VOTE: Venus Orbiter for Thermal Exploration

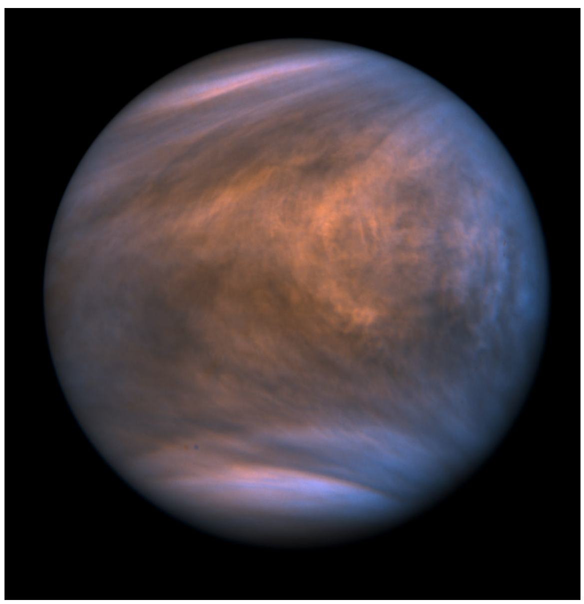
Harvard EPS 160 Final Project

Spring 2020

Ethan Manninen

Cameron Morgan

Amia Ross



Abstract

VOTE will be one of the few temperature profilers to collect data on Venus' thermosphere and the first in over a decade. Launching with either the VERITAS or the DAVINCI+ missions between 2025 and 2029 and spending 2-11 Earth years in a slightly elliptical orbit in Venus' thermosphere, VOTE is designed to provide insight into the processes of Venus' atmospheric loss and its relation to solar activity. VOTE will achieve these goals using an Ion and Neutral Mass Spectrometer (INMS) to retrieve number density values for common species in Venus' thermosphere and create a temperature profile. The improved and updated temperature profile created by VOTE will hopefully be of benefit to future exploration missions to Venus.

Mission Overview

The goal of the VOTE mission is to gather information on the temperature profile of Venus' thermosphere. The primary instrumentation used to do so will be an Ion and Neutral Mass Spectrometer. The satellite will also include sun sensors and reaction wheels for attitude measurement and control, a transmitting dipole antenna for telecommunications, an silver paint coating for thermal control, and Li-ion batteries and solar cells as power sources. These subsystems will be held in an EnduroSat 6U Structure, which has a mass of less than 1 kg and standard 6U cube satellite volume (*EnduroSat*, 2020a).

VOTE will launch to a 250 km by 400 km elliptical equatorial orbit over Venus between 2025 and 2029, which allows it to cover a large portion of the thermosphere. The mission is set to take place over 2 Earth years after insertion to Venus orbit, or the equivalent of about 3 Venus years. This means that the high and low points of VOTE's orbit will change between the day and night side of Venus as it orbits the Sun, allowing for a complete seasonal profile of thermospheric temperature. This mission duration will also allow VOTE to measure differences that occur in Venus' thermosphere when at perihelion versus aphelion. A stretch goal that we hope to achieve if VOTE's orbit is stable and instrumentation does not fail is to remain on-station for at least 11 Earth years, which is a full solar cycle. This will allow us to quantify how Venus' thermosphere reacts to variability in solar activity, including the effects of solar flares and long dormant periods. Regardless if we hit the stretch goal or not, we hope our temperature data across Venus' thermosphere will help refine models of Venus' atmosphere in order to better understand Venus' past and to better prepare for future missions.

EnduroSat 6U Cube Satellite Structure (*EnduroSat*, 2020a).

Scientific Motivation

The first temperature profile of Venus' thermosphere was developed using data from the 1978 Pioneer Program missions to Venus, which deployed four atmospheric descenders equipped with mass spectrometers (*Von Zahn et al.*, 1979; *Hedin et al.*, 1983). The 2005 Venus Express also created temperature profile data of the thermosphere using an infrared spectrometer (*Mahieux et al.*, 2010). Other than these two sets of observations, one of which was made four decades ago, the only temperature profiles have been incomplete and generated from ground based data (*Clancy et al.*, 2012). There has not yet been long term and *in situ* observation of Venus' thermosphere.

Such a temperature profile, generated by VOTE, would give insight to the processes of atmospheric loss that have driven the evolution of Venus' atmosphere over its 4.5 billion year history. The MAVEN mission's thermosphere profile of Mars has been analyzed to understand the Red Planet's atmospheric loss and how it relates to solar activity, with respect to diurnal variation, seasonal variation, and the eleven year solar cycle (*Bougher et al.*, 2015, 2017). VOTE would provide similar insight to Venus, and increase the number of unique solar system case studies for atmospheric loss.

