Number	Key people/teams	Time	Nominal start	Nominal stop	Category
Transportation to launch site	640	Transport contractor	1 month	February 2028	March 2028	Launch Campaign
Launch	650	Launch provider	N/A	March 2028	N/A	
LEOP and commissioning	660	Ground team				Space operations

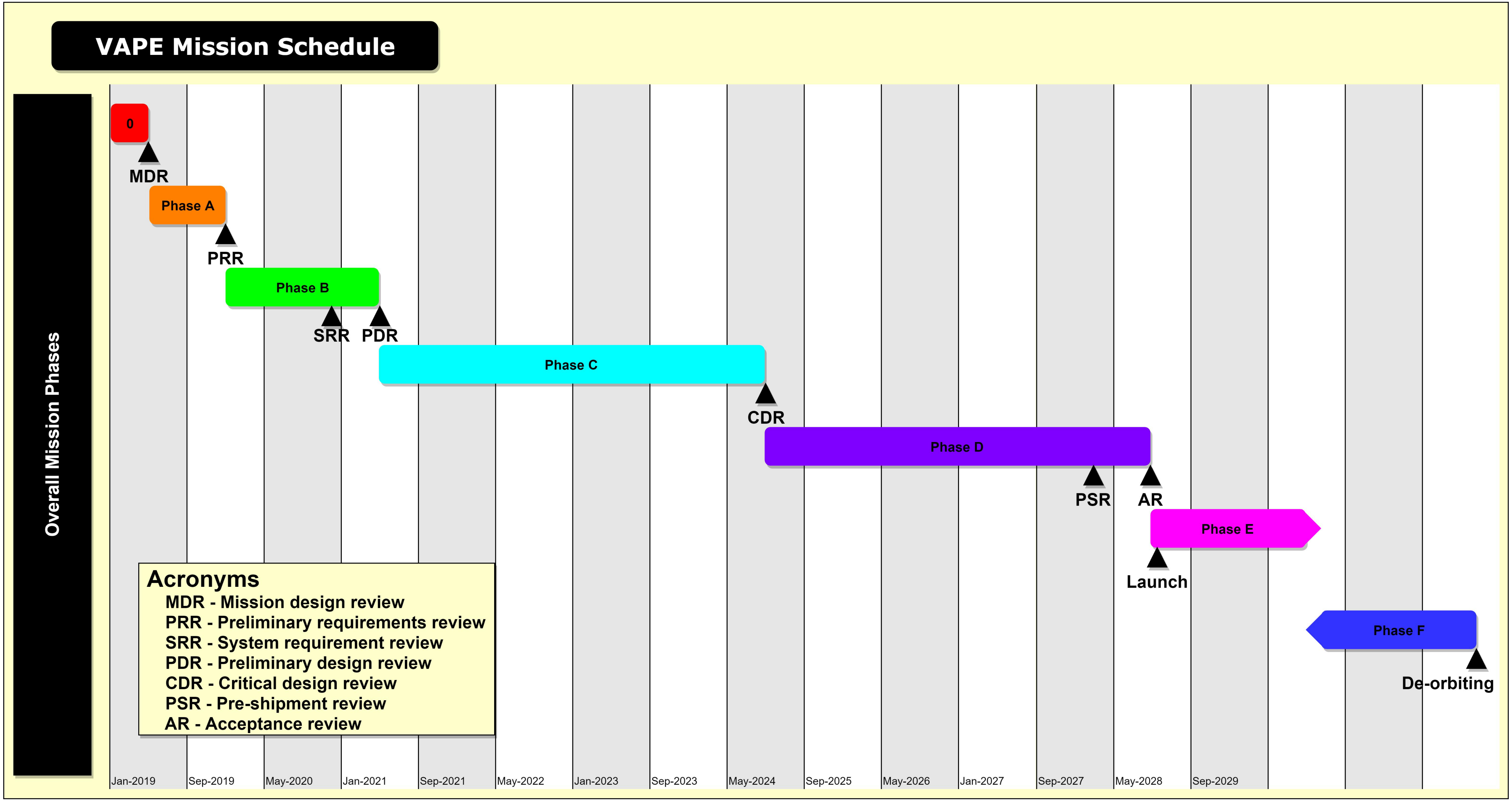
Interplanetary transport	670	Ground team				
Venus orbital insertion and manuevers	680	Ground team				
Nominal operations	690	Ground team				

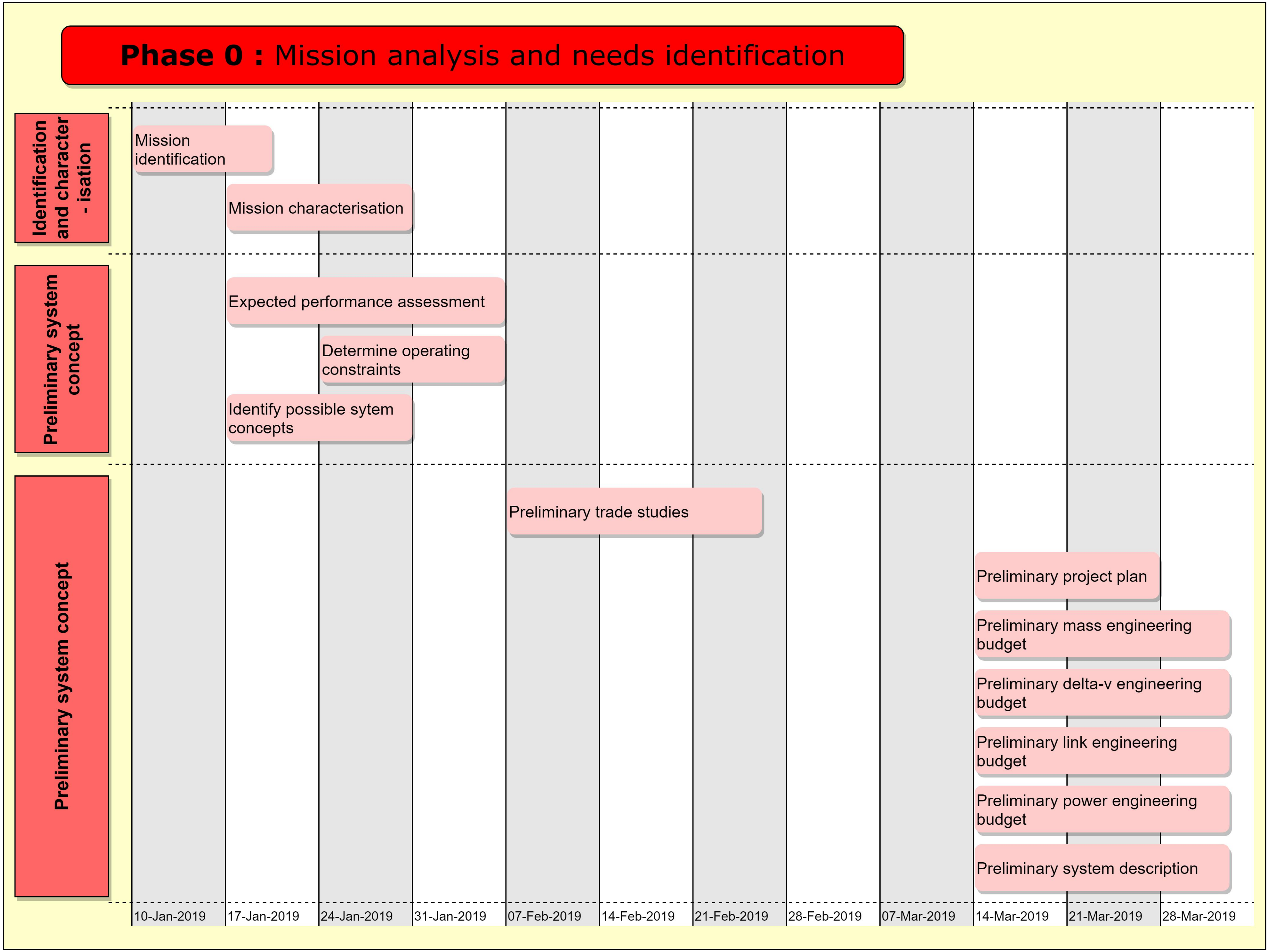
Table 19 – Work packages for phase E

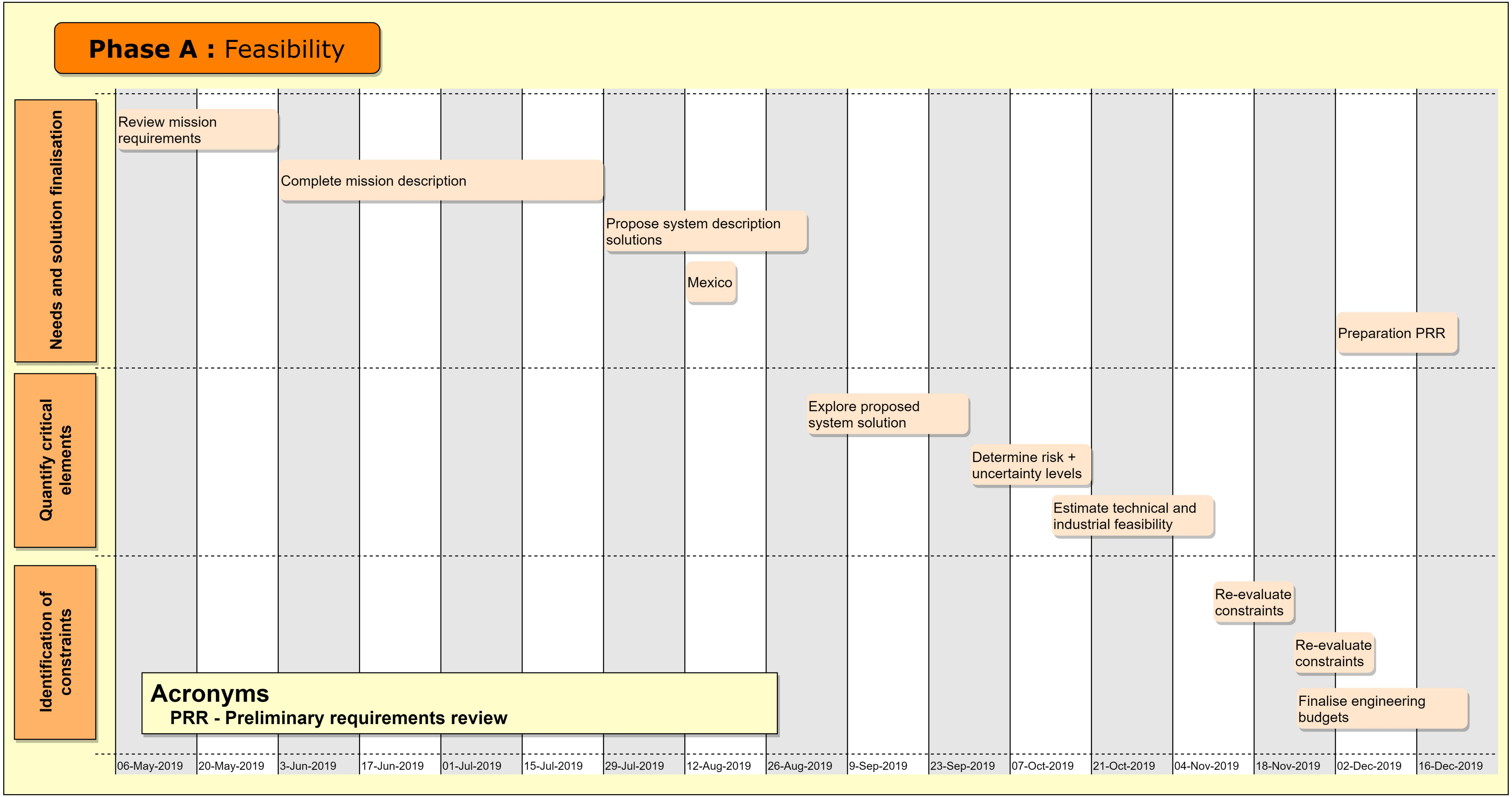
Title	Number	Key people/teams	Time	Nominal start	Nominal stop	Category
EOL procedures	700	Ground team				EOL
De-orbiting	710	Ground team				
Final goodbyes	720	Ground team				

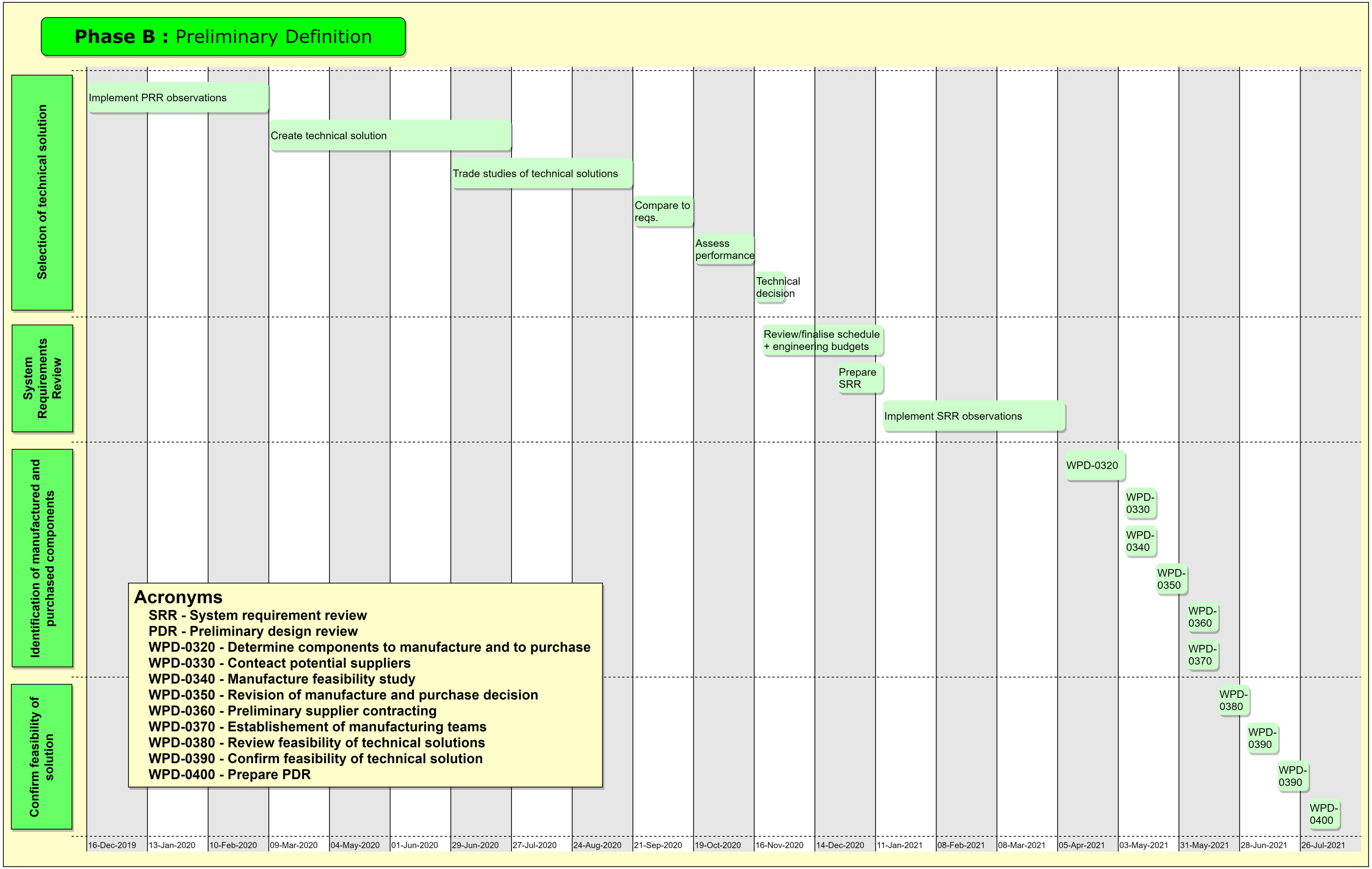
Table 20 – Work packages for phase F

Mission and phases Gantt Charts

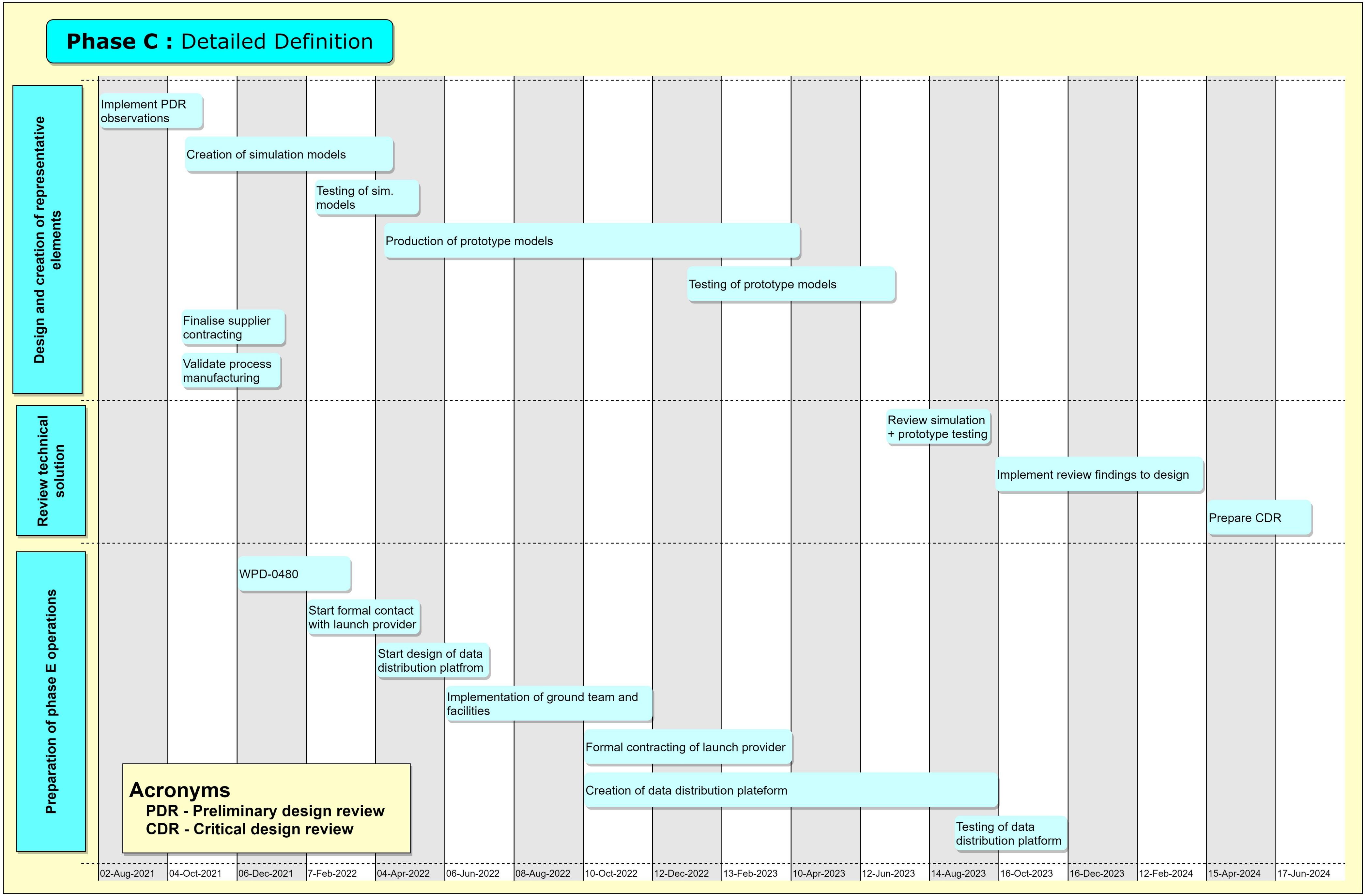

VAPE Mission Schedule
Overall Mission Phases
0
MDR
Phase A
PRR
Phase B
SRR
PDR
Phase C
CDR
Phase D
PSR
AR
Phase E
Launch
Phase F
De-orbiting
Acronyms
MDR - Mission design review
PRR - Preliminary requirements review
SRR - System requirement review
PDR - Preliminary design review
CDR - Critical design review
PSR - Pre-shipment review
AR - Acceptance review
Jan-2019
Sep-2019
May-2020
Jan-2021
Sep-2021
May-2022
Jan-2023
Sep-2023
May-2024
Sep-2025
May-2026
Jan-2027
Sep-2027
May-2028
Sep-2029

