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ThermaSat White Paper
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ThermaSat™ Innovation:

Howe Industries LLC (HI) has conceived a low power, safe propulsion system for CubeSats known as ThermaSat. This first of its kind solar thermal propulsion system permits rapid maneuvering for spacecraft in the 8-50kg range. Traditionally, solar thermal power systems require a large deployable concentrator to focus solar energy onto a point to directly heat the propellant stream, causing rapid heating and expansion of the propellant to produce thrust. ThermaSat operates on a similar principal but utilizes a novel optical system to heat an intermediate thermal capacitor via solar energy. With no power input from the spacecraft bus, ThermaSat can reach

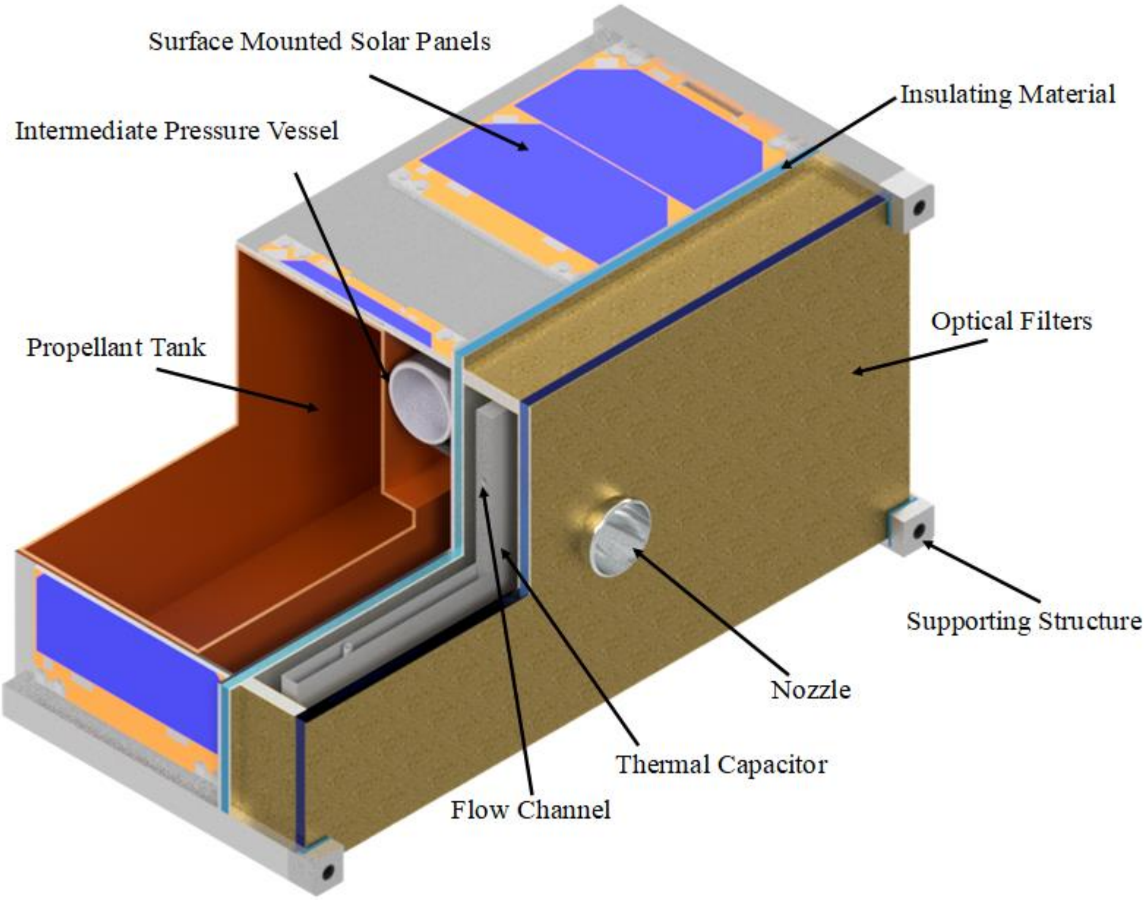


Figure 1: Rendering of the ThermaSat baseline model which is capable of high thrust maneuvers with 203s of specific impulse and 1.02N of thrust. The golden optical system on the bottom allows for high temperature operation and high performance.

temperatures in excess of 1000K and produce 1N of thrust at greater than 200s of specific impulse. The advantages of such a system include:

