

Violet: A High-Agility Nanosatellite for Demonstrating Small Control-Moment Gyroscope Prototypes and Steering Laws

Jessica Gersh¹ and Mason Peck²
Cornell University, Ithaca, NY, 14850

Violet is a highly agile nanosatellite whose primary mission is to experimentally validate novel control-moment gyroscope (CMG) steering laws. It is Cornell University's entry in the University Nanosat-6 Competition, following on to Cornell's successful CUSat program. With an array of eight CMGs, Violet is capable of hosting guest investigators' steering algorithms for a variety of CMG configurations, including a 4 pyramid and 4-6 CMG "roof" arrays. The attitude-control design combines high-precision sensors, such as a star tracker and a fiber-optic rate gyroscope, with high-agility kinematics: 10 °/sec and 10 °/sec², with the possibility of four times that agility. The spacecraft's name derives from its ultraviolet telescope, which includes flight-spare Deep Impact CCDs and serves as a representative payload for purposes of the CMG experiments as well as optional science investigations.

I. Introduction

Single-gimbal control-moment gyroscopes (CMGs) are attitude-control actuators used on spacecraft that require far more torque than reaction wheels can provide for an achievable amount of power¹. The resulting agility enables a satellite to slew its payload quickly through large angles, which helps maximize the time during which the payload can perform its intended function. The gyroscopic constraint torque that results from gimbaling a CMG's spinning rotor enables a spacecraft to accelerate to a velocity of several degrees per second, coast at a maximum velocity, and then decelerate, all for orders of magnitude lower power than a typical reaction wheel would require for such a maneuver^{2,3}. The CMGs operate as a so-called array, which is characterized by both the number of the CMGs and the (fixed) orientations of the CMGs' gimbal axes with respect to the spacecraft bus structure⁴.

Although an array consisting of three CMGs can be sufficient to regulate spacecraft attitude, using more than three offers the prospect of optimally distributing the torque among these actuators⁴. The performance parameter to be optimized is the envelope of the momentum and torque that the array of CMGs can provide. However, it is not a simple matter to steer the CMG array such that at every instant the combination of gimbal angles is free of kinematic singularities throughout this envelope. Decades of research in both academia and industry have provided a range of solutions to this problem, some more promising than others⁵. The details of implementations in current spacecraft are not publicly available, but several new patents point to the fact that questions remain about the best way to steer CMGs^{6,7,11}. By providing an in-orbit testbed for steering algorithms, the Violet project is designed to uncover some of the answers.

In this respect, Violet's mission complements that of AFRL's Advanced PnP Technologies (APT) satellite, the spacecraft that until recently was known as TACSAT-5. Among other objectives, APT is meant as an experimental platform for Honeywell's plug-and-play momentum-control system, their Mini-MCS⁸. Through collaboration the two programs ought to constitute a more complete suite of experiments than either spacecraft on its own. The following list summarizes of how APT's and Violet's CMG experiments are distinct but complementary, to the extent that the author has correctly interpreted information in the 2009 TACSAT-5 Broad Agency Announcement:

- APT's objective in this area is to experimentally validate the MMCS, focusing on its suitability for plug-and-play integration in a responsive, agile spacecraft bus. In doing so it will evaluate a specific

¹ Graduate Research Assistant, Department of Mechanical and Aerospace Engineering, 127 Upson Hall, Student Member AIAA.

² Assistant Professor, Department of Mechanical and Aerospace Engineering, 212 Upson Hall, Member AIAA.

CMG array architecture appropriate for responsive space. In contrast, Violet will investigate the general problem of high-performance CMG steering, without explicit relevance to responsiveness.

- Violet's experimental objectives include studying CMG array architectures of four, five, and six CMGs that are different from the APT array. The result is that the two spacecraft together represent a broad range of array architectures.
- APT's CMGs and its bus are more than an order of magnitude larger than Violet's. They occupy different operational spaces for tactical spacecraft. So, taken together, the two spacecrafts' CMG experiments represent an assessment of CMG steering performance across a broad range of spacecraft scale.
- Violet will experiment with very high agility (10-40 °/sec), while APT will evaluate its CMG performance for a maximum base rate of 3 °/sec. These kinematics may be relevant for different missions, but the larger dynamic range of the two spacecraft taken together will make the CMG experiments relevant for a wider range of applications than would either spacecraft on its own.
- APT's MMCS is designed so that the CMGs are mechanically aligned relative to each other with high precision, and this alignment is unaffected by its soft isolation mount. In contrast, Violet's CMGs are individually isolated and mounted. The two spacecraft will therefore be able to evaluate CMG steering in the presence of these two architectures to determine experimentally the relative benefits.
- APT and Violet can run some of the same experiments on a four-CMG box-90 array, which offers several benefits:
 - (a) The distinctions listed above (different scale, different agility, and different vibration-isolation schemes) can be evaluated for an identical steering law
 - (b) Two different CMG designs can be compared
 - (c) Two data points can be collected to validate the steering law with greater confidence
 - (d) The earlier spacecraft can represent risk mitigation for the later one
- Both Violet and APT offer a means for guest investigators to provide steering-law experiments. APT's access is governed by restrictions related to proprietary data agreements and security classification. Violet's content cannot be classified because it is an academic project, and its experimental platform is open to representatives from many different US companies. Therefore, the two spacecraft represent experimental opportunities for complementary groups of researchers, although both can run experiments associated with academic research.

Figure 1 shows the exterior of the spacecraft. Violet's name derives from its planned ultraviolet telescope, which includes flight-spare Deep Impact CCDs and serves as a representative payload for purposes of the CMG experiments as well as optional science investigations. Candidate uses for the telescope include calculating the spin period of Vega; surveying the lunar surface; observing upper-atmosphere electrical discharges or near-Earth objects like meteors; surveying globular star clusters; and observing seasonal variations in methane production on Mars.

As Cornell's entry in the University Nanosat-6 Competition, Violet follows on to Cornell's successful CUSat program, which won a launch through the University Nanosat-4 Competition. Technical lessons learned from CUSat are incorporated into the Violet program, and Cornell's programmatic approach to Violet is similar to its approach to CUSat, blending self-directed student participation with hands-on faculty involvement in the research. Students are involved at all levels, with lead faculty advisors providing technical expertise and organizational support for this primarily student-run team. Undergraduates, Master of Engineering (M. Eng.) students, and Ph.D. students all contribute to Violet, with the undergraduates and M. Eng. Students focusing on the satellite construction and the Ph.D. students working on the advanced dynamics and controls design and analysis. The intent of this approach is to provide an experience that is both educational and conducive to meaningful research. The prospect of new space science from Violet's payload has led to the creation of the Violet Science Working Group, which brings together a number of faculty and students from Cornell, MIT, and elsewhere.

