The MOMENT Magnetic Mapping Mission
Martian Science on a Nanosatellite Platform

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MOMENT (Magnetic Observations of Mars Enabled by Nanosatellite Technology) will obtain high-resolution maps of remnant-magnetic fields over Mars' southern highlands. A sub-nanotesla magnetometer employed in a highly-elliptical and low-nightside-periapsis (100 km) orbit will provide greater spatial resolution and anomaly delineation than is available from Mars Global Surveyor. During the aerobraking phase of that mission, low-altitude measurements were corrupted by solar wind because they were acquired in sunlight, where solar winds interacted with the crustal-magnetic field. During the mapping phase, spatial resolution was limited to about 400 km. Improving upon these limitations, MOMENT's mapping strategy will allow detailed studies of regional tectonics and core-dynamo history. MOMENT's design is based on the Space Flight Laboratory's Generic Nanosatellite Bus. Developed for the BRITE and CanX-4&5 missions, MOMENT re-uses this technology to provide a rapid and cost-effective mission. Implementation of the mission requires payload space on a larger carrier spacecraft and use of Martian communication relays to transfer information to and from Earth; MOMENT is otherwise fully autonomous. This paper describes the conceptual MOMENT mission (funded by the Canadian Space Agency) and illustrates that nanosatellite technology is a relatively-simple and cost-effective means to enhance solar system exploration.

INTRODUCTION

Within days of Mars Global Surveyor's entry into orbit around Mars, an important discovery was made that had been left as an open question by previous missions to the red planet: the existence of a planetary-magnetic field [1]. Though not global in nature, the small but strong crustal-magnetic field contains a wealth of information on the planet and its history. While data from Mars Global Surveyor has set the foundation for magnetic studies of Mars, there is room for significant increase in knowledge with a mission that is designed specifically to explore these magnetic phenomena - now that the existence of a strong crustal field has been established.

Mars Global Surveyor provided valuable magnetic data during both the aerobraking and mapping phases of its mission. During the aerobraking phase, measurements were made at low altitudes of 100 to 200 km. These were, however, taken in daylight, meaning that the results are contaminated by external fields associated with ionospheric and magnetospheric currents and the interaction of the solar wind with these regions. During the mapping phase, measurements were obtained at two distinct times: 2 a.m. and 2 p.m. By using the nighttime information, the whole data set was corrected for external fields with a resulting 0.5 nT accuracy [2]. However, the measurements were made between 360 and 420 km, meaning that the results suffer from lower resolution because of the strong decay of the crustal-magnetic field with increasing altitude. The impact of this lower resolution is illustrated with the terrestrial example given in Figure 1, where the axes show lattitude versus longitude and the colour scale denotes magnetic-field strength in nanotelsas.

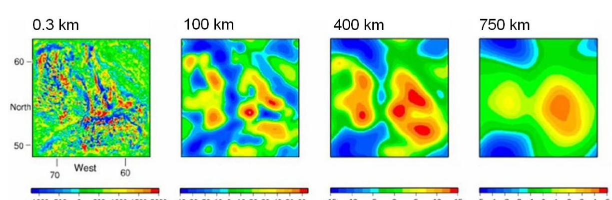

Figure 1: Anomalies over Eastern Canada

The different planetary curvatures (and thus spherical harmonics) of Earth and Mars mean that the roughly 400 km altitude of the Mars Global Surveyor data corresponds to the 750 km Earth-altitude resolution in the figure above; opportunity clearly exists for enhanced resolution.

To add value to the scientific community, the Magnetic Observations of Mars Enabled by Nanosatellite Technology (MOMENT) mission will pick up where Mars Global Surveyor left off. The key aspect of the MOMENT mission is a 100 km nightside periapsis around which magnetic measurements will be made with a high-fidelity magnetometer. To minimize the effects of drag at this altitude, the orbit will be highly elliptical. To narrow the scope of the baseline map, the periapsis of the primary mission will drift over Cimmeria and Sirenum Terrae. Current data for this region of high-magnetic strength lack coherent signals with wavelengths less than about 400 km [3], leading to the observation that this area is a prime candiate for MOMENT's increased-resolution-mapping objectives. This focus is affirmed by Figure 2, where the major magnetic anomalies are located in the southern highlands that MOMENT will target.

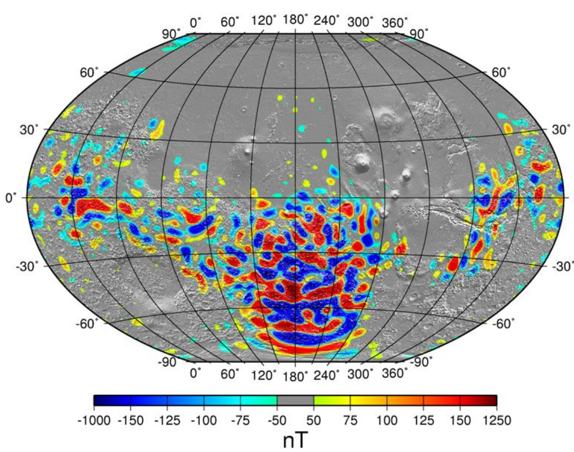

Figure 2: Radial Magnetic Field of Mars

The full baseline-map zone for MOMENT ranges from 150 to 210 degrees eastern longitude and 35 to 85 degrees southern lattitude. Centred on the most dense region of Figure 2, this zone is shown in Figure 3, where 'up' corresponds to 'south', the baseline region to be mapped by MOMENT is shaded with a light yellow and MOMENT's projected orbit is shown in green.

