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THE CONSTELLATION FOR MARS POSITION ACQUISITION USING SMALL SATELLITES: CUBESAT DESIGN FEASIBILITY AND CHALLENGES

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A satellite constellation concept called the Constellation for Mars Position Acquisition using Small Satellites (COMPASS) is introduced as a communications and navigation network for Mars. The constellation will bolster user operation and capability for future Mars missions. This paper outlines the constellation and examines top level feasibility and design challenges for the satellite hardware. Using existing satellite components made commercially available, such a satellite may be realizable but the requirements of the proposed design will challenge the capabilities of the contemporary CubeSat.

INTRODUCTION

Mars is the nearest habitable planet in our solar system and is enjoying an increase in the public's interest as technology brings us ever closer to humanity's first steps on the red planet. Concurrent with this growth in the public's interest in Mars is the advancement in small satellite capabilities. The miniaturization of technology is making small satellite ventures more and more sophisticated, particularly in the realm of CubeSats. One ambitious application of note is that of Mars CubeSat One (MarCO).[1] MarCO is a 6U CubeSat developed by the Jet Propulsion Laboratory (JPL) which will be sent to Mars with the InSight Mars Lander. This mission will be among the first to test the capabilities of CubeSats in deep-space environments, and the first deployment of a CubeSat for Mars orbit. This project is representative of the current state of the space industry, as it presents a marriage between our fascination of both small satellite technology and Mars.

The Constellation for Mars Position Acquisition using Small Satellites (COMPASS) will serve as a communications and navigation network for future assets on Mars. With growing interest in Mars-based mission applications, including talks of manned missions in the near future, the need for a space-born, Mars support system is made apparent. Currently, Martian assets are reliant on communications with a small number of orbiters and the Deep Space Network (DSN). One way to address the future demands of rovers, and potentially colonies, is in the establishment of a comprehensive Mars network of satellites.

The proposed constellation will have a structure and purpose similar to that of the Earth-based GPS constellation. Utilizing a Ballard-Rosette constellation design, 15 satellites will be distributed

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evenly across 5 planes to provide global coverage, as well as user access to at least four member satellites at a given time.

A major challenge of the COMPASS project is in the design of the candidate spacecraft. The constellation will consist of sophisticated CubeSats with sub 12U form factors. Satellite payloads will consist of a high-precision clock and a radio frequency transmitter. To provide accurate navigational support to a surface user on Mars, the satellite must continuously transmit precise, time-stamped ephemeris information. Development of precise, compact atomic clocks will be essential to the success of the COMPASS mission. The transmitter must be capable of continuous downlink from an aereosynchronous altitude, where the COMPASS constellation will be established. All other subsystems will be designed to support the operations of the atomic clock and transmitter.

Due to the characteristically lower masses associated with CubeSats, low-thrust propulsion systems provide excellent design choices for the COMPASS satellite. All propulsion needs can be handled using a combination of cold gas thrusters, for detumble and attitude control, and either an electric propulsion system (EPS) or solar sail. Solar sails have been proven to be effective candidates for propulsion of small satellites, and may provide a viable means of orbit maintenance for COMPASS satellites. Electric propulsion will certainly provide more operational flexibility, but will incur higher power requirements. To date, no deep-space CubeSat mission has been flown. Downscaling and radiation hardening the necessary components for CubeSat use will prove the most daunting design task. Ultimately, obtaining a feasible deep-space CubeSat design will prove an ambitious and novel undertaking.

CONSTELLATION DESIGN

The proposed constellation design will provide global coverage of Mars, allowing users access to navigation and communications resources anywhere on the planet. Ideally, this will be achieved using the fewest amount of satellites and orbital planes. To this end, the COMPASS architecture consists of 15 satellites in a Ballard-Rosette configuration. Ballard-Rosette constellations are characterized by a number of circular, inclined satellite orbits, with evenly-spaced separation about an equatorial belt, i.e., evenly-spaced right ascensions of the ascending nodes between each of the orbits.[2] This design is fully defined using the properties in Table 1.