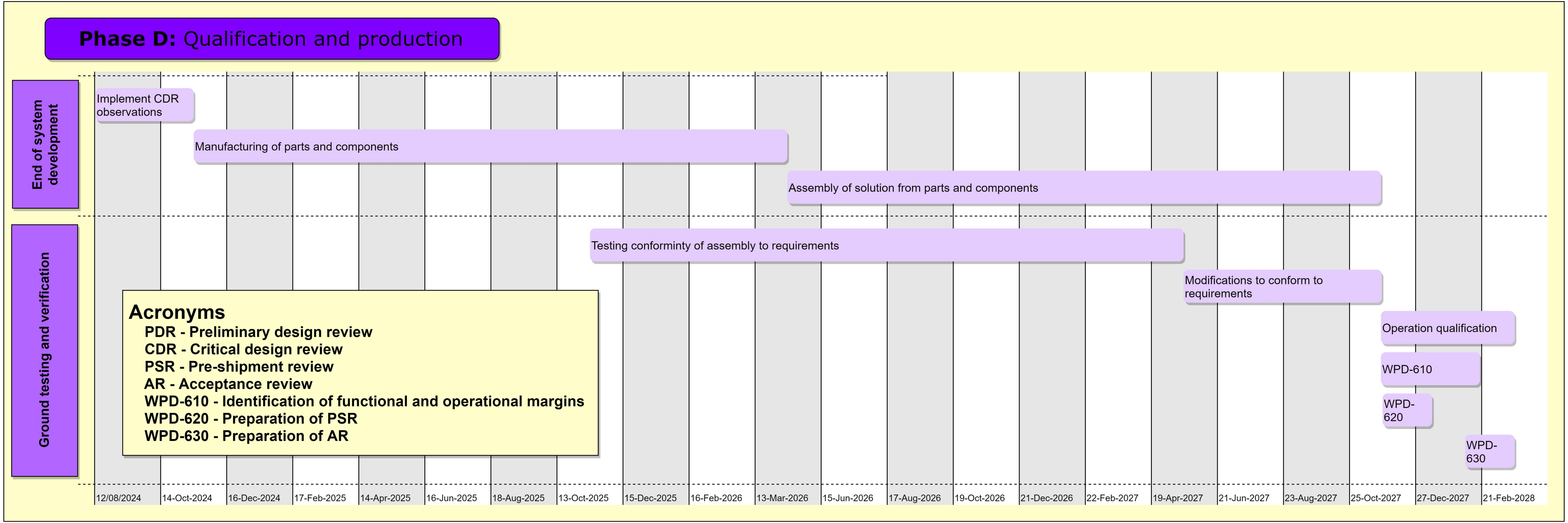

Phase 0 : Mission analysis and needs identification
Identification and character -isation
Mission identification
Mission characterisation
Preliminary system concept
Expected performance assessment
Determine operating constraints
Identify possible sytem concepts
Preliminary system concept
Preliminary trade studies
Preliminary project plan
Preliminary mass engineering budget
Preliminary delta-v engineering budget
Preliminary link engineering budget
Preliminary power engineering budget
Preliminary system description
10-Jan-2019
17-Jan-2019
24-Jan-2019
31-Jan-2019
07-Feb-2019
14-Feb-2019
21-Feb-2019
28-Feb-2019
07-Mar-2019
14-Mar-2019
21-Mar-2019
28-Mar-2019

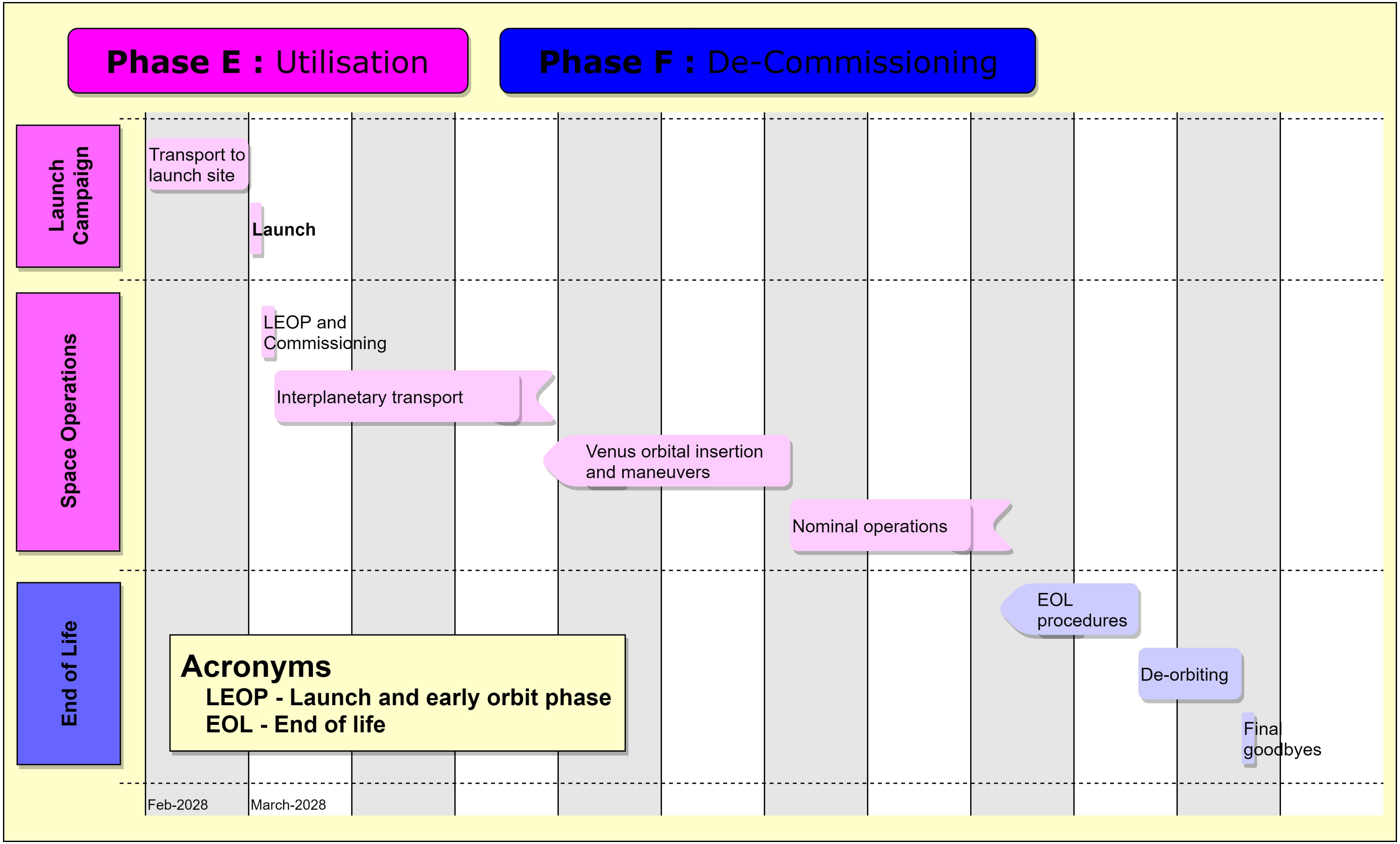

Phase A : Feasibility
Needs and solution finalisation
Review mission requirements
Complete mission description
Propose system description solutions
Mexico
Preparation PRR
Quantify critical elements
Explore proposed system solution
Determine risk + uncertainty levels
Estimate technical and industrial feasibility
Identification of constraints
Re-evaluate constraints
Re-evaluate constraints
Finalise engineering budgets
Acronyms
PRR - Preliminary requirements review
06-May-2019
20-May-2019
3-Jun-2019
17-Jun-2019
01-Jul-2019
15-Jul-2019
29-Jul-2019
12-Aug-2019
26-Aug-2019
9-Sep-2019
23-Sep-2019
07-Oct-2019
21-Oct-2019
04-Nov-2019
18-Nov-2019
02-Dec-2019
16-Dec-2019



Phase B : Preliminary Definition
Selection of technical solution
Implement PRR observations
Create technical solution
Trade studies of technical solutions
Compare to reqs.
Assess performance
Technical decision
System Requirements Review
Review/finalise schedule + engineering budgets
Prepare SRR
Implement SRR observations
Identification of manufactured and purchased components
WPD-0320
WPD-0330
WPD-0340
WPD-0350
WPD-0360
WPD-0370
Confirm feasibility of solution
WPD-0380
WPD-0390
WPD-0390
WPD-0400
Acronyms
SRR - System requirement review
PDR - Preliminary design review
WPD-0320 - Determine components to manufacture and to purchase
WPD-0330 - Conteact potential suppliers
WPD-0340 - Manufacture feasibility study
WPD-0350 - Revision of manufacture and purchase decision
WPD-0360 - Preliminary supplier contracting
WPD-0370 - Establishement of manufacturing teams
WPD-0380 - Review feasibility of technical solutions
WPD-0390 - Confirm feasibility of technical solution
WPD-0400 - Prepare PDR
16-Dec-2019
13-Jan-2020
10-Feb-2020
09-Mar-2020
04-May-2020
01-Jun-2020
29-Jun-2020
27-Jul-2020
24-Aug-2020
21-Sep-2020
19-Oct-2020
16-Nov-2020
14-Dec-2020
11-Jan-2021
08-Feb-2021
08-Mar-2021
05-Apr-2021
03-May-2021
31-May-2021
28-Jun-2021
26-Jul-2021


Phase C : Detailed Definition
Design and creation of representative elements
Implement PDR observations
Creation of simulation models
Testing of sim. models
Production of prototype models
Testing of prototype models
Finalise supplier contracting
Validate process manufacturing
Review technical solution
Review simulation + prototype testing
Implement review findings to design
Prepare CDR
Preparation of phase E operations
WPD-0480
Start formal contact with launch provider
Start design of data distribution platfrom
Implementation of ground team and facilities
Formal contracting of launch provider
Creation of data distribution plateform
Testing of data distribution platform
Acronyms
PDR - Preliminary design review
CDR - Critical design review
02-Aug-2021
04-Oct-2021
06-Dec-2021
7-Feb-2022
04-Apr-2022
06-Jun-2022
08-Aug-2022
10-Oct-2022
12-Dec-2022
13-Feb-2023
10-Apr-2023
12-Jun-2023
14-Aug-2023
16-Oct-2023
16-Dec-2023
12-Feb-2024
15-Apr-2024
17-Jun-2024


Phase D: Qualification and production
End of system development
Ground testing and verification
Implement CDR observations
Manufacturing of parts and components
Assembly of solution from parts and components
Testing conforminty of assembly to requirements
Modifications to conform to requirements
Operation qualification
WPD-610
WPD-620
WPD-630
Acronyms
PDR - Preliminary design review
CDR - Critical design review
PSR - Pre-shipment review
AR - Acceptance review
WPD-610 - Identification of functional and operational margins
WPD-620 - Preparation of PSR
WPD-630 - Preparation of AR
12/08/2024
14-Oct-2024
16-Dec-2024
17-Feb-2025
14-Apr-2025
16-Jun-2025
18-Aug-2025
13-Oct-2025
15-Dec-2025
16-Feb-2026
13-Mar-2026
15-Jun-2026
17-Aug-2026
19-Oct-2026
21-Dec-2026
22-Feb-2027
19-Apr-2027
21-Jun-2027
23-Aug-2027
25-Oct-2027
27-Dec-2027
21-Feb-2028



Phase E : Utilisation
Phase F : De-Commissioning
Launch Campaign
Space Operations
End of Life
Transport to launch site
Launch
LEOP and Commissioning
Interplanetary transport
Venus orbital insertion and maneuvers
Nominal operations
EOL procedures
De-orbiting
Final goodbyes
Acronyms
LEOP - Launch and early orbit phase
EOL - End of life
Feb-2028
March-2028

Appendix A – Subsystem block diagrams

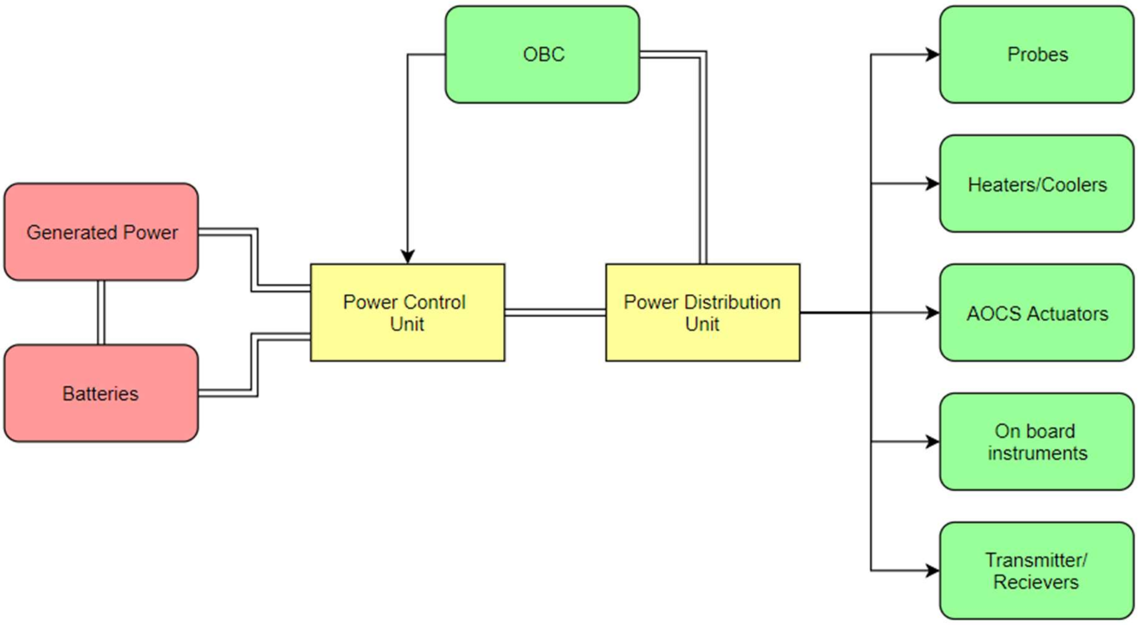


Figure 39 – Power subsytem block diagram

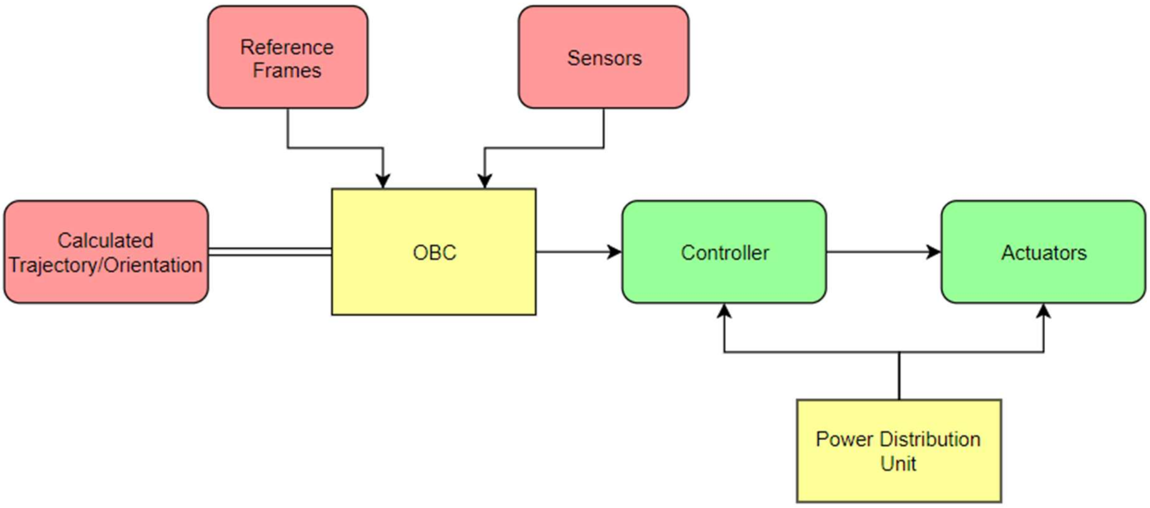


Figure 40 - Attitude control subsystem block diagram

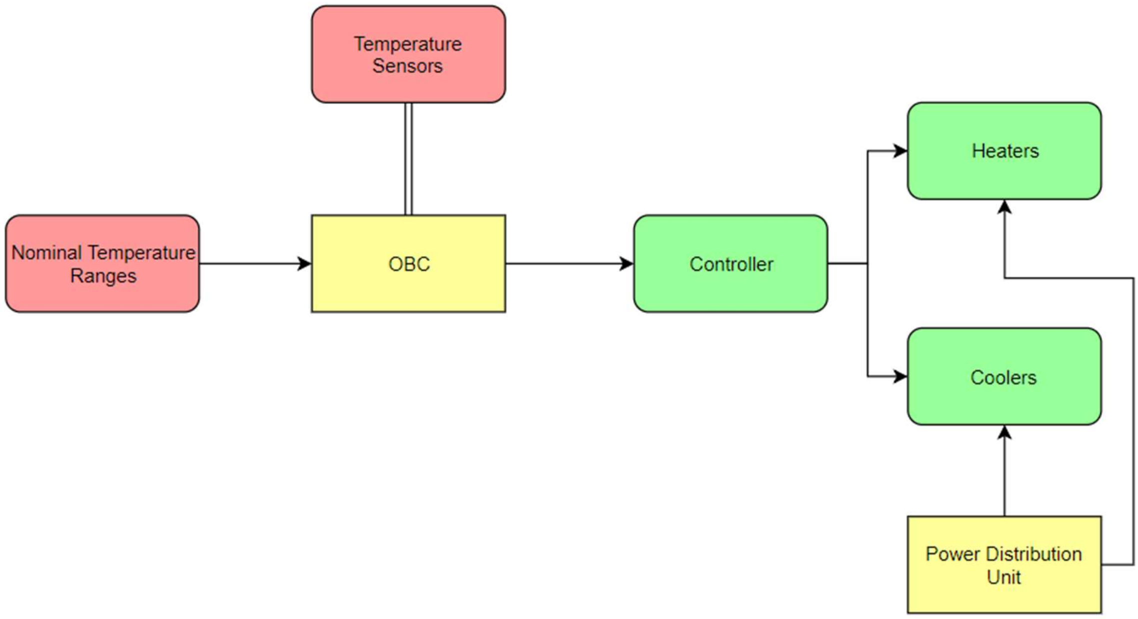


Figure 41 - Thermal subsystem block diagram

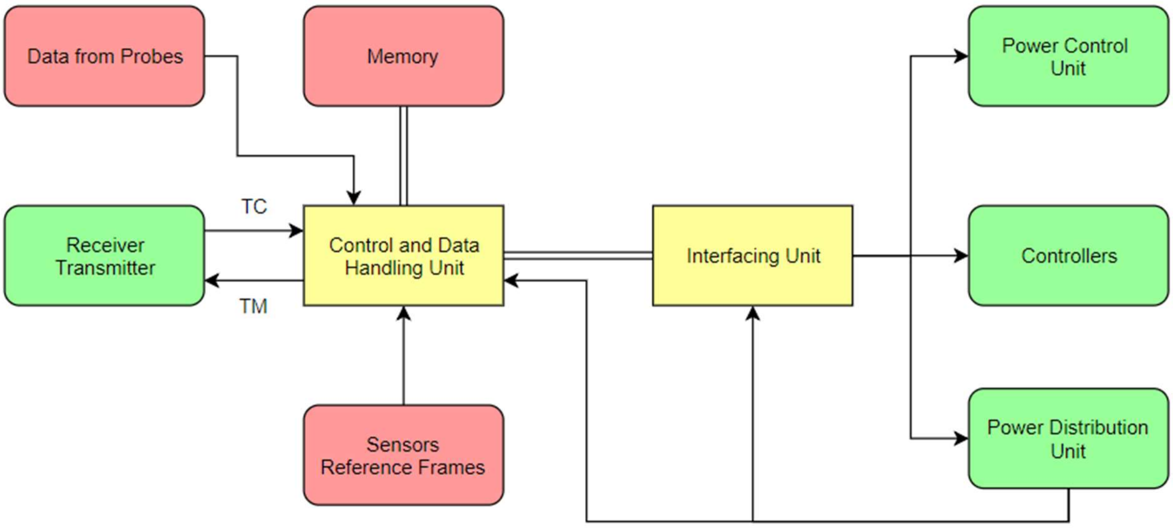


Figure 42 - Computer subsystem block diagram

Appendix B – Orbital parameters trade study

Criteria

Criterion	Justification
Ground station access time	Crucial to relay the information for analyzing
Perturbations	More corrections to gain an accurate data
Power generation	Propulsion system for satellite in Venus orbit
Global coverage	More areas to cover and more data

So, we shall apply each of these criteria on each orbit we have and see the most suitable one for our mission objectives based on our mission requirements.

