SWIMSat: Space Weather and Meteor Impact Monitoring using a Low-Cost 6U CubeSat

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ABSTRACT

Networks of spacecraft are necessary to characterize and constantly monitor near-Earth threats such as Coronal Mass Ejections (CMEs) from the Sun, or impacts by large meteoroids. A network of CubeSat is ideally suited because of the low development cost and for demonstrating continuous monitoring of rare phenomena. In this paper, we describe the ongoing development of a single prototype spacecraft called SWIMSat (Space Weather and Impact Monitor Satellite) that has two goals: (1) monitor solar CMEs, and (2) monitor Earth meteor impacts. SWIMSat will be ideally located in geostationary orbit permitting continuous tracking and communication with ground. The advent of newly available, low-cost CubeSat and rad-tolerant technology for deep space makes it feasible to start now, within the scope of the University Nanosatellite Program, and achieve sizable gains towards the security of near-Earth space within a low cost budget. SWIMSat will utilize a suite of smart autonomous control software and radiation mitigation techniques to overcome the hostile environment beyond Low Earth Orbit and operate autonomously. We show that an even lower cost mission can achieve comparable meteor-monitoring objectives operating from low-Earth orbit, so we also describe that mission which we call MSat.

INTRODUCTION

The impact of space hazards on modern civilization is increasingly recognized as a serious threat by international governing bodies, prompting recent studies focused on mitigation and advancement of our predictive capabilities [1-7]. Two of these space hazards include Coronal Mass Ejections (CMEs) and meteor impacts. CMEs can pose substantial dangers to manned space exploration and critical technologies so fundamental to modern life - from GPS based processes such as timing financial transactions, navigation, and communications to fundamental infrastructure such as our vast electrical power grid. Another hazard is meteoritic impacts, particularly from objects 10 m in length and larger. Such objects, as they enter the earth's atmosphere, can cause explosions of a few hundreds of kilotons, similar to the Chelyabinsk meteor airburst in 2013 (Figure 1).

There lacks a dedicated satellite network to observe and characterize meteor impacts in the upper atmosphere. This would require selection of a camera with the right wavelength to pick up relatively hot meteor trails and other distinct characteristics of meteor impacts, and would require optimization in order to detect and track fireball clouds that persist for hours after such explosions. Current data are gathered from weather satellites, analogous to how meteors are detected in weather Doppler data [9].

Long, dedicated observation time will help to quantify the true effect of these meteor impacts on Earth, their frequency of occurrence as a function of size and some basic characterization regarding the meteor trail that is created [8]. A dedicated observation satellite could be used to give some insight into the composition of the meteors and chance of ground impact in addition to providing some predictive capability in regards to meteorite impact locations.

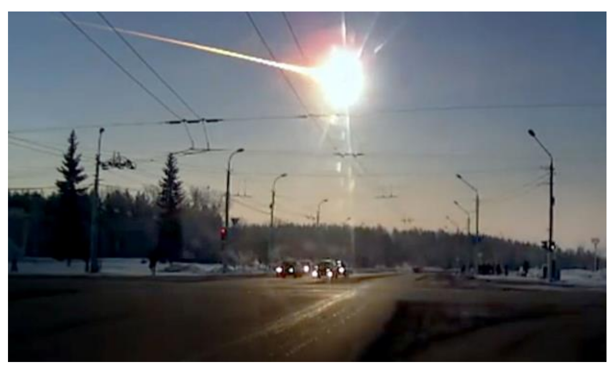

Figure 1: Chelyabinsk Meteor Trail captured from the ground in 2013.

CME monitoring face similar challenges. Detection are currently done by the LASCO instrument on the SOHO spacecraft at the Earth-Sun L1 point, supplemented by SECCHI observations from STEREO, whose heliocentric orbit drifts with respect to the Earth at a rate of approximately 20 degrees per year. Both instruments observe the Sun at low duty cycle, below 5 %, because they need to share time with a suite of other instruments.