Table 1. COMPASS Constellation Parameters

Number of Planes	5
Satellites Per Plane	3
Orbit Inclination	$45°$
Orbit Altitude	$20,427$ km

From geometry, each orbital plane requires at least three satellites in order to gain complete circumferential coverage of the planet. Unfortunately, no single plane is capable of achieving global coverage, so multiple planes are necessary for the constellation design. The number of required planes is motivated by the purpose of the constellation. In order to provide accurate navigational information to a surface user, four unique satellite signals are required, requiring at least four orbital planes.[3] To account for geometric coverage gaps associated with each plane, an additional plane is needed. These requirements result in a constellation design consisting of 15 member satellites.

The chosen altitude and inclination of the constellation orbits have influence over planetary coverage efficiency. Altitude impacts the efficiency of each satellite, while inclination impacts the efficiency of the orbital planes. Higher altitudes allow satellites more access to the Martian surface. Higher inclinations allow for coverage at increase latitudes. With this in mind, an areosynchronous orbital altitude is chosen with an inclination of $45°$. The areosynchronous altitude allows for 97 percent surface coverage of Mars for each orbital plane. Additionally, this altitude provides predictable orbital patterns, from an operational perspective, of one complete orbit per Martian day. The $45°$ inclination is sufficient to provide satellite access to potential users at the higher latitudes, including Mars' poles. The COMPASS constellation is illustrated in Figure 1.

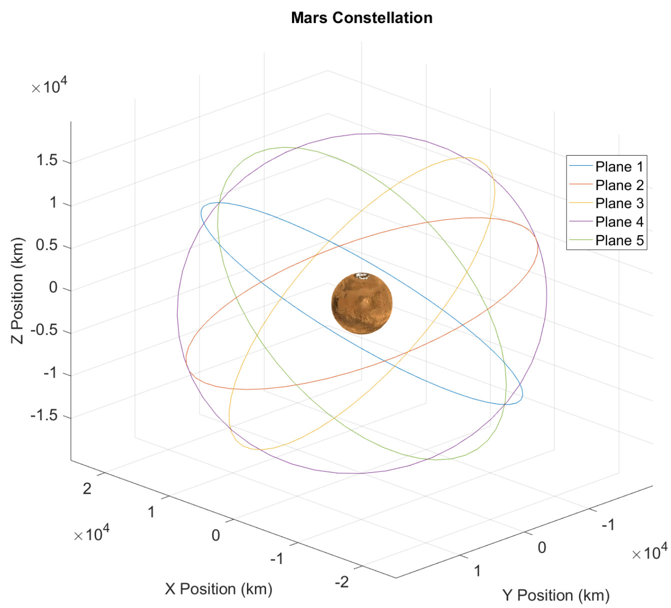


Figure 1. 3-Dimensional Illustration of COMPASS Constellation

PAYLOAD REQUIREMENTS

The COMPASS satellite payload consists of the telemetry suite, consisting of an antenna, receiver, and transmitter, and atomic clock. The transmitter is required to broadcast a time-stamped ephemeris and identifier signal to Martian surface users at all times. The receiver is required to accept orbital and ephemeris updates from the COMPASS control stations, to be located on the Martian surface. Receivers and transmitters would also be capable of relaying signals between member satellites within the COMPASS constellation.

Communications

The Martian atmosphere is significantly thinner than that of Earth's due to the absence of a strong magnetosphere. Thus, there are fewer space weather related disturbances that affect signal propagation, making the Martian ionosphere a welcoming environment for low frequency radio communication. Transmissions can be made with minimal ionospheric interference so long as the propagated radio signal is greater than the ionosphere's critical frequency around 4 MHz (vertical incidence).

Even with the added strength of an induced magnetosphere caused by incidental solar winds, the dayside solar maximum of the Martian ionosphere is roughly one third that of Earth.[4] Since most space grade transmitters and receivers are designed for Earth, communications operate at or above VHF (30-300MHz) frequencies. These VHF designs result in a greater RF output power requirement.