GROUND STATION ACCESS TIME

Low inclination orbit

- Three Ground stations access times; we shall see how long it takes for the data to be transfer going back and forth from the ground stations to the satellite with inclination of 35 deg

```
                                                                              6 Mar 2019 18:00:47
FOR UNFUNDED EDUCATIONAL USE ONLY
Facility-Hartebeesthoek_STDN_HB33-To-Satellite-Satellite2:  Access Summary Report


Hartebeesthoek_STDN_HB33-To-Satellite2
--------------------------------------
                   Access      Start Time (UTCG)           Stop Time (UTCG)        Duration (sec)
                   ------   ------------------------   ------------------------    --------------

Global Statistics
-----------------
Min Duration           1    6 Mar 2019 01:24:36.356    6 Mar 2019 01:37:27.071           770.714
Max Duration           2    6 Mar 2019 02:13:24.423    6 Mar 2019 03:10:28.554          3424.131
Mean Duration                                                                           3128.695
Total Duration                                                                         28158.256
                                                                              6 Mar 2019 18:02:31
FOR UNFUNDED EDUCATIONAL USE ONLY
Facility-MILA_STDN_MILA-To-Satellite-Satellite2:  Access Summary Report


MILA_STDN_MILA-To-Satellite2 - Hartebeesthoek_STDN_HB33-To-Satellite2
---------------------------------------------------------------------
                   Access      Start Time (UTCG)           Stop Time (UTCG)        Duration (sec)
                   ------   ------------------------   ------------------------    --------------
                        1    5 Mar 2019 16:55:14.281    5 Mar 2019 17:52:19.586          3425.305
                        2    5 Mar 2019 18:28:15.953    5 Mar 2019 19:25:21.061          3425.108
                        3    5 Mar 2019 20:01:17.621    5 Mar 2019 20:09:44.776           507.155
                        4    6 Mar 2019 09:58:32.788    6 Mar 2019 10:55:35.922          3423.134
                        5    6 Mar 2019 11:31:34.461    6 Mar 2019 12:28:37.401          3422.940
                        6    6 Mar 2019 13:04:36.131    6 Mar 2019 14:01:38.866          3422.736
                        7    6 Mar 2019 14:37:37.792    6 Mar 2019 15:34:40.338          3422.546
                        8    6 Mar 2019 16:10:39.454    6 Mar 2019 16:50:46.413          2406.959

Global Statistics
-----------------
Min Duration            3    5 Mar 2019 20:01:17.621    5 Mar 2019 20:09:44.776           507.155
Max Duration            1    5 Mar 2019 16:55:14.281    5 Mar 2019 17:52:19.586          3425.305
Mean Duration                                                                           2931.985
Total Duration                                                                         23455.883
                                                                              6 Mar 2019 18:03:50
FOR UNFUNDED EDUCATIONAL USE ONLY
Facility-SGS_Oakhanger_Site_Annex-To-Satellite-Satellite2:  Access Summary Report


SGS_Oakhanger_Site_Annex-To-Satellite2 - Hartebeesthoek_STDN_HB33-To-Satellite2
-------------------------------------------------------------------------------
                   Access      Start Time (UTCG)           Stop Time (UTCG)        Duration (sec)
                   ------   ------------------------   ------------------------    --------------
                        1    6 Mar 2019 05:20:38.445    6 Mar 2019 06:16:31.467          3353.022
                        2    6 Mar 2019 06:52:29.420    6 Mar 2019 07:49:32.943          3423.523
                        3    6 Mar 2019 08:25:31.086    6 Mar 2019 09:22:34.416          3423.331
                        4    6 Mar 2019 09:58:32.757    6 Mar 2019 10:55:35.887          3423.131
                        5    6 Mar 2019 11:31:34.417    6 Mar 2019 12:28:37.357          3422.940
                        6    6 Mar 2019 13:04:36.086    6 Mar 2019 13:48:56.952          2660.866

Global Statistics
-----------------
Min Duration            6    6 Mar 2019 13:04:36.086    6 Mar 2019 13:48:56.952          2660.866
Max Duration            2    6 Mar 2019 06:52:29.420    6 Mar 2019 07:49:32.943          3423.523
Mean Duration                                                                           3284.469
```

Figure 19; showing the access time between VAPE and the stations

- The access full time duration for D-1 station is 7.8 Hour
- The access full time duration for D-2 station is 0.66 Hour
- The access full time duration for D-3 is 5.47 Hour

Sun-synchronous orbit

- Three Ground stations access times; we shall see how long it takes for the data to be transfer going back and forth from the ground stations to the satellite with inclination of

```
                                                                                   6 Mar 2019 18:06:49
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Facility-Hartebeesthoek_STDN_HB33-To-Satellite-Satellite2:  Access Summary Report


Hartebeesthoek_STDN_HB33-To-Satellite2 - Hartebeesthoek_STDN_HB33-To-Satellite2
-------------------------------------------------------------------------------
                  Access      Start Time (UTCG)           Stop Time (UTCG)        Duration (sec)
                  ------  ------------------------  ------------------------  --------------
                       1  6 Mar 2019 01:24:36.394   6 Mar 2019 01:57:44.050         1987.657
                       2  6 Mar 2019 02:26:57.178   6 Mar 2019 03:30:42.656         3825.479
                       3  6 Mar 2019 03:59:58.031   6 Mar 2019 05:03:41.281         3823.249
                       4  6 Mar 2019 05:32:58.890   6 Mar 2019 06:36:39.915         3821.026
                       5  6 Mar 2019 07:05:59.737   6 Mar 2019 08:09:38.562         3818.825
                       6  6 Mar 2019 08:39:00.590   6 Mar 2019 09:42:37.213         3816.623
                       7  6 Mar 2019 10:12:01.431   6 Mar 2019 11:15:35.869         3814.438
                       8  6 Mar 2019 11:45:02.278   6 Mar 2019 12:48:34.523         3812.245
                       9  6 Mar 2019 13:18:03.113   6 Mar 2019 14:05:46.242         2863.129

Global Statistics
-----------------
Min Duration           1  6 Mar 2019 01:24:36.394   6 Mar 2019 01:57:44.050         1987.657
Max Duration           2  6 Mar 2019 02:26:57.178   6 Mar 2019 03:30:42.656         3825.479
Mean Duration                                                                       3509.186
Total Duration                                                                     31582.671
```

```
                                                                                   6 Mar 2019 18:07:56
FOR UNFUNDED EDUCATIONAL USE ONLY
Facility-MILA_STDN_MILA-To-Satellite-Satellite2:  Access Summary Report


MILA_STDN_MILA-To-Satellite2 - Hartebeesthoek_STDN_HB33-To-Satellite2
---------------------------------------------------------------------
                  Access      Start Time (UTCG)           Stop Time (UTCG)        Duration (sec)
                  ------  ------------------------  ------------------------  --------------
                       1  5 Mar 2019 17:08:51.879   5 Mar 2019 18:12:51.245         3839.366
                       2  5 Mar 2019 18:41:52.762   5 Mar 2019 19:45:49.810         3837.048
                       3  6 Mar 2019 10:12:01.370   6 Mar 2019 11:15:35.744         3814.374
                       4  6 Mar 2019 11:45:02.207   6 Mar 2019 12:48:34.411         3812.204
                       5  6 Mar 2019 13:18:03.050   6 Mar 2019 14:21:33.087         3810.037
                       6  6 Mar 2019 14:51:03.881   6 Mar 2019 15:54:31.774         3807.893
                       7  6 Mar 2019 16:24:04.718   6 Mar 2019 16:50:46.411         1601.693

Global Statistics
-----------------
Min Duration           7  6 Mar 2019 16:24:04.718   6 Mar 2019 16:50:46.411         1601.693
Max Duration           1  5 Mar 2019 17:08:51.879   5 Mar 2019 18:12:51.245         3839.366
Mean Duration                                                                       3503.231
Total Duration                                                                     24522.616
```

```
                                                                                   6 Mar 2019 18:08:26
FOR UNFUNDED EDUCATIONAL USE ONLY
Facility-SGS_Oakhanger_Site_Annex-To-Satellite-Satellite2:  Access Summary Report


SGS_Oakhanger_Site_Annex-To-Satellite2 - Hartebeesthoek_STDN_HB33-To-Satellite2
-------------------------------------------------------------------------------
                  Access      Start Time (UTCG)           Stop Time (UTCG)        Duration (sec)
                  ------  ------------------------  ------------------------  --------------
                       1  6 Mar 2019 05:32:58.802   6 Mar 2019 06:36:39.849         3821.048
                       2  6 Mar 2019 07:05:59.650   6 Mar 2019 08:09:38.489         3818.839
                       3  6 Mar 2019 08:39:00.502   6 Mar 2019 09:42:37.134         3816.632
                       4  6 Mar 2019 10:12:01.343   6 Mar 2019 11:15:35.791         3814.448
                       5  6 Mar 2019 11:45:02.190   6 Mar 2019 12:48:34.449         3812.259
                       6  6 Mar 2019 13:18:03.025   6 Mar 2019 13:48:56.964         1853.939

Global Statistics
-----------------
Min Duration           6  6 Mar 2019 13:18:03.025   6 Mar 2019 13:48:56.964         1853.939
Max Duration           1  6 Mar 2019 05:32:58.802   6 Mar 2019 06:36:39.849         3821.048
Mean Duration                                                                       3489.527
Total Duration                                                                     20937.165
```

98 deg

Figure 20; showing the access time between VAPE and the stations

- The access full time duration for D-1 station is 8.7 Hour
- The access full time duration for D-2 station is 6.8 Hour
- The access full time duration for D-3 is 5.8 Hour

Polar orbit

- Three ground stations access times; we shall see how long it takes for the data to be transfer going back and forth from the ground stations to the satellite with inclination of 90 deg

6 Mar 2019 18:10:40

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Facility-Hartebeesthoek_STDN_HB33-To-Satellite-Satellite2: Access Summary Report

Hartebeesthoek_STDN_HB33-To-Satellite2 - Hartebeesthoek_STDN_HB33-To-Satellite2

	Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
	1	6 Mar 2019 01:24:36.386	6 Mar 2019 01:54:25.558	1789.172
	2	6 Mar 2019 02:23:05.606	6 Mar 2019 03:27:24.613	3859.007
	3	6 Mar 2019 03:56:07.231	6 Mar 2019 05:00:23.686	3856.455
	4	6 Mar 2019 05:29:08.841	6 Mar 2019 06:33:22.767	3853.926
	5	6 Mar 2019 07:02:10.447	6 Mar 2019 08:06:21.862	3851.415
	6	6 Mar 2019 08:35:12.041	6 Mar 2019 09:39:20.959	3848.918
	7	6 Mar 2019 10:08:13.630	6 Mar 2019 11:12:20.060	3846.431
	8	6 Mar 2019 11:41:15.216	6 Mar 2019 12:45:19.167	3843.951
	9	6 Mar 2019 13:14:16.796	6 Mar 2019 14:05:46.207	3089.411
Global Statistics				
Min Duration	1	6 Mar 2019 01:24:36.386	6 Mar 2019 01:54:25.558	1789.172
Max Duration	2	6 Mar 2019 02:23:05.606	6 Mar 2019 03:27:24.613	3859.007
Mean Duration				3537.632
Total Duration				31838.686

6 Mar 2019 18:11:52

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Facility-MILA_STDN_MILA-To-Satellite-Satellite2: Access Summary Report

MILA_STDN_MILA-To-Satellite2 - Hartebeesthoek_STDN_HB33-To-Satellite2

	Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
	1	5 Mar 2019 17:04:55.588	5 Mar 2019 18:09:30.448	3874.860
	2	5 Mar 2019 18:37:57.252	5 Mar 2019 19:42:29.464	3872.212
	3	6 Mar 2019 10:08:13.596	6 Mar 2019 11:12:19.940	3846.344
	4	6 Mar 2019 11:41:15.180	6 Mar 2019 12:45:19.054	3843.873
	5	6 Mar 2019 13:14:16.759	6 Mar 2019 14:18:18.174	3841.415
	6	6 Mar 2019 14:47:18.325	6 Mar 2019 15:51:17.306	3838.981
	7	6 Mar 2019 16:20:19.889	6 Mar 2019 16:50:46.411	1826.523
Global Statistics				
Min Duration	7	6 Mar 2019 16:20:19.889	6 Mar 2019 16:50:46.411	1826.523
Max Duration	1	5 Mar 2019 17:04:55.588	5 Mar 2019 18:09:30.448	3874.860
Mean Duration				3563.458
Total Duration				24944.207

6 Mar 2019 18:12:20

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Facility-SGS_Oakhanger_Site_Annex-To-Satellite-Satellite2: Access Summary Report

SGS_Oakhanger_Site_Annex-To-Satellite2 - Hartebeesthoek_STDN_HB33-To-Satellite2

	Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
	1	6 Mar 2019 05:29:08.757	6 Mar 2019 06:33:22.687	3853.930
	2	6 Mar 2019 07:02:10.361	6 Mar 2019 08:06:21.770	3851.410
	3	6 Mar 2019 08:35:11.964	6 Mar 2019 09:39:20.868	3848.905
	4	6 Mar 2019 10:08:13.555	6 Mar 2019 11:12:19.968	3846.413
	5	6 Mar 2019 11:41:15.141	6 Mar 2019 12:45:19.079	3843.938
	6	6 Mar 2019 13:14:16.717	6 Mar 2019 13:48:56.949	2080.232
Global Statistics				
Min Duration	6	6 Mar 2019 13:14:16.717	6 Mar 2019 13:48:56.949	2080.232
Max Duration	1	6 Mar 2019 05:29:08.757	6 Mar 2019 06:33:22.687	3853.930
Mean Duration				3554.138
Total Duration				21324.828

Figure 21; showing the access time between VAPE and the stations

- The access full time duration for D-1 station is 8.8 Hour
- The access full time duration for D-2 station is 6.65 Hour
- The access full time duration for D-2 is 6.1 Hour

Based on the calculations for the three orbits, we found out that the most appropriate orbit that keep sending data with the longest duration is the **polar orbit**. Which means, more data

Perturbations

Low inclination orbit

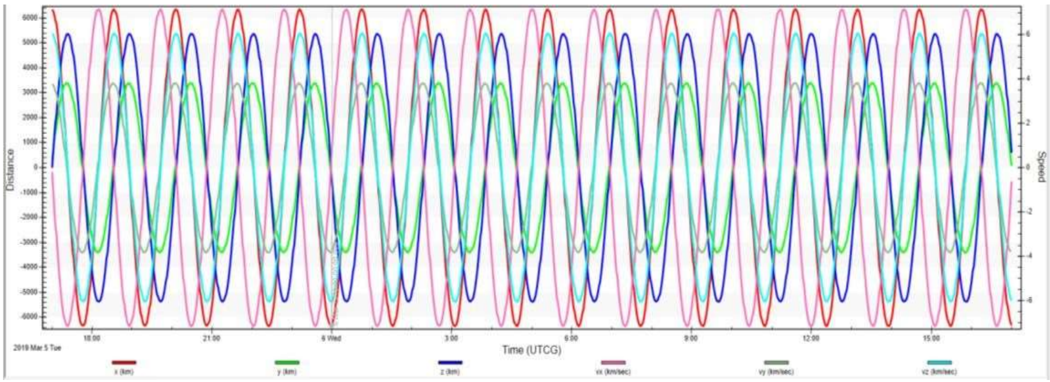

Figure 22; showing the Vape perturbations over Venus

As we see the p correction, especially with y component (displacement) and Vz component (speed)

Sun-synchronous orbit

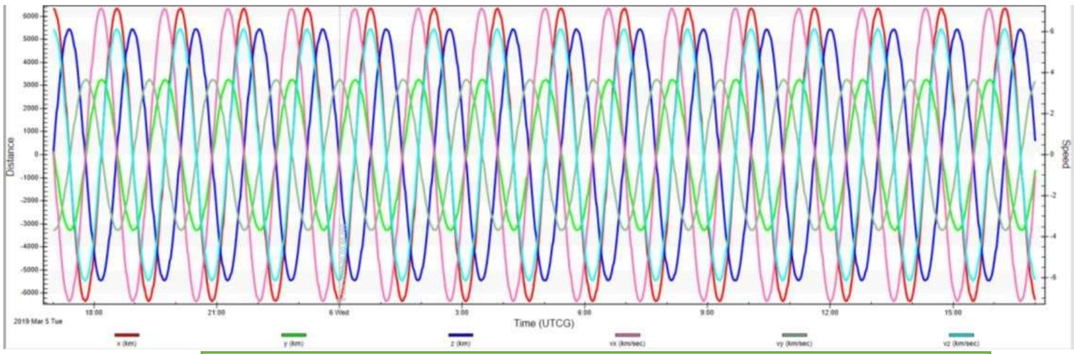

Figure 23; showing the Vape perturbations over Venus

Over here, the rate of error is much less than the previous orbit, but we still have some major perturbations with Vz component (speed) and y component (displacement).

