ESSE 4360 | Payload Design

Final Design Review: Written Report

An Analysis of the Seasonal Variation of Concentration Levels of CH_4 and CO_2 in the Mars Atmosphere

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INTRODUCTION

This report encapsulates the content that our group explored throughout the four-month period of this project. It is the final phase of our design review process, and it concludes the overall design that is appropriate to our mission objectives and requirements. Contents of this report include a trade study, cost analysis, component breakdown, etc. that further validates our design choice.

MISSION PURPOSE AND OBJECTIVE

A more detailed description of this section is covered in the Letter of Intent, which can be found in the Appendix of this paper. To summarize the content:

- JPL team identified a seasonal variation of CH_4 (methane), which correlates to an active replenishment of the substance (possible indication of biological sustainability)
- Recent studies have shown that the current CO_2 levels hinder our ability to terraform Mars
- Both of these studies want to be explored further to understand the complex atmosphere of Mars
- Hope to obtain relevant data in relation to the habitability of Mars in reference to methane and carbon dioxide levels

TEAM INTRODUCTION AND ROLES

Thipeeshan Balakrishnan | *Project Manager*

As Project Manager, Thipeeshan ensured that the work was constrained to the project scope and objectives by defining requirements of the payload. Additional work included progress updates with stakeholders (Gurpreet Singh (Technical Advisor), approving approaches and methods taken by team members, and collating all of the content for the project.

Yaseen Al-Taie | *Head of Design*

Yaseen explored the various components that could potentially be implemented for the payload design. He ensured that they met the requirements of the project, and were designed for optimal utilization.

Pavithra Kugarajah | *Head of Research*

Finally, Pavithra worked primarily on the research side of the project. Amongst proposing the project and doing the initial research for it, she further identified potential solutions to the payload design and explored future aspects (i.e. costs and project timelines).

LIST OF CRITICAL REQUIREMENTS

The following table (Table 1), defined by our team, represent our payload requirements with reference to our mission, environment and overall project scope:

Table 1: Critical Requirements List

REQUIREMENT	ASSUMPTION(S)	VERIFICATION / VALIDATION
The payload shall detect carbon dioxide (CO_2) and methane (CH_4) concentration levels	Payload will be able to detect both trace gases simultaneously	Spectrometer detection ability will be tested with carbon emissions during the pre-launch time period
The payload shall have a lens that enables detection of the wave fronts at a precise measurement	Specific lens is required for low altitudes since we are doing measurements at low altitudes	Lens will be tested out on carbon emissions and the one enabling the most precise measurement will be used
The payload shall filter out a specific spectra of wavelengths	Filter will constrain range in a way that will endorse accurate detection	Band pass filter that filters out all wavelengths except corresponding values
The payload shall have thermal restraints based on its operational functions.	Coating and material choice shall be sufficient enough for thermal control / configuration	Testing will be done via simulation and NX software tools and expected environmental conditions of Mars
The payload shall have a focal length of 100mm ($\pm$ 5mm)	Defined focal length will restrict pointing system as well	Measurements will be verified through expected values, and positional verification.
The payload shall occupy a laser that is set to emit near the absorption line of the gases	Emitting the laser near the absorption line can be enabled by temperature and current configuration	Testing laser and verifying that its emission is analogous to the trace gases.
The payload shall have environmental neglecting processes on the system.	Materials used with reference to the thermal constraints won't hinder its stability with the environment.	Testing the payload in a vacuum that simulates the environment of the Mars surface.
The payload shall have column measurements upwards of 2km from the surface.	Defined column measurement parameters will define field of view as well; concentrations are abundant at low altitudes.	Analyzing the spectrums produced during the testing period with reference to the expected data of the same altitudes on Earth.

POTENTIAL SOLUTIONS
When exploring viable solutions to our payload project, three notable ones presented themselves. This section provides a brief description on each, and their applications in atmospheric studies.

AMULSE (Atmospheric Measurements by Ultra-Light Spectrometer)
AMULSE was designed in reference to the simplicity that diode laser spectroscopy brings to gas detection. Based on direct absorption spectroscopy, it is an open-path tunable laser-based sensor that emits continuously in a specified region. Through the WMS technique (shifting detection to higher frequencies to reduce noise and to modulate the intensity near the transition), a targeted absorption line (either CO_2 or CH_4) is isolated and analyzed. The following figure (Figure 1) depicts a typical AMULSE whose components are specified for CO_2 detection:

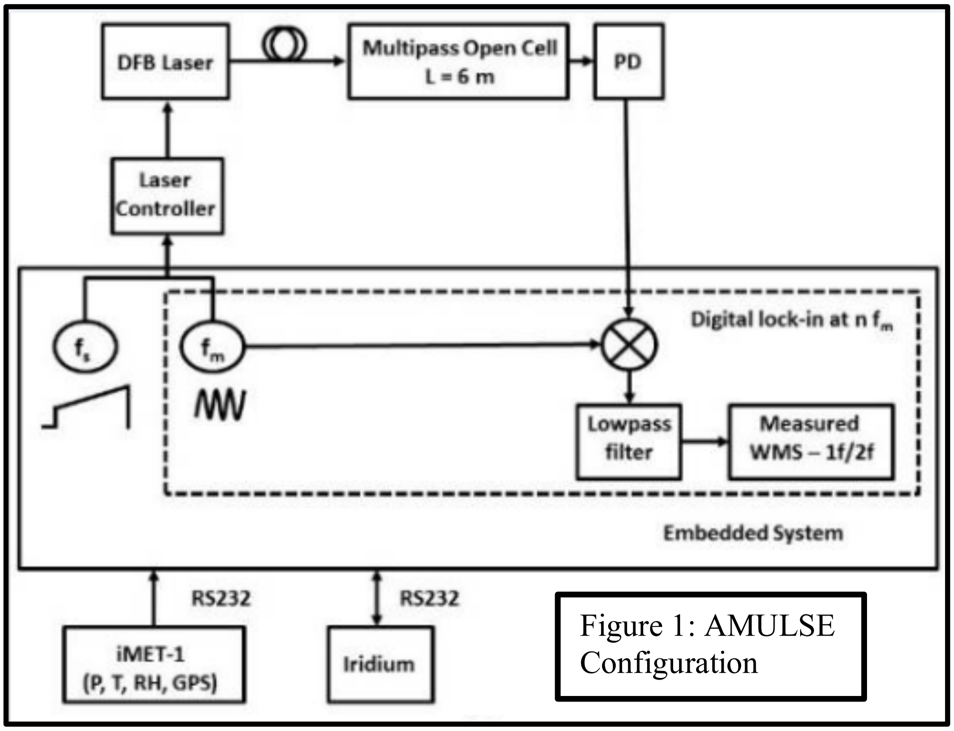
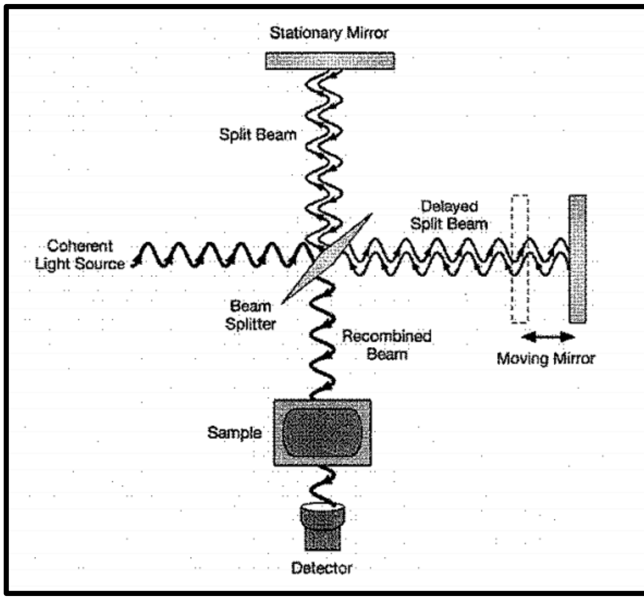


Figure 1: AMULSE Configuration

FTIR (Fourier Transform Infrared Spectroscopy)
Essentially the Michelson interferometer configuration, with the exception of one of the reflective mirrors being movable. The offset between the reflected light is detected simultaneously with the mirror movement, and the result is the intensity that is Fourier transformed into a function of the wavenumber.

Through IR absorption spectrum detection of the source, the FTIR endorses a quantitative study of the sample. The detector signals go through computers in order to obtain the absorption spectrum of the sample. The figure(s) (Figure 2) below depict the configuration and detection methodology of the FTIR.



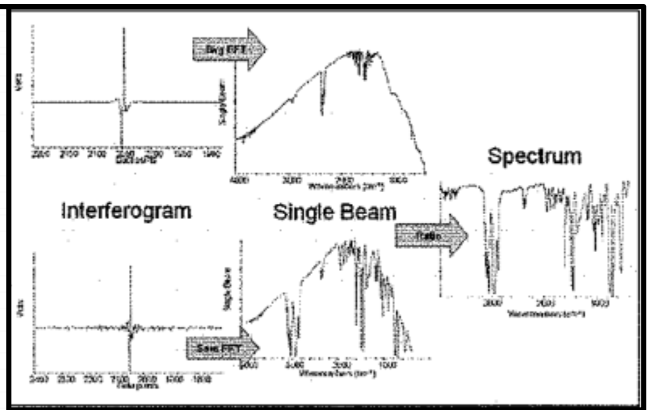


Figure 2: FTIR Set-up and Interferogram Production through detection

IASI (Infrared Atmospheric Sounding Interferometer)
(Add more when you get home; from sheet).
Measurements through IASI derive temperature and humidity profiles of atmospheres with high precision. The technique is based on passive IR remote sensing, enabled by Fourier Transform Spectroscopy in a specified region. Interferorgrams are processed through onboard digital subsystems and produces the soundings via IR imagers that work cohesively alongside the interferometer. Typically, IASI measurements can go upwards of 2 kilometer, with an accuracy of within one Kelvin and 10% (for humidity). Figure 3 depicts the fundamental instrument components of an IASI.

