Remote Sensing of Venusian Seismic Activity with a Small Spacecraft, the VAMOS Mission Concept

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Abstract— **The Venusian atmosphere creates inhospitable temperature and pressure conditions for the surface of Venus, Earth's twin planet, making in-situ measurements of any appreciable length difficult, expensive, and risky to obtain. Yet, because of the apparent youthfulness of Venus' surface features, long-duration seismic observations are in high demand in order to determine and understand the dynamic processes taking place in lieu of plate tectonics. The Venus Airglow Measurements and Orbiter for Seismicity (VAMOS) mission concept would make use of the dense Venusian atmosphere as a medium to conduct seismic vibrations from the surface to the ionosphere. Here, the resulting atmospheric gravity waves and acoustic waves can be observed in the form of perturbations in airglow emissions, the basic principles for which have been demonstrated at Earth following a tsunami and at Venus with the European Venus Express's Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) instrument. In addition, these observations would enable VAMOS to determine the crustal structure and ionospheric variability of Venus without approaching the surface or atmosphere themselves. Equipped with an instrument of modest size and mass, the baseline VAMOS spacecraft is designed to fit within a SmallSat form factor and travel to Venus predominantly under its own power. VAMOS would enter into an orbit uniquely suited for the long-duration, full-disk staring observations required for seismic readings. VAMOS' journey would be enabled by modern solar electric propulsion technology and SmallSat avionics, which allow the spacecraft to reach Venus and autonomously filter observation data on board to detect Venus-quake events. Currently, trade studies are being conducted to determine mission architecture robustness to launch and rideshare opportunities. Key spacecraft challenges for VAMOS, just as with many SmallSat-based mission concepts, include thermal and power management, onboard processing capabilities, telecommunications throughput, and propulsion technology. The VAMOS mission concept is being studied at JPL as part of the NASA Planetary Science Deep Space SmallSat Studies (PSDS3) program, which will not only produce a viable and exciting mission concept for a Venus SmallSat, but will have the opportunity to examine many issues facing the development of SmallSats for planetary exploration. These include SmallSat solar electric propulsion, autonomy, telecommunications, and resource management that can be applied to various inner solar system mission architectures.**

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1. INTRODUCTION

Observations which can reveal characteristics of Venus's internal structure, crustal dynamics, and level of seismic activity are highly desirable, yet very hard to obtain via surface investigations. Surface missions utilizing a seismometer would take direct measurements of seismic phenomena, but suffer incredibly harsh conditions to do so, drastically limiting their lifetimes and driving up costs. By exploiting the medium of airglow, an ionospheric phenomenon which reveals pressure waves in the atmosphere, and the strongest in the solar system of which happens to belong to Venus, orbital infrared measurements can supplant risky and difficult surface investigations. A second advantage of orbital measurements is that these observations replace the need for a seismic network, since each pixel corresponds to a seismic record.

The Venus Atmospheric Measurements and Orbiter for Seismicity (VAMOS) concept has the potential to collect invaluable and classically difficult to obtain data from orbit within small mass, volume, and cost allocations. The use of a relatively simple instrument and compact spacecraft enables the delivery of VAMOS to Venusian orbit via a variety of launch date-flexible and cost-effective means. The orbit and launch of the VAMOS concept are designed to be flexible and make use of Venus-bound as well as popular commercial geostationary transfer orbit (GTO) rideshare opportunities, while the spacecraft fits within the EELV Secondary Payload Adapter (ESPA) mass and volume allocations. VAMOS can be readily paired with other concepts in a synergistic manner to increase overall science return, serving to revive interest in and reveal the secrets of Earth's twin planet.

The difficulties faced in the development of the VAMOS concept are common to the majority of investigations which rely on SmallSat technology, such as small solar electric propulsion (SEP), SmallSat component lifetime and technology readiness level (TRL), and on-board processing and autonomy. The resulting lessons learned will benefit large space investigations and the growing SmallSat class alike.

2. Proposed Science Investigation

The VAMOS mission concept study for a comprehensive geophysical investigation of Venus includes seismicity, crustal structure, atmospheric waves, and ionospheric variability. This study is inspired by the fact that the formation, evolution, and structure of Venus remain an unsolved mystery more than fifty years after the first visit by a robotic spacecraft. To understand how Venus formed as a planet, we now need to probe its interior. The morphology and youthfulness of Venus' surface structural features testify to the potential for seismic activity. There is ample evidence that the crust of Venus has experienced stress since the relief of that stress is expressed in a wide range of structural features. In the absence of any plate tectonics, what are the dynamic processes that shape these features? What is the thickness and structure of the crust and lithosphere? How do they control the planetary evolution? What are the relationships with the dense Venus atmosphere, which envelops Venus like an ocean? Our mission concept, named VAMOS (Venus Airglow Measurements and Orbiter for Seismicity), is designed to address these fundamental questions.

Phenomenon & Hypothesis

The VAMOS concept details an architecture to enable a small spacecraft in Venus orbit to detect and characterize the perturbations of the neutral atmosphere and ionosphere induced by seismic waves. Venus is surrounded by the brightest naturally occurring airglow layer known in the Solar System. Airglow is a result of various atoms, molecules, and ions that get photoionized by ultraviolet radiation from the Sun and then release energy as visible and infrared light during recombination. Perturbations in the neutral atmosphere caused by seismicity on Venus leave an imprint in this airglow layer, which spans altitudes from 90-150 km. We use remote optical observations of this layer to study these perturbations, allowing us to infer the currently unknown seismicity and crustal structure of the solid planet below. Additional perturbations from atmospheric sources (i.e., gravity waves) are also present in this airglow layer and provide insight into Venus' atmospheric dynamics, particularly the variability in the zonal wind on dayside and nightside. The unexplained day-to-day variability in the airglow and hence the oxygen atom abundance is an additional target of investigation.