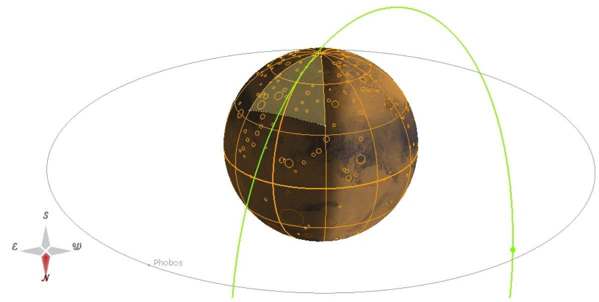

Figure 3: MOMENT's Baseline Map

MOMENT's mapping strategy will lead not only to an improved magnetic map and clearer understanding of what is already known in part but will also provide fresh insight into the nature of Mars. Able to retain retain a wavelength that is four times shorter than what is currently available, MOMENT will yield clues into the effects of dust storms on the crustal-magnetic field and into the details of the tectonic regime that occurred during the formation of the stagnant lithosphere within the planet's first half-billion years. MOMENT will also work to better understand the formation of a highly-magnetic crust and the magnetic carrier required to give rise to the strong magnetic anomalies in the southern hemisphere. MOMENT will provide an excellent means to determine the paleomagnetic poles and thus the polar wander of Mars.

While the potential of MOMENT's map promises to be significant, the engineering necessary to make it happen does not warrant creating a large spacecraft that is typical of deep space missions. The suggested alternative to this is to design a nanosatellite that can undertake this narrow-scope concept. MOMENT is envisioned to be a nanosatellite whose sole purpose is to obtain high-resolution-magnetic maps of Mars for the key areas of interest. Riding to Mars as a small payload on a larger carrier craft (for which the mission will have to wait, but whose only requirement is that it be willing and able to acommodate a passenger) MOMENT will separate upon arrival to perform its focused mission while the carrier continues on with its own unrelated agenda. Due to limited power resources, MOMENT will execute its mission autonomously, relaying data to and from Earth via Mars-orbiting satellites present at the mission's epoch.

With a brief outline of the MOMENT mission and driving science in hand, the remainder of this paper serves to describe the conceptual study (funded by the Canadian Space Agency) by overviewing the nanosatellite and its component subsystems.

THE CanX PROGRAM

To understand the environment in which MOMENT was conceived and is being developed requires a brief look at the Canadian Advanced Nanospace eXperiment (CanX) program that is run and operated by the Space Flight Laboratory at the University of Toronto. The CanX program has two objectives that guide each phase of every mission. The first and foremost is to train students at the master's level. In this way, the University of Toronto sustains Canada's public and private space sectors through the continual supply of space engineers. The second objective is to provide a low-cost and accessible means by which independent researchers may perform experiments and specialized tasks in space. Figure 4 shows the nanosatellites (along with their associated launch dates) that have been, and are currently being, produced by the CanX program.

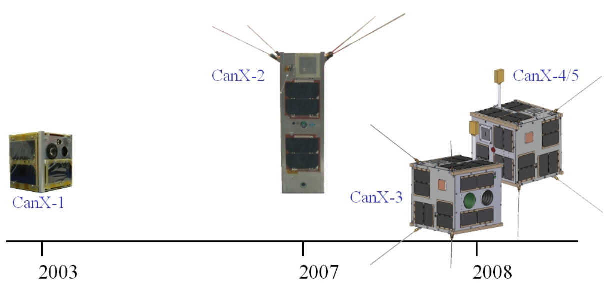

Figure 4: Current CanX Satellites

The CanX-3 (BRITE) space-astronomy mission and CanX-4&5 formation-flight mission are built upon the Space Flight Laboratory's Generic Nanosatellite Bus. This technology provides the capability to produce multiple and diverse missions based on a central construct [4]. Following the microspace philosophy to incorporate the latest commercial technology in a simplified design that improves risk mitigation [5], the Generic Nanosatellite Bus is a modular design that leads to a reliable, low-cost and short-schedule base upon which to build future missions.

MOMENT is based on the Generic Nansosatellite Bus. Taking the basic structure and subsystems with as little modification as is feasible, MOMENT is an extension of current knowledge, expertise and heritage. This leads to a satellite that is tailored to MOMENT's specific mission without the cost, lead time or uncertainty that would otherwise be present in a from-scratch design.

STRUCTURAL LAYOUT

Pictured in Figure 5, MOMENT is a 16 kg nanosatellite. Similar to the Generic Nanosatellite Bus' cubic form factor, MOMENT has the notable addition of a two-metre boom. The design of the boom ensures that the first natural frequency is well above 100 Hz, which is necessary both to prevent low-frequency oscillations from influencing attitude dynamics and to ensure that resonance of MOMENT will not be reached in either its launch or orbital environments.