1. Eliminates requirements from the spacecraft bus to provide power for the system.
2. Water propellant reduces safety concerns during integration, launch, and operations around ISS.
3. Water is stored in an unpressurized tank at launch, mitigating any launch vehicle safety concerns for secondary payloads
4. Simple design with few moving parts reduces complexity and potential failure points.
5. Provides rapid maneuverability to avoid orbital debris and other satellites
6. Provides rapid constellation deployment
7. Provides orbital station-keeping to:
    a. Compensate for drag to increase orbital lifetimes.
    b. Permit station-keeping of constellations
    c. Enable lower orbits for increases in image resolution proportional to altitude.
    d. Enable ionosphere missions to explore novel environments.
8. Controlled deorbiting of satellite at end of lifetime.
9. Low RF interference with a virtually invisible water vapor exhaust
10. The ability to co-locate components such as command and control boards, ACS, radios, etc. within ThermaSat
11. The ability to thermally isolate ThermaSat from the rest of the spacecraft bus.

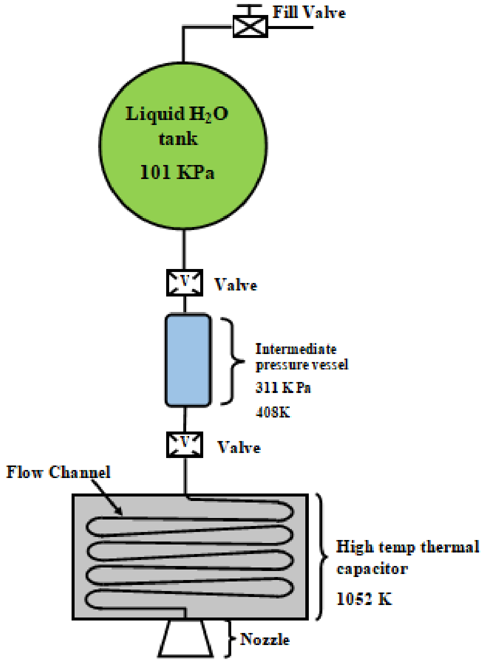


Figure 2: Diagram of ThermaSat propulsion system including various temperatures and pressures within the system. No pressure exceeds 1 atm during launch. During operations intermediate pressure vessel will reach 311KPa

System Characteristics:

The baseline ThermaSat system has been designed to fit within a 2U structure providing high thrust and total impulse to 6U and larger spacecraft. In its basic configuration it has the following properties:

- Operating phase change material (PCM) temperature: 1,052K
- Thrust: 1.02N

- Specific Impulse: 203.1 N
- Total Impulse: 1,800Ns
- Minimum Impulse Bit: 0.04-0.1 Ns
- Maximum Impulse Bit: 60 Ns
- Wet Mass: 2,445g
- Dry Mass: 1,445g