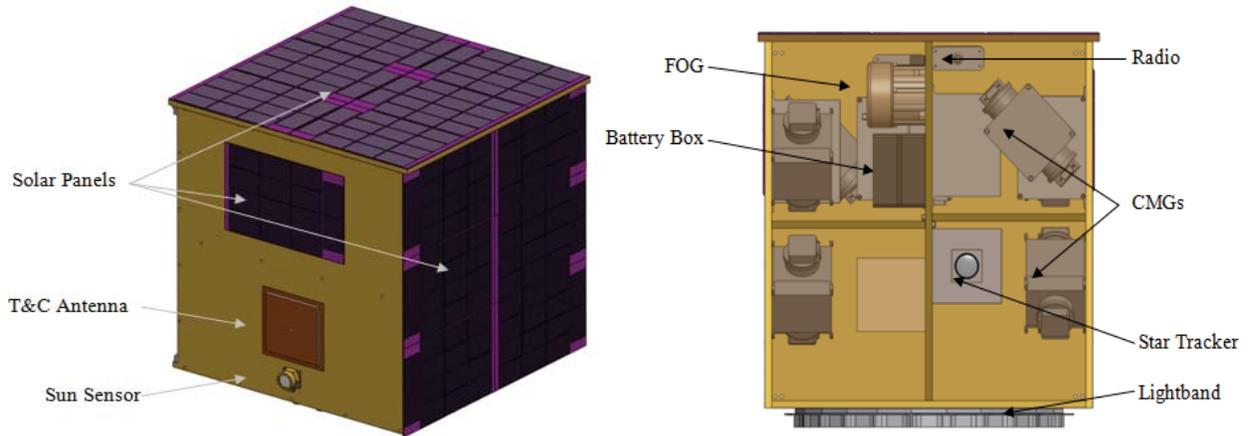


Figure 1. External View of the Violet Spacecraft (Left) and Selected Internal Components (Right)

Violet is the first agile nanosatellite. In fact, small scale enables agility, a principle that has just now begun to be exploited in the creation of new spacecraft architectures^{9,10}. As of this writing, Violet’s design is at the Preliminary Design Review (PDR) level. This paper provides an overview of the Violet project as it currently stands. It focuses on the CMG-steering experiments and describes the planned guest-investigator program. Also offered is a current summary of Violet’s key subsystems that relate to the CMG steering experiments.

II. CMG Steering

Figure 2 is a control block diagram that shows the relationship among Violet’s dynamics, compensation, sensors, and steering law. The steering law, highlighted in yellow in the figure, is not meant to alter the gain of the compensation. In its simplest form, it merely maps the three-dimensional torque computed by the compensator into the multidimensional space of individual CMG kinematics (typically only CMG gimbal rates). In the case of an array of three CMGs, there is only one choice, only one set of gimbal-rate commands that produce the required torque for a specific set of gimbal angles. Figure 3 shows a more precise view of the steering-law block, one that suggests likely data I/O. Table 1 describes the data.

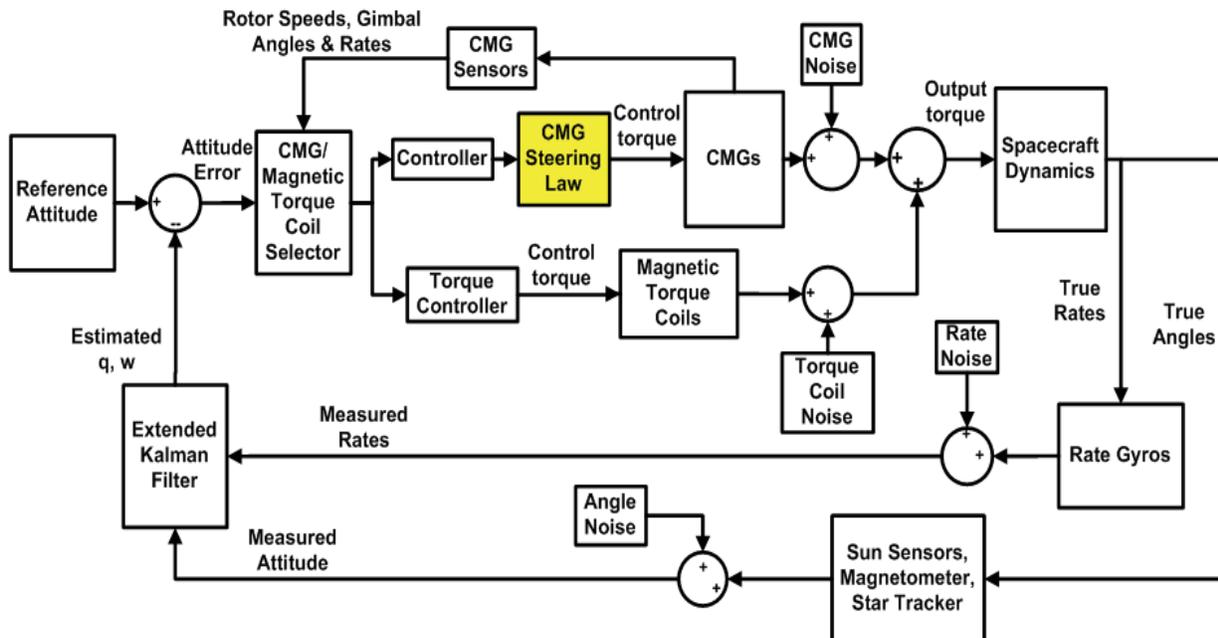


Figure 2. Control Block Diagram for Violet’s Attitude Control System with Steering Law Highlighted

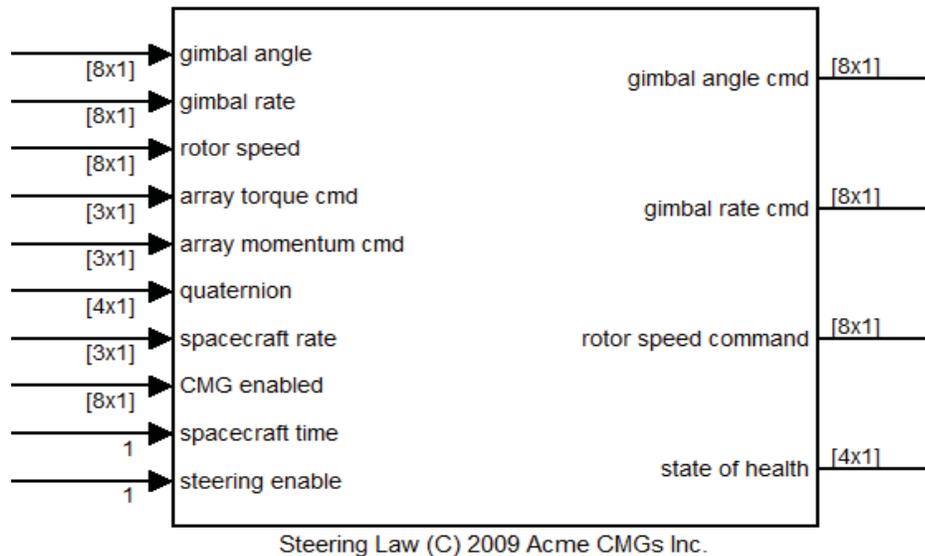


Figure 3. A Guest-Investigators’s Steering-Law Block As It Might Be Implemented in MATLAB/Simulink.

Violet’s flight code is being developed via MATLAB through MATLAB/Simulink autocode. Therefore, the format for the steering will likely be a single, discrete-time Simulink subsystem. It is likely that the subsystem can contain pre-compiled code in a way that further protects proprietary information. The MATLAB version to be used, data types, and other details will be specified in the Guest Investigator ICD to be released in September 2009. The ICD will also specify data rates, coordinate systems, CMG gimbal axis orientations and reference gimbal angles, base-rate limits, and kinematic limits. These parameters will be accessible to the steering-law block through the inputs shown in Figure 3 and may be adjusted via upload after launch.