Polar orbit□

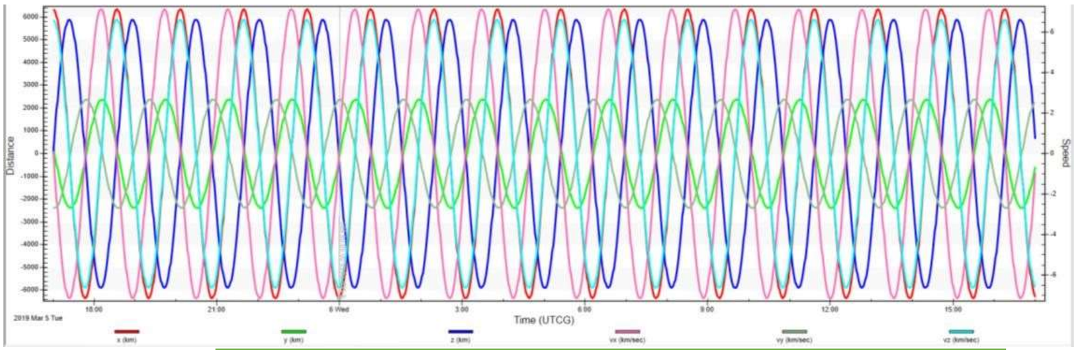

Figure 24; showing the Vape perturbations over Venus

Based on the last two previous orbits, we can see that the **polar orbit** is the most suitable orbit, which needs a little of corrections for Vz component only. That means less observation □ less cost □ and spend more time to focus on the main objective of the mission.

Power generation□

Satellites can generally receive signals and send them bac to Earth, so to make this possible, a satellite must produce its own power, generating electricity from sunlight falling on solar panels.

Low inclination orbit □

Time (UTCG)	Power (W)	Solar Intensity
5 Mar 2019 17:00:00.000	46.331	1.000000
5 Mar 2019 17:30:00.000	46.323	1.000000
5 Mar 2019 18:00:00.000	0.000	0.000000
5 Mar 2019 18:30:00.000	46.288	1.000000
5 Mar 2019 19:00:00.000	46.292	1.000000
5 Mar 2019 19:30:00.000	0.000	0.000000
5 Mar 2019 20:00:00.000	46.272	1.000000
5 Mar 2019 20:30:00.000	46.280	1.000000
5 Mar 2019 21:00:00.000	0.000	0.000000
5 Mar 2019 21:30:00.000	46.248	1.000000
5 Mar 2019 22:00:00.000	46.245	1.000000
5 Mar 2019 22:30:00.000	0.000	0.000000
5 Mar 2019 23:00:00.000	46.221	1.000000
5 Mar 2019 23:30:00.000	46.217	1.000000
6 Mar 2019 00:00:00.000	0.000	0.000000
6 Mar 2019 00:30:00.000	0.000	0.000000
6 Mar 2019 01:00:00.000	46.189	1.000000
6 Mar 2019 01:30:00.000	0.000	0.000000
6 Mar 2019 02:00:00.000	0.000	0.000000
6 Mar 2019 02:30:00.000	46.166	1.000000
6 Mar 2019 03:00:00.000	46.150	1.000000
6 Mar 2019 03:30:00.000	0.000	0.000000
6 Mar 2019 04:00:00.000	46.134	1.000000
6 Mar 2019 04:30:00.000	46.134	1.000000
6 Mar 2019 05:00:00.000	0.000	0.000000
6 Mar 2019 05:30:00.000	46.079	1.000000
6 Mar 2019 06:00:00.000	46.095	1.000000
6 Mar 2019 06:30:00.000	0.000	0.000000

Figure 25; showing the power generation results

As we see here, the power generation (source □ panels) provides low rate power, which would cost us more money to generate more power

Sun-synchronous orbit

Time (UTCG)	Power (W)	Solar Intensity
5 Mar 2019 17:00:00.000	232.213	1.000000
5 Mar 2019 17:30:00.000	0.000	0.000000
5 Mar 2019 18:00:00.000	231.796	1.000000
5 Mar 2019 18:30:00.000	231.517	1.000000
5 Mar 2019 19:00:00.000	231.364	1.000000
5 Mar 2019 19:30:00.000	213.138	0.922212
5 Mar 2019 20:00:00.000	230.861	1.000000
5 Mar 2019 20:30:00.000	230.637	1.000000
5 Mar 2019 21:00:00.000	0.000	0.000000
5 Mar 2019 21:30:00.000	230.212	1.000000
5 Mar 2019 22:00:00.000	230.012	1.000000
5 Mar 2019 22:30:00.000	0.000	0.000000
5 Mar 2019 23:00:00.000	229.556	1.000000
5 Mar 2019 23:30:00.000	229.348	1.000000
6 Mar 2019 00:00:00.000	0.000	0.000000
6 Mar 2019 00:30:00.000	228.872	1.000000
6 Mar 2019 01:00:00.000	228.644	1.000000
6 Mar 2019 01:30:00.000	0.000	0.000000
6 Mar 2019 02:00:00.000	228.188	1.000000
6 Mar 2019 02:30:00.000	227.964	1.000000
6 Mar 2019 03:00:00.000	0.000	0.000000
6 Mar 2019 03:30:00.000	227.543	1.000000
6 Mar 2019 04:00:00.000	227.335	1.000000
6 Mar 2019 04:30:00.000	0.000	0.000000
6 Mar 2019 05:00:00.000	226.879	1.000000
6 Mar 2019 05:30:00.000	226.671	1.000000
6 Mar 2019 06:00:00.000	0.000	0.000000
6 Mar 2019 06:30:00.000	226.203	1.000000
6 Mar 2019 07:00:00.000	225.983	1.000000

Figure 26; showing the power generation results

As we see here, the rate of power generation is high and it should be suitable for our mission, gaining more free power, low cost.

Polar orbit

Time (UTCG)	Power (W)	Solar Intensity
5 Mar 2019 17:00:00.000	226.219	1.000000
5 Mar 2019 17:30:00.000	225.983	1.000000
5 Mar 2019 18:00:00.000	0.000	0.000000
5 Mar 2019 18:30:00.000	225.492	1.000000
5 Mar 2019 19:00:00.000	225.291	1.000000
5 Mar 2019 19:30:00.000	0.000	0.000000
5 Mar 2019 20:00:00.000	224.831	1.000000
5 Mar 2019 20:30:00.000	224.591	1.000000
5 Mar 2019 21:00:00.000	0.000	0.000000
5 Mar 2019 21:30:00.000	224.128	1.000000
5 Mar 2019 22:00:00.000	223.931	1.000000
5 Mar 2019 22:30:00.000	0.000	0.000000
5 Mar 2019 23:00:00.000	223.404	1.000000
5 Mar 2019 23:30:00.000	223.271	1.000000
6 Mar 2019 00:00:00.000	0.000	0.000000
6 Mar 2019 00:30:00.000	222.728	1.000000
6 Mar 2019 01:00:00.000	222.567	1.000000
6 Mar 2019 01:30:00.000	0.000	0.000000
6 Mar 2019 02:00:00.000	222.060	1.000000
6 Mar 2019 02:30:00.000	221.848	1.000000
6 Mar 2019 03:00:00.000	0.000	0.000000
6 Mar 2019 03:30:00.000	221.408	1.000000
6 Mar 2019 04:00:00.000	221.105	1.000000
6 Mar 2019 04:30:00.000	0.000	0.000000
6 Mar 2019 05:00:00.000	220.720	1.000000
6 Mar 2019 05:30:00.000	220.382	1.000000
6 Mar 2019 06:00:00.000	0.000	0.000000
6 Mar 2019 06:30:00.000	219.997	1.000000
6 Mar 2019 07:00:00.000	219.725	1.000000

Figure 27; showing the power generation results

As we see here, the rate of power generation has similar rate as Sun-synchronous orbit.

- This time for our mission objective, Sun-synchronous orbit is more suitable for power generation as it generates more free power than low inclination orbit.

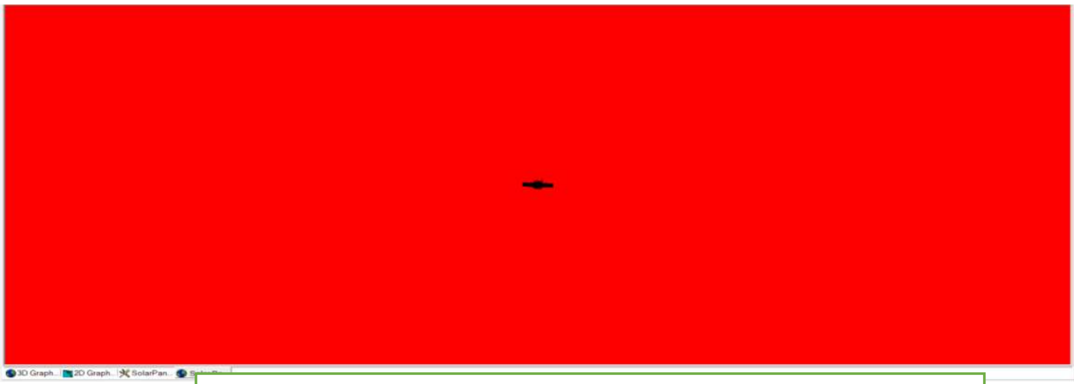

Figure 28; showing the power generation

Converge access time of the satellite above Venus

Low inclination orbit

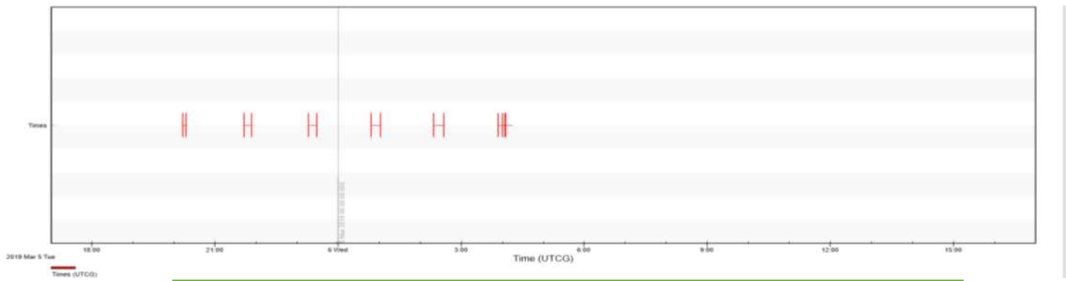

Figure 29; showing the coverage access time

Depends on our simulations on STK, for this orbit, we can see from the figure that coverage time doesn't cover the whole points. Just specific points with specific time.

Sun-synchronous orbit

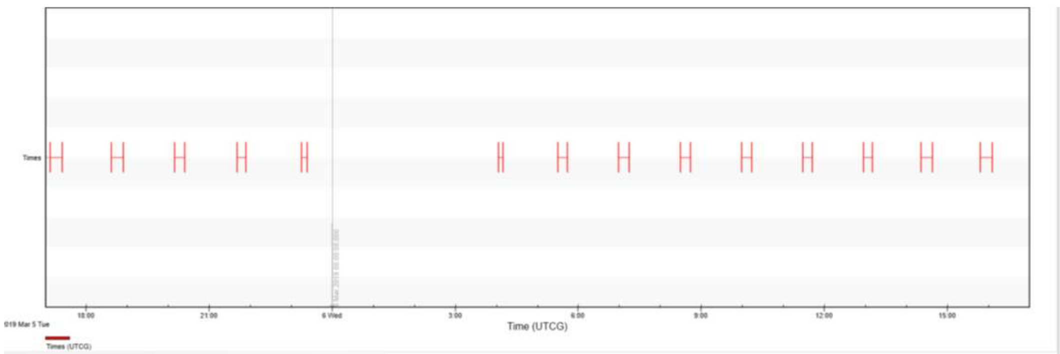

Figure 30; showing the coverage access time

Depends on our simulations on STK, for this orbit, we can see from the figure that coverage time covers more than 60% which is good for our objective.

Polar orbit

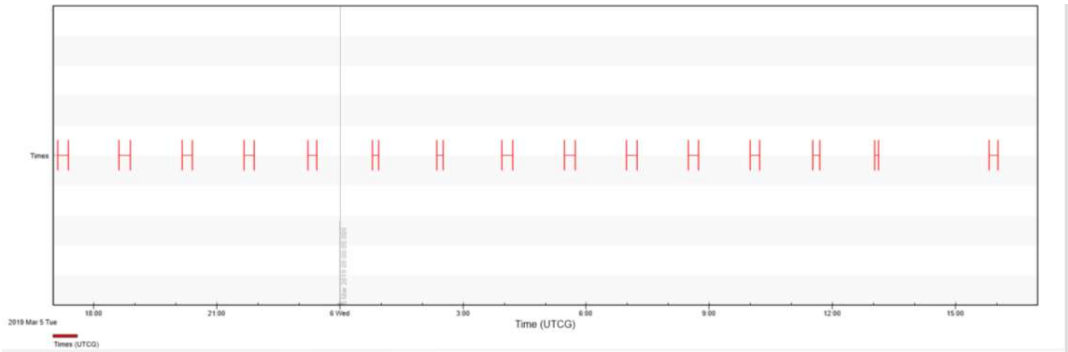

Figure 31; showing the coverage access time

Depends on our simulations on STK, for this orbit, we can see from the figure that coverage time covers almost the whole points. Which consider the best orbit to cover more points, and that means more accurate date. About 90% coverage

- **Polar orbit** coverage access time to Venus orbit is higher than the previous two orbits

Appendix C – Launch vehicle trade study

Timeline

In terms of a launch timeline, this mission segment can be fundamentally broken down into 4 sub-phases:

a. The launch event
b. Insertion into parking orbit
c. Plane change maneuvre
d. Earth-Venus Hohmann Transfer

These sub-phases describe a set of steps necessary for the spacecraft to get from Earth to Venus. The LV will be responsible for executing these steps. It must be noted that the launch provider will not have to account for the entire Hohmann transfer, only the first maneuvre (Earth ejection).

Considering time, interplanetary missions has relatively longer flight profiles in comparison to Lunar or geocentric. The launch event is the quickest and is often less than 5 minutes [1]. For this document, the launch event is being defined as the duration of time between the liftoff and fairing separation.The next sub-phase is the parking orbit. After the spacecraft is out of the atmosphere and the fairing has been separated, the LV either continues or executes some sort of roll program. This type of maneuvre is used to place the spacecraft in a desired orbit from the launch event. Because the VAPE spacecraft's desired orbit is not around Venus, a parking orbit is used to make fine orbital adjustments to prepare for Venus transfer. This step requires more time and can take several hours. After a parking orbit is achieved, during a Venus launch window, the spacecraft would now need to conduct a plane change maneuvre to align its orbital plane with that of Venus (inclined approximately 3.39^{o} from Earth's orbital plane [2]). This maneuvre will ensure that the spacecraft will have the closest encounter with Venus as possible. The final sub-phase is the

Hohmann transfer. As stated earlier, this part contains multiple steps and the launch provider will only be responsible for the first maneuvre. This will set the satellite on an interplanetary trajectory towards Venus and leads into what is called the ‘interplanetary coast’. This launch segment for the VAPE Mission is expected to last some time between 3-12 months [3].

Computation

This section will cover how exactly metrics will be graded. To avoid bias and arbitrary valuations, all metrics are measured with the same technique. This ensures that every viable solution has an equal chance for competing in the trade study. However, because each metric uses the same grading technique, this does not mean that each metric carries equal weight. The weightings of each of the metrics will be discussed next.

To properly valuate each metric, a few key parameters are required:

- Values for each solution (v)
- The maximum value (v_{max})

To create an equal-opportunity situation for each solution, the technique of metric evaluation is ratios. This means that the individual evaluation of a given solution (e) is the ratio its value to the maximum value offered by another solution. This means that the solution with the highest value in a specific metric will receive a ‘perfect’ grade. This technique creates a mathematical space whereby if two solutions have similar value, they receive proportional evaluations. The formula used for evaluations during the trade study is:

$$e_i = \frac{v_i}{v_{max}}$$

Where i denotes the i^{th} solution being evaluated. This grading system also allows for two solutions with the same value to receive the same evaluated grade. In total for a given solution the following pieces of information are required:

- Payload mass to LEO [kg]
- Launch site latitude [°]
- Number of successful launches [ ]
- Number of total launches [ ]
- Cost [$]
- Interplanetary flight heritage [ ]

Metric Weightings

As each individual metric carries different importance to the VAPE mission, each metric has been assigned a unique weighting. To account for this in calculation, all metrics are to be valuated out of the same scale. During the trade study all metrics will be graded out of a minimum 0 and maximum 10 points. The metrics have the following weightings associated with them:

Metric	Weighting [%]
Launch Capability	45
Launch Efficiency	20
Reliability	25
Cost	10
Interplanetary Flight Heritage	N/A (binary metric)

Total	**100**

Table 21 – Trade study metrics and weighting

Solutions at Hand

For this trade study 4 viable solutions will be evaluated. They are all of the same class of LV's and at first glance share many properties. All options that are obviously not suited for the VAPE mission were excluded. The options chosen for study are:

Mitsubishi's H-IIA

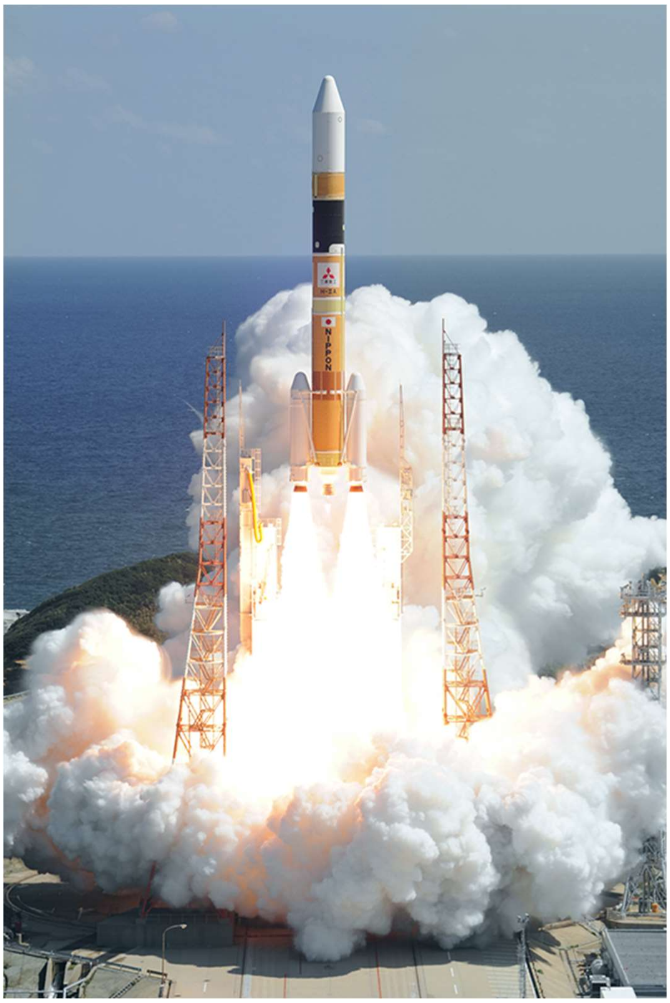

Figure 43 - Mitsubishi H-IIA launching

Payload mass to LEO: 10,000kg [4]