Additionally, better constraining the temperature profile of Venus' thermosphere will benefit future missions by improving knowledge of the required operational parameters. Data on thermospheric temperature variations will help constrain thermal requirements for future missions, as well as allowing for a more comprehensive pressure model to be developed and utilized. Later exploration of Venus, whether it be through landers, long-term orbiters, or floating platforms in the atmosphere, will all benefit greatly from the models VOTE's data will help build.

Launch System

The VOTE satellite will reach Venus' orbit by riding along with either NASA's VERITAS mission (Venus Emissivity, Radio Science, InSAR Topography And Spectroscopy) or DAVINCI+ mission (Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging Plus). Both missions are competing to be one of two proposals approved by NASA in late 2021 for paired launches in either 2025 and 2026 or 2028 and 2029. (*Clark*, 2020) Considering NASA has not launched a mission to Venus in over 30 years (since 1989), we have reason to believe it is highly probable that at least one of these two missions will be selected for funding and launch.

Our preference would be for the VOTE satellite to piggyback with the VERITAS mission. The goal of the VERITAS mission is to collect high-resolution imagery and topography of

Venus' entire surface to develop the first-ever compositionality map of Venus' surface. The VERITAS mission will be managed by JPL and flown on a Lockheed-Martin manufactured spacecraft bus. The VERITAS mission will occur across two scientific phases utilizing the two different main instruments in VERITAS' payload, the first phase beginning after insertion into a polar elliptical orbit, and the second phase beginning after the VERITAS spacecraft utilizes aerobraking to park the spacecraft in an average 220 km orbit. (*Hensley et al.*, 2016) We plan for the VOTE satellite to separate from the larger VERITAS mission after the stabilization of orbit.

If the VERITAS mission does not fly but the DAVINCI+ mission does, we will opt to fly with the DAVINCI+ mission instead. The DAVINCI+ mission plans to send a descent probe into Venus' atmosphere to better understand its atmospheric origin, evolution, composition, surface interaction, and surface properties. The spacecraft will do a flyby 4 months after launch to target the probe's atmospheric entry point and another flyby 15 months afterwards to allow the probe to descend into Venus' atmosphere. (*Glaze et al.*, 2017) The VOTE satellite could descend into the atmosphere using the same operations as the DAVINCI+ probe and adjust course to achieve the orbit described below. However, this would likely require the addition of a small propulsion system to the VOTE satellite. If this were required, we could use one IFM Nano Thruster for CubeSats, which, while fitting in the mass and volume constraints (adding at most an extra .87 kg and fitting within a 0.6U volume), would greatly increase the power load (by at most 40 W) and monetary costs (by more than $32.5k) of the mission. This would in turn require additions to the power systems of the satellite, which would consequently increase the mass, volume, and cost of the spacecraft.

Orbit

The mission's goal is to build a model for temperature in Venus' thermosphere, which means our spacecraft's orbit must also be within that region of the atmosphere. Venus' thermo-

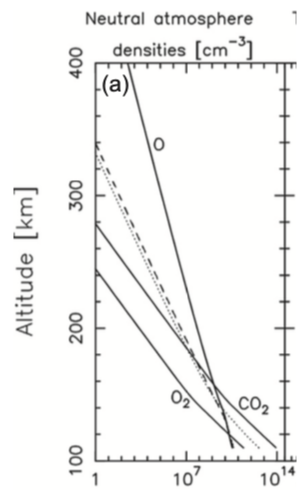


Figure 1: Density (particles per cubic cm) of various species in Venus' thermosphere (*Gronoff et al.*, 2008)

sphere extends from an altitude of about 120 km to approximately 350 km, at which point the atmosphere can be considered collision-less (*Pätzold et al.*, 2007). Deep in the thermosphere, atmospheric density is still rather high so drag on the spacecraft would be significant. This means the selection of an orbit depends on two factors: being within the thermosphere and being high enough to avoid orbital decay for the mission's duration.

Given these constraints, the target orbit must stay below 350 km most of the time while also taking into consideration the atmospheric density at the various orbital altitudes.

Fig. 1 shows that the dominant species in the atmosphere at the altitudes we are interested in is atomic oxygen. Using a ruler to extend the y-axis and the atomic oxygen line, an equation for atmospheric density at a given altitude can be developed:

$$\rho = 10^{\frac{487.5km - alt}{36.36km}}, \tag{1}$$

where ρ is the density of atomic oxygen in particles per cm^3 and alt is the altitude from Venus' surface in km. This model allowed us to create a Python script that uses

$$\tau_d = \frac{m}{C_d A \rho}\sqrt{\frac{r}{GM}} \tag{2}$$

from Slide 15 of Lesson 4 to calculate the orbital decay timescale τ_d (see Orbit Script 1 in Appendix).

A C_d of 2.2 was assumed from Lecture 4 Slide 15, which states that as an appropriate value for a highly rarefied fluid regime, which Venus' thermosphere is. The cross-sectional area of 367 cm^2 is the average surface area of a face on our spacecraft, which accounts for all sides of the spacecraft facing in the direction of motion. This code gives the decay timescale (not accounting for runaway drag from decreasing altitude) for a circular orbit at 250 km to be about 139 days.