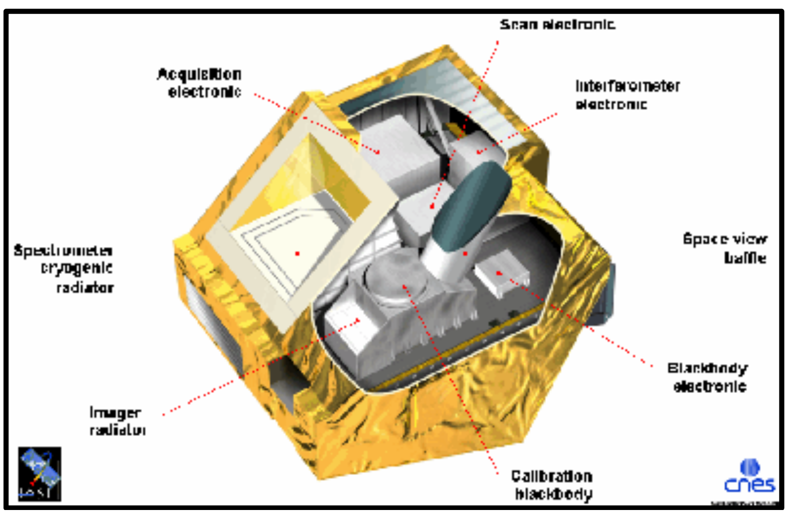


Figure 3: IASI Internal Configuration

These three spectrometers will be analyzed through a trade study, and based on the parameters that we evaluate, one will be chosen as the the appropriate solution of our problem space.

TRADE STUDY
The parameters that were analyzed for our trade study were the detection, filtering, precision and power of the subsequent systems. These were chosen due both to their relevance in comparison to the other requirements, as well as the similar properties amongst these spectrometers that make the requirements relevant for comparison (i.e. thermal constraints, environmental neglecting constraints, etc.)

	AMULSE		**FTIR**		**IASI**	
Detection Methodology / Hindrances (/ 4)	WMS technique through vertical profiling	3	Detector produces an interferogram based off of retardation	4	Collects vertical structure of the atmosphere via temperature and humidity profiling	2
Filtering / Constraint Method (/ 2)	WMS technique colluded with absorption line targeting	1	Mirror positioning and laser set near absorption line	1	Infrared part of EM spectrum only	1
Measurement Precision (/ 3)	Ideally: 0.96ppm in 1 second of integration time	2	SNR ratio is improved upon by multiplex and throughput; precision is thorough	3	Upwards of 1-2 km with a precision of $\pm$ 1K (temperature) and 10% for humidity; horizontal resolution of 25km	2.5
Relative Power of System (/ 3)	8W on average power consumption	3	<10 W power consumption	2	8W on power consumption	3
Total Score (/ 12)	9		10		8.5	

From our scoring hierarchy, it is seen that the FTIR is the favoured solution to our payload project. Its precision coupled with simple detection method places it slightly above the other two. It should be noted that the AMULSE was considered for its low power consumption because of the significance of data relaying, but ultimately, its inability for simultaneous detection makes it less valuable as a choice.

OVERALL DESIGN

The following diagram, produced by the head of design, is a schematic of our payload design. It showcases the critical components and the interaction between how it will collect data and process it.