The communications suite for MarCO provides an encouraging example of CubeSat receiving and transmitting capabilities. Specifically, the Iris V2.1 transponder is designed to enable deep-space communications using X-Band, Ka-Band, S-Band, or UHF.[5] With a 0.5 U form factor, the Iris transponder is compatible for CubeSat integration and more than exceeds the projected COMPASS uplink and downlink requirements. Additionally, the architecture is robust to the effects of radiation, handling linear energy transfers up to 37 Mev-cm^2/mg and total ionizing dose levels of 15 krad, resulting in an estimated lifetime of approximately 3 years. The Iris V2.1 Transponder is illustrated in Figure 2 with specifications listed in Table 2.

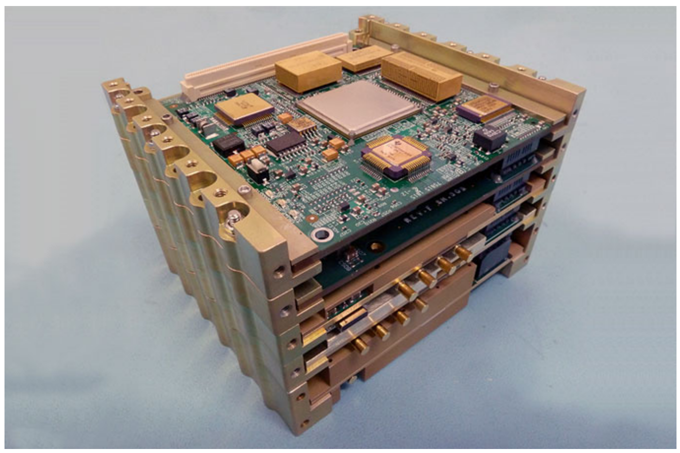


Figure 2. Iris V2.1 Transponder

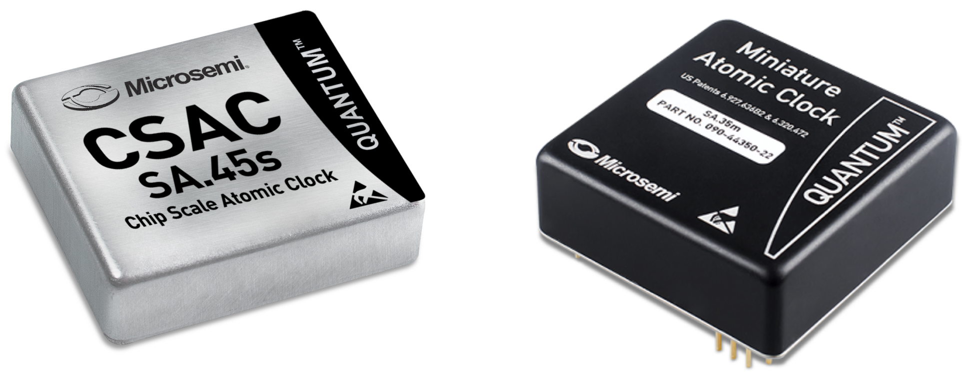
Table 2. Iris V2.1 Specifications

Design Lifetime	3 years
Receive Frequency Bands	X-band, UHF
Transmit Frequency Bands	Ka, S, UHF transmit
Volume	$100.5 \times 101.0 \times 56.0$ mm
Operating Temperature	-20°C to 50°C
Single Event Latchup Levels	LET $>$ 37 MeV-cm^2/mg (Virtex 6)
Total Ionizing Dose Levels	15 krad

Atomic Clock

The onboard clock is an integral component of the COMPASS design. Accurate time-keeping is essential for navigation updates, especially when position estimates are obtained from multiple time-stamped signals. Clock errors as little as 1 ns can accumulate range-rate estimate errors on the order of centimeters using conservative uncertainty models. Accounting for atmospheric effects, multipath disturbances, and other sources of uncertainty adds to the measurement uncertainty, clock precision becomes very important.