Airglow, Gravity Waves, & Seismic Waves

Two specific airglow emissions are investigated in the VAMOS concept, one occurring at 1.27 μm (visible on the night-side) and the other at 4.28 μm (visible on the dayside). The significant advantage of observing nightglow on Venus is that it is much brighter on Venus compared to Earth [22] and that airglow lifetime (~4,000 sec) is significantly longer than the period of seismic waves (10-30 sec) required to be detected to answer the aforementioned questions [30]. This makes airglow very attractive for directly detecting surface waves on Venus. This is in sharp contrast with Earth where the lifetime of airglow is about one order of magnitude smaller (~110 sec) than, e.g., the tsunami waves we routinely observe on Earth with 630 nm airglow instruments [31]. We also investigate the use of a 4.28 μm infrared (IR) channel to detect slow moving processes including gravity waves and signals of non-adiabatic heating of the atmosphere generated by the Venus quakes. The 4.28 μm channel complements the 1.27 μm one by possibly sensing epicentral waves (generated by quakes) at altitude of 120 km, since energy is dissipated as heat at this altitude.

Modeling Airglow Excitation by Planetary Quakes

Due to the dynamical coupling between the solid planet and the atmosphere, the waves generated by quakes propagate and can be detected in the atmosphere [12,28,29]. This has been demonstrated on Earth using various techniques with different observations and physical principles. For example, the excitation of the visible 630 nm airglow and GPS total electron content (TEC) perturbations resulting from the propagation of tsunami waves and Rayleigh waves was detected after several earthquakes over the past five years [3,18,19,21,34,35,37,38]. See movie: http://goo.gl/r0Av4C.

Initial modeling of seismic-wave-generated 1.27-μm airglow intensity variations on Venus demonstrated the possibility of identifying seismic events by remote sensing of planetary airglow signals. The seismic displacements induce a variation in the concentration of excited O_2, and thus in the volumetric emission rate (VER) [30]. This fluctuation can then be computed at every point and radially integrated to give the intensity fluctuation as seen from outside the atmosphere.

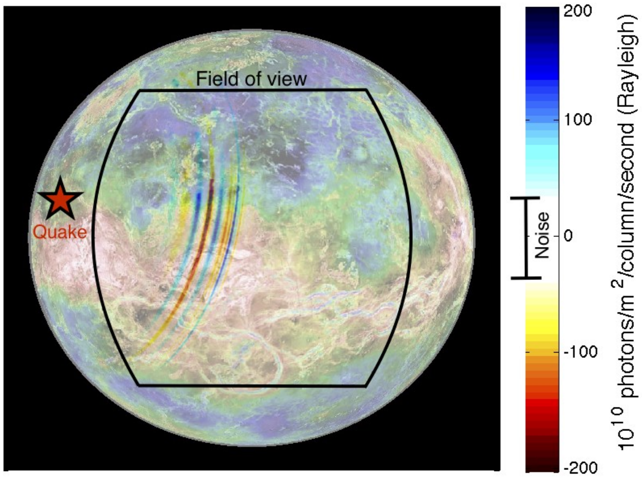

Figure 1- Modeled airglow fluctuations due to 20-sec seismic waves generated by a M_w=5.8 quake. The star is the quake location and the colors indicate airglow fluctuations above the conservative ±30 Rayleigh detection noise estimate using 0.3° planetary resolution

Similar synthetic measurements may be used to develop and test automated detection techniques. Normal modes and surface waves can be numerically computed for a fully coupled solid planet/atmosphere system [25]. This technique allows the calculation of the seismic signals within the atmosphere and in the airglow layer in particular.

Terrestrial Analogs

The VAMOS science team has extensive expertise in detecting airglow wave signatures on Earth such as those generated by atmospheric gravity waves [1], traveling ionospheric disturbances [32], and tsunamis. The first detection of the tsunami-induced waves in the airglow was reported by Makela *et al* [31] for the region over Hawaii using the redline emission at 630 nm during the Tohoku tsunami of March 11, 2011. Grawe and Makela [18] reported the observation of ionospheric signatures from a tsunami caused by the October 28, 2012 earthquake in Haida Gwaii (Mw 7.8) in both the airglow and TEC observed over Hawaii. More recently Grawe and Makela [19] developed an automated technique that requires little human interaction in processing airglow measurements (see http://goo.gl/FSyO6b) and applied that technique to the detection of the airglow signature generated by the tsunami launched by the September 16, 2015 earthquake in Chile. These observations have been performed for long period waves, with observation times of ~5 min. On Venus, the much stronger airglow (by a factor of 100) will allow observations of the seismic waves with much shorter periods.

3. Proposed Science Implementation

The VAMOS instrument is a relatively simple infrared telescope designed to vigilantly stare at Venus at all times, waiting for evidence of seismic events. The design features optics that facilitate observation of a large fraction of the planet at once from the nominal orbit. It features novel algorithms running on a dedicated processor to detect and record events from a real-time stream of incoming data.