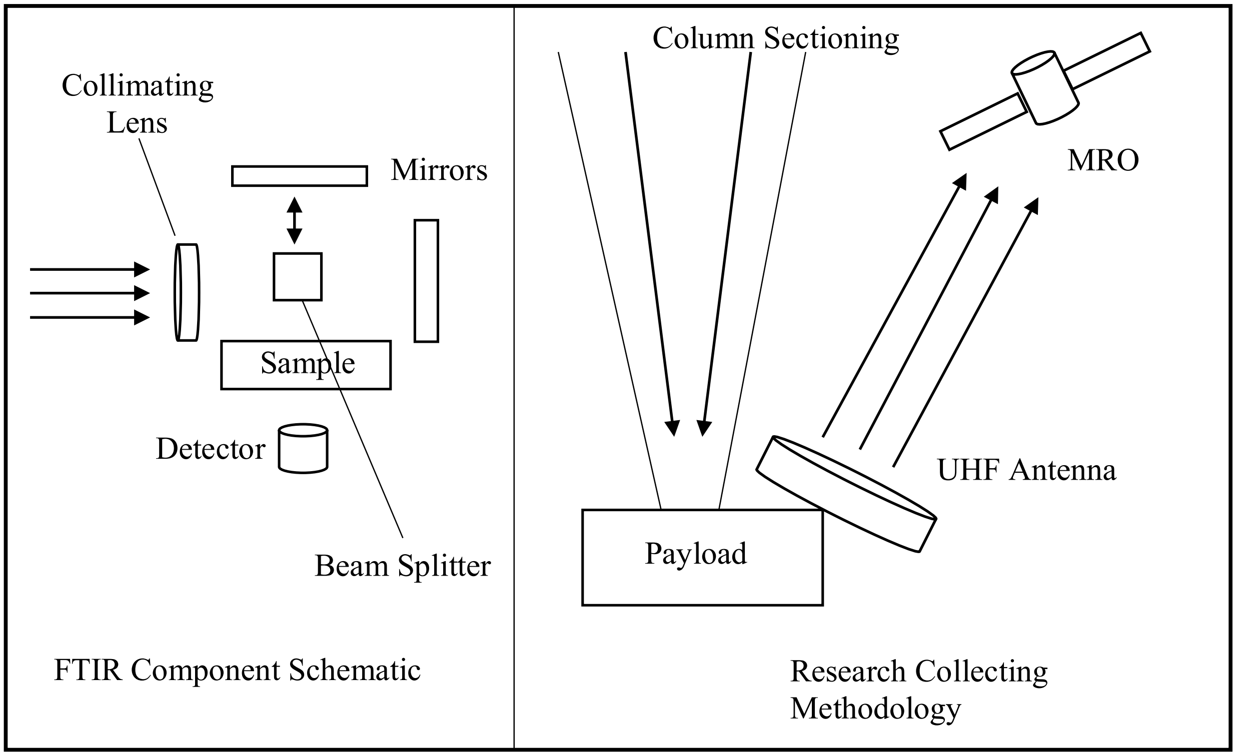


Figure 4: Fundamental Design Schematic of Payload and Design of Research Collecting Environment

FTIR Components

Michelson Interferometer
The interferometer splits the beam of light that originates from a single source; the beam splitter in the middle of the configuration splits the source of light to both mirrors, where one mirror moves in correspondence to the emission. The resulting reflected and transmitted waves are then re-directed by ordinary mirrors to a screen where signals are being created. This is known as interference by division of amplitude. The purpose of the interferometer is to create an interference pattern once the split beams combine again. These interference patterns can be constructive and destructive, carrying information about the original wave. The OPD (Optical Path Difference) is the relative distance between the offset, governs the interference pattern.

Beam Splitter Cube
In the form of a cube (two triangular glass prisms) enable splitting of waves. In the case of the FTIR, it is used to enable the interference (i.e. promote OPD).

Retro-reflective Mirrors
Specific mirrors that will ultimately enable reflected light to be parallel to the incoming light, which is particularly useful in our application of redirecting light.

InGaAs Detector
Standard InGaAs has a long wavelength cut off, which is used in gas analyses; it is connected after the beam to detect specific wavelengths.

Precision Components

Collimating Lens
Utilized to ensure the entering wave fronts are parallel. It is advantageous to our payload since it will configure no variation and will contribute to the stability and repeatable measurements of our project.

HeNe Laser
Used constrain the incoming emission of light in order to keep it in line with reference to the specific absorption line of the emission. Relatively cheap in comparison to other lasers that produce similar functions.

Communications Components

UHF Antenna
Will be implemented alongside the payload in order to communicate with Earth through the MRO satellite system (400 MHz), both for receiving operational commands and relaying its data.

MRO (Mars Reconnaissance Orbiters)
Will be used to downlink operations / relay data from the payload to the Earth station. It is notably accessible because of its large field of view of Earth, and it will enable easier communication than either direct communication signals to Earth or even via the Deep Space Network.

METHODOLOGY

The incident light will enter the instrument, via the collimating lens, thus ensuring that the entering wave fronts are parallel. It goes towards the Michelson Interferometer set-up and is split by the beam splitter, heading in perpendicular directions towards the retro-reflective mirrors. The mirror positions will be adjusted accordingly (through a distance $\lambda/4$, the path difference changes by $\lambda/2$), and will result in a fringes based on the offset of the mirrors (OPD). The recombined light will enter the detector to produce an interferogram, that is further analyzed via a Fourier transform, and analyzed based off wavenumber it is in coherence with. The interferogram is sent with its corresponding wavenumber through the antenna to the MRO, and then relayed back to the Earth ground station, where it will be analyzed.