Atomic clocks with space flight heritage include crystal oscillators,[6] rubidium,[7] and cesium[8] device types. Crystal oscillator clocks exhibit only short term frequency stability and would cause severe clock drift errors in a matter of days compared to cesium and rubidium alternatives. To comply with the CubeSat form factor, rubidium clocks would likely be used for the COMPASS constellation as a number of commercially avaiable chip-scale atomic clocks (CSAC) have been developed. The SA.45m from Microsemi has a mass less than 85 g with less than 50 cm^3 volume.[9] With Allan deviation less than 8×10^{-12} ($\tau = 100$ sec.) and an aging rate of less than 1×10^{-10}, the SA.45m Miniature Atomic Clock is the best commercially available option on the market.[10] Alternatively, Microsemi's SA.45s Chip Scale Atomic Clock provides a backup solution. The SA.45s is slightly smaller, with a mass of 35 g and volume less than 17 cm^3. The Allan deviation is less than 3×10^{-11} ($\tau = 100$ sec.) with age rate of less than 9×10^{-10}. The major pitfall with these



(a) Quantum SA.45s CSAC

(b) Quantum SA.35m MAC

Figure 3. Microsemi atomic clocks

two clocks, as they currently stand, is the lack of space flight heritage and radiation testing. Clocks with flight heritage are currently too bulky to comply with any CubeSat form factor. One promising space flight experiment is CHOMPTT, which will test optical time transfers using a spaceborne CSAC SA.45s.[11] Even so, this mission is to take place within the Earth's magnetic field, sheltering the CHOMPTT satellite from the worst of any potential radiation exposure.

Table 3. Microsemi Clock Comparison

	CSAC SA.45s	**MAC SA.35m**
Allan Deviation ($\tau = 100s$)	$\leq 3 \times 10^{-11}$	$\leq 8 \times 10^{-12}$
Aging (Monthly)	$\pm 9 \times 10^{-10}$	$\pm 1 \times 10^{-10}$
Power Consumption	< 120 mW	8 W
Volume	$< 17\ \text{cm}^3$	$< 49.5\ \text{cm}^3$
Mass	35 g	< 85 g
Operating Temperature	$-10°$C to $75°$C	$-10°$C to $70°$C

SATELLITE BUS REQUIREMENTS

Requirements on the satellite bus exist to ensure the successful operation of the COMPASS satellite payload. These requirements include attitude determination and control subsystems and pointing of the satellite antenna. A propulsion system is also required, to perform orbit and attitude corrections during the primary mission phase. Finally, power, structure, and data handling subsystems are required, to manage the operations of the COMPASS satellite and protect against the harshest environmental factors.

Propulsion

CubeSat propulsion solutions for the COMPASS orbits can be handled by use of solar sails or electric propulsion (EP) systems. Use of impulsive thrusters for orbital maneuvering is less efficient than low-thrust alternatives for long-term mission designs. Impulsive thrusters may generate greater propulsive forces; however, the specific impulse (Isp) associated with with EP systems are magnitudes greater in comparison. Fuel requirements are significantly less demanding as well, as EP systems are more efficient.[12] Concerns for fuel efficiency are essentially nullified using solar sails, as all propulsion can be obtained by means of solar radiation pressure (SRP).

Solar Sails The characteristically light-weight design of a CubeSat renders itself well for use with solar sails. Solar sails are becoming more popular propulsion candidates, as made evident with such projects as LightSail-2[13] and NEA Scout.[14] Though solar sailing concepts alleviate fuel requirements, significant constraints are introduced on the availability of desirable thrust vectors and thrust magnitudes. For a perfectly reflective solar sail, the propulsive force generated from a SRP takes on the approximate form

$$\boldsymbol{F}_{\mathrm{SRP}} \approx -F_c \cos^2\theta \hat{\boldsymbol{n}} \quad , \quad \theta \in [-\pi/2, \pi/2] \tag{1}$$

where F_c is the maximum available SRP force and θ is the sail cone angle measured from the sun-sail line to the sail surface normal. Figures 4 and 5 illustrate the relationship between the available SRP force and sail cone angle. The complexity of the sail deployment and attitude