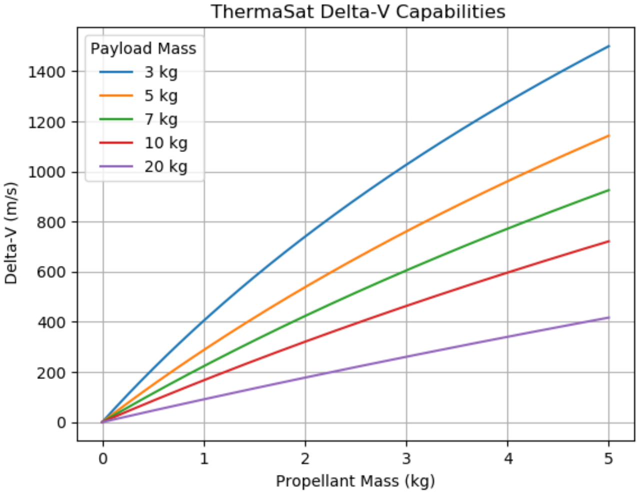
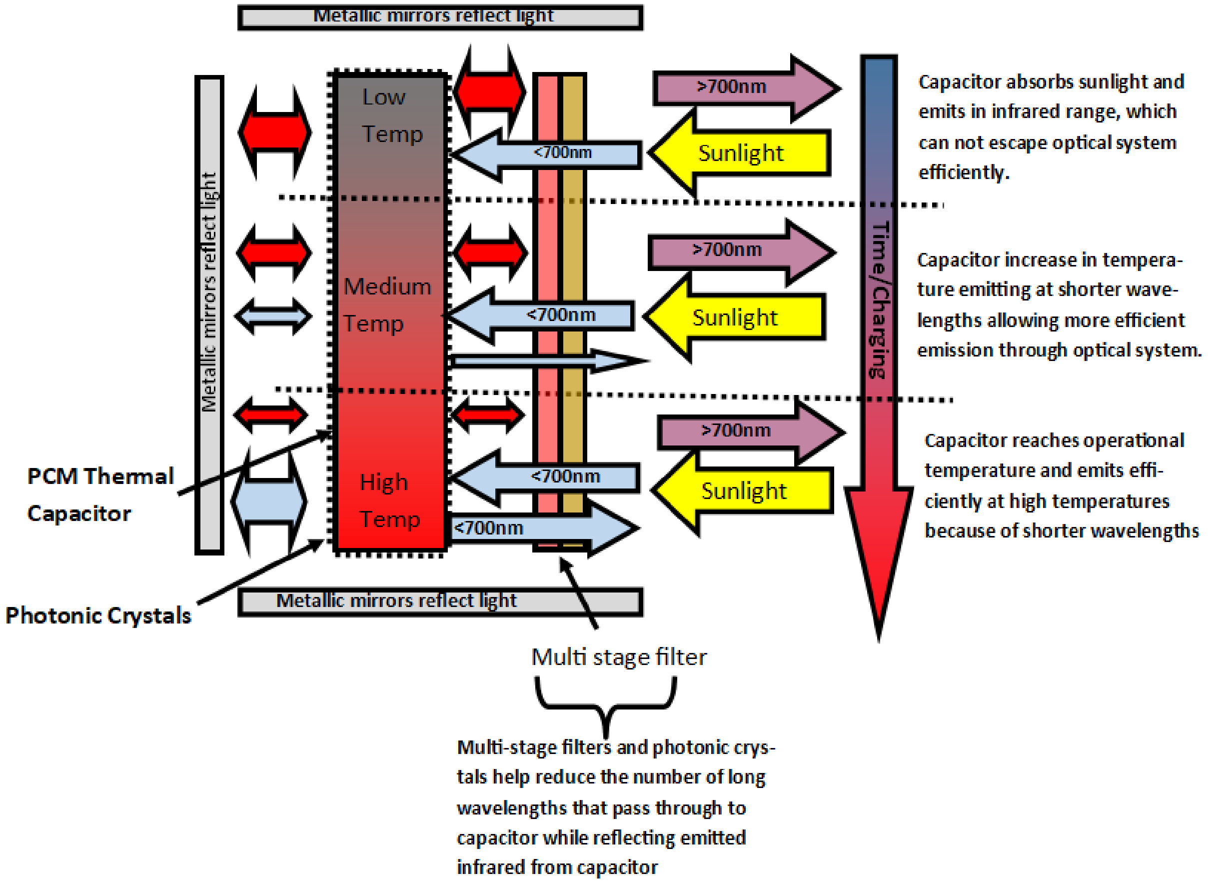


Figure 3: Delta-V capabilities of the ThermaSat with varying amounts of propellant. Payload mass consists of the dry mass of the spacecraft bus that ThermaSat will transport.

Figure 1 shows a rendering of the ThermaSat propulsion system, and Figure 2 shows the propulsion schematic with various operating pressures and temperatures. It should be noted that the liquid water tank filled before launch maintains an internal pressure of 1 atm. During the operation of the thruster, the intermediate pressure vessel will be used to gasify the propellant prior to introducing it to the thermal capacitor. This will be accomplished via passive heating from the thermal capacitor and solar flux. A long flow channel within the thermal capacitor is used to heat the propellant to its maximum operating temperature of 1,052 K before expanding it out of nozzle. ThermaSat is currently designed to fire for as up to 60s for high impulse and rapid maneuvers. Smaller impulse bit maneuvers are available to desaturate reaction wheels. A wide range of impulse bits is made possible by the thermal capacitor. Having few moving components also ensures the simplicity of the propulsion system and enhances its reliability Sensors can also be attached to various components of the propulsion system to monitor its health during operation.