We propose to develop a low-cost 6U (36 cm × 24 cm × 12 cm) CubeSat called SWIMSat (Space Weather and Impact Monitoring) Satellite (Figure 2) that will be situated in Geostationary orbit, but Low Earth Orbit and Sun synchronous orbit are credible alternatives as described below. This will require research and development of a robust rad-hardened coronagraph for CubeSats that provides continuous autonomous monitoring and detection of Coronal Mass Ejections. It will also require a visible imager to autonomously track, investigate and characterize meteor impacts into Earth's upper atmosphere.

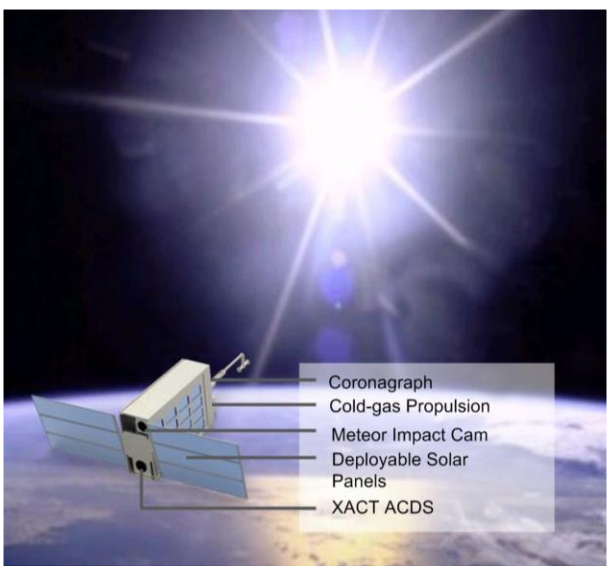

Figure 2: Artist Image of SWIMSat (Space Weather and Impact Monitoring) Satellite.

Meteor observations have been conducted from the ISS (see Figure 5) although not in a systematic manner as considered here. The investigation currently flying on ISS will observe the meteor shower, for example. But those investigations focus on predictable phenomena (meteor showers) with relatively small discrete events, whereas for SWIMSat and MSat the focus is on imaging the few brightest events, not part of any shower, that are impossible to predict -- and to connect those observations to the flux and effect of potentially hazardous bodies tens of meters and larger.

In the following sections we will present a preliminary design of the proposed spacecraft, followed by concept of operations, details on the instruments, autonomous event detection software, discussion of the meteor-monitoring-only MSat spacecraft, and conclusions.

THE SPACECRAFT

The proposed CubeSat is a 6U (36 cm × 24 cm × 12 cm) spacecraft (Figure 2, 3) with a mass of 12 kg (including margin). The spacecraft will be located in Geostationary Orbit (GEO). Placing the spacecraft at GEO simplifies operation, maximizes communication time with ground, while providing a high enough altitude for long duration solar observations. The maximum eclipse time is expected to be within 70 minutes during the equinoxes.

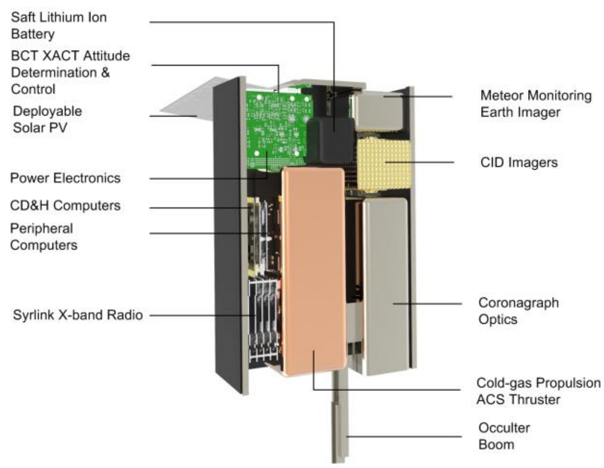

Figure 3: Spacecraft Internal Layout.