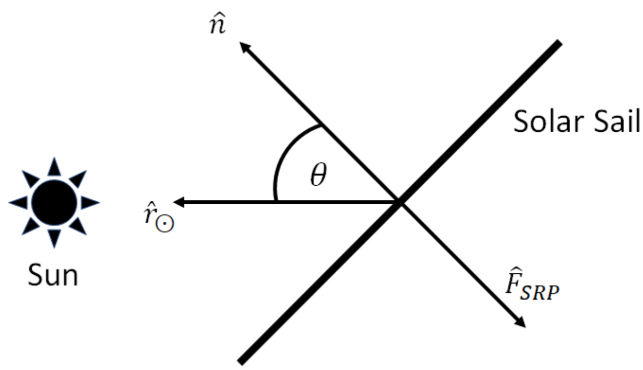


Figure 4. Relationship between sun-sail line, $\hat{\boldsymbol{r}}_\odot$, sail surface normal, $\hat{\boldsymbol{n}}$, cone angle θ, and direction of srp force, $\hat{\boldsymbol{F}}_{\mathrm{SRP}}$.

control mechanism may render solar sailing a less attractive propulsion solution.

Electric Propulsion Electric propulsion systems can be scaled to meet CubeSat design requirements and have modest fuel requirements when compared to conventional, impulsive propulsion

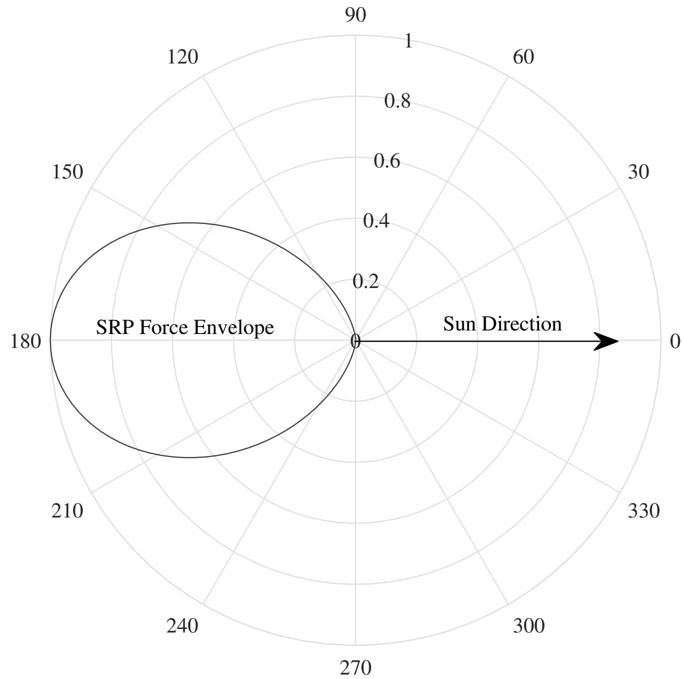


Figure 5. 2-D polar representation of SRP force envelope with respect to the sun direction.

systems. In particular, the Busek BET-1mN Electrospray Thruster has characteristics which can be integrated within the COMPASS satellite design. Key specifications are listed in Table 4. Flight heritage for the BET-1mN includes spaceflight with the LISA Pathfinder mission. Assuming the thruster will only be used for orbital corrections during the mission phase, the BET-1mN could provide a viable propulsive solution to for the COMPASS constellation.

Table 4. BET-1mN Busek Electrospray Thruster

Thrust	0.7 mN nominal
Specific Impulse	800 sec
ΔV	151 m/sec
System Mass	1.5 kg
System Volume	1 U (including electronics)
System Power	15 W

Attitude Determination and Control

The attitude determination and control system (ADCS) may be the most important subsystem in the satellite bus in terms of supporting COMPASS mission success criteria. The ADCS must accommodate for attitude determination, detumble, satisfaction of pointing requirements set by the communications payload, as well as attitude maneuvering for thruster alignment and solar panel alignment. Fortunately, ADCS modules are abundant in the CubeSat community, providing many viable solutions for the COMPASS mission.

Perhaps the largest ADCS obstacle of note is Mars' lack of a magnetic field. Consequently, attitude determination for Mars applications must take place without the use of magnetometers. Alternatives are plentiful, in the form star trackers, sun, star, or horizon sensors, as well as gyroscopes and motion reference units. Ultimately, attitude determination and control solutions do not pose significant design challenges for COMPASS satellite development.