Instrument Design Rationale

The instrument images the disk of Venus at two wavelengths: the 1.27-µm airglow band for non-sunlit regions, and the 4.28-µm band for the sunlit regions. The resolution requirement is to detect waves in the airglow region with a wavelength of 70 km over a significant portion of the visible disk, so the resolution at nadir must be near 5 km/pixel, taking into account foreshortening from the planet and the Nyquist criterion. The minimum field of view for seismic science is out to a latitude of 65 degrees, while for gravity (buoyancy) waves, a much larger field of view is desired. The current baseline field of view is 75 degrees latitude. The instrument design uses two Teledyne H2RG detectors with two Teledyne SIDECAR readout ASICs. In order to save on cost, both detectors are likely to be 5.3-µm cutoff, and both kept near 80 K in order to reduce dark noise. The two SIDECAR ASICs are controlled by a radiation-hard CubeSat-style electronics board set, consisting of a LEON3 processor and a Microsemi FPGA.

Event Detection Algorithms

VAMOS would use the previously mentioned automated technique developed by Grawe and Makela [19] for measurement processing. The technique has a potential in large-scale statistical studies and potential real-time monitoring of seismic events. The technique utilizes Gabor filtering, commonly used as a tool for feature extraction. A Gaussian RMS width, orientation, and wavelength fully specify the function. A set of Gabor kernels is convolved with the image to find the "best match," which then specifies the wave's orientation and wavelength. These parameters may be fully adjusted to control the frequency domain properties of the kernel. Performing operations for each of the images collected by the camera generates energy surfaces resulting in estimated orientation and wavelength for dominant wave features [19].

Instrument Processing & Data Packaging

The instrument takes data at a frame rate near 10 Hz. These frames pass through a second-order noise filter and are then co-added into 2.5-second images. Images are collected into a ten-minute block and then analyzed for patterns that are periodic in both time and space (see Figure 2). Events are found by peak-finding in the periodogram. Any block of data with no periodic structure is discarded.

After transmission to Earth, the waves' speed can be extracted from the sequences of images enabling, through a frequency analysis, the determination of the group velocity as a function of frequency. Such dispersion curves can then be routinely inverted for retrieving the crustal and upper mantle

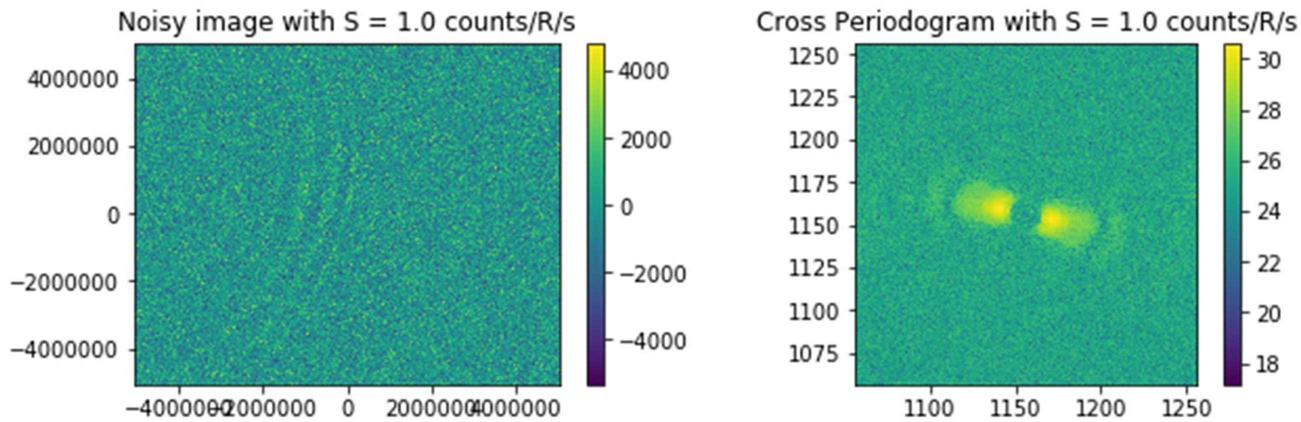

Figure 2- Simulated image of raw data (left); periodogram showing detection (right)

shear wave velocity, as illustrated on Earth with GPS ionospheric observations [8].

4. MISSION CONCEPT IMPLEMENTATION

The VAMOS concept delivers a single instrument to Venus orbit within the constraints of ESPA-class launches, allowing significant flexibility to launch date and trajectory. Two major options have been investigated, which are primarily delineated by their propulsion technology. A SEP-driven spacecraft is capable of reaching the ideal high-altitude circular orbit for the prescribed science, and a cheaper, higher TRL, chemical option delivers the spacecraft to Venus in an orbit which likely to be non-circular and highly tilted, effecting a degradation to the science observation strategy

Orbit Selection Rationale

The VAMOS instrument is designed to operate at a maximum orbital radius of 45,000 km. For a spacecraft with a Solar-Electric Propulsion (SEP) system, achieving this orbit is merely a matter of time and propellant. Higher orbits, which would require heavier optics, require less time and propellant, while lower orbits, with their lighter optics, require more. A radius of 45,000 km was chosen as a balance point between the xenon mass to achieve the orbit and the instrument mass to observe from it (Figure 3). For a spacecraft with a high-thrust chemical propulsion system, this orbit can be achieved for 1,500 m/s by leveraging the solar tides. A 480 m/s capture orbit places the spacecraft into a highly elliptical 6,301 x 864,900 km orbit, oriented such that at the next periapsis 34 days after capture, solar tides have pulled periapsis up to the desired 45,000 km radius. At this time, a 1,000 m/s circularization burn is executed. The chemical propulsion system that VAMOS can carry within the 180 kg ESPA constraint limits this architecture to an 8,750 x 45,000 km orbit. Here, the capture orbit is smaller, 6,300 x 536,640 km, requiring a larger, 503 m/s burn. Periapsis is raised to 8,750 km after 18 days, and the 659 m/s burn reduces apoapsis to 45,000 km as in the optimal scenario. In both cases, the resulting orbital inclination is approximately 153 deg.