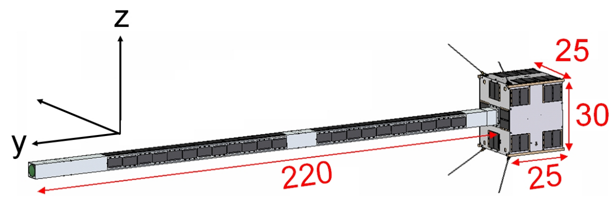

Figure 5: External Configuration (cm)

Near the tip of this boom is a high-fidelity magnetometer, mounted away from the main body to avoid magnetic interference from the spacecraft in order to achieve 1 nT overall accuracy. A second magnetometer is located midway along the boom to provide a means by which to dynamically subtract the spacecraft dipole from the scientific measurements and also provide some redundancy. Also located at the tip is a star tracker, where such placement helps minimize alignment errors between the magnetometer and the attitude determination sensors. It also simplifies attitude control manœuvres during mapping, which occur in the relatively-dense atmosphere near periapsis. Covering much of the boom and a large portion of the main body's surface area are body-mounted-solar cells which, in addition to a battery, provide the means to power MOMENT. The remaining free surfaces on MOMENT are used for thermal control. A quad-canted-UHF attena is mounted to the main body in such a way that antenna-pattern interference in the forward (anti-boom) and transverse directions due to the presence of the boom are minimized.

Internally, MOMENT is illustrated by Figure 6. Like the design of the Generic Nanosatellite Bus upon which MOMENT is designed, the internal structure uses two trays to mount most of the various subsystem components while simultaneously providing a relatively large volume to be dedicated to payload space. For MOMENT, this volume is occupied not by the mission's payload (magnetometer) but by the propulsion subsystem. Hydrogen peroxide and propane are the fuels of choice in this bi-propellant fuel system, whose goal is to manœuvre MOMENT from a parking orbit into its mapping orbit and to maintain the period of that orbit over the mission's duration (about three hundred days for the baseline). Eight propulsive thrusters use this fuel to move and rotate MOMENT and are aligned with the body 'y' axis (four per direction). Visible in the internal layout diagram are three reaction wheels that provide attitude control. Three magnetorquers are also shown, but cannot be used for actuation because the strenth of the crustal magnetic field that does exist around Mars is too weak to be effective. Instead, they are present to provide an additional tool for calibration of the two magnetometers. Finally, MOMENT's two computer boards are located in one of the trays. One board is dedicated to housekeeping and communication tasks while the other hosts the attitude and navigation routines. The power subsystem hardware is distributed over the two computer boards.

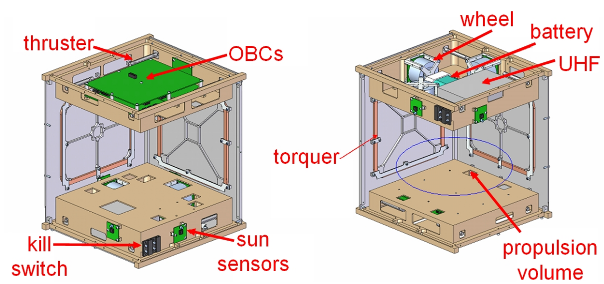

Figure 6: Internal Configuration

THE MAGNETOMETER PAYLOAD

Mapping the strength and direction of the crustal magnetic field around Mars requires a three-axis-vector magnetometer. To allow generous margin on current field-strength estimates near MOMENT's periapsis, the magnetometer will have a range of at least ±4000 nT. It will also have at least a 0.5 nT resolution in order to map weaker fields with the desired sensitivity. Similar to Mars Global Surveyor, imperfections in modeling the spacecraft will likely limit practical precision to about 0.1 nT. MOMENT will use the magnetometer to sample the crustal-magnetic field at a rate of 1 Hz, which ensures that the along-track distance between field measurements is not greater than the desired ground-track spacing (around 20 km).

Magnetometers flying aboard interplanetary spacecraft are almost invariably custom designed and built. Commercial units, not having such missions as a target demographic, are rare at best. As a nanosatellite program, MOMENT cannot afford to develop its own science-grade magnetometer and has therefore sought out a suitable sensor program: a prototype magnetometor developed by SRI Graz. The key performance parameters of this magnetometer include picotesla-level resolution (again, limited in practice), an adjustable dynamic range that ends around ±8000 nT, total power consumption of 200 mW or less, a ±100°C thermal envelope and low mass and volume of both the sensor and its electronics [6].

MAPPING ORBIT

MOMENT's operational orbit depends in part on the initial orbit of its carrier spacecraft, since MOMENT has limited manœvring ability. For purposes of planning and illustration, the initial orbit of Mars Reconnaissance Orbiter has been used as a reasonable example of what can be expected from a larger Mars orbiter. MOMENT's nominal mapping orbit would then be elliptical (100 km by 33934 km) at an inclination of 93.3°, with the periapsis roughly over the south pole at the start of southern-hemisphere autumn. This orbit has a period that is slightly less than one (sidereal) Martian day. Precession due, for the most part, to Mars's equatorial bulge moves the periapsis slowly northward over the nightside of Mars.