Calculations

Field of View:

The field of view of the aperture can be calculated using:

$$AFOV(°) = 2 \times tan^{-1}\left(\frac{Horizontal\ FOV\ (mm)}{2 \times WD\ (mm)}\right)$$

or

$$Horizontal\ FOV(mm) = 2 \times WD\ (mm) \times \tan\left(\frac{AFOV\ (°)}{2}\right)$$

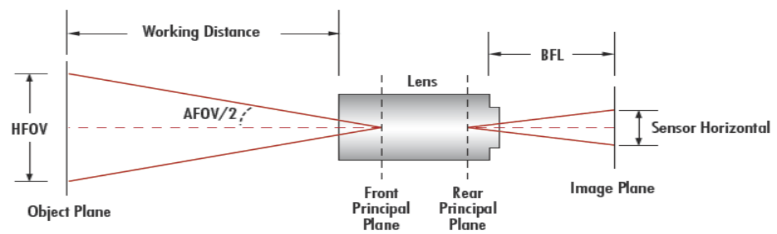


Figure 5: Field of View Diagram

Using a 101 mm lens to photograph a scene focused at 3m from the camera:

M = 101 / (3000 - 150) = 0.0348

Using a ruler of 1m (1000mm) length, with the camera imaging a maximum of 3872 pixels, assume that the ruler in the digital image measures 1940 pixels. Therefore:

A_{mm} = 3872 * 1000 * 0.0348 / 1940 = 68.65mm (Effective Image Aperture)

Due to the large area covered, an observation distance of 3m and a horizontal FOV of 68.65mm, (the effective focal length is 65.6mm) chosen for this purpose. Therefore:

$$\theta_{FOV} = 2\tan^{-1}\left(\frac{(68.65)*(3000-150)}{(2*3000*150)}\right) = 36.4\,°$$

$$f = \sqrt{\frac{(R^2 * A(d))}{A(O)}} = \sqrt{\frac{((101)^2*(6000)}{(3000)}} = 142.8\,mm$$

$$F = \frac{f}{D} = \frac{142.8}{101} = 1.4$$

Spot size of the beam (Radius of the beam)

Represents the resulting geometrical spot size after the beam has exited the lens, with an assumed distance (x):

$$\text{Spot size} = \left(\frac{D}{f}\right)*(f-x) = \left(\frac{101}{142.8}\right)*(142.8-80) = 44.4mm$$

Diffraction limited resolution:

Aperture size will be limited by the rover structure (1m x 1m x 4m). It will be mounted on a 1m x 4m face. Therefore, assume an aperture diameter of 150mm. This gives a ground resolution of:

$$x = \frac{1.22\lambda}{D} = \text{arcseconds}$$

For L band (1600nm):

$$x = \frac{1.22(1600nm)}{101mm} = 0.398\ arcseconds$$

For C band (1500nm):

$$x = \frac{1.22(1500nm)}{101mm} = 0.373\ arcseconds$$

Spectral Resolution

$\frac{\lambda}{\Delta\lambda}$ = m.N ➔ grating(N) = 120000,➔ so our spatial resolution is

$$\frac{1}{N.m.1000} = \frac{1}{(12000)(1)(1000)} = 8.33*10^{-9} \text{ per pixel}$$

Spectral range

$$\Delta\lambda = \frac{\lambda}{m.N} = \frac{450*10^{-9}}{(1)(120000)} = 3.75*10^{-12}m$$

Quality Factor:

The quality factor of the optical system can be computed as follows:

$$Q = \frac{d}{d'} \; ; \; d' = 2.44\frac{\lambda f}{D} = 2.44\lambda F$$

And d is the pixel size obtained from the detector. Assuming pictures with resolution 3872 x 1940 pixels, the pixel size can be computed using: diagonal sensor size (20mm x 14mm)

$$d = \frac{20mm}{3872} \times \frac{14mm}{1940} = 5.3\mu m \times 7.2\mu m$$ ➔ Diagonal is 8.9 µm

Now the Quality factor can be computed as:

For L band➔ $d' = 2.44(1600nm)(1.4) = 5.46$

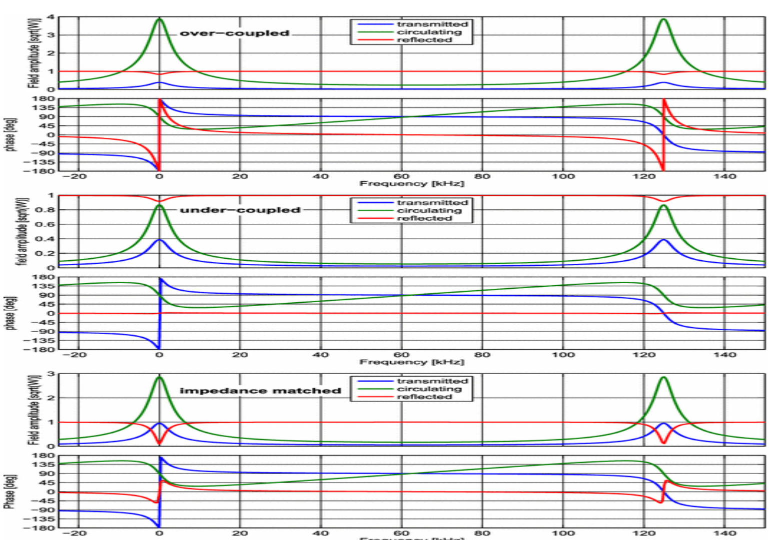
$$Q = \frac{8.9}{5.46} = 1.63$$

For C band ➔ $d' = 2.44(1500nm)(1.4) = 5.12$

$$Q = \frac{8.9}{5.12} = 1.74$$

Data Processing

Level 0 data is the raw data obtained from the interference patterns generated by the FTIR



The figure on the left depicts Level 2 data, and is computed after the Level 1 data has been obtained. The required values for the concentration can be found by comparing the Level 1 data to the Mars radiation spectrum, and the difference will determine the reflected amount to determine wavelengths.

Figure 6: Level 2 Data

CONSTRAINTS OF THE PAYLOAD DESIGN

Operational Constraints

The most notable constraints in relation to the operations of our payload are the noise monitoring. We want to ensure that the expected main sources (i.e. dark and shot) do not contribute to hindering our data collection. At higher temperatures, dark noise is prominent, so to prevent that, minor cooling applications to the detector have been applied.

Thermal and Environmental Constraints

Because of the Martian cold environment, several additional measures have been taken to ensure that the payload functions properly. The most notable add-on we have incorporated is a warm electronics box, which will protect the payload's vital components and keep them temperature-controlled. It is assumed that the WEB will not hinder measurement applications as in encompasses the payload structure.

In addition, gold coating will reduce the energy radiated by the body, and will minimize the radiation heat transfer across the system. Aerogel will also be applied within the walls of the payload to minimize the outward radiation. Finally, thermoelectric heaters (~ 1W) will be attached as well, to neglect power waste that may occur during the colder temperatures.

While the temperatures can drop to -96 degrees Celsius, we do not want to overheat the structure because of these aforementioned add-ons and the solar arrays absorbing radiation for power utilization. As such, a heat rejection system is implemented that will utilize a pump to collect excess heat of the system.

COST ANALYSIS

Existing missions, i.e. GOSAT, rationalized our cost analysis for this three-year mission. Due to the time constraint, the numbers indicated in the table below are chosen as a rough estimate. It should be noted that the launch segment, ground segment development and operations cost are not included in this analysis.

Table 3: Cost Analysis Table

	PART	DESCRIPTION	COST
	Payload	(imbedded inside a (1m x 1m x 4m))	~ 250000
	Structure	Aluminum 6061 frame	~ 900000
	Communications	Full Ground Station Kit + (transmitter)	~ 182800
	Power	GaAs Cells + High Energy Density Battery	~ 19000
	Thermal	- WEB Box - Thermoelectric Coolers	~ 15000 ~ 10000
	ADCS	Reaction wheels	~ 90000
	Propulsion	Micro-propulsion System	~ 200000
Total (Euro)			1666800
Total (CAD)			$ 2508031.33

SCHEDULE OF CURRENT / FUTURE PHASES

Mission Lifetime

The goal of the mission is to provide measurements to specify column-averaged dry air mole fraction of CH_4 and CO_2 on mars layer (specifically lower atmosphere) for a period of a three years. Therefore, the mission will last 3 years so that a more complete understanding of its effectiveness is shown. After 3 years the mission will have the option of extending its lifetime or de-orbiting.