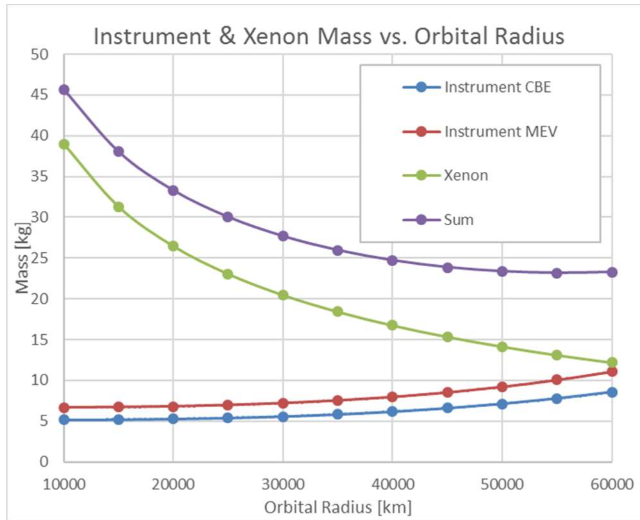

Figure 3- Mass trends of instrument optics and xenon propellant required as a function of nominal orbital radius

Launch, Cruise, & Orbit Insertion

Getting to Venus such that either the SEP-enabled ideal orbit or the chemical-limited orbit is achieved requires a rideshare, as a dedicated launch is typically beyond the resources of a SmallSat. The chemical option requires that the launch vehicle's targets include Venus. That is, VAMOS with this architecture would have to co-manifest with a mission already going to Venus, much as the MarCO CubeSats are hitching a ride to Mars with InSight's launch. The orbit baselined above was sized assuming a 3 km/s approach velocity, which is typical of Venus missions which desire to minimize orbit insertion ΔV or entry velocity. Missions choosing to use Venus for a gravity assist may want higher velocities. For example, Cassini's first Venus flyby was over 6 km/s, far in excess of what VAMOS could use. This greatly limits the potential rideshare options for this lower-cost architecture.

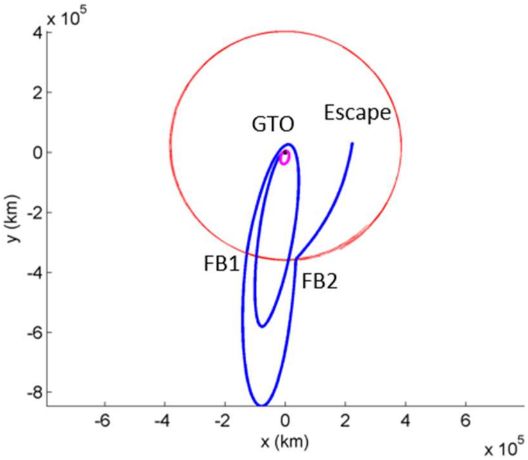

Figure 4- Example of lunar-assisted escape sequence #1 trajectory (initial GTO LAN = -100°)

However, the more- capable SEP architecture could launch using almost any launch into a Geosynchronous Transfer Orbit (GTO).

Lunar Escape Strategy for GTO Launch w/SEP

For a planetary SmallSat concept like VAMOS, a dedicated launch is currently unaffordable. One of the most likely rideshare options is to launch with a commercial geostationary satellite to a Geostationary Transfer Orbit. This rideshare option results in a substantially reduced launch cost, but there is no control of the launch conditions and the spacecraft is obviously not nominally on an escape trajectory from the Earth. Instead, an indirect escape route must be taken in this case. First, the upper stage of the launch vehicle must boost the VAMOS spacecraft to an apogee well beyond the Moon. Then a series of maneuvers is performed to target a sequence of lunar flybys, producing the desired escape conditions. Depending on the particular time of the launch at a given day, the GTO node can be distant from the Moon's orbital node, therefore it is generally necessary to perform a plane change at apogee (a plane change is efficient there because the spacecraft velocity is so low) so that the orbit of the spacecraft can intersect the Moon's orbit. Because of the significant ΔV cost of this plane change, SEP is required for this rideshare option.