To a first approximation, MOMENT's orbit remains fixed in space as Mars rotates beneath. Given an altitude constraint, the shape of the orbit determines the length of a periapsis pass. MOMENT's mapping passes are defined to be the time that MOMENT is within 20 km of the periapsis altitude, which for the chosen orbit makes the passes about 18° long. The position of the orbit in space determines the latitude of the periapsis. The longitude of the periapsis is determined by the relationship between MOMENT's orbit period and the planet's rotation period: how far Mars rotates between periapsis passes. For the nominal mapping orbit, with a period about 88 s short of the planet's rotation period, each periapsis is about 0.36° (about 15 km at 45° latitude) to the east of the previous one.

MOMENT's orbital timing has to be quite precise to achieve the closely-spaced passes needed for high-resolution mapping. To control pass longitude to about ±1 km at a latitude of about 45°, MOMENT's orbit period must be controlled to about ±6 s, corresponding to control of periapsis velocity to about ± 0.01 m/s. Fortunately, this does appear to be feasible using a combination of optical navigation to locate the spacecraft relative to the planet and an accelerometer to measure the drag loss during a pass. This tight requirement does, however, immediately preclude the simple strategy of allowing aerodynamic drag to remove energy from MOMENT's orbit so that the period would shorten as the misson proceeds. This would very quickly spoil the synchronization between the spacecraft and the planet, causing subsequent periapsis passes to be at nearly random longitudes. Since the target region covers only 60° of longitude, only about one sixth of all periapsis passes would be useful. Therefore, MOMENT's orbit must be actively and precisely maintained.

Various alternative orbits have been examined, but none of them are appealing. An orbit whose period is not an integer number of Martian days would lead to unproductive periapsis passes outside of the target, increasing drag losses without increasing the data yield. Although a less-elliptical orbit would match the planet's curvature better at periapsis such that the mapping passes would be longer, the actual gain in pass length is small until the orbit approaches circularization. The one-day orbit appears to be optimal for low-altitude mapping of a small region of Mars.

The nominal orbit's periapsis will remain within Mars's shadow for nearly half a Martian year, at around 300 orbits plus some margin for avoiding dawn and dusk. During that time, its periapsis will precess northward about 45°, which is extremely convenient since changing the latitude of periapsis by rocket burns is costly. This precession allows the 18°-long passes to cover most of the target area, extending from 85°S to 35°S.

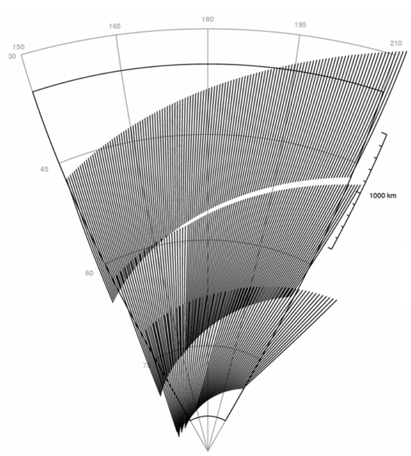

Figure 7: Passes for a 279 by 44500 km Orbit

Figure 7 is an example of a possible coverage pattern, with the orbital period being varied slightly to maintain roughly-uniform-east-west-track spacing. Twice during the pattern, the orbital period is briefly raised substantially to let Mars's rotation 'catch up', moving the passes back to the western edge of the target area (the heavy outline).

The nominal orbit has periapsis at an altitude of 100 km. This is, however, a nominal value and not a certainty. The density of Mars's upper atmosphere is extremely variable from day to night, from winter to summer and somewhat randomly with wind patterns and dust storms (which heat the lower atmosphere and cause it to balloon upward). To have reasonable hope of doing most of the mapping with a 100 km periapsis, MOMENT must map not only at night but in southern winter, when the target region is cold and the upper atmosphere is thin. (Atmospheric density at 100 km at high-southern latitudes varies by more than a factor of ten between winter and summer.) Conveniently, this is also a time when major dust storms are rare. Even so, to keep propulsion requirements within reason, it has been necessary to define MOMENT's actual operating periapsis altitude in terms of drag, not height: MOMENT will map at whatever periapsis altitude holds drag loss to an average of 1 m/s per pass. At night in southern winter, this will usually be 100 km or less, but it can be expected to vary somewhat during the course of the mission, perhaps on short notice.

OPERATING MODES

For each mapping orbit, MOMENT will operate in a number of task-specific modes. These are illustrated in Figure 8, where all portions of the line not overlayed with a mode circle correspond to an 'idle' mode.