The standard propellant tank onboard the 2U ThermaSat contains ~1kg of propellant. Additional, or smaller propellant tanks can be customized to match a variety of delta-v requirements. Figure 3 shows the ThermaSat performance for various payload sizes and propellant masses. “Payload” refers to everything that is not the propulsion system (bus components, science payload, structure etc.). Co-location of components is possible with lower delta-v requirements as propellant tank size can be scaled down.



Capacitor absorbs sunlight and emits in infrared range, which can not escape optical system efficiently.

Capacitor increase in temperature emitting at shorter wavelengths allowing more efficient emission through optical system.

Capacitor reaches operational temperature and emits efficiently at high temperatures because of shorter wavelengths

Multi-stage filters and photonic crystals help reduce the number of long wavelengths that pass through to capacitor while reflecting emitted infrared from capacitor

Figure 4: Optical system that enables the phase changing material (PCM) thermal capacitor to reach high temperatures with little to no electrical input.

Operations:

The key to ThermaSat's success is its novel optical system which allows the thermal capacitor to reach its operational temperature. This system consists of several natural and custom selective emitters which creates a favorable non-Planckian radiation spectrum to reach temperatures in excess of 1,000K via direct solar energy. The optical system and thermal capacitor outlined in Figure *4* permit only specific wavelengths to pass through. As the thermal capacitor heats from the sun's energy, it begins to emit light in the infrared region. However, because the novel optical design, these wavelengths cannot be transmitted through the optical system. This causes the thermal capacitor to increase in temperature and radiate at shorter and shorter wavelengths until the energy input into the system is equal to the energy output. This is similar to the green-house effect in a sense. The optical system and thermal capacitor are thermally isolated from the rest of the spacecraft via high temperature ceramics and other insulators. This ensures minimal heat transfer to the rest of the spacecraft body to prevent damage to vital bus components.

An intermediate pressure vessel is used to store propellant for firing of the thruster. It is heated passively by the thermal capacitor to 408K. This pre-heats the propellant, pressurizing the tank and ensuring there will be no back flow of propellant during operation (a check valve is included to prevent back flow as well). The heated propellant is fed into the thermal capacitor flow channel, which winds its way through the thermal capacitor to ensure it reaches high temperatures. A nozzle expands this steam into the vacuum of space to produce thrust.

Charging of the thermal capacitor is dependent on several factors. The most important being the angle of incidence to the sun, position of the propulsion system on the spacecraft, orbit, and pointing regime. In most cases the thermal capacitor can be charged to operational temperatures via direct solar energy and, when needed, side mounted solar panels with no electrical input from the primary spacecraft bus. If faster charging is required, the capability exists to accept power from the spacecraft bus. Aligning the propulsion system with the CubeSat's primary solar array will allow the propulsion system to charge while the spacecraft also receives power from the sun. This becomes much easier if the spacecraft is in a sun synchronous orbit. While this is a highly desirable orbit, trade studies were conducted to ensure nadir, random, and sun pointing missions were a possibility in LEO without hindering the mission in a significant manner (Figure 5). Side mounted solar panels are included on the ThermaSat system to aid the thermal capacitor during these pointing regimes; however, the input power required is minimal compared to other types of thrusters.

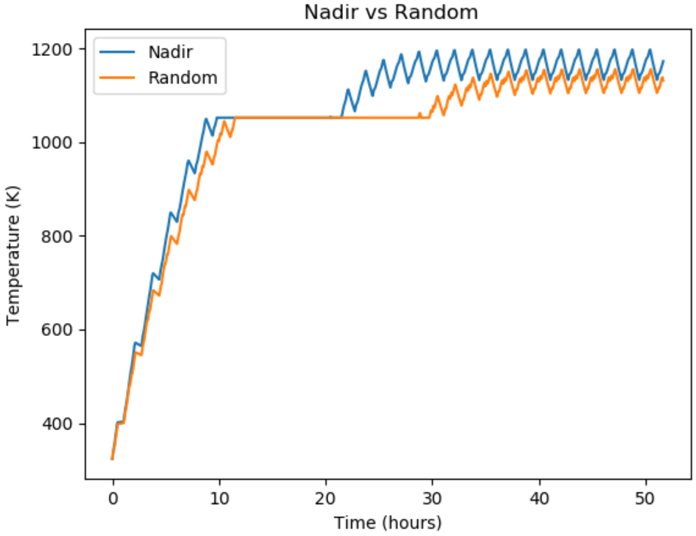


Figure 5. Example mission of a 6U spacecraft with nadir (Earth facing) and random pointing regimes. Enough power is generated via direct solar energy and side mounted solar panel input to charge the system. Dips in the graph represent eclipse times where the thermal capacitor is only radiating energy, not absorbing. Pointing regimes will affect the maximum temperature achievable by the thermal capacitor.