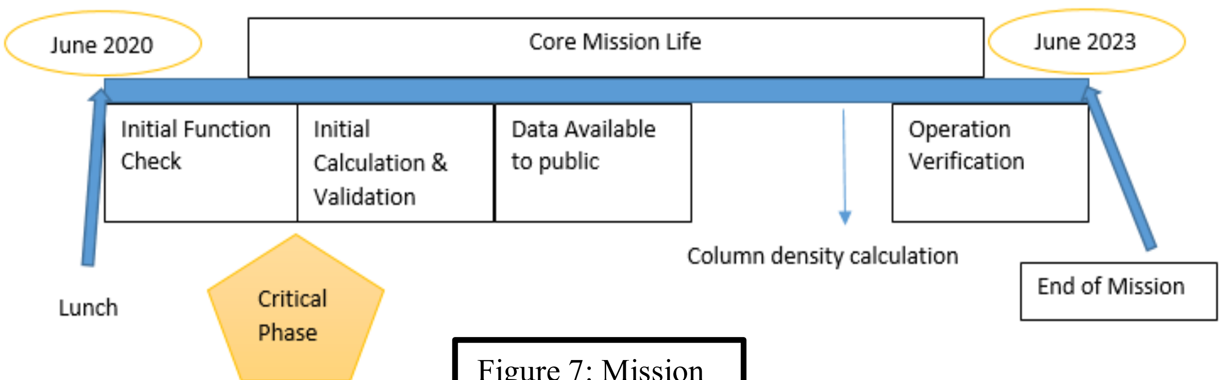


Figure 7: Mission Lifetime

Project Schedule

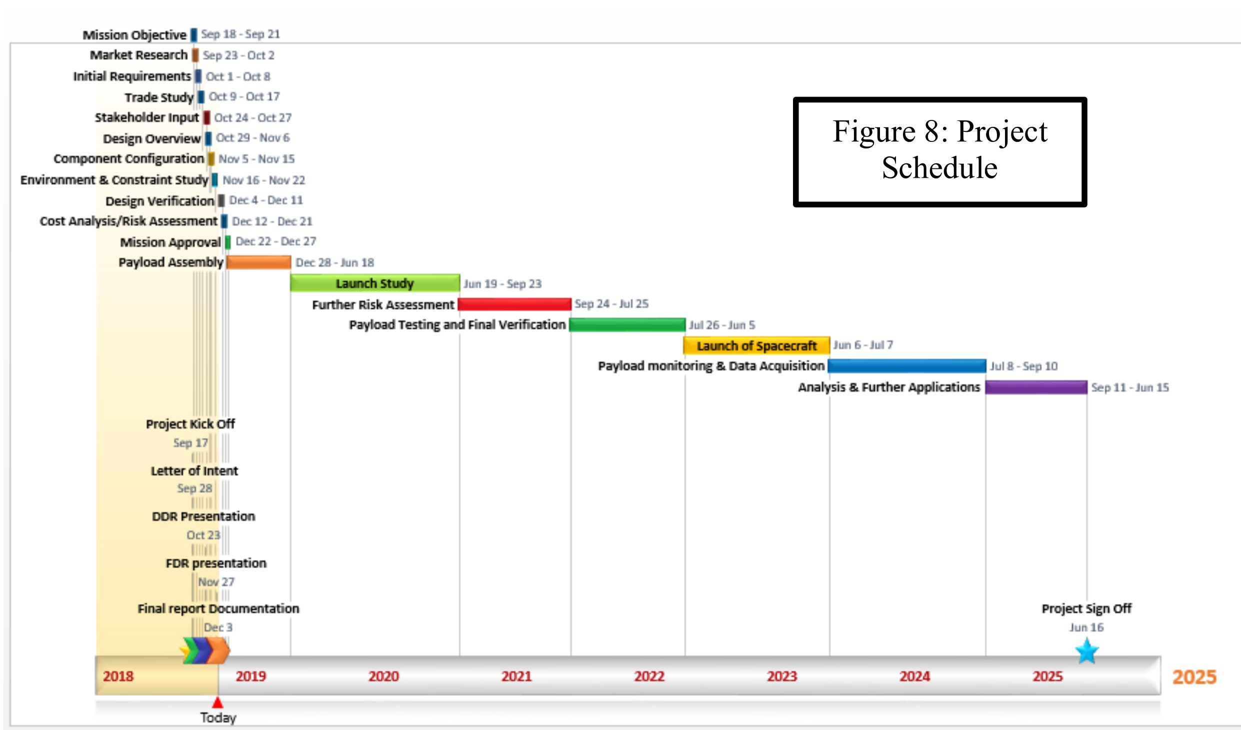


Figure 8: Project Schedule

The schedule above gives a quick rundown of the main project elements that occurred from September to December, and onwards moving forward, to a projected date of June 2025. The initial phases of this project included defining the mission objective and performing market research. This was followed by an understanding of requirements and potential solutions, which cultivated the majority of our Detailed Design Review. The feedback taken from the DDR (from stakeholders and self-evaluations) enabled a more intricate look at our design and mission study. This was finalized for this report and FDR presentation that occurred at the end of the project phase.

Currently, we are in our mission phase, where verification and risk assessment are being implemented currently. Once our cost analysis has been validated, the steps taken to approve our mission will take place. Upon approval, payload assembly, launch study and further risk assessment will be taken upon. This will essentially lead us into our final verification and testing, within a three-year time frame (2019-2021). The spacecraft will hopefully launch at the start of 2022, with a three-year operational life that requires monitoring, constant data acquisition, and implementing its utility for future mission applications.