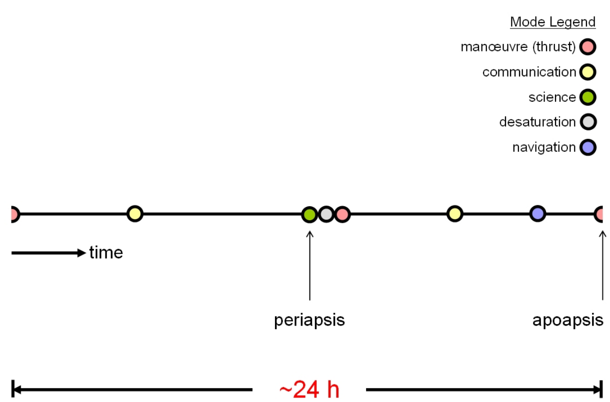

Figure 8: MOMENT's Operating Modes

Idle mode is synonomous with 'standby', where MOMENT is not performing any specific task. In this case, the attitude is set to maximize power potential. In its communication mode, MOMENT exchanges data to and from Earth through a relay satellite over UHF frequencies. From an attitude perspective, this mode is almost identical to the idle mode, except that control is applied as necessary to keep any null regions in the nearly omni-directional antenna pattern away from the line of sight toward the relay satellite. The science mode is where mapping of the crustal magnetic field occurs. Due to aerodymic forces, it also means that MOMENT must re-orient itself such that the long boom is trailing behind the body. Artificial damping is applied here to keep oscillations of the boom sufficiently damped in order to achieve the target mapping accuracy. The desaturation mode takes advantage of the strong aerodynamic forces just outside of the mapping altitudes to remove angular momentum from the reaction wheels, thus saving on fuel. Orbital maintenance occurs in the manœuvre mode, where the propulsion subsystem is active. This occurs twice each orbit: once just after desaturation (as close to periapsis as possible) and once at apoapsis. Finally, the navigation mode aims the star tracker to image the two Martian moons under certain conditions, from which three-space-position vectors, and consequently orbital elements, can be determined.

The timing of the science, desaturation and manœuvre modes is fixed, while both communication and navigation occur as external circumstances (contact windows and celestial alignment) permit. Changing between these modes is designed to be autonomous so that ground operations can be minimized, which in turn creates less reliance on the availability of an independent relay satellite.

POWER ENVIRONMENT

The power generation environment for MOMENT will, nominally, be quite favourable. With a highly elliptical orbit and a low-nightside periapsis, the worst case scenario will see 88% of the 24.57 hour orbital period in direct sunlight. Compared to SFL's BRITE and CanX-4&5 missions that use the same Generic Nanosatellite Bus upon which MOMENT is designed, the power generation environments are actually very similar. While the CanX satellites will see about twice the solar flux in a low-Earth orbit that MOMENT will at Mars, the eclipse fractions of the former are dramatically longer. For power during eclipses and for surge power for propulsion and communications, MOMENT will use the same 5.3 Ah battery as the Generic Nanosatellite Bus.

Mapping during the southern hemisphere's winter corresponds to Mars aphelion and the lowest solar flux, around 490 W/m^2. A total of 15 cell pairs will be mounted to the body and boom per face, leading to a total potential of about 12.25 W at this flux level. MOMENT currently implements direct energy transfer as part of its design. While sunlight exposure is large enough that peak-power tracking is not warranted, changes to the Generic Nanosatellite Bus for terrestrial missions may see MOMENT follow suit to maintain as much similarity of design as possible. Power generation figures assume a 2D-isometric-sun-pointing attitude. Should an attitude be realized whereby one of the small faces (defined by the two faces whose normals are collinear with the boom's axis) alone points toward the sun, then power potential drops to 2.3 W. In this case, nominal operations cannot continue, but the power input is sufficient to maintain a safe-hold configuration. By and large, MOMENT's power analysis shows that for the majority of each orbit, no more than half of the available power will be required.

THERMAL ENVIRONMENT

The thermal control subsystem for MOMENT consists primarily of passive control measures, where a low-emission surface is required to limit radiative-heat losses. Through material selection and heat-path geometry, the conductance between the bus and each component is considered and adjusted on a case-by-case basis. Components that are isolated conductively may require wrapping with multi-layer insulation to limit heat transferred through radiation. To maintain survival temperatures and to precisely regulate temperatures on systems which have thermally-sensitive performance, local heaters are employed. In particular, MOMENT has heaters for its battery, propulsion subsystem, star tracker and magnetometers. To minimize heater power, any component that requires active control is conductively isolated from the support structure.

The thermal state of MOMENT is a function of eclipse time, environmental heat loads (solar, albedo, planetary-infrared and aerodynamic), spacecraft attitude, power dissipation and the state of degradation of the surfaces' thermo-optical properties. Figure 9 shows a simulation of the nominal thermal case. Corresponding to the nominal modes of operation, it also illustrates a given mapping orbit's attitude profile.

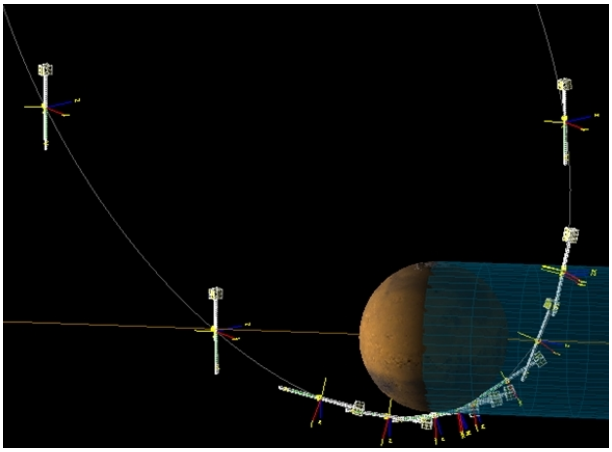

Figure 9: Nominal Thermal-Case Simulation

The attitude of the spacecraft with respect to the solar vector was found to be the principal factor in characterizing (and controlling) the thermal state of the spacecraft. In order to simulate the extremes in the thermal envelope, the worst-case-hot simulations consist of inertially-fixed attitudes where maximum surface projections of the bus and the boom with respect to the sun are held. The opposite (minimum surface projections) is true of the worst-case-cold scenarios. Fortunately for MOMENT, the worst-case scenarios do not represent an insurmountable obstacle. On the hot side, atmospheric heating is only a transient event and over-heating is not a concern in the nominal attitude configuration (the two long faces isometrically pointing toward the sun). On the cold side, eclipses during the nominal mapping phase of the mission last for half an hour or less during which temperature drops do not fall below operational limits. Outside of the mapping phase, eclipses would be much longer, but can be reduced by lowering the apoapsis altitude - albeit at the cost of extra fuel.