Launch site latitude: ~30.0º N [5]

Number of successful launches: 39 [6]

Number of total launches: 40 [6]

Cost: 90-112.5 M$ [7]

Interplanetary flight heritage: Yes [6]

Roscosmos' Soyuz-FG

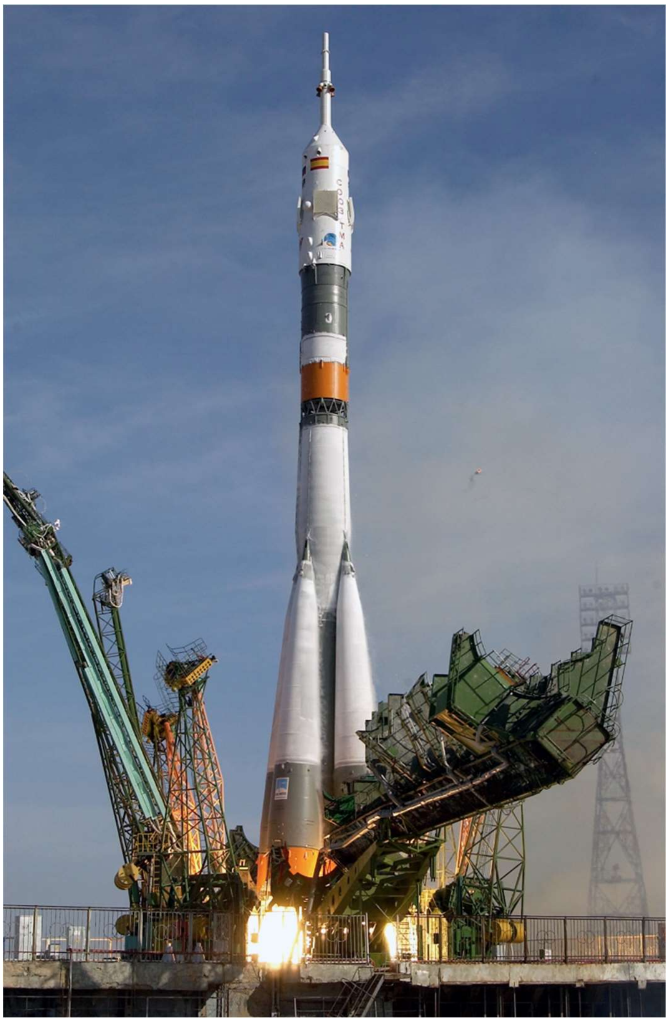

Figure 44 - Soyuz-FG with fregat

Payload mass to LEO: 7,100kg [8]

Launch site latitude: ~46.0° N [9]

Number of successful launches: 66 [10][11]

Number of total launches: 67 [10][11]

Cost: 50 M$ [12]

Interplanetary flight heritage: Yes [11]

ULA’s Atlas V 551

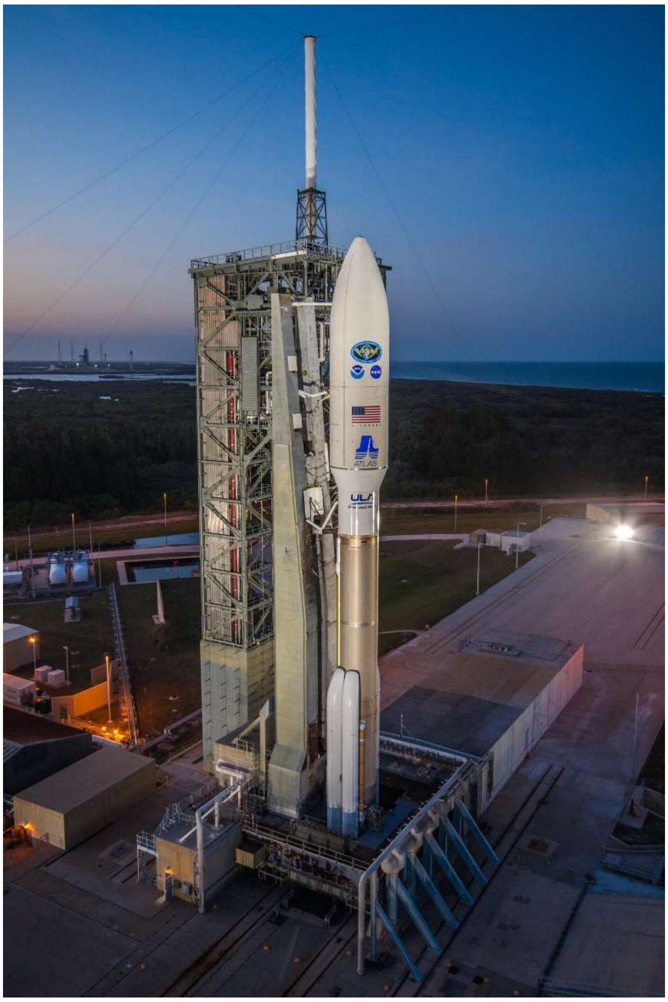

Figure 45 - Atlas V at KSC

Payload mass to LEO: 18,814kg [7]

Launch site latitude: ~28.5º N [13]

Number of successful launches: 78 [14]

Number of total launches: 79 [14]

Cost: 158 M$ [7]

Interplanetary flight heritage: Yes [14]

SpaceX's Falcon Heavy

Figure 46 - Falcon Heavy test flight at KSC

Payload mass to LEO: 63,800kg [15]

Launch site latitude: ~28.5° N [13]

Number of successful launches: 1 [16]

Number of total launches: 1 [16]

Cost: 90 M$ [15]

Interplanetary flight heritage: No [16]

Trade Study Table

Metric	H-IIA	Soyuz-FG/Fregat	Atlas V	Falcon Heavy
Launch Capability (45%)	0.71	0.55	1.33	4.50
Launch Efficiency (20%)	1.87	1.14	2.00	2.00
Reliability (25%)	2.44	2.48	2.47	0.8
Cost (10%)	0.49	1.00	0.32	0.56
Interplanetary Flight Heritage	Yes	Yes	Yes	No
Total	5.51 (Yes)	5.17 (Yes)	**6.12 (Yes)**	7.86 (No)

Table 22 – First trade study results

Reading the table carefully, one will notice that none of the solutions have a perfect score in Reliability. This fact does not conform with the aforementioned ratio technique. This is because instead of making ratios for the reliability, it was thought to be more logical to apply the success rates to 100. This is a result of the success rating being in percent. Therefore to achieve a perfect score in reliability, a solution must have a 100% successful track record. None of the proposed solutions fulfilled this condition, although most came close.

Also upon examination, one might find the reliability rating of Falcon Heavy to be incorrect. According to the found results, the Falcon Heavy has had 1 flight and 1 success, thus achieving a 100% success rating. Because this is an quasi experimental LV, with the one flight being an experiment and not an actual precision launch, this was discounted. To obtain a reliability rating, the success rate of the Falcon 9 was taken. This was done because the Falcon Heavy uses 3 Falcon 9's for its main stage and boosters. With this, if one of the Falcon 9's were to fail, the entire LV would fail. This type of OR probability uses multiplication as an operator. This is exactly how the reliability of the Falcon Heavy was calculated. Since there are 3 Falcon 9's being used, the success rating was cubed. This provided a large disadvantage for the Falcon Heavy. It is speculation that if more launches had been made at the time, its reliability could have been much higher.

Preferred Solution

As seen in the table above, the preferred solution from this trade study is the Atlas V. Having a perfect or almost perfect score in 2 of the 4 graded metrics, it achieves a score of 6.12/10 or 61.20%. This is only 6.1% higher than the 'runner up', the H-IIA. The defining reason as to why the Atlas V is preferred is the launch capability. It receives similar scores in other metrics compared to the H-IIA and Soyuz-FG, but has a relatively higher ability to carry mass. The trade-off to this weight carrying ability however, is the price. The Atlas V is the most expensive LV of the viable solutions at $158,000,000.00. Another benefit of the Atlas V is it's reliability. In its years of operation, only one flight has had a failure. This was a USN intelligence satellite as part of the NOSS (codename "Intruder"). The satellite was inserted into a lower than intended orbit. To compensate, the spacecraft used its own propellant system at the cost of operational time. The USN still declared the launch a success[14].

As mentioned, the Atlas V won the trade study by a margin of 6.1%. Because this is a rather small amount, sensitivity testing was done to see if the result of the trade study differs. The new metric weightings were:

- Launch Capability (55%)
- Launch Efficiency (10%)
- Reliability (25%)
- Cost (10%)
- Interplanetary Flight Heritage

The new resulting scores were:

Metric	H-IIA	Soyuz-FG/Fregat	Atlas V	Falcon Heavy
Launch Capability (55%)	0.86	0.61	1.62	5.50
Launch Efficiency (10%)	0.93	0.61	1.00	1.00
Reliability (25%)	2.44	2.48	2.47	0.8
Cost (10%)	0.49	1.00	0.32	0.56

Interplanetary Flight Heritage	Yes	Yes	Yes	No
Total	4.72 (Yes)	4.70 (Yes)	**5.41 (Yes)**	7.86 (No)

Table 23 – Trade study results after sensitivity test

As it can be seen, changing the weightings of the metrics still yields the Atlas V as the preferred solution. In fact, the lead from Atlas V to H-IIA increased to 6.9%. By enlarging the importance of the launch capability by 10% and lessening that of the launch efficiency (not within the VAPE Mission team's control), the lead of the preferred solution increased by 13.11%.

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[2] "Venus Fact Sheet" *NASA Space Science Data Coordinated Archive*, National Aeronautics and Space Administration, nssdc.gsfc.nasa.gov/planetary/factsheet/venusfact.html.

[3] "Venus Express Factsheet." *ESA*, European Space Agency, www.esa.int/Our_Activities/Space_Science/Venus_Express/Venus_Express_factsheet2.

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[7] “SURPLUS MISSILE MOTORS: Sale Price Drives Potential Effects on DOD and Commercial Launch Providers.” *United States Government Accountability Office*, United States Government Accountability Office, www.gao.gov/assets/690/686613.pdf.

[8] “Soyuz FG Fregat.” *Spaceflight101*, Spaceflight101, www.spaceflight101.net/soyuz-fg-fregat.html.

[9] Latitude.to. “GPS Coordinates of Baikonur Cosmodrome, Kazakhstan. Latitude: 45.9200 Longitude: 63.3420.” *Latitude.to, Maps, Geolocated Articles, Latitude Longitude Coordinate Conversion.*, latitude.to/articles-by-country/kz/kazakhstan/1312/baikonur-cosmodrome.

[10] “Soyuz-FG (11A511U-FG).” *Gunter's Space Page - Information on Spaceflight, Launch Vehicles and Satellites*, space.skyrocket.de/doc_lau_det/soyuz-fg.htm.

[11] “Soyuz-FG Fregat (11A511U-FG).” *Gunter's Space Page - Information on Spaceflight, Launch Vehicles and Satellites*, space.skyrocket.de/doc_lau_det/soyuz-fg_fregat.htm.

[12] *Voskhod 2*, www.astronautix.com/s/soyuz-fg.html.

[13] Latitude.to. “GPS Coordinates of Kennedy Space Center Launch Complex 39, United States. Latitude: 28.6050 Longitude: -80.6026.” *Latitude.to, Maps, Geolocated Articles, Latitude Longitude Coordinate Conversion.*, latitude.to/articles-by-country/us/united-states/5748/kennedy-space-center-launch-complex-39.

[14] “Atlas-5(401) (Atlas-V(401)).” *Gunter's Space Page - Information on Spaceflight, Launch Vehicles and Satellites*, space.skyrocket.de/doc_lau_det/atlas-5-401.htm.

[15] “Capabilities & Services.” *SpaceX*, SpaceX, 28 Nov. 2012, www.spacex.com/about/capabilities.

[16] “Falcon-Heavy.” *Gunter's Space Page - Information on Spaceflight, Launch Vehicles and Satellites*, space.skyrocket.de/doc_lau_det/falcon-9-heavy.htm.

Appendix D – Probe trade study

Probe design Trade Study

The probe is one of the most integral aspects of our mission as it is the means for completing all of the scientific measurements of the Venusian atmosphere. The probes primary mission goals are to measure seasonal variability of atmospheric behaviour and composition to improve our atmospheric models of Venus. The composition analysis includes measurements at different altitudes looking for the presence of different greenhouse gases, noble gases, and measurements of downwelling longwave radiation. The probes secondary mission goal is to detect the presence microbial life in potential algae plumes that form in areas with similar pressures and temperatures as here on earth.

Relevant Mission requirements

The mission requirements driving the probe design are mainly focused around the specific measurements we need to make in order to improve our atmospheric models. These include the need for the ability to detect the presence of different greenhouse gases, noble gases, and measurements of downwelling longwave radiation as well as measure seasonal variability.

VAPE-REQ-FUNC-0001	Description	The mission shall sample the Venusian atmosphere during the science phase of the mission.		Time/Level of Verification	Component, and, Full spacecraft integration	
	Comment			Nature of Verification	Test all components and later that completed MDS meets science objectives	
	Rationale	Our mission goal is to provide scientific data about Venus's atmosphere.				
				Version	V-1.0	
	Written on	05 FEB 2019	Initial Author	Michael Tabascio	Last modified	13 FEB 2019

VAPE-REQ-FUNC-0050				
	Description	The payload MSD(s) shall survive in the atmosphere of Venus for a minimum of TBD unit of time (TBC).	Time/Level of Verification	Payload system assembly
	Comment	Base duration on technology level and scientific needs.	Nature of Verification	Environmental simulations
	Rationale	Allow reasonable time frame for measurements and observations to be made during the science phase.	Version	V-1.0

VAPE-REQ-FUNC-0051				
	Description	The science phase of the mission shall last for a minimum of one (1) Venus year.	Time/Level of Verification	Payload system assembly
	Comment		Nature of Verification	Environmental simulations
	Rationale	Interested in how regions of atmosphere change seasonally. So, need measurements for a least 1 cycle.	Version	V-1.0

VAPE-REQ-FUNC-0085				
	Description	The probe shall collect Carbon Dioxide, Sulfuric Acid and Radiative balance (GHG) data up to ppm accuracy.	Time/Level of Verification	Component
	Comment	Based on ISO 15859-12:2004 (Space systems-- Fluid characteristics, sampling and test method) standard	Nature of Verification	Ensure sensors that are used can provide required accuracy through testing and verification
	Rationale	To differentiate between normal and extreme amounts of concentration.	Version	V-1.0

VAPE-REQ-FUNC-0080				
	Description	The payload MDS shall have an on-board instrument whose function is to measure noble gas concentration.	Time/Level of Verification	Component
	Comment	Precision of measurement in PPM are TBD.	Nature of Verification	Test instrument for desired properties.
	Rationale	Fulfil mission need and scientific objectives reported in mission statement and preliminary presentation.	Version	V-1.0

VAPE-REQ-FUNC-				
	Description	The payload MDS shall have on on-board mass spectrometer instrument.	Time/Level of Verification	Component
	Comment		Nature of Verification	Test instrument for desired properties.
	Rationale	To provide scientific data on chemical composition.	Version	V-1.0

Another applicable type of requirement to the probe is the communications restrictions between the probe and the orbiting space craft, The orbiter will handle the data link back to earth.

VAPE-REQ-FUNC-0040						
	Description	The payload MDS shall save telemetry on-board using an on-board memory device in a continuous manner.		Time/Level of Verification	Flat-sat	
	Comment	Total amount of data to store at one time is TBD.		Nature of Verification	Testing of software processes under nominal conditions.	
	Rationale	Provides means of recording data prior to downlink and for housekeeping purposes.		Version	V-1.0	
	Written on	05 FEB 2019	Initial Author	Matthieu Durand	Last modified	13 FEB 2019

VAPE-REQ-INTE-0010				
	Description	The spacecraft and payload MDS shall interface appropriately the selected communication network.	Time/Level of Verification	Full spacecraft assembly
	Comment	Network in question TBD by trade study. The spacecraft must be compatible with pre-existing long-range communication networks.	Nature of Verification	Testing of communications with network regulations and protocols in anechoic chamber.
	Rationale	Communicating with network will allow for easier data, GNC and TT&C between ground station and satellite.	Version	V-1.0

These requirements provide the necessary aspects of design that the probe must comply with and they provide a way to remove probe designs that do not meet the needs before completing a trade study on them, for example any probes that descend fast wont be able to make the precise measurements we need

Probe design criteria

Payload Capacity: The payload capacity is the amount of volume the probe has available to hold different scientific instruments. This includes the spectrometers needed for atmospheric composition analysis, pressure sensors for altitude determination, sensors for measuring the downwelling long wave radiation and others. If possible, the probe will hold the largest instrument onboard a microscope device for measuring microbial life when inside the proposed algae blooms. The ideal probe will be able to hold all of the instruments needed for the mission either on a single probe or specific instruments on multiple probes.

Lifespan: The lifespan of the probe is very important as Venuses atmosphere is very hostile for man made objects and a major goal of the mission is to measure seasonal variability of the atmosphere so ideally the probe will be able to survive in the atmosphere for 1 Venusian year.

Atmospheric coverage: being able to have a large variety of data is important so we can create a full encompassing atmospheric model. This means the larger the area of the atmosphere of which the probe can take measurements from is an important metric.

Mass: Sending anything to space takes a lot of fuel and going interplanetary takes a lot of energy so the less mass the probe has the better for the mission.

Simple design: Having a simple design with minimal moving parts is the idea way to design a system that has to travel through space as there are less things to go wrong so the probe with a simpler design will receive more points.

Cost: Because this is a science mission the cost is better the lower it gets as this will have to be government funded for the purpose of research, we won't make any money off of it.

Criteria weightings

Payload Capacity = 30%. Payload capacity is very important for the probe as well need to be able to complete all of our science goals, therefore this is the most important metric.

Lifespan = 10%. The lifespan is important for a single part of the mission to try to measure seasonal variability, so it receives 10%.

Atmospheric coverage = 25%. Being able to measure a large sample area of the atmosphere will improve our models and make the data gathered more useable so it is our second most important weighting metric.

Mass = 10%. The lower the mass the better but this is also just the probe and not the space craft as a whole so this is weighted lower.

Simple design = 20%. Our probe needs to be functional even after the long voyage to Venus and the simpler the design the higher likelihood of it working so it is weighted as the third highest metric for the trade study.