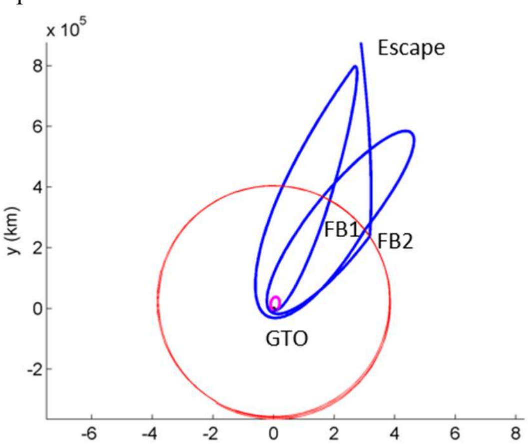

Figure 6- Example of lunar-assisted escape sequence #2 trajectory (initial GTO LAN = -75°)

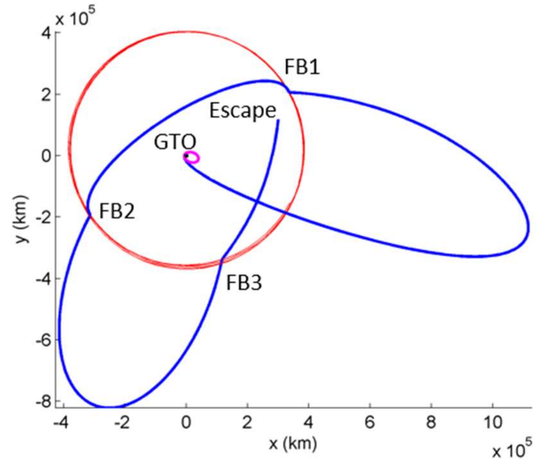

Figure 5- Example of lunar-assisted escape sequence #3 trajectory (initial GTO LAN = --20°)

An analysis was performed to bound (approximately) the range of required SEP ΔV for a spacecraft departing the Earth-Moon system from a GTO. The optimal magnitude and direction of the hyperbolic velocity vector is provided by the reference Mission Analysis Low-Thrust Optimizer (MALTO) interplanetary solution, departing from Earth in June 15, 2022. Literature shows that two lunar flybys can produce a hyperbolic escape energy C3 of about 2 km^2/s^2 [23]. To be conservative and increase the range of feasible escape sequences, the escape C3 is constrained to be less than 1 km^2/s^2 in MALTO. To consider all possible GTO orientations, trajectories are solved over a 360-degree range in initial GTO longitude of ascending nodes (LAN) in 10-degree increments. Four families of lunar flyby sequences are considered to find trajectories than match exactly the MALTO escape conditions:

- Sequence #1: one outbound lunar flyby, one inbound lunar flyby (Figure 4).
- Sequence #2: two outbound lunar flybys (Figure 6).

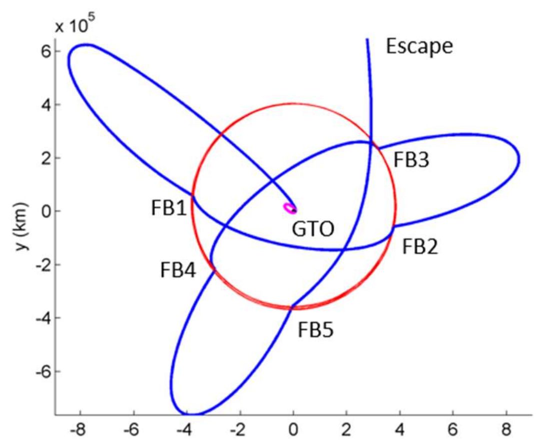

Figure 7- Example of lunar-assisted escape sequence #4 trajectory (initial GTO LAN = 140°)

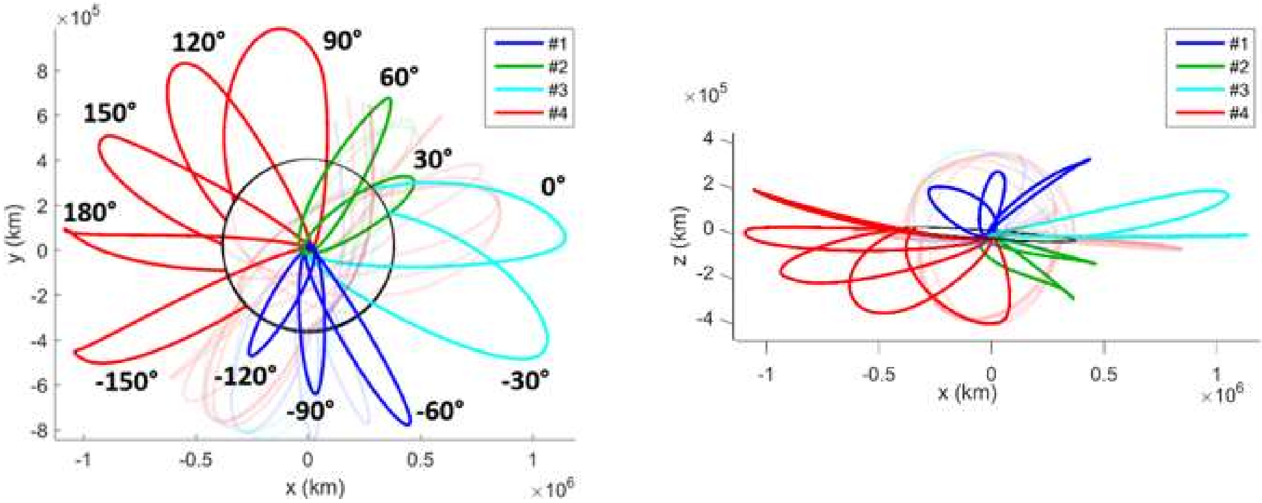

Figure 8- Trajectory solutions for 360 degree range initial GTO LAN in 30-degree increments. Left: top view; right: side view. For easier visualization, all trajectories are transparent after the first lunar flyby.