This is too short for the entire mission to be carried out at this altitude, but we want an elliptical orbit anyway in order to sample at various parts of the thermosphere. This means our apoapsis can be at a higher altitude. Running the program again with an altitude of 400 km shows that the decay timescale for a 400 km circular orbit is on the order of 2.35 million days, which demonstrates the collision-less nature of the atmosphere at that altitude.

An elliptical orbit of 250 km by 400 km covers a wide range of the thermosphere, but also seems to be high enough not to decay before the mission can be completed. We do not have an equation to calculate orbital decay for an elliptical orbit, but the spacecraft will spend virtually all of its time above 250 km, which means the decay timescale will be significantly longer than for a 250 km circular orbit. Even if having an apoapsis at 400 km only quadruples the orbital lifetime due to the higher velocity at the 250 km periapsis, a mission lifetime of 560 days is sufficient. We will go for an equatorial orbit in order to stay in the area of Venus' atmosphere that has the most consistent application of sunlight, rather than travelling through areas that receive low solar flux year-round. With this target orbit, it is unlikely that orbital decay will be the limiting factor in mission longevity or success.

Now that we know the target orbit, the other important aspect is the sunlit and eclipse time the spacecraft will experience each orbit. Using the information from Lesson 17 Slide 30, we constructed another Python script that calculates the eclipse time and sunlit time the spacecraft will experience given a particular circular orbit (see Orbit Script 2 in Appendix).

This code shows that, for a 250 km circular orbit, the eclipse time is 37.69 minutes and the sunlit time is 54.23 minutes. For a 400 km circular orbit, the times are very similar, with an eclipse time of 36.88 minutes and a sunlit time of 58.34 minutes. This means the times for our elliptical orbit must be somewhere between these numbers. When planning the rest of the mission, it is important to consider the longest possible eclipse that must be endured and the shortest possible sunlit time in order to recharge the batteries, so we will use an eclipse time of 37.69 min and a sunlit time of 58.34 minutes for subsequent calculations.

Instrument

VOTE will carry an Ion and Neutral Mass Spectrometer (INMS) that is designed specifically for CubeSats and has been proven in missions in Earth's atmosphere (*Paschalidis*, 2018). The INMS will retrieve number density values for the most common species in Venus' thermosphere, atomic oxygen, as well as other neutral and ionic species(*Paschalidis*, 2018). Attitude control with keep the intake of the instrument oriented parallel to the craft's velocity vector. One part of the data handling process to create a temperature profile for each species will be to use the following formula:

$$T = \frac{1}{n}\left(\frac{m_{mol}g}{k_b\sigma_c}\right)$$

In LEO, the INMS aboard the Dellingr CubeSat retrieved measurements of Earth's thermosphere (*NASA*, 2018). The INMS is capable of measuring Dellingr was still able to gather meaningful data even when its attitude control failed and it entered an uncontrolled spin, indicating that should our mission's attitude control eventually fail, it still may be able to generate science (*NASA*, 2018).