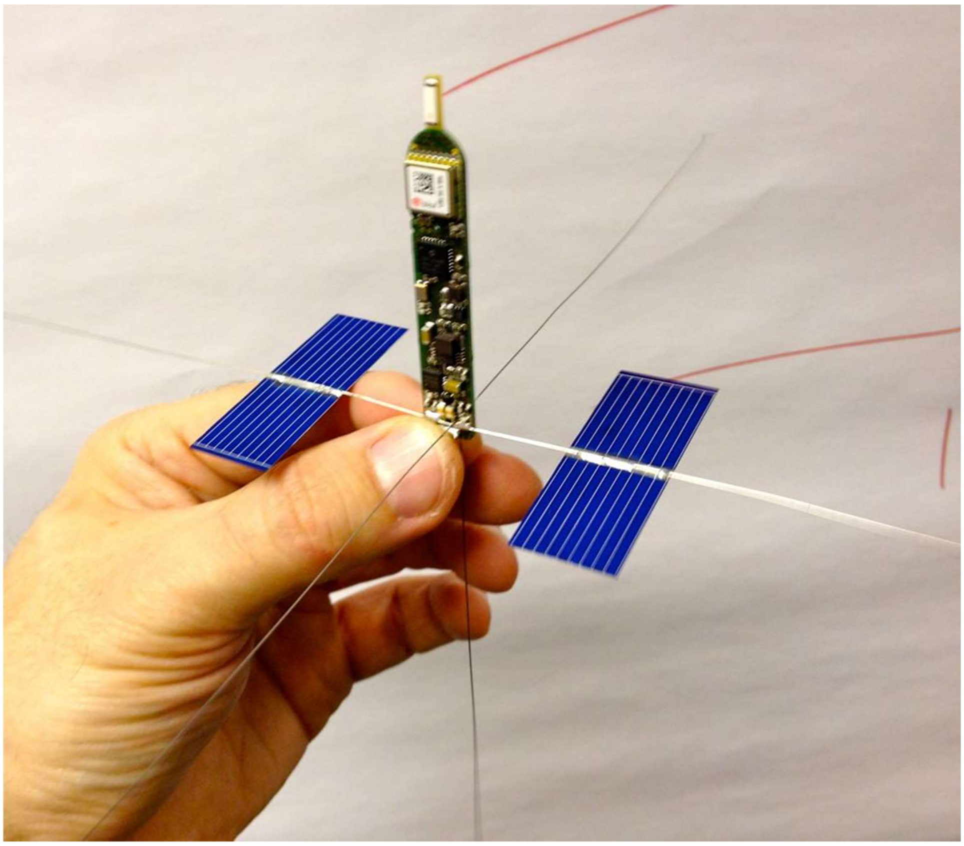
Cost = 5%. Because this mission will be government funded cost is a criterion to be considered but it is much lower than the need for the instruments to work.

Probe design options

From the criteria two main design options are best suited for our application. First is a balloon suspended large probe that would hold all of the mission essential instruments in one housing. (Figure 1) We would be able to pressurize the balloon such that the probe floats at a desired height and we could let out some pressure to descend and take measurements lower in the atmosphere if needed. The probe would be able to hold large instruments and would allow us to complete our secondary mission to look for microbial life. The probe would navigate the Venusian atmosphere through wind-based propulsion so we could theoretically float across large areas of the atmosphere. The lifespan could be very long which would allow us to measure seasonal variability.

(Figure 1) shows a large probe suspended by a balloon

The second viable option would be a cluster of Pico or Nano sized probes that would be single use and would take measurements while descending through the atmosphere possibly utilizing a parachute to descend slowly. (Figure 2) Each probe would house a single instrument and would be tasked with taking a specific set of data at a certain height as it descends. These probes could possibly be sent on the scale of about 10-20 probes. This would allow us to send down probes at different times to still be able to measure the seasonal variability of the atmosphere. We would be able to cover a large area of the atmosphere because we could drop probes anywhere onto the planet if the mothership orbit allowed it. But because of the size the secondary mission instrument it would not be able to be completed as a microscope would be too big and take too much power to operate.



(Figure 2) Shows a sample of a Pico sized probe that could take a single measurement.

Decision matrix

Metric	Score (rated out of 100)	Balloon suspended probe (weighted)	Score (rated out of 100)	Pico-sized cluster of probes (weighted)
Payload capacity (30%)	100	30	25	8
Lifespan (10%)	100	10	10	1
Atmospheric coverage (25%)	75	19	100	25
Mass (10%)	50	5	100	10
Simple design (20%)	75	15	65	13
Cost (5%)	50	2.5	80	4
Total: /100		81/100		61/100

Ideal option

From the decision matrix found in the appendix a balloon suspended large probe that would hold all of the mission essential instruments in one housing is the clear winner at 81% over the pico-cluster probe design at 61%. With this probe design we will be able to pressurize the balloon such that the probe floats at a desired height and we could let out some pressure to descend and take measurements lower in the atmosphere if needed so we can get full coverage of the measurements we need to take. The probe would be able to hold large instruments and would allow us to complete our secondary mission to look for microbial life. The probe would navigate the Venusian atmosphere through wind-based propulsion so we could theoretically float across large areas of the atmosphere and gather large samples of data. The lifespan could be very long which would allow us to measure seasonal variability. Since it will be only a single probe the cost will be feasible as well and the design will be simple with no extra moving parts.

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Appendix E – Drone trade study

Introduction

The mission Venus Atmosphere Penetrating Explorer (VAPE) is tasked with travelling to the second planet of our solar system. Here it shall explore the atmosphere and communicate the data collected back to Earth for scientific research. The mission objective as stated by the team is,

"To provide in situ measurements and gather scientific data on Venus by penetrating the atmosphere of the planet in order to investigate its greenhouse effect and atmospheric composition."

To design a solution capable of meeting these needs, our team envisioned a mission consisting of a mother ship craft transporting daughter ship crafts to Venus. They would be launch from Earth as one spacecraft and set into an interplanetary trajectory by the launch vehicle.

The mission shall require advanced communication capabilities to relay the data collected. The daughter ships shall also carry scientific instrumentation to be operated in the Venusian atmosphere. To these ends, the following trade studies are to be conducted by member of the VAPE team:

- Mother ship orbit type about Venus
- Daughter ship design – drone
- Daughter ship design – probe
- Instrumentation – mass spectrometer and IR spectrometer
- Communications – deep space and mother-to-daughter
- Launch provider

As seen above, two trade studies on the daughter ship design are to be conducted. They are divided by craft type; with the first dealing with drones and the second with probes. The two trade studies shall evaluate their alternatives in a similar fashion as to unify the determined outcomes.

System under analysis

This report outlines and conducts a trade study for the drone alternatives of the daughter ship design. As mentioned above these would be deployed by the mother ship once in orbit above Venus and penetrate the atmosphere of the planet. This is intended to complete the science goals of the mission.

A drone navigates the atmosphere of the planet, while a probe would descend almost uncontrollably to the surface. This allows decisions to be made on the precise location of the measurements collected by the mission. Also, a drone has a longer lifespan in the atmosphere compared to probes.

In investigating the alternatives, only the type of drone is discussed. There are no mentions, as side from examples, of specific models of drones. Once a type of drone is selected for the mission, the model could be selected off-shelf via a further trade study, it could be modified to fit the requirements, or the design solution could dictate that a new drone model be designed in-house.

The final product would ideally carry several daughter ships to Venus. This could be as few as three or four and up to the hundreds. The decision on the quantity to transport would depend on size, mass, and the amount of measurements determined to be needed to complete the mission objective. Additionally, the mother ship should be equipped with both drones and probes. The trade study performed in this report solely recommends the best drone alternative that is to be used.

System goals and objectives

From the previous documents and presentations, the objectives of the daughter ship are to:

- Measure seasonal variability of atmospheric behaviour to improve our models
- Analyse the chemical composition at different altitudes, this includes:
    - Greenhouse gases
    - Noble gases
- Measure the downwelling longwave radiation (DLR) of the planet
- Detect the presence of potential microbial life in algae plumes (secondary)

In addition to these, the system would have to:

- Survive the hazards of the atmosphere
- Transmit is telemetry
- Carry hardware (solar panels, communication subsystems, OCB)
- In the case of a drone, navigate the atmosphere in a controllable fashion
- Be controlled autonomously

The mission requirements documentation also provides information of the goals and objective of the system. Table 1 outlines each relevant requirement and the direct implication for the system. In addition to those presented here, the regulatory requirements apply to the system. However, these have little to do with the functions of the system, rather they dictate the procedures surrounding the design process.

Req. ID	Statement	Implication for system
VAPE-REQ-FUNC-0060	The payload MDS shall survive on the surface of Venus for a minimum of 24 hours (TBC).	Survivability in the environment must be assessed.
VAPE-REQ-FUNC-0070	The payload MDS shall have an on-board instrument whose function is to measure DLR.	Relates to the objectives. At least one drone/probe shall carry such an instrument.
VAPE-REQ-FUNC-0074	The payload MDS shall have on on-board infrared spectrometer instrument for thermal analysis.	Relates to the objectives. At least one drone/probe shall carry such an instrument.
VAPE-REQ-FUNC-0075	The payload MDS shall have an on-board instrument whose function is to measure atmospheric pressure.	Relates to the objectives. At least one drone/probe shall carry such an instrument.
VAPE-REQ-FUNC-0077	The payload MDS shall have on on-board mass spectrometer instrument.	Relates to the objectives. At least one drone/probe shall carry such an instrument.
VAPE-REQ-FUNC-0080	The payload MDS shall have an on-board instrument whose function is to measure noble gas concentration.	Relates to the objectives. At least one drone/probe shall carry such an instrument.
VAPE-REQ-FUNC-0085	The probe shall collect Carbon Dioxide, Sulfuric Acid and Radiative balance (GHG) data up to ppm accuracy.	Relates to the objectives. At least one drone/probe shall carry such an instrument to carry out such function.

VAPE-REQ-FUNC-0090	The payload MDS shall have an on-board instrument to analyse the composition of the atmosphere.	Relates to the objectives. At least one drone/probe shall carry such an instrument.
VAPE-REQ-FUNC-0095	The MDS shall measure concentration of CO2, CH4, H2O in Venusian atmosphere.	Relates to the objectives. At least one drone/probe shall carry such an instrument to carry out such function.
VAPE-REQ-FUNC-0100	The payload MDS shall have an on-board instrument to capture optical images in a digital format.	Relates to the objectives. At least one drone/probe shall carry such an instrument
VAPE-REQ-FUNC-0120	The spacecraft and payload MDS shall be provided enough electrical power for all required activities, by the electrical power subsystem.	Some sort of electrical storage device needs to be present and carried by the system.
VAPE-REQ-PERF-0010	The payload MDS shall sample the atmosphere in the range of one (1) to ten (10) ATM.	Relates to the objectives. At least one drone/probe shall carry such an instrument to carry out such function.
VAPE-REQ-PERF-0030	The payload MDS shall regain attitude control within seven (7) seconds (TBC) after being struck by gust of winds reaching TBD km/h.	Means of controlling the attitude of the system needs to be integrated.
VAPE-REQ-INTE-0010	The spacecraft and payload MDS shall interface appropriately the selected communication network.	A means of communication needs to be transported by each drone.
VAPE-REQ-PROG-0050	The payload MDS shall operate using the local Venus solar time of the location in enters the atmosphere.	Provides details on the operations of the OBC of the system.

Table 24 – Requirements applicable to the system and their impact on it

Selected alternatives

For this trade study, four types of drone alternatives were selected. These are: multi-rotor, fixed-wing, single-rotor, and fixed-wing hybrid. These were chosen either because of their extended presence or reputation in the drone industry. Each one has different advantages and disadvantages. The following paragraphs provide an overview of each of the selected alternatives along with an example image.

Multi-rotor drones are equipped with three or more rotor systems and are capable of vertical take-off. They are commonly used in photography and indoor activities. Overall, these types of drones are easy to control, in addition to, being the least expensive alternative of the four. However, they have shorter flight times due to the extra motors and rotors, as well as, lower payload mass capacity. An example of a multi-rotor drone is shown in the image on the left.

Image: ("Drone sky camera remote control robot aircraft technology", public domain)

Fixed-wing drones use wings to generate lift, rather than rotors. This means that they take-off and land horizontally. They are comparable to aircrafts except for the lack of an on-board pilot. These types of drones have the longest range and greatest flight times of the four alternatives. Fixed-wing drone flight dynamics is more complex than rotor mechanics, consequently making them harder to fly and control.

Image: (Atherton, "PARROT DISCO DRONE", 2016)

Single-rotor drones resemble helicopters. Just like multi-rotor drones they take advantage of rotor mechanics to achieve flight. They are commonly seen in agriculture surveying. This type of drone has a better payload mass capacity than their multi-rotor counterparts. They also have an improved endurance. However, they are usually the most expensive and are difficult to fly safely.

Image: (Hans, "Velos UAV", 2017)

Fixed-wing hybrid drones are a combination of the multi-rotor and fixed-wing types. This means that they can take-off vertically but are flown like an aircraft. They are being testing for home delivery operations by firms like Amazon. Being from a hybrid design they possess the benefits of multi-rotor drones and fix-winged drones; however, they bring some of the drawback as well. Additionally, their technology is still in development.

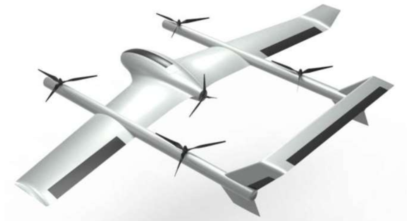

Image: (Tyan & Van Nguyen, "Hybrid UAV concept ", 2016)

Measures and measurement methods (models) used

To perform the trade study, eight different criterions were selected. These will be used the compare the different alternatives and recommend one for the mission. As we are looking at types of drone rather than models, we shall use an agreed upon range for each type rather than a unique specification.

The first is the **carriable mass** in kilogrammes. This is the mass that the drone can transport efficiently; where, an efficient transport is one that does not severely impact the flight capabilities of the craft. This metric is important as the solution will need to be modified at least with instruments and a communication system. As such, we wish to maximise the value of the carriable mass. Overall, this criterion will influence the payload that the drone can transport into the atmosphere of Venus.

The second is the **system mass** in kilogrammes. This is the mass of the drone without its payload. Launch costs, flight navigation, and the number of drones carried to Venus are part of the areas of the project that will be affected by this metric. Hence, we wish to minimise the value of the system mass. A perfect drone type would have zero mass and be able to transport and infinite number of instruments.

Thirdly, we have the **technological maturity** of the drone type. This evaluates the development of the technology in a fashion similar to the technology readiness level (TRL) used by several space agencies for space-based systems. Using the TRL method was considered, however, the drones being used outside of the space environment made the metric inappropriate to our research. Evaluating and maximising the technological maturity is important as we wish to work with well understood and reliable systems.

The next criterion is the **quantity of moving parts** found in the system. This would include, for example, motors and rotors, gyroscopes, and flaps. In examining this metric, we aim to reduce the risk of failure, as having more parts that move increases the wear on the system. Also, this will impact the mitigations and contingencies the design will require to be put in place. So, we look to minimise this amount.

The fifth criterion is the **control and stability**. This criterion encompasses, the resistance to atmospheric disturbances, such as, winds, the ease with which the craft is controlled, and its stability in the air. We've deemed this of importance because the drone will have to cope will high altitude winds and provide accurate pointing for certain scientific activities. Consequently, we shall aim to maximise this metric.

The subsequent criterion is the average **unit price**. This is simply the cost to commercially purchase one unit of the drone type in USD. The financial cost will impact the mission budget and planification, as well as, the number of units that can be transported to Venus. As such, this metric should also be minimised.

The seventh criterion is the average **top-flight time** of the drone type. Specifically, this is the maximum amount of time that one drone can usually spend in the air before having to recharge. Having a longer flight time allows for more measurements to be collected. This directly influences the total amount of data that we can retrieve from the atmosphere. Thus, we wish to maximise this metric.

The last criterion is the average **top-flight speed** of the drone type. Here, we'll be examining the maximum speed that one drone can travel at while in flight. With a greater flight speed the selected alternative will be able to cover and sense a larger area. As with the top-flight time, this influences the amount of data that we can retrieve from the atmosphere. Thus, we wish to maximise this metric.

Data sources

In the study of drone technology, the users that provide the largest volume of data are hobbyists and professionals. Hobbyists use drones for leisure purposes such as photography and racing. Professionals may also participate in photography; however, they commonly use drones for sensing, sports events, and other activities. Many hold websites containing reviews and guides on different drone types. For this trade study a majority of the information originates from these sources.

In addition, retail, reseller, and manufacturer websites provided some information; along with certain science and engineering reviews and magazines. There are lastly a few research papers with some of the most in-depth analysis and information that were used to compile together this trade study. All of these are listed in the references section of the end of the report.

Selection rule

Performing the trade study analysis requires a grading system. For this report, a five-point scale shall be used. The scale starts at zero, being the lowest mark, and goes up to four, the highest mark. Ideally, a four would represent a metric that is perfectly suitable for the mission, while a zero indicates that the metric is unknown or that the result obtained is not suitable.

Each criterion will be assigned a weighting as gauged by their importance and relevance to the successful completion of the mission. Their score on the five-point scale will be divided by four (the highest score attainable) and multiplied by the weighting of the criterion. The alternative with the highest final mark consequently becomes the recommended alternative. In the eventually that two or more options obtain a similar highest score a sensitivity analysis shall be conducted.

Criterion	Implication or range of score					Weight
	0	1	2	3	4	
Carriable mass	0 – 0.5 kg	0.5 – 2.5 kg	2.5 – 5.0 kg	5.0 – 10.0 kg	10.0+ kg	20
System mass	100+ kg	50 – 100 kg	25 – 50 kg	5.0 – 25 kg	0 – 5.0 kg	20
Technological maturity	Still being developed	Recent commercial availability	2 – 10 years of availability	10 – 25 years of availability	25+ years of availability	15
Quantity of moving parts	64 +	32 – 64	16 – 32	4 – 16	0 – 4	10
Control and stability	Acts like a baby when wind blows	Control and stabilise without winds	Control and stabilise in low winds	Control and stabilise in medium wind	Control and stabilise in strong winds	15
Unit price [USD]	400k +	300k – 400k	200k – 300k	100k – 200k	0k – 100k	10
Top-flight time	Less than 15 minutes	15 – 30 minutes	30 – 60 minutes	60 – 120 minutes	More than 120 minutes	5
Top-flight speed	0 – 10 kph	10 – 25 kph	25 – 50 kph	50 – 90 kph	90+ kph	5

Table 25 – Criterions and meaning of their scores

The table above provides the implication of each possible score in the different categories. A majority are easily quantifiable, however, one or two have been expressed without empirical ranges. Using the data sources discussed previously, information was gathered on the different alternatives and is presented in the tables on the next pages. This data shall allow us to assign each drone type a score between zero and four.