- Sequence #3: one inbound lunar flyby to set up a lunar backflip, one outbound lunar flyby, one inbound lunar flyby (Figure 5). The lunar backflip directs the spacecraft back to the Moon on the opposite side of the Earth, about 14 days later, so that the orbit geometry is better suited to initiate a double lunar flyby escape.
- Sequence #4: five lunar flybys in total, including two lunar backflips (Figure 7).

Trajectories from different sequences spanning the 360° LAN range are displayed in Figure 8. From Figure 4 to Figure 8, all trajectories are plotted in the Earth-centered, inertial EMO2000 frame. The corresponding SEP ΔV requirements are given in Figure 9. One can see that a 300 m/s SEP ΔV allocation covers most GTO LANs. Because of the different initial GTO plane orientations, the cost of targeting the Moon from the first apogee changes significantly depending on the initial GTO plane orientation, which explains the large variations in the SEP ΔV requirement among lunar flyby families. The SEP ΔV cost is largest (near 300 m/s) for solutions near 90° of initial GTO LAN. Combining results from all families, a curve giving the percentage of LAN GTO covered as a function of available SEP ΔV can be readily obtained (Figure 10). It was found that a 200 m/s SEP ΔV is compatible with 80% of GTO LANs. Note that the initial GTO impulsive ΔV is typically between 700 and 750 m/s for all families, assuming the burn occurs at perigee. Flight time varies between 40 days and 140 days.

Once escape has been achieved, the spacecraft need only consume approximately 25 kg of xenon and execute a pair of flybys. The first flyby is of Earth. SEP thrusting between launch and the Earth flyby increases the Earth-relative energy such that this flyby sets up a ballistic transfer down to Venus. The Venus flyby which follows simultaneously reduces the heliocentric apoapsis and, critically, alters the heliocentric inclination to match Venus'. SEP thrusting following the Venus flyby sets up the rendezvous and spiral-down described above. An example trajectory is illustrated in Figure 11.

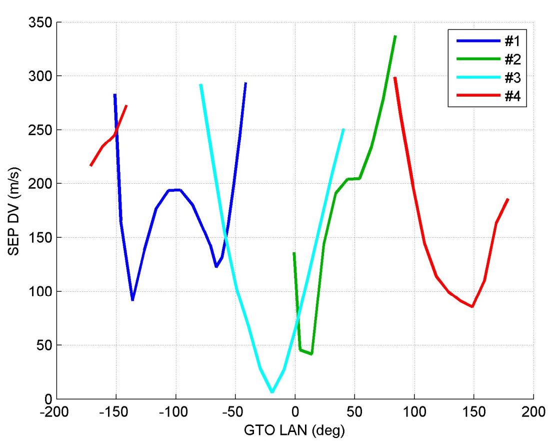

Figure 9- SEP ΔV required for initial GTO LAN values ranging from -180 to 180 degrees

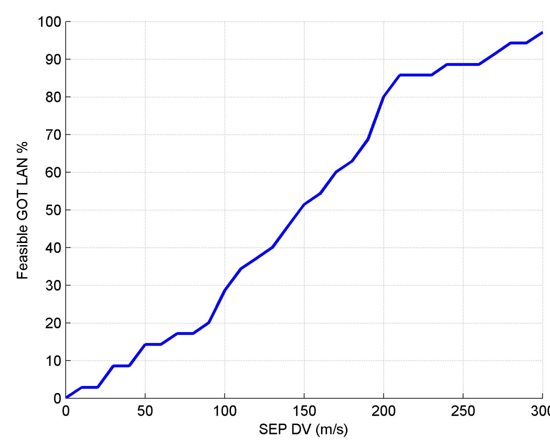

Figure 10- Percentage of allowable GTO LAN as a function of SEP ΔV

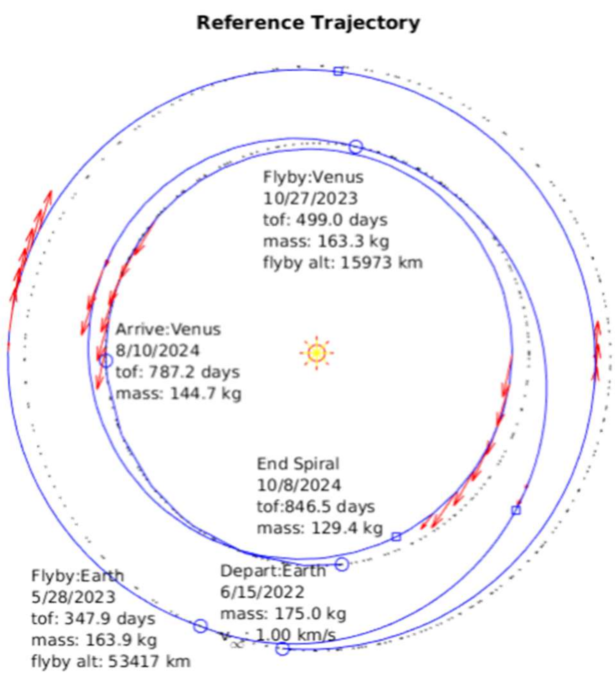

Figure 11- An example SEP interplanetary cruise trajectory

With 50 kg of xenon available and allocating the full 300 m/s required to launch with any GTO orientation, the 45,000 km orbit can be achieved for an Earth departure any time between January 1, 2022 and May 1, 2022 with a flight time of less than 36 months (including the spiral-down, but not the Earth escape). A secondary opportunity is available a year earlier with approximately the same flyby and arrival dates (Figure 12). The flight time is correspondingly longer. The Earth-Venus synodic period is 19 months, and so a similar trajectory should be available in the summer and fall of 2023.