SPACECRAFT ATTITUDE

MOMENT has several attitude scenarios corresponding to the different operating modes. Its driving requirement, however, is that the attitude of the magnetometer be known to ± 1 arcminute while mapping. De-rating this value by 50% to allow for alignment errors and considering both the tendancy for MOMENT to oscillate in the low atmosphere and the readout rate of the magnetometer means that, while mapping, MOMENT must be able to point with $\frac{1}{3}$-degree accuracy and maintain that direction with 12-arcsecond stability over each 1 s control cycle. These requirements will not be overly difficult for MOMENT to achieve because BRITE, one of its Generic Nanosatellite Bus precursors, already operates with higher fidelity.

The other control modes are less stringent, and so do not drive the design of the attitude subsystem. Both the navigation and desaturation modes require $\frac{1}{2}$-degree accuracy and stability. Propulsive manœuvres follow suit at 1-degree accuracy and stability while the idle and communications modes round out the requirements with 4-degree accuracy and 1-degree stability.

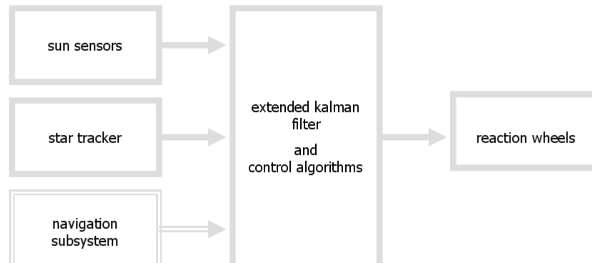

Figure 10: Attitude Subsystem Layout

To meet these various requirements, MOMENT's attitude determination and control subsystem is organzed as shown in Figure 10. On the determination side of the subsystem, a star tracker (with heritage on the BRITE space-astronomy mission) will provide the nominal, and most accurate, solution to the attitude determination problem, including lost-in-space capabilities. Six sun sensors will complement the star tracker, providing limited attitude knowledge, where rate sensors from the Generic Nanosatellite Bus may be added to improve estimation. An extended Kalman filter is used to estimate the full position and angular velocity state from the static measurements. The navigation subsystem is distinct from the attitude subsystem in design and implementation, but provides fundamental information (orbital elements) in the form of occasional updates. On the control side of the subsystem, the only actuator will be a set of three orthonganally-mounted-reaction wheels, the same ones designed in an SFL partnership and used on the Generic Nanosatellite Bus.

NAVIGATION

Navigation is a challenging problem for MOMENT because very precise orbit control is required, while the usual approach of radio tracking from Earth is not practical due to the great distance between the planets combined with very limited transmitter power. For MOMENT, there are two approaches to navigation: optical and radio tracking by other Mars orbiters. The former will be the primary method, while the latter, relying on foreign-asset services, will only be used occasionally and when available.

MOMENT's navigation camera is synonymous with its star tracker, where the array's image will be read out in addition to the standard quaternion output. Relaying these images to Earth for processing is not planned due to limited communication opportunities. Instead, navigation will be done autonomously on board. The images will be processed to determine the directions of Mars' two moons with respect to the spacecraft. Comparing to onboard ephemerides, the separation distance of the moons may be found, and simple triangulation will give a relative position. Factoring in Mar's own position relative to the moons will result in a position estimate in a fixed Martian frame of reference to correspond to the mapping requirement that each magnetometer reading be accompanied by a position estimate. For MOMENT, this navigational approach must be accurate to a small fraction of MOMENT's 100 km periapsis. Mars Reconnaissance Orbiter, as one example of the many missions that have used such optical navigation, is currently flying a similar experiment (sensor and method) and is seeing ± 1 km accurate results [7]. One of the tricks to this approach is the timing of the images, where both Phobos and Deimos need to be in the same (narrow) field of view. Fortunately, Phobos' short orbital period (just under eight hours) means that the maximum duration between conjunction of the two moons, as viewed from Mars, will be about half a day. The mapping orbit has a high apoapsis well above the solar plane such that capturing these views will also be relatively straightforward. Moreover, the mapping orbit's apoapsis is on the daylight side of the planet such that the moons will be illuminated from MOMENT's perspective so long as they themselves are not in eclipse. This leads to fewer concerns about exposure when imaging the moons. Exposure (saturation) by Mars itself, however, will likely pose a problem. Therefore, like Mars Reconnaissance Orbiter, the navigation images will exclude Mars from the star tracker's field of view.