Table 1. Simulink Interface for the CMG Steering Law

Inputs (to the Steering Law Block)		Outputs (from the Steering Law Block)	
<i>Parameter (units)</i>	<i>Dimensions</i>	<i>Parameter</i>	<i>Dimensions</i>
Current gimbal angles (rad)	8x1	Gimbal angle commands (rad)	8x1
Current gimbal rates (rad)	8x1	Gimbal rate commands (rad/sec)	8x1
Rotor Speeds (rad/sec)	8x1	Rotor speed command (rad/sec)	8x1
Array torque command (Nm)	3x1	State of health (boolean)	4x1
Array momentum command (Nms)	3x1		
Spacecraft attitude (quaternion)	4x1		
Spacecraft angular rate (rad/sec)	3x1		
CMG enabled status (8 bits)	8x1		
Spacecraft clock time (sec)	1		
Steering enable/disable bit (boolean)	1		

Although an array of three CMGs is sufficient to control spacecraft attitude, a steering law may be able to distribute the required attitude-control torque optimally among CMGs if the spacecraft uses an array consisting of four or more. Honeywell, for example, has recently applied for a patent on a steering law that does so for an array of four or six CMGs with pairs of parallel gimbal axes¹¹, and Cornick describes the use of a six-CMG pyramid¹² with similar objectives. Optimality may involve minimizing power, but in any case it certainly involves steering the CMGs to prevent kinematic singularities. These singularities arise when no combination of gimbal motions can produce torque in a certain direction. Singularity-free steering laws are those that simultaneously command gimbal rates to produce the desired torque vector and distribute those motions so that the array never encounters singularities. Near a singularity, CMGs typically experience high gimbal rates that stress the electromechanical design. Theoretical studies of steering generally do not account for such subtleties of the actuators themselves, focusing only on the mathematics of idealized CMGs. Violet offers an opportunity for a more realistic assessment

of steering laws in the space environment. For these reasons, Violet will likely advance the technology readiness level (TRL) of successful steering laws.

The design of array and its steering law go hand-in-hand. So, any meaningful steering-law experiment presupposes a specific array. Violet is meant to serve as a general-purpose testbed. That objective necessitates an array that can be adapted to different architectures. While mechanically reconfigurable arrays have been proposed¹³, Violet has opted for a simpler implementation that includes an array of eight CMGs, any subset of which can serve as an array of possible interest. We refer to this design as the “Roof + 2” array, which is shown in Figure 4. It consists of two three-CMG sets and a two singleton CMGs. All CMGs in each set of three have a common gimbal-axis direction. The common gimbal-axis direction of one set of three is 90° from that of the other set of three. These six constitute a six-CMG roof⁴. The other two CMGs’ gimbal axes are also mutually orthogonal. All eight CMGs’ gimbal axes are oriented 45° from a single reference, here the spacecraft Z axis. Using only three of its eight CMGs at full rotor speed provides agility of about 10 °/sec, 10 °/sec², and 50 °/sec³. The best use of six CMGs may quadruple that agility, provided that Violet’s power subsystem can maintain the required gimbal-motor torque. The CMGs can be operated at lower rotor speeds to establish a desired relationship between CMG kinematics and spacecraft agility.

Figure 4 is a sketch of the orientations of all eight CMGs. In this figure, the cylinders represent the gimbal torque motors, and the arrows extending from them indicate the direction of positive gimbal rotation. The spheres indicate the volume swept out by the gimbaling inner-gimbal assemblies. Their locations in the bus are irrelevant for steering-law implementation, but are shown in Figure 5.

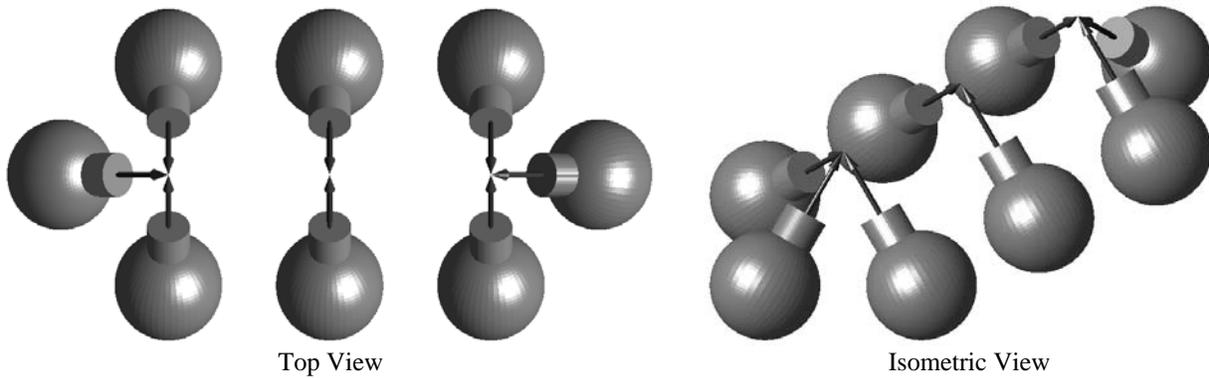


Figure 4. Eight-CMG Architecture: the “Roof + 2”

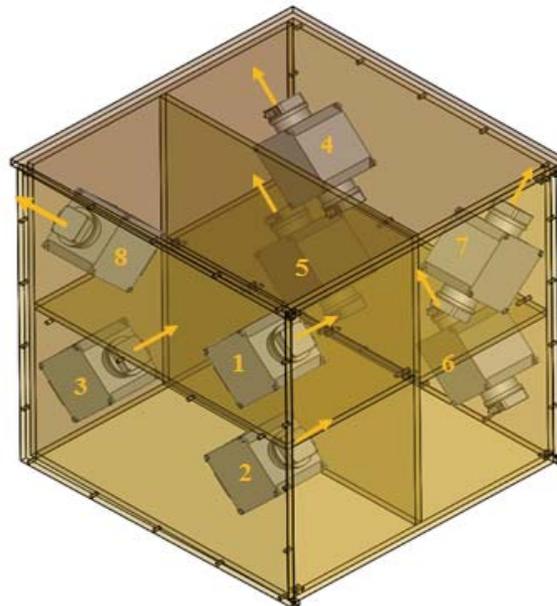


Figure 5. CMG Numbering Convention and Locations within Bus Structure

It is expected that Violet will not operate more than six CMGs simultaneously. The eight CMGs offer subsets of fewer CMGs that represent arrays of possible research interest, often with fault tolerance. They are summarized in Table 2. As an example, Figure 6 highlights those CMGs that would constitute the four-pyramid and the six-roof as sub-arrays of the eight in Violet's array.

Table 2. Arrays Available for CMG Steering-Law Experiments within the Roof+2

Type of Array	# of CMGs	Tolerates n-m individual CMG failures	Notes
Box - 90	4	1 - 4	Already included in APT
3 CMG subset of a Box - 90	3	3 - 5	Violet's ACS baseline
$\beta=45^\circ$ four-pyramid	4	0 - 4	
Roof	6	0 - 2	
Six-Roof with 1 failure	5	1 - 3	For validating failure-case laws
3 near-orthogonal scissored pairs with 1 failure	5	1 - 3	For validating failure-case laws
3 nearly orthogonal CMGs	3	1 - 5	Likely unpopular

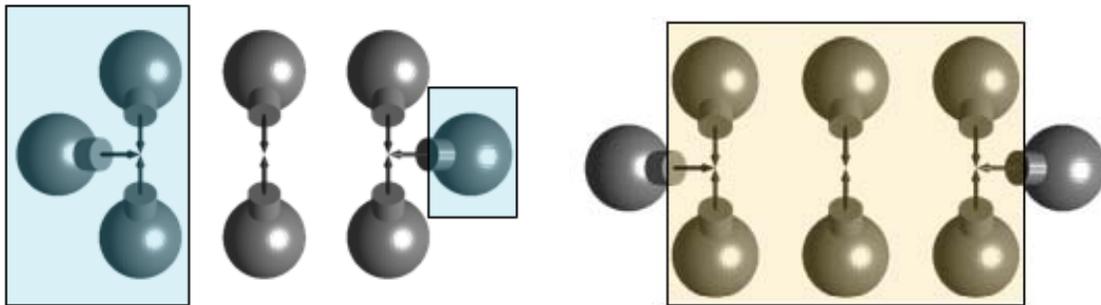


Figure 6. Violet CMG Sub-Arrays: Four-Pyramid (Left) and Six-Roof (Right)

III. Subsystems

This section describes the key technologies that enable Violet's mission and the overall design and enabling subsystems of the nanosatellite. To meet the requirements of the University Nanosat-6 Program, Violet will have a mass no greater than 50 kg and linear dimensions of 50 cm or less. There are other requirements associated with compatibility with the ESPA¹⁴ interface and Violet's prospective role as a secondary payload¹⁵.