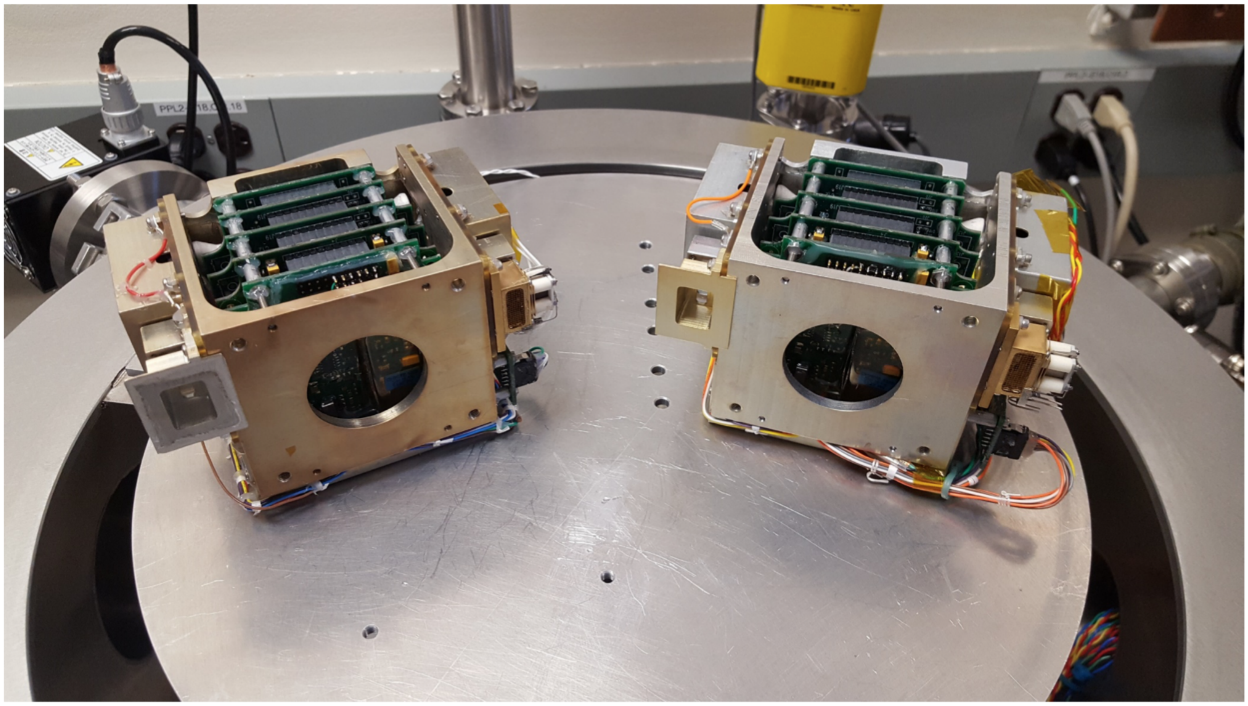


Figure 2: Ion and Neutral Mass Spectrometer (?)

Telecommunication

The VOTE satellite will use an off-the-shelf S-band transmitting dipole antenna (*IQSPacecom*, 2020). This is a simple, light weight, and proven option.

The antenna transmits with a power of 27 dBm (*IQSPacecom*, 2020). Converting to mW:

$$P_{mW} = 10^{\frac{dBm}{10}} = 501\text{mW}$$

Calculating the flux received from such an antenna on Earth when Venus and Earth are at their most distant:

$$F_R = \frac{P_T}{4\pi d^2} = \frac{P_T}{4\pi r_{EJ}^2} = 5.85 * 10^{-22}\ \text{Wm}^{-2}$$

The NASA Deep Space Network (DSN) is an array of antennas equally spaced around the world that maintains contact with missions throughout and beyond the Solar System

(*NASA*, 2020). Its 70 m diameter receivers have a gain of 63.6 dBi in the S-band (*Slobin and Pham*, 2013).

We approximate an atmospheric attenuation factor of $1 * 10^{-4}$.

To calculate the power received by DSN:

$$P_R = \frac{P_T G_R \lambda^2}{(L4\pi r_{ve})^2} = 1.43 * 10^{-27\ \mathrm{W}}$$

Our chosen antenna transmits at a maximum rate of Mbps, we will likely never use even a small fraction of that capability (*IQSPacecom*, 2020). We estimate a Kb of telemetry and number density data for every day of observation. The satellite will transmit its data in bursts when Earth is occluded by neither Venus or the Sun and the DSN has availability.

New developments in space telecommunications are gearing up to make pico-class satellites viable for exploration in the Solar System beyond LEO. For example, we considered implementing a collapsible $\frac{1}{2}$ meter antenna designed for use with cubesats and communication with the DSN (*Chahat et al.*, 2017). However, we decided that instead to rely on proven, off the shelf technology. Apart from the fact that this antenna has not yet been tested in space, we decided that the having the success of the mission rely on an added complexity in external moving parts was not worth the risk.

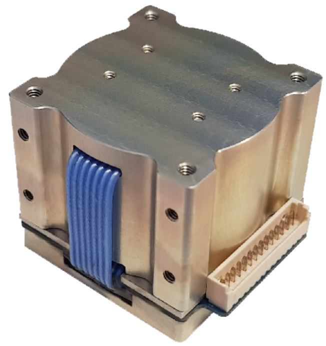
Attitude Control

For attitude measurement and control, the VOTE satellite will rely on sun sensors and reaction wheels. We chose sun sensors because the Sun is a reliable source of reference as compared with more Earth-related sensors such as Earth-horizon sensors or magnetometers (especially given Venus does not have a magnetic field), as well as more overall budget-friendly than star sensors or gyroscopes. We chose to use small reaction wheels due to their compact size, low cost, feasibility, and lesser power requirements as opposed to thrusters, magnetic control (again, difficult on Venus), or gravity gradient (tested in LEO but unclear if effective on other planets).

For the sun sensors, we will be using 2 Nano-SSOC-A60 analog sun sensors, which provide highly accurate sun-tracking, pointing, and attitude determination. Each device can measure the incident angle of the sun in two orthogonal axes, so two will be required to cover three dimensions (both will be installed on orthogonal sides of the satellite). The sensors have an accuracy of $< 0.5°$ and a precision of $< 0.1°$. The sensors have been used on more than 10 operational missions, which implies their reliability and accuracy. (*Technologies*, 2016)

Nano-SSOC-A60 analog sun sensor (*Technologies*, 2016).