Research results

Alternative	Information	Score	Source
Multi-rotor drone	The average payload capacity for the weight range given in the next table is six kilogrammes.	3	[11]
Fixed-wing drone	From the sources given on the right, the usual payload mass is between two and six kilogrammes.	2	[12]
Single-rotor drone	Single-rotor drones have similar weight transport capacity to that of multi-rotor drones.	3	–
Fixed-wing hybrid drone	Fixed-wing hybrid drones have similar weight transport capacity to that of fixed-wing drones.	2	–

Table 26A - Results for carriable mass

Alternative	Information	Score	Source
Multi-rotor drone	System mass range is usually between ten to twenty kilogrammes.	3	[11]
Fixed-wing drone	System mass range is usually between two to four kilogrammes.	4	[10]
Single-rotor drone	Single-rotor drones have similar system masses as that of multi-rotor drones.	3	–
Fixed-wing hybrid drone	Fixed-wing hybrid drones have system masses as that of fixed-wing drones.	4	–

Table 3B – Results for system mass

Alternative	Information	Score	Source
Multi-rotor drone	This drone type was first commercially available in 2010.	2	[8]
Fixed-wing drone	This type of technology in almost as old as World War II. The first successful product was released in the year 2000.	4	[9]
Single-rotor drone	This alternative is similar to helicopters. However, as drones, they are just a bit younger than multi-rotor ones.	3	[8]
Fixed-wing hybrid drone	Fixed-wing hybrid drones are still under development. Notably by Amazon and other delivery firm. So, not on market.	0	[1]

Table 3C – Results for technological maturity

Alternative	Information	Score	Source
Multi-rotor drone	The number of moving parts in multi-rotor drones depends on the number of rotors. It is usually between three and eight.	3	–
Fixed-wing drone	These can have zero parts in the case of a glider. In general, they have flaps and propellers. In total this can range from four to ten.	3	–
Single-rotor drone	Due to the nature of their design, single rotor drones only have two moving parts.	4	–
Fixed-wing hybrid drone	Somewhere between a multi-rotor and fixed-wing drone, this type can have between seven to eighteen moving parts.	3	–

Table 3D – Results for quantity of moving parts

Alternative	Information	Score	Source
Multi-rotor drone	Capable of hover in flight giving stability. They are also known to be performant in confided areas, showing good control.	4	[2]
Fixed-wing drone	These cannot hover in flight and due to the nature of their motion controlling they can be complex.	2	[2]
Single-rotor drone	Being similar to multi-rotor drones gives them an advantage, however they are known for being hard to fly.	2	[1][2]
Fixed-wing hybrid drone	Mixing the flight natures of both multi-rotor drones and fixed-wing drones gives them good control and stability.	3	[2]

Table 3E – Results for control and stability

Alternative	Information	Score	Source
Multi-rotor drone	$5k - 65k\ [USD]$	4	[1]
Fixed-wing drone	$25k - 120k\ [USD]$	3	[1]
Single-rotor drone	$25k - 300k\ [USD]$	2	[1]
Fixed-wing hybrid drone	This drone type is still in development and little speculation can be found on their release price.	0	[1]

Table 3F – Results for quantity of unit price

Alternative	Information	Score	Source
Multi-rotor drone	Have a top-flight time between 15 to 45 minutes.	1	[5][6]
Fixed-wing drone	Have a top-flight time between 60 to 90 minutes.	3	[6]
Single-rotor drone	Have a top-flight time between 15 to 45 minutes.	1	[7]
Fixed-wing hybrid drone	Have a top-flight time between 60 to 90 minutes.	3	[5]

Table 3G – Results for top-flight time

Alternative	Information	Score	Source
Multi-rotor drone	Have a top-flight speed around 30 mph, that is just under 50 kph.	2	[3]
Fixed-wing drone	Have a top-flight speed around 80 kph.	3	[6]
Single-rotor drone	Have a top-flight speed around 200 kph.	4	[4]
Fixed-wing hybrid drone	Have a top-flight speed like fixed-wing drone type.	3	[7]

Table 3H – Results for top-flight speed

Recommended alternative

	Multi-rotor	Fixed-wing	Single-rotor	Fixed-wing hybrid	Weighting
Carriable mass	3	2	3	2	20
System mass	3	4	3	4	20
Technological maturity	2	4	3	0	15
Quantity of moving parts	3	3	4	3	10
Control and stability	4	2	2	3	15
Unit price [USD]	4	3	2	0	10
Top-flight time	1	3	1	3	5
Top-flight speed	2	3	4	3	5
Score	73,75	75	70	56,25	

Table 4 - Trade study

From the table above it is clear that the fixed-wing hybrid is not a viable option. From the data in the previous section it can be deduced that this is likely a result of its younger development stage. Changing the two values that were zero due to this put it on even ground with the other alternatives.

The remaining scores are close together. However, single-rotor being the furthest from the top shall cause it to be eliminated from the selection. Then, to determine the recommended alternative from the two drone types that remain we need to perform a sensitivity analysis.

The sensitivity analysis can rapidly be performed by adding a criterion. This new metric would be the take-off and landing method used by the drone type. It was not added previously because it could not be fitted to a five-point scale. This is because for drones only two methods of take-off a landing exists.

The first it known as vertical take-off and landing (VTOL) and it used by the multi-rotor and single-rotor drone types. The second is conventional take-off and landing (CTOL). This is the method used by airplanes and it requires the presence of a horizontal area of land. In our trade study, the fixed-wing drone type utilizes this method. Note that, the fixed-wing hybrid is capable of VTOL and CTOL.

VTOL is advantageous in unknown terrain as taking off and landing can be done almost anywhere. As such, it would be an important feature to have for our drone to Venus. Adding this criterion to the trade study allows the multi-drone alternative to surpass the fixed-wing.

Discussion and conclusion

From the previous section, we see that the multi-rotor drone type is the recommended alternative. The trade study table originally pointed towards the fixed-wing alternative, then, taking into consideration the take-off and landing method changed this outcome. However, it should be noted that the fixed-wing hybrid would have been a more serious candidate if the technology had been further developed.

Prior to performing the trade study, it was expected that the fixed-wing option would be the recommend alternative. It would have been followed by the multi-rotor and then the single-rotor. The hybrid was expected to be last. Once the trade study was completed, the first two options switched positions.

In the case of the VAPE mission, we are not limited to transported only one type of drone. The multi-rotor is the recommended alternative and a plurality of them is expected to be see in the final concept. We must also keep in mind that due to the low battery life of many models the drones need to be fitted with a manner of safely recharging their battery.

This would likely result in a future trade study on the selection of the drone model to transport to Venus. The main options to consider are a set of commercially available drones modified to fit our needs or a custom designed drone tailored specifically to meet the objectives of the mission.

References

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Appendix F – Ground station trade study

OBJECTIVE

The primary objective of this trade study involves determining the most feasible ground station to use as communications between the V.A.P.E mothership and the science team on Earth. A trade study will be required as communications are a vital part of a space mission. Should communications be lost, the mission will come to an end and be deemed a failure. Therefore, it shall be required to decided what communication network is best suited for this mission.

CRITERIA

In this trade study, the communications availability, the service time (reliability), the data rate possibilities, cost, coverage area, and data packet protocol will be used to consider the most suitable ground station.

Communications availability will need to be known should a stakeholder want to receive data at a specific time or if there is a known issue with the spacecraft that needs to be rectified immediately. When defining continuous communications, it is stated that during the window of operation, there will be no interference allowing for continuous data flow. In terms of the service time or reliability, it will be required that the ground station has been proven reliable or can be proven reliable. This is a mandatory as communications are critical and should the ground station fail for any reason the mission will be deemed a failure unless another ground station will be able to be used. This criterion also includes the range abilities of the ground station as it shall be capable of detecting signals from 261 million km from Earth as that will be the furthest Venus will ever be from Earth. Data rates are very important as this will determine how quickly we will be able to receive our data and process it. With data rates, bandwidths are also determined as higher BWs allow for more data to be transmitted but there is the drawback of higher chance of data loss.

When analysing the cost of each option, it is important to look at the operating cost over the lifespan of the mission (5-10) years as well as if any additional structures would be needed to be constructed. Data packet protocol also needs to be considered as each network contains its own protocol and security. Should an on-site antenna be constructed, either a previously before used protocol will need to be used or a new protocol will require to be created.

CRITERIA THRESHOLDS

Communications Availability

- Possibility of communications minimum 16 hours a day
  - 16 hours has been chosen as 14 hours of communication a day once a week is being considered and there shall be a 1-hour buffer zone before and after the desired communication time to allow proper detection and verification of the signal.
- Continuous Communication throughout the 14 hours of communication
  - There shall be no interruption during the period of communication to minimize the data losses
  - Should there be any known cutouts or transmission interruptions, the ground station shall not be considered

Service Time / Reliability

- The station shall be operational at least 95% of the time.
    - The only down time expected should be any unexpected outages. Should there be any planned maintenance or outages of the station there shall be another antenna readily available.

Data Rate

- The available minimum data rate shall be 128kb/sec
    - This rate is determined by the known size of the data that the spacecraft will be collecting. This is also determined by how quick the scientists will receive the data.
    - At the furthest point, it will take 14.5 minutes to transmit 112Mb of data. Each data packet will be approximately 100Mb as it will contain photos as well as raw scientific data.
- Should the minimum data rate drop below 128kb/sec the ground station shall not be considered

Cost

- The cost will not contain any strict thresholds. This is primarily due to the amount of funding to be received is unknown. In addition to this, cost may vary greatly should the mission continue past its expected lifetime. Cost shall only be considered on overall cost over a 5-year lifespan.

Coverage Area

- The coverage area shall be at least 240°.
    - This is to meet the communication times. As communications are required 16/24 hours, at least 240° will be required to be covered in that time.

Data Packet Protocol

- As the protocol is standard for deep space communications, the protocol will not be considered unless the ground station to be used will be a new station that will require the use of a new unverified protocol.

CRITERIA WEIGHTING

Each criterion as mentioned above shall be weighted based on importance to the mission:

Communications Availability – 20%

Service Time / Reliability – 30%

Data Rate – 10%

Cost – 10%

Coverage Area – 30%

Each criterion will be judged on a scale of 1-10.

In terms of communication availability, 1 indicates that the station will have communication availability of 14 hours which is the bare minimum not including the buffer times. A score of 10 indicates it has 24 hours of potential communication availability.

The service time and reliability will receive a score of 1 if the station has frequent outages or is unproven to be available. A score of 10 will be given to the station that is always operational or if there is an outage, has a secondary antenna that may be used.

For data rates, a score of 1 is assigned if the minimum downlink speeds are met and a score of 10 indicated 10+ Mb/s of downlink availability.

The cost rating will be judged based on the cost referenced to the least expensive solution given a 10, and every 10% additional increase in cost will lose a point.

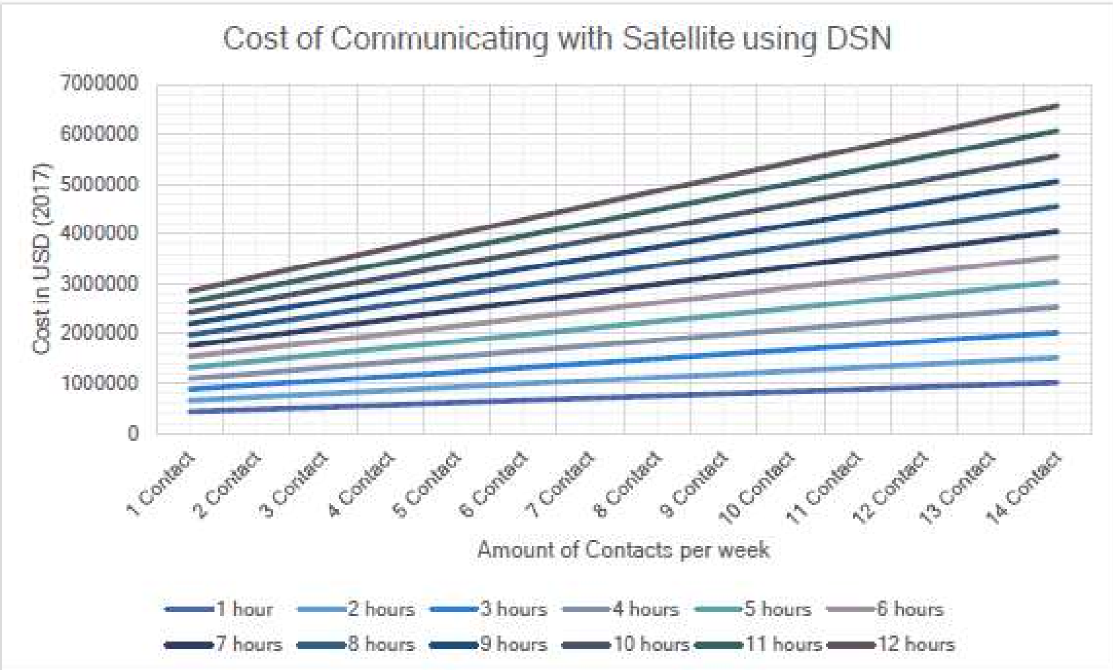
Coverage area scores are judged by 1 being 200-240° of coverage and a score of 10 assigned to 360° of coverage.

OPTIONS

In this study there will be 2 primary options that will be considered. These are NASA's Deep Space Network and the ESA's ESTRACK.

Deep Space Network (DSN)

The DSN has 3 communications facilities that are spread out by 120° around the world. 1 in Goldstone California, 1 in Canberra Australia, and 1 in Madrid Spain. Each of these facilities contain 4 antenna dishes each ranging from 14-65m in diameter. These antennas use the Ka, S, and X bands for communication purposes. With all these antennas, the DSN has a service rate of 99% as one antenna in each location is always available for communication purposes. As proven by doing so, the antennas can receive signals as low as -160dBm (Voyager 1 and Voyager 2 for reference). In addition to distinguishing such low power, the antennas also communicate between 128kb/s and 4Mb/s. An example for the cost of using the DSN is provided below:



ESTRACK

Unlike the DSN, ESTRACK has stations all over the world including Argentina, Australia, and multiple in Europe allowing for 360° of coverage. This system contains a total of 18 antennas which primarily use the X-bands for deep space communications but are able to use Ka and S bands with certain antennas. By the date of the launch, most of these antennas should be equipped with Ka and Ku band capabilities. Because the system contains so many spread out dishes, ESTRACK has a 99% service availability.

Ground Stations not being considered

- Antenna built on-site
  - Such an antenna would be a very large cost, only be able to cover 120° of the sky at most, as well as be unreliable and prone to failure as it has not been proven to function. Too much risk associated.
- Others not considered due to lack of coverage include:
  - Soviet Deep Space Network
  - Chinese Deep Space Network
  - Usuda Deep Space Center

TRADE SPREADSHEET

Criteria	Weighting	Deep Space Network	ESTRACK
Communication Availability	20%	10	10
Service Time / Reliability	30%	9	9
Data Rate	10%	4	8
Cost	10%	5	5
Coverage Area	30%	10	10
Total	/100%	86%	90%

DISCUSSION

Upon analysis of the trade spreadsheet it is visible that ESTRACK would be the more beneficial communication network. A cost of 5 has been given to both DSN and ESTRACK as there is not an available price estimate for both in order to adequately compare the cost.

SENSITIVITY ANALYSIS

The final decision is sensitive to the weightings, scores, and cost. Should date rate or cost be determined to be more important to the mission, there is a possibility of DSN being a more suitable option. The decision is based on cost differential as a cost had not been provided to be compared.

CONCLUSION

ESTRACK is the beneficial network and will be chosen to be used as the ground station to communicate with the spacecraft at Venus.

Appendix G – Instrumentation trade study

The mission we are designing is know as the Venus Atmospheric Penetration Explorer, also known as VAPE. Our primary mission objective is to provide in situ measurements by penetrating the Venusian atmosphere. The scientific data we seek is composition of the atmosphere as a function of altitude. The data is meant to investigate its accelerated greenhouse effect, which can then be applied to a better understanding of the greenhouse effect here on Earth. We also wish to provide global coverage and seasonal variability during the mission, using numerous probes dropped at specific times.

The purpose of this trade study is to provide an answer on which instrument(s) will be mounted on the probe to provide measurements for our mission objectives. The justification of this trade study is that the Venusian environment is extreme, and there has not been much atmospheric data prior to the launch of our mission. Since we are dropping probes into the atmosphere, the measurements need to be taken efficiently and effectively. By solving which instrument(s) will be used, we can develop the solution to the probe design by knowing how big it must be, where the instruments can be mounted on the probe to take measurements and what precautions can be taken to allow our probe, and the instruments onboard, to last as long as it can. The longer the probes last, the more data can be obtained and the less the overall mission cost will be as less probes will need to be made for the mission.

As a team a list of requirements were made to help us meet our objective. For the trade study, key requirements will be chosen from these documents to ensure the instrument(s) chosen will help us meet our mission need. In total four (4) requirements were chosen from the documents, as they were deemed essential to the mission objective and need to be met (figure 1).

VAPE-REQ-FUNC-0001			
Description	The mission shall sample the Venusian atmosphere during the science phase of the mission.	Time/Level of Verification	Component, and, Full spacecraft integration
Comment		Nature of Verification	Test all components and later that completed MDS meets science objectives
Rationale	Our mission goal is to provide scientific data about Venus's atmosphere.	Version	V-1.0
Written on	05 FEB 2019	Initial Author	Michael Tabascio
Last modified	13 FEB 2019		

VAPE-REQ-FUNC-0095			
Description	The MDS shall measure concentration of CO2, CH4, H2O in Venusian atmosphere.	Time/Level of Verification	Component
Comment		Nature of Verification	Expose system to volume with known concentration of gas
Rationale	Concentration data needed for scientific analysis	Version	V-1.0
Written on	05 FEB 2019	Initial Author	Jessie Atamanchuck
Last modified	13 FEB 2019		

VAPE-REQ-PERF-0010			
Description	The payload MDS shall sample the atmosphere in the range of one (1) to ten (10) ATM.	Time/Level of Verification	Payload assembly
Comment		Nature of Verification	Pressure (environmental) testing and verifications
Rationale	This range allows us to look at different types of aerosols that have been confirmed in the Venus atmosphere and how the composition of the atmosphere changes with altitude.	Version	V-1.0
Written on	05 FEB 2019	Initial Author	Michal Tabascio
Last modified	13 FEB 2019		

VAPE-REQ-PERF-0091			
Description	The payload MDS shall detect a minimum number density of 2×10^{19} particles per cm^3.	Time/Level of Verification	Component
Comment		Nature of Verification	Test instrument for measurement limits in a controlled environment
Rationale	The minimum number density for the upper limit of the range of the atmosphere we wish to sample.	Version	V-1.0
Written on	05 FEB 2019	Initial Author	Michael Tabascio
Last modified	13 FEB 2019		

Figure 1: The list of the four (4) key requirements chosen to provide direction for the trade study.

When choosing candidates for the trade study, the instruments shall meet the requirements listed above or they cannot be considered. Also, since we are developing an interplanetary mission with numerous probes being dropped, there is a focus on risk mitigation. Knowing this, instruments with space heritage will only be considered, as we want to ensure that the instruments have been used on previous missions, which shows they have been developed for the harsh environment of space.

There are 5 criteria that will be used for the decision matrix in the trade study. The first criteria are the effectiveness of the measurements. This means do the measurements that are taken from the instrument provide data on the composition of the atmosphere at different altitude heights or will the data need to be compared with multiple different measurements to provide data that can be used to answer this question. The second criteria are quality of the measurements. This means how well does the measurements taken allow us to meet our objectives for the mission. The third criteria is the ability to take measurements. As the probe will be dropped into the atmosphere, the winds and changing air pressure of Venus will affect the orientation of the probe continuously during the science phase. Therefore, the ability to take measurements tells us if the instruments can take measurements at any time and any orientation of the probe, or will a preferred orientation be needed for the instrument to conduct its measurements. The fourth criteria is size. This deals with the physical dimensions and weight of the instruments, as this will drive the probe size. The final criteria is cost, which deals with the cost to make or buy each of the instruments chosen.