Figure 7 outlines the operations concept (CONOPS) for Violet in terms of a sequence of mission phases. Violet is expected to separate from the launch vehicle spinning about its maximum axis of inertia at 3 °/sec. After this launch phase, in which Violet is completely unpowered and has no energy stored in its batteries, the system is initialized in a safe sequence that includes CUSat-heritage operations practices¹⁶. All subsequent mode changes are initiated by the ground, beginning with an initial health-check. Violet spins up three CMG rotors to a fraction of their full rotor-speed and uses them to achieve three-axis control. It then performs a sun-acquisition maneuver. In this zero-momentum state, it is prepared to perform large-angle slews to demonstrate CMG steering. When a steering-law experiment is not underway, high-precision sensors are disabled, and the spacecraft relies only on coarse attitude determination and low-speed CMGs. However, when a steering-law experiment is about to begin, the spacecraft performs a fine attitude-determination maneuver using a star tracker and a fiber-optic gyro, which remain in use until the slew(s) are complete. Before the slew experiment, a magnetic momentum dump either zeroes the momentum or establishes whatever momentum bias the experiment requires. Then, the requisite CMGs are enabled, and their rotors are spun up to the desired speed in a null-momentum gimbal-angle configuration. Steering authority passes from the default steering law (a three-of-four box-90) to the guest investigator's steering law.

The slew consists of following a prescribed attitude trajectory determined as a collaboration of the guest investigator and the Violet operations team. It is expected that the steering-law experiments will comprise four categories of slew, with possibly only one slew per category:

- Slew that encounters the maximum array torque

- Slew that encounters the maximum array momentum
- Slew whose array momentum passes a hyperbolic singularity
- Slew whose array momentum passes an elliptical singularity

Ideally these slews would be identical for all steering laws that use a certain array type, but guest investigators will likely be given flexibility to define what they take to be suitable slews consistent with the steering law. Subject to meeting these requirements, the inertial path of each slew will be chosen to maximize attitude-determination measurements (i.e. availability of stars) during the maneuver while also meeting sun-relative attitude requirements associated with power, thermal, and payload subsystems. A time history of the attitude kinematics and CMG-related variables is stored on board and is telemetered to the ground on the next available pass.

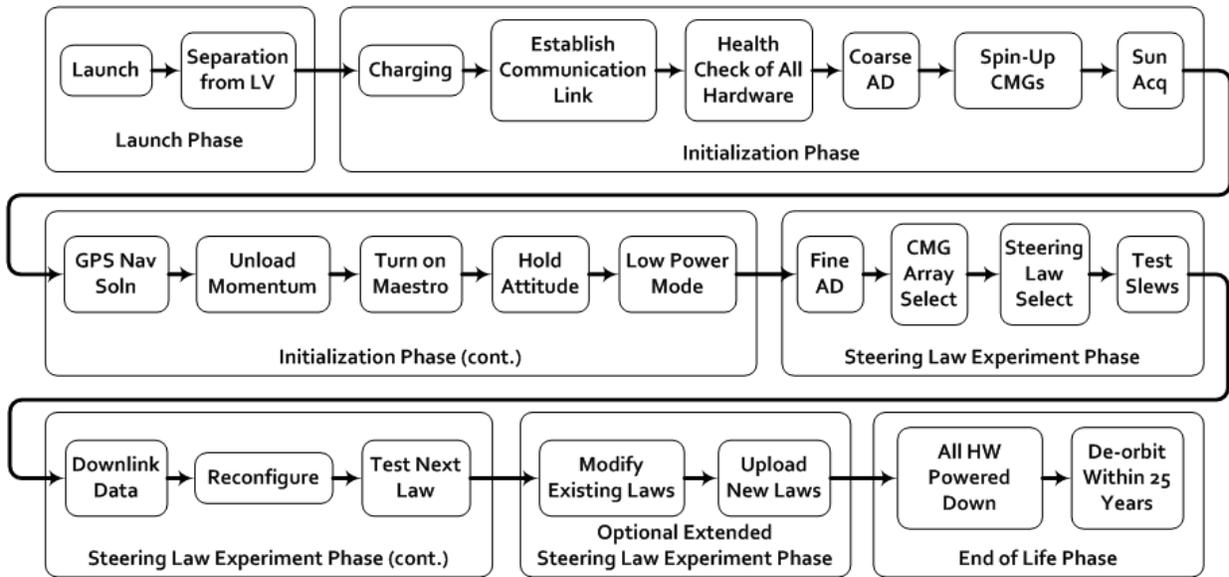


Figure 7. Mission Phases

Figure 8 shows the six subsystems that comprise the Violet spacecraft and indicates that the ground segment of the project uses two ground stations. Key subsystems are described in subsequent sections.

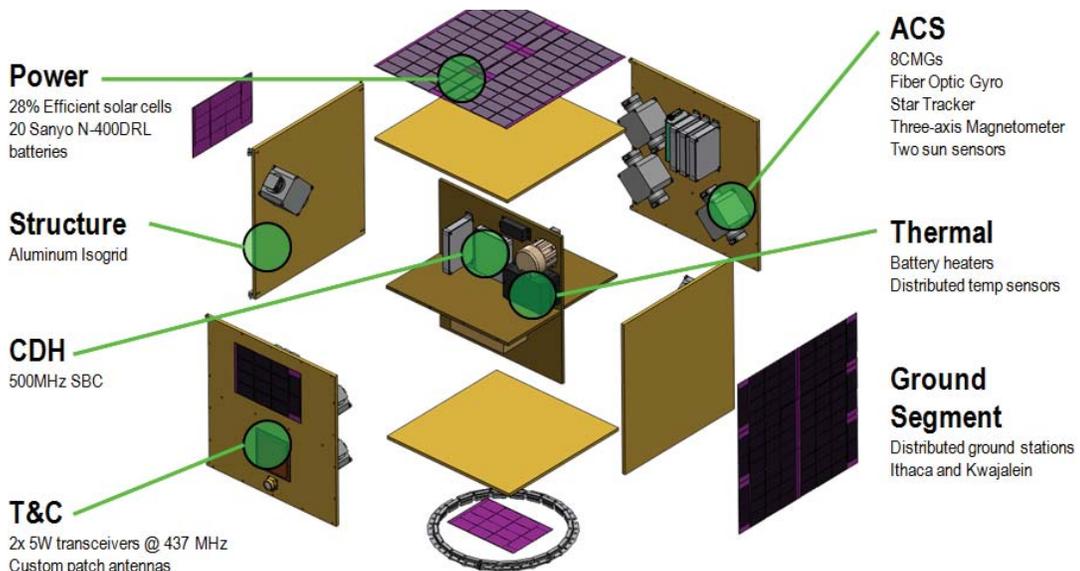


Figure 8. Exploded View of the Violet Spacecraft

Attitude Control Subsystem

Violet uses coarse attitude sensors to initialize attitude determination and an Aero Astro star tracker for fine pointing relative to that reference attitude. The design includes two Sinclair SS-41 sun sensors (0.1 deg. sun-vector knowledge) and a Honeywell HMR2300R magnetometer. An LN-200 fiber-optic gyro (FOG) provides high-precision angular-velocity measurement. FOGs offer low angle-random walk, a feature that ensures highly accurate propagation of attitude from an initial fine estimate to the end of the slew. The LN200 has space heritage (e.g. on the Spirit and Opportunity rovers). It provides three-axis angular-rate measurement and three-axis translational acceleration. The latter may be used to assess jitter in orbit. The flight hardware will consist of either an engineering-development unit or a production unit. The combination of these sensors is expected to yield better than 10 arcseconds pointing stability.