For the reaction wheels, we will be using 4 CubeWheel Small reaction wheels to exchange angular momentum with the VOTE satellite. Each compact reaction wheel utilizes a brushless motor to minimize friction and can be integrated with the I2C interface in the iEPS (see below). The reaction wheels have a speed range of ±8000 RPM, a speed control accuracy of < 5 RPM, a maximum torque of 0.23 mNm, and a momentum storage of 1.7 mNms. (*CubeSpace*, 2014)



CubeWheel Small (*CubeSpace*, 2014).

Power

The required load power of our spacecraft is the sum of the loads of the telecommunications system (< 5 W), the attitude control system (sun sensor - nominal, reaction wheels - 0.65W/wheel for a total of 2.6 W), and the instrument (1.8 W) for a maximum total load power of 9.4 W. The voltages required are 3.3V for the instrument, 3.3V/sensor for a total of 6.6V for the sun sensors, and 3.3V/wheel for a total of 13.2V for the reaction wheels. As such, we chose a bus voltage of 24 V. We'll be using 8 Panasonic NCR18650GA lithium ion batteries, which are standard for cube satellite missions and have a tested flight heritage. These batteries have a minimum voltage of 2.5 V, a maximum voltage of 4.2 V, and a nominal voltage of 3.6 V. (*Panasonic*, 2015) We'll be storing these batteries in 2 Type B ISIS iEPS Electrical Power Systems, each of which includes an iEPS board with a modular 4 Li-ion battery cell. Each iEPS can deliver 20 W at a maximum of 5 V over 4 output channels (*ISIS*, 2018), so 1 iEPS will be connected to the 4 reaction wheels and the other iEPS will be connected to the 2 sun sensors and the mass spectrometer (all channels will be delivering 3.3 V). The system can sustain 3 battery failures and still deliver the necessary voltage to the spacecraft. The iEPS's also have low idle power consumption and will not impact the total power load on the spacecraft. The recommended depth of discharge for these batteries is 40% (2.5/4.2 V). Therefore, the total charge (in amp-hours) required is:

$$\frac{P_{load} \cdot t_{ecl}}{\frac{V_b \cdot DoD_R}{60}} = \frac{9.4 \cdot 36.88}{\frac{24 \cdot 0.4}{60}} = 0.6$$

Each iEPS can store 12.8 amp-hours of charge, so there should never be a deficit of battery power in eclipse periods.

ISIS Electrical Power System Type B (*ISIS*, 2018).

We'll be using EnduroSat flight-tested 3U Solar Panels X/Y with a voltage of 16.31 across a single array at maximum power. One array is comprised of 7 Triple Junction Solar Cells InGaP/GaAs/Ge, each with effective area 30.15 cm^2 and efficiency of 29.5%. The solar array utilizes an internal by-pass diode for optimized power output and has high radiation resistance. In addition, the solar array has a built in sun sensor and gyroscope in case finer attitude measurement and control adjustments are necessary. (*EnduroSat*, 2020b)

EnduroSat 3U Solar Panel X/Y (*EnduroSat*, 2020b).

The required power for the solar array in a sunlit period is $P_{load} \cdot (1 + (\frac{t_{ecl}}{t_{sun}}) \cdot \text{eff}) = 9.4 \cdot (1 + (\frac{36.88}{54.23}) \cdot 0.295) = 10.6$ W. Since our max bus voltage is 24, we plan to use $\lceil 24/16.31 \rceil = 2$ solar arrays in series. At maximum power, the current from a single array is 0.517 amps. Thus, we'll receive P = IV = $0.517 \cdot (2 \cdot 16.31) = 16.71$ W from a single string of solar arrays, so we only need to use one string of 2 solar arrays to meet the power requirement. The total solar array area is thus 422.1 cm^2. We plan to arrange the solar arrays in such a way that one of the 3U arrays is mounted on one of the 6U faces of the satellite structure while the other array is deployable in series with the mounted array. Due to Venus' lack of a magnetic field and radiation belts, as well as around 90% of solar radiation being reflected off of Venus' higher atmosphere before penetrating the atmosphere, we expect a negligible radiation damage factor. (*Titov et al.*, 2007a)

Thermal Control

Another important aspect of the spacecraft's mission is thermal management. Our power supply system has an operating range of -20 - 60°C (*ISIS*, 2018), so we will work with keeping a spacecraft temperature within that range.

With these parameters in mind, we created a Python script that, using the equation from Lesson 17 Slide 21, calculates the equilibrium temperature of the spacecraft in both sunlit and eclipse regimes (see Thermal Script in Appendix).

This script allows the user to input the absorptivity and emissivity coefficients corresponding to the coating material they chose from the table on Lesson 17 Slide 14. The cross-sectional area is 367 cm^2 like in the Orbit section because it is the average area of a side. The altitude factors into several of the calculations, but there is essentially no difference between an altitude of 250 km and 400 km in this regard, as they produce numbers off by only a tenth of a degree Celsius. Therefore, we will leave the input at 250 km and assume it provides sufficiently accurate information for our elliptical orbit. None of the components we have used have reported a value for their own heat emission, so we have assumed an internal heating of 0 W.