Command and Data Handling

The command and data handling (CDH) board will manage data from all subsystems and sensors. Commands from ground stations and messages relayed between member COMPASS satellites will be processed with the CDH as well. Essentially, the CDH board serves as the "brains" for the COMPASS satellite. Any system required to manage flight operations must necessarily be reliable and resilient to harsh radiation effects. The RAD 750 3U CompactPCI from BAE Systems is a compact flight CPU featuring multiple interfaces including PCI bus, UART, and JTAG.[15] Additionally, the board is advertised as "immune" to latchup and is resilient to total ionizing dose of 100 krad. Specifications are listed in Table 5.

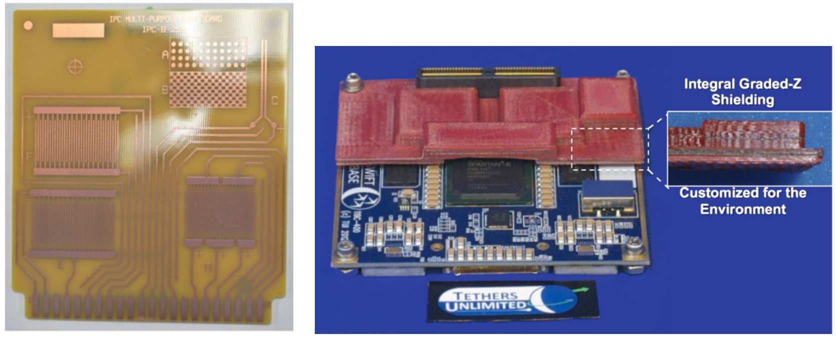
Table 5. RAD750 3U Compact PCI

Form Factor	100 mm $\times$ 160 mm
	549 g
Memory	128 MB SDRAM
	256 kB SUROM
Radiation Hardness	TID $>$ 100 Krad (Si)
	SEU 1.9×10^{-4} errors/card-day
	Latchup immune
Performance	$>$ 260 Dhrystone 2.1 MIPS at 132 MHz
	4.3 SPECint95 4.6 SPECfp95 at 132 MHz
Power Dissipation	$<$ 10.8 W
Rail Temperature Range	$-55°$C to $70°$C

Thermal and Structural

Structurally, challenges include protection from radiation and thermal regulation for the atomic clocks and electronics. Radiation protection can be built in to most subsystems as indicated in the previous sections; however, the major concern is radiation effects on the atomic clocks. Protective measures must be placed to ensure the successful operation of the clocks. Possible solutions include shielding enclosures or protective coatings. NASA's Shield-1 CubeSat mission incorporates a vault shielding design which is expected to increase CubeSat lifespans from the order of months to the order of years.[16] The protective vault is composed of fiber metal laminates which protect electronics from radiation exposure from protons, electrons, and x-rays. Coating solutions include the LUNA XP-CD-B charge dissipating transparent conformal coating which enables improved radiation hardening and electrostatic discharge management.[17] Tethers Unlimited markets a similar coating called the Versatile Structural Radiation Shielding (VSRS) which demonstrates two orders of magnitude improvement in electron attenuation than traditional aluminum shielding.[18] Figure 6 displays these coatings.

The operating thermal range for any proposed COMPASS satellite design is projected to be between $-10°$C to $50°$C, based primarily on the tolerances of the Microsemi clocks and Iris V2.1 specifications. These values can be realized using a combination of existing passive technologies used for CubeSat thermal regulation. These include multi-layer insulation, paints, coatings, or thermal straps. Active alternatives include patch heaters, such as Kapton polyimide film insulated



(a) LUNA XP-CD-B (b) VSRS

Figure 6. IPC-B-25A test board coated in LUNA XP-CD-B and CubeSat Radio with conformal VSRS cover

heaters.[19] These flexible films can be placed virtually anywhere in the satellite and demonstrate excellent outgasing properties in high vacuum environments.