Figure 9 is a diagram of the connectivity and data rate associated with the sensors and actuators. Comprised largely of commercial, off-the-shelf components, Violet's imaging payload consists of a 23.5-cm Schmidt-Cassegrain telescope, a Deep-Impact heritage CCD, a beamsplitter, and a second detector for attitude control.

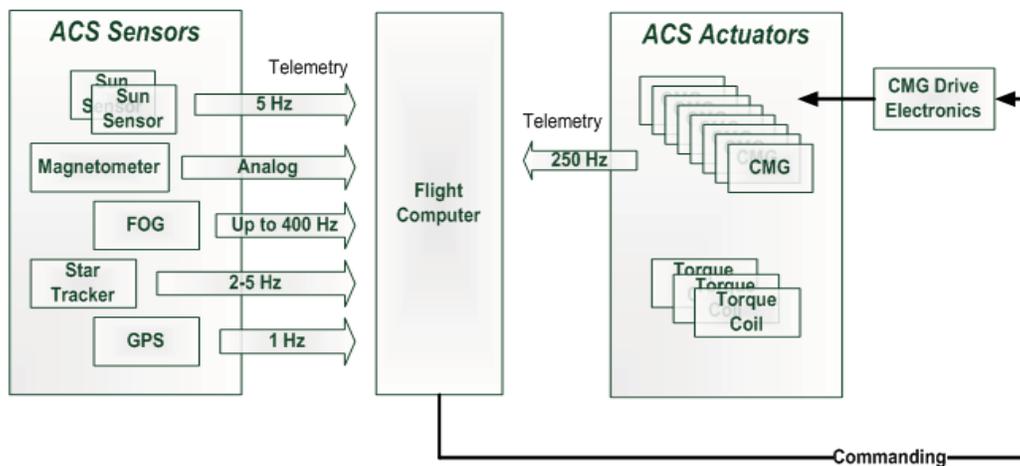


Figure 9. Connectivity of ACS Components

Violet's small control-moment gyroscopes (CMGs) are central to its mission objectives. Provided by Goodrich/Ithaco, these small-scale, high-speed CMGs are compact and conveniently modular while still providing Violet with unprecedented agility for a nanosatellite. Figure 10 shows the exterior view of a single CMG, and Table 1 summarizes its performance details. Each CMG is mounted to the bus structure via Lord BTR series elastomeric mounts. Each CMG, with its mounts, has a first mode at roughly 35 Hz. The six significant modes are close to each other in frequency, and the transmissibility is such that the disturbance rolls off at roughly -40 dB/decade after this 35Hz break frequency.

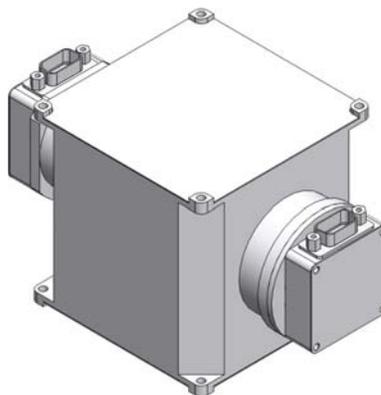


Figure 10. Exterior of One of Violet's 0.3 Nms CMG (Goodrich/Ithaco)

Table 3. CMG Performance Parameters

Property	Value	Notes
Rotor Speed	9250 rpm	(adjustable 0 – 20,000)
CMG Torque	0.31 Nm	At 1 rad/sec gimbal rate
Total Mass	1.28 kg	
Width	0.094 m	
Height	0.092 m	
Length	0.17 m	

Violet has baselined Cornell’s Cougar GPS receiver, which has recent heritage in the CUSat program. This receiver, shown in Figure 11, is designed and built by Dr. Paul Kintner’s Space Plasma group, and it is based on the Plessey chipset. It has been specifically ruggedized for space applications, and the firmware has already been developed for the CUSat mission. The receiver has been demonstrated in several sounding rocket experiments funded by NASA, and it is robust both in terms of its ability to withstand environment effects such as vibrations and in terms of software issues associated with the very fast Doppler shift of receivers in satellite missions.



Figure 11. Cornell’s Cougar GPS Receiver

Command and Data Handling Subsystem

Violet will use a shielded, conformally coated, and staked COTS flight computer: the Technologic Systems TS-7800. One is shown in Figure 12. Its physical characteristics and performance features are summarized in Table 4. The high-speed computations are required for Violet’s Extended Kalman Filter, which incorporates high-bandwidth measurements from the LN-200 and estimates attitude, rate, gyro bias, and gyro scale-factor error.

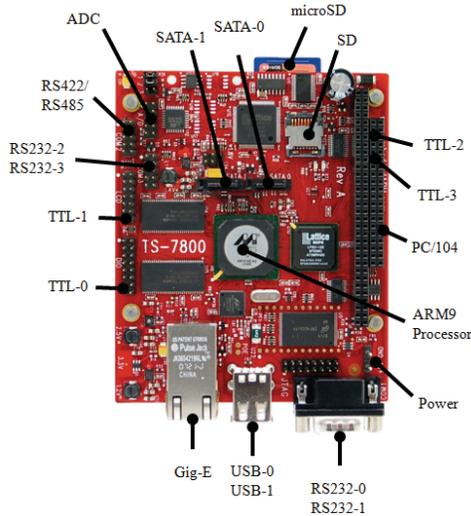


Figure 12. TS-7800 Flight Computer

Table 4. Characteristics of Violet's Flight Computer.

Physical Characteristics
• Technologic Systems TS-7800
• 115mm x 95mm x 20mm, 240 grams
• TTL, RS232, RS485, Gig-E, ADC, USB
Performance Characteristics
• 4W @ +5V power requirement
• 512MB internal NAND flash
• 500 MHz ARM-9 Marvell Processor
• Boots in under 2 seconds

The flight code will be developed in MATLAB/Simulink, which provides a single environment for code development, simulation, and autocode generation. RealTime Workshop will autocode the Simulink model, which will run in Debian Linux with Linux Kernel 2.6.21. Figure 16 shows the harness interconnections.