Flight System

The VAMOS concept's spacecraft makes use of commercial off the shelf (COTS) CubeSat and SmallSat hardware wherever available, but lives in a new niche class of spacecraft mass, size, and capability. The ESPA classification limits margined wet mass to no more than 180 kg, and limits the stowed volume envelope to 61 cm by 71 cm by 96 cm. The critical systems under the most intense investigation are the propulsion systems, which will be described briefly here.

The baseline SEP system is based on the Busek BHT-600 thruster, a TRL 5 hall thruster that operates at 600 W. This means that the SEP system will require technology development, and incurs some implementation risk as a result. However, such a system would be able to deliver the VAMOS spacecraft to the nominal target orbit with just under 50 kg of xenon propellant.

Two chemical (monopropellant) propulsion systems were evaluated as alternatives for the SEP baseline: a conventional hydrazine system and a LMP-103S (Swedish green propellant) system. Thrusters using both propellants have flown, so are at TRL 9. A small increase in ΔV capability could be realized with LMP and may lead to eventual selection. However, both options are reserved pending future trades.

The hydrazine system could provide 1,180 m/s of ΔV, while the LMP system could provide an additional 110 m/s. See Table 1 for a comparison of the two options. At this time, both chemical propulsion systems have nearly identical designs. They both utilize six 22 N thrusters for the main impulse, which enables thrust vector control. Six 1 N thrusters are used for RCS. In each case, the system is sized to provide the maximum total impulse within the allocated wet mass (180 kg) as defined by the ESPA-class designation. The LMP propellant has a higher density and slightly higher performance, and can therefore provide more ΔV.

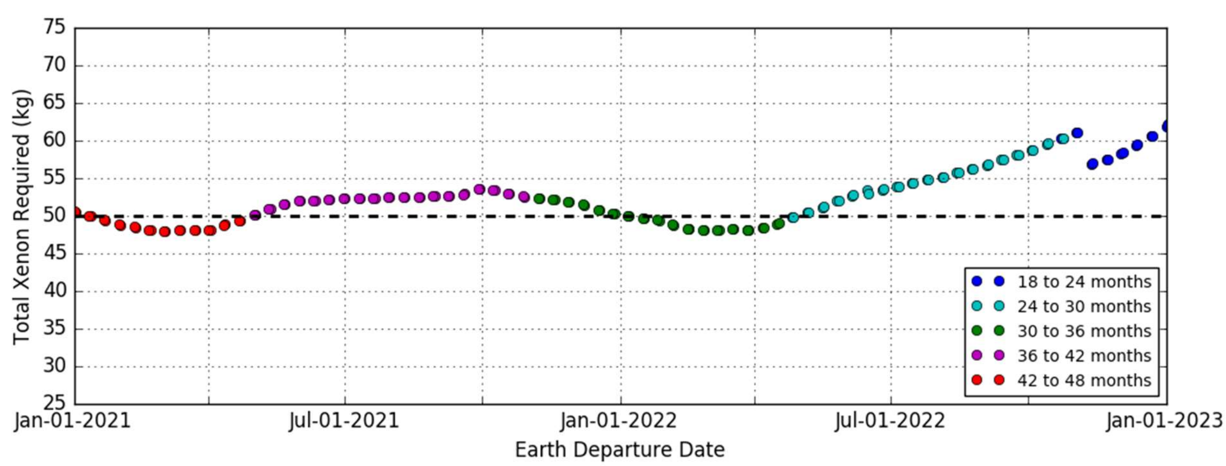

Figure 12- Required xenon propellant to exact SEP interplanetary cruise to Venus, as a function of Earth departure date and color-coded by time of flight

Table 1- Masses and performance values for the chemical propulsion options

Event	Unit	Hydra-zine	LMP
Delta-Velocity (ΔV)	[m/s]	1180	1290
Specific Impulse (I_{sp})	[s]	223	250
S/C Mass (wet MEV)	[kg]	180	180
Propulsion Dry Mass	[kg]	19	20
RCS Propellant	[kg]	2	2
Usable Propellant	[kg]	75	74
Tank Pressure	[psi]	275	380
Propellant Tank Diameter	[cm]	59.4	59.4
Pressurant Tank Volume	[cm^3]	7866	8849

The chemical designs both leverage a commercially available, spherical, titanium propellant tank with a diaphragm for propellant management. This particular tank is nearly the ideal size for the hydrazine propulsion system. Unfortunately, this tank is not optimal for the LMP system since the density of LMP is 24% higher than hydrazine, which results in a decreased volume requirement. Further penalizing the LMP design, the available propulsion tank is at lower pressure than what would be desired for LMP operation and peak specific impulse. The LMP option would be much more favorable if allowed to exceed the 180 kg limit to take advantage of the oversized tank (while remaining within the volume constraints of the ESPA-ring class spacecraft) or if a custom, smaller propellant tank could be used. COTS pressurant tanks are available in sizes within about 330 and 130 cm^3 of optimal for the hydrazine and LMP each option respectively. However, they are rated to higher pressures than the flow components selected for the rest of the system. Custom, conventional, lightweight Composite Overwrap Pressure Vessel (COPV) tanks could possibly be made for these designs at relatively low cost. If not, the propulsion systems may each grow by about 1 kg in order to leverage the COTS tanks.