Placing the spacecraft at the Earth's bow shock is another possibility, but this requires placing the spacecraft into a desired elliptical trajectory. The spacecraft will be equipped with two science observational instruments, namely a rad-hardened coronagraph and earth observing imager to measure meteor impacts. The coronagraph and earth imager are positioned in opposite directions and in theory, solar observations could be made simultaneously while earth is being monitored for meteor impacts. The selected imager will have high readout speeds and support random-access of pixels. CMEs and meteor impacts events will only cover a small portion of the imager. We will have the ability to monitor and autonomously document critical events. Detailed event reports depending (on the urgency) will be transmitted down to ground.

This unique 6U CubeSat design provides robust margins (see Table 1) with at least one level of redundancy for most subsystem excluding propulsion and payload instruments. The spacecraft uses 2 CD&H computers consisting of 2 Tyvak Intrepids for spacecraft watchdog functions, navigation, communication and control and 2 Space Micro CSPs for interfacing with the coronagraph and earth observing imager and for performing heavy computation onboard the spacecraft. Each Tyvak Intrepid has 6-levels of watchdog that enable robust handling of Single Event Upsets (SEUs). The spacecraft will utilize Syrlink's X-band radio system for communication.

The Tyvak Intrepid while being extremely power efficient, lacks the required computational capability to perform the required data processing from the instruments and other devices. Hence these functions are performed using the Space Micro CSP equipped with two ARM 9 processors and a Xylinx Virtex 5 FPGA.

Transmitting down all of the captured video will be impractical, due to the high power required for data transmission. This also presents challenges to thermal control. In addition, it will require ground operators to be constantly on watch which makes infeasible. Therefore, these challenges require the spacecraft software perform data reduction and enable autonomous detection and reporting of critical events. The spacecraft will use the Syrlink's X-band radio system throttled to 250 Kbps data rate with a margin exceeding 10 dB margin.

Table 1: Preliminary System Budgets

System	Mass (kg)	Volume (cm^3)	Avg. Power (W)
Communications	0.5	500	8
Onboard CPUs	0.2	100	5
Instruments	3.0	2000	15
Power Conv.	1.5	700	2
Propulsion	1.8	2100	0.5
Navigation	0.9	500	2
Structure	1.1	1500	-
Thermal	0.1	100	3
Total	8.9	7500	36
Margin	24 %	26 %	41 %

The on board Attitude Determination Control System (ADCS) consists of the Blue Canyon Technologies XACT that combines a suite of sensors such as a star tracker and sun sensor to perform inertial measurements. For attitude control the system contains 3-axis micro reaction wheels. As a backup, 8 mini attitude control thrusters can also be used to periodically desaturate the reaction wheels. This provides a total attitude determination and control system. The on board attitude control solution will provides very accurate pointing capability of 20-30 arc seconds.

CONCEPT OF OPERATIONS

A concept of operations for the proposed spacecraft is shown in Figure 4. The spacecraft needs to be launched into a Geostationary Orbit. The first month will be spent calibrating the instruments and testing all subsystems to ensure the system is fully operational. This will be followed by a 6-month primary mission, followed by a 1 year secondary and 6 month tertiary mission, wherein CME and meteor impacts events will be observed. During the primary mission, recorded video data will be transmitted to ground, in addition to operation and results from the autonomous CME detecting flight software.

The results from these experiments will be used to verify/validate the CME detection software and look for miscategorization. Based on these early results, further analysis will be performed to improve the detection rate of the software. A parallel strategy will be used to validate the meteor impact detection software. Improvements will be made to reduce false positives. The collected data will be compiled into datasets available to the public for evaluation with other software.

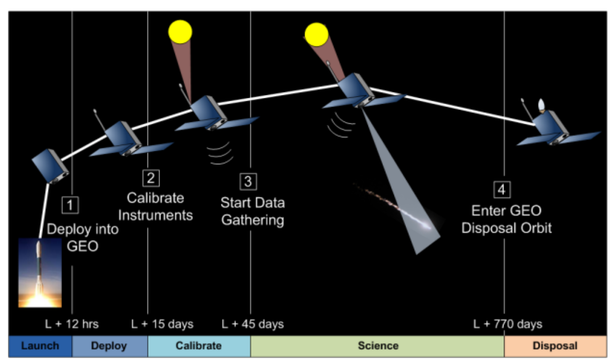

Figure 4: Concept of Operations.