Technical Use Cases:

Lifetime Extension:

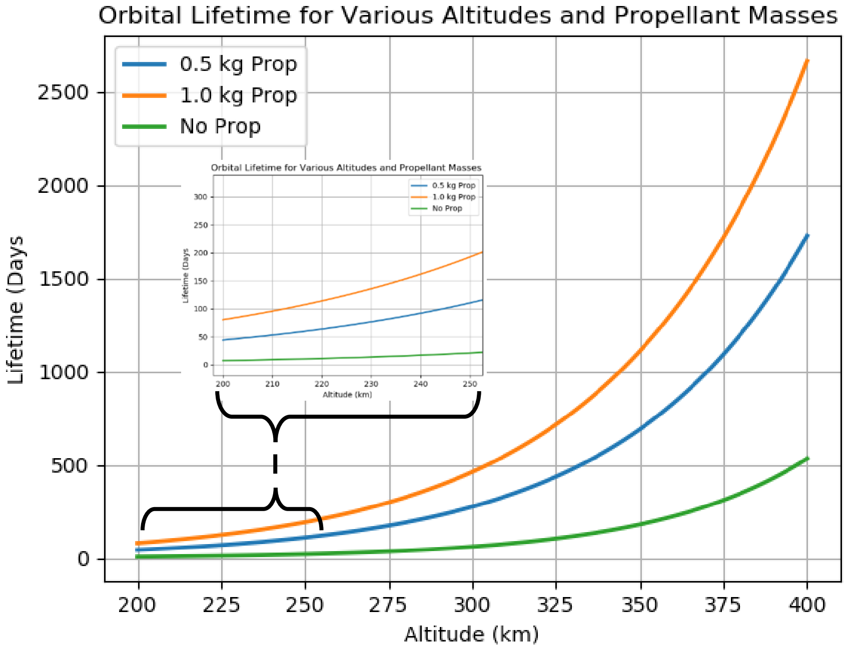


Figure 6: Lifetime of an 8kg 6U spacecraft with 0.02m^2 drag area for various altitudes with and without various amounts of propellant.

ThermaSat is highly capable and can be used for several different mission applications. One of the most prominent use cases is to perform orbit maintenance for a satellite in LEO, particularly under 400km altitude. There are several advantages to decreasing one's orbital altitude, such as an increase in total communication throughput and increases in resolution for remote sensing satellites. Figure 6 shows how ThermaSat can increase orbital lifetimes with little to no electrical input from the spacecraft bus. In this case a 6U satellite was used with the Jacchia-Roberts Drag model and NASA's General Mission Analysis Tool (GMAT) to simulate the orbital decay of the spacecraft, with a 200cm^2 surface area. This area represents the smallest front face of a 6U CubeSat in a constant nadir pointing regime (largest 6U face towards Earth). The satellite's altitude was corrected every time it dropped 20km.

ThermaSat can extend spacecraft lifetime significantly. Satellite operators can drop their altitudes and match their previous lifetime to get higher image resolution. If future FCC regulations further limit CubeSat lifetimes in common orbits, this could be highly advantageous as one could maximize their lifetime in a lower orbit for higher data rates and better data resolution. Constellations can also save significant amounts of money by keeping their satellites in orbit for longer periods of time with the ThermaSat. This saves on all recurring costs associated with replenishing and maintaining a constellation.

Studies in the relatively unexplored ionosphere region can also be executed. While extremely low ionosphere studies are difficult, there is a substantial increase in the time one can stay alive in these areas of interest. Temporal based studies are also important for various missions such as astronomy and astrophysics. Maintaining long orbit lifetimes allows for users to get much more out of their satellite, which especially important for missions with high value payloads.

Orbit Raising

ThermaSat can efficiently and effectively change spacecraft orbit parameters after deployment from the launch vehicle. One such example would be increasing altitude after deployment from the International Space Station (ISS) to decrease the orbital decay rate, offer more mission flexibility, and to eliminate the possibility of recontact with ISS. The ThermaSat design is such that it meets the payload safety requirements to fly to, and from ISS. ThermaSat can perform high impulse maneuvers to ensure it leaves ISS orbit quickly. Such a mission is shown in Figure 7 depicting launch from an ISS orbit and raising the satellite's orbit by 50km.