In calculating sunlit equilibrium temperature, we used

$$T = \left(\frac{A\alpha F_s + A\alpha f F_s A_V + A\epsilon F_{V,IR} + Q_i}{SA\epsilon\sigma}\right)^{1/4}, \tag{3}$$

following the assumption made in Problem Set 9, Question 3, to use a Sun zenith angle of 60°. For the eclipse equilibrium temperature, we used the assumption from the same problem set question that visible planetshine is negligible, producing the equation

$$T = \left(\frac{A\epsilon F_{V,IR} + Q_i}{SA\epsilon\sigma}\right)^{1/4}. \tag{4}$$

F_s was found given solar luminosity and Venus' semi-major axis around the Sun. f, the planetshine visibility factor, was assumed to be 0.5 from the chart on Lesson 17 Slide 23, using Earth as an analogue because we could not find equivalent data for Venus. There could be error here, but the behavior of the graph around the altitude we are using and the small nature of the term it is associated with suggest this is a safe assumption to make. Finally, $F_{V,IR}$, the infrared flux from Venus' atmosphere, is calculated by multiplying a standard value by $(\frac{r_V}{r_V+alt})^2$. For the standard value, we used 160 W/m^2, a value obtained from an article using Pioneer data to discuss radiation in Venus' atmosphere (*Titov et al.*, 2007b).

Because the equation used to find the equilibrium temperature is constructed in terms of incoming and outgoing power, or energy per second, we were able to also use the program to find the timescale for heating and cooling when in sunlight and eclipse. Using the specific heat capacity assumption of 650 J/kg/K from Problem Set 9 Question 3, we calculated the energy it would take for the spacecraft's temperature to leave its optimal operation range, a change of 60 K. The heating of the spacecraft is fastest when its own temperature is lowest (it has the lowest emissivity to remove energy), and the cooling is fastest when the spacecraft's temperature is highest (it has the highest emissivity to remove energy), so the calculations were made assuming the fastest conditions (i.e. worst-case) for both possibilities. If the worst-case timescale to leave operational parameters is longer than the time the spacecraft will spend in that situation, then we can safely assume the spacecraft will stay at an adequate temperature, especially considering it will not always be emitting at the worst-case temperatures.

By changing around the α and ϵ values in the program, we found that the coating material that best fits our operational parameters is silver paint ($\alpha = 0.37, \epsilon = 0.44$). It has a sunlit equilibrium temperature of 38.21 °C and an eclipse equilibrium temperature of -128.65 °C. The sunlit equilibrium temperature is near the top end of our operational range, so we do not actually need to worry about the spacecraft getting too hot. From the Orbit section, we know eclipse time is at most 37.69 minutes. With the silver paint coating, the time to leave operational parameters (going from a maximum temperature to below the operational temperature) in the worst-case conditions is 41.94 minutes, which means the spacecraft temperature should never dip below -20 °C. In fact, because the sunlit time is longer than the eclipse time, the greater amount of heating than cooling means the spacecraft's temperature should hover on the higher end of the range anyway, decreasing the risk of temperature ever falling anywhere close to the cold eclipse equilibrium temperature.

This analysis shows that, beyond the silver paint coating, the spacecraft should not require any further thermal management systems. None of the instruments or components we are using reported any amount of heat generation, so that was not included in the initial calculations, but no process is completely efficient, so it would be prudent to assume some latent heat generation from various electronics. If an internal heat source of 10 W were added, the sunlit equilibrium temperature would increase to about 52 °C, and the eclipse equilibrium temperature would increase to about -55 °C, with the heating/cooling timescales remaining unchanged. This variation thus has no noticeable impact on the spacecraft or its operations, other than granting its operations a safety net.

Budgets

Table 1: Budgets sheet for weight, power, monetary cost, volume, and TRLs.

Item	Weight (g)	Power (W)	Cost ($)	Volume	TRL (1-9)
Antenna	75	5	$7,100	95 x 46 x 15 mm	9
INMS	560	1.8		135 x 90 x 90 mm	9
Sun Sensors (2)	7.4	-	$4,765.58	2 x (27.4 x 14 x 5.9 mm)	9
Solar Arrays (2)	272	-	$7,798.21	-	9
Reaction Wheels (4)	240	2.6	$19,495.53	4 x (23 x 31 x 26 mm)	9
iEPS (2)	630	-	$13,863.49	2 x (96 x 92 x 11.34 mm)	9
Batteries (8)	384	-	$40.00	-	9
6U Structure	1000	-	$5,956.97	100 x 222.6 x 366 mm	9
Total	3168.4	9.4	$59,020		
the friends we made along the way			priceless		

Final Summary

Realistically, the only limiting factor on whether VOTE could fly is the availability of a carrier vehicle like VERITAS or DAVINCI+. With that secured, VOTE is a very plausible spacecraft to build using simple parts already on the market, as well as instruments with a proven flight heritage. Operations are simple, so the only plausible fail-cases would be random equipment failure or premature orbital decay due to the elliptical nature of VOTE's orbit. In a real implementation of the design, more robust calculations could be performed to more accurately assess and mitigate possible failure points. There was also significant space left in the mass and volume budget, which could allow for the installation of more advanced technology, more sensors, and backup systems to expand upon the mission.