A 1 year secondary mission will utilize improvements to the detection algorithm and other spacecraft operating strategies to minimize detection error of CMEs and meteor impacts. The results from these algorithm improvements will be compared with earlier obtained results and further changes implemented for the tertiary mission. After 2 years, the spacecraft will be put into a GEO disposal orbit.

INSTRUMENTS

SWIMSat will be equipped with two onboard instruments, namely a coronagraph and a meteor imaging camera designed for observations from ~34000 km altitude. MSat is designed around a single instrument, a meteor imaging camera designed for observations from ~800 km altitude.

Coronagraph

The proposed coronagraph is derived from the LASCO C3 designed and built by NRL [10]. One of the major challenges with miniaturizing a coronagraph for space applications is to minimize Fresnel diffraction. Fresnel diffraction occurs due light leaking around an external occulter which serves to block the intense photospheric emissions and allow for the relatively weak emission from coronal sources to be observed. LASCO uses an external occulter coupled with an internal occulter that blocks out stray light diffractions from the external occulter.

Meteor Imaging Camera

The Meteor Imaging Camera (MIC) shall be able to detect 1m (~0.1kT equivalent yield) and larger meteors from the spacecraft orbit, that impact the Earth several times per month (Brown et al. 2002). The instrument shall also be able to resolve cigar-shaped fireball clouds, 30 km or longer, above a sunlit surface with a 20% albedo.

For operating from GEO (~34,000 km above the surface of the Earth), the meteor imager will have a relatively narrow angle (~10°) FOV to place a footprint on the Earth. With a frame size 1024 × 1024, each target pixel will have a scale of ~6 km. For operating from high altitude LEO (~800 km above the Earth surface) discussed below for MSat, the situation is much different. The camera must be wide angle (~120°) to place a large footprint on the Earth, but the pixel scale will vary from ~1 km at nadir to ~5 km at the edge of the image.

As part of an ongoing trade-study, we will be evaluating, CCDs, CID (Charge Injection Devices) and CMOS cameras.

AUTONOMOUS EVENT DETECTION

Events of interest such as meteor streaks and impacts greater than or equal to 0.1 kT will be rare and occur only a few times a month. Such rare occurrences are suited for autonomous event detection, where the camera monitors continuously and smart imaging processing onboard the spacecraft. Smart image processing techniques include the ability to detect bright spots, flashes and streaks. Detection is possible using basic vision algorithms such as the Canny edge detector, in addition to detection of lines, points and corners. Figure 5 shows a meteor streak imaged from a visible camera onboard the International Space Station. The image on the right identifies all the bright spots. We are exploring the efficiency of these and other processes in reducing and tagging events data prior to transmission to the ground station.

Figure 5: Image detection of meteor streaks and events of interest from the ISS.

The challenge remains in misdetection of other high-intensity (bright) phenomena in space including lightning flashes and moving orbital debris. However considering all of these events are rare, there will nevertheless be a significant reduction in this data of interest. Figure 6 shows an artificially generated meteor streak video. On the right is our vision algorithm able to detect and track the event.

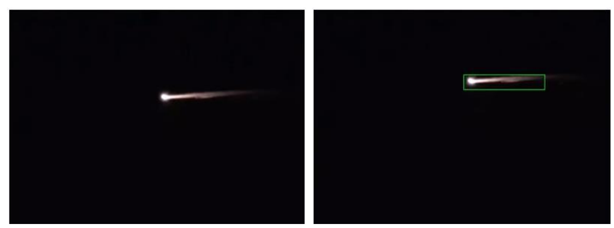

Figure 6: Autonomous tracking of a artificial meteor trail.