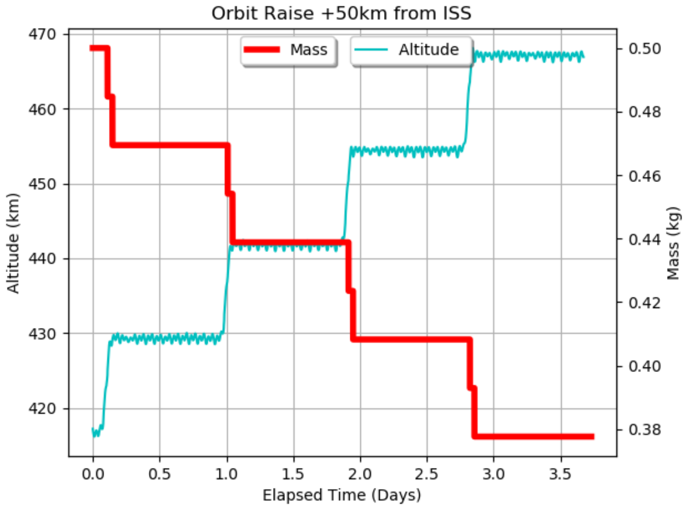


Figure 7: Altitude change and propellant mass of a 6U CubeSat launched from the ISS. Raising a satellite's orbit beyond its original insertion expands capabilities for that satellite. ThermaSat is unique in that it contains no pressurized containers, hazardous materials, or large batteries for its propulsion system. It can reach a 50km difference in altitude in days, with propellant to spare for the duration of the mission to perform additional station keeping and eventual deorbit.

It takes just over three days for the altitude of the ThermaSat to raise 50km. This includes the expected charging time at that altitude for a nadir pointing mission. If the mission was sun pointing this time can be reduced. Only a small fraction the water propellant is used to perform this maneuver leaving extra for station keeping and eventual deorbit if the satellite will not naturally decay within the FCC's allocated window.

Orbit raising can be used at any altitude to modify the original insertion orbit to achieve missions that are not entirely dependent on the primary payload of the launch vehicle. ThermaSat in its current configuration is capable of large orbit altitude changes and can perform limited inclination changes for satellites.

Constellation Deployment:

ThermaSat can be used to maintain a constellation in the same orbit, the proper phasing between satellites. This can significantly decrease the time required to deploy a functioning constellation compared to variable drag separation. ThermaSat can deploy a constellation without sacrificing satellite lifetime due to variable drag methods.

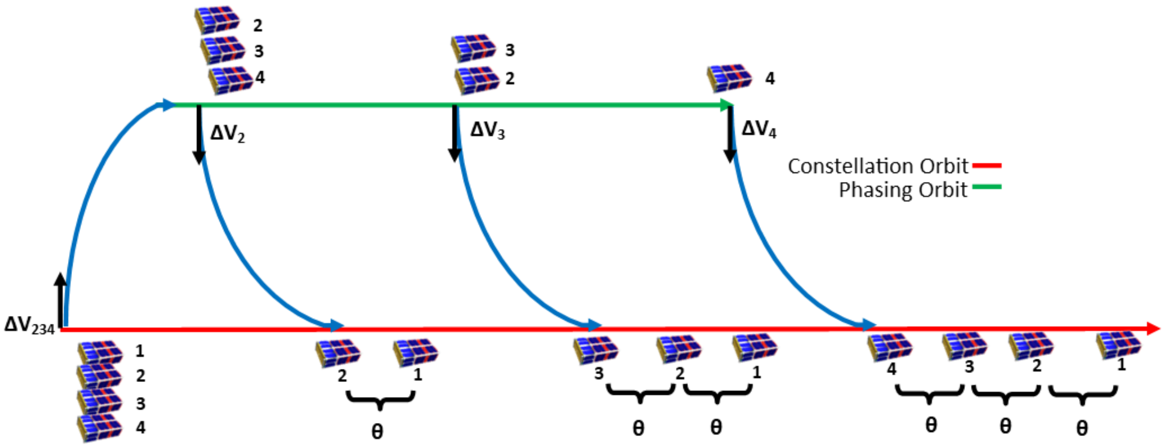


Figure 8: Example constellation deployment of several satellites to an orbit with equal phasing between each satellite. ThermaSat's high thrust and specific impulse allows the constellation to reach the correct phase angle quickly decreasing total time required to deploy the constellation.