The chemical propulsion options both use single-string redundancy and AIAA-S2000 margins. COTS valves are used wherever possible and are compatible with the 28 V power supplied by the spacecraft. Two kilograms of monopropellant for the RCS has been assumed to be sufficient to complete the mission for all cases. This requirement will be refined as the mission design matures.

5. OPTION COMPARISON & MAJOR TRADES

The VAMOS concept is still young, and belongs to a class which is yet sparsely examined. Several major trades were conducted in the development of the concept, as described here.

Trade: Instrumentation

The major ongoing instrument trade is between a set of reflective and refractive designs. One reflective design is an unobstructed Three-Mirror Anastigmat (TMA). Since this all-mirror design has no wavelength dependence and can be made all aluminum, the design has no defocus with temperature, and the two detectors can share one set of optics by using a beamsplitter. The drawback of the all-reflective design is that the TMA has no internal field stop, so the only method of controlling stray light from the sun is to use an external baffle. As the field of view of the instrument is very large (more than 15 degrees), the baffle must be almost as long as the spacecraft, and is only able to control stray light when the sun is more than 10 degrees from Venus. This design would therefore require a steep orbital tilt with respect to the ecliptic in order to take data when a significant fraction of the non-sunlit side of Venus is being viewed.

Several other reflective designs were also considered, namely a Cassegrain telescope with a mirror collimator, as well as a lengthened TMA with an internal field stop. Both of these designs were highly telecentric (unacceptable because of the narrow filter bandpasses), and would require correction with wavelength dependent prism field flatteners.

The refractive concept (Figure 13), similar to that used on VIRTIS/VEM [44], has an internal field stop, and is easily able to exclude stray sunlight. Refractive designs can suffer from thermal issues, so the refractive design may require careful thermal control of the lenses. Because of the internal field stop, an un-tilted orbit is optimal, since more of Venus is either lit or unlit by the sun.

Trade: Orbital Shape & Size vs. Instrumentation & Science

Perhaps the most obvious trade for the VAMOS concept is between the two previously defined “options”, i.e.: the SEP baseline and the chemical propulsion alternative. A circular orbit provided by a SEP system is best for instrument design, since the instrument can be optimized for a single resolution at the airglow altitude. Higher altitudes require a longer focal length for the instrument assuming a fixed resolution, and

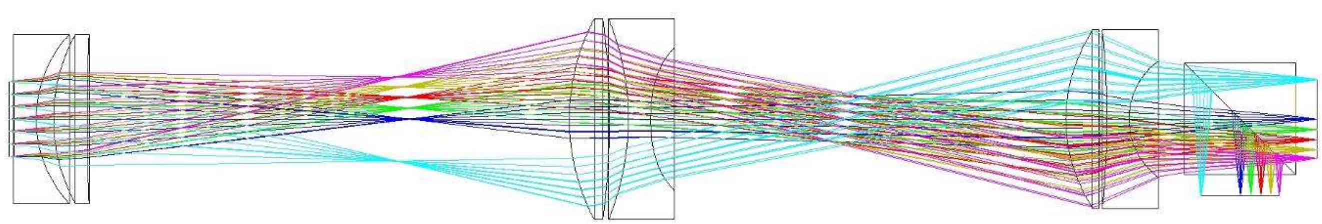

Figure 13- Baseline concept refractive design (aperture to the left, detectors behind a beamsplitter to the right)

consequently a larger instrument mass. A trade was performed for altitudes of 30,000 – 60,000 km, and the systemic optimum radius was found to be 45,000 km.

Since the chemical propulsion option can only provide an elliptical orbit, the optimal choice is to choose an orbit with a 45,000 km apoapsis. Most of the time during the orbit is spent near the optimal radius of 45,000 km. Since the instrument is sized with a significantly larger field of view (75° latitude) than the minimum required for the seismic science (65° latitude), useful data is collected at acceptable resolution for most of the orbit.

Trade: On-board Autonomy vs. Telecom Capabilities

A somewhat short-lived trade was between on-board processing and ground processing of the observation data. Due to the nature of the VAMOS seismic observations, a large amount of data is generated at all points in the orbit, so downlinks would have to be often and data volumes would be large, negatively impacting the concept of operations and dictating the need for a large telecommunications system. It was decided that the difficulties of the telecom problem outweighed the difficulties and/or technology development efforts needed to process the data on-board. Determining the best methods and components for on-board science data processing is a major area of continued work.

6. Conclusions & Future Work

The investigations undertaken in the development of the VAMOS concept have shown that the growing planetary SmallSat niche offers a wealth of opportunity, but also requires a great deal of further development. The lessons learned in this development will serve to advance the maturity of planetary SmallSat and classical planetary spacecraft mission formulation processes alike.

The VAMOS concept itself offers two point-design cases that can achieve highly-valued science observations in a SmallSat form factor and cost category, watching for, detecting, and reporting on Venus's potential seismic activity. The concept is flexible to a wide swath of rideshare options and can be combined with synergistic elements, or entire missions, to increase overall science return.

The VAMOS mission concept will be under development, as part of NASA's Planetary Deep Space SmallSat (PSDS3) program, until early 2018. Further investigation, beyond the charter of this program, would be beneficial particularly in the areas of SmallSat on-board processing capabilities, how they benefit planetary seismic observations from orbit, SmallSat propulsion, and SmallSat systems engineering in general.

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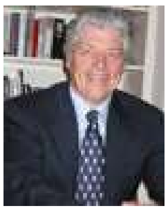

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