The science VOTE would generate would improve models of Venus' atmospheric development as well as improve understanding of early atmospheres more broadly. It would also prepare us for future missions to Venus.

In conclusion, VOTE is a highly plausible and valuable CubeSat mission to take place within the decade that has room to expand and meet wider mission requirements as needed.

Appendix

Orbit Script 1:

```
import math

# User Input
alt = 250       # altitude, km
Cd = 2.2        # coefficient of drag
A = 367         # cross-sectional area, cm^2
m = 3.168          # mass, kg

# Density
rho = 10**((487.5 - alt) / 36.36)      # cm^-3, atomic O
rho = rho * (100 * 100 * 100)          # m^-3
rho = rho / (6.02 * 10**23) * 15.999  # kg / m^3
```

```
# Unit Conversions
alt = alt * 1000    # altitude, m
A = A / (100 * 100) # area, m^2

# Constants
G = 6.67 * 10**-11  # gravity constant, m^3 kg^-1 s^-2
M = 4.87 * 10**24   # mass of Venus, kg

# Calculation - timescale in seconds
time = (m / (Cd * A * rho)) * math.sqrt(alt / (G * M))
print("Decay timescale in seconds:", time)

time = time / 60 / 60 / 24  # timescale in days
print("Decay timescale in days:", time)
```

Orbit Script 2:

```
import math

# Input
alt = 250       # altitude, km

# Constants
r_v = 6051.8    # Venus radius, km
G = 6.67 * 10**-11  # gravity constant, m^3 kg^-1 s^-2
M = 4.87 * 10**24   # mass of Venus, kg

alt = alt * 1000
r_v = r_v * 1000
```

```
# Calculation
f = math.asin(r_v / (r_v + alt))
R_dark = f / math.pi

t_dark = R_dark * math.sqrt((4 * (math.pi)**2 * (r_v + alt)**3) / (G * M))
t_sun = (math.sqrt((4 * (math.pi)**2 * (r_v + alt)**3) / (G * M)) - t_dark)
print("Eclipse time in minutes:", t_dark / 60)
print("Sunlit time in minutes:", t_sun / 60)
```

Thermal Script:

```
import math

# Input
alt = 250       # altitude, km

# Constants
r_v = 6051.8    # Venus radius, km
G = 6.67 * 10**-11  # gravity constant, m^3 kg^-1 s^-2
M = 4.87 * 10**24   # mass of Venus, kg

alt = alt * 1000
r_v = r_v * 1000

# Calculation
f = math.asin(r_v / (r_v + alt))
R_dark = f / math.pi
```

```
t_dark = R_dark * math.sqrt((4 * (math.pi)**2 * (r_v + alt)**3) / (G * M))

t_sun = (math.sqrt((4 * (math.pi)**2 * (r_v + alt)**3) / (G * M)) - t_dark)

print("Eclipse time in minutes:", t_dark / 60)

print("Sunlit time in minutes:", t_sun / 60)
```

TeleCom Script:

```
##### TELECOM CALCS

### convert units

dbm <- 27 #dBm

PT <- 10^(.1*dbm) #mW

print(paste("The transmitted power is", pw, "mW"))

### find flux recieved on earth

rve <- 261e9 #m

FR <- PT/(4*pi*rve^2)

print(paste("flux recieved: ",FR, "Wm-2"))


### calculate power recieved by DSN reciever

L <- 1e4

GRdb <- 63.6

GR <- 10*log10(GRdb)

cc <- 3e8 #ms-1

freq <- 2295e6#hz

lamb <- cc/freq


PR <- (PT*GR*(lamb^2))/(L*(4*pi*rve)^2)

print(paste0("Power Recieved is ", PR, " W"))
```

References

Bougher, S. W., T. E. Cravens, J. Grebowsky, and J. Luhmann (2015), The Aeronomy of Mars: Characterization by MAVEN of the Upper Atmosphere Reservoir That Regulates Volatile Escape, *Space Sci Rev*, *195*(1-4), 423–456, doi:10.1007/s11214-014-0053-7.