PROPULSION

To insert itself into the mapping orbit after separation from the carrier spacecraft and to maintain that orbit, MOMENT requires a propulsion subsystem. For a nanosatellite, the demands of undertaking the journey from Earth to Mars are too high, which is why MOMENT must piggy-back on a larger spacecraft. Once in a reasonable Martian orbit, however, MOMENT can provide enough propulsion to stand alone.

The range of propulsive options is wide, and several were considered for the mission. Monopropellants were avoided because of excessive fuel volume associated with their low specific impulses. Electrical systems cannot be used because power demands exceed the generation capacity of MOMENT's solar cells. Instead, MOMENT's propulsion subsystem will use high-test-peroxide (HTP) as an oxider and propane as fuel in a bi-propellant design. Expected to achieve a 270 s specific impulse on a total power consumption of about 1.3 W for its valves and electronics, the propulsion subsystem will provide about 460 m/s to the mission.

Figure 11 shows a high-test-peroxide tank centred on the satellite's centre of mass (inasmuch as possible). This minimizes the change of the spacecraft's inertial properties over time as fuel is depleted. Three smaller tanks are situated below: liquid propane is stored in two of them while gaseous nitrogen (pressurant) is stored in the other. There are also eight thrusters, mounted to the trays such that four will point in the +y direction and four in the -y direction.

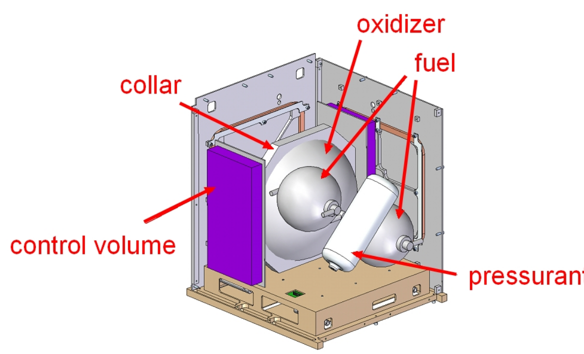

Figure 11: Propulsion Subsystem Layout

COMPUTERS

Making the most of heritage, MOMENT will implement a computing architecture that is almost identical to that of the Generic Nanosatellite Bus. The design centres on an ARM7 microcontroller that provides internal SRAM and FLASH, along with synchronous and asynchronous serial ports, timers, a real time clock, a multi-channel-pulse-width modulator and a watchdog timer. As oscillator clocks the processor with a frequency stability of 1.5 ppm over the entire expected temperature range, which is more than sufficient to meet the timing requirements imposed by mapping near periapsis. MOMENT has two computer boards based on this architecture: a housekeeping computer and an attitude-plus-navigation computer.

Software for each of MOMENT's computers adopts a two-tier approach. The first level, called Bootloader, provides very basic functionality. Its program instructions are written in external ROM, while generated-program data is housed internally in SRAM. The idea behind Bootloader1 is to provide the basic means to talk, and upload new software, to the spacecraft. It also allows for basic troubleshooting and diagnostics, but contains no autonomous functionality. The second tier of the software architecture is the application software. Known as the Canadian Advanced Nanosatellite Operating Environment (CANOE), this tier allows for support of multiple-user threads, scheduling, resource sharing, inter-process and inter-computer messaging, dynamic-thread loading and execution, and time-tag switching.

COMMUNICATIONS

In theory, there are two ways for MOMENT to communicate with Earth: directly or indirectly via a relay satellite. The former is unfeasibile mostly because of the power required to overcome free-space losses and due to minimal access to adequate terrestrial facilities. The primary strategy that MOMENT will implement is to carry a UHF antenna and transceiver, using Proximity-1 protocols. Communicating with a Mars orbiter will be the nominal means of data transfer. Strategically, relying on a foreign asset is a risk, but the advantages of doing so outweigh the problems of developing a high-gain-link system (on both ends) that does not build on existing SFL technology. UHF is the radio band of choice not so much because Proximity-1 protocols do not allow higher frequencies but because to date no Mars orbiter has implemented them, and there is no specific indication that this will change in the near future.

One of the few non-portable aspects of MOMENT's design is that the communication strategy precludes the Generic Nanosatellite Bus' current radio subsystem. While there is a full UHF transceiver in place, it uses a form of frequency-shift keying that does not conform to the Proximity-1 protocols that are required on MOMENT to ensure that communication with Martian relay orbiters is possible. Proximity-1 adopts phase-shift keying, which necessities a completely different hardware layout. Instead, an S-band radio that has heritage on SFL's MOST microsatellite will be modified so that it transmits and receives on UHF frequencies, operating in a half-duplex mode.

The transission and reception frequencies are quite close, using the Proximity-1 UHF band. Within MOMENT's mass, power and volume budgets, it appears unfeasible to filter the receiver heavily enough to avoid desensitization when the transmitter is active. This leads to a half-duplex design, where the concern is that, if the transmitter freezes in an active state, MOMENT will not be able to receive a reset command. To address this reliability issue, a simple watch-dog timer acts as a monitor. Independent from the operating system (that is, hard coded and unchangeable after launch), it will track two parameters: the amount of time that the transmitter is on and the amount of time that it is off. By defining the former as a simple on and the latter as a total off, situations where rapid transmitter switching occurs are avoided. That is, the watchdog timer will enforce a maximum on time, will consider 'stand-by' (on but not transmitting) as synonomous with 'on' (transmitting) and will enforce a minimum off time, where the whole transmitter must be shut down. This mechanism will improve confidence that if a transmitter error occurs, a reset command can still be received by MOMENT through a relay satellite.