CONLUDING REMARKS

To conclude the final design report, we feel that we have identified the essential aspects of our mission and payload design that have led to this final phase of our design review process, and it concludes the overall design that is appropriate to our mission objectives and requirements**.**

With our requirements defined, our team was able to perform a trade study, thus resulting a comparative study of our potential solutions for the project. Amongst the solutions, the FTIR was quantitatively and qualitatively the best solution, and it was implemented into our payload design. Components were identified, and a breakdown of our baseline geometry was showcased in our methodology and calculations section.

Furthermore, the constraints of our mission were addressed, and additional measures to ensure minimal disturbance were discussed, both in terms of operations and the Martian environment (thermal). Finally, a rudimentary cost analysis was performed, tabulating the expected values of our major components. This was followed with an overview of our project timeline, both in terms of the design and mission phases.

We proposed this mission and payload design in order to better comprehend the complex nature of the Mars atmosphere, and our team is hopeful that our study can lead to a more cohesive understanding of it. In addition, we hope our findings can promote a future where the Martian environment can be terraformed and eventually habituated by our civilization.

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Pavithra:

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APPENDIX

LETTER OF INTENT

September 28th, 2018
Michael Daly
Petrie Science and Engineering Building
York University
RE: Design Project

Dear Professor Michael Daly,

With the recent discoveries from the various studies involving spacecrafts and telescopes monitoring the atmosphere of Mars, our interest in this area has grown immensely. Our concern is largely in relation to the discovery (from JPL team) of a seasonal variation of CH_4, indicating an active replenishment of the substance. This is where our prime interest lies because it is potentially indicative of many biological hypotheses highlighting the existence of life on Mars (both in the past and currently)[i]. In addition, recent studies have also shown that that the current CO_2 levels hinder our ability to enable terraforming (modification of a planet's conditions to make it habitable) with our current technology[ii].

The mission we are proposing involves the usage of spectroscopy and interferometry to measure the concentration levels and other parameters of these two molecules, and analyzing the variance throughout a three-year time period. By designing a fly-by orbit using a gravity assist, we hope to send a satellite to Mars, where it will land our probe onto the surface of the planet. The payload will dock onto the planet for a three-year time period, up-linking its measured data and findings to the Mars Reconnaissance Orbiter (MRO) which is currently orbiting the planet[iii].

To measure concentration levels, a spectrometer will be used to measure the spectrum of solar light across many wavelengths, including IR, visible and UV. A Michelson Interferometer will also be used, since it is able to generate a spectrum with respect to wavelength given a source of electromagnetic radiation. The MIDAC FTIR configuration of a spectrometer, interferometer and various optics (i.e. beam splitters and mirrors) will produce data that can be analyzed in relation to concentration variances (using interferometry and Fourier analysis)[iv]. Sensors will be attached to our payload to measure seasonal variations of other properties as well, including pressure, wind speed, ground and vapour temperature, isotropic variation, etc. Both of these components will relay their respective data to the MRO every 10 minutes of a typical Mars hour, thus emphasizing specific changes and intensities at a more precise level.

The following is a list of requirements of our mission, specifically with our payload design:

- The system shall measure varying concentration levels of methane on Mars
- The system shall measure varying concentration levels of carbon dioxide on Mars
- The system shall measure variation periodically, in increments of ten minutes ($\pm$ 1 minutes) relative to a Mars hour
- The system shall sustain on the surface of Mars for at least three years (within an accuracy of 1%)
- The system shall use solar arrays to generate energy for subsystem usage

- The system shall be able to read varying wavelengths and frequencies of electromagnetic radiation
- The system system shall be able to relay its gathered info back to the ground station
- The system shall have a configuration to optimize data and solar radiation collection

All of our measurements for this mission are to further understand the complex atmosphere of Mars. We hope to obtain relevant data in relation to the habitability of Mars, and what measures need to be taken, whether in our advancement in technology or modification of the planet, to progress terraforming and colonization on Mars.

Sincerely,

Pavithra Kugarajah | Thipeeshan Balakrishnan | Yaseen Al-Taie

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DIVISION OF WORK

Thipeeshan Balakrishnan | Project Manager:

- Introduction
- Mission Purpose and Objective
- Team Introduction and Roles
- List of Critical Requirements (with Verification / Validation)
- Potential Solutions
    - AMULSE
    - FTIR
    - IASI
- Trade Study
- Thermal Constraints of the Payload Design
- Concluding Remarks

Yaseen Al- Taie | Head of Design:

- Overall Design
    - Critical Component Breakdown
- Methodology
- Calculations
- Data Processing

Constraints of the Payload Design

- Operational
- Thermal Constraints

Pavithra Kugarajah | Head of Research:

- Cost Analysis
- Schedule of Current / Future Phases

Note: Thipeeshan collected all the content done by
the team members and compiled it into the final version of the report.