MSAT

SWIMSat is based on the concept of launch to a geostationary-like orbit for long duration monitoring and continuous communications. However, no CubeSat has yet been placed into GEO, and the propulsion requirements to attain GEO from a more common launch availability might be prohibitive. We are therefore also considering a more limited version of SWIMSat, called MSat, that focuses only on meteor monitoring, and is based on a relatively high altitude low-Earth orbit and no onboard propulsion. With these descopes, MSat should fit inside a 3U configuration so the baseline is to fly two identical spacecraft as a single coordinated mission. See Table 2 for comparison.

A mission operating in LEO has launch advantages, of course, but some operational disadvantages. Primarily the field of view of Earth is so wide that to achieve the monitoring capability of looking at an appreciable fraction of Earth, a very wide angle camera is required.

The good news is that such cameras can be inexpensive and compact. The bad news is that the distortion must be accounted for in data analysis. In particular, a single image will include nadir-looking observations and limb observations, so that some meteors will be seen from above, and others will be seen from the side, producing a different sort of data set.

Table 2. SWIMSat compared with MSat.

Mission	SWIMSat	MSat
Size	6U	3U
Number of Sats	1	1-2
Orbit	GEO	LEO
Science	CMEs, Meteors	Meteors
Earth FOV	Disk (5000 km)	Swath (1000 km)
Instruments	2	1
Propulsion	Yes	No

The sweet spot for observing fireballs is in the pre-dawn quadrant of Earth, where the planet is dark yet the orbital velocity around the Sun (30 km/s) is prograde. The sweet spot for observing meteor-derived dust clouds will vary; bright daytime against a cloudless ocean, or just pre-dawn where the background Earth is not lit but the high stratosphere is lit. During the operations we intend to lean exactly which observing modes are the most efficient at producing reliable data.

Utilizing a more compact camera and without requiring propulsion, MSat can probably be made to fit into a 3U configuration; this study is underway. If that is the case, then twin 3U satellites will be developed for launch from the same deployer, that will double the coverage, to make up for the fact that observing from LEO leaves a large fraction of the Earth unobserved at any one time. It will also train us in the operation of multiple spacecraft and their coordination, for example, MSat-B can conduct follow-up observations targeting a meteor flash detected by MSat-A.

STUDENT INVOLVEMENT

This project will increase interest, participation and innovation in space weather and meteor impact monitoring, detection and instrumentation development at Arizona State University. Graduate students working on this project will have a strong appreciation for the open research questions and challenges particularly in space weather and meteor impact monitoring. These students will bring a new infusion of ideas and solutions to the many open challenges in the field. The project will further develop graduate student expertise in the rapid development and testing of CubeSats and the required subsystems for operation beyond Low Earth Orbit.

This project is funded for a 24-month Phase A through the AFRL University NanoSat Program (UNP). It will train graduate engineering and space science students in the design and development of space hazard monitoring spacecraft technologies using commercial grade hardware. Funding for student effort began in June 2016 so this paper reports on efforts made possible thus far. The launch and operation of the spacecraft will enable investigation of the feasibility of using CubeSats to monitor CMEs and meteor impact explosions using low-cost CubeSat hardware.

DISCUSSION

Development of this 6U CubeSat will be a pathfinder for construction of a network of strategically placed low-cost small satellites that would enable constant monitoring for space threats. Significant advancements have been made in CubeSat computers, electronics, Attitude Determination and Control System (ADCS) and power supplies. However, optical systems, particularly ones that require a deployable such as a coronagraph are severely limited in the CubeSat form factor. Furthermore, significant limitations exist in terms of allocatable volume for propulsion. These factors leave open the possibility of using a 12U or ESPA-class bus for the envisioned network of satellites.

These factors leave open the possibility of using a 12U or ESPA-class bus for the envisioned network of satellites, so our present effort includes a trade study of an LEO meteor monitor MSat, versus SWIMSat including CME detectoion, versus a larger system of small coordinated spacecraft to montor both categories of threats.

The CubeSat platform will provide invaluable flight experience and experience required to scale up to a space threat monitoring network. Our proposed demonstration mission would enable development and testing of CubeSat hardware for high-radiation environment within the Van Allen belt and beyond. Furthermore the results from this development path will have direct applications on more capable small-satellites.