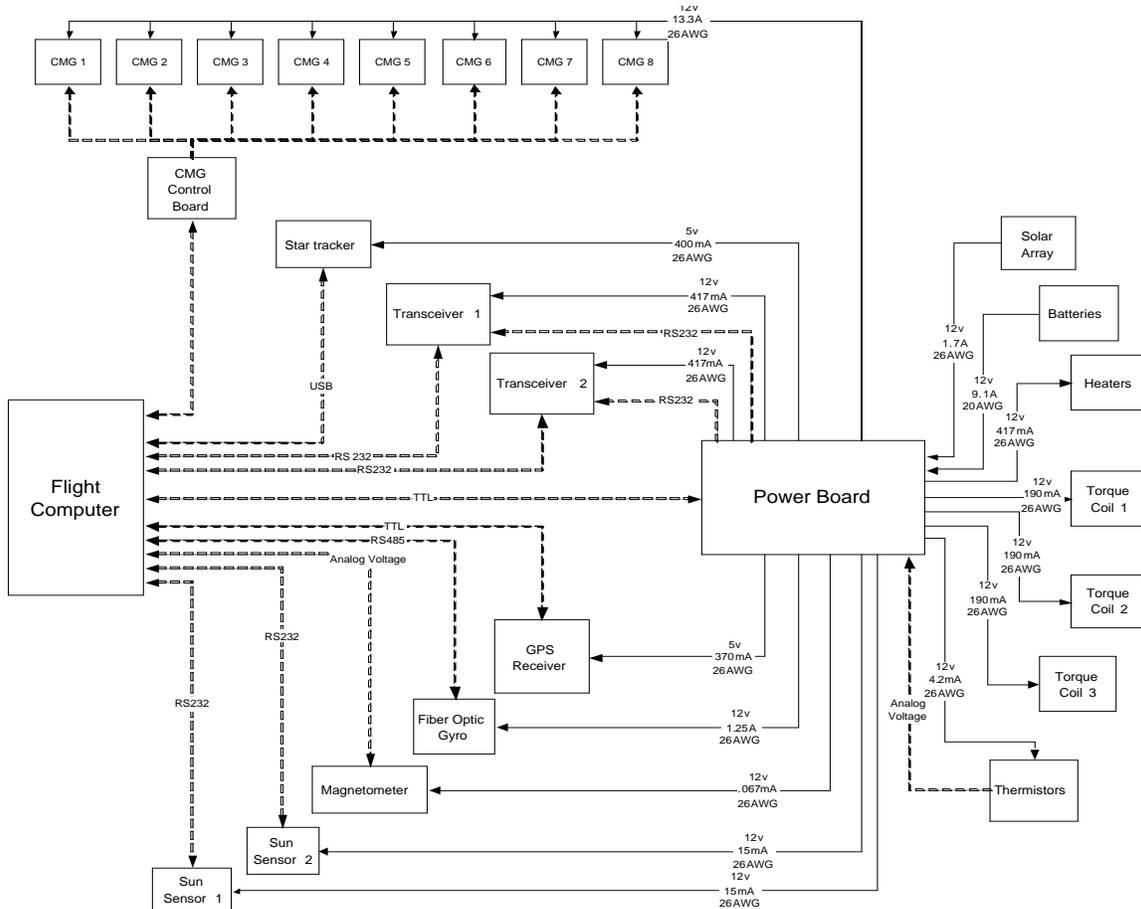


Figure 13. Harness Block Diagram

Power

The power subsystem includes 20 NiCd batteries, triple-junction GaAs solar panels from Spacequest Inc, appropriate harnesses, and the CUSat-heritage power distribution boards. The solar cells are built into small, modular panels that fit approximately 6 per bus face. These small panels simplify integration and allow for a less expensive and more robust approach to spares. Two or three faces are completely covered with such solar panels, which are mounted directly to the aluminum isogrid bus panels. The remaining faces (which include star tracker and telescope apertures, are not meant to face the sun, but each has a single small panel to provide power in the event of a series of failures that would prevent sun from reaching the fully-populated faces. Figure 14 shows the layout.

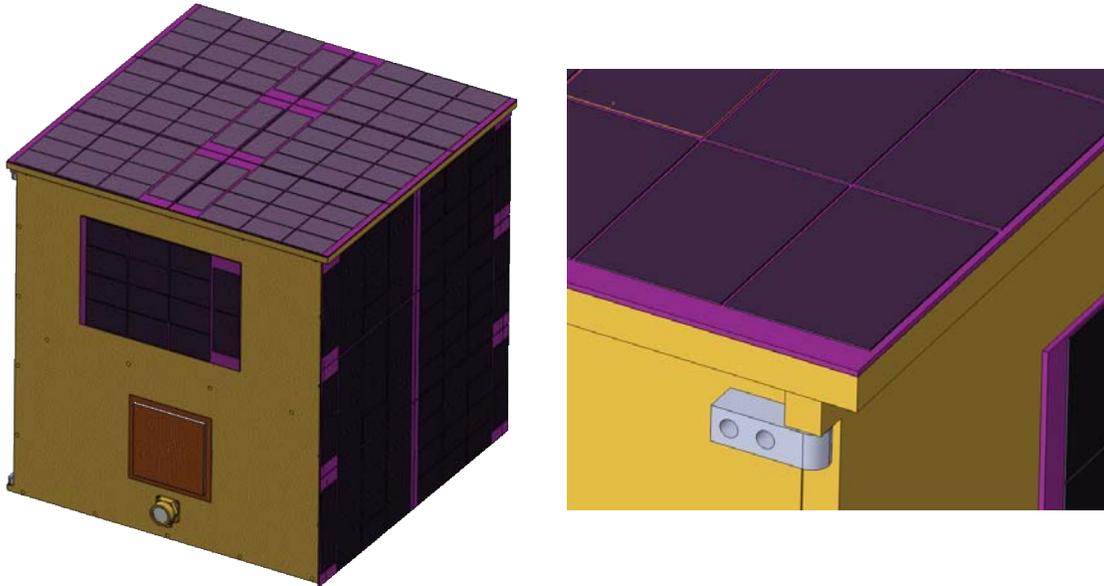


Figure 14. Solar Panel Locations on the Bus (Left) and Close-Up View (Right)

The batteries are Sanyo N-4000DRL cells, as required by the University Nanosat Program. They are configured in 10 cell boxes, as shown in Figure 15, each individually fused. All surfaces of the boxes are anodized. The cells are bonded to the cell-holder with Eccobond 285 thermal epoxy, and the voids are filled with absorbent Nomex felt. This simple design has successfully completed environmental testing at AFRL as part of the CUSat program.

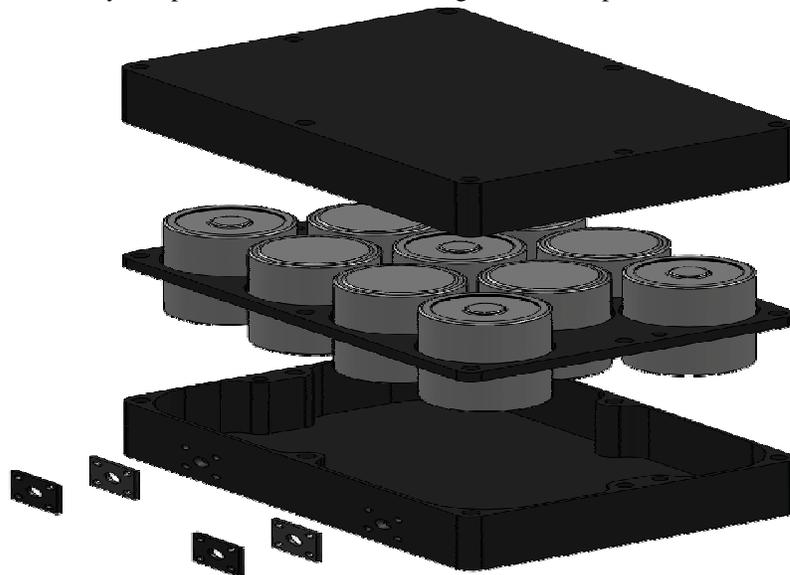


Figure 15. Violet's Battery Box (One of Two on the Spacecraft)

Telemetry and Command Subsystem (T&C)

Violet will use the T&C subsystem architecture from CUSat. For added robustness, it will use the commercially available ZRT 470TR-5 Transceiver, which offers up to 5W power (and is variable) for 4800 baud communications. The downlink and uplink will be in the 70 cm band, permitting the program to use the ground station on Kwajalein that CUSat set up in preparation for the Jumpstart mission and the new ground station being installed on Mount Pleasant, near Ithaca, NY. Figure 19 shows the topology of the ground stations and the CUSat Mission Control Center (MCC). In Violet's operations concept, the data for a slew is stored and then forwarded to the ground at the next available opportunity, initiated by ground command. As a result, continuous T&C coverage is unnecessary.