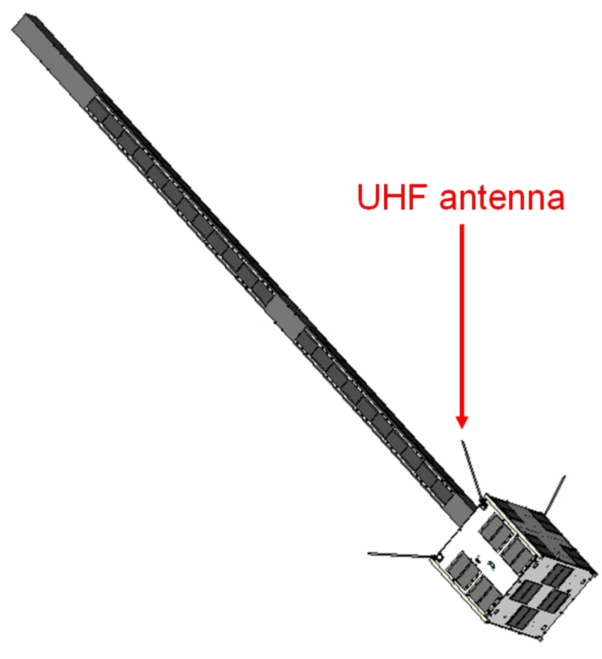

Figure 12: Antenna Configuration

Figure 12 shows how UHF antennas will be laid out on MOMENT. The simplest approach would be to implement a single-monopole antenna whose main lobe (perpendicular to the antenna axis) might nominally point toward (or near) a relay satellite's orbit, but which in any case would provide close to omni-directional coverage. The link margin and underlying power availability, however, have shown that MOMENT cannot sustain both the omni-directional gain hit (3 dB) and the linear-to-right-hand-circularized polarization loss (another 3 dB). (Circular polarization is common for Mars orbiters with UHF transceivers.) MOMENT's design uses the standard configuration of the Generic Nanosatellite Bus: a quad-canted set of UHF monopoles to provide right-hand-circularized polarization with an antenna pattern that is close to omni-directional - made possible by the presence of four, not one, antennas.

RIDING TO MARS

The journey from Earth to Mars on a carrier spacecraft means that MOMENT must be able to mount to another (larger) craft. It must also be assumed that the carrier will not want MOMENT to be active during the trip but will be willing to supply small amounts of power for any active heating required and to periodically poll critical telemetry. To mount to a carrier, MOMENT will use an altered design of SFL's XPOD. This deployment mechanism, which has space heritage on the SSETI Express mission, is a spring-based pusher. Figure 13 shows MOMENT stowed inside of an XPOD.

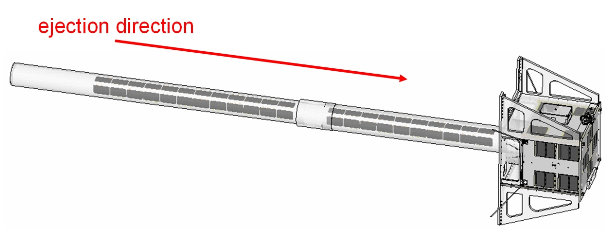

Figure 13: Stowed for Passage

Two sides of the XPOD are open on faces containing the UHF antennas. This is to allow these antennas to be pre-deployed, which reduces risk associated with deployable mechanisms. The rest of the XPOD fully encloses the satellite, where the two-metre boom is enclosed in a 'scabbard' tube that is designed, in part, to keep it from interfering with the carrier spacecraft. The front-end face is a spring-loaded door that is released with a specific activation signal. At the plane between MOMENT's body and boom, the XPOD has a spring-loaded plate that pushes the satellite out once the door has been opened.

CONCLUSION

As it stands, MOMENT is a nanosatellite that builds on the established heritage, resources and experience of the Space Flight Laboratory. Moreover, being a tailored version of the Generic Nanosatellite Bus has allowed MOMENT to re-use the vast majority of strategies and components in its design. This leads to a viable design with high reliability that also minimizes development schedule and implementation costs. While employing a nanosatellite at Mars would be uncharted territory, MOMENT's design, objectives and equipment are not a significant engineering challenge, representing looser design constraints than other missions in the same family that are currently being developed at the laboratory.

MOMENT does not just represent an interesting satellite design whose realization would be for its own sake. Rather, it is a mature concept that would provide significant benefit to the fields of both science and engineering. Vast areas of inter-planetary exploration have yet to be studied, and even those that have (like the Martian crustal-magnetic field) still hold great secrets. Performing cutting-edge science on a nanosatellite platform is the premise on which the Space Flight Laboratory operates, and a mission like MOMENT is a clear example of how this is possible. It is not always desirable (and, perhaps, not always practical) to devote multi-billion-dollar spacecraft to niche areas of exploration ... but carried deep into the unknown and let loose for a focused task, nanosatellites are perfect for the job of enhanced solar-system exploration.

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