This mission will also require the development of autonomous spacecraft software. A critical component is the agile science software that will be used to identify the rare meteor streaking through the atmosphere or stealth CMEs which remain quite challenging to identify and be able to concisely relay threats down to ground. These message will consist not only of a detection signal but where possible a dossier/report of the event, tracking information and video. The additional information will be critical for ground operators to validate the autonomous software and determine next steps, including relaying information to the Joint Space Operations Center (JSPOC), and providing close to real time data for use in directing meteorite searches. Finding a fresh fallen meteorite is always a scientific coup, because the most rare and scientifically valuable meteorites are porous, fragile, and volatile-rich, and become highly degraded in time.

The ability to host many cameras from many viewpoints in space needs to be coupled with the networking software that can correlate this data to provide new insight. This new insight can provide clues to the composition of the incoming meteor and increase detection success rates, and vastly increase the number of successfully located meteorite falls. The ability to stitch or even correlate image data from multiple-viewpoints from multiple satellites will offer unprecedented detection capability. Such an approach will help to simplify the detection problem and at times provide redundant data streams. This is where a network of satellites holds great potential. Ideally if these satellites are operated in decentralized control architectures, damage to one or more satellites will only result in graduated degradation to the network as opposed to a catastrophic loss to a single large spacecraft.

CONCLUSION

Network of spacecraft are crucial for characterizing and constantly monitoring the impact from CMEs. Similarly, network of satellites can be used to track, monitor and alert of incoming meteors exploding in the atmosphere. Both classes of events are rare but the potential damage caused from these events can be catastrophic. A network of satellites that provide alerts minutes ahead can provide just enough time to take precautions. In this paper, we propose development of a 6U pathfinder CubeSat to demonstrate the critical technologies required to develop a network of threat monitoring spacecraft. We also consider the development of two 3U ‘meteor monitor’ spacecraft with limited goals, looking down for meteors only, but operating two spacecraft in coordination.

Critical technologies include instruments and accompanying smart image detection software to detect and track these events. Advancement in CubeSat hardware enables testing of mission critical and relevant hardware at low-cost, through accelerated development timelines. This provides invaluable experience for students in the design and development of the spacecraft hardware and software for low-cost. The lessons learned from this mission will be applied to our goal of developing a real-time network of satellites to monitor space threats.

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References

1. P. Brekke et al., Space Weather effects on SOHO and its space weather warning capabilities, Vol 176, pp 109–122. Springer, 2005.
2. National Research Council. Severe Space Weather Events–Understanding Societal and Economic Impacts. The National Academies Press, Washington, 2008.
3. National Space Weather Program Council. Report on space weather observing systems:. Office of Technology Policy, 2013.
4. WMO Congress & WMO Executive Council. Four-year plan for WMO coordination of space weather activities: Towards a space weather watch. WMO, 2015.
5. M. Hapgood and A. Thomson. Space weather: its impact on Earth and implications for business. Lloyds 360 Risk Insight, 2010.
6. C. J. Schrijver. Socio-economic hazards and impacts of space weather: The important range between mild and extreme. Space Weather, 13(9):524–528, 2015. 2015SW001252.
7. C. J. Schrijver, et al., Understanding space weather to shield society. Advances in Space Research, 55(12):2745 – 2807, 2015.
8. S. Proud, Reconstructing the orbit of the Chelyabinsk meteor using satellite observations Geophys Res Lett: 2013.
9. M. Fries, J. Fries. Doppler Weather Radar as Meteorite Recovery Tool, Meteoritics and Planetary Science, Vol. 45, 1476-1487.
10. NRL, LAS, Max Planck Inst., Univ. of Birmingham, LASCO Handbook for Scientific Investigators, 1994.
11. T. A. Howard and R. A. Harrison, Stealth Coronal Mass Ejections: A Perspective. Solar Physics, Vol 285, Number 1, 269-280, 2013.