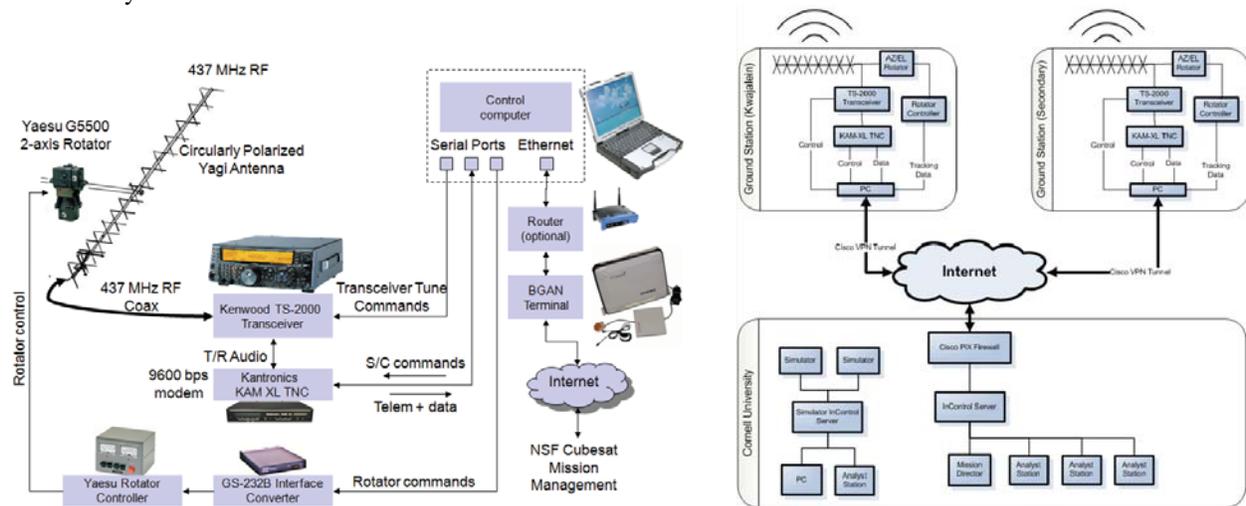


Figure 16. Violet Ground Segment (Kwajalein and Mount Pleasant Stations Shown). Violet Will Replace the CUSat TS-2000 Transceivers Shown Here with ZRT 470TR-5 Radios.

Structure

Violet's structure is simple and stiff. Aluminum isogrid walls comprise the exterior walls, which carry most of the load and support the solar panels, and the interior payload walls. Two of the walls are mounted to the bus structure with hinges. When the spacecraft is integrated, these two walls are fastened to the rest of the structure with helicoils, like everything else, preventing the hinges from carrying load. During integration and test activities, these walls swing outward, allowing ready access to components without requiring that harnesses be demated or structure disassembled. A close-up view of the hinge appears in Figure 14

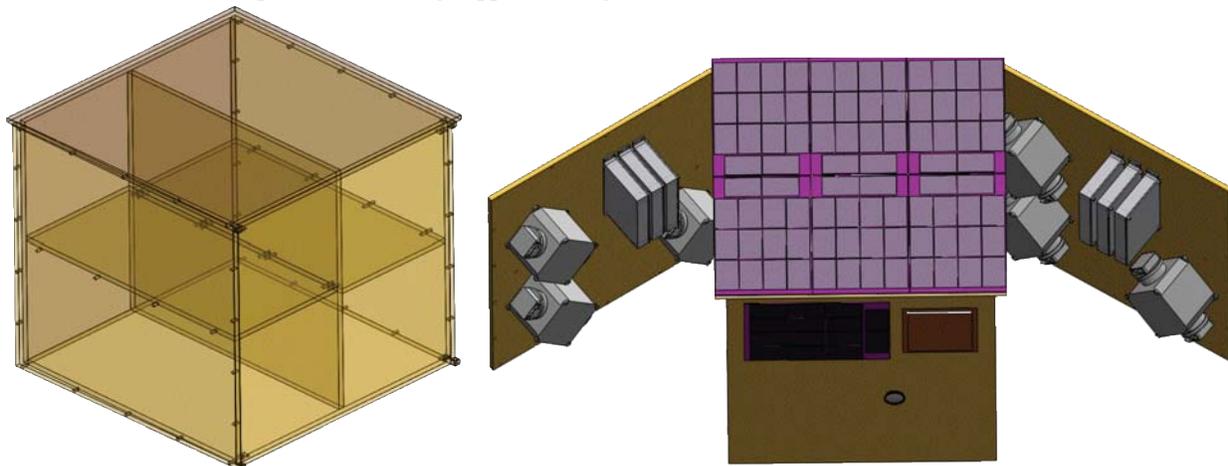


Figure 17. Structure Design: Transparent View of Closed Structure (Left) and Hinged Walls (Right)

IV. Potential Science Objectives

In addition to imaging a reference star or constellation for attitude determination and steering law evaluation, Violet's telescope can be used to complete a variety of science objectives. These objectives fall into two basic categories: pointing objectives, which require Violet to lock onto a stationary target and provide stable images, and tracking objectives, which require Violet to locate and follow a moving target. The science missions under consideration for Violet are outlined below.

Three-Axis Pointing Missions

By operating in the mid-ultraviolet (180-320 nm), Violet is able to perform observations that are impossible for ground-based systems, which are limited by the atmospheric cut-off of approximately 350 nm. Violet can take advantage of the cool star background suppression and the deep minimum in the natural sky background that occur in this band. In other words, Violet is not only capable of performing observations that are impossible for ground-based telescopes, but it also operates in a band with minimal background noise. As a result, Violet is well-suited for photometry-related science.

A. Conducting a Large-Field-of-View Survey of Important Globular Star Clusters, the Magellanic Clouds, and Other Targets of Interest in the Galactic Plane to Complement Observations by GALEX

Hot stars, or stars whose surface temperatures exceed 10,000 K, come in several different varieties, including massive main-sequence stars and low mass, post-giant, helium burning objects, and each type of hot star is important astrophysically because of the unique information that it provides about a stellar population. Massive main-sequence stars, for example, are responsible for most of the ionization, mechanical energy input, and nucleosynthesis in a stellar population, and since they live for only a few hundred million years, they are important indicators of the age of stellar systems. Low mass, post-giant, helium burning objects, on the other hand, appear only in stellar populations that are older than 5 billion years, and their properties are very sensitive to age, heavy element abundances, and helium abundance, which is very difficult to study by other means in stellar systems. However, while hot stars are of great interest astrophysically, they have yet to be studied thoroughly.

Since hot stars are much brighter in the mid-ultraviolet than at longer wavelengths, a telescope operating in the mid-ultraviolet would have a higher sensitivity for the detection of hot stars than a telescope operating in the visible or infrared bands. The deep minimum in the natural sky background in the mid-ultraviolet also makes this band an excellent choice for hot star observations. However, since the mid-ultraviolet lies below the atmospheric cutoff of approximately 320 nm, it requires space instrumentation, and few ultraviolet imaging systems have been launched to date.

The most notable ultraviolet system is the Galaxy Evolution Explorer (GALEX), one of the NASA Small Explorer (SMEX) missions. Since 2003, GALEX has been running a broad ultraviolet survey of the sky, but unfortunately, its coverage is limited by its detector technology, which does not allow it to observe bright ultraviolet point sources. As a result, it is incapable of observing some important globular star clusters, the Magellanic Clouds, and other sources in the plane of the Milky Way. The inability to observe some important globular clusters is particularly noteworthy because it means that GALEX is missing out on an invaluable opportunity to study the hot stars in these clusters; the normally overwhelming cool giant background light is suppressed in the mid-ultraviolet band, so hot stars in these clusters can be isolated and observed more easily.

B. Observing the Lunar Surface to Complement Observations by the LRO

In preparation for returning astronauts to the moon as part of its Vision for Space Exploration, NASA is developing the Lunar Reconnaissance Orbiter (LRO). During its one-year mission, the LRO will map the day-night temperatures on the lunar surface, search for water in permanently shadowed polar regions, return high resolution color images of the lunar surface, and determine the moon's ultraviolet albedo. To complement these measurements, Violet could create low resolution ultraviolet images of the lunar surface.

C. Calculating the Spin Period of Vega

As the first star to be photographed after the sun, Vega is the star that serves as the reference point for the photometric brightness scale; it is a star whose magnitude is set at zero. Since Vega is used as a reference star for numerous astronomical calculations, it is important to have an accurate model of its properties. However, Vega has turned out to be a more complex star to model than initially thought due to its high rotation speed¹⁷. Consequently,

measuring its rotation period would provide important constraints on the stellar astrophysics and astronomical calibration.