The weighting of the criteria listed above was driven from the mission objectives and the need of the trade study (figure 2). Since the environment of Venus is a big concern for our mission, each probe will need to be designed to get the most measurements possible given the limited time it will have to be functional. When we look at previous mission to Venus, such as Venera 7, it lasted only a few hours on the surface until it went offline. Therefore, we gave a 30% weighting to size, as the size of the probe will determine how quickly it will fall into the atmosphere, and 25% to measurement ability as the instrument(s) chosen should provide as much data as they can given the limited time, and one that can take measurements with little or no orientation restrictions will provide the most data. 20% was given to measurement quality, as we may be limited on the number of probes that will be used on our mission. The final weightings are cost 15% and measurement effectiveness 10%, as both do not impact our mission severely.

Criteria	**Weight**
Measurement Effectiveness	10
Measurement Quality	20
Measurement Ability	25
Size	30
Cost	15

Figure 2: Table with criteria and weighting in percentage.

Since the instruments chosen to need to meet the key requirements of the mission, the requirements will be given a mandatory score of 1, with the criteria given a score of 0. This means any option scoring 0 for the requirements will be given a total score of 0. The two scoring options for mandatory 1 are 0, if the option fails to meet the requirement, and 1, if the option passes the requirement. For the criteria listed in figure 2, a score from 0 – 3 can be given, depending on the range for each criterion. Figure 3 lists the score rankings for measurement effectiveness. The data that is taken from the instrument will be considered for scoring. A score of 0 will be given if more than 3 different measurements will be needed to determine composition. A score of 1 will be given if 3 different measurements will be needed to determine composition. A score of 2 will be given if 2 different measurements will be needed to determine composition. A score of 3 will be given if only one type of measurement will be needed to determine composition. To determine these for the options, the measurements that are taken will be looked at in order to determine what additional measurements are needed.

Measurement Effectiveness Score	Reason
0	More than 3 different measurements
1	3 different measurements
2	2 different measurements
3	Only one measurement

Figure 3: Scoring and reasoning for Measurement effectiveness criteria

Next the scoring for Measurement Quality will be discussed. Figure 4 lists the score rankings for measurement quality. For quality, there are many secondary mission objectives that were stated in our mission baseline presentation. We will look how the measurements taken on the instrument(s) will help us achieve our secondary goals. A score of 0 will be given if the measurements help us achieve 0 of our secondary objectives. A score of 1 will be given if the measurements help us achieve 1 of our secondary objectives. A score of 2 will be given if the measurements help us achieve 2 of our secondary objectives. A score of 3 will be given if the measurements help us achieve more than 2 of our secondary objectives.

Measurement Quality Score	Reason
0	Measurement applies to 0 secondary objectives
1	Measurement applies to 1 secondary objective
2	Measurement applies to 2 secondary objectives
3	Measurement applies to more than 2 secondary objectives

Figure 4: Scoring and reasoning for measurement quality.

Next, scoring for measurement ability will be discussed. For measurement ability, a sphere will be used as reference. The instrument will be assumed to point in a preferred direction and the score will be based on a percentage on how much of the sphere will the instrument be able to take measurements on. Figure 5 lists the scoring and reasoning for measurement ability. For example, a score of 3 will mean that the instrument can take measurements on more than 75% of the sphere, depending on the orientation of the device. A score of 2 will mean the instrument can take measurements on more than 50 % of the sphere, depending on the orientation of the device. A score of 1 will mean the instrument can take measurements on more than 25% of the sphere, depending on the orientation of the device. A score of 0 will mean the instrument can take measurements on less than 25% of the sphere, depending on the orientation of the device.

Measurement Ability Score	Reason
0	Can measure in less than 25% of possible orientations
1	Can measure in more than 25% of possible orientations
2	Can measure in more than 50% of possible orientations
3	Can measure in more than 75% of possible orientations

Figure 5: Scoring and reasoning for measurement ability

Next, the scoring for size will be chosen. Size can be combined into both volume and mass. The mass will be taken more into account for the grading, as this will affect the decent speed of the probe. Figure 6 lists the scoring and reasoning for size. For this grading, each of the options will be compared to each other, using instrument specifications on manufacturer websites. Ideally, various sizes and weights would be found for each type of instrument so that it can be averaged.

Measurement Quality Score	Reason
0	Worst size
1	2nd worst size
2	2nd best size

3	Best size

Figure 6: Scoring and reasoning for size

Finally, the last scoring to be decided will be for cost. The cost for each instrument will be averaged from numerous manufactures. If the instruments price for space missions can be found that will also be taken into consideration. The scoring will be same as the grading for size, which the best result will be given a 3 and the worst will be given a 0. Figure 7 lists the scoring and reasoning for cost.

Measurement Quality Score	**Reason**
0	Worst cost
1	2^{nd} worst cost
2	2^{nd} best cost
3	Best cost

Figure 7: Scoring and reasoning for cost

The first option we will be considering is a mass spectrometer. A mass spectrometer works by capturing particles from outside the instrument and ionizing them. These ions are then accelerated through a magnetic field where the amount of deflection depends on the molecular weight of the ions (Figure 8). The magnet can be tuned to act as a bandpass for molecular weight to a detector. The ions that are passed through this area hit the detector where the relative abundance is stored as a function of molecular weight. Figure 9 shows the type of data that can be obtained using a mass spectrometer. The cost and sizing was found using data sheets from a specification sheet found online [1].

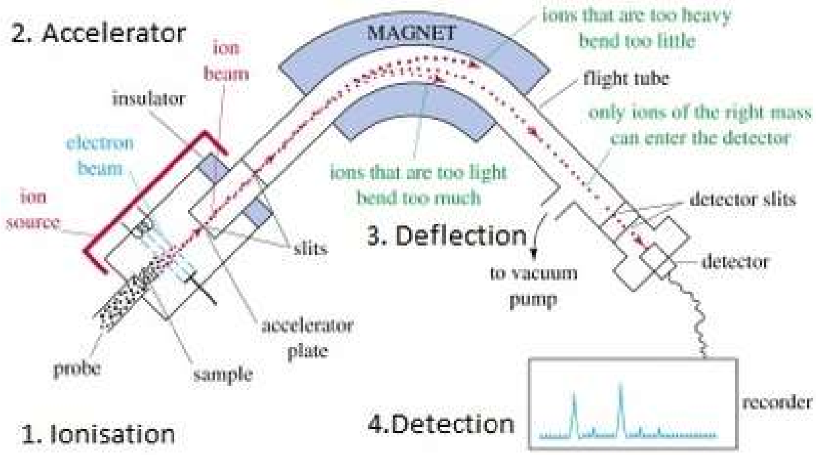


Figure 8: Standard setup for a mass spectrometer

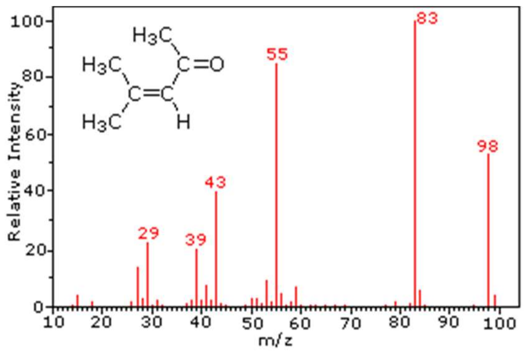


Figure 9: Plot of data taken from a mass spectrometer

The second option we will be considering is a grating spectrometer. A grating spectrometer uses a lens to capture light from outside the instrument. Mirrors are used to deflect the light towards a grating, which splits the light into different wavelength segments. The grating and the distance between the gratings can be changed depending on the wavelength range that is desired.

These wavelength segments are then reflected using another mirror towards a detector (Figure 10). The detector looks at the intensity of the light at each wavelength segment in the given wavelength range. Figure 11 shows the type of data that can be received using a grating spectrometer. The grating spectrometer looks at the emission spectra of the particles it is looking at, as particles emit light at different wavelengths. A NIR grating spectrometer was found online which operates between 0.9 – 2.3 microns, which would be the wavelength range used for our mission [2].

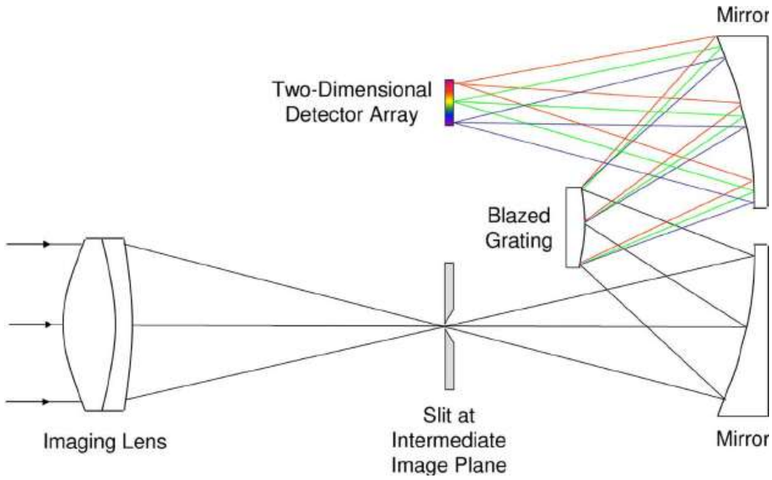


Figure 10: Standard setup for a grating spectrometer

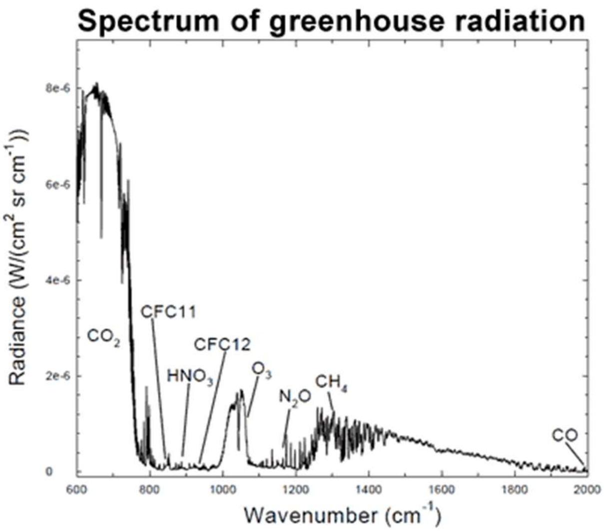


Figure 11: Data from a grating spectrometer based on radiance vs wavelength

The third option that will be looked at is a FTIR spectrometer. FTIR stands for Fourier Transform Infrared. Just like the grating spectrometer, the FTIR spectrometer works by capturing light using a lens. The light is split into 2 sections using a beam splitter. One beam of light travels a fixed distance to a mirror and is reflected to the beam splitter. The other beam of light travels a distance to a moveable mirror and is also reflected to the beam splitter. Once the two beams arrive back at the beam splitter they will be combined again. Depending on the distance of the moveable mirror, the interference caused back at the beam splitter can be constructive or destructive for different wavelengths. This causes increased intensity at harmonics of certain wavelengths. These wavelengths are then captured using a detector (figure 12). The type of data received is the same as a grating spectrometer, as it is intensity vs wavelength. Like the grating spectrometer, it also looks at the emission spectra of particles to determine which particles are where the instrument is looking. A data sheet was found online for an FTIR in similar wavelength range as above [3].

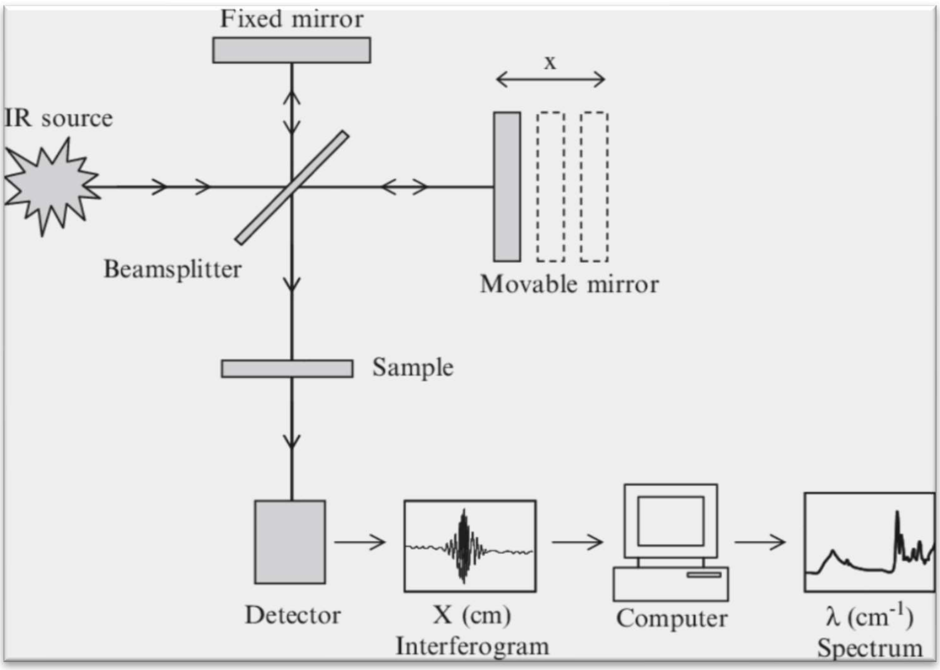


Figure 12: Standard setup for an FTIR spectrometer

The final option that will be looked at is a TDLAS. This stands for Tunable Diode Laser Absorption Spectrometer. First, gas is captured in a chamber from outside. Then a laser is emitted into the chamber. The laser has a wavelength range on it that is known. As the laser travels through the chamber, the gas particles within the chamber will absorb the light from the laser at different wavelengths, depending on what the particles are. After a calculated pathlength of the laser, it exits the chamber and the intensity is recorded on a detector (figure 13). The intensity of the laser based on wavelength is compared to the intensity of the laser based on wavelength before it enters the chamber. This is done to see at what wavelengths the laser was absorbed to determine which particles are in the chamber (figure 14). An infrared TDLAS was found online and the data sheet will be used [4].

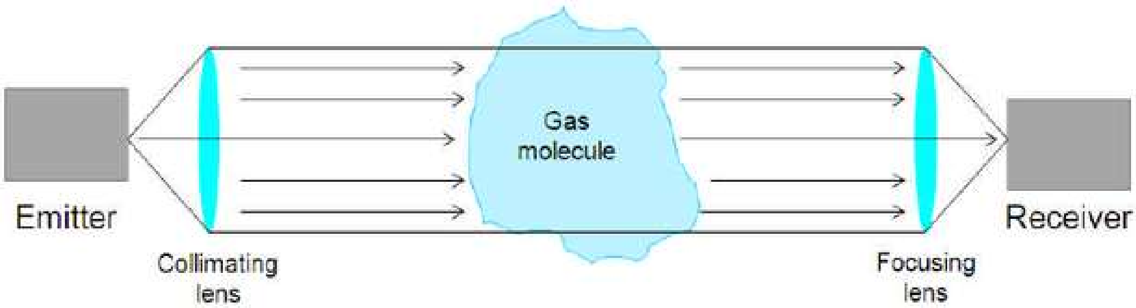


Figure 13: Standard setup for a TDLAS

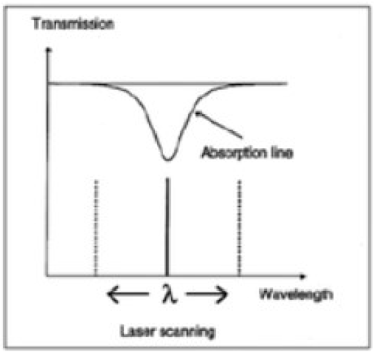


Figure 14: Data for a TDLAS with laser reference and absorption line

We will now put the 4 options in the decision matrix. Figure 15 shows the decision matrix for the options considered. The grade is converted to a percentage and then multiplied by the weight. This is done for each criterion and the total is added up and shown in the last row. The options are in the same order as they were discussed in this trade study, which is Mass spectrometer, grating spectrometer, FTIR spectrometer and TDLAS respectively.

Criteria	Mandatory (0,1)	Weight (%)	Grade	Option 1	Option 2	Option 3	Option 4
REQ-FUNC-0001	1	X	0 – 1	1	1	1	1
REQ-FUNC-0095	1	X	0 – 1	1	1	1	1
REQ-PERF-0010	1	X	0 – 1	1	1	1	1
REQ-PERF-0091	1	X	0 – 1	1	1	1	1
Measurement Effectiveness	0	10	0 – 3	1	3	2	3
Measurement Quality	0	20	0 – 3	3	3	2	2
Measurement Ability	0	25	0 – 3	2	1	1	3
Size	0	30	0 – 3	2	1	0	3
Cost	0	15	0 – 3	2	3	1	0
TOTAL		100		70	63	43	**78**

Figure 15: Decision matrix for trade study, with total score on the bottom row

This shows that the TDLAS appears to be the best option. However, it is only 8 higher than the mass spectrometer. This can be due to the weighting of the trade study, so a secondary decision matrix will be made for sensitivity testing. For the secondary matrix, more of an emphasis will be put on the measurements itself rather than the size of the probe. Figure 16 outlines the new decision matrix, where size was reduced from 30 to 25, cost was reduced from 15 to 10 and measurement effectiveness increased from 10 to 20. This now means that 65% of the weight is based off the characteristics of the instruments.

Criteria	Mandatory (0,1)	Weight (%)	Grade	Option 1	Option 2	Option 3	Option 4
REQ-FUNC-0001	1	X	0 – 1	1	1	1	1
REQ-FUNC-0095	1	X	0 – 1	1	1	1	1
REQ-PERF-0010	1	X	0 – 1	1	1	1	1
REQ-PERF-0091	1	X	0 – 1	1	1	1	1
Measurement Effectiveness	0	20	0 – 3	1	3	2	3
Measurement Quality	0	20	0 – 3	3	3	2	2
Measurement Ability	0	25	0 – 3	2	1	1	3
Size	0	25	0 – 3	2	1	0	3
Cost	0	10	0 – 3	2	3	1	0
TOTAL		100		67	67	43	**87**

Figure 16: Second decision matrix used for sensitivity testing

What this test shows is that the TDLAS is the best option as it was the winner for both trade studies. There are a few key factors about the TDLAS that makes it the best option. When comparing it to the grating spectrometer and the FTIR spectrometer, the TDLAS controls the amount of light that enters the chamber, since the laser is on the instrument. This means it only needs to capture the gas which is outside the system. The grating spectrometer and FTIR spectrometer work based on the light that enters the system. Since Venus has a high optical depth, it will be difficult to capture enough light to see these changes and would only work using a limb view technique. This means the instrument must be oriented at the Sun, which means the measurement ability is extremely low. The mass spectrometer also operates like the TDLAS, the main difference here is that the effectiveness of measurements is less for the mass spectrometer than for the TDLAS. This is because different measurements must be used to verify results using a mass spectrometer, as you will not be able to differentiate between molecules with the same molecular weight. The absorption spectra for different compounds has multiple wavelengths where a change can be seen, so you can look at a different wavelength range if you need to differentiate between two compounds.

Overall, this trade study shows that the TDLAS will be used as the primary instrument on the probes and the requirements for our mission will now be updated for using a TDLAS as the main instrument.

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