Bougher, S. W., K. J. Roeten, K. Olsen, P. R. Mahaffy, M. Benna, M. Elrod, S. K. Jain, N. M. Schneider, J. Deighan, E. Thiemann, F. G. Eparvier, A. Stiepen, and B. M. Jakosky (2017), The structure and variability of Mars dayside thermosphere from MAVEN NGIMS and IUVS measurements: Seasonal and solar activity trends in scale heights and temperatures, *J. Geophys. Res. Space Physics*, *122*(1), 1296–1313, doi:10.1002/2016JA023454.

Chahat, N., R. E. Hodges, J. Sauder, M. Thomson, and Y. Rahmat-Samii (2017), The Deep-Space Network Telecommunication CubeSat Antenna: Using the deployable Ka-band mesh reflector antenna., *IEEE Antennas and Propagation Magazine*, *59*(2), 31–38, doi:10.1109/MAP.2017.2655576.

Clancy, R. T., B. J. Sandor, and G. Moriarty-Schieven (2012), Thermal structure and CO distribution for the Venus mesosphere/lower thermosphere: 2001–2009 inferior conjunction sub-millimeter CO absorption line observations, *Icarus*, *217*(2), 779–793, doi:10.1016/j.icarus.2011.05.032.

Clark, S. (2020), Nasa to assess proposals for probes to venus, moons of jupiter and neptune.

CubeSpace (2014), Cubewheel specsheet v1.1.

EnduroSat (2020a), 6u structure datasheet.

EnduroSat (2020b), Solar panel 3u datasheet rev 1.4.

Glaze, L. S., J. B. Garvin, B. Robertson, N. M. Johnson, M. J. Amato, J. Thompson, C. Goodloe, and D. Everett (2017), Davinci: Deep atmosphere venus investigation of noble gases, chemistry, and imaging, *2017 IEEE Aerospace Conference*, doi:10.1109/aero.2017.7943923.

Gronoff, G., J. Lilensten, C. Simon, M. Barthélemy, F. Leblanc, and O. Dutuit (2008), Modelling the Venusian airglow, *A&A*, *482*(3), 1015–1029, doi:10.1051/0004-6361:20077503.

Hedin, A. E., H. B. Niemann, W. T. Kasprzak, and A. Seiff (1983), Global empirical model of the Venus thermosphere, *Journal of Geophysical Research: Space Physics*, *88*(A1), 73–83, doi:10.1029/JA088iA01p00073.

Hensley, S., S. Smrekar, D. Nunes, N. Mueller, J. Helbert, and E. Mazarico (2016), Veritas: Towards the next generation of cartography for the planet venus, *47th Lunar and Planetary Science Conference*.

IQSPacecom (2020), S-Band Transmitter for Pico and Nanosatellites.

ISIS (2018), Isis electrical power system brochure.

Mahieux, A., A. C. Vandaele, E. Neefs, S. Robert, V. Wilquet, R. Drummond, A. Federova, and J. L. Bertaux (2010), Densities and temperatures in the Venus mesosphere and lower thermosphere retrieved from SOIR on board Venus Express: Retrieval technique, *Journal of Geophysical Research: Planets*, *115*(E12), doi:10.1029/2010JE003589.

NASA (2018), Dellingr: The Little CubeSat That Could.

NASA (2020), Deep Space Network - NASA Jet Propulsion Laboratory.

Panasonic (2015), Ncr18650ga datasheet specs for panasonic sanyo 18650 battery.

Paschalidis, N. P. (2018), Mass Spectrometers for Cubesats, p. 20.

Pätzold, M., B. Häusler, M. K. Bird, S. Tellmann, R. Mattei, S. W. Asmar, V. Dehant, W. Eidel, T. Imamura, R. A. Simpson, and G. L. Tyler (2007), The structure of Venus' middle atmosphere and ionosphere, *Nature*, *450*(7170), 657–660, doi:10.1038/nature06239.

Slobin, S. D., and T. Pham (2013), 101 70-m Subnet Telecommunications Interfaces, p. 42.

Technologies, S. M. (2016), nanossoc a60 technical specifications.

Titov, D. V., M. A. Bullock, D. Crisp, N. O. Renno, F. W. Taylor, and L. V. Zasova (2007a), Radiation in the atmosphere of venus, *Exploring Venus as a Terrestrial Planet Geophysical Monograph Series*, p. 121–138, doi:10.1029/176gm08.

Titov, D. V., M. A. Bullock, D. Crisp, N. O. Renno, F. W. Taylor, and L. V. Zasova (2007b), Radiation in the atmosphere of Venus, in *Geophysical Monograph Series*, vol. 176, edited by L. W. Esposito, E. R. Stofan, and T. E. Cravens, pp. 121–138, American Geophysical Union, Washington, D. C., doi:10.1029/176GM08.

Von Zahn, U., D. Krankowsky, K. Mauersberger, A. O. Nier, and D. M. Hunten (1979), Venus Thermosphere: In situ Composition Measurements, the Temperature Profile, and the Homopause Altitude, *Science*, *203*(4382), 768–770, doi:10.1126/science.203.4382.768.