Tracking Missions

With its high agility, Violet can track near-Earth objects for up to several minutes. This capability is relevant to several possible science objectives, outlined here.

D. Observing Sprites

A sprite is a flash of light in the atmosphere that occurs directly above an active thunderstorm. Although reports of sprites date back more than a century and images have been obtained from the ground, aircraft, and the space shuttle, the processes that trigger them are still uncertain. Since sprites are visible in the ultraviolet, it might be possible to use Violet to characterize sprites and their emissions. Then, with this data, it might be possible to characterize and better understand such phenomena.

E. Tracking Near-Earth Objects

Although a catastrophic collision with a near-Earth object within the next 100 years seems unlikely, there are several groups dedicated to discovering near-Earth objects and tracking the ones that are currently known. The main focus is on detecting and tracking potentially hazardous near-Earth objects, objects whose size and distance of closest approach make them candidates for a catastrophic collision. Violet can assist in this research by tracking objects that, by reflecting sunlight, are bright enough in the ultraviolet to be detectable by the imaging system. Alternatively, Violet could exploit its attitude-control capabilities to the fullest, tracking near-Earth objects as they approach the Earth and enter its atmosphere and capturing the ultraviolet signal of their demise.

V. Conclusion: Program Plan

Violet's design will be refined through red-team reviews, followed by a sequence of design reviews required by the UNP-6 program. The red team is comprised of technical experts from the aerospace industry, including several prospective guest investigators. Figure 18 shows a schedule of these gates. The Flight Competition Review, in 2011, is a downselect point at which one of the UNP-6 teams will be chosen for launch.

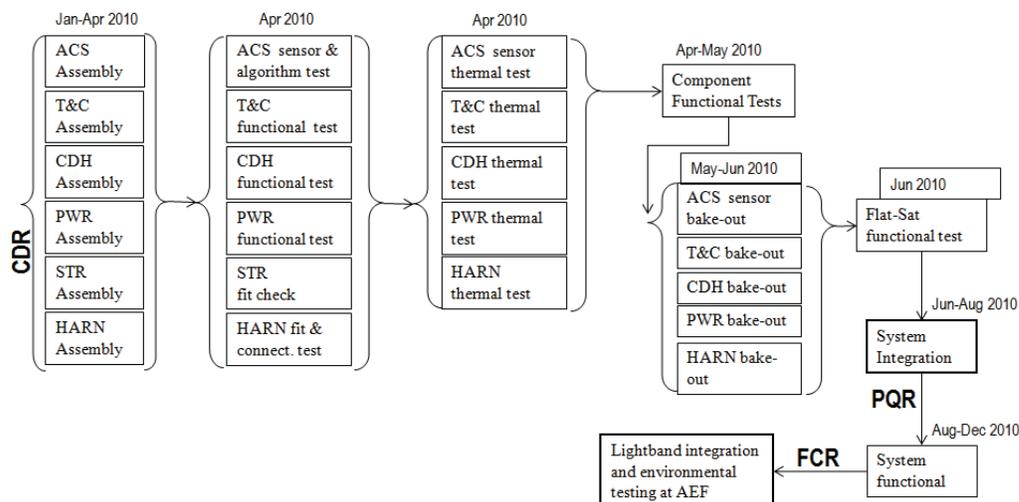


Figure 18. Key Program Dates

The students own the systems-engineering process on Violet, with mentorship from both red-team members and faculty with expertise in this area. Their work has included creating a Systems Engineering Management Plan (SEMP). It specifies Violet's approaches to project planning (master schedule, personnel budget, subsystem architecture & statements of work); project tools (document/ software revision control, action item tracking); and

other systems processes (CM/QA, Risk Tracking & Mitigation, ICDs, budgets, integration & testing plans). Violet's CM/QA plan reflects current industry practice. Hardware and software are subject to configuration management (CM) via cert. logs, document revision, control, and tracking of flight hardware. The Violet team hopes that this rigor will help ensure that Violet's contribution to steering-law research will be successful.

References

- ¹ P. M. Oppenheimer, M. Romano, A. Blocker, and J. Hall, "Novel Three Axis Attitude Control System for Cubesat with High Agility and Pointing-Accuracy Requirements," Paper AAS 09-088, 32nd Annual AAS Guidance and Control Conference, January 30 – February 4, 2009, Breckenridge, Colorado.
- ² D. Brown and M. Peck, "Scissored-Pair CMGs: A Mechanical Constraint Saves Power," *AIAA Journal of Guidance, Control, and Dynamics* Nov-Dec 2008, pp. 1823-1825.
- ³ M. Carpenter and M. Peck, "Dynamics of a High-Agility, Low-Power Imaging Payload," *IEEE Transactions on Robotics*, vol. 24, no. 3, pp. 666-675, 2008.
- ⁴ Davis, P, "Momentum System Concepts and Trades for the New Class of Smaller Lower Cost Satellites," 29th Annual AAS Guidance and Control Conference, February 4-8, 2006 Breckenridge, Colorado.
- ⁵ Kurokawa, H., "Survey of Theory and Steering Laws of Single-Gimbal Control Moment Gyros," *Journal of Guidance, Control, and Dynamics*, vol.30 no.5, pp. 1331-1340.
- ⁶ D. Bailey, "Continuous Attitude Control that Avoids CMG Array Singularities," U.S. Patent 6131056, Oct. 10, 2000.
- ⁷ M. Peck, B. Hamilton, and B. Underhill, "Method and System for Optimizing Torque in a CMG Array," U.S. Patent 7014150, March 21, 2006.
- ⁸ "Plug and Plan (PnP) Spacecraft Technologies (Tacsat-5)," BAA-RV-09-01, AFRL Space Vehicles Directorate, Kirtland AFB, Jan. 15, 2009.
- ⁹ J. Atchison and M. Peck, "Spacecraft Dynamics at the Microscale," Space 2008 Conference and Exposition, Sept. 9-11, San Diego, California.
- ¹⁰ J. Atchison and M. Peck, "A Microscale Infinite Impulse Spacecraft," 2008 AIAA Young Professional, Student, and Education Conference, November 21, 2008, Laurel, Maryland.
- ¹¹ M. R. Elgersma, D. P. Johnson, M. A. Peck, B. K. Underhill, G. Stein, B. G. Morton, and B. J. Hamilton, "Method and system for controlling sets of collinear control moment gyroscopes," U.S. Patent Application 20070124032, Nov. 30, 2005.
- ¹² Cornick, D., "Singularity Avoidance Control Laws for Single-Gimbal Control-Moment Gyros," Guidance and Control Conference, Boulder, Colo., August 6-8, 1979, Collection of Technical Papers. New York, American Institute of Aeronautics and Astronautics, Inc., 1979, p.20-33.
- ¹³ J. Bonn and M. Peck, "Dynamic CMG Array and Method," U.S. Patent 7561947, July 14, 2009.
- ¹⁴ T. Chavez, M. Barrera, and M. Kanter, "Operational Satellite Concepts for ESPA Rideshare," 2007 IEEE Aerospace Conference, March 3-10, 2007, pp. 1-7.
- ¹⁵ University Nanosat-6 Program, "Nanosat-6 User's Guide," UN6-0001, Air Force Research Laboratory, Space Vehicles Directorate.
- ¹⁶ K. Young, W. Shaun, and M. Peck, "CUSat Console Manual," Cornell University, 2009.
- ¹⁷ Fortney, J. J.; Ladders, K.; Marley, M. S.; Freedman, R. S., "A Unified Theory for the Atmospheres of the Hot and Very Hot Jupiters: Two Classes of Irradiated Atmospheres," *The Astrophysical Journal*, Volume 678, Issue 2, pp. 1419-1435.