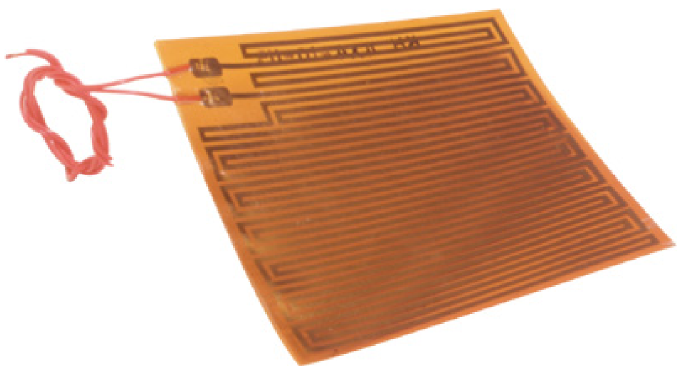


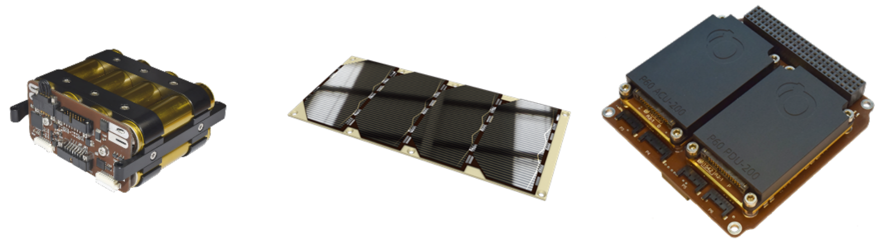
Figure 7. Polyimide film insulated flexible heater

Power

Power management is a major obstacle in terms of feasibility of the COMPASS satellite design. Compiling the projected power budgets for the types of subsystems listed in the previous sections, the total power budget is projected to be well over 30 Wh for standard mission operations. This only includes projected payload requirements of approximately 8 Wh for the atomic clocks and over 20 Wh for the transponder. Due to the uncertainty in the specific modes of operation, an uncertainty factor of 200 percent will be assessed in determining the amount of power storage required in the COMPASS satellite batteries. Existing battery packs can accommodate for these demands. For example, GOMspace produces the NanoPower BPX battery pack with specifications listed in Table 6.[20] These battery packs can be stacked to increase overall storage capacity for the satellite system.

Table 6. GOMspace NanoPower BPX Specifications

Capacity	77 Wh
Mass	500 g
Dimensions	$92.2 \times 85.5 \times 40.5$ mm



(a) NanoPower BPX (b) NanoPower MSP (c) NanoPower P60

Figure 8. Example GOMspace power system solution

Solar panels may be used to recharge the batteries when sunlight is available. The NanoPower MSP modular solar panel is an example of a potential solar panel system to be used for the COMPASS satellite design.[21] Specifications for the MSP modular solar panel are given in Table 7. A notable concern with any commercially available component is how the expected performance will measure up when placed outside of Earth orbit. Power generation is projected to be approximately half that on Earth due to Mars' greater orbital radius from the sun.

Table 7. GOMspace NanoPower MSP Specifications

Solar Cell Efficiency	30 percent
Power Generation	1.15 W per cell (LEO)
Compatibility	$\geq$ 6U form factor

Power management can be handled using a commercial subsystem such as the NanoPower P60 modular power system.[22] This assembly contains an array conditioning unit and power distribution unit for power distribution between the solar panels, batteries, and satellite subsystems. Figure 8 illustrates the GOMspace power solution subsystem.

CONCLUSION

The COMPASS constellation is an ambitious CubeSat mission concept which aims to achieve continuous global coverage of Mars to provide navigation and communications support for Mars users. The constellation consists of 15 advanced CubeSats with sub 12U form factors. This manuscript provides a high-level feasibility study into the availability of potential subsystems to create a COMPASS member satellite. Using the current state of the art in commercially available and near future technologies, a viable COMPASS satellite design may be obtained given a detailed concept of operations. The next step will be to assemble a detailed satellite design with accompanying mass, power, and link budgets, as well as cost estimates, given appropriately selected commercially available subsystems.

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