Deploying a constellation is simple matter of using a phasing orbit to achieve the required phase difference for the satellites. An example is illustrated in Figure 8. The time it takes for the satellite to reach the correct phase angle is dependent on the delta-v imparted. With up to 1,800Ns of total impulse, ThermaSat can phase a constellation of CubeSats rapidly and with propellant to spare for station keeping and other future maneuvers.

Versions:

Three versions of ThermaSat are under investigation to enable more missions and serve different satellites. These include ThermaSat, ThermaSat Plus (TS+) and ThermaSat Lite. The ThermaSat Lite is a scaled down version of the ThermaSat system and consists of a 1U propulsion system that can be used in 3U satellites. It has virtually identical features to the ThermaSat system, only with a lower total impulse due to the reduced size. Charging times for the ThermaSat Lite configuration remain relatively consistent with the baseline ThermaSat model. A 4U ThermaSat version is also being investigated for possible uses.

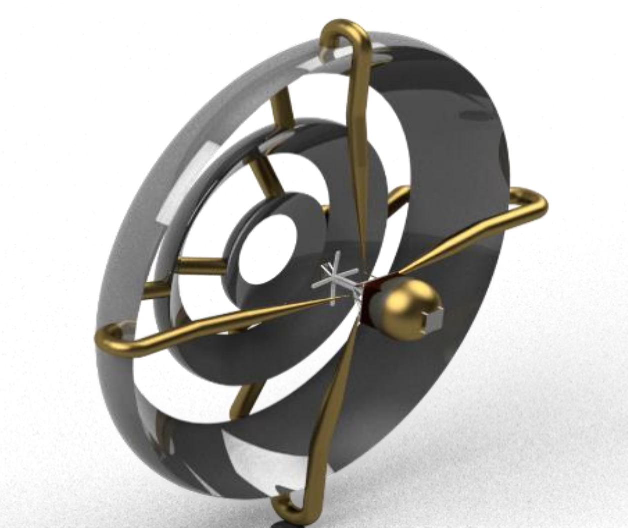


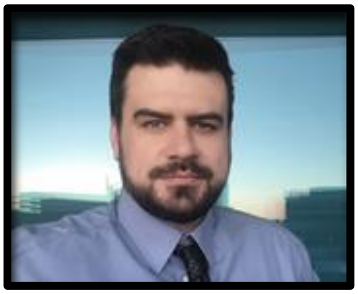
Figure 9: ThermaSat Plus configuration with deployable solar thermal concentrator for high specific impulse maneuvers with hydrogen as a propellant. The satellite bus and payload would attach to the mounting points near the hydrogen propellant tank.

TS+ is a much larger version than the baseline ThermaSat and is visible in Figure 9. This version is intended for much larger class applications in the 200kg+ range of satellites. It will utilize hydrogen as the propellant and use a solar concentrator to focus light onto the thermal capacitor and optical system. Its operating temperature will be 2,500 K enabling a specific impulse of 858s. These features enable highly efficient maneuvers to achieve larger changes in velocity including geostationary transfers, and lunar missions from LEO. One such example mission for TS+ is the establishment of a Lunar GPS constellation in a 24:6:1 Walker-Delta Constellation. Such a spacecraft would be capable of transporting itself from a LEO parking orbit to the moon forming a GPS network for future missions on the lunar surface. TS+ can also be used in a parking orbit for rapid response missions, such as asteroid intercepts between the moon and Earth, short term phenomenon investigation, emergency/tactical response on Earth, and investigating objects of interest in deep space.

Technical Work:

The ThermaSat system is currently being studied under a Phase I National Science Foundation (NSF) Small Business Innovation Research (SBIR) grant. The current study has shown not only the physical viability of ThermaSat but also the commercial viability. It is the intent of Howe Industries to pursue a Phase II NSF SBIR grant to raise the TRL of the baseline ThermaSat system. Numerous tests are planned for Phase II, and the goal of this program would be to have a complete prototype brought to TRL 6 and ready for a test flight in space. Howe Industries will pursue testing of the optical system, propellant feed system, and flight computer to ensure they operate as predicted.